AN INVESTIGATION INTO TURBINE VENTILATORS AS A POTENTIAL ENVIRONMENTAL CONTROL MEASURE TO MINIMISE THE RISK OF TRANSMISSION OF TUBERCULOSIS –

A LABORATORY AND FIELD STUDY

A thesis submitted to the Faculty of Health Sciences, University of Cape Town, in partial fulfilment of the requirements for the degree of Master of Science in Medicine (Biomedical Engineering)

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DECLARATION

I, FAATIEMA SALIE, know the meaning of plagiarism and declare that all work in this document, save for that which is properly acknowledged, is my own.

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ABSTRACT

TB is an airborne infectious disease which is spread by droplet nuclei, carrying *Mycobacterium tuberculosis*, in the air. The droplet nuclei small enough to enter human respiratory pathways are 1-5 µm in size and are able to travel long distances (Hodgson, et al., 2009) (WHO, 1999), and can be distributed widely throughout (hospital) buildings (Beggs, Noakes, Sleigh, Fletcher, & Siddiqi, 2003). These droplet nuclei may remain suspended in the air until they are removed by dilution ventilation or other disinfection methods (Parsons, Hussey, Abbott, & de Jager, 2008) (National Department of Health, 2007). Dilution ventilation refers to the dilution of contaminated air with "clean" air (ACGIH, 2005), thereby reducing the concentration of contaminants in the room. One of the recognised approaches for minimising the risk of transmission of TB is to adequately ventilate the contaminated room/space. A higher ventilation rate can provide higher dilution capability, in turn reducing the risk of airborne infections (WHO, 2009). The parameters of concern in ventilation design are ventilation flow rate and airflow pattern in the room (and building). The former reduces contaminant concentration while the latter aims to move uncontaminated air to high risk areas, and contaminated air away from occupied areas, usually to the outside.

The shortcomings of conventional natural ventilation strategies are well documented. The aim of this research project is to review and study the effectiveness of natural ventilation design supplemented by a turbine ventilator. The project was divided into two components: a field study and laboratory experiments. In the field study, a turbine ventilator was installed into a bedroom of a low-income house in Pretoria. Tracer gas (concentration decay) tests were performed to determine the ventilation flow rates, mean age of air and air change efficiency of four natural ventilation configurations. These included infiltration/leakage (IL), two cases of single-sided ventilation (SS1 and SS2), and cross-ventilation (CV). Three baseline (without the turbine ventilator) and three turbine ventilator tests were performed, one each in the morning, noon and afternoon. The tests were performed between February and April 2011 on typical summer days.

The turbine ventilator was then tested in a laboratory environment under wind, buoyancy and a combination of wind and buoyancy forces. The wind speeds were low, ranging from 0.0 to 0.5 m/s (0.0 to 1.8 km/h), and the temperature differential tested was in the range of 5.5 to 9.3˚C. The in-duct velocities and centreline velocities were investigated to establish if, under the subjected force(s), a capture envelope described by Dalla Valle's equation could be measured. This envelope would be used to determine if the turbine ventilator could potentially reduce the concentration of airborne contaminants in the test volume.

In the field study baseline tests, IL, SS1, CV and SS2 mean – and range of - ventilation flow rates of 0.6 [0.5 – 0.6], 8.1 [6.8 – 9.3], 16.9 [14.7 – 19.0] and 7.4 [7.0 – 7.9] ACH, respectively, were reported. The baseline tests highlight the potential of cross-ventilation where, by simply opening windows and doors, a ventilation rate exceeding IPC recommendations was obtained. All configurations, save

SS1, appear to have approached the fully-mixed case.SS1 also showed the greatest variability in ventilation flow rates. This finding is not unexpected, as air exchange in single-sided ventilation is due to wind pressure fluctuations, which varied across each test. In addition, in all tests it was found that the ventilation flow rate was dependant on the natural ventilation configuration and openable area, and not necessarily environmental conditions. In the turbine ventilator tests, the mean ventilation flow rates for IL, SS1, CV and SS2 were 1.8 [1.6 – 2.1], 5.4 [5.2 – 5.7], 17.7 [16.0 – 18.6] and 9.5 [8.5 – 10.1] ACH, respectively. The mean ventilation flow rate increased in IL and SS2 with the installation of the turbine ventilator, while in SS1 a decrease was reported. The increase in ventilation flow rate in IL was found to be due to natural convection, where the turbine ventilator merely facilitated the exhaustion of warm air. The results of the field study are specific to the environmental conditions at the time of the test, and are not generalizable.

In the laboratory experiments, the in-duct velocity increased with an increase in wind speed and temperature differential. For a given temperature differential, an increase in wind speed resulted in a decrease in in-duct velocity. Across all tests, no centreline velocity profile, described by the Dalla Valle equation, could be measured. In the wind speed tests, no capture envelope could be established. This was due to the low wind speed test range, where the resulting centreline velocity was beyond the limit of detection of the thin-film sensors. In the buoyancy forces test, a turbulent region near the base of the turbine ventilator was realised, where the magnitude and direction of the air flowing at 1.5D continuously changed. This turbulent region was again observed in the combined wind and buoyancy forces tests, though the magnitude was smaller and occurrence less frequent. The results of the laboratory experiments are specific to the parameters tested, and are not generalizable.

By correlating the field study, laboratory experiments, and previous (similar) studies, it was concluded, that, under the tested conditions, adding a turbine ventilator as a supplement to natural ventilation system will not reduce the concentration of contaminants in the occupied zone in a room.

TABLE OF CONTENTS

SYMBOLS

Symbol	Variable/Parameter	Unit of Measurement
A	Area	m^2
p	Breathing rate of exposed individuals	l/s
$\lvert CO_2 \rvert$	Concentration of Carbon Dioxide	ppm
c	Concentration of tracer gas	ppm
c_e	Contaminant concentration in the exhaust	ppm
i	Counter	
ρ_p	Density of particle	kg/m^3
d	Diameter of spherical particle	m
x	Distance from hood to contaminant source	m
D	Drag force	N
N_t	Droplet nuclei concentration	kg/m.s
μ	Dynamic viscosity of fluid	
F	Effective aerodynamic area	m^2
C_f	Flow coefficient of ventilator	
V_i	Free field velocity incident on ventilator	m/s
p_∞	Free stream pressure	Pa
U_∞	Free stream velocity	m/s
q	Generation rate of infectious agents	
v_h	Hood capture velocity	m/s
c_0	Initial concentration of tracer gas	ppm
N_0	Initial droplet nuclei concentration	
T_{int}	Internal temperature	°C
$\bar{\tau}$	Mean age of air	min
$\langle c \rangle$	Mean contaminant concentration in room	ppm
τ_n	Nominal time constant	min
XDW	Non-dimensional centreline distance	

I	Number of infectious sources/agents	
C	Number of new cases	
S	Number of susceptible occupants/agents	
T_{out}	Outside/Ambient temperature	°C
Y	Percentage centreline velocity	
P_B	Pressure due to buoyancy	Pa
R	Radius	m
ω_0	Rotational speed of ventilator at arbitrary wind speed	rpm
ω'	Rotational speed of ventilator at other wind speeds	rpm
h	Stack height	m
p_s	Static pressure	Pa
C_p	Static pressure coefficient	
ΔT	Temperature differential between intake and exhaust air	°C
v_t	Terminal velocity	m/s
t	Time	min or s or hours
n	Total number of measuring points	
V_V	Velocity through the ventilator	m/s
λ	Ventilation flow rate	ACH
Q	Ventilation flow rate	ACH or l/s/p or m^3/s
Q_0	Ventilation flow rate at ω_0	m^3/s
Q'	Ventilation flow rate at ω'	m^3/s
v_w	Wind velocity (directional)	m/s

GLOSSARY

Air Change Efficiency	A rating given to a ventilation system to express how efficient the ventilation system is at replenishing exhausted air with fresh/cleaner air.
Balometer	An airflow hood which measured airflow through a diffuser.
Capture Velocity	The velocity at any point in front of a hood necessary to overcome opposing air currents and capture the contaminated air by causing it to flow into the hood (ACGIH, 2005).
Contaminant Removal Effectiveness	Contaminant removal effectiveness is a measure how quickly an airborne contaminant is removed from a room (REHVA, 2004).
Cross Ventilation	A ventilation strategy in which air flows from an opening on side of the room to an opening on the opposite side of the room
Cut-in Speed	The speed at which a rational component, like a fan, is subjected to before its starts to rotate.
Droplet Nuclei	Particles one to ten µm in diameter, implicated in the spread of airborne infection; the dried residue formed by evaporation of droplets coughed or sneezed into the atmosphere or by aerosolisation of infective material (Medical Dictionary).
Duct Velocity	Air velocity through the duct cross-sectional area (ACGIH, 2005).
Ethambutol	An antibacterial drug used in combination with other drugs, in the treatment of pulmonary TB (The American Heritage Medical Dictionary, 2007)
Infiltration	The unintentional or accidental entry of air into a building (ASHRAE, 2007).
In vitro	A reaction which occurs in an artificial environment.
Isoniazid	An antibacterial compound used in the treatment of TB (Miller-Keane Encyclopedia and Dictionary of Medicine, Nursing and Allied Heath, 2003) .

Leeward	On the side sheltered from the wind.
Nosocomial	Acquired in a hospital.
Openable wind area	The area of a window through which air can flow. Synonymous with operable window area.
Pyrazinamide	An antibacterial, derived from nicotinic acid, used in the treatment of TB (Miller-Keane Encyclopedia and Dictionary of Medicine, Nursing and Allied Heath, 2003)
Quantum	A quantity or an amount (The American Heritage Medical Dictionary, 2007).
Rifampicin	A derivative of rifamycin which is an antibacterial and antifungal agent used in the treatement of mycobacterial infection, actinomycosis and histoplasmosis (Saunders Comprehensive Veterinary Dictionary 3rd Edition, 2007).
Ventilation	The process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity or temperature within the space (ASHRAE, 2007).
Windward	Facing the wind.

LIST OF ABBREVIATIONS

AIDS	Acquired immune deficiency syndrome
ACH	Air changes per hour
AS	Australian standard
CDC	Centres for Disease Control and Prevention
CFD	Computational fluid dynamics
CRE	Contaminant removal effectiveness
CSIR	Council for Scientific and Industrial Research
CV	Cross-ventilation
EPTB	Extra pulmonary tuberculosis
HEPA	High efficiency particulate air (filter)
HIV	Human immunodeficiency virus
HVAC	Heating, ventilation and air-conditioning
IL	Infiltration/Leakage
IPC	Infection prevention and control
IQR	Interquartile range
l/s/p	Litres per second per person
MDR-TB	Multi drug-resistant tuberculosis
NZS	New Zealand standard
OPD	Out patients department
SD	Standard deviation
PPE	Personal protective equipment
STP	Standard temperature and pressure
TB	Tuberculosis
UVGI	Ultraviolet germicidal irradiation

VSD	Variable-speed drive
WHO	World Health Organisation
XDR-TB	Extensively drug-resistant tuberculosis

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 Background

Tuberculosis (TB) is the disease associated with infection of the *M.tuberculosis* bacillus. It may be pulmonary, where infection occurs in the lungs, or extra pulmonary, where infection occurs in other parts of the body. The standard treatment regimen for TB in South Africa is broken down into two phases. The intensive phase, which usually lasts about two months, comprises Isoniazid, Rifampicin, Pyrazinamide and Ethambutol (National Department of Health, 2004) . The continuation phase, which commences after two consecutive sputum smear negative results, comprises Isoniazid and Rifampicin for four months (National Department of Health, 2004). The evolution of the *M.tuberculosis* bacillus over time and its resistance to certain anti-TB drugs has resulted in multidrug-resistant (MDR) TB and extensively drug-resistant (XDR) TB. MDR TB refers to strains of *M.tuberculosis* resistant to the key first line drugs Rifampicin and Isoniazid (Blomberg, Spincai, Fourie, & Laing, 2001) (CDC, 1999). XDR TB is a sub-group of MDR TB, and refers to strains of *M.tuberculosis* with invitro resistance to any of the fluoroquinolones plus one or more of the injectable second-line anti-TB drugs (CDC, 2006). Drug resistance may either be primary or secondary (Ruiz-Manzano, et al., 2008). Primary resistance refers to resistance resulting from infection with resistant microorganisms, and is found in patients who have never received anti-TB treatment (Ruiz-Manzano, et al., 2008). Secondary or acquired resistance commonly follows erratic TB treatment, i.e. interrupting treatment frequently and for long enough to allow the regrowth of bacteria, favouring resisting mutants (Blomberg, Spincai, Fourie, & Laing, 2001) (Ruiz-Manzano, et al., 2008). If a patient acquires drug-resistant TB, the resultant spread will be drug-resistant TB.

A 2006 article published in The Lancet, entitled "*Extensively drug-resistant tuberculosis as a cause of death in patients co-infected with tuberculosis and HIV in a rural area of South Africa*" (Ghandi, et al., 2006), highlighted the prevalence of MDR TB and XDR TB in South Africa, as well as the high mortality rate associated with XDR TB. The article details a study which surveyed drug-resistant TB in a rural area in KwaZulu Natal, South Africa. In the period 1 January 2005 to 31 March 2006, the sputum of 1539 patients had been cultured. Of these cultures, 221 cases of MDR TB were identified, 53 of which were identified to be XDR TB. Of the 53 XDR TB cases, 55% had never been treated for TB before, and an additional 30% had previously been cured for TB or had previously completed their treatment regimen. In the two years preceding the diagnosis of XDR TB, 67% of the XDR TB patients had been admitted to the district hospital, treated for any cause, not necessarily TB. Contact tracing was conducted for all 53 XDR TB patients. The patients were found to be from a dispersed geographical region. Apart from receiving healthcare from the same district hospital there was no evidence of known contact between any of these patients. Of all 53 patients, no family member had TB before. The authors assumed that transmission, rather than acquisition, of XDR TB had occurred. The assumption was supported by performing genotyping on XDR TB isolates. Genotyping results indicate that 85% of the XDR TB isolates tested were from the KZN family of TB strains and were genetically similar. Nosocomial transmission of XDR TB (airborne route) is suspected here because almost two-thirds of the XDR TB patients were hospitalised before the onset of XDR TB and two healthcare workers died from XDR TB.

TB is an airborne infectious disease which is spread by droplet nuclei, carrying *M.tuberculosis*, in the air. When an infectious TB patient sneezes, coughs, laughs, or sings, *M.tuberculosis bacilli* becomes aerosolised into small droplets of water or bodily fluid (Parsons, Hussey, Abbott, & de Jager, 2008). This can be seen in Figure 1.

Figure 1: An illustration of particle dispersal when a person sneezes (e! Science News, 2009)

Some of these droplets evaporate to form droplet nuclei and become airborne (Parsons, Hussey, Abbott, & de Jager, 2008) . These droplet nuclei vary between approximately 1-5 µm in size (CDC, 1999) and contain microorganisms together with solutes, proteins, and cellular debris and are the carriers of airborne respiratory infection (Nardell & Macher, 1999) . In still air, particles with diameters of 1-5 µm have terminal velocities in the range of 0.3 to 8 $mm.s^{-1}$ (Nardell & Macher, 1999). They are able to travel long distances (Hodgson, et al., 2009) (WHO, 1999), and can be distributed widely throughout hospital buildings (Beggs, Noakes, Sleigh, Fletcher, & Siddiqi, 2003). Droplet nuclei may remain suspended in the air until they are removed by dilution ventilation or other disinfection methods (Parsons, Hussey, Abbott, & de Jager, 2008) (National Department of Health, 2007). A 10µm droplet nucleus may carry three to ten *M.tuberculosis* bacilli (Bloom, 1994), only one of which is needed to cause infection (CDC, 1999) .

In an attempt to minimise the risk of transmission of TB, the number of droplet nuclei containing *M.tuberculosis* in the room air could be reduced. A potential measure to minimise the risk of transmission of TB is to adequately ventilate the contaminated room/space. ASHRAE (ASHRAE,

2007) defines "ventilation" as the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity or temperature within the space. Dilution ventilation refers to the dilution of contaminated air with "clean" air (ACGIH, 2005), thereby reducing the concentration of contaminants in the room. A higher ventilation rate can provide higher dilution capability, in turn reducing the risk of airborne infections (WHO, 2009). Ventilation may be mechanical, i.e. machinery is used as a driving force to produce a certain controlled airflow pattern; natural, which relies on natural forces such as wind and buoyancy to drive the airflow in a room; or a combination of natural and mechanical.

The design and installation of mechanical ventilation requires skilled engineering. Maintenance is essential to ensure that the designed mechanical ventilation system operates as intended. There is an initial capital investment to acquire these systems, as well as a life-cycle cost to maintain performance of these systems.

Natural ventilation systems are challenging to design and control from airborne infection prevention and control (IPC) perspective, and the performance of the system will be variable. It is also difficult to validate the performance of natural ventilation systems because wind and buoyancy forces continuously change. The three major disadvantages of a naturally ventilated system are (WHO, 2009):

1. The fluctuation of the ventilation rate due to variable natural driving forces, with the probability of ventilation rates dropping to near zero at times.
2. The difficulty in achieving consistent airflow directions, and the probability of airflow direction reversing presenting a cross-infection risk.
3. The difficulty in achieving a comfortable internal temperature in extreme climates.

For the purposes of airborne IPC, the parameters of concern in ventilation design are ventilation flow rate and airflow pattern in the room/space (and building). The former reduces contaminant concentration, and the latter aims to move uncontaminated air to high risk areas, and contaminated air to the outside. When compared to mechanical ventilation, natural ventilation generally offers higher ventilation rates, however, in many cases the efficacy of the natural ventilation system is dependant on an amenable climate, openings on the façade, and on the user (i.e. the day to day opening of windows and doors).

This research project investigates turbine ventilators as supplements to natural ventilation from an airborne IPC perspective.

1.2 Motivation for this research project

Ventilation rates and airflow patterns can be controlled by mechanical ventilation. However, mechanical ventilation is not feasible for all levels of public sector healthcare in South Africa, and particularly at the primary level where the majority of patient/client interactions occur and where the majority of health workers are deployed. The shortcomings of conventional natural ventilation strategies are well documented. The aim of this research project is to review and study the effectiveness of natural ventilation design assisted by turbine ventilators, introduced to minimise the risk of transmission of airborne pathogens like TB.

1.3 Hypothesis

It is hypothesised that:

"Turbine ventilators are able to reduce the concentrations of particles of specified mass and size from a room, within specified performance parameters."

If this statement is to hold true, it should be true in the worst case scenario too. In natural ventilation design, climates with high temperatures and low wind speeds, offer low ventilation flow rates. This research project will investigate turbine ventilators under these conditions.

1.4 Objectives of this study

This research project is divided into two components, i.e. laboratory experiments and a field study.

The objectives of the laboratory experiments are:

1. To establish the velocity profile at the base of turbine ventilators in a laboratory environment under varying wind conditions.
2. To establish the velocity profile at the base of turbine ventilators in a laboratory environment under varying temperature differentials.
3. To establish the velocity profile at the base of turbine ventilators in a laboratory environment under a combination of varying wind conditions and temperature differentials.
4. To establish if the turbine ventilator is able to reduce concentrations of particles of a specified mass and size.

The objectives of the field study are:

1. To incorporate the turbine ventilator into a control volume i.e. an existing low-income house. The field study involves using the Tracer Gas (Concentration Decay) Method to measure the air change efficiency of the turbine ventilator.
2. To establish any improvement in weighted average Air Changes per Hour (ACH) achieved when incorporating the turbine ventilator into a natural ventilation strategy.

1.5 Limitations of this study

While many factors are at play in natural ventilation, the ultimate aim of this research project is to determine if turbine ventilators are able to reduce the concentration of particles of specified mass and size, from a target volume below the device. This research project does not aim to find a ventilation solution which provides thermal comfort for occupants, nor does it seek to optimise natural ventilation strategies given the large number of possible health facility room designs and spaces, as well as the large variation in patient volumes and movement within health facilities.

1.6 Dissertation structure

A literature survey of TB-related IPC, particularly in the South African context, is reported in **Chapter 2**. The Field Study Protocol and Laboratory Experimental Protocol are presented in **Chapters 3 and 4,** respectively. Field Study results are reported in **Chapter 5**, and Laboratory Experimental results are reported in **Chapter 6**. A discussion of all results is presented in **Chapter 7.** Conclusions and Recommendations for Further Study are included in **Chapter 8**.

2. NATURAL VENTILATION AS A POSSIBLE ENVIRONMENTAL CONTROL MEASURE TO MINIMISE THE RISK OF TRANSMISSION OF TB

Controlled natural ventilation can minimise the risk of transmission of TB (National Department of Health, 2007), and it may present as a cost-effective solution in IPC in all levels of healthcare facilities in South Africa. This section will explore the fundamentals of airborne IPC, fundamentals of natural ventilation and its relevance to airborne IPC, guidelines for naturally ventilated healthcare facilities design, and investigate turbine ventilators as an innovative technique which may be used to increase the efficacy of natural ventilation strategies.

2.1 Quantifying the airborne infection mechanism of TB

The infective dose of a pathogenic agent is the number of organisms or the amount of toxin required to produce infection or disease (Nardell & Macher, 1999). Infection with *M.tuberculosis bacilli* may occur when one or more droplet nuclei are inhaled (Parsons, Hussey, Abbott, & de Jager, 2008), (National Department of Health, 2007). To spread TB disease, there must be a source, i.e. an infectious TB patient, and a recipient, i.e. an exposed person who inhales droplet nuclei containing the *M.tuberculosis bacilli* (National Department of Health, 2007). TB is an example of a disease in which many infected individuals never develop active disease or become infectious (Nardell & Macher, 1999).

Infectious particles may be relatively dilute and unevenly distributed in air (Nardell & Macher, 1999). For a given exposure, by chance, some individuals will inhale more than one infectious dose, while other individuals will inhale none (Nardell & Macher, 1999). In 1955, Wells developed the concept of a "quantum". A "quantum" represents the required dosage of a pathogen needed to cause infection. It is based on Poisson's Law of small chances, where a "quantum" is the average number of microorganisms needed to infect approximately 63% of susceptible individuals (Nardell & Macher, 1999).

Under steady-state conditions, the expected number of cases amongst a given number of susceptible individuals is proportional to the average concentration of infectious droplet nuclei in a room, and the probability that the particles will be inhaled (Nardell & Macher, 1999). The steady-state equation describing this relation is given by (Nardell & Macher, 1999):

$$C = S\left(1 - e^{-\frac{Iqpt}{Q}}\right)$$ **… Equation 1**

where:

C = expected number of new cases

S = number of exposed susceptible individuals

I = number of sources of infectious aerosols

q = generation rate of infectious agents

p = breathing rate of exposed individuals

t = exposure time

Q = Ventilation flow rate

Equation 1 is known as the Wells-Riley Equation. This theoretical model may not produce accurate estimations because contaminant concentration is not likely to reach steady-state conditions during brief exposures, with extremely infectious sources, or in very large rooms (Nardell & Macher, 1999). The conditions of many infectious exposures however, have materialised such that the assumption of steady-state conditions appear to be reasonable (Nardell & Macher, 1999).

2.2 Infection prevention and control (IPC) practices to minimise the risk of TB transmission

The incorporation of IPC practices may interrupt the transmission of TB in healthcare facilities. The World Health Organisation (WHO) and Centres for Disease Control and Prevention (CDC) have produced IPC guidelines for airborne infectious diseases, such as TB. These guidelines have been adapted to address resource-limited settings. In all of these proposed guidelines exists a hierarchy of control measures, which are:

1. Administrative control measures
2. Environmental control measures
3. Personal protective equipment

2.2.1 Administrative control measures

The most important level of control is the use of administrative control measures to prevent the generation of droplet nuclei, thereby reducing the exposure of healthcare workers and patients to *M.tuberculosis bacilli* (Parsons, Hussey, Abbott, & de Jager, 2008). Administrative control measures include the early diagnosis of potentially infectious TB patients, the initiation of appropriate anti-TB treatment, assessing the risk of transmission in the healthcare facility, the development of a facilitycustomised TB infection control plan and adequate training of healthcare workers to implement the infection control plan (Parsons, Hussey, Abbott, & de Jager, 2008).

Inadequate implementation of administrative controls would result in environmental control measures not being effective in minimising the risk of transmission of TB (WHO, 1999).

2.2.2 Environmental control measures

Environmental control measures are used in high risk areas to reduce the concentration of droplet nuclei in the air (Parsons, Hussey, Abbott, & de Jager, 2008). Environmental control measures can be divided into three broad streams:

1. Control measures which remove airborne pathogens from the room space. Examples of these control measures are ventilation (natural or mechanical) and filtration.

2. Control measures which disinfect the room air. An example is ultraviolet germicidal irradiation (UVGI) lamps.

3. Control measures which contain pathogens to a space. An example would be negatively pressurised airborne infection isolation rooms.

The aim of this dissertation is to explore turbine ventilators as a supporting environmental control measure to minimise the risk of transmission of TB.

2.2.3 Personal protective equipment

Personal protective equipment (PPE) refers to personal control measures undertaken by healthcare workers, and other patients in a facility, to protect themselves from inhaling infectious droplets in high risk settings such as MDR-TB and XDR-TB facilities (Parsons, Hussey, Abbott, & de Jager, 2008). For TB IPC, the PPE used are N95 respirators. This respirator has the ability to effectively filter 95% of particles 0.3 µm in diameter (3M, 2002). These respirators have elastic bands and an adjustable nose band to create a snug-fit around the nose and mouth area.

Surgical face masks are made of cloth or paper, and do not have a snug fit around the nose and mouth. The use of a surgical face mask does not significantly protect healthcare workers, patients or visitors against TB infection, however, it can be worn by TB patients to reduce the number of aerosolised TB particles in the room (OSHA, 2009).

2.3 Natural ventilation as a solution in TB IPC

The Wells-Riley equations relates the probability of infection to environmental control measures through the ventilation flow rate, Q. In this research project, natural ventilation is chosen over mechanical ventilation as a potential environmental control measure, as it may present as a more realistic solution in primary healthcare facilities in South Africa.

2.3.1 Natural ventilation fundamentals

The two driving forces of natural ventilation are wind and buoyancy. The flow of air between any two points is due to the presence of a pressure difference between those two points (ACGIH, 2005). When wind strikes a building it induces a positive pressure on the windward side and a relative negative pressure on the leeward side (WHO, 2009), (Khan, Su, & Riffat, A review on wind-driven ventialtion techniques, 2008). This forces air to flow through the windward openings into the building, towards the lower-pressure openings at the leeward side, as illustrated in Figure 2 (CIBSE, 2005). Air flow patterns are of great importance because they determine the path of the droplet nuclei (Bolashikov & Melikov, 2009).

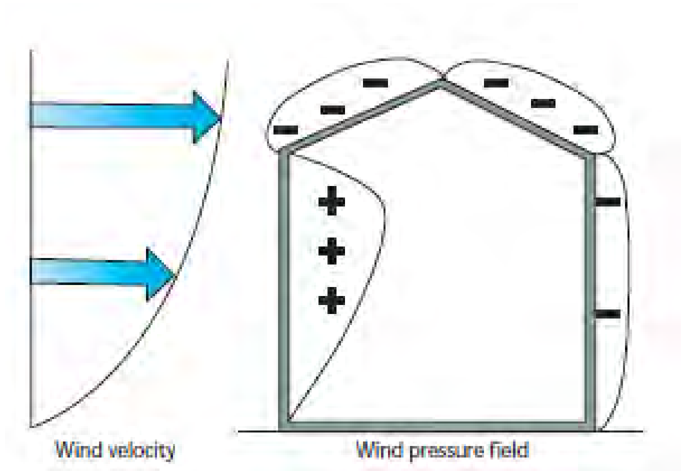


Figure 2: Wind pressures on the façade of the building (CIBSE, 2005)

Buoyancy forces are generated from the air temperature or density differences between the indoor and outdoor air (WHO, 2009), (Khan, Su, & Riffat, A review on wind-driven ventialtion techniques, 2008). This difference generates an imbalance in the pressure gradients of the indoor and outdoor air columns, causing a vertical pressure difference (WHO, 2009). When the room is warmer than the outside, the room air is less dense than the outside air, and rises, as in Figure 3. Air enters through lower openings and escapes through upper openings (WHO, 2009). Buoyancy forces are dominant during periods of low wind speed and are reduced in summer periods when temperature differences are minimal (Khan, Su, & Riffat, A review on wind-driven ventialtion techniques, 2008). In low-wind conditions, air exchange that is caused by buoyancy may not generate enough internal air movement (WHO, 2009).

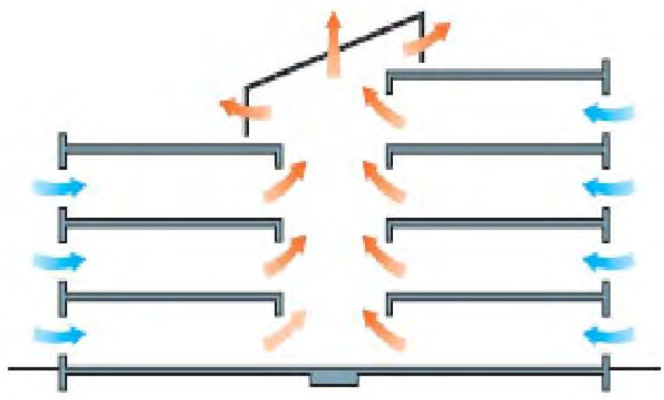


Figure 3: Atrium stack ventilation - an example of natural ventilation by buoyancy forces
(CIBSE, 2005)

Designing natural ventilation systems is systematic, and involves a multi-layered approach. These include [(WHO, 2009)refers to (Priolo, 1998):

1. Site design, which extends to building location, site layout, building orientation and landscaping.
2. Building design – The form and function of the building, the building envelope and natural ventilation strategy, thermal mass, heating, ventilation and air-conditioning (if present).
3. Vent opening design – Positioning of openings, type of opening, size of opening, and a control strategy.

2.3.2 Natural ventilation as a solution in TB IPC

In 2009, the WHO published *Natural Ventilation for Infection Control in Health-Care Settings* (WHO, 2009). The document is divided into two parts. Part 1 promotes the natural ventilation design for IPC in healthcare facilities. Part 2, describes the basic principles of natural ventilation systems to design, construct, operate and maintain an effective natural ventilation system. According this document, the WHO recommends that, for natural ventilation, the following ventilation criteria should be met:

- For all new health-care facilities or facilities undergoing major renovation, an hourly average ventilation rate of 160 l/s/patient for airborne precaution rooms, with a minimum of 80 l/s/patient.
- A minimum hourly averaged ventilation rate of 60 l/s/patient for out-patient departments (OPD) and general wards.

- A minimum hourly averaged rate of 2.5 $l/s/m^3$ for corridors and other transient spaces without a fixed occupancy.

The guideline further recommends that the natural ventilation design should allow for the overall airflow to bring air from contaminant sources to areas of sufficient dilution, and preferably be exhausted to the outside.

The (CDC, 2005) guidelines replaces the (CDC, 1994) guidelines, in which the minimum ventilation rate for airborne infectious isolation rooms are set to 12 ACH. Facilities built, or majorly renovated, post (CDC, 1994) were to comply with a minimum ventilation rate of 12 ACH, and facilities built prior to (CDC, 1994) were to comply with a minimum ventilation rate of 6 ACH. According to (WHO, 2009), the rationale for setting the minimum ventilation rate to 12 ACH is based on two main aspects. The first is the effect of the ventilation rate on the decay of droplet nuclei in a ventilated space. The second is the mathematical model, the Wells-Riley Equation (Equation 1), to estimate the effect of the ventilation rate on the risk of infection for known airborne diseases. These two principles indicate that a higher ventilation rate results in a more rapid decay of airborne pathogens in the room air (WHO, 2009). By rephrasing the Equation 1, the theoretical relationship between the removal of droplet nuclei and the ventilation flow rate can be expressed as Equation 2 (Parsons, Hussey, Abbott, & de Jager, 2008):

$$\frac{N_t}{N_0} = e^{-Qt} \quad \ldots \textbf{ Equation 2}$$

where:

N_t = droplet nuclei concentration at time t

N_0 = initial concentration of droplet nuclei

Q = ventilation flow rate in ACH

Based on this model, in high-risk areas, for an exposure time of 15 minutes in a room ventilated at 12 ACH, the probability of infection would be below 5% (WHO, 2009).

When ACH is used to measure the ventilation performance, the volume of the ventilated space becomes an important parameter (WHO, 2009). For a given ACH, a ventilated space with a larger volume may provide a larger airflow rate (m^3/s or l/s) compared to a ventilated space with a smaller volume (WHO, 2009). A study done by Nardell *et al* (Nardell & Macher, 1999), used Equation 1 to estimate the effect on TB infection rate by increasing the building's ventilation rate (Nardell & Macher, 1999). The results of the study are shown in Figure 4. From Figure 4 it can be seen that doubling the ventilation rate reduces the number of infected individuals to about 40%..This study assumes a well-mixed room, and does not account for variability in occupancy and contaminants in the room.

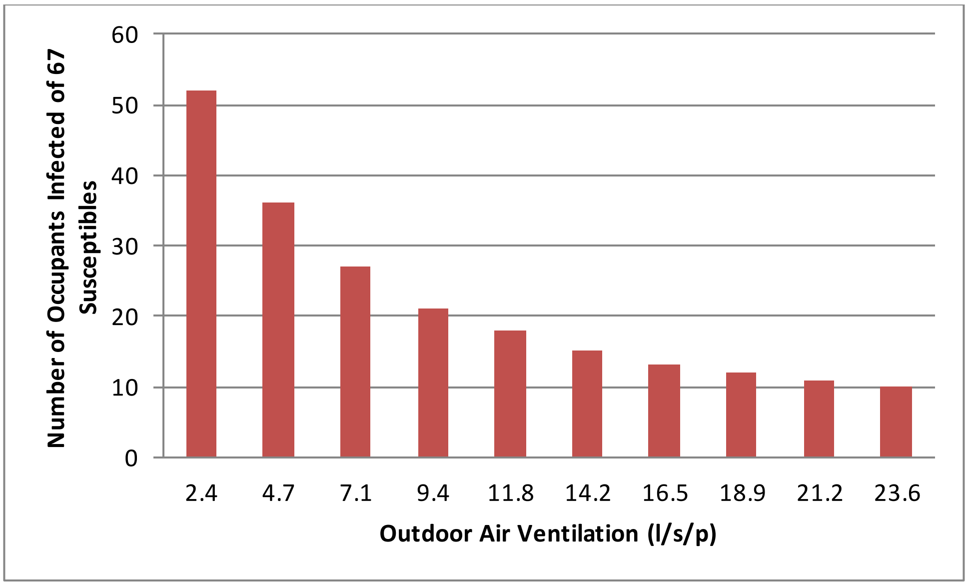


Figure 4: An illustration of the effect of ventilation flow rate on TB infection, adapted from (Nardell & Macher, 1999)

Escombe (Escombe, et al., 2007) investigated ventilation in hospitals and clinics in Lima, Peru, where infectious patients may be encountered. (Escombe, et al., 2007) investigated the determinants of natural ventilation, and used mathematical modelling to calculate the effect of natural ventilation on the airborne transmission of TB. In their study, 368 experiments were performed in 70 naturally ventilated rooms in eight healthcare facilities. Five of these facilities were built pre-1950, hereafter called "old-fashioned", and three of these facilities were built between 1970 and 1990, hereafter referred to as "modern". The architectural and environmental determinants under consideration were areas of windows and doors open, presence of open windows or doors on opposite walls to facilitate cross-ventilation, ceiling height, floor area, elevation of room above ground level, temperature, relative humidity and wind speed at the window.

(Escombe, et al., 2007) used a tracer gas decay technique to measure the ventilation flow rate in the rooms. The following naturally ventilated configurations were investigated: all windows/doors closed; some, but not all, window/doors opened; and all windows/doors fully opened. Ventilation was assessed in two ways, i.e. absolute ventilation and ACH. Absolute ventilation was calculated by multiplying the ACH by the room volume. The risk of airborne infection was calculated by the Wells

Riley Equation (Equation 1), where certain assumptions about quanta generation and exposure were made.

The number of rooms tested in (Escombe, et al., 2007) was large, and the data was collated and evaluated statistically. This approach makes it difficult to assess the performance of each room's natural ventilation strategy in its respective environment. For all naturally ventilated facilities, when all windows and doors were closed, the median absolute ventilation rate was 0.03 m^3/s (121 m^3/h), and an ACH of 1.5 ACH. Opening all windows and doors resulted in a median absolute ventilation rate of 0.69 m^3/s (2,477 m^3/h) and the mean ACH was 28 ACH. (Escombe, et al., 2007) also found that opening increasing numbers of windows and doors, increased the ventilation flow rates. A comparison between old-fashioned and modern naturally ventilated healthcare facilities was also made by (Escombe, et al., 2007). The median absolute ventilation rate was 1.04 m^3/s (3,769 m^3/h) for old-fashioned naturally ventilated facilities, and 0.33 m^3/s (1,174 m^3/h) for modern naturally ventilated facilities. Compared to modern naturally ventilated building, old-fashioned naturally ventilated buildings were larger (85m^3 vs. 60m^3), had higher ceilings (4.2m vs 3.0m), had bigger windows (6.6m^2 vs. 3.4m^2), and were more likely to have windows and doors on opposite walls (56% of rooms vs. 19% of rooms). Statistically, (Escombe, et al., 2007) found the driving determinants of natural ventilation to be the area of openable windows and doors, placement of windows on opposite walls (cross ventilation), floor area and wind speed at the window. The significant difference in median volumetric airflow rates between modern and old-fashioned volumetric flow rate could therefore not be explicitly contributed to openable area to the room. The orientation of the building, and the position of respective room in that building, also plays a role. A response by (Levin, 2007) to (Escombe, et al., 2007) points out that the ventilation rate through windows is a function of the window size, the number and location of windows, and the indoor-outdoor temperature differences and the wind velocity.

Using the Wells-Riley model (Equation 1), under the assumption of 24 hour exposure, and 13 quanta of infectious agents per infectious TB patient, the calculated median estimated risk of TB transmission was 97% for all naturally ventilated facilities with windows and doors closed. The patient loading (floor area per patient) for old-fashioned and modern natural ventilated buildings was 9.2m^2 vs. 9.3m^2, respectively. The calculated median estimated risk of TB transmission was, with all windows and doors opened, 33% in modern naturally ventilated facilities and 11% in old-fashioned naturally ventilated facilities. (Escombe, et al., 2007) further investigated the estimated risk of TB transmission by increasing the source infectiousness, i.e. increasing quanta of infectious agents. The model predicted that the dilution effect reduces with increasing infectious material. The model also predicts that all exposed individuals will become infected when the duration of exposure increases sufficiently. The results and discussion presented here of (Escombe, et al., 2007) are specific to the study conducted in Lima, Peru, and are not generalizable (Levin, 2007).

When designing a naturally ventilated healthcare facility, the design must take into account fluctuations in the ventilation rate. A literature review, reported in (WHO, 2009), on the link between ventilation and airborne infection transmission, highlighted the following points:

1. Increased infection or outbreaks of airborne diseases are associated with lack of ventilation or low ventilation rates.

2. The risk of airborne infection could be decreased by high ventilation rates. A higher ventilation rate is able to provide a higher level of dilution and consequently reduces the risk for airborne infection.

3. The airflow from an infectious patient can lead to infection further away from the patient. The rate of infection reduces with an increase in physical distance from the infectious patient. An essential condition of airflow-induced infection is that the airborne pathogen concentration in the patient location has to be sufficiently high to cause infection to susceptible individuals.

4. It appears as though airflow from an infectious patient with sufficiently high dilution may not lead to further infection. There is, however, insufficient data to support this observation and there is no available data on the minimum dilution needed to minimise infection transmission.

This section has highlighted the important design factors for airborne IPC, i.e. ventilation flow rate and airflow patterns.

2.4 Turbine ventilators

A turbine ventilator, shown in Figure 5, is a wind-driven air extractor comprising a number of vertical blades, which may be straight or curved, arranged in a spherical or cylindrical manner, mounted onto a frame (Khan, Su, & Riffat, A review on wind-driven ventialtion techniques, 2008). A weather-proof dome is located on top of the frame (Khan, Su, & Riffat, A review on wind-driven ventialtion techniques, 2008). Turbine ventilators have traditionally been used to extract hot air from attics during summer months. As the stale hot air is extracted, it is replaced with fresh ambient air entering through doorways and windows. In this way the indoor temperature is decreased. In winter months, turbine ventilators extract moisture-laden air which may condense in roofs and attics.

Figure 5: A turbine ventilator

The operation of a turbine ventilator is illustrated in Figure 6.When wind reaches the aerofoil vanes, the resulting lift and drag forces cause the turbine to rotate (Khan, Su, & Riffat, A review on wind-driven ventialtion techniques, 2008). This rotation produces a negative pressure inside the turbine ventilator and air enters the turbine axially from the base and is expelled radially (Khan, Su, & Riffat, A review on wind-driven ventialtion techniques, 2008). (Khan, Su, Riffat, & Biggs, Performance testing and comparison of turbine ventilators, 2008) noted that the turbine ventilators work through a combination of the negative pressure induced by the ventilation rotation and the negative pressure induced by the external wind, as illustrated in Figure 6. In the absence of wind, a turbine ventilator facilitates ventilation by buoyancy forces (Khan, Su, & Riffat, A review on wind-driven ventialtion techniques, 2008).

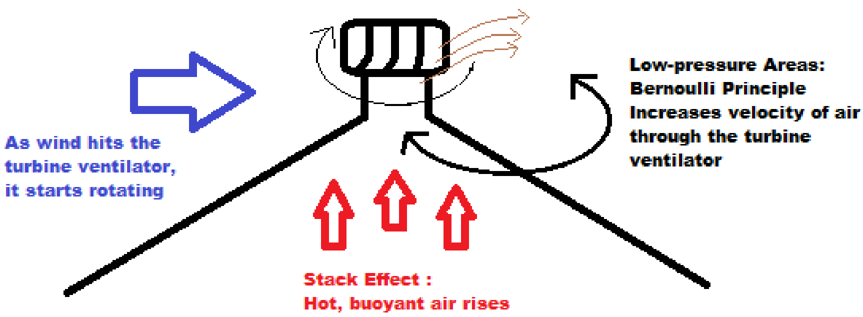


Figure 6: Operation of a turbine ventilator. Adapted from (How it works)

Lai (Lai, 2003) investigated the efficiency of turbine ventilators used for building and factory ventilation. Flow visualization tests were performed to provide insight into the way in which air flows through a turbine ventilator. When air from outside enters the turbine ventilator, the flow is divided into two streams on the same horizontal plane. The flow on the one side follows the same rotation as the turbine and becomes the force which causes continuous rotation. This air flows through the ventilator towards the wake region. The second stream is in the opposite direction to the blades and dampens the ventilation rotation. The two streams converge in the wake region. Figure 7 illustrates the flow of air through the turbine ventilator using a tracer gas.

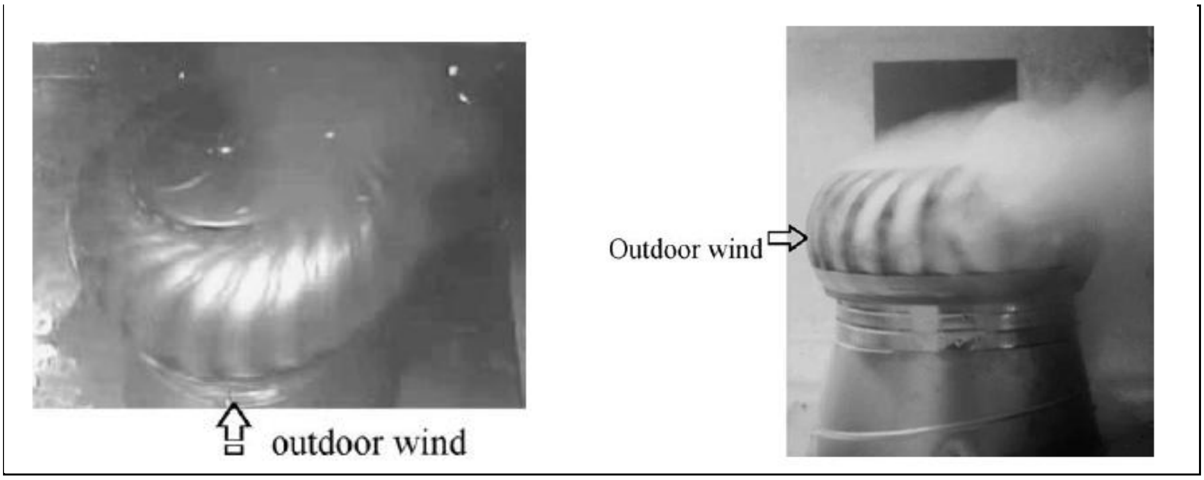


Figure 7: Flow structure through a turbine ventilator (Lai, 2003)

Lai (Lai, 2003) performed three groups of experiments. The first investigated the installation effect of ventilators; the second investigated the effect of turbine ventilator size; and the third investigated inner vane effect. The experiments were performed in a low-speed wind tunnel. In the first set of experiments, (Lai, 2003) showed that the turbine ventilator was helpful in inducing airflow. The first experiment also showed that when the turbine ventilator was out of order, or stationary, the turbine ventilator would block the airflow and the resulting ventilation rate was then lower than if there were no turbine ventilator installed.

Results of Lai's (Lai, 2003) second set of experiments are shown in Figure 8. Three turbine ventilators, of sizes 150 mm (6 in), 360 mm (14 in) and 500 mm (20 in) were tested. The results indicate that the bigger the size of the turbine ventilator, the bigger the ventilation rate it induces, though the difference between the 0.36 m (14 in) and 0.5 m (20 in) turbine ventilators were not significant. The sizes of the turbines differ, and are not geometrically equivalent. In the third set of experiments, (Lai, 2003) showed that inner vanes increase the induction of flow, though not significantly.

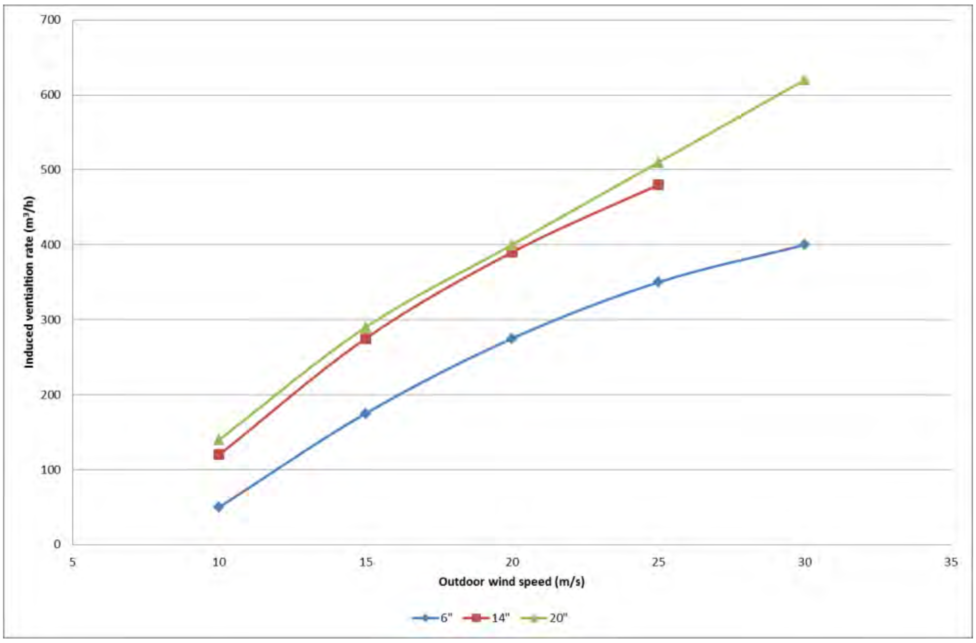


Figure 8: Effect of turbine ventilator size on ventilation capacity, adapted from (Lai, 2003)

Khan et al (Khan, Su, Riffat, & Biggs, Performance testing and comparison of turbine ventilators, 2008) tested and compared the performance of four turbine ventilators using the rig described in AS/NZS 4740 (AS/NZS 4740, 2000). A full description of the rig is described in **Appendix D**. The turbine ventilators tested include a 300 mm straight vane turbine ventilator, a 300 mm curved vane turbine ventilator and two 250 mm polycarbonate straight vane turbine ventilators, one of which was transparent for day lighting. The results, presented in Figure 9, showed that the 300 mm turbine ventilators had significantly greater ventilation rates than the 250 mm turbine ventilators. The 300 mm curved vane turbine ventilator had a greater ventilation capacity than the 300 mm straight vane turbine ventilator. This difference could be attributed to the difference in blade configuration and construction material (Khan, Su, Riffat, & Biggs, Performance testing and comparison of turbine ventilators, 2008).

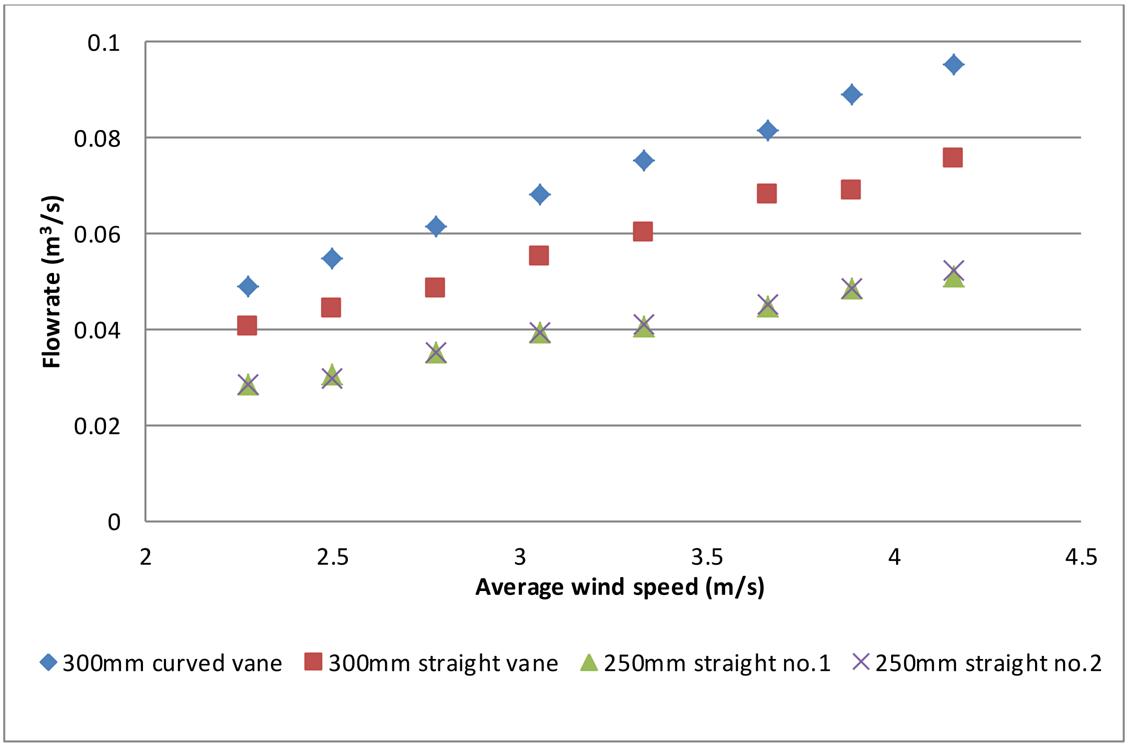


Figure 9: Flow rate as a function of wind speed, adapted from (Khan, Su, Riffat, & Biggs, Performance testing and comparison of turbine ventilators, 2008)

(Khan, Su, Riffat, & Biggs, Performance testing and comparison of turbine ventilators, 2008) refers to a study done by Havens (Havens, 2004) where (Havens, 2004) compared a turbine ventilator to a backward curved centrifugal fan. (Khan, Su, Riffat, & Biggs, Performance testing and comparison of turbine ventilators, 2008) then compared the measured data of the four turbine ventilators to a calculated value, given by Equation 3, if the turbine ventilator obeyed the fan law:

$$\frac{Q'}{Q_0} = \frac{\omega'}{\omega_0}$$ … **Equation 3**

where:

ω_0 = rotational speed at an arbitrary wind speed

Q_0 = flow rate at ω_0

ω' = rotational speed at other wind speeds

Q' = calculated flow rate at ω'

The measured and calculated flow rates for three of the turbine ventilators are presented in Table 1. From Table 1, it can be seen that the measured values are in good agreement with the calculated values for the three turbine ventilators. This would suggest that turbine ventilators perform like centrifugal fans (Khan, Su, Riffat, & Biggs, Performance testing and comparison of turbine ventilators, 2008).

Table 1: **Fan law applied to three turbine ventilators, adapted from** (Khan, Su, Riffat, & Biggs, Performance testing and comparison of turbine ventilators, 2008)

	Measured value	Calculated value	% Difference
300 mm Straight vane ventilator	43.7	43.8	0.34
	48.9	49.0	0.26
	54.1	54.3	0.21
	59.4	59.5	0.17
	64.6	64.7	0.15
	69.8	69.9	0.12
	75.1	75.1	0.11
300 mm Curved vane ventilator	54.4	53.6	1.46
	61.3	60.5	1.15
	68.1	67.4	0.93
	74.9	74.3	0.77
	81.7	81.2	0.65
	88.5	88.0	0.55
	95.3	94.9	0.47
250 mm Straight vane ventilator	31.0	31.2	0.78
	34.5	34.7	0.62
	38.0	38.2	0.50
	41.5	41.7	0.41
	45.0	45.2	0.35
	48.5	48.7	0.30
	52.0	52.2	0.26

(Khan, Su, Riffat, & Biggs, Performance testing and comparison of turbine ventilators, 2008) then used a 12-24 DC motor, coupled to a power supply through a voltage controller for speed control, to rotate a 300 mm straight vane turbine ventilator. The flow rate as a function of turbine rotational speed was compared to the results obtained in the wind driven tests, and is shown in Figure 10. From Figure 10 it can be seen that, for the same turbine ventilator rotational speed, a higher flow rate is achieved in the wind-driven case than in the motor-driven case. (Khan, Su, Riffat, & Biggs, Performance testing and comparison of turbine ventilators, 2008) convey that this may be experimental evidence to confirm that the turbine ventilator works through a combination of negative pressures induced by the turbine ventilator rotation and the negative pressure induced by the overpassing wind. The difference in flow rates between the two cases is related to additional negative pressure induced directly by the wind.

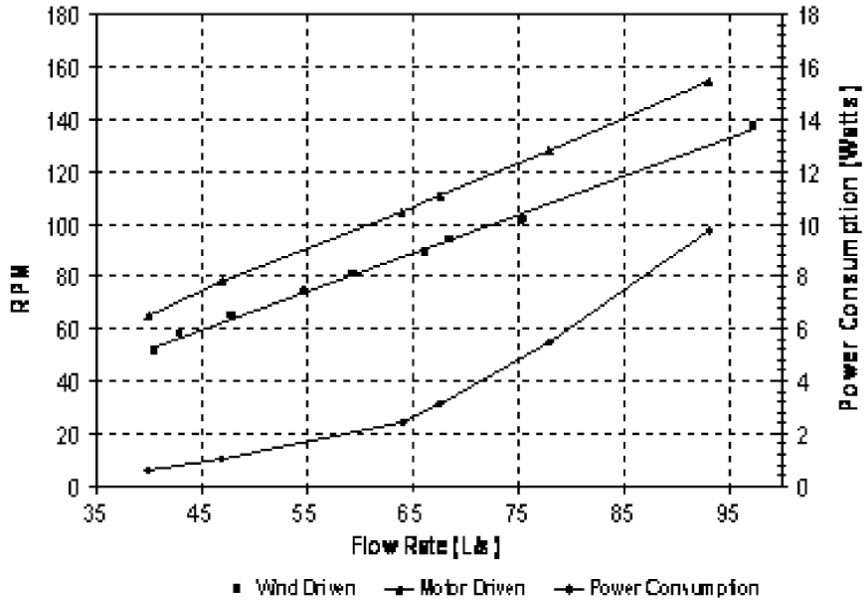


Figure 10: Flow rate as a function of turbine rotational speed for wind and motor driven tests

(Khan, Su, Riffat, & Biggs, Performance testing and comparison of turbine ventilators, 2008)

Lien and Ahmed (Lien & Ahmed, Wind driven ventilation for enhanced indoor air quality, 2011) summarised the work done on turbine ventilators at the University of New South Wales. The first study, also presented in (Lien & Ahmed, Effect of inclined roof on the airflow associated with a wind driven turbine ventilator, 2011), investigates the effect of roof inclination angle on forces on the turbine ventilator, the effect of roof inclination angle on turbine ventilator rotation speed and the effect of roof inclination angle on static pressure on the roof, in a wind tunnel. The physical experiment set-up is shown in Figure 11.

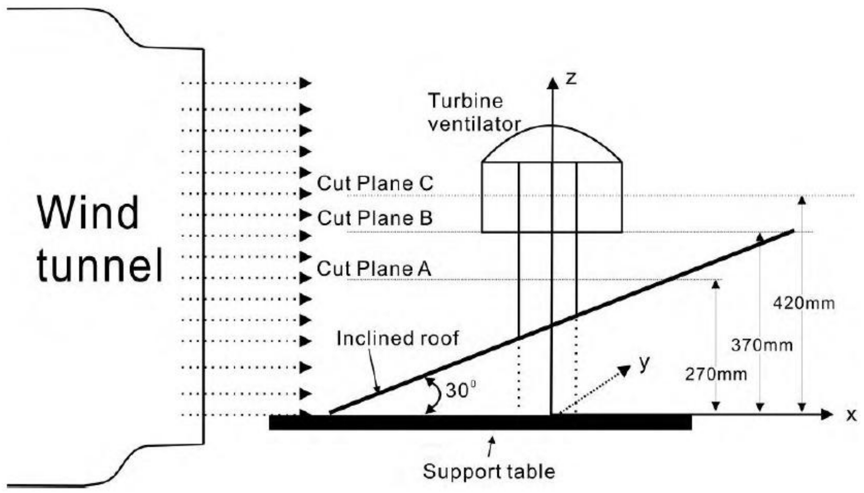


Figure 11: Experimental set-up to investigate the effect of roof inclination on turbine ventilator performance (Lien & Ahmed, Wind driven ventilation for enhanced indoor air quality, 2011)

The total force and the force components in the x, y and z directions on the turbine ventilator were investigated at inclination angles of 0˚, 15˚ and 30˚. Results of these tests indicate that forces acting on the turbine ventilator increase with an increase in free stream velocity. The increasing trend was most prominent in the x direction, which implies that the roof inclination angle has the greatest effect on the force component which contributes to drag.

The force components were then normalised to force coefficients by $0.5\rho U_\infty^2 A$, where ρ is the density of air, U_∞ is the free stream velocity, and A is the total wetted area of the turbine ventilator, and is calculated from the total area of the turbine ventilator exposed to the flow. The force coefficients were examined against the Reynolds number based on the rotor diameter. It was found that the force acting on the turbine ventilator was independent on the Reynolds number beyond a certain turbine ventilator rotational speed and very relevant at lower wind speeds.

The study also looked at the effect of the roof inclination angle on the turbine ventilator rotational speed. The results are shown in Figure 12. The results show that there is a linear relationship between the turbine ventilator rotational speed and the free stream velocity. It also indicates that the increasing roof inclination angle reduces the turbine rotational speed. From Figure 12 it can be seen that this point is more noticeable at higher wind speeds, suggesting that the roof inclination angle has little effect of the total mass flow extracted by the turbine ventilator at low wind speeds.

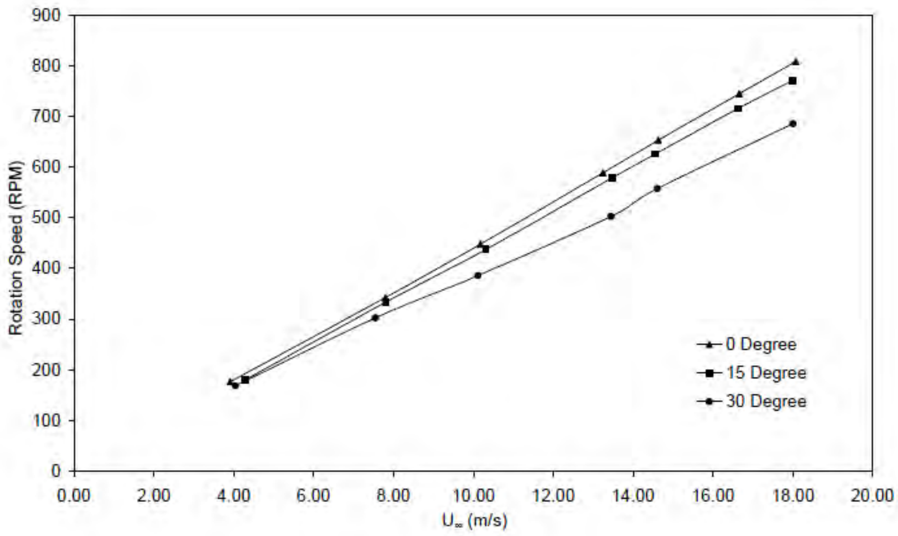


Figure 12: Effect of roof inclination angle on turbine ventilator rotational speed (Lien & Ahmed, Wind driven ventilation for enhanced indoor air quality, 2011)

In the same study, the pressure profiles on the roof were established. The results of the static pressure distribution, presented as a non-dimensional coefficient, C_p, on the roof at different roof inclination angles, at a free stream velocity of 10 m/s, are shown in Figure 13. The static pressure coefficient, C_p, is given by Equation 4:

$$C_p = \frac{(p_s - p_\infty)}{0.5\rho_\infty U_\infty^2}$$ … **Equation 4**

Where:

p_s = static pressure at the measuring point

p_∞ = static pressure of the free stream flow

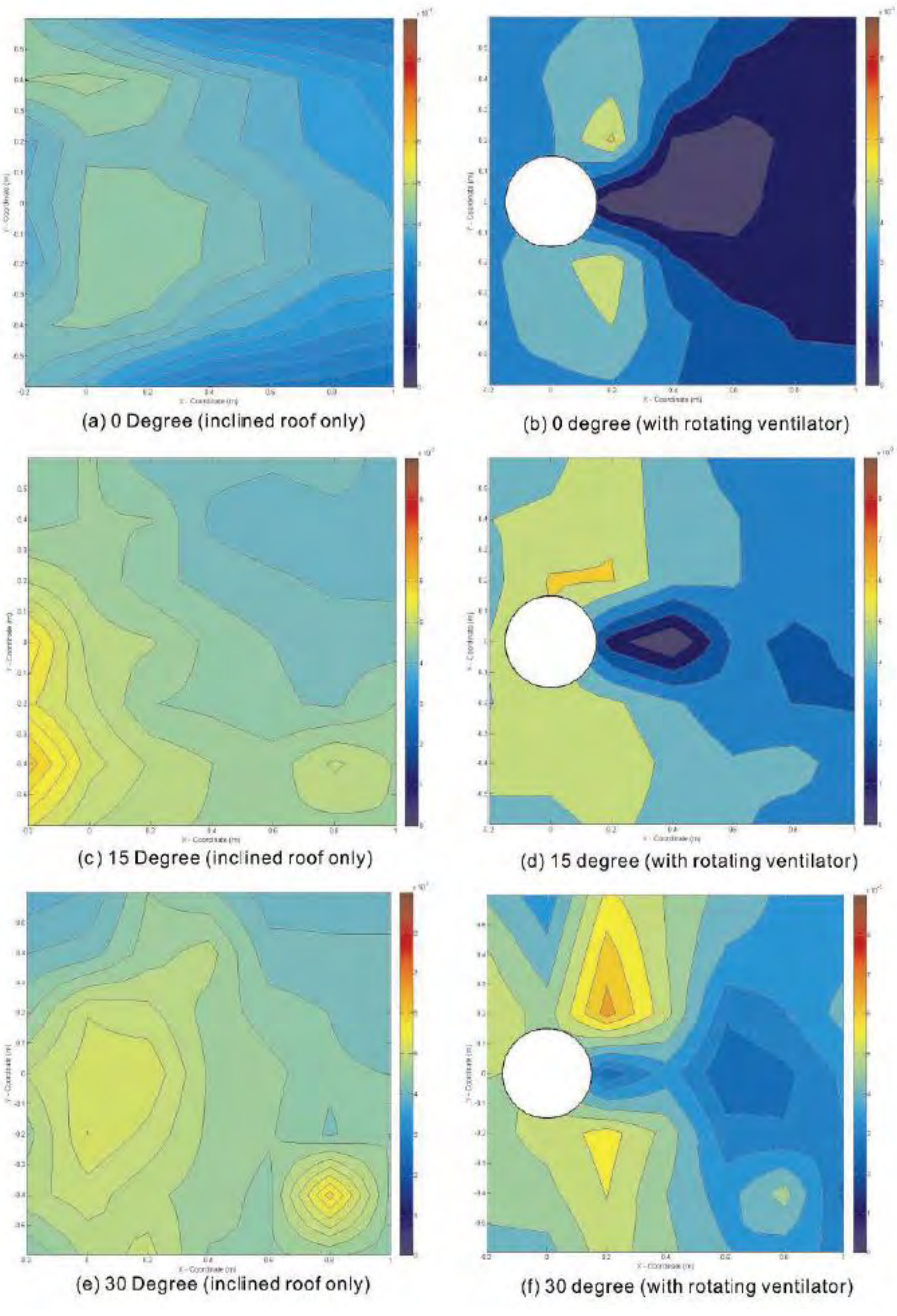


Figure 13: Static pressure distribution on roof for different roof inclination angles at a free stream velocity of 10 m/s (Lien & Ahmed, Wind driven ventilation for enhanced indoor air quality, 2011)

In Figure 13, the value of C_p ranges from +1 to any negative number. When C_p is positive, the flow is slowing down to the limiting value of +1 which is the zero velocity condition. When C_p is negative, the flow is accelerating, with a more negative value indicating a higher acceleration. A comparison between pressure profiles in the left hand-side diagrams (inclined roof only) and the right hand-side diagrams (rotating turbine ventilator) at different roof inclination angles show that the turbine ventilator imposes a pressure gradient on the free stream flow, slowing the flow across the roof.

The performance of the turbine ventilator was then investigated by computational fluid dynamics (CFD). The domain modelled was similar to that of the physical experiments. The CFD model was used to determine external flow across and internal flow through the turbine ventilator. A three-dimensional flow path for a 10m/s free stream velocity is shown in Figure 14. In Figure 14, it can be seen that the left-hand side flow follows the turbine ventilator rotation (clockwise) and the right-hand side flow is against the turbine ventilator rotation (counter-clockwise). The forces from the right-hand side flow results in the formation of a secondary circulation between the separated flow and the turbine ventilator blades on the right-hand side flow (Lien & Ahmed, Wind driven ventilation for enhanced indoor air quality, 2011).

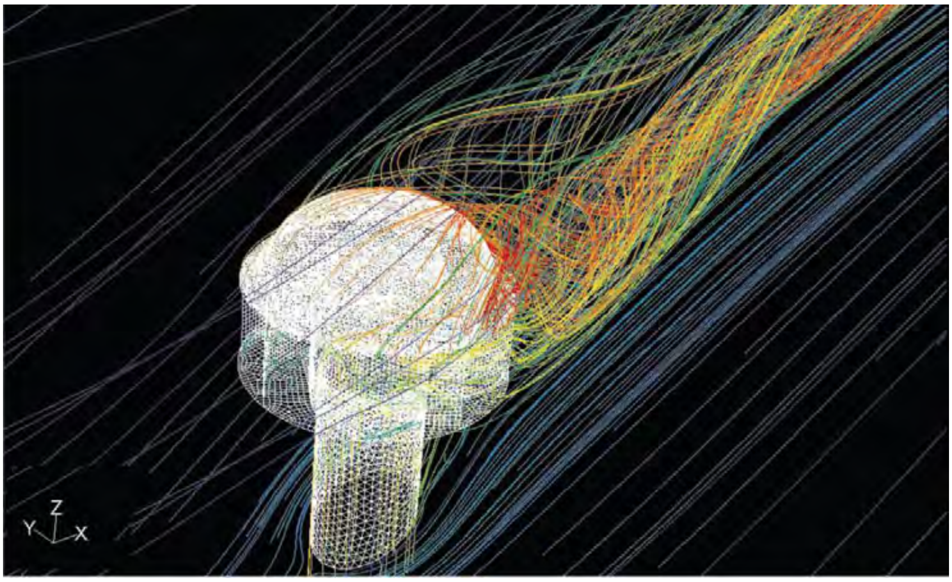


Figure 14: Path lines of flow associated with a rotating turbine ventilator at a free stream velocity of 10m/s (Lien & Ahmed, Wind driven ventilation for enhanced indoor air quality, 2011)

The flow through the turbine ventilator at different wind speeds in cut plane B (left) and cut plane C (right) are shown in Figure 15. The cut planes are illustrated in Figure 11. The flow inside the turbine ventilator duct swirls upward to mix with the secondary circulation of the wake region on the right-hand side downstream of the turbine ventilator. The simulation was run at wind speeds of 5, 10 and 15 m/s. Results of the simulation show that the wake region behind the turbine ventilator increases in size with increasing wind speeds. This results in increased suction behind the turbine ventilator, and increases the swirl component in the turbine ventilator. The observation of the CFD model is in agreement with the flow visualisation of Lai (Lai, 2003).

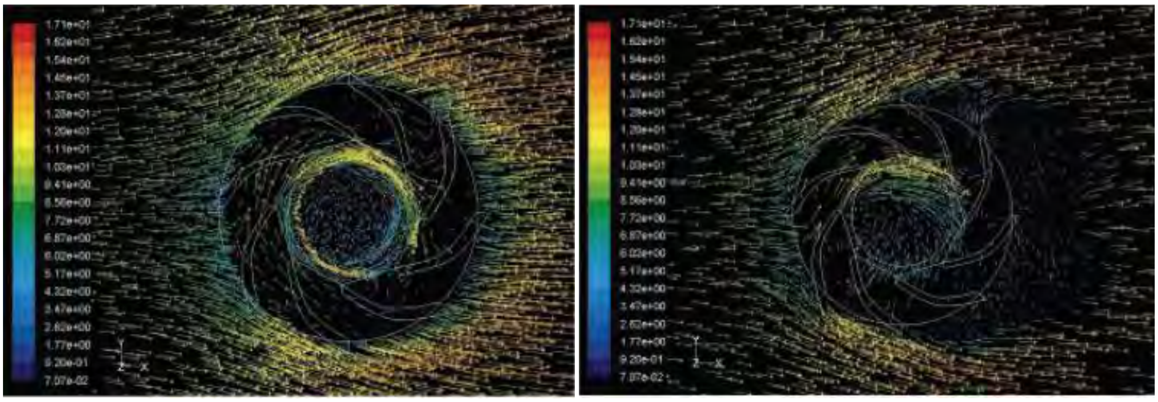


Figure 15: Velocity vectors through the turbine ventilator at cut plane B (left) and cut plane C (right) at a free stream velocity of 10 m/s (Lien & Ahmed, Wind driven ventilation for enhanced indoor air quality, 2011)

The use of turbine ventilators for airborne infection control has been documented in (WHO, 2009). The International Organisation for Migration (IOM) Holding Centre in Damak accommodates migrants in isolation units, shown in Figure 16, while they undergo health screening. The isolation units have three large windows and a large 800 mm gap between the upper part of the wall and the eaves. A turbine ventilator is installed on the apex of the unit to increase ventilation rates and to ensure an upward movement of air. The design is intended to maximise natural ventilation by allowing a constant updraft of air, which enters through the windows and exits through the eaves and turbine ventilator. There is no formal study on the performance of these isolation units to minimise infection amongst suspected and confirmed infectious migrants.

Figure 16: Isolation units at the IOM Holding Centre in Damak (WHO, 2009)

Cox et al (Cox, et al., 2012) investigated turbine ventilators as a way to improve ventilation for TB infection control in health facilities. The aim of the study was to assess the efficacy of turbine ventilators to achieve recommended ventilation rates. The study was performed in primary care clinics in Khayelitsha, South Africa. Turbine ventilators were ducted into four rooms of three different clinics. If the room had a ceiling, flexible ducting was used to duct through the roof space to ceiling level. The turbine ventilators were all made of aluminium, had curved vanes and were locally supplied. A louvered air intake grille was mounted onto a wall or door in the room where the turbine ventilator had been installed. The location of the air intake grille was chosen based on where the freshest air could be provided.

The ventilation flow rate of the ventilation system was measured over a 5-8 minute period using tracer gas decay testing. The decay was measured in the centre of the room, at a height of a seated person. Wind data was recorded simultaneously using an anemometer located on the roof, no more than two meters from the turbine ventilator. Three natural ventilation system scenarios were tested:

1. All doors and windows were closed and the turbine ventilator and air intake grille blocked.
2. One window was opened, with the door closed and the turbine ventilator and air intake grille blocked.
3. Only the turbine ventilator and air intake grill were opened, windows and doors were closed.

In the period April 2009 to March 2011, a total of 332 tracer gas decay tests were performed in the four rooms. As wind speed and ventilation rate were significantly skewed, median values were used to describe wind speed and ventilation rate. The mean wind speed recorded was 2.8 m/s (10.1 km/h) and the external temperature recorded ranged from 15.1˚C to 34˚C during tests. Clinic A was located in a geographical depression and recorded consistently lower wind speeds compared to clinic B and C. The temperature differential between inside and outside temperature was small, a mean difference of 0.4˚C and a standard deviation of 1.7˚C.

The ventilation flow rate and wind speed data of all four rooms were pooled, and assessed in terms of quartiles of wind speeds [Q1 : 0.28 – 1.90 m/s (1.0 -6.8 km/h); Q2 : 1.90 – 2.81 m/s (6.8 – 10.1

km/h); Q3 : 2.81 – 3.72 m/s (10.1 – 13.4 km/h) and Q4 : 3.72 – 13.90 m/s (13.4 – 50.0 km/h)], as presented in Figure 17. Results indicate that the median ventilation flow rate increased with increasing wind speed quartiles for each of the three ventilation system scenarios. A comparison between the different scenarios shows that the turbine ventilator and air intake grille perform better than single-sided ventilation across all wind speed quartiles.

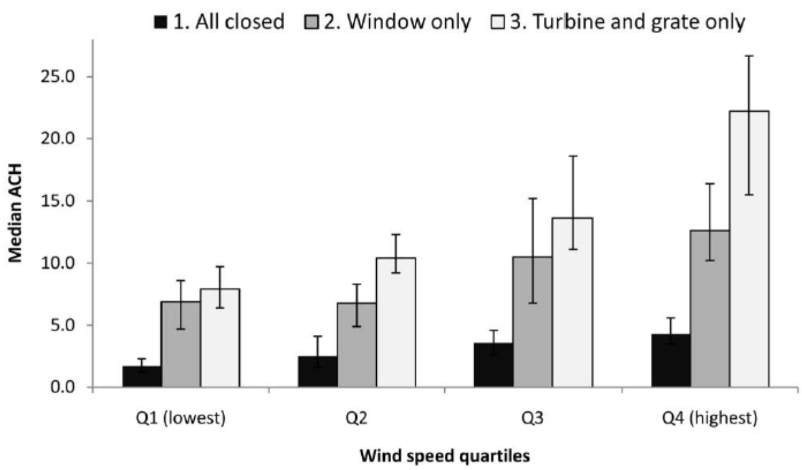


Figure 17: Median ventilation rates given in terms of wind speed quartiles (Q) for all rooms combined (Cox, et al., 2012)

The performance of the turbine ventilator and intake grille compared to single-sided ventilation, across the four rooms, was further investigated and presented in Table 2. The WHO recommended ventilation flow rate of Table 2 is determined by the amount of air needed to deliver 60 l/s/person for a single occupant for the volume of that room. From Table 2 it can be seen that turbine ventilators and air intake grilles only produced higher median ventilation flow rates than windows opened only. Table 2 also shows that the number of times the turbine ventilator and intake grille met or exceeded the WHO requirement was significantly greater than the number of times the opened window met or exceeded the WHO recommendation.

Table 2: Median ventilation flow rate and number of time ventilation flow rate is above the WHO recommendation (Cox, et al., 2012)

	Room 1	Room 2	Room 3	Room 4	Total (all rooms)
WHO recommended ACH	*10.0*	*6.7*	*7.4*	*6.5*	
Window only (scenario 2)					
Number of experiments	51	5	26	24	106
Median ACH	8.1	3.7	7.3	11.4	8.5
IQR	6.2–10.1	2.7–4.8	3.5–11.2	7.2–15.7	5.5–11.5
Range	2.1–29.6	2.0–4.6	1.3–16.4	2.4–24.8	1.3–29.6
No. above WHO recommendation	15 (29%)	0 (0%)	13 (50%)	20 (83%)	48 (45%)
Turbine and grate only (scenario 3)					
Number of experiments	43	7	23	22	95
median ACH	8.9	13.5	16.7	13.4	11.3
IQR	5.8–12.0	10.6–16.4	9.4–24.1	8.0–18.9	7.2–15.4
Range	3.2–21.6	9.2–17.2	8.4–30.0	6.3–37.7	3.2–37.7
No. above WHO recommendation	20 (47%)	7 (100%)	23 (100%)	21 (95%)	71 (75%)
Comparison between scenarios 2 and 3					
P value (comparison of medians)	0.28	0.004	<0.000	0.07	<0.000
P value (comparison of proportion above WHO recommendation)	0.09	0.004	<0.000	0.40	<0.000
% Contribution of roof turbine to ACH* (95% CI)	71 (64–78)	61 (48–75)	49 (43–55)	40 (36–43)	58 (53–62)

*Calculated by using the measurement of actual flow through the turbine, at the same time as overall ACH measurement.

During the tracer gas concentration decay tests, an airflow capture hood was used to measure the flow through the turbine ventilator. The capture hood was used to take manual measurements at one minute intervals, and was averaged over the test period. These measurements were used to calculate the contribution of the turbine ventilator to the room ventilation rate. From Table 2 it can be seen that the fraction of the total estimated mean ventilation flow rate through the turbine ventilator was 71% in room 1, 61% in room 2, 49% in room 3 and 40% in room 4, and 58% for all rooms combined. (Cox, et al., 2012) highlighted that the advantage of turbine ventilators over windows in their study is likely related to variability of wind, as turbine ventilators will rotate regardless of wind direction if positioned optimally on roof apexes, whereas ventilation via windows, especially single-sided ventilation in their case, was very subjective to changes in wind direction.

In this chapter, airborne infection control to minimise the risk of transmission of airborne pathogens was discussed. Dilution, via natural ventilation, was considered as an environmental control measure, the aim of which is to reduce the number of airborne pathogens, thereby minimising the risk of airborne transmission. The limitations of natural ventilation were discussed, and turbine ventilators were presented as a potential solution to increase the ventilation rate and compromise control of internal airflow in buildings. From the literature discussed in this section, the factors affecting the performance of turbine ventilators are:

1. The presence of wind and buoyancy forces

2. The shape of turbine ventilator blades
3. The diameter of the turbine ventilator
4. Roof inclination angle
5. Location of the turbine ventilator relative to the apex of the roof
6. Openings in the room

In the following chapters, the performance of the turbine ventilator will be investigated in a Field Study and Laboratory Experiments.

3. FIELD STUDY SET-UP AND PROTOCOL

The aim of the field study was to determine the ventilation flow rate and air change efficiency achieved when incorporating a turbine ventilator into a naturally ventilated system. This was accomplished by performing tracer gas (concentration decay) tests.

3.1 Objectives of the field study

The objectives of the field study were:

1. To incorporate the turbine ventilator into a control volume – a room in an existing low-income house - as a field study. Tracer gas (concentration decay) tests were used to measure the air change efficiency of the turbine ventilator.

2. To establish any improvement in weighted average ventilation flow rate (in ACH) achieved when incorporating the turbine ventilator into a natural ventilation strategy.

3.2 Test materials

3.2.1 The turbine ventilator

In **Chapter 2** it was found that turbine ventilators with longer blades and a wider turbine base diameter perform better than their counterparts. In this study, the best performing turbine ventilator was not tested. Instead, a more common, cost-effective and locally available turbine ventilator was selected.

Tests were performed on the 300 mm Windmaster Tornado® Turbine Ventilator, shown in Figure 18. The turbine ventilator is made of galvanised steel, and weighs 6.3 kg. It is reported to have an air removing capacity of 0.41 m^3/s (1,489 m^3/h) at an average wind speed of 4.17 m/s (15 km/h). Specifications for the Windmaster Tornado® Turbine Ventilator are provided in **Appendix A**.

Figure 18: A 300mm Windmaster Tornado turbine ventilator

3.2.2 Description of the low-income house

The low-income house used in this field study, hereafter referred to as the “reference house” and shown in Figure 19, is situated on the CSIR Built Environment Innovation Site at the CSIR’s Pretoria campus. A layout of the reference house is shown Figure 20 and architectural drawings are presented in **Appendix B.**

The reference house has a floor area of 39.6 m^2, and a volume of 110.5 m^3. It has two bedrooms, a living room, kitchen and bathroom. The external walls are made of 140 mm solid cement block, and the internal walls of 90 mm solid cement block. All internal walls have a cement slurry finish. The floor is a 75 mm concrete slab with a 75 mm power-floated concrete finish. The roof is made of 0.5 mm hard galvanised roof sheeting.

Figure 19: The reference house

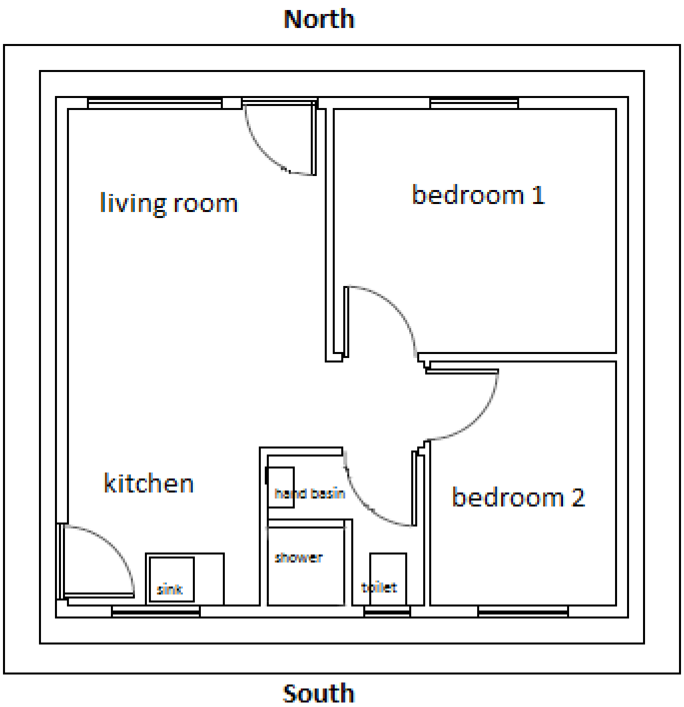


Figure 20: Layout of the reference house

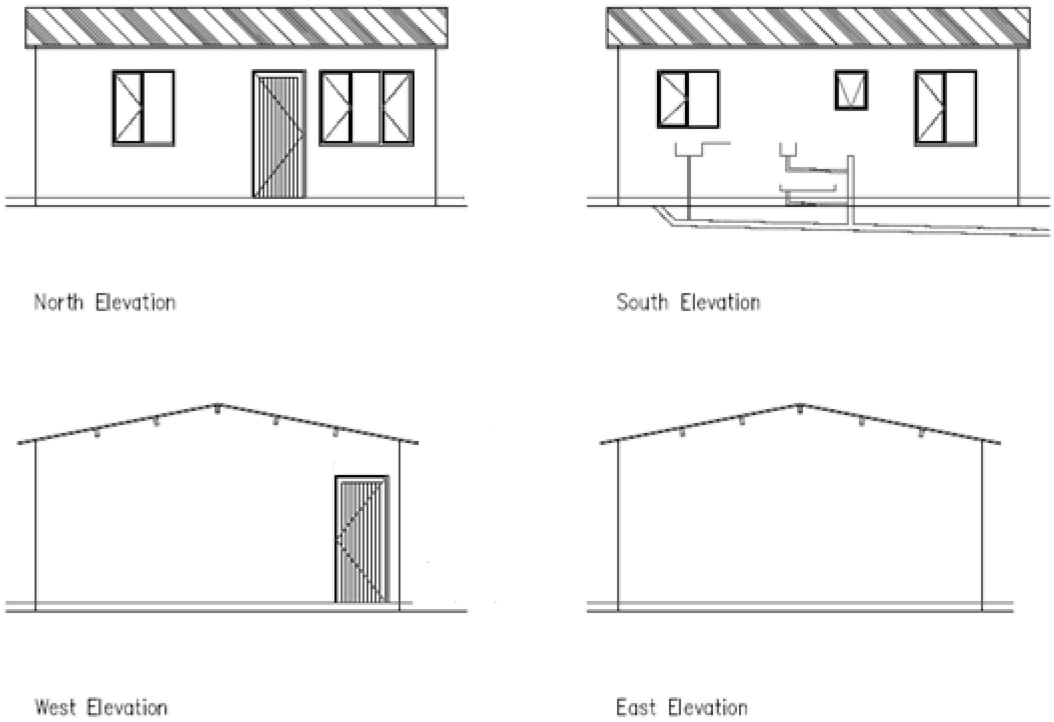


Figure 21: North, south, west and east elevations of the reference house

Figure 21 is an illustration of each façade of the house. Windows are located on the northern and southern facades, and doors on the southern and western facades. The windows of the reference house are not efficient in delivering the maximum available air for natural ventilation to all areas of the house. The windows of bedroom 1 and 2, and the living room and kitchen are side-hung windows which open to the outside. The window in the bathroom is a top-hung window which also opens to the outside. The openable window area on the northern façade is 1.92 m^2, and 1.62 m^2 on the southern façade. Openable window area is an important parameter because it is directly related to the amount of air which can enter and leave the house. Side-hung and top-hung windows greatly reduce the effective openable area of windows. The northern and southern facades are 2.5 m high. The eastern and western facades have been inclined at 11˚, and peaks at the centre at a height of 3.08 m. The prevailing winds at the test site were from the North Eastern direction. Wind roses for Pretoria are presented in **Appendix C**.

3.2.3 Thermal considerations of the reference house

The thermal performance of the reference house (without the presence of a turbine ventilator) was studied by Osburn (Osburn, 2010). Using Energy Plus (v 3.0.0.028) (Osburn, 2010) was able to establish the temperature profiles inside the house as a function of outside temperature, in extreme conditions. (Osburn, 2010) assumed an accommodation schedule in the reference house which accounted for heat generation (due to occupants and appliances). (Osburn, 2010) also assumed that air exchange was due to infiltration/exfiltration. During summer months, most of the low-income houses in South Africa are not heated or cooled, and the internal temperature changed according to the outdoor temperature (Makaka, Meyer, & McPerson, 2008). Figures 22 and 23 are temperature profiles of a hot and cold day, respectively. The "well insulated house" referred to in these figures is a newly proposed low-income house developed by the CSIR Built Environment which added carpeting, a ceiling and insulation to the reference house.

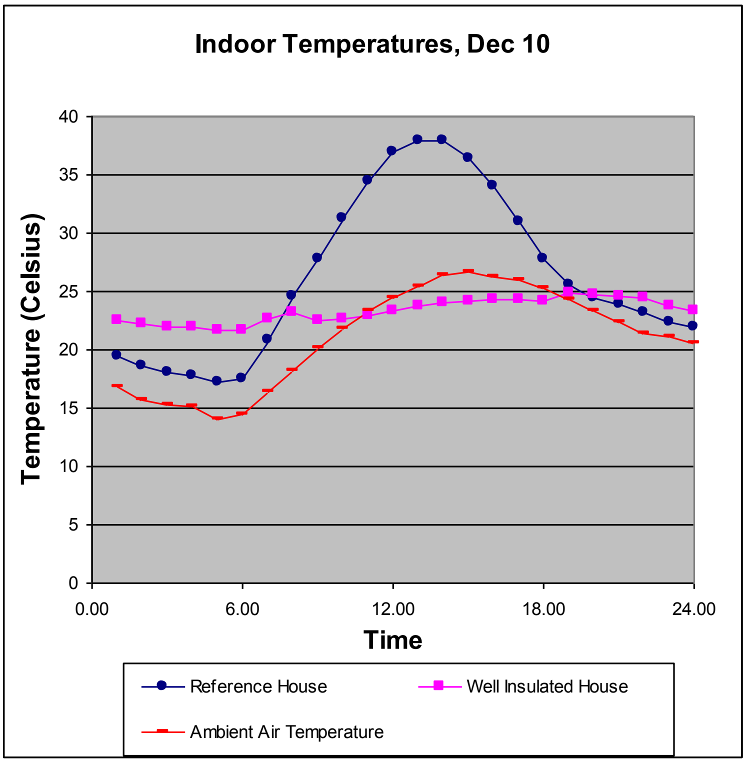


Figure 22: Temperature profiles on a hot day (Osburn, 2010)

From Figures 22 and 23, the internal temperature of the reference house varied with the outside temperature. The inside temperature was always higher than the outside temperature. This was attributed to the presence of the galvanised roof sheeting. The region closest to the roof would be warmer than the lower parts of the house (Osburn, 2010). Because heat always travels from warmer to colder regions, heat will move from the roof region to lower parts of the house. In this way the inside of the house is heated. While this may be acceptable in winter, it may be uncomfortable in summer. This is evident in Figure 22, where the internal temperature was up to 12˚C higher than the outside temperature. (Osburn, 2010) recommended that windows and doors be left open to increase the air exchange rate, thereby reducing the internal temperature.

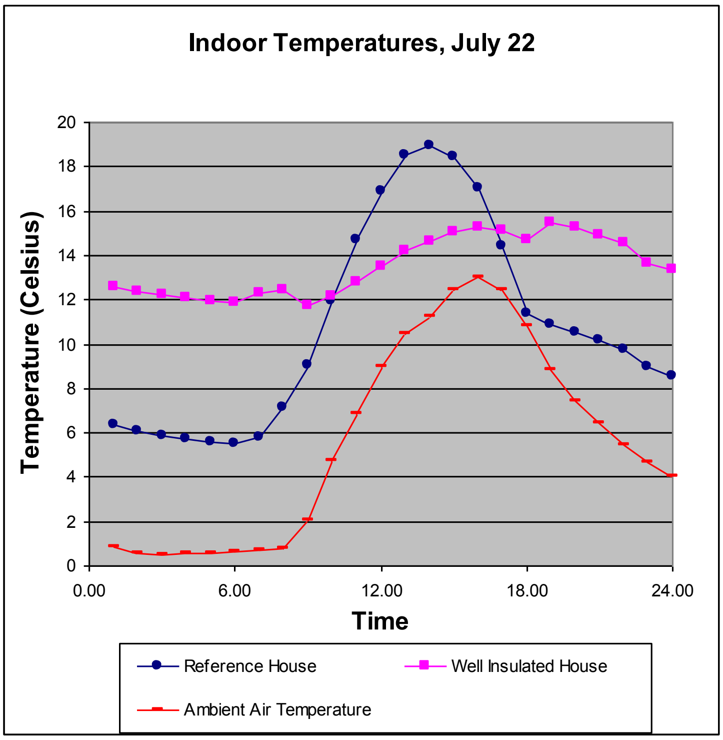


Figure 23: Temperature profiles on a cold day (Osburn, 2010)

Air in contact with the roof would be warmer, and subsequently less dense, than air of the rest of the house. By incorporating a turbine ventilator on the roof of the house, an escape port for the warm air would be introduced. While there is no scientific literature to indicate the temperature differential needed to cause free rotation of the turbine ventilator, one manufacturer's specification sheet (Turbovent Data Sheet, 1996) indicated that a temperature differential in the order of approximately 14˚C is needed to obtain free rotation of the turbine ventilator.

If warm air was constantly being exhausted via the turbine ventilator, and being replaced by cooler air from the outside, the internal temperature of the house would then be lowered.

3.3 Tracer gas (concentration decay) tests

The tracer gas (concentration decay) test is performed by releasing a tracer gas into a space and allowing it to decay without disturbing the movement of air by the ventilation system and other natural sources (Nordtest, 1985). The tracer gas concentration is recorded at predetermined time intervals, and at specified locations in the space. The data from these tests reflect the decay due to the ventilation strategy at those specific points in the room. These points are then used to calculate the ventilation flow rate, mean age of air (MAA) and air change efficiency of the ventilation system. The results are specific to the test conditions.

3.3.1 Tracer gas testing equipment and instrumentation

The equipment used in tracer gas testing includes:

- A cylinder of tracer gas
- A gas analyser
- Tubing for the injection of the tracer gas
- Fans for effective mixing
- Ribbons to indicate the direction of airflow

According to REHVA (REHVA, 2004), the tracer gas needs to meet the following requirements:

1. The tracer gas should not be naturally present in high concentrations in the room air. If it was naturally present in high concentrations of room air it may influence the measured concentration. If the tracer gas was present naturally in the room air its concentration should be constant.
2. The density of the ideal tracer gas should be equal to the density of air to facilitate easy mixing.
3. During the measurement period, no reactions between the tracer gas and other substances within the room should occur.
4. The tracer gas should not have properties that cause it to stick to, or be adsorbed, by surfaces or objects in the room.
5. The tracer gas should be readily available at a reasonable cost.
6. The tracer gas should be easily measurable by readily available commercial measuring devices.
7. The tracer gas should be non-toxic, non-flammable, and environmentally friendly.

Historically, the most commonly used tracer gases were Nitrous Oxide (N_2O) and Sulphur Hexafluoride (SF_6) (REHVA, 2004). Carbon Dioxide (CO_2) may be used if the background concentration is constant (REHVA, 2004). The tracer gas used in this field study was CO_2. Properties of CO_2 are shown in Table 3.

Table 3: Properties of CO_2 (REHVA, 2004) and Air

	Density (kg/m^3)	**Threshold Limit Value, 8 hours (ppm)**	**Chemical Stability**
CO_2	1.9	5000	Soluble in water
Air	1.02	-	-

*****Air densit o to ia at C, barometric pressure of 85.87 Pa** (Altitude and Density Chart, 2010)

A fan is used to mix the tracer gas to a uniform concentration (Nordtest, 1985). The tracer gas should be mixed with the space air continuously as it is supplied (REHVA, 2004). If the room air is not completely mixed, inaccuracies in calculations may occur. Figure 24 is an illustration of the mixing process in the field study of this research project.

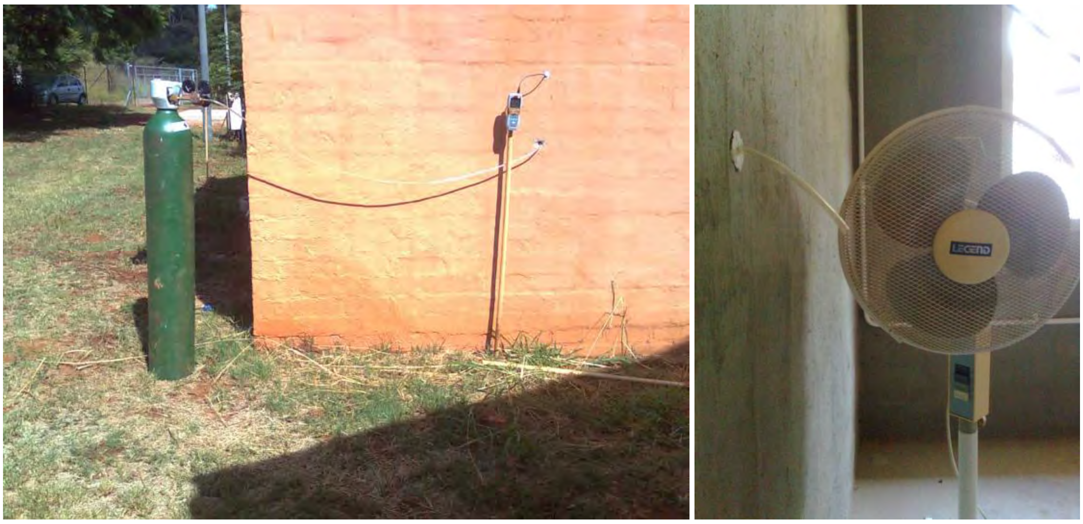


Figure 24: Tracer gas testing equipment. Left: A cylinder of CO_2 which releases gas into the room via tubing. The data logger of CO_2 analyser is also shown. Right: Tubing from CO_2 cylinder carries gas into room and is released in front of a mixing fan.

*****Please note that the cylinder of CO_2 in Figure 24 is for illustrative purposes. Cylinders of CO_2 must always be secured and supported, as in Figure 25 (right).**

A SENTRY® ST303 CO_2 analyser was used to measure and record the concentration of Carbon Dioxide at the specified points in bedroom 2. The SENTRY® ST303 CO_2 analyser is a non-dispersive infrared gas concentration measuring device (SENTRY Optronics Corporation, 2009). It has a built in data logger, which can be programmed to measure the gas concentration at predetermined intervals. The manufacturer reports an accuracy of ±50 ppm in the 0 – 5,000 ppm range (SENTRY Optronics Corporation, 2009).

A SENTRY® ST732 hot-wire anemometer is used to measure and record the wind speed, v_w ,and outside temperature, T_{out}. The hot-wire anemometer probe is directional and only measures wind speed in one plane. The SENTRY® ST732 has a built-in data logger which can be programmed to measure and record data at predetermined time intervals.

3.4 Field study design

This section provides details about the physical layout of the reference house during the tests. It also describes the rationale for the positioning of the turbine ventilator and instrumentation, and provides details about window and door orientations in each test, and the expected outcomes thereof.

3.4.1 Position of the turbine ventilator

It is important to identify the highest risk area in the reference house. In this case, it is important to position the infectious TB patient in the reference house, i.e. where is the patient most likely to be? Firstly, it was assumed that the infectious TB patient was not at work during the period he/she was infectious, and would spend his/her time recovering at home. At night the patient would be sleeping, presumably in a bedroom. TB patients experience heavy coughing episodes in the mornings after waking up. This is due to the accumulation of mucous material in the lungs during the night. For best IPC practice, the air in the room must be expelled directly from the bedroom to the outside, i.e. air should not be carried to other rooms. By introducing the turbine ventilator into the bedroom, the bedroom should, in theory, be at a negative pressure relative to the adjacent rooms and hallways, and air from adjacent rooms and hallways would tend to flow towards the patient's bedroom. In this way occupants in the rest of the house would be less likely exposed to contaminated air.

If the turbine ventilator is placed in any other room, that room would be at negative pressure relative to the adjacent rooms, the contaminated air would flow out of the bedroom and other occupants of the house would be more likely to be exposed to this contaminated air. It was for these reasons that the turbine ventilator was located on the roof of bedroom 2. It was assumed that all other occupants of the house would reside in bedroom 1 during the evenings, and would be at work or school during the day. The position of the turbine ventilator on the reference house is shown in Figure 25.

Figure 25: The turbine ventilator on the roof of the reference house

In designing the field study, the required ventilation flow rate needs to be established. (WHO, 2009) recommends a minimum hourly-averaged ventilation rate of 160 l/s/p for airborne precaution rooms. Typically, where an infectious TB patient is isolated or accommodated, this recommendation would apply. (WHO, 2009) recommends a minimum hourly-averaged ventilation flow rate of 60 l/s/p for general wards and outpatient departments. In reality, patients who receive the correct treatment become non-infectious after a short period of time, and the recommendation of 60 l/s/p for bedroom 2 of the reference house becomes more appropriate. This corresponds to a 12.9 ACH ventilation flow rate in the volume of bedroom 2.

According to the Windmaster Calculator (Windmaster), taking into account the volume of the house (110.5 m^3), only one 300 mm Tornado turbine Ventilator would be required to achieve 12.9 ACH in the reference house. Suppliers and installers provide details about choosing the best position when installing the turbine ventilator. The turbine ventilator was located as close to the apex of the roof as possible. This was done to ensure that the turbine ventilator blades receive maximum exposure to wind when installed on an inclined roof.

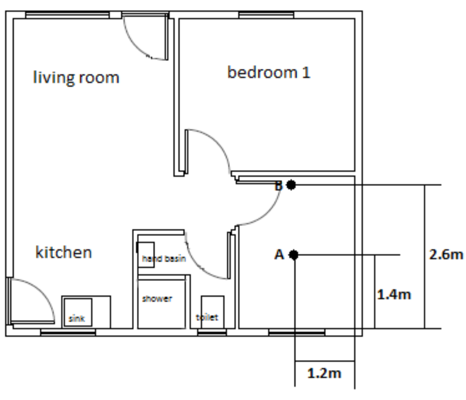
3.4.2 Position of the sensors

In the field study, the parameters displayed in Table 4 were measured and recorded.

Table 4: Field study measured parameters

Parameter	Symbol	Instrument
Internal Temperature (dry bulb)	T_{int}	Hot-wire anemometer
Outside Temperature (dry bulb)	T_{out}	Hot-wire anemometer
Concentration of CO_2	$\lvert CO_2 \rvert$	CO_2 analyser
Wind Speed	v_w	Hot-wire anemometer

The $\lvert CO_2 \rvert$ was measured at two points in the room, points A and B as shown in Figure 26. Point A was situated at the geometric centre of the plan view of bedroom 2, and elevated to 1.54 m above the ground. The average South African male is 1.69 m tall (National Department of Health, 1998), and the average South African woman is 1.59 m tall (National Department of Health, 1998). Point A would therefore be in the average nose and mouth region of South African adult males and females. The criterion of standing height was selected over sitting height (1.1m above the ground) for two reasons. The first is that standing height was closer to the geometric centre of the room vertically, and may be more representative of the room. The second reason is due to the potential separation of flow streams in the room, the standing height may favour the flow between the window/door and the turbine ventilator. Point B was located at the base of the turbine ventilator, inside bedroom 2. As the infrared sensors require air to pass through the sensor to measure the $\lvert CO_2 \rvert$ concentration, this sensor is positioned at the base of the turbine ventilator where air flows across the sensor through the turbine ventilator.



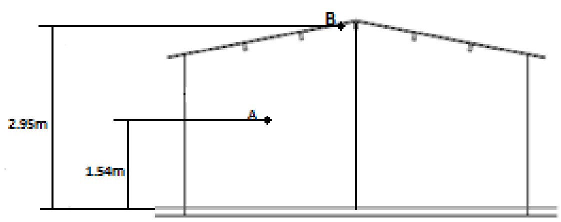


Figure 26: Measuring points A and B in plan view (left) and elevation (right)

T_{int} and $|CO_2|$ are measured at Point A, as shown in Figure 26. T_{out} and v_w are measured at Point C, shown in Figure 27. Point C is located away from the reference house, at a height of 1.5m, to determine the wind speed and temperature at the site. In this way, the effect of the building envelope on the airflow around the house does not influence the wind speed and temperature measurements. The hot-wire anemometer used in this field study had a directional probe, i.e. it was only able to measure wind speed in one direction. For the purposes of this field study, the chosen direction was the plane perpendicular to the northern façade of the house. It was assumed that this component of the wind velocity would play the biggest role in ventilating the house, as it is the component perpendicular to windows of the house.

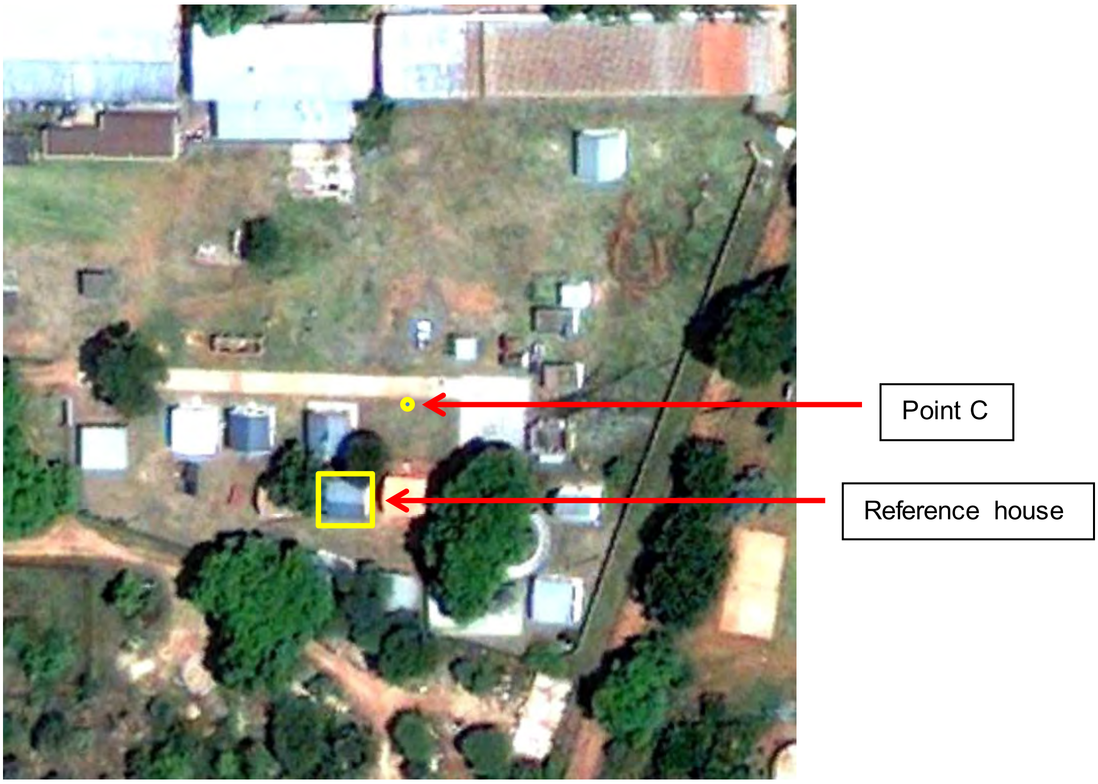


Figure 27: A Google Earth image of the reference house and the position of Point C

3.4.3 Position of flow ribbons

Flow ribbons were used to determine the air flow patterns through the house. A flow ribbon essentially serves the same purpose as a smoke tube. The flow ribbons used in this research project were made of tissue paper, and were each approximately 10 mm x 150 mm. Flow ribbons have been positioned on the window frames of all windows. Figure 28 shows the flow ribbons on the window frames on the northern façade of the reference house. They were also useful for determining the windward and leeward side of the house.

Figure 28: Flow ribbons on reference house

The field study comprised of 4 tests, described in Sections 3.4.4 – 3.4.7. In all of these tests, the status (open or closed) of the windows and doors were important as the windows and doors serve as inlets and outlets. In all tests, the doors on the northern and western facades of the reference house were closed, and the doors of bedroom 1 and the bathroom were open. The status of bedroom 2's changed depending on the test performed. The areas between the door and the door frame play a significant role, acting as inlets and outlets due to leakage, and in some tests, would be the only means of air exchange.

3.4.4 Infiltration/Leakage Test

Figure 29 is an illustration of the layout of Infiltration/Leakage (IL) test. In Figures 29 to 32, a green line indicates that either the window or door at that location was open, and a red line indicates that either the window or door in that location was closed. In IL:

- All windows were closed
- Bedroom 2's door was closed

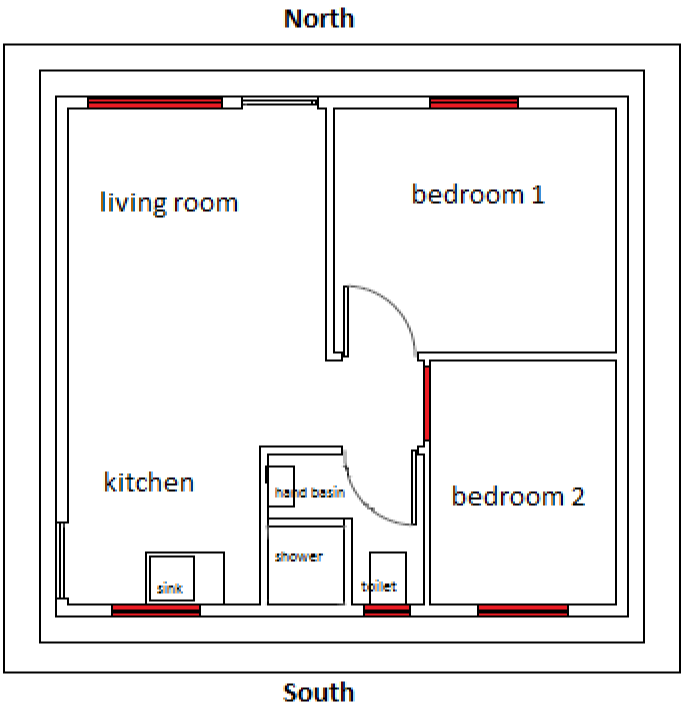


Figure 29: An illustration of the layout of IL

The possible outcome of this test is that all air will enter the house through gaps and move into bedroom 2, travel towards the turbine ventilator, to be discharged to the outside.

3.4.5 Single-sided ventilation case 1

Figure 30 presents the layout of the single-sided ventilation case 1 (SS1) test. In SS1:

- Bedroom 2's window was opened
- Bedroom 2's door was closed
- All other windows were closed

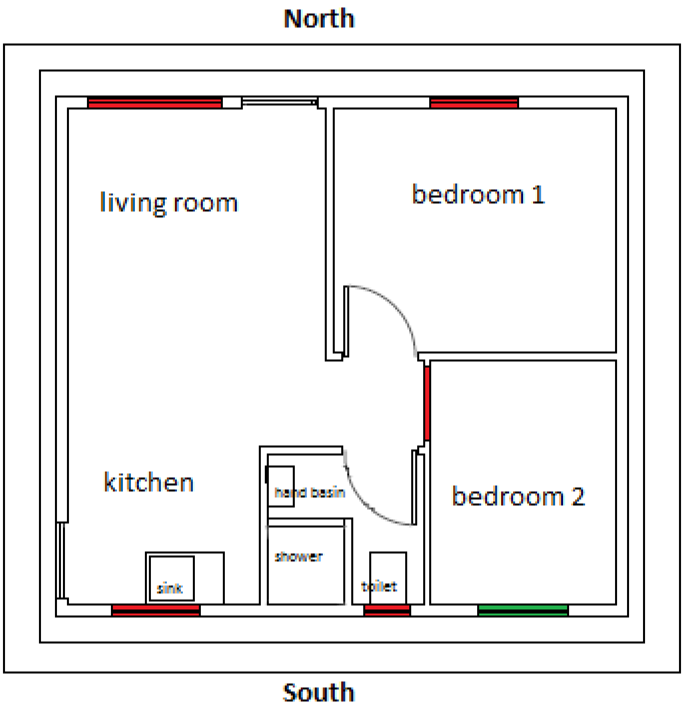


Figure 30: An illustration of the layout of SS1

There were three possible outcomes of this test:

1. If bedroom 2's window was on the windward side of the house, air would flow through the window, and bedroom 2 would most likely be at greater pressure relative to the rest of the house. Air would be exhausted via the turbine ventilator.
2. If bedroom 2's window was on the leeward side of the house, air would enter the house through leakages, and flow from other rooms into bedroom 2, and will be exhausted through the open window. A small amount of air may be exhausted through the turbine ventilator.
3. Bedroom 2 would experience single-sided ventilation, where the window of bedroom 2 would serve as both an inlet and outlet for air.

3.4.6 Cross ventilation

Figure 31 is an illustration of the layout of the cross ventilation test. In CV:

- All windows were opened
- All interior doors were opened

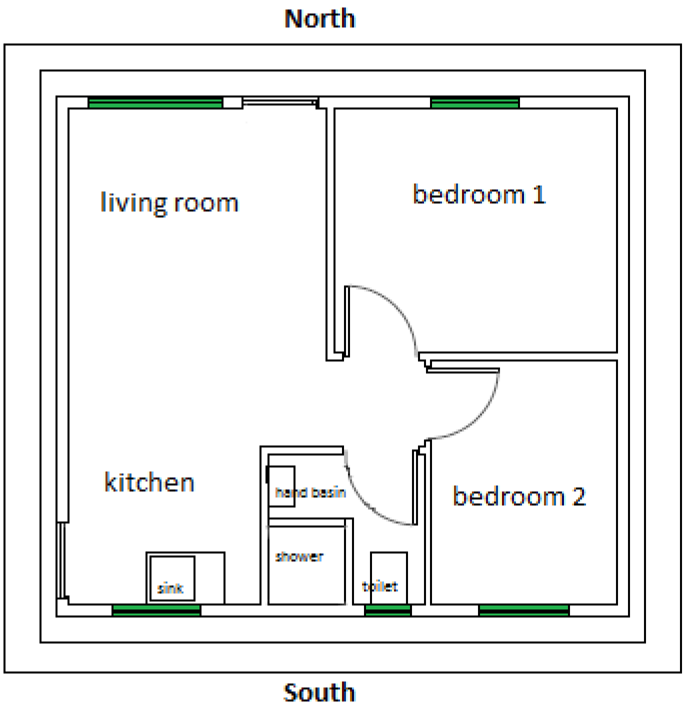


Figure 31: An illustration of the layout for CV

There were two possible outcomes for this test:

1. If the window of bedroom 2 opened to the leeward side of the building, air would enter bedroom 2 through its door, and be exhausted through the window and the turbine ventilator.
2. If the window of bedroom 2 opened to the windward side of the building, air enters bedroom 2 through the window, flows to the adjacent rooms and would be exhausted through windows and gaps on the leeward side of the building. A small portion of the air may be exhausted through the turbine ventilator.

3.4.7 Single-sided ventilation case 2

Figure 32 is an illustration of the layout of the single-sided ventilation case 2 (SS2) test. In SS2:

- Bedroom 2's window was closed
- All other windows were opened
- All interior doors were opened

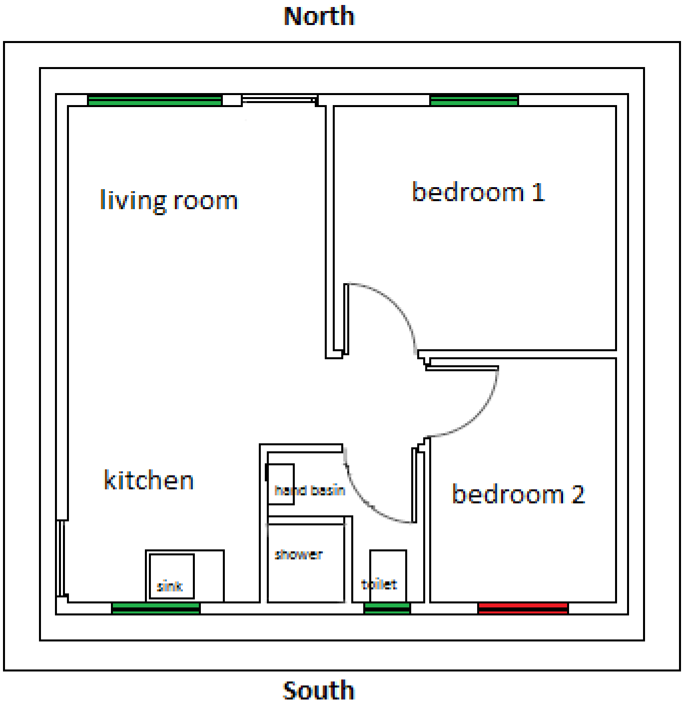


Figure 32: An illustration of the layout of SS2

There were two possible outcomes for this test:

1. If the negative pressure induced by the turbine ventilator was more negative than the relative negative pressure on the leeward side of the building, some air would pass from the windward side into bedroom 2 and would be exhausted through the turbine ventilator. The rest of the air would be exhausted at windows on the leeward side of the building.

2. If the relative negative pressure on the leeward side of the house was significantly more negative than the negative pressure induced by the turbine ventilator, air would flow out of bedroom 2, to adjacent rooms and passages, and follow the cross-ventilation stream.

3.4.8 Field study baseline tests

Before the turbine ventilator was installed, a set of baseline tests was performed. The layout of the baseline tests would follow the same layout as those tests discussed in Sections 3.4.4 – 3.4.7, except that in the baseline tests a turbine ventilator had not yet been installed. The baseline tests would be used as a basis to which the turbine ventilator tests would be compared.

3.5 Field study testing procedure

There are several standards/methods available which outline a methodology to perform tracer gas concentration decay tests. The two methods incorporated in this research project are:

- REHVA Guidebook, Ventilation Effectiveness, Chapter 6 (REHVA, 2004)
- Nordtest Method NT VVS 047 (Nordtest, 1985)

The method and calculations outlined in the REHVA Ventilation Effectiveness Guide was selected as the method of choice for these tests, as it provided the most comprehensive description of the testing and analysis for concentration decay tests. The testing procedure was performed as follows:

1. Ensure that all outer windows and doors of the reference house have been closed.
2. Measure and record the internal temperature at Point A.
3. Measure and record the internal temperature near the roof, directly above Point A.
4. Vacate the house.
5. Measure and record the background concentration of CO_2.
6. Switch ON the fan.
7. Release a small amount of CO_2 into the room to achieve a uniform concentration of approximately 5000 ppm.
8. Allow the fan to run for an additional one minute after the gas has been released to ensure adequate mixing to a uniform concentration.
9. Switch OFF the fan.
10. Switch on the CO_2 analysers and the hot wire anemometer. The data loggers of these instruments have been set to measure and record every two minutes.
11. Open the required windows and doors as described for the particular test. (Refer to Sections 3.4.4 – 3.4.7).
12. Allow the gas to decay to a concentration of approximately 500 ppm.
13. Switch off the CO_2 analysers and hot wire anemometer.
14. Open all windows and doors to allow excess CO_2 to leave the room.

The data from these tests reflect the decay due to the ventilation system at the measuring points. This data is then used to calculate the ventilation flow rate, MAA and air change efficiency at these points, and are presented as a reflection of the ventilation system in the room. The results are specific to the test conditions.

3.6 Quantifying the ventilation performance of the system

(REHVA, 2004) details a method of calculating the ventilation flow rate, MAA, air change efficiency and CRE from the data collected from the tracer gas tests. An outline of these calculations is presented here.

The output generated from the tracer gas tests are concentration as a function of time. The data can then be plotted in a single logarithmic graph of concentration as a function of time. Figures 33 and 34 are illustrations of these graphs.

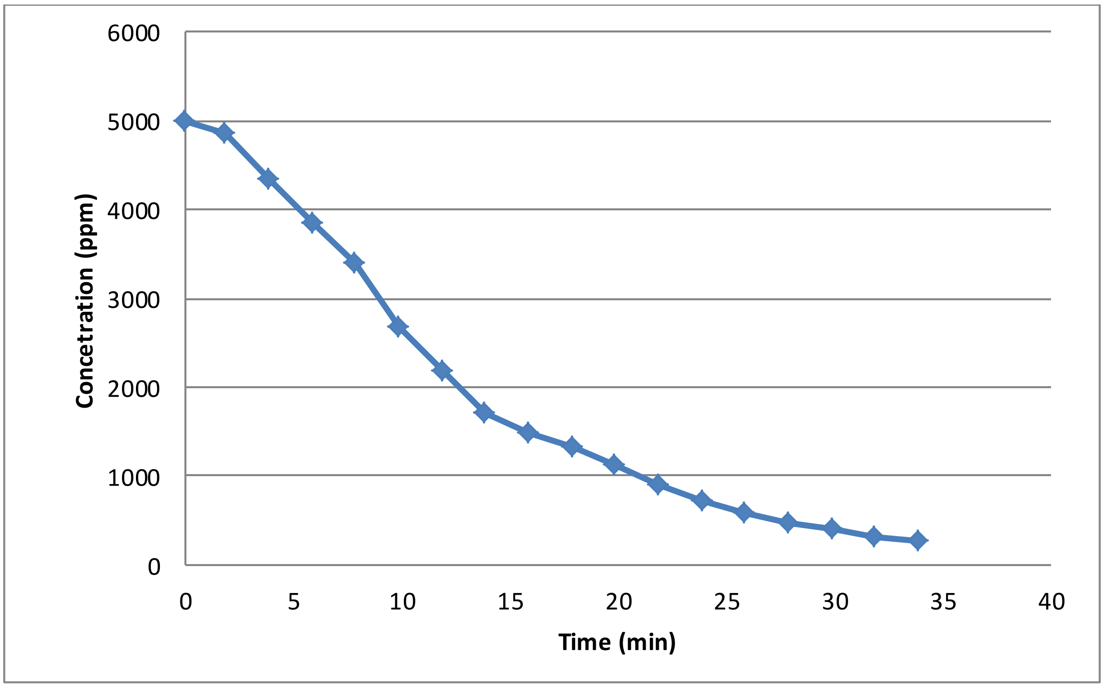


Figure 33: Concentration decay curve for a tracer gas test

The logarithmic graph should be in the form of a straight line. There may be an initial lapse in the curve if mixing in the room was not complete at the start of the experiment. The number of air changes per minute is given by the slope of the logarithmic concentration decay curve. The number of air changes per hour (ACH) is calculated by multiplying the slope of the curve by 60.

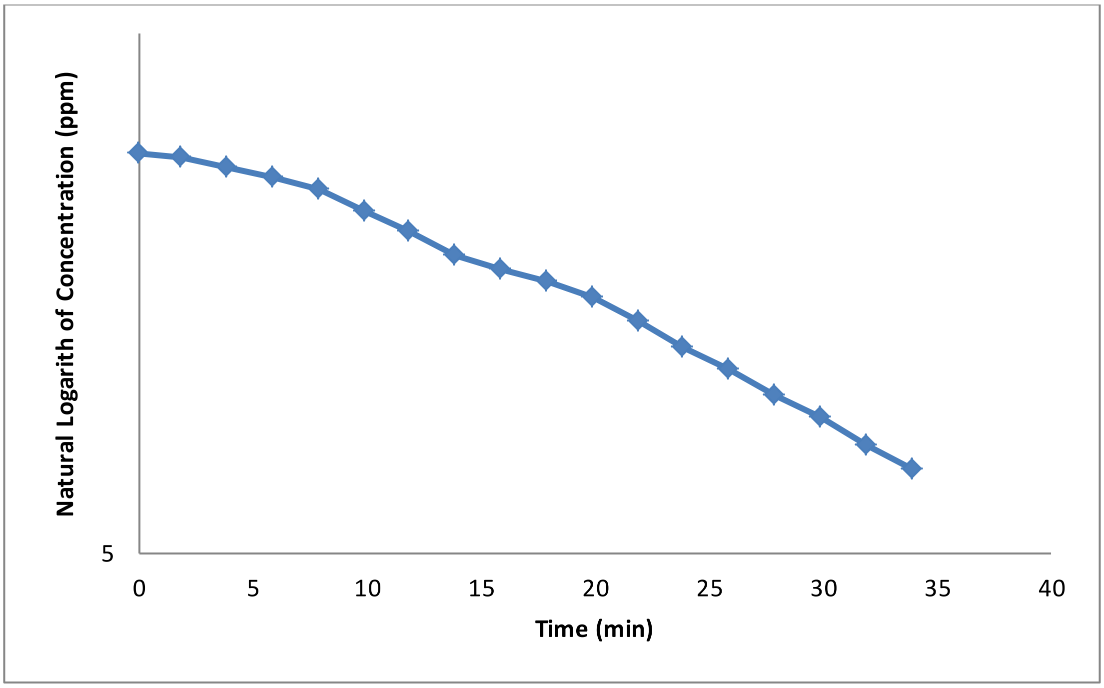


Figure 34: A logarithmic curve to illustrate concentration decay

The MAA is the average time required to replenish a pocket of air in the room with fresh air. The MAA of the space would be calculated from the weighted area under the concentration decay curve, and is given by Equation 5 (REHVA, 2004):

$$< \bar{\tau} >= \frac{\sum_{i=1}^{i=n} \left[\frac{c_i + c_{i-1}}{2} \cdot (t_i - t_{i-1}) \cdot \frac{t_i + t_{i-1}}{2} \right] + \frac{c_n}{\lambda} \cdot \left[\frac{1}{\lambda} + t_n \right]}{\sum_{i=1}^{i=n} \left[\frac{c_i + c_{i-1}}{2} \cdot (t_i - t_{i-1}) \right] + \frac{c_n}{\lambda}}$$

...Equation 5

where:

$\bar{\tau}$ = mean age of air

i = counter

n = total number of measured points

c = Concentration

t = Time

λ = Decay or gradient of the linear part of the original Concentration-Time curve

The nominal time constant would then be calculated from Equation 6 (REHVA, 2004):

$$\tau_n = \frac{\sum_{i=1}^{i=n} \left[\frac{c_i + c_{i-1}}{} \cdot (t_i - t_{i-1}) \right] + \frac{c_n}{\lambda}}{c_0}$$ **... Equation 6**

where:

τ_n = nominal time constant

c_0 = initial concentration

The air change efficiency can then be calculated by Equation 7 (REHVA, 2004):

$$\varepsilon^a = \frac{\tau_n}{2 \cdot < \bar{\tau} >} \cdot 100[\%]$$ **... Equation 7**

The air exchange efficiency is a rating given to a ventilation system, where for piston-type ventilation; the air change efficiency is 100% (WHO, 2009). Piston-type ventilation is the benchmark where air removed at the exhaust is replaced with fresh air at the inlet. There is no mixing of air in the room, simply the replenishment of exhausted air. For fully mixed ventilation, as illustrated in Figure 37, the air exchange efficiency is 50% (WHO, 2009). The air exchange efficiency for displacement ventilation is between 50% and 100%, and for short-circuiting systems, the air exchange efficiency is always less than 50% (WHO, 2009). In displacement ventilation, some of the incoming air mixes with the room air before being exhausted. In short-circuiting systems, incoming air takes the shortest path to the exhaust, without effectively removing air in the room.

The CRE is a measure of how quickly an airborne contaminant is removed from a room (REHVA, 2004). CRE is defined as the ratio of steady-state contaminant concentration of contaminant in the exhaust air, c_e, to the steady-state mean contaminant concentration of the room, $\langle c \rangle$. It is defined by Equation 8 (REHVA, 2004):

$$\varepsilon^{c} = \frac{c_e}{\langle c \rangle}$$ **… Equation 8**

When the air is fully mixed, the contaminant concentration in the exhaust would be equal to the contaminant concentration everywhere in the room, i.e. $\langle c \rangle = c_e$ (REHVA, 2004). When the contaminant sources are not uniformly distributed in the room, the position of the contaminant source influences the CRE (REHVA, 2004). Figures 35 and 36 illustrate the effect of the position of the contaminant source on the exhaust concentration in a mechanically ventilated room.

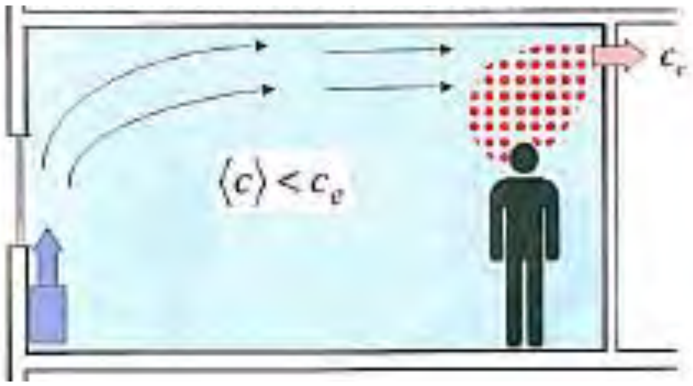


Figure 35: An illustration of the contaminant concentration in the room and exhaust air when the contaminant source is located close to the exhaust (REHVA, 2004)

In Figure 35, the contaminant source is close to the exhaust. In this way, incoming air carries contaminants out of the room before it is able to mix in the room. The mean contaminant concentration in the room is less than the contaminant concentration in the exhausted air. In Figure 36, the contaminant source is located in a stagnant zone. When the contaminant source is located in a stagnant zone, the ventilation air flow pattern is not able to encapsulate the contaminants, and the contaminant concentration in the room increases. The contaminant concentration of the exhaust air is then very low.

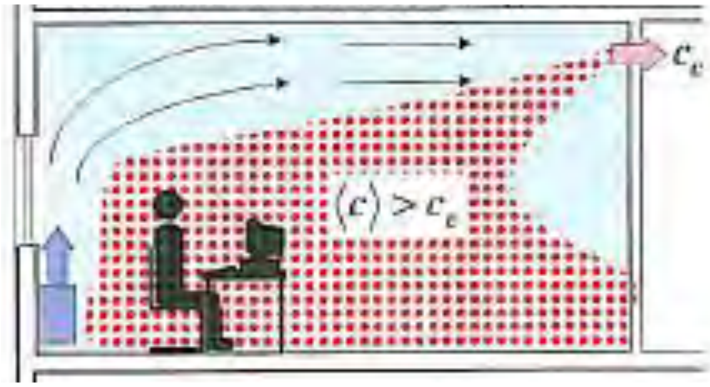


Figure 36: An illustration of the contaminant concentration in the room and exhaust air when the contaminant source is located in a stagnant zone (REHVA, 2004)

(Novoselac & Srebric, 2003) compared air change efficiency and CRE as performance indicators for indoor air quality. Air exchange efficiency is an indicator of air distribution quality because it quantifies how good the airflow pattern is. CRE is an indicator of the contamination level in the room. Air change efficiency considers the size and intensity of recirculation in the room, by comparing the room airflow pattern to the airflow pattern of piston flow. CRE is dependent on the airflow pattern, intensity, area and positions of contaminant sources in the room. For well-known positions of contaminant sources, CRE provides good indication of air quality, and provides more informative results. However, in the space where contaminants are unknown, the air exchange is a more useful indicator because it provides a general indication of air quality independent of contaminant source positions.

In natural ventilation, steady-state conditions are unlikely to be reached, as the airflow in the varies with the environmental conditions. For this reason, CRE cannot be evaluated by tracer gas concentration decay testing. Air change efficiency is considered to be a more appropriate indoor air quality indicator in this research project.

3.7 How does the field study of this research project differ from previous studies?

The field study of this research project has been strongly influenced by the work of (Escombe, et al., 2007) and (Cox, et al., 2012), presented in Chapter 2. This section provides an explanation on how the field study of this research project differs from (Escombe, et al., 2007) and (Cox, et al., 2012).

The field study of this research differs from (Escombe, et al., 2007) and (Cox, et al., 2012) in the following ways:

1. The objective of (Escombe, et al., 2007) was to investigate the determinants of natural ventilation. The objective of (Cox, et al., 2012) was to assess the efficacy of turbine ventilators

compared to current recommended practices for natural ventilation. The objectives of this field study is to establish any improvement in weighted average ventilation flow rate achieved when incorporating the turbine ventilator into a natural ventilation strategy, and to measure the air change efficiency of the turbine ventilator.

2. The sizes of each of the studies are different. (Escombe, et al., 2007) performed 368 experiments, in 70 rooms, evaluating three configurations. The sizes (and functions) of the rooms varied, from small isolation rooms to larger general wards. (Cox, et al., 2012) performed 332 experiments in four consulting rooms, evaluating three configurations, over a period of 24 months. In this field study 24 tests are performed on a single room, evaluating four configurations. This study is focused on the performance of the turbine ventilator in a single control volume in a climate conducive to the lower end performance of the turbine ventilator. In this way, a single volume is characterised under a set of configurations, in its environment.
3. The methodology of the tracer gas test in (Escombe, et al., 2007) and (Cox, et al., 2012) are similar. (Escombe, et al., 2007) measured concentration decay using a centrally located infrared analyser. CO_2 levels decayed from between 3,000-10,000 ppm (room size dependant) to below 200 ppm (baseline) to account for occupant CO_2 production. Wind speed was measured at the window using a thermal anemometer. In (Cox, et al., 2012), concentration decay was measured over a 5 to 8 minute period, at 15 second intervals. The measuring point of the infrared analyser was at the centre of the room, at a height of a seated person. Wind speed was measured by anemometer, positioned on the roof, at the same level as the turbine ventilator, no more than two meters from the turbine ventilator. Airflow through the turbine ventilator was measured using a balometer. Additionally, both (Escombe, et al., 2007) and (Cox, et al., 2012) had occupants in the rooms during a test. In this research project, ambient conditions were measured at the site, away from the building envelope. Pure CO_2 was injected into and mixed in the room, and allowed to decay to levels near the background concentration. An evaluation was done on the total decay, whether the period was 120 minutes or 12 minutes. A balometer was not used as the presence of the balometer, and the operator of a balometer, may have greatly influenced the airflow in a room of this volume. Airflow through the turbine ventilator was assessed by placing an infrared analyser at the base of the turbine ventilator.
4. The turbine ventilator installation design of (Cox, et al., 2012) results in a natural ventilation system, with a low-level air intake grille inlet, and a high-level exhaust at the turbine ventilator. In the field study of this research project, the turbine ventilator is added as a supplement to the natural ventilation system, in an effort to enhance the already present natural ventilation configuration.
5. The analysis of data in this field study is different to the previous studies. (Escombe, et al., 2007) and (Cox, et al., 2012) presented their data similarly, where the ventilation flow rates achieved were statistically interpreted as a function of quartiles of wind speed. (Escombe, et al., 2007) ventilation flow rate results were presented in terms of two wind speed quartiles as

less than 0.56 m/s (2 km/h) and greater than 0.56 m/s (2 km/h) . (Cox, et al., 2012) results were presented in four quartiles of wind speed, from lowest to highest where the highest recorded wind speed was 13.89 m/s (50 km/h). These wind speed ranges are dependent on both the measuring point, and the probability of wind at the test location. As only three tests per configuration will be tested in this field study, only simple statistics of the data will be performed.

In the field study, the ventilation flow rate, MAA and air change efficiency of the natural ventilation will be investigated. These measures will be used to evaluate the potential of the natural ventilation system to provide an environment conducive to airborne IPC standards.

4. LABORATORY EXPERIMENTAL SET UP AND PROTOCOL

The laboratory experiments were performed to provide an understanding of the local flow dynamics of the turbine ventilator under wind and buoyancy, and a combination of these forces. This chapter lays out the objectives of the laboratory experiments, discusses the apparatus design and instrumentation, calibration of the laboratory apparatus, and the protocol for the experiments.

4.1 Objectives of laboratory experiments

The objectives of the laboratory experiments were:

1. To establish the ventilation capacity of the turbine ventilator under varying wind conditions.
2. To establish the ventilation capacity of the turbine ventilator under varying temperature differentials.
3. To establish the ventilation capacity of the turbine ventilator under a combination of varying wind conditions and temperature differentials.
4. To establish if the turbine ventilator is able to reduce concentrations of particles of a specified mass and size, under the tested parameters.

4.2 Laboratory experimental apparatus and instrumentation

Performance testing of turbine ventilators has been concerned with the amount of air the turbine ventilator is able to remove from a specified volume. The focus of this research project is to determine if the turbine ventilator is able to reduce the number of particles, in a space, which are of a specified mass and size.

At the outset in the design of these experiments, certain assumptions are made about the effect of wind and buoyancy on the flow induced by the turbine ventilator. These assumptions have also influenced the design of the laboratory test apparatus. These assumptions are:

1. There is an initial cut-in wind speed needed to cause the turbine ventilator to rotate.

2. There is an initial temperature differential across the turbine ventilator, i.e. temperature difference between the base of the turbine ventilator and the ambient air, which has to produce a force large enough to cause (and maintain) rotation of the turbine ventilator blades.

3. The rotation of the turbine ventilator induces a negative pressure at the base of the turbine ventilator duct, thereby extracting air from the volume below it.

4. Wind speeds below the cut-in wind speed may result in air extraction via the turbine ventilator, even in the absence of turbine ventilator rotation.

5. Temperature differentials below that of the temperature differential needed to cause turbine ventilator rotation may result in extraction via the turbine ventilator, even in the absence of turbine ventilator rotation.

In designing the test apparatus, existing standards for performance testing of ventilators, AS/NZS 4740:2000 Natural Ventilators – Classification and Performance (AS/NZS 4740, 2000), particle extraction techniques and fundamental fluid dynamic laws and concepts were investigated. A review of these concepts is presented in **Appendix D**. The concept reviewed in **Appendix D** forms the basis for the testing apparatus conceptual design described below.

4.2.1 Laboratory experimental apparatus design

An illustration of the laboratory apparatus is presented in Figure 37. An axial flow fan is coupled to a motor, the speed of which is controlled by a variable-speed drive (VSD). As the fan rotates air is channelled through the diffuser across the airflow straightener to the turbine ventilator. The airflow straightener is employed to reduce the cyclonic flow induced by the fan. The turbine ventilator is placed at the centre, on top of the control volume. The control volume is, in essence, a box, which has an inlet on two opposite sides, near the lower end. The total inlet area is 10% of the floor area of the control volume. The apparatus has been designed such that airflow into the box is symmetrically drawn. A heating element is placed at the inner base of the control volume and is used to develop a temperature differential between the control volume and the outside.

4.2.2 Design and construction of components of the laboratory experimental apparatus

Structural frame

The laboratory experimental apparatus is made of a structural 1 inch (25.4 mm) steel frame. It can be physically separated into four parts:

1. Heating element box
2. Control volume
3. Airflow channel
4. Fan support frame

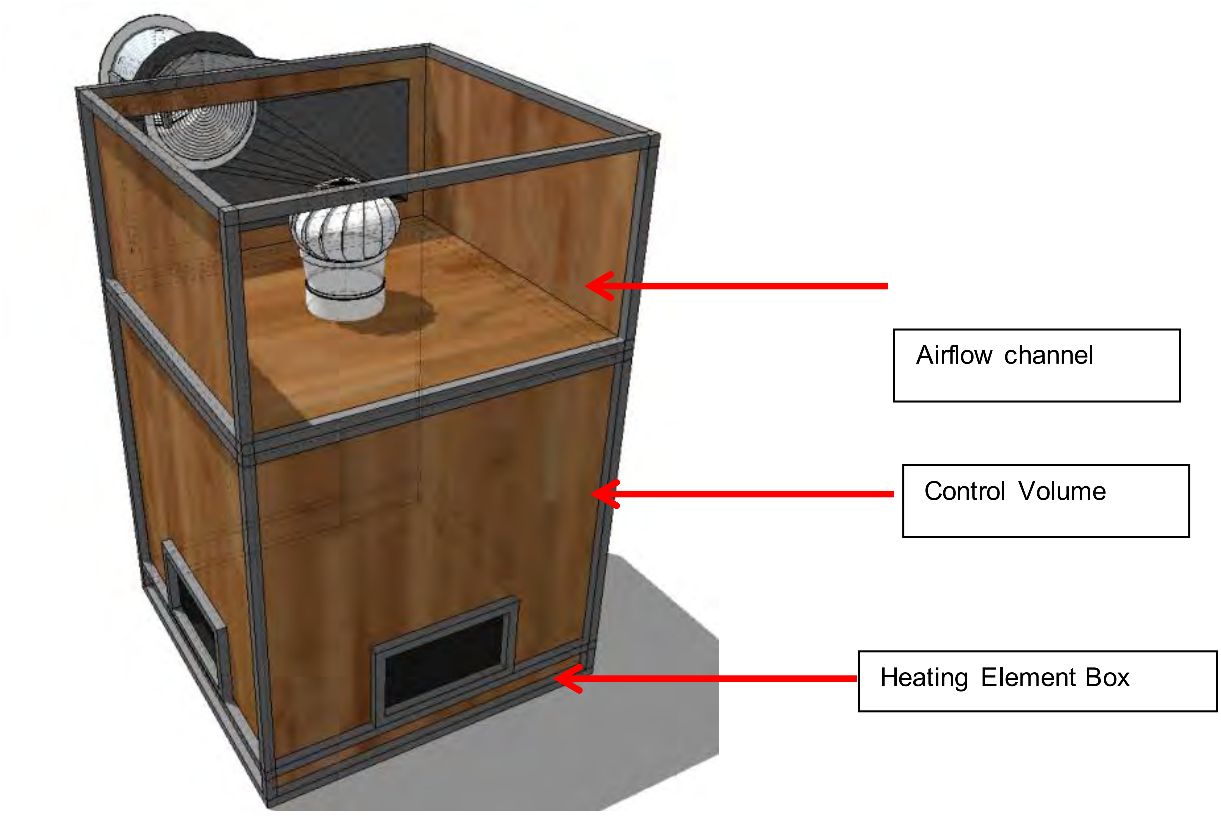


Figure 37: Laboratory apparatus showing the compartments of the structural frame (Tobias van Reenen)

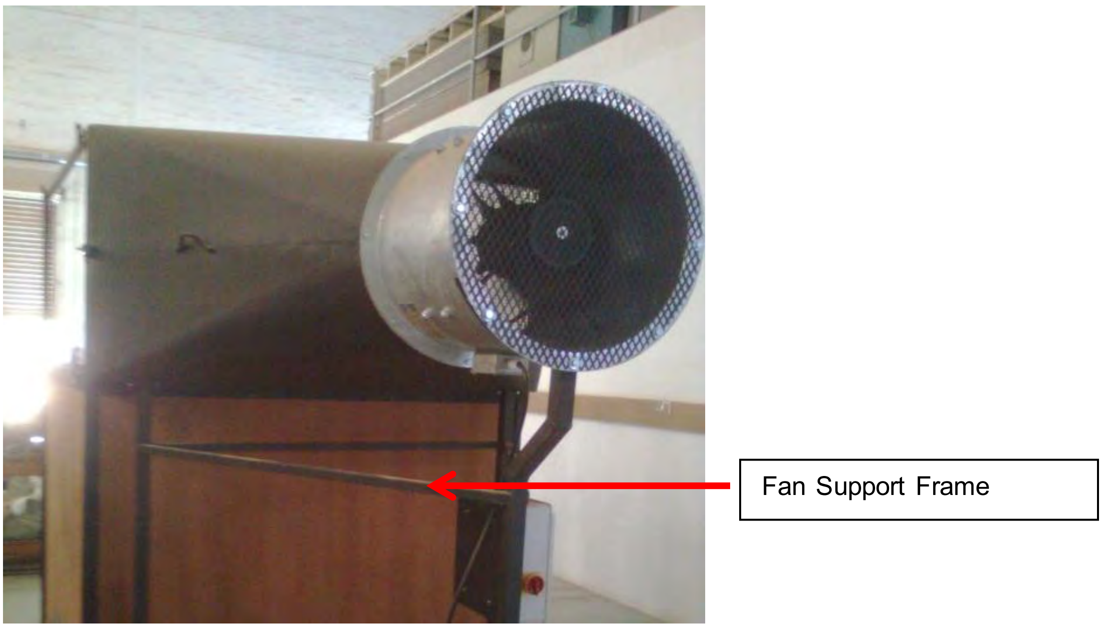


Figure 38: Laboratory apparatus showing the fan support frame

The heating element box, control volume and airflow channel are made of 9mm thick panels of plywood, which have been firmly secured to the steel frame.

Control volume

The control volume has dimensions of 1500 mm x 1500 mm x 1300 mm high. It has two inlets, as shown in Figure 39, on opposite sides of the control volume, in total equal to 10% of the floor area of the control volume. The control volume is not adjustable to test the effect of roof inclination angle, as (Lien & Ahmed, Wind driven ventilation for enhanced indoor air quality, 2011) showed that the roof inclination angle had very little effect on mass flow rate extracted by the turbine ventilator at low wind speeds.

Figure 39: Control volume of the laboratory apparatus showing inlets

Heating element

The heating element box has dimensions of 1500 mm x 1500 mm x 200 mm high, with a steel plate on its topside and is open on its underside to the floor. A heating element is shaped to cover the floor area of the control volume. A steel plate is laid on top of the element. In this way the heating element heats up the steel plate, which heats up the incoming air. The steel plate is employed to provide a more uniform radiating surface.

The heating element is controlled by a thermostat, which maintains the temperature inside the control volume to a prescribed temperature. The heating element can maintain the temperature inside the control volume to a set maximum of 30˚C.

Axial flow fan

A low-speed, low-pressure axial flow fan, Luft® LCA 500/63, shown in Figure 40, is used to generate the wind . The fan motor is controlled by a VSD. The desired rotational fan speed is directly dialled in, in Hz. The calibration of the fan for the laboratory apparatus is presented in Section 4.3.

Figure 40: Low speed, low pressure axial flow fan and VSD

Diffuser

A diffuser, shown in Figure 41, connects the fan to the airflow channel. The diameter on the fan is 500 mm, and the cross-sectional area of the airflow channel is 1500 mm x 750 mm. The diffuser is thus circular (500 mm) at one end and rectangular (1500 mm x750 mm) at the other end. The diffuser is 1000 mm long.

Figure 41: Diffuser (left) and airflow straightener (right)

4.3 Calibration of the laboratory experimental apparatus

While specifications of the fan and heating element were provided by the suppliers, there performance based on the apparatus design had to be measured. This section describes the testing of the fan to simulate wind speed and the heating element to generate a buoyancy force.

4.3.1 Simulating wind speed

To simulate the wind speed, the rotational speed of the fan to deliver the required wind speed is measured. The rotational speed of the fan is controlled by a variable speed drive, which allows the speed to be dialled in directly. The wind speed is measured in front of the turbine ventilator, midway between the diffuser and the turbine ventilator.

The rotational speed of the fan ranges from 3Hz to 66Hz, which is equivalent to 180 to 3960 rpm. The wind speed is measured from 300 to 3900 rpm, in increments of 300 rpm. These sets of 13 tests were used to characterise the fan to deliver the required wind speed. Three sets of tests are performed to qualify repeatability of results.

In each test, the fan speed was set. A hot-wire anemometer was placed 225 mm in front of the turbine ventilator, in its central plane, as illustrated in Figure 42. The directional wind speed was recorded every minute. Each test lasted 30 minutes. The time average of the wind speed for a given fan speed for the three sets of tests are presented in Figure 43.

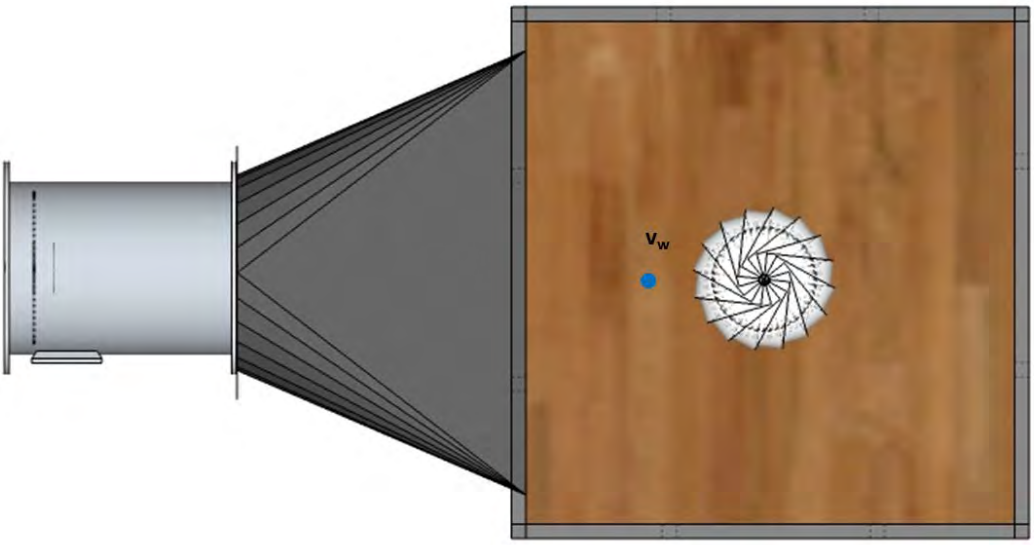


Figure 42: Position of the hot-wire anemometer to establish wind speed

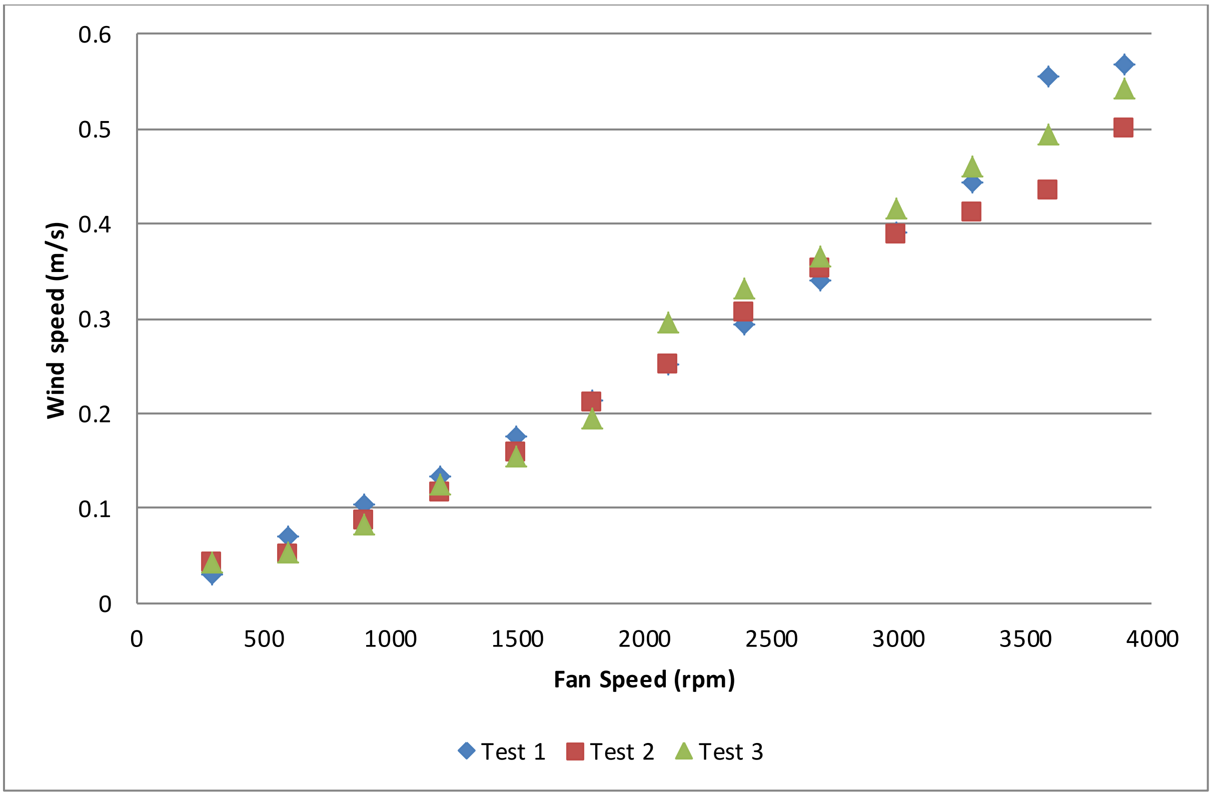


Figure 43: Relationship between wind speed and rotational fan speed in the laboratory apparatus

As can be seen in Figure 43, the time averaged wind speeds for a given rotational speed are consistent for fan speeds 300 to 3000 rpm. There is some fluctuation in the time averaged wind speeds between 3300 to 3900 rpm. The average of the three sets of tests were calculated, and linearly approximated, as given in Figure 44. The x-intercept is set at 180 rpm, as the fan rotation starts from 180 rpm. The relationship between wind speed and fan rotational speed is then given by:

$$y = 0.0001x - 0.03$$ ... **Equation 8**

Equation 8 is only valid within the parameters tested, i.e. 300 – 3900 rpm. Using Equation 8, the rotational fan speed required to deliver the wind speed parameter are calculated, and reported in Table 5.

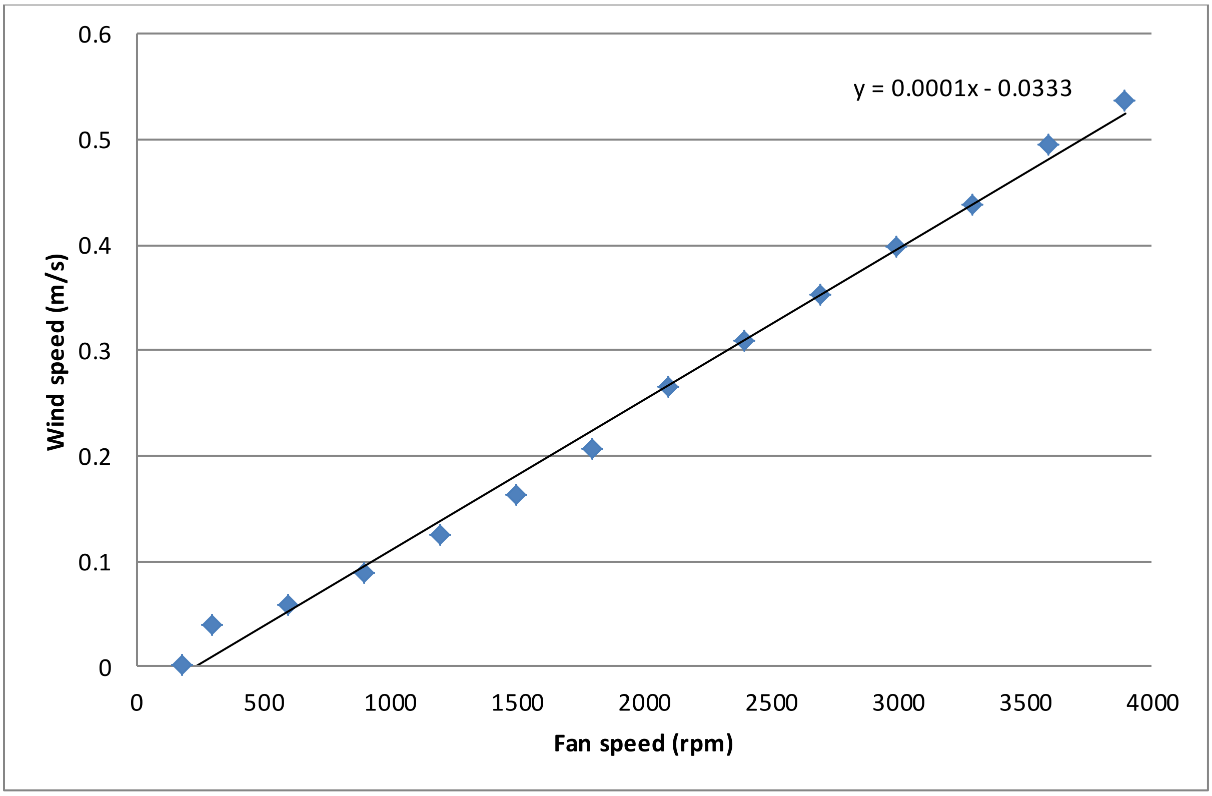


Figure 44: Averaged wind speed as a function of fan rotational speed in laboratory apparatus

Table 5: Rotational fan speed to deliver required wind speed

Wind Speed (m/s)	Fan Speed (rpm)
0.1	928
0.2	1625
0.3	2323
0.4	3021
0.5	3719

4.3.2 Simulating buoyancy forces

To simulate the buoyancy force generated by the heating element, the temperature differential between the ambient temperature and the temperature in the box are measured. The heating element is controlled by a thermostat. The heating element is able to provide a maximum temperature of 30˚C inside the control volume. The thermostat is set at 30˚C, and monitored for a period of three hours. Figure 45 is an example of the calibration tests of the heating element to deliver a temperature differential.

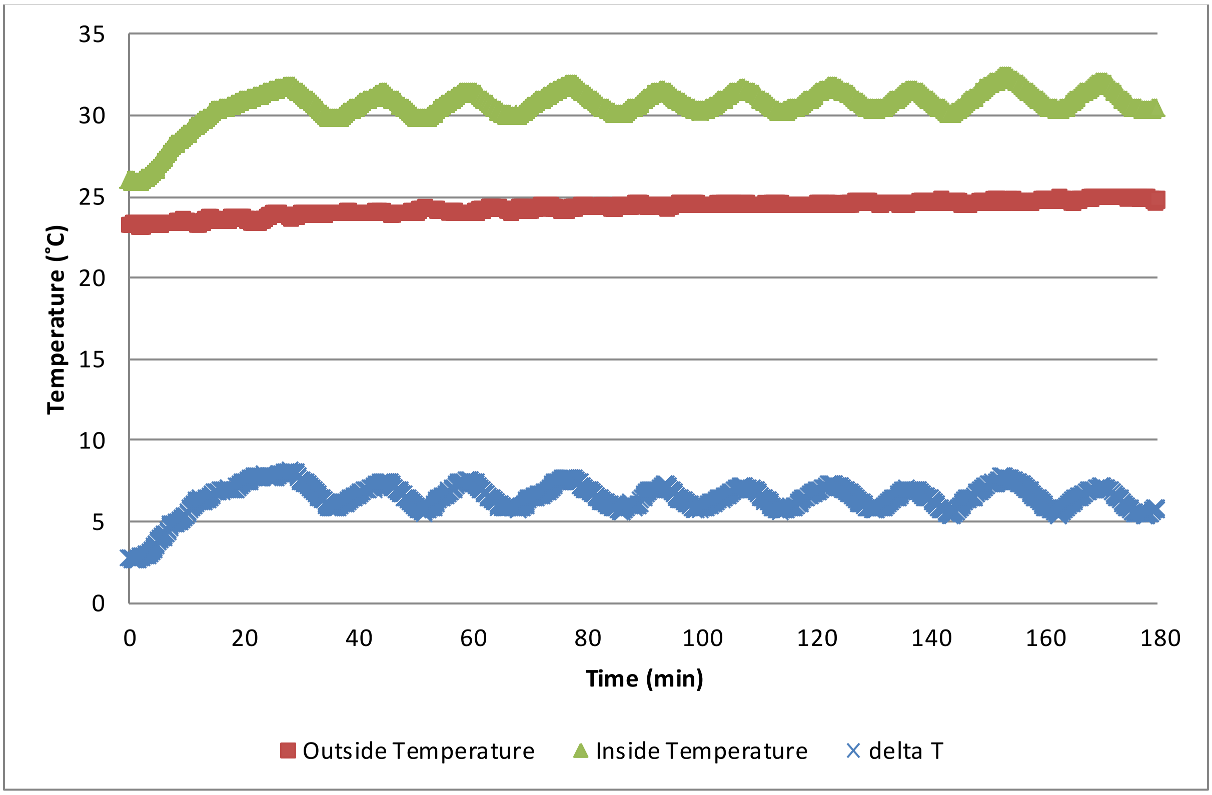


Figure 45: Relationship between ambient temperature and control volume temperature to establish temperature differential

Over the three hour test period, the ambient temperature in the workshop increased steadily from 23.2˚C to 24.8˚C. When the heating element is switched on, the temperature inside the control volume rises. The thermostat controls the heating element to maintain a temperature of 30˚C inside the control volume. The temperature range inside the control volume is maintained between 29.4˚C to 32˚C. The temperature differential thus varies accordingly.

The experimental set-up of this experiment has indicated that a temperature differential of approximately 7˚C is needed to cause rotation of the turbine ventilator. Once the turbine ventilator had started rotating, it would continue rotating, even if the temperature differential dropped below that of the initial temperature differential required to produce rotation via convection. In order to establish the required temperature differential, tests were only performed when the ambient temperatures were lower than 23˚C.

4.4 Instrumentation

In the laboratory experiments, the velocity pressure and temperature differentials are the “known” parameters. The variables needed to predict the performance of the turbine ventilator are presented in Table 6, and there location is illustrated in Figure 46.

Table 6: Description of variables and position of sensors for laboratory experiments

Variable	Description of variable	Position of sensor
T_{amb}	Ambient temperature in the workshop	50 mm above the apparatus
T_i	Temperature inside the control volume	Centreline velocity at a distance of 0.5D from the turbine ventilator base
V_{ID}	Upward velocity in the duct of the turbine ventilator	In-duct, 100 mm above the base of the turbine ventilator
$V_{0.5D}$	Upward centreline velocity in the control volume at 0.5D from the turbine ventilator	0.5D from the base of the turbine ventilator
V_D	Upward centreline velocity in the control volume at 1D from the turbine ventilator	1D from the base of the turbine ventilator
$V_{1.5D}$	Upward centreline velocity in the control volume at 1.5D from the turbine ventilator	1D from the base of the turbine ventilator

The temperature differential, dT , is calculated by:

$$dT = T_{\text{int}} - T_{out}$$ ... **Equation 9**

Type K thermocouples are used to measure T_{out} and T_{int}, and thin film sensors are used to measure V_{ID}, $V_{0.5D}$, V_D and $V_{1.5D}$.

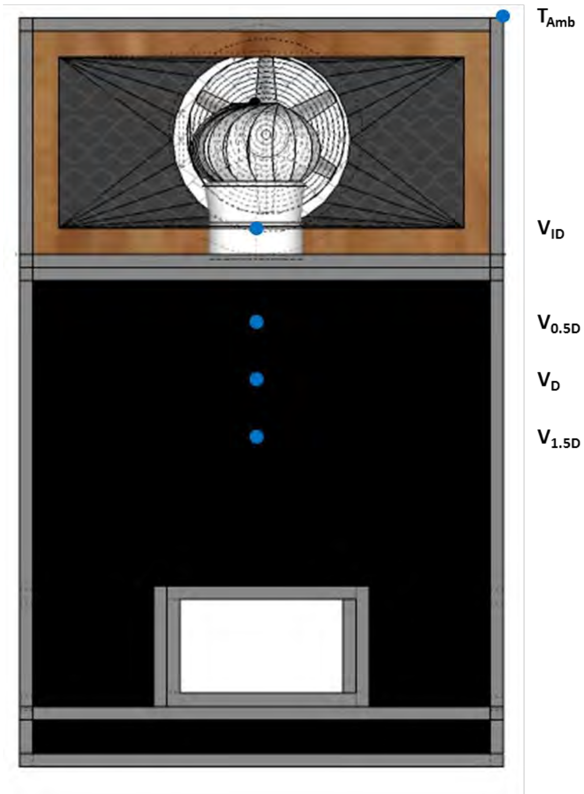


Figure 46 : An illustration of the position of measuring points in the laboratory apparatus

4.4.1 Thermocouples

Two types of thermocouples were used to monitor and measure temperature in these experiments. Type J thermocouples are positioned on the hot plate on the heating element to monitor the temperature change as the thermostat establishes the required temperature inside the control volume. These thermocouples are able to measure temperatures up to 650˚C for continuous use.

Type K flexible Teflon thermocouples are used to measure the air temperatures in the experiment. These thermocouples can measure up to 200˚C, and can bend to reach a required location.

4.5.2 Thin film sensors

Thin film sensors are typically thin, multi-layer electromechanical devices that produce an electrical signal when exposed to a stress or strain. Thin film air speed sensors use the strain developed within the film by air velocity pressure to measure the air velocity.

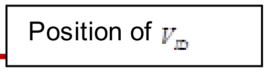


Figure 47: Position of thin film sensor, V_{ID}

Delta OHM HD2903T thin film sensors were used in this research project to measure the velocity profiles at the base of the turbine ventilator, $V_{0.5D}$, V_D and $V_{1.5D}$ as well as the in-duct velocity, V_{ID}. The output of Delta OHM HD2903T was 4 to 20 mA signal, and was set to a measure an air speed range of 0.05 to 1 m/s, with a reported accuracy of ±0.04 m/s + 2% of the measurement. The thin film sensors were directional, and their positions are shown in Figures 46.

4.4.3 Hot wire anemometers

A hot-wire anemometer is a device used to study rapidly varying flow conditions (Holman, 2001). A fine wire is electrically heated and placed in a flow stream. Hot-wire probes are used extensively for measuring transient flows, especially measurements with turbulent fluctuations (Holman, 2001). A SENTRY® ST732 hot-wire anemometer was used to measure and record the wind speed delivered by the fan during the apparatus calibration. The hot-wire anemometer probe is directional and only measures wind speed in one direction. The SENTRY® ST732 has a built-in data logger which can be programmed to measure and record data at predetermined time intervals. The manufacturer reports an accuracy of ±(0.03+3%) m/s for the air velocity measurements (SENTRY Optronics Corporation, 2010).

4.4.4 Data logging

Two Type J thermocouples, three Type K thermocouples and four thin film sensors are connected to a Data Trekker multichannel data logger. The data of all tests are recorded in real time, with a time interval of 15s between each reading. The programme to the run the code is appended in **Appendix E**. Data is output in .CSV files, and analysis is performed in MS Excel.

4.5 Laboratory experimental test protocol

Laboratory experiments were performed under worst case conditions. The effect of wind speed was measured at low wind speeds. The effect of temperature differential was measured at the lowest recorded temperature differentials to cause the turbine ventilator to rotate in the absence of any wind.

4.5.1 The effect of wind speed on the turbine ventilator

The turbine ventilator was tested under the influence of wind speed only. The wind speeds were low, in the range of 0.1 to 0.5 m/s, in increments of 0.1 m/s.

The following steps were taken to complete a wind speed test:

1. The required fan speed was dialled into the VSD.
2. The program to the data logger was initiated to record measurements every 15s.
3. Each test was run for a period of one hour.
4. After one hour, the program to the data logger was terminated.

Three sets of tests (0.1-0.5 m/s) were performed to establish repeatability of results.

4.5.2 The effect of buoyancy forces on the turbine ventilator

The turbine ventilator was tested under the influence of buoyancy forces alone.

The following steps were taken to complete a wind speed test:

1. The thermostat was set to maintain the air inside the control volume at 30 ˚C.
2. The data logger was programmed to record measurements every 15s.
3. Each test lasted 12 hours.
4. After 12 hours, the program to the data logger was terminated.

Three tests were performed to monitor the effect of the varying temperature differential on the airflow through the turbine ventilator.

4.5.3 The combined effect of wind speed and buoyancy forces

The turbine ventilator was tested under the combined effect of speed and buoyancy forces.

The following steps were taken to complete a wind speed test:

1. The heating element was switched on.
2. The fan is set to deliver a wind speed of 0.1 m/s.
3. The program to the data logger was initiated to record measurements every 15s.

4. After one hour the fan speed was increased incrementally by 0.1 m/s (up to 0.5 m/s).

5. After all five tests are performed the program to the data logger was terminated.

6. In the event where time had elapsed for the day, the incremental increase would occur on the following day.

Each set of tests was performed three times.

The protocols of the field study and the laboratory experiments have been presented. The results of the field study are presented in **Chapter 5**, and the results of the laboratory experiments are presented in **Chapter 6**. A discussion of both sets of results is presented in **Chapter 7**.

5. FIELD STUDY RESULTS

Each field study test is complex because the parameters within the test were constantly changing. It is for this reason that an overview of the field study results is presented first. Thereafter, the results of each test configuration (both baseline and turbine ventilator tests), are presented.

At the outset of the presentation of the field study results, the following blanket statement is made for ALL results presented here: ***The results presented here are under the specific environmental conditions and ventilation strategy at the time of the test, and are not generalisable.*** This statement will not be repeated at every point, but most certainly, does apply.

5.1 An overview of the field study results

The field study was divided into two stages. A set of baseline tests were performed to assess the performance of natural ventilation in bedroom 2 of the reference house. After these tests were completed, the turbine ventilator was installed, and the turbine ventilator tests were performed. This section will present an overview of the results of both sets of tests. For clarity, the four configurations are repeated in Table 7.

For each of the four test configurations, three tests were performed. One in the morning at around 9AM, one at noon at around 12PM and one in the afternoon at about 3PM. Details of the (measured) environmental conditions of the baseline and turbine ventilator tests are reported in Table 8 and 9, respectively.

The temperature, $T_{i,A}$ of Bedroom 2 is measured at Point A (See Figure 26), at the start of each test. The average outside temperature is calculated from Equation 10:

$$T_{out} = \frac{\sum_{i=1}^{n} T_{out,i}}{n} \quad \text{... Equation 10}$$

where:

T_{out} = average outside air temperature

$T_{out,i}$ = outside air temperature

n = total number of recorded measurements

As the hot-wire anemometer was positioned at Point C (see Figure 27), and point C was not shaded, the outside air temperature may be affected by solar radiation effects.

The average wind speed component, perpendicular to the reference house (x-direction), is given by Equation 11:

$$v_{w_x} = \frac{\sum_{i=1}^{n} v_i}{n} \text{ ... } \textbf{Equation 11}$$

where:

v_{w_x} = average wind speed in the x-direction

v_i = wind speed in the x-direction

n = total number of recorded measurements

The baseline tests were performed a month prior the turbine ventilator tests. The progression of seasons were such that the turbine ventilator tests were, in general, performed at lower temperatures and higher wind speeds than the baseline tests. In most instances, the average outside temperature, T_{out}, was higher than the measured inside temperature, $T_{i,A}$, at the start of the test. This differs from the simulations of (Osburn, 2010) for two reasons. The first is that (Osburn, 2010) assumed an accommodation schedule of the house which accounted for heat generation due to occupants and appliances. In the field study, the low-income house was empty, aside from the test equipment. Secondly, (Osburn, 2010) assumed that air exchange was due to infiltration/exfiltration. In the field study, between each test, all the windows and doors were left open so that all the CO_2 could be removed from the reference house.

Table 7: Test configurations (Green = Open; Red = Closed)

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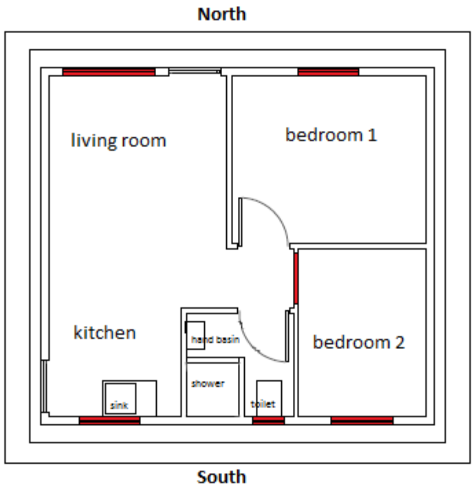
Infiltration/Leakage (IL)



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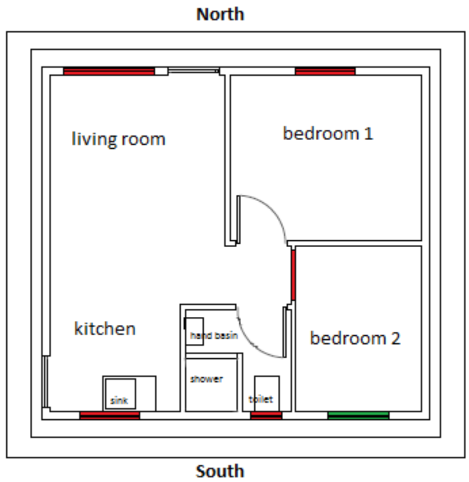
Single-sided ventilation 1 (SS1)



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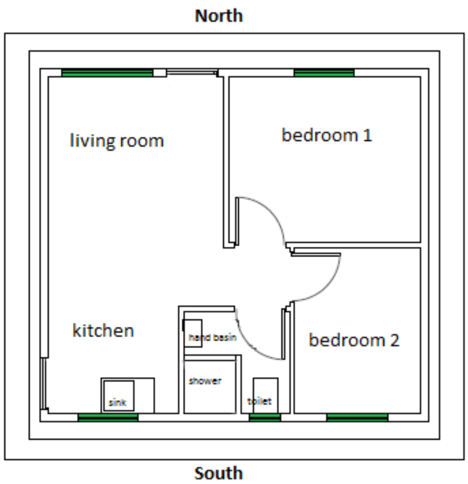
Cross-ventilation (CV)



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Single-sided ventilation 2 (SS2)

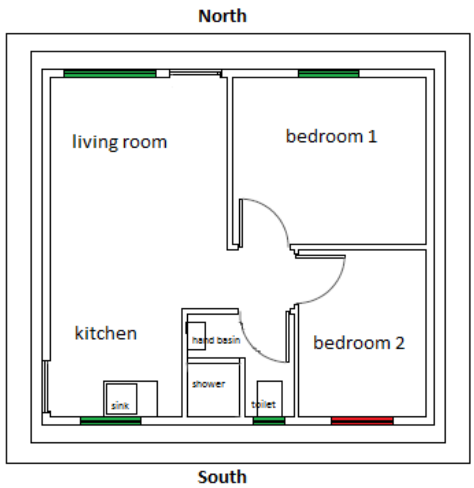

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Table 8: $T_{i,A}$ and average T_{out} and v_{w_x} for baseline tests

	Date		$T_{i,A}$ start of test (˚C)	Average T_{out} (˚C)	Average v_{w_x} (m/s)
Baseline test IL	26 February 2011	Morning	21.5	24.0	0.79
		Noon	25.4	27.0	0.76
		Afternoon	29.3	27.8	0.50
Baseline test SS1	1 March 2011	Morning	22.4	26.1	0.86
		Noon	24.9	28.8	0.75
		Afternoon	25.8	31.3	0.73
Baseline test CV	7 March 2011	Morning	22.6	25.8	0.86
		Noon	27.1	31.6	0.55
		Afternoon	26.7	32.0	0.93
Baseline test SS2	8 March 2011	Morning	23.2	22.4	1.72
		Noon	24.9	29.0	0.70
		Afternoon	26.0	31.8	0.90

Table 9: $T_{i,A}$ and average T_{out} and v_{w_x} for turbine ventilator tests

	Date		$T_{i,A}$ start of test (˚C)	Average T_{out} (˚C)	Average v_{w_x} (m/s)
Turbine ventilator test IL	14 April 2011	Morning	18.5	17.7	0.58
		Noon	20.0	23.8	0.72
		Afternoon	21.1	25.0	0.82
Turbine ventilator test SS1	4 April 2011	Morning	21.7	26.8	0.98
		Noon	23.1	30.5	0.96
		Afternoon	24.0	27.4	0.38
Turbine ventilator test CV	12 April 2011	Morning	23.5	22.1	1.25
		Noon	26.0	25.3	0.83
		Afternoon	25.0	24.1	0.88
Turbine ventilator test SS2	12 April 2011	Morning	24.3	24.2	0.80
		Noon	24.8	24.4	1.15
		Afternoon	26.2	24.6	0.67

5.1.1 Concentration decay for baseline and turbine ventilator tests

The morning, noon and afternoon tests of each configuration, with the exception of the SS1 configuration, reported similar results. For this reason, only the noon test is presented here for discussion. The concentration decay curves for the noon baseline tests are shown in Figure 49. IL shows a very slow decay of the tracer gas. In IL, the tracer gas did not decay to 500 ppm, and was stopped after two hours, as per the protocol outlined in **Chapter 3**. The reason for this slow decay is that there were no formal openings to bedroom 2 in this test, and air was exchanged through infiltration/leakages in the building envelope and adjacent rooms.

The fastest decay occurred in CV. In CV, all the windows of the reference house were opened and the door of bedroom 2 is also opened, allowing a cross-ventilation stream. Bedroom 2 was exposed to the maximum possible openable area in this configuration, thereby diluting and flushing out the tracer gas most effectively.

The rate of decay for SS1 and SS2 was between the two extremes of IL and CV. In SS1, the window of bedroom 2 was opened, and bedroom 2 is ventilated by single-sided ventilation. In SS2, the door of bedroom 2 was opened, and the window of bedroom 2 was closed. All other windows of the reference house were opened, and air entered and exhausted at the door of bedroom 2. Air leaving bedroom 2 formed part of the cross-ventilation stream across the reference house, where it was exhausted at the leeward side of the reference house.

The concentration decay curves of the noon turbine ventilator tests are shown in Figure 50. A comparison between Figures 48 and 49 showed a faster decay in IL, decaying to 500 ppm, when a turbine ventilator was installed in bedroom 2. The reason for the faster decay is that in the turbine ventilator IL, the turbine ventilator acted as a formal opening, allowing air to be exhausted through it.

In the turbine ventilator tests, CV also recorded the fastest decay, again exceeding 12.9 ACH. SS1 is the only test which recorded a slower decay rate with the installation of a turbine ventilator compared to its baseline tests.

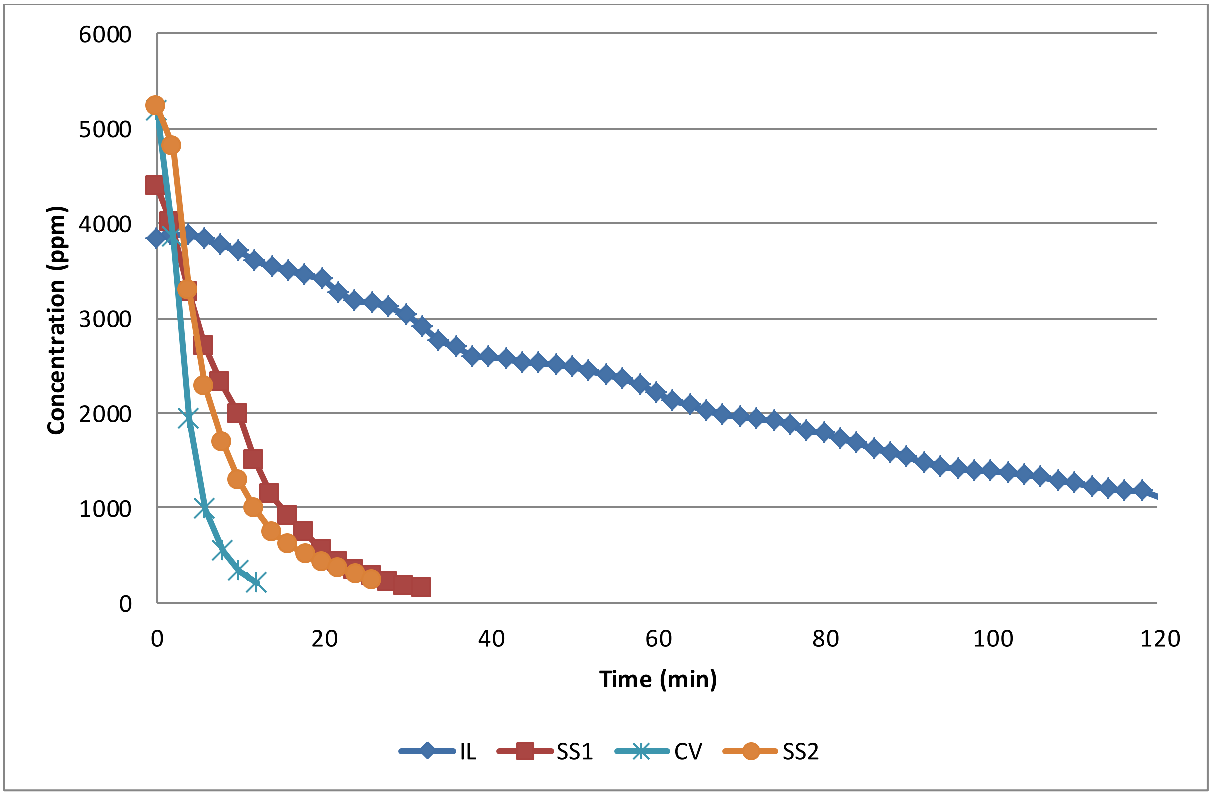

Figure 48: Concentration decay curves for noon baseline tests

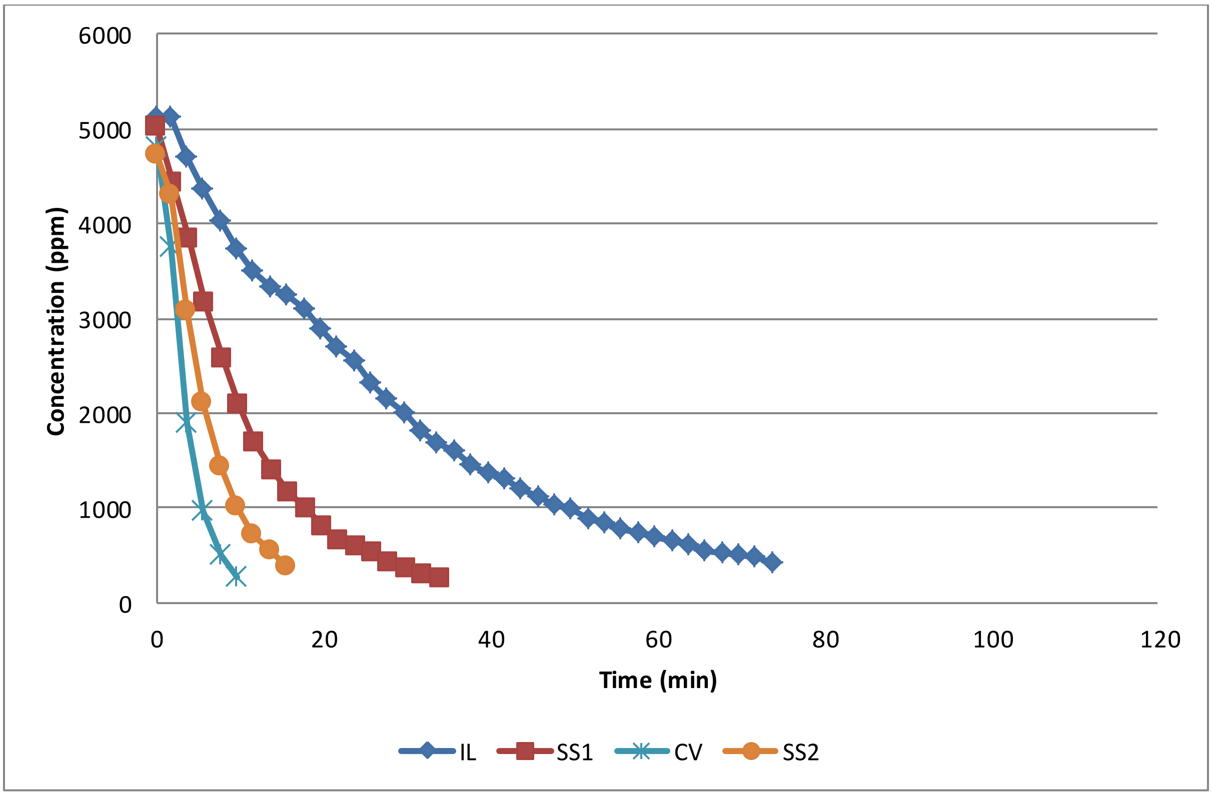

Figure 49: Concentration decay curves for the noon turbine ventilator tests

Accounting for accuracy in concentration decay measurements

The manufacturer of the SENTRY ST303 CO_2 analyser reports an accuracy of ±50 ppm in the range 0 - 5000 ppm (SENTRY Optronics Corporation, 2009). At 5000 ppm, this level of accuracy may not be significant, as the accuracy would be within 1%. At 500 ppm, the accuracy of the concentration reading could be up to 10%. Consider Figure 50 below.

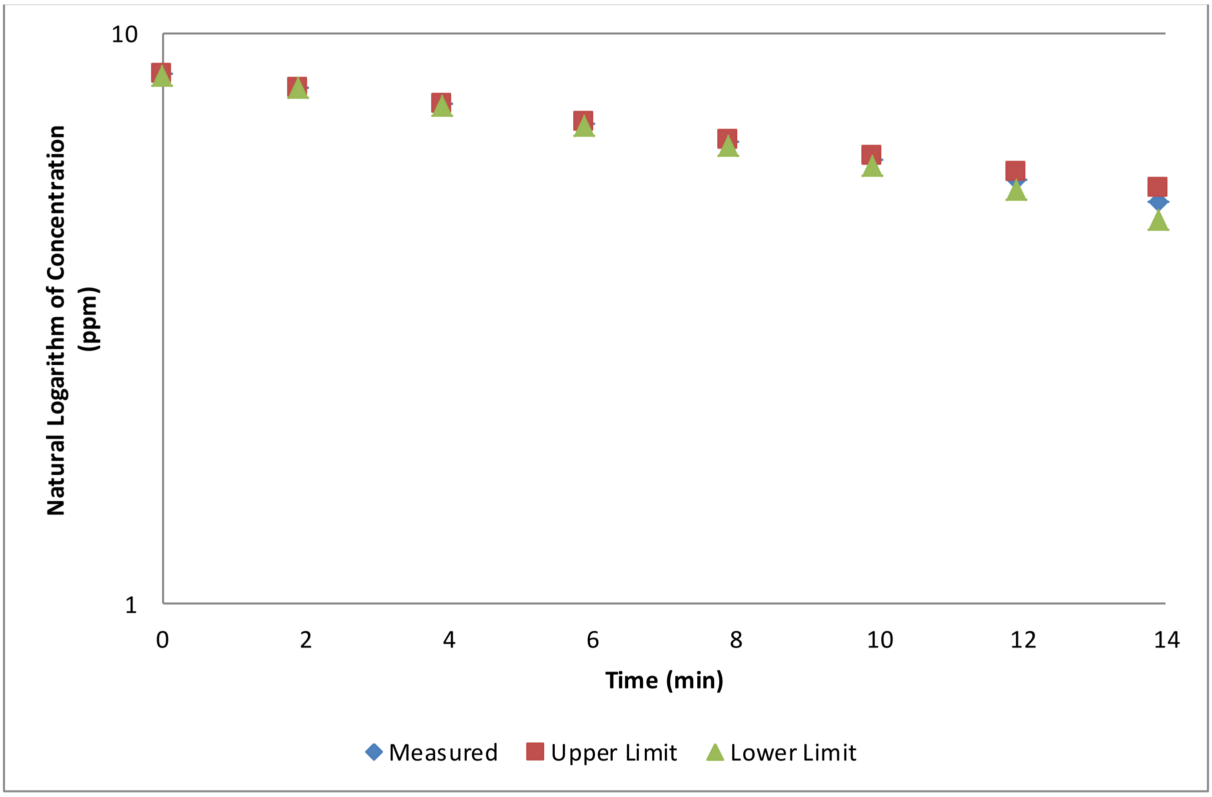

Figure 50: An illustration of accuracy in concentration decay

In Figure 50, the “Measured” curve presents the data of the natural logarithm of concentration for a test. The “Upper Limit” assumes the measured data plus 50 ppm, and the “Lower Limit” assumes the measured data minus 50 ppm. It is apparent in Figure 51 that, at higher concentrations, the ±50 ppm accuracy has very little effect in creating variation from the “Measured” curve. The “Upper Limit” and “Lower Limit” curves do separate from the “Measured” curve towards the end of the test (near 500 ppm). If we consider the gradient of the “Upper Limit” and “Lower Limit” curves to be the two extremes of the concentration decay, by considering the test presented in Figure 51, the resulting ventilation flow rates would be 13.6, 14.7 and 16.1 ACH for the “Upper Limit”, “Measured” and “Lower Limit” curves, respectively. This corresponds to a difference of 7.5% in the “upper Limit” and 9.5% in the lower limit.

5.1.2 Ventilation flow rates

The ventilation capacity of a ventilation system can be determined by the number of fresh air changes achieved every hour (ACH) by the system. The ACH was calculated from the slope of the logarithmic concentration decay curves. The number of ACH achieved in the baseline tests and turbine ventilator tests are shown in Figures 51.

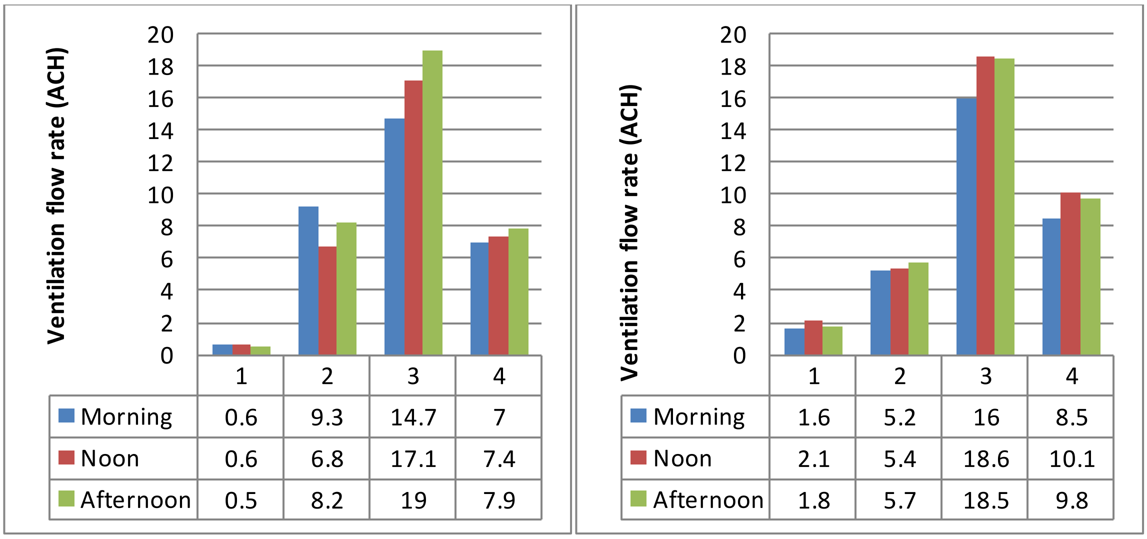

Figure 51: Ventilation flow rates of baseline (left) and turbine ventilator (right) tests

In the baseline tests, IL reported less than one ACH across all tests. CV is the only test that achieved greater than 12.9 ACH, reporting between 14 and 19 ACH in the baseline tests.

The turbine ventilator tests reported an approximate increase of one ACH in IL compared to its baseline tests. CV was the only test to achieve greater 12.9 ACH, reporting 16-18 ACH in the turbine ventilator tests. This result did not indicate an increase in ACH by incorporating the turbine ventilator. It did however highlight the fact that simply opening the windows of the reference house and the door of bedroom 2 was enough to achieve ventilation flow rates of IPC standard for this reference house.

Accounting for accuracy in ventilation flow rate results

Following from Figure 50, the “Upper Limits” and “Lower Limits” for each of the baseline and turbine ventilator tests are reported in Tables 10 and 11, respectively. The “Measured” ventilation flow rates correspond to the results presented in Figure 51. If the accuracy of the instrument is taken into account, the percentage difference in ventilation flow rate may be significant. In the baseline tests, this difference was calculated to be between 0 – 20% in IL, 7.4 – 13% in SS1, 5.8 – 13% in CV and 5.4 – 8.9% in SS2. In the turbine ventilator tests, this difference was calculated to be between 0 – 6.3% in IL, 5.3 – 7.7% in SS1, 3.8 – 6.5% in CV and 3.5 - 5.0% in SS2.

Table 10: Measured, Upper Limits and Lower Limits of ventilation flow rates for baseline tests

Test Configuration	Test	Upper Limit (ACH)	Measured (ACH)	Lower Limit (ACH)	% Difference of Upper Limit	% Difference of Lower Limit
IL	Morning	0.6	0.6	0.7	0.0	17
	Noon	0.6	0.6	0.7	0.0	17
	Afternoon	0.5	0.5	0.6	0.0	20
SS1	Morning	8.6	9.3	10.5	7.5	13
	Noon	6.3	6.8	7.5	7.4	10
	Afternoon	7.5	8.2	9.3	8.5	13
CV	Morning	13.6	14.7	16.1	7.5	9.5
	Noon	16.1	17.1	18.4	5.8	7.6
	Afternoon	17.4	19.0	21.5	8.4	13
SS2	Morning	6.6	7.0	7.5	5.7	7.1
	Noon	7.0	7.4	7.9	5.4	6.8
	Afternoon	7.4	7.9	8.6	6.3	8.9

Table 11: Measured, Upper Limits and Lower Limits of ventilation flow rates for turbine ventilator tests

Test Configuration	Test	Upper Limit (ACH)	Measured (ACH)	Lower Limit (ACH)	% Difference Upper Limit	% Difference Lower Limit
IL	Morning	1.5	1.6	1.7	6.3	6.2
	Noon	2.0	2.1	2.1	4.8	0.0
	Afternoon	1.7	1.8	1.8	5.6	0.0
SS1	Morning	4.9	5.2	5.6	5.8	7.7
	Noon	5.1	5.4	5.7	5.6	5.6
	Afternoon	5.4	5.7	6.1	5.3	7.0
CV	Morning	15.4	16.0	16.8	3.8	5.0
	Noon	17.7	18.6	19.8	4.8	6.5
	Afternoon	17.6	18.5	19.5	4.9	5.4
SS2	Morning	8.2	8.5	8.9	3.5	4.7
	Noon	9.7	10.1	10.6	4.0	5.0
	Afternoon	9.4	9.8	10.2	4.1	4.1

5.1.3 Mean age of air (MAA)

The MAA is the average time required to replenish a pocket of air in the room with fresh air. The MAA was calculated from the area under the concentration decay curves. The MAA for the baseline tests and turbine ventilator tests are shown in Figure 52.

In Figure 52 the true effect of the slow decay in IL is highlighted. IL has a MAA of almost 100 minutes. This implies that in the IL configuration, it would take more than one and a half hours to replace potentially contaminated air with fresh air. SS1, CV and SS2 have a significantly smaller MAA compared to IL.

In the turbine ventilator tests, the MAA for IL was greatly reduced, to below 40 minutes. This single ACH resulted in a significant drop in the MAA. While these MAA results were not adequate to sufficiently dilute and remove contaminated air from the room according to TB IPC guidelines, they reduced the MAA results by more than half, when compared to the MAA achieved in the baseline tests.

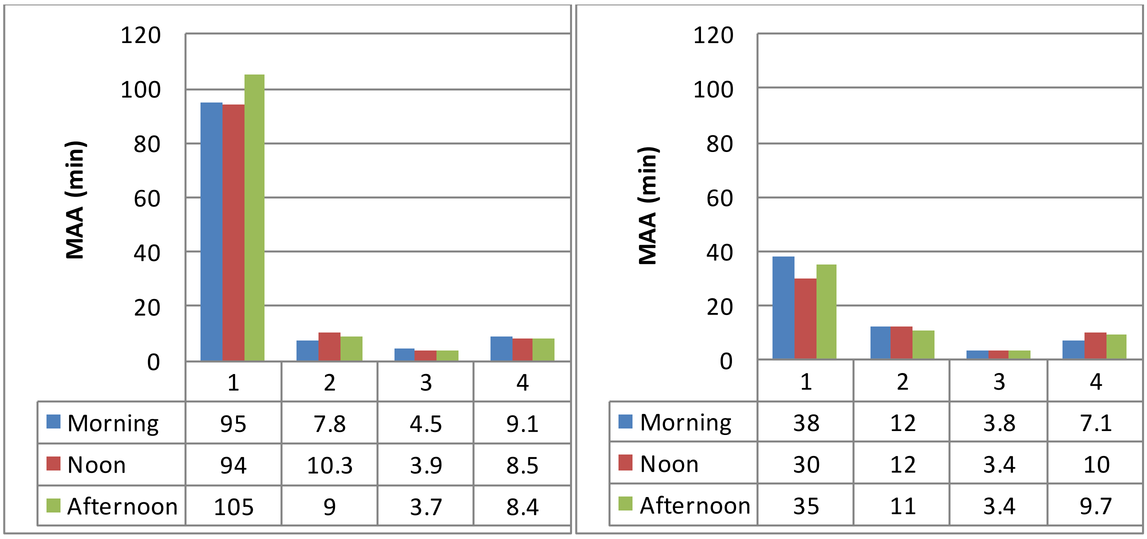

Figure 52: MAA for baseline (left) and turbine ventilator (right) tests

5.1.4 The effect of environmental conditions on ventilation effectiveness

In all baseline tests, and the majority of turbine ventilator tests, the predominant wind direction was from the north east with regard to the reference house, as shown in Figure 53. This implies that, in most instances, the window of bedroom 2 would lie on the leeward side of the house, and would work against the turbine ventilator.

Figure 53: Predominant wind direction in the field study tests

Figures 54 and 55 are diagrams which illustrate the effect of wind speed and temperature on the ventilation flow rate for baseline and turbine ventilator tests, respectively. In these graphs, the size of the bubble is indicative of the magnitude of the ventilation flow rate achieved for that test, i.e. the bigger the bubble, the greater the ventilation flow rate.

In Figure 54, all the bubbles of a test have similar size, e.g. the orange bubbles of SS2 are all of similar size, and the blue bubbles of CV are also of similar size, but the blue bubbles of CV are bigger than the orange bubbles of SS2, implying that the ventilation flow rate of CV is greater than that of SS2. This implies that each of the morning, noon and afternoon tests of the test configurations all achieved ventilation flow rates of similar magnitude. From Figure 54, it appears that this magnitude does not depend on the directional wind velocity or the temperature at which the test is performed. The ventilation flow rate is more dependent on the openable area of bedroom 2.

From Figure 55 it can be seen that the temperature range and directional wind speed ranges of the turbine ventilator tests were greater than that of the baseline tests shown in Figure 54. Figure 55 also shows that the ventilation flow rate achieved is dependent on the configuration, hence openable area, not necessarily the environmental conditions.

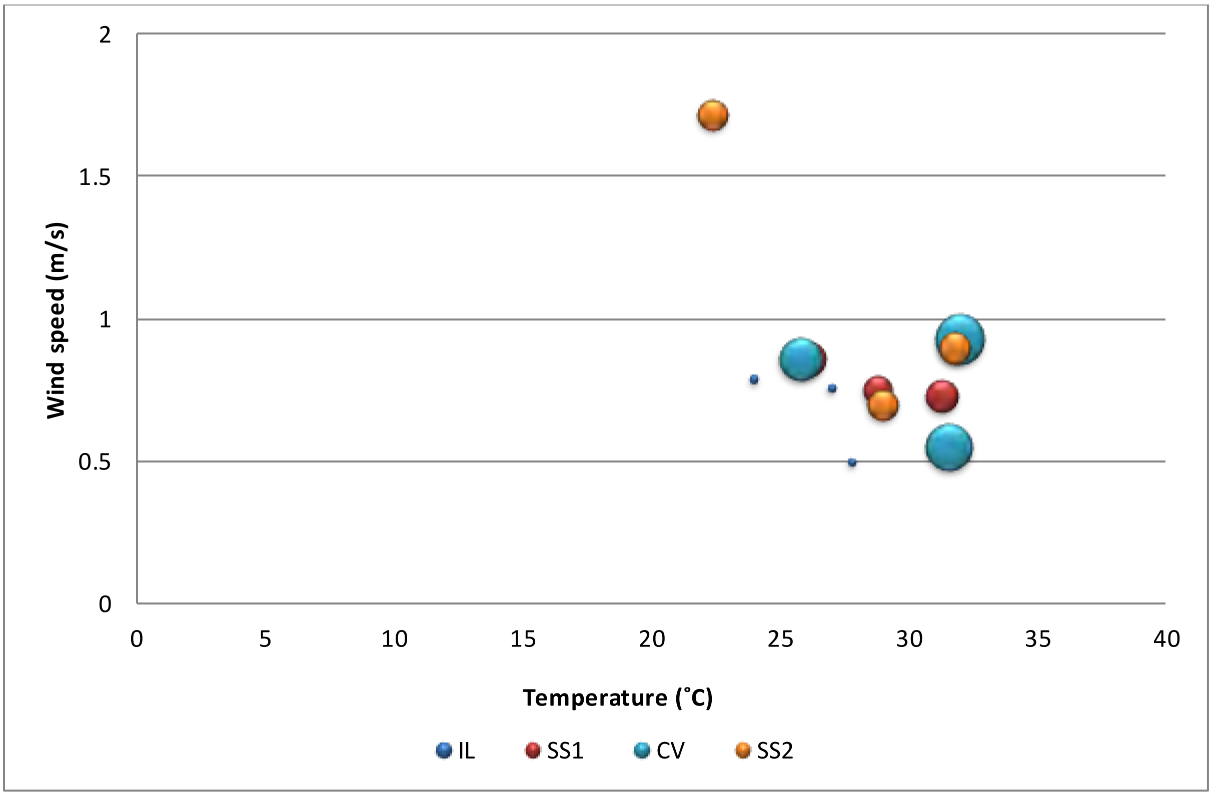

Figure 54: Ventilation flow rate as a function of velocity and temperature for baseline tests

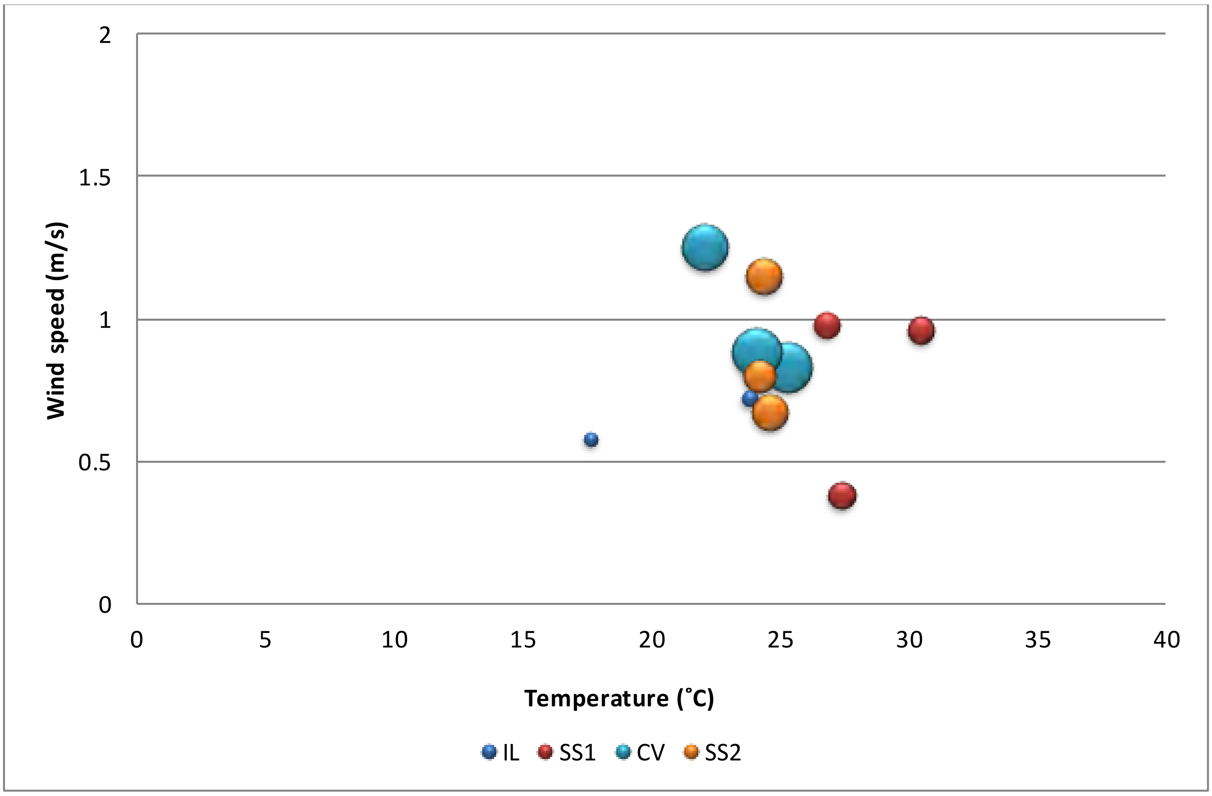

Figure 55: Ventilation flow rate as a function of velocity and temperature for turbine ventilator tests

5.1.5 Air change efficiency

The air change efficiency is a measure of how efficiently fresh air is distributed in the room (REHVA, 2004). The air change efficiency was described by Equation 7 in **Chapter 3**. The air change efficiency was calculated for each of the morning, noon and afternoon tests of all field study configurations. They are presented in Table 12.

Table 12: Calculated air change efficiency for all field study tests

Test configuration	Test	Baseline (%)	Turbine Ventilator (%)
IL	Morning	55	57
	Noon	59	54
	Afternoon	57	56
SS1	Morning	70	58
	Noon	62	56
	Afternoon	61	55
CV	Morning	54	58
	Noon	60	60
	Afternoon	52	56
SS2	Morning	52	59
	Noon	54	59
	Afternoon	54	55

As mentioned in **Chapter 3**, an air change efficiency of 100% represents piston flow, and an air change efficiency of 50% represents fully mixed flow. Displacement ventilation lies somewhere between 50 and 100%. An air change efficiency of less than 50% represents short-circuiting of the ventilation system.

In the baseline tests, the air change efficiency of the IL, CV and SS2 configurations range between 52 and 60%. This implies that in these configurations, the air in the room can be considered to be well-mixed. SS1 was the only configuration which had higher air change efficiencies, in the range of 61 to 70%. This result implies that the room air was less well-mixed than the other configurations.

In the turbine ventilator tests, the air change efficiency of all test configurations ranged between 54 and 60%. The most notable change in air change efficiency with the addition of the turbine ventilator is in SS1, where the air change efficiency is reduced from a range of 61 to 70% in the baseline tests, to a range of 55 to 58% in the turbine ventilator tests. None of the tests reported short-circuiting in the natural ventilation system.

5.2 Infiltration/Leakage

In IL, all windows of the reference house were closed, and the door of bedroom 2 was closed. Air in bedroom 2 was exchanged through infiltration and leakages across the building envelope and adjacent rooms.

5.2.1 Baseline IL

The concentration decay curves and the logarithmic concentration decay curves for Baseline Test IL are shown in Figure 56. The morning, noon and afternoon tests of Baseline IL did not decay to 500 ppm, and the test was stopped after two hours, as per the protocol outlined in **Chapter 3**. Figure 56 shows that the concentration decay of the morning, noon and afternoon tests were very similar.

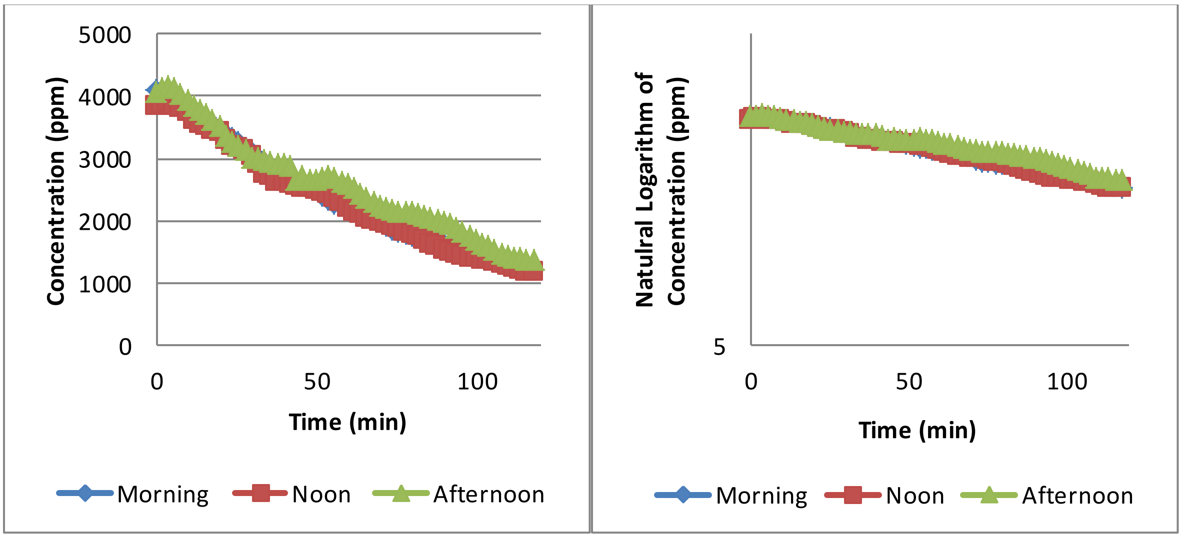

Figure 56: Concentration decay (left) and logarithmic concentration decay (right) curves for baseline IL test

The logarithmic concentration decay curve of Figure 56illustrate the slow decay of Baseline IL. The resulting ventilation flow rate is between 0.5 and 0.6 ACH. The weighted area under the concentration decay curves of was used to calculate the MAA, and the slope of the logarithmic curves was used to calculate the number of ventilation flow rate for Baseline IL Test. These results, as well as the average external temperatures and average directional wind speed, are reported in Table 13.

Table 13: Baseline IL test results

	Average T_{out} (˚C)	Average v_{w_x} (m/s)	MAA (min)	Ventilation flow rate (ACH)	Ventilation flow rate (l/s)
Morning	24.0	0.79	95	0.6	9.9
Noon	27.0	0.76	94	0.6	9.9
Afternoon	27.8	0.50	105	0.5	8.3

In the morning and noon tests, the average recorded velocities were of similar magnitude. The ventilation flow rates in the morning and noon tests were also similar. In the afternoon test, the average recorded velocity was less than that of the earlier tests, so too was the measured ventilation flow rate.

5.2.2 Turbine Ventilator IL

The concentration decay curves and the logarithmic concentration decay curves for turbine ventilator IL are shown in Figures 57 and 58, respectively. In the morning test, the turbine ventilator slowed to a complete stop two minutes into the test. This stop was for a short period of time, and the turbine ventilator started rotating again due to a strong wind. 70 minutes into the afternoon test, the turbine ventilator slowed to a complete stop, stopped momentarily, and began rotating again due to a strong wind. These points have been marked in Figure 57. The afternoon test was stopped at the 74th minute due to rain.

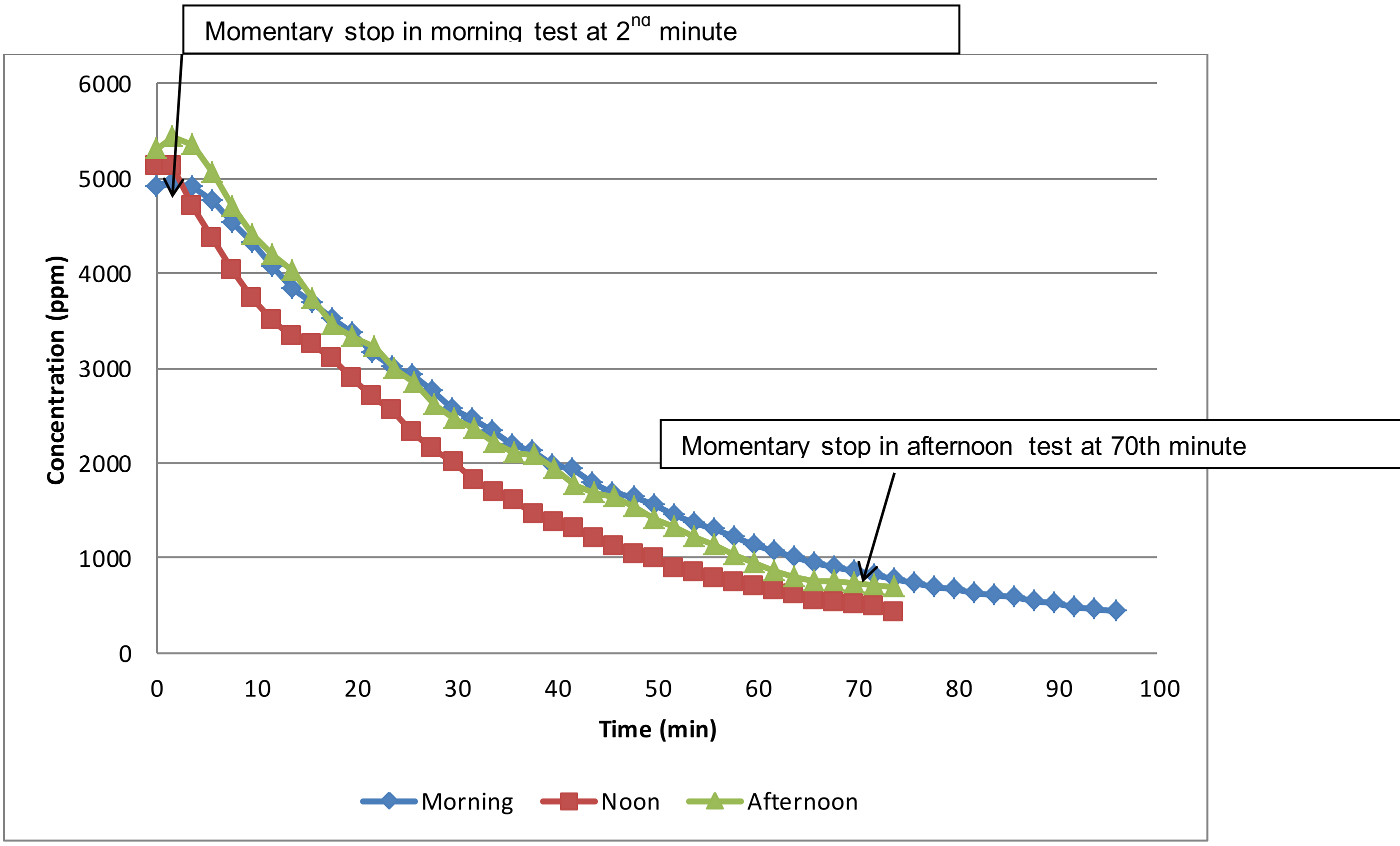

Figure 57: Concentration decay curves for Turbine Ventilator IL

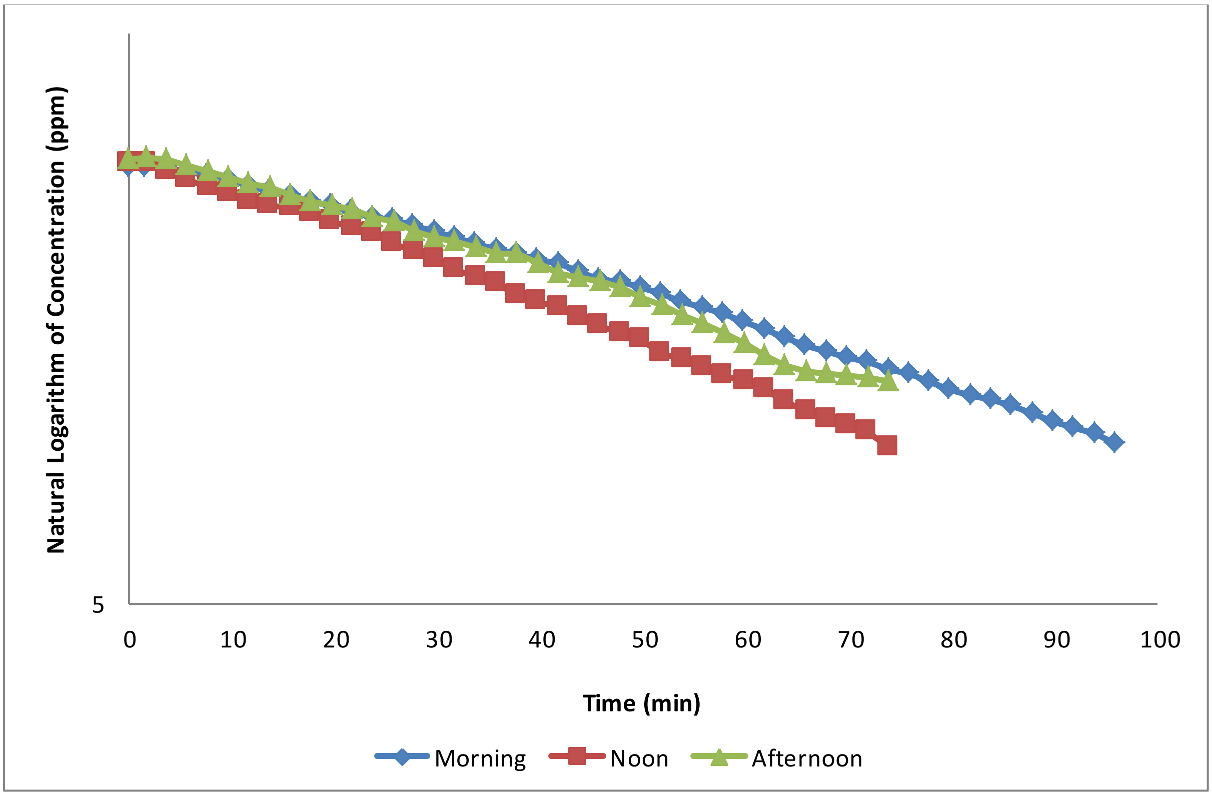

Figure 58: Logarithmic concentration decay curves for Turbine Ventilator IL

In the morning, noon and afternoon tests of Turbine Ventilator IL, the tracer gas decayed to 500 ppm. The duration of the morning test was 96 minutes, and the duration of the noon and afternoon tests were 74 minutes. The curves of Figures 57 and 58 showed very little variation in concentration decay for the morning, noon and afternoon tests.

The results of Turbine Ventilator IL are reported in Table 14. The morning test was run at the lowest average velocity for this configuration, and resulted in the lowest reported number ventilation flow rate. The afternoon test was conducted at the highest average velocity but did not report the highest ventilation flow rate.

Table 14: Turbine Ventilator IL results

	Average T_{out} **(˚C)**	**Average** v_{w_x} **(m/s)**	**MAA (min)**	**Ventilation flow rate (ACH)**	**Ventilation flow rate (l/s)**
Morning	17.7	0.58	38	1.6	26
Noon	23.8	0.72	30	2.0	35
Afternoon	25.0	0.82	35	1.7	30

The concentration decay curves for the room and through the turbine ventilator of the morning, noon and afternoon test are shown in Figure 59. There is a distinct difference between the decay in the room and the decay through the turbine ventilator in all three tests. As the turbine ventilator rotated, tracer gas in the close vicinity of the turbine ventilator was removed, reducing the concentration of tracer gas in the air near the turbine ventilator.

As the test progresses, the decay rate at the turbine ventilator stabilised. After approximately 50 – 60 minutes, the air in the room was at a higher temperature than it was at the beginning of the test, and begins to rise, due to natural convection, towards the opening at the turbine ventilator. The rising air reduced the tracer gas concentration in the room, and was transferred to the tracer gas concentration through the turbine ventilator.

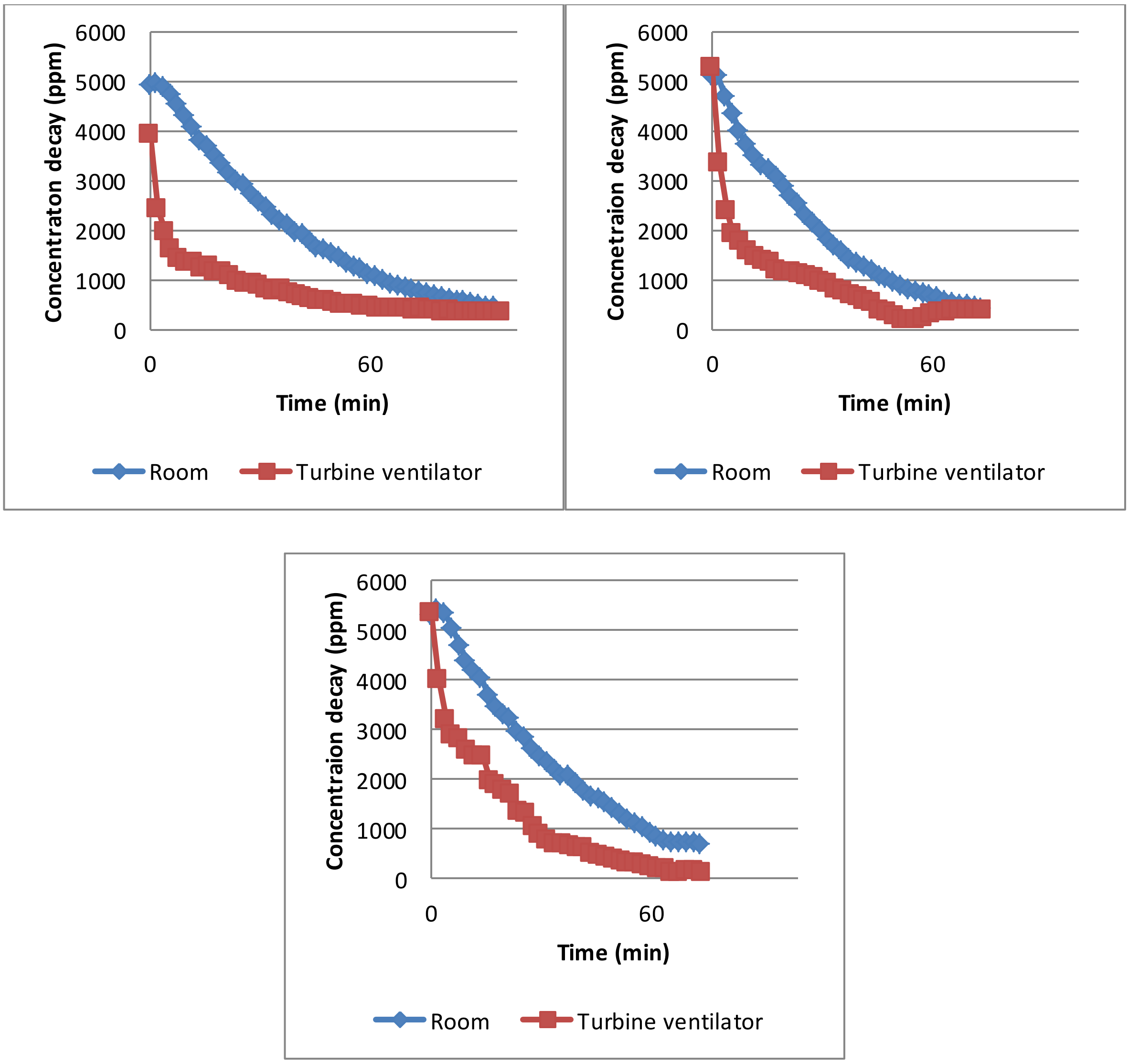

Figure 59: Concentration decay curves of the decay through the turbine ventilator and the decay in the room in the morning (top left), noon (top right) and afternoon (bottom) tests of Turbine Ventilator IL

5.3 Single-sided ventilation: Case 1

In Baseline SS1, the only formal opening was the window of bedroom 2. In Turbine Ventilator SS1 the formal openings were the window of bedroom 2 and the turbine ventilator. In both cases, bedroom 2 may experience single-sided ventilation.

5.3.1 Baseline SS1 results

The concentration decay curves and the logarithmic concentration decay curves for Baseline SS1 are shown in Figure 60. The tracer gas decayed to 500 ppm in the morning, noon and afternoon tests. The duration of each test differed: 22 minutes for the morning test, 32 minutes for the noon test, and 30 minutes for the afternoon test.

The logarithmic concentration decay curves of Figure 60 highlight the variance in decay rate of the morning, noon and afternoon tests. As reported in Table 15, the mean ventilation flow rate varied between 6.8 and 9.3 ACH, a difference of 2.5 ACH. The difference in ventilation flow rate was attributed to single-sided ventilation. Single-sided ventilation occurs as a result of wind pressure fluctuations. These fluctuations resulted in air moving both in and out of bedroom 2's window. Because the wind speed and direction fluctuated in each test, the rate at which air is exchanged at the window of bedroom 2 constantly fluctuated. From Table 15 it can be seen that an increase in wind speed did not necessarily result in an increase in ventilation flow rate.

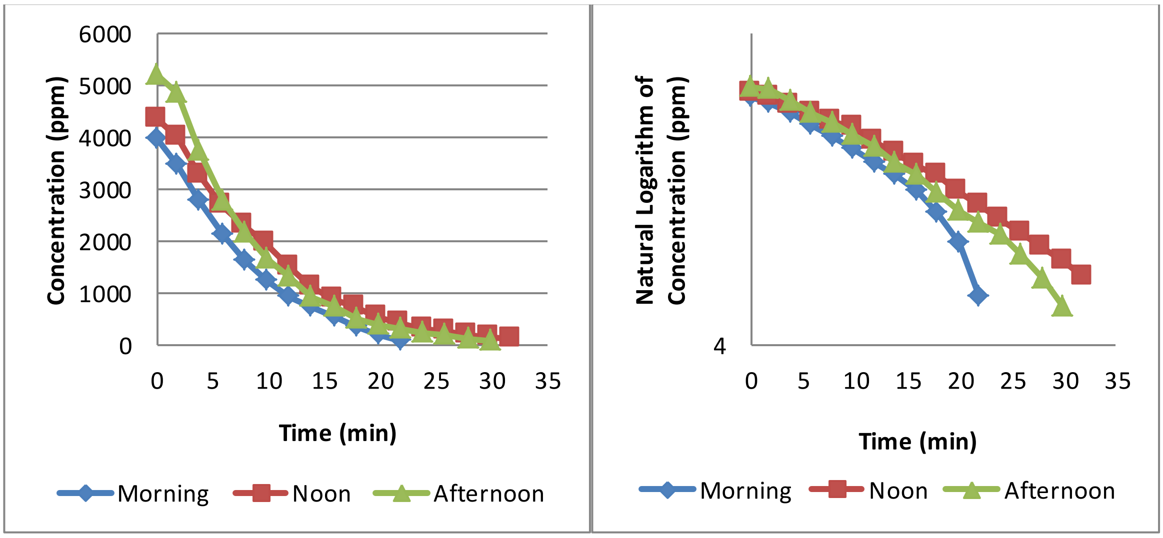

Figure 60: Concentration decay curves for Baseline SS1

Table 15: Results of Baseline SS1

	Average T_{out} (˚C)	Average v_{w_x} (m/s)	MAA (min)	Ventilation flow rate (ACH)	Ventilation flow rate (l/s)
Morning	26.1	0.86	7.8	9.3	153
Noon	28.8	0.75	10.3	6.8	112
Afternoon	31.3	0.73	9.0	8.2	135

5.3.2 Turbine Ventilator SS1

The concentration decay curves and the logarithmic concentration decay curves for Turbine Ventilator SS1 are shown in Figures 61. The tracer gas decayed to 500 ppm in all tests. The duration of the tests was similar: 34 minutes for the morning and noon test and 36 minutes for the afternoon test.

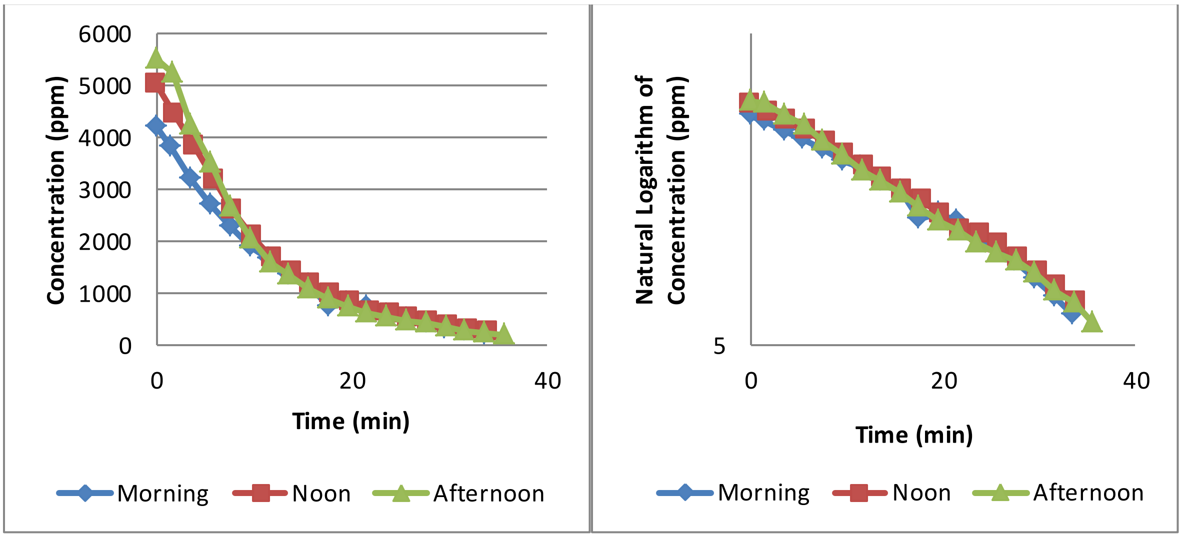

Figure 61: Concentration decay curves for Turbine Ventilator SS1

The concentration decay curves for the morning, noon and afternoon tests showed little variation. This is apparent in the logarithmic concentration decay curves of Figure 61, where the straight-line graphs have almost identical gradients.

In the morning and noon tests, the turbine ventilator was always rotating. In the afternoon test, the turbine ventilator was stationary for the most part of the test. The concentration decay curve for the afternoon test is shown in Figure 62. This graph highlights the time periods during the test when the turbine ventilator was stationary. Even though the turbine ventilator was stationary for a large part of the afternoon test, the rate of decay in bedroom 2 was similar to that of the morning and noon test, where the turbine ventilator had been rotating continuously. Table 16 reports the results of Turbine Ventilator SS1.

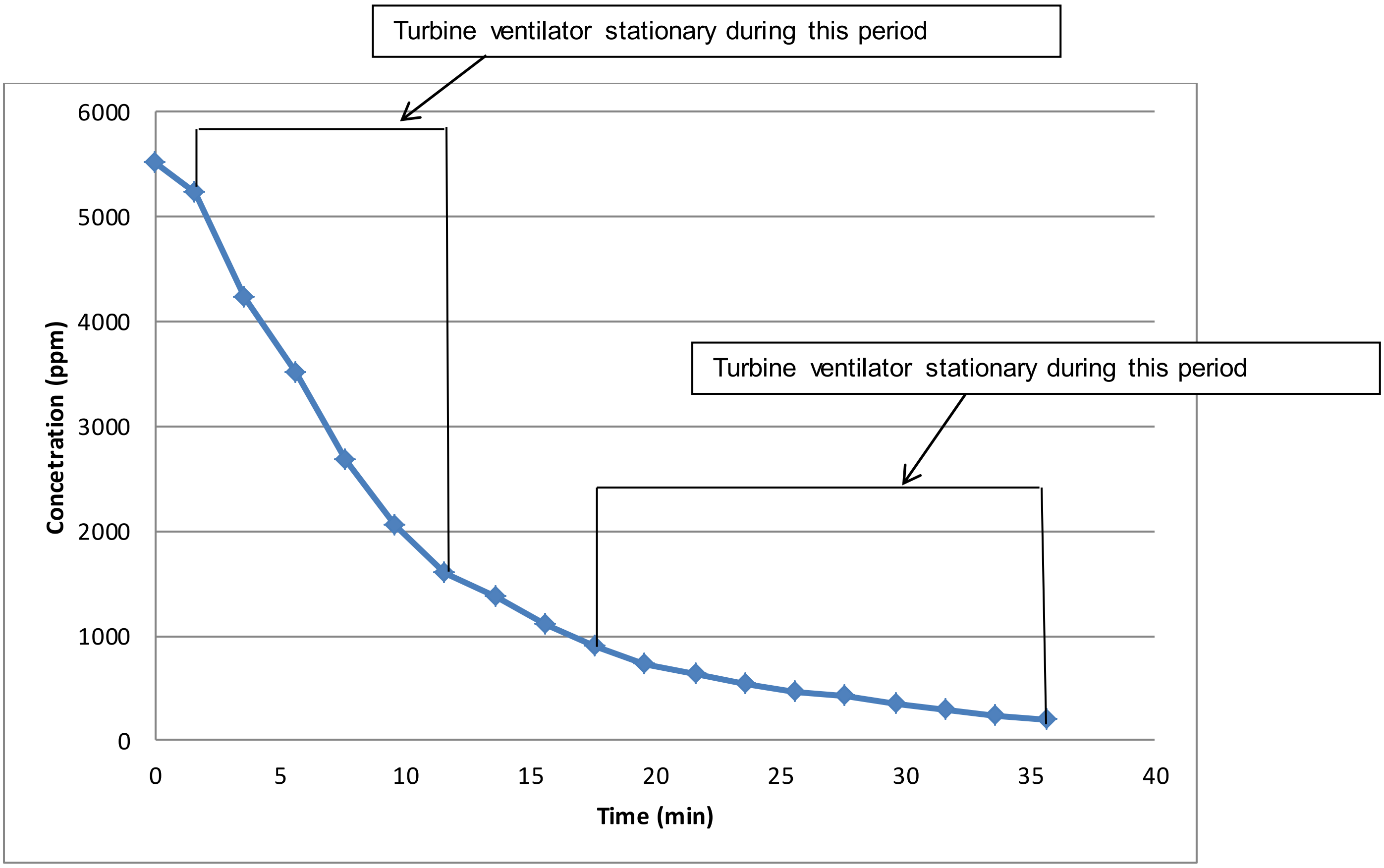

Figure 62: Concentration decay curve of afternoon Turbine Ventilator SS1 showing stationary periods of turbine ventilator

Table 16: Results of Turbine Ventilator SS1

	Average T_{out} (˚C)	Average v_{w_x} (m/s)	MAA (min)	Ventilation flow rate (ACH)	Ventilation flow rate (l/s)
Morning	26.8	0.98	12.2	5.2	86
Noon	30.5	0.96	11.8	5.4	89
Afternoon	27.4	0.38	11.3	5.6	94

Figure 63 show the concentration decay curves for the tracer gas decay through the turbine ventilator and tracer gas decay in the room for these tests. In the morning, noon and afternoon tests, it was evident from the movement of flow ribbons that air was entering and leaving bedroom 2 at the window of bedroom 2, resulting in single-sided ventilation. In all three tests, the decay in the room is steady, and similar. However, the decay through the turbine ventilator in the morning and noon tests are erratic, decaying rapidly to the background concentration in the noon test. The decay through the turbine ventilator in the afternoon test is steady, and similar to the decay in the room. In the afternoon test however, the wind was very low, and the turbine ventilator was stationary for the most part of the test.

The results of these tests suggest that the suction created by the turbine ventilator was not strong enough to move the tracer gas from the room to be exhausted by the turbine ventilator. Instead, the tracer gas in the room is exhausted through the pressure differential created across the window of bedroom 2.

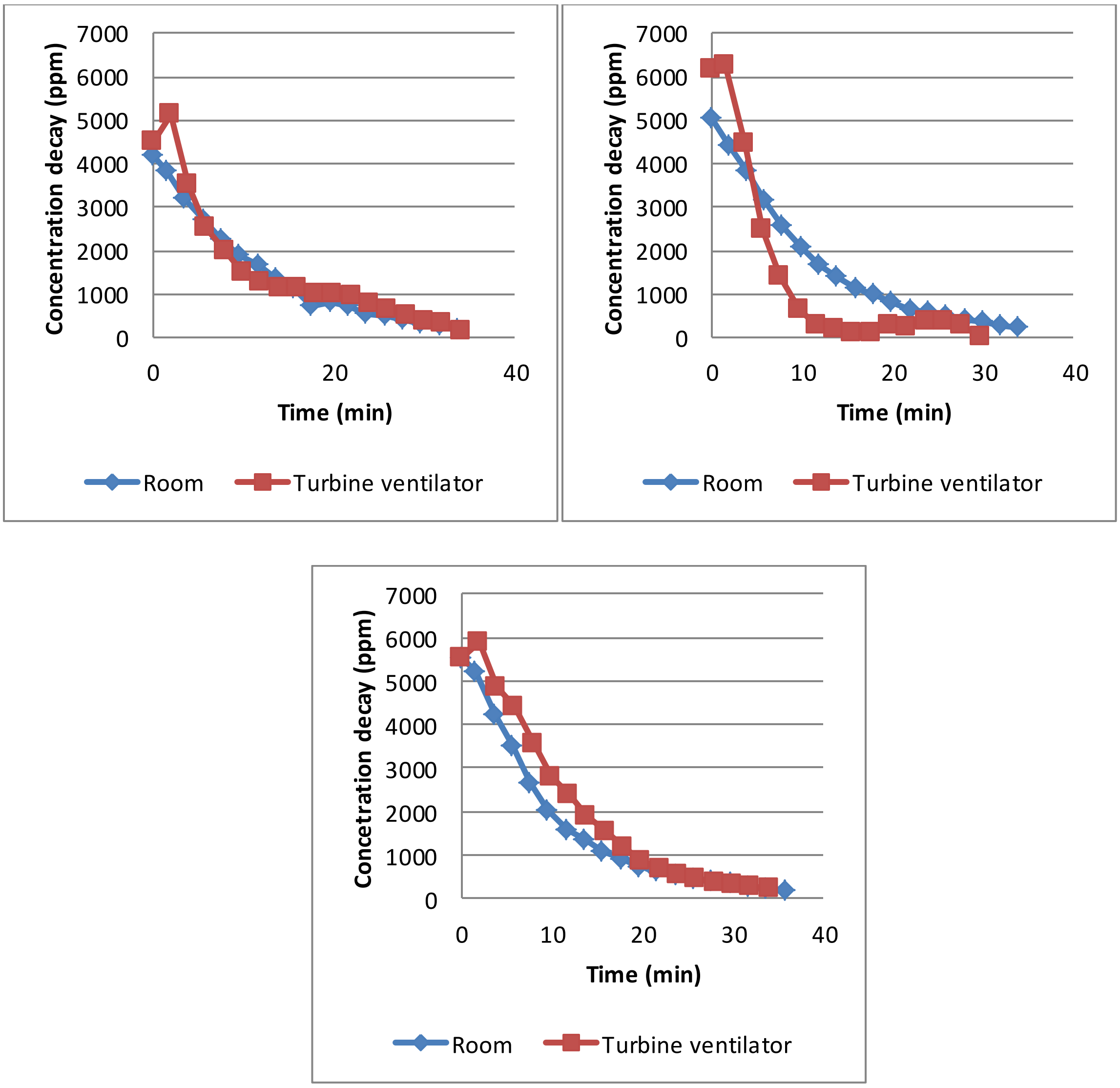

Figure 63: Concentration decay curves of the decay through the turbine ventilator and the decay in the room in the morning (top left), noon (top right) and afternoon (bottom) tests of Turbine Ventilator SS1

While tracer gas (concentration decay) testing provides detail about the ventilation flow rates, MAA and air change efficiency of the room, and through the turbine ventilator, it cannot calculate CRE, and a true reflection of the contaminant sources leaving the turbine ventilator cannot be established. For the IL configuration, a constant injection tracer gas test, could have determined the CRE in the room, as steady state would have likely been reached.

5.4 Cross-ventilation

In CV, all windows of the house were opened, and bedroom 2's door was opened. Bedroom 2 is exposed to the maximum openable area and was expected to achieve the highest ventilation flow rate.

5.4.1 Baseline CV

The concentration decay curves and the logarithmic concentration decay curves for Baseline CV are shown in Figure 64. The tracer gas decayed to below 500 ppm in the morning, noon and afternoon tests. The duration of the morning test was 16 minutes, and the duration of the noon and afternoon tests was 14 minutes. The concentration decay curves of Figure 64 show a similar decay rate in the morning, noon and afternoon tests. The logarithmic curves of Figure 64 emphasise the fast decay in the afternoon test.

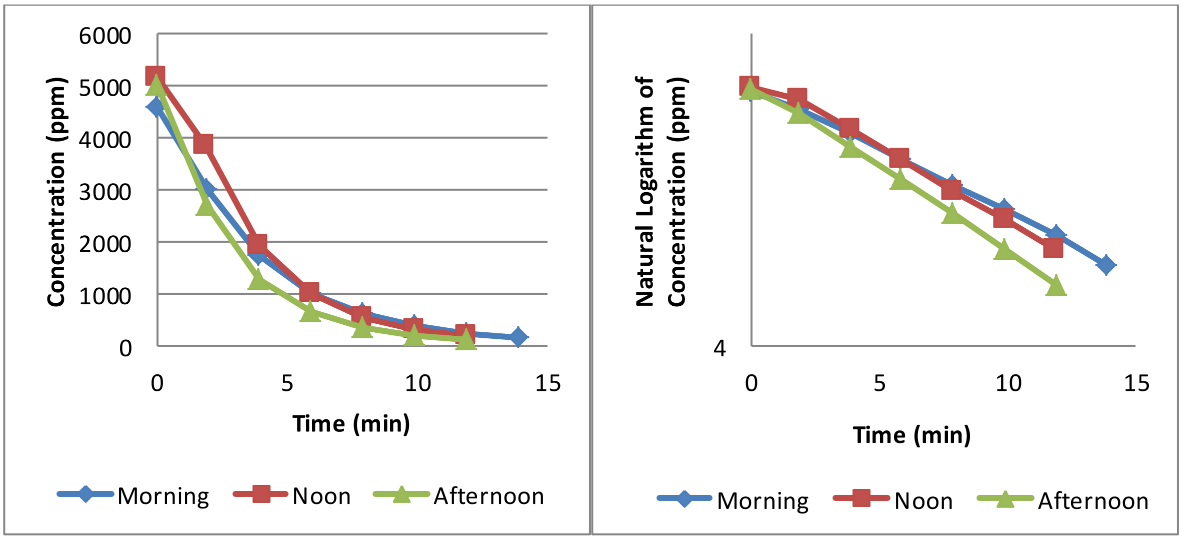

Figure 64: Concentration decay curve of Baseline CV

The results of Baseline CV are reported in Table 17. The ventilation flow rate of Baseline CV was between 14.6 – 19.0 ACH. A higher average wind velocity did not necessarily result in a higher ventilation flow rate. Baseline CV exceeded the TB IPC guidelines. Even with low wind velocities in the noon test, averaged at 0.55 m/s (2.0 km/h), Baseline CV reported a ventilation flow rate 17.1 ACH.

Table 17: Results of Baseline CV

	Average T_{out} (˚C)	Average v_{w_x} (m/s)	MAA (min)	Ventilation flow rate (ACH)	Ventilation flow rate (l/s)
Morning	25.8	0.86	4.5	14.7	243
Noon	31.6	0.55	3.9	17.1	282
Afternoon	32.0	0.93	3.7	19.0	314

5.4.2 Turbine Ventilator CV

The concentration decay curves and the logarithmic concentration decay curves for Turbine Ventilator CV are shown in Figure 65.

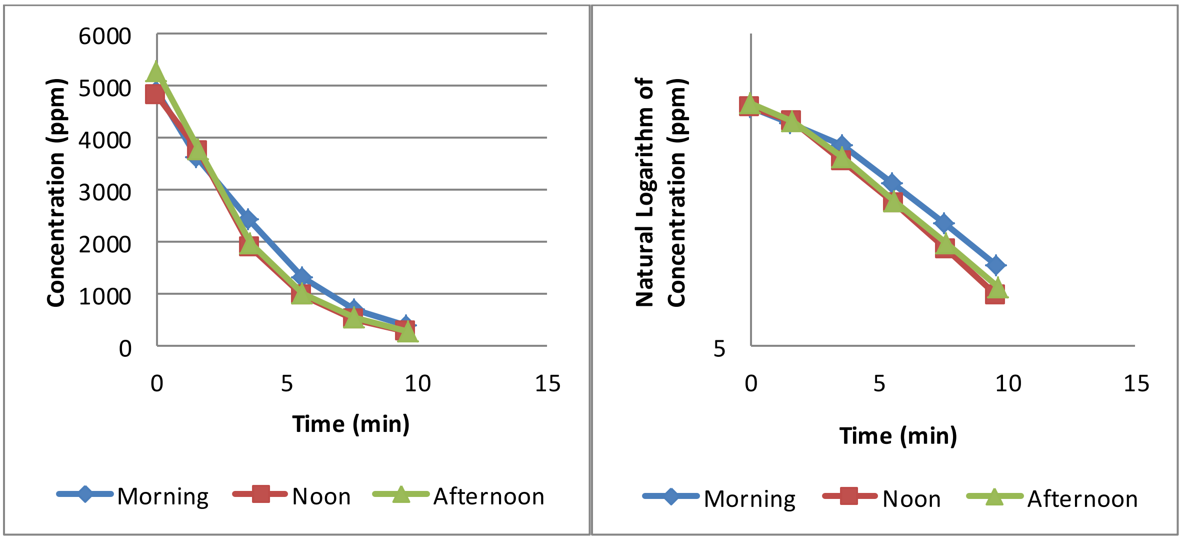

Figure 65: Concentration decay for Turbine Ventilator CV

The morning, noon and afternoon tests all decayed to below 500 ppm. The duration of all tests was 10 minutes and the concentration decay curves of these turbine ventilator tests are almost identical. The results of Turbine Ventilator CV are reported in Table 18. The ventilation flow rate reported for

Turbine Ventilator CV was in the range of 16.0 - 18.6 ACH. This was similar to the ventilation flow rates of Baseline CV.

Table 18: Results of Turbine Ventilator CV

	Average T_{out} (˚C)	Average v_{w_x} (m/s)	MAA (min)	Ventilation flow rate (ACH)	Ventilation flow rate (l/s)
Morning	22.1	1.25	3.8	16.0	264
Noon	25.3	0.83	3.4	18.6	307
Afternoon	24.1	0.88	3.4	18.5	305

The TB IPC minimum ventilation flow rate recommendation of 12.9 ACH was exceeded for both Baseline and Turbine Ventilator CV. It is desirable for air to enter bedroom 2 at the door of bedroom 2, and then be exhausted via the turbine ventilator or the window of bedroom 2. In this way potentially contaminated air is exhausted directly to the outside. If however, air enters bedroom 2 through the window of bedroom 2, and is exhausted to the rest of the house, potentially contaminated air moves to the rest of the house.

The concentration decay curves for the tracer gas decay through the turbine ventilator and the tracer gas decay in the room for Turbine Ventilator CV are shown in Figure 66. The trend in decay at the turbine ventilator and the decay in the room is quite similar and rapid with both decaying below 500 ppm in ten minutes. The decay rates through the turbine ventilator and in the room are almost identical in the afternoon test.

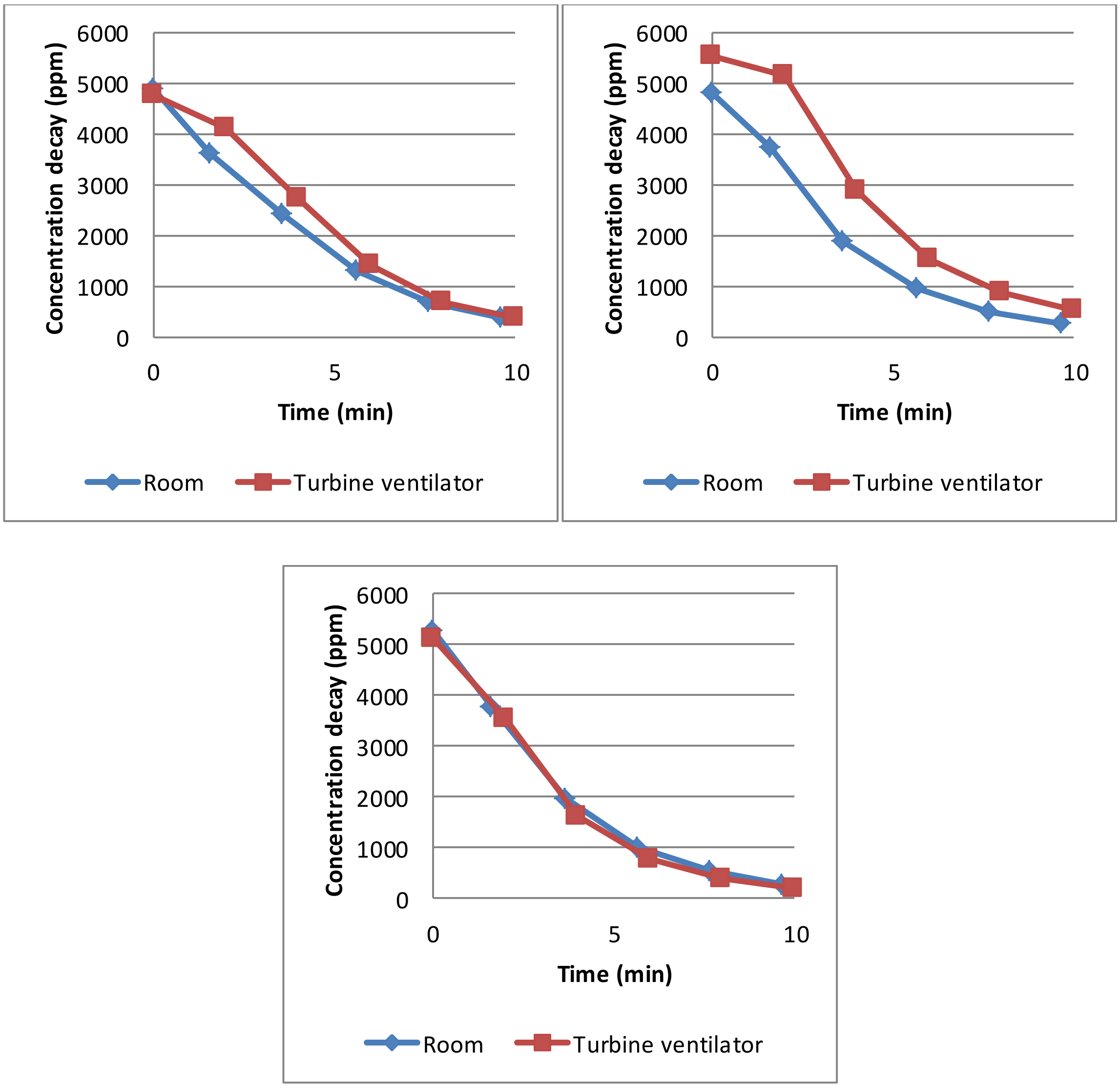

Figure 66: Concentration decay curves of the decay through the turbine ventilator and the decay in the room in the morning (top left), noon (top right) and afternoon (bottom) tests of Turbine Ventilator CV

5.5 Single-sided ventilation: Case 2

In SS2, all windows except bedroom 2's window were opened. The door of bedroom 2 was also opened. The configuration of SS2 is not ideal for TB IPC, as potentially contaminated air would leave bedroom 2 and mix with the air in the rest of the reference house.

5.5.1 Baseline SS2

The concentration decay curves and logarithmic concentration decay curves for Baseline SS2 are shown in Figure 67. The morning, noon and afternoon tests all decayed to 500 ppm. Each of these tests lasted 26 minutes. The morning, noon and afternoon tests presented and almost identical decay, as highlighted in the logarithmic concentration decay curves of Figure 67.

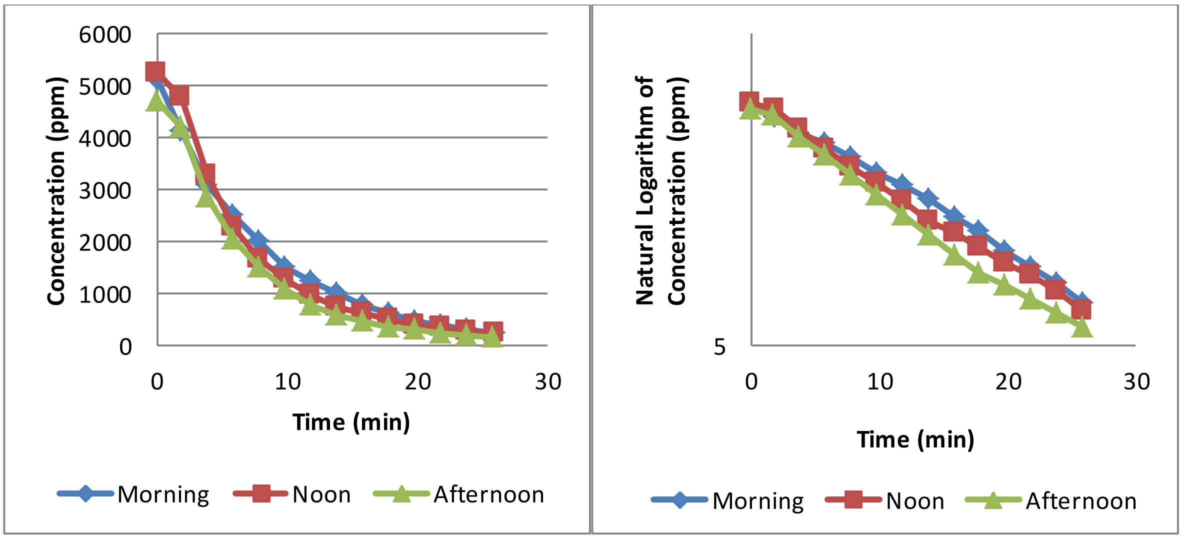

Figure 67: Concentration decay curves for Baseline SS2

The results of Baseline SS2 are reported in Table 19. The ventilation flow rate reported in the morning, noon and afternoon tests were similar, ranging from 7.0 ACH in the morning test, to 7.9 ACH in the afternoon test. The highest reported average wind velocity was in the morning test at 1.72 m/s. The morning test also recorded the lowest ventilation flow rate of Baseline SS2. In Baseline SS2, a higher reported average wind velocity did not necessarily result in higher ventilation flow rate.

Table 19: Results of Baseline SS2

	Average T_{out} (˚C)	Average v_{w_x} (m/s)	MAA (min)	Ventilation flow rate (ACH)	Ventilation flow rate (l/s)
Morning	22.4	1.7	9.1	7.0	115
Noon	29.0	0.7	8.5	7.4	122
Afternoon	31.8	0.9	8.4	7.9	130

5.5.2 Turbine Ventilator SS2

The concentration decay curves and the logarithmic concentration decay curves for Turbine Ventilator SS2 are shown in Figure 68. The morning, noon and afternoon tests, all decayed to 500 ppm. The duration of the morning test was 20 minutes, and the duration of the noon and afternoon tests was 18 minutes. The concentration decay for all tests was similar.

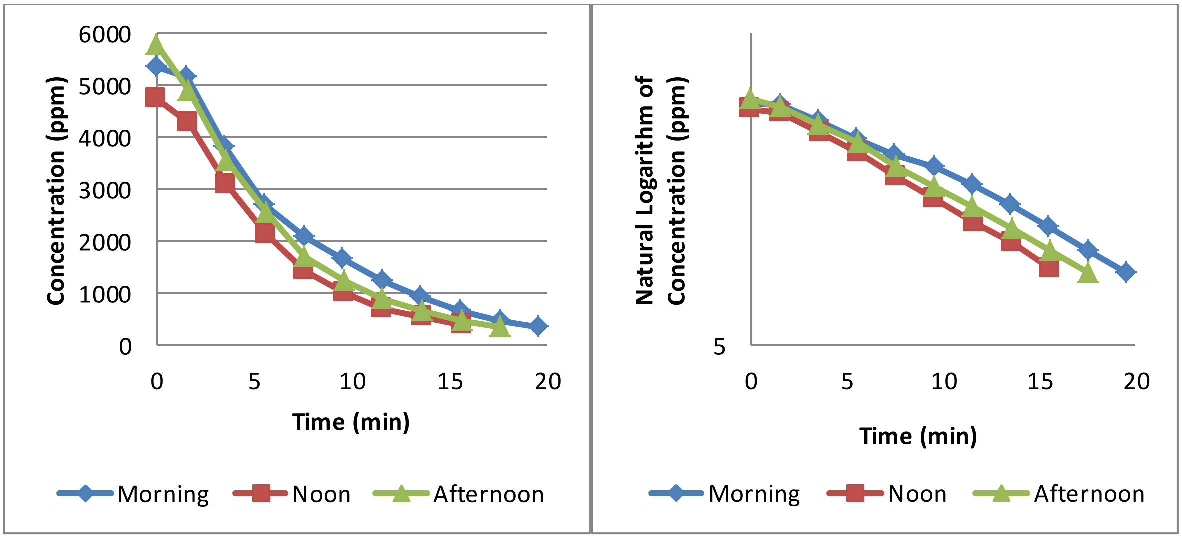

Figure 68: Concentration decay curves for Turbine Ventilator SS2

The results of Turbine Ventilator SS2 are reported in Table 20. The ventilation flow rate ranged between 8.5 to 10.1 ACH. As with the baseline tests, a higher reported average wind velocity did not necessarily result in a higher ventilation flow rate. The ventilation flow rates of Turbine Ventilator SS2 are higher than those reported in Baseline SS2.

Table 20: Results of Turbine Ventilator SS2

	Average T_{out} (˚C)	Average v_{w_x} (m/s)	MAA (min)	Ventilation flow rate (ACH)	Ventilation flow rate (l/s)
Morning	24.2	0.8	7.1	8.5	140
Noon	24.4	1.2	6.0	10.1	167
Afternoon	24.6	0.7	6.3	9.7	162

The concentration decay curves for the tracer gas decay through the turbine ventilator and the tracer gas decay in the room for Turbine Ventilator SS2 are shown in Figure 69. The decay rate through the turbine ventilator in the morning test was rapid, and significantly faster than the decay in the room. The decay rate though the turbine ventilator and the decay rate in the room for the noon and after noon test were similar.

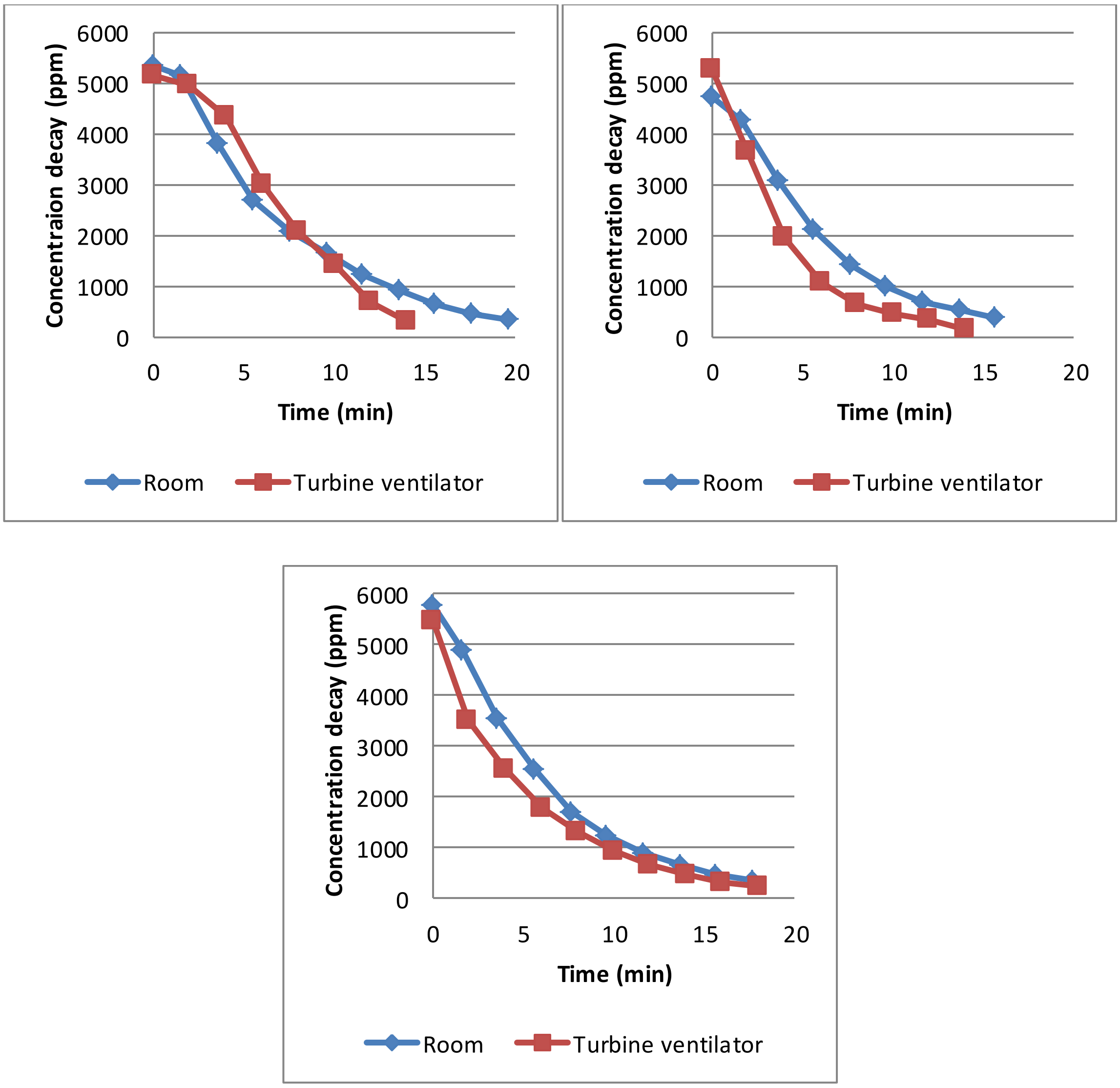

Figure 69: Concentration decay curves of the decay through the turbine ventilator and the decay in the room in the morning (top left), noon (top right) and afternoon (bottom) tests of Turbine Ventilator SS2

The results of the field study have been presented here. The results of the laboratory experiments are presented in **Chapter 6**, and a discussion of both the Laboratory and Field studies are presented in **Chapter 7**.

6. LABORATORY EXPERIMENTAL RESULTS

The performance of the turbine ventilator under a set of specified parameters, discussed in **Chapter 4,** was investigated in a laboratory environment. This chapter presents the results of the laboratory experiments.

In this chapter, a "Test" refers to an individual evaluation process of a specified parameter. A "Set" refers to a collection of Tests. The data presented here may be constructed of several Tests and Sets.

6.1 The effect of wind speed on the turbine ventilator

The protocol of **Chapter 4** sets out to test the performance of the turbine ventilator under wind velocities of 0.1, 0.2, 0.3, 0.4 and 0.5 m/s. When performing the 0.1 m/s test, V_{ID}, $V_{0.5D}$, V_D and $V_{1.5D}$ recorded no detectable readings, i.e. readings ≥ 0.05 m/s, for the full hour of the test. Consequently, no further 0.1 m/s wind speed tests were performed. Figures 70 to 73 present the results of the in-duct velocity, V_{ID}, of the 0.2, 0.3, 0.4 and 0.5 m/s tests, respectively.

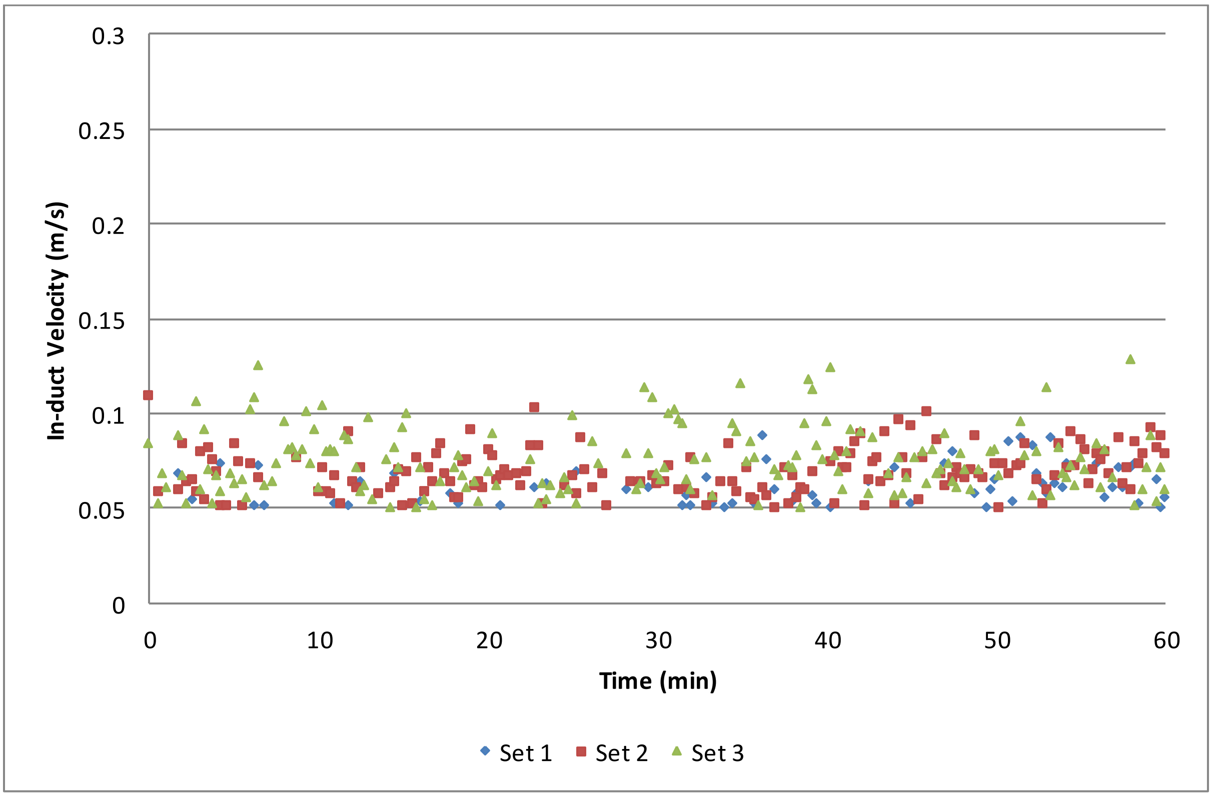

Figure 70: V_{ID} through the turbine ventilator at a wind speed of 0.2 m/s

In the 0.2 m/s tests, the turbine ventilator remained stationary for the duration of the tests. As the thin film sensors detect velocities from 0.05 m/s upwards, only readings from greater than 0.05 m/s were presented here. As such, the number of readings presented per set varies. The undetectable readings were not simply set to zero, as the velocity may be anywhere between 0.00 and 0.05 m/s. The data in Figure 70 is presented as data points as the data was discontinuous. The 0.2 m/s tests revealed that air was moving through the turbine ventilator, even in the absence of turbine ventilator rotation.

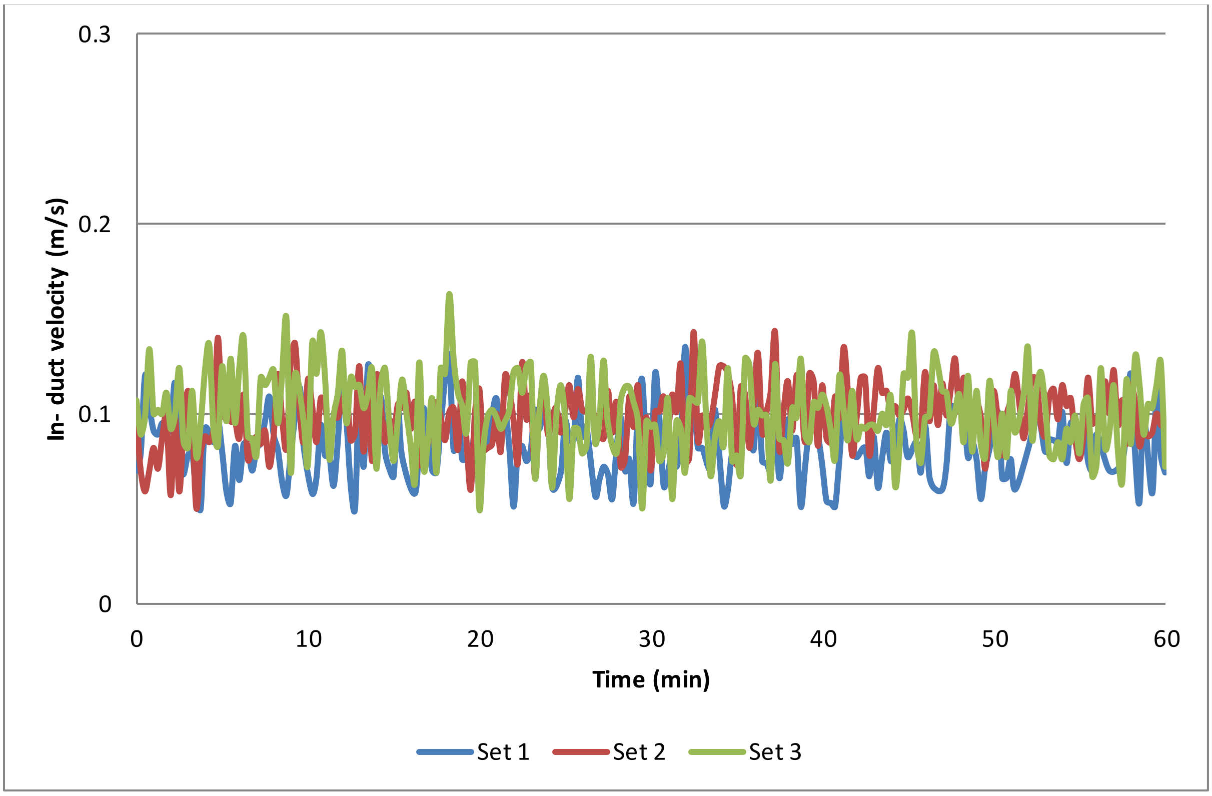

Figure 71: V_{ID} through the turbine ventilator at a wind speed of 0.3 m/s

In the 0.3 m/s tests, the turbine ventilator was always rotating. The cut-in speed for this turbine ventilator lies somewhere between 0.2 and 0.3 m/s, though this actual speed was never established. The turbine ventilator was constantly rotating in all of the 0.3, 0.4 and 0.5 m/s tests. The results of the wind speed tests show V_{ID} constantly fluctuates inside the turbine ventilator duct as air is exhausted through the turbine ventilator. The results also show that, while there are constant fluctuations of V_{ID}, the value of V_{ID} increased with an increase in the wind speed.

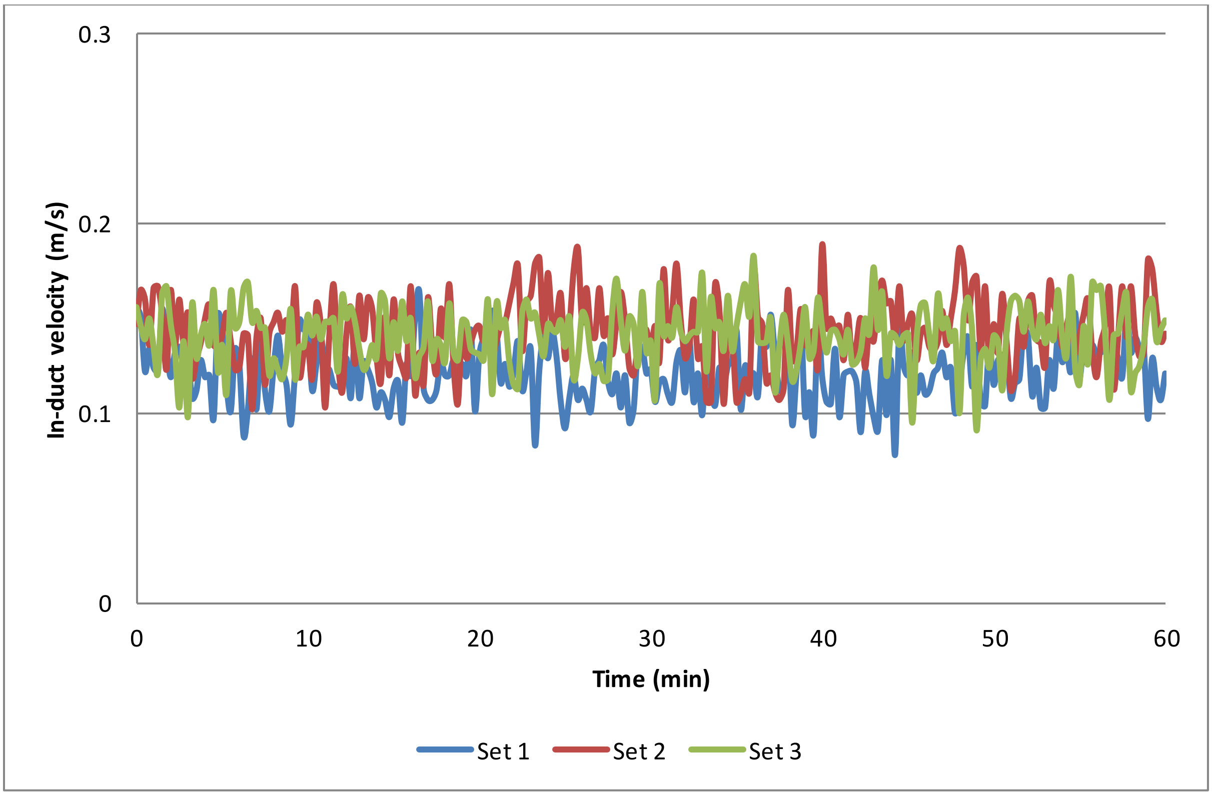

Figure 72: V_{ID} **through the turbine ventilator at a wind speed of 0.4 m/s**

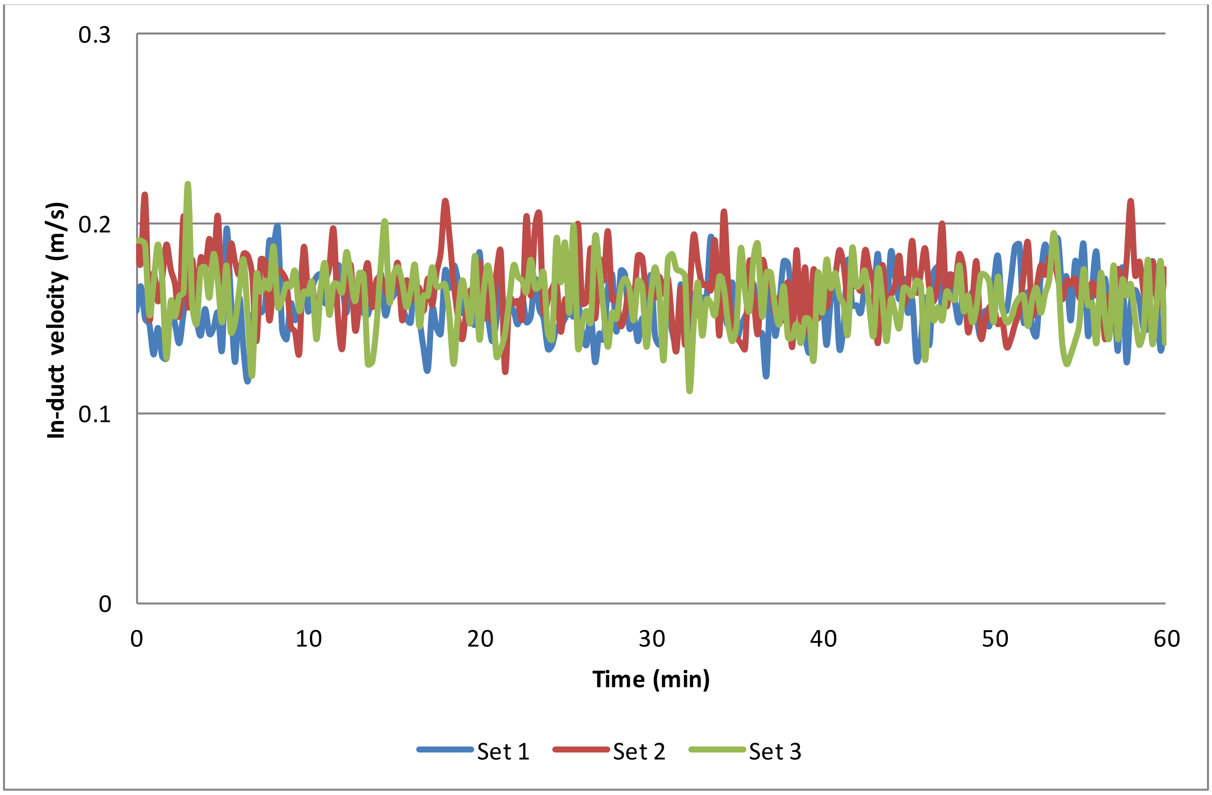

Figure 73: V_{ID} **through the turbine ventilator at a wind speed of 0.5 m/s**

The manufacturer of the Delta OHM HD2903T thin film sensors report an accuracy of ±0.04 m/s + 2% of the measurement in the 0.05 to 1 m/s range. The upper and lower limit of the accuracy range has been calculated, and averaged for each of the tests. Table 20 presents the mean V_{ID} and its standard deviation, as well as the upper and lower accuracy limits.

Table 21: Mean V_{ID}, standard deviation, and upper and lower accuracy limits of the wind speed tests

	Mean V_{ID} (m/s)	Standard Deviation	V_{ID} Upper Limit (m/s)	V_{ID} Lower Limit (m/s)
0.2 m/s tests				
Set 1	0.06	0.01	0.10	0.02
Set 2	0.07	0.01	0.11	0.03
Set 3	0.08	0.02	0.12	0.04
0.3 m/s tests				
Set 1	0.08	0.02	0.13	0.04
Set 2	0.10	0.02	0.14	0.06
Set 3	0.10	0.02	0.14	0.06
0.4 m/s tests				
Set 1	0.12	0.02	0.16	0.08
Set 2	0.14	0.02	0.19	0.11
Set 3	0.14	0.02	0.18	0.10
0.5 m/s tests				
Set 1	0.16	0.02	0.20	0.12
Set 2	0.17	0.02	0.21	0.13
Set 3	0.16	0.02	0.20	0.12

The mean V_{ID} of the wind speed tests are plotted in Figure 74. Sets 2 and 3 show similar time-averaged V_{ID} across the range of v_w tested, while Set 1 recorded consistently lower readings. The trend in all three sets is the same, i.e. V_{ID} increases with an increase in v_w .This mean and standard deviation of this data was calculated, and is presented in Table 21.

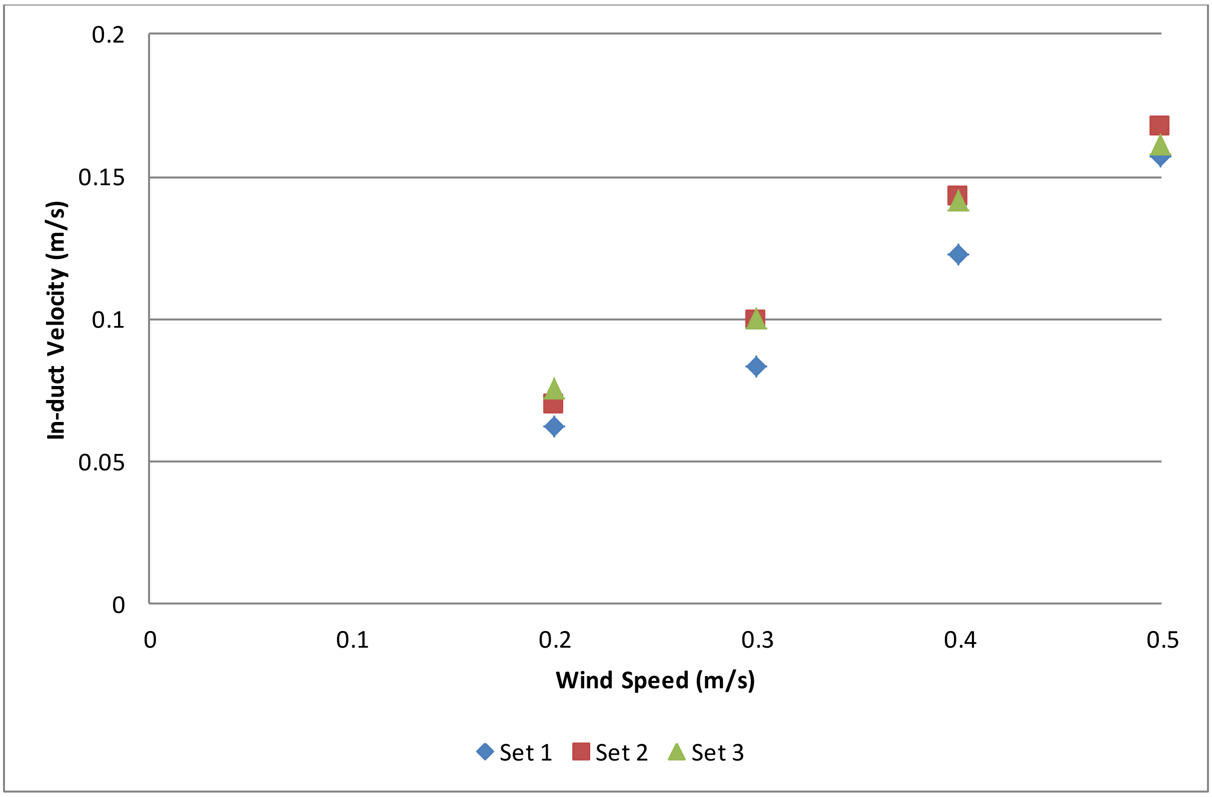

Figure 74: Mean V_{ID} of the three sets of wind speed tests

Table 22: Mean V_{ID} and standard deviation of wind speed tests

	Mean (m/s)	**Standard Deviation**
0.2 m/s	0.07	0.01
0.3 m/s	0.09	0.01
0.4 m/s	0.14	0.01
0.5 m/s	0.16	0.01

The velocities $V_{0.5D}$, V_D and $V_{1.5D}$ were measured but were undetectable at all points, in all tests. Following form Equation (something) in **Appendix D**, the predictive centreline velocities for the wind speed tests are presented in Figure 75. The centreline velocities are expected to be reduced to 32% of V_{ID} at $V_{0.5D}$, 10% of V_{ID} at V_D and 4.5% of V_{ID} at $V_{1.5D}$.

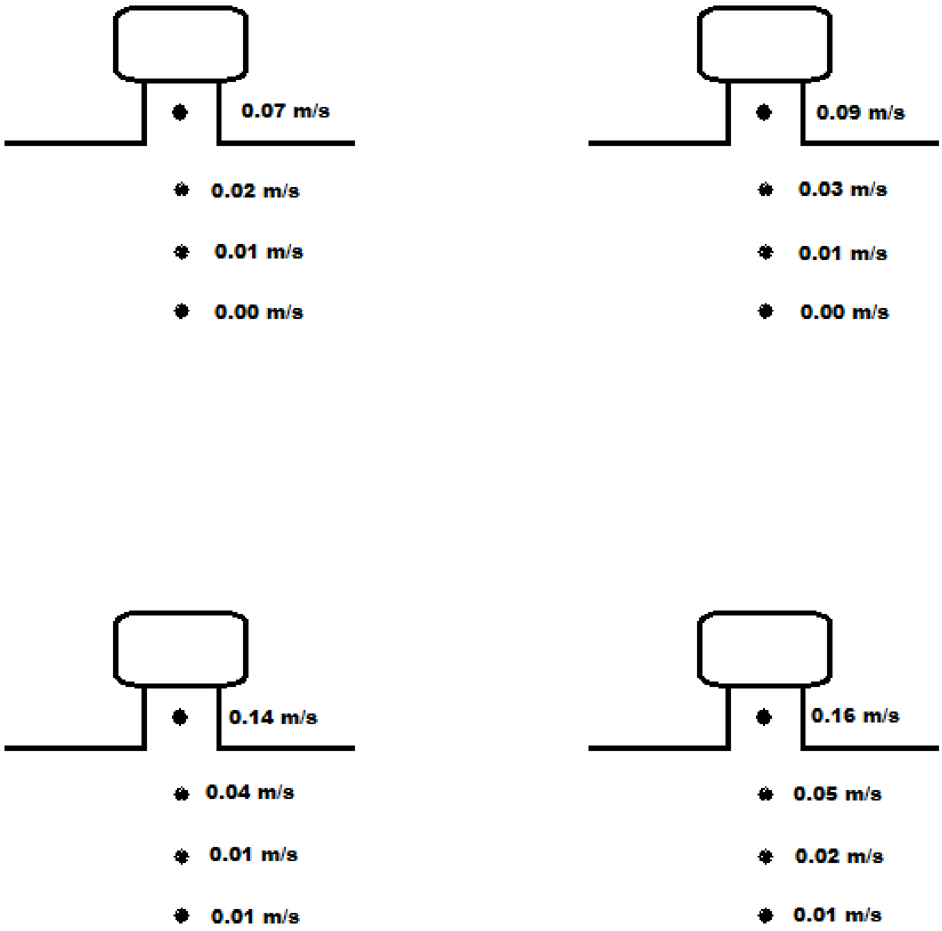

Figure 75: Dalla Valle predictions of centreline velocities for wind speed tests

From Figure 75 it can be seen that the predicted centreline velocities could not be detected by the thin film sensors as they were either at, or beyond, the limit of detection of the thin film sensors. As the centreline velocities values could not be verified, the local airflow dynamics below the turbine ventilator could not be described by Dalla Valle's Equation.

6.2 The effect of buoyancy on the turbine ventilator

The thermostat allows the heating element to warm the air inside the control volume to a set maximum of 30 ˚C. The laboratory apparatus was located in a workshop of the CSIR Built Environment. The ambient temperature of the workshop changes during the day, and is also influenced by the activity of the occupants and procedures in the workshop. Tests were thus performed over a 12 hour period overnight. The ambient temperature was expected to drop during the night, and hence greater temperature differentials, dT , could be established. The data logger was set to record every 15s. Because of the high number of measurements in these 12 hour tests, the data is presented in three minute intervals in Figures 76, 77 and 78.

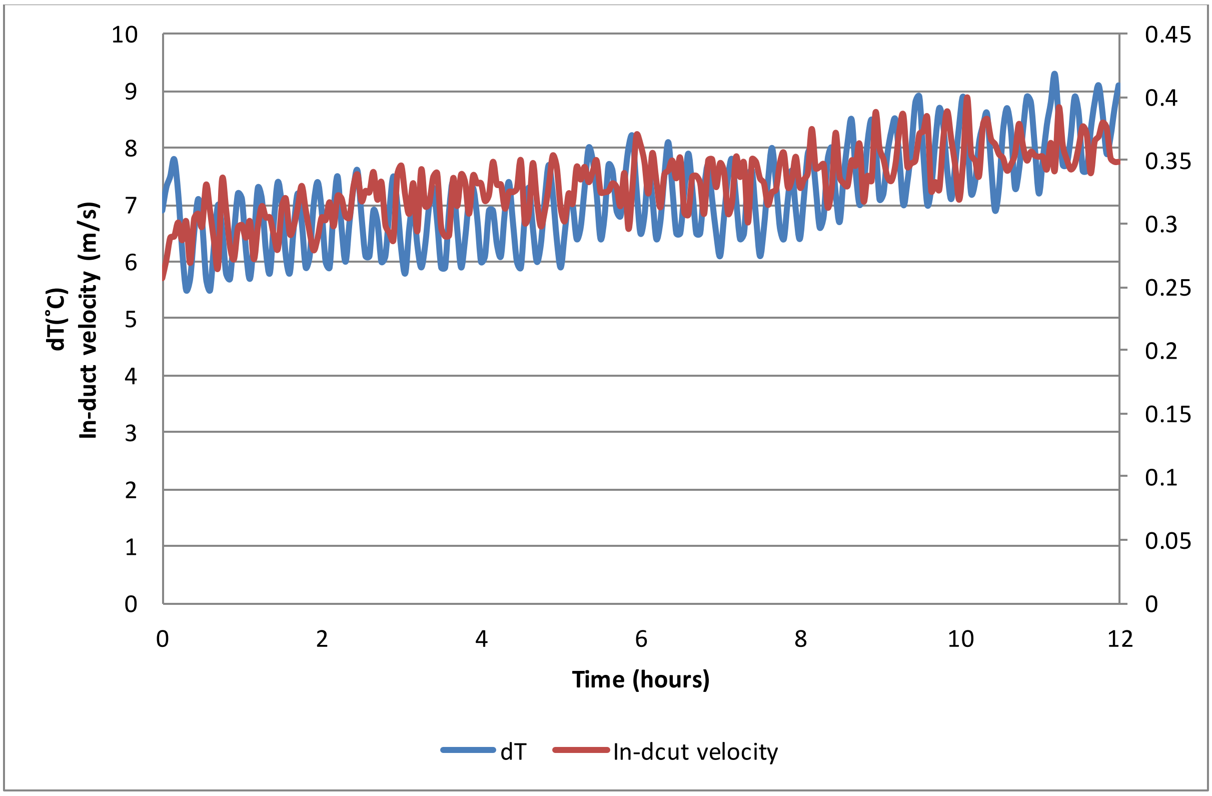

Figure 76: V_{ID} through the turbine ventilator in buoyancy test 1

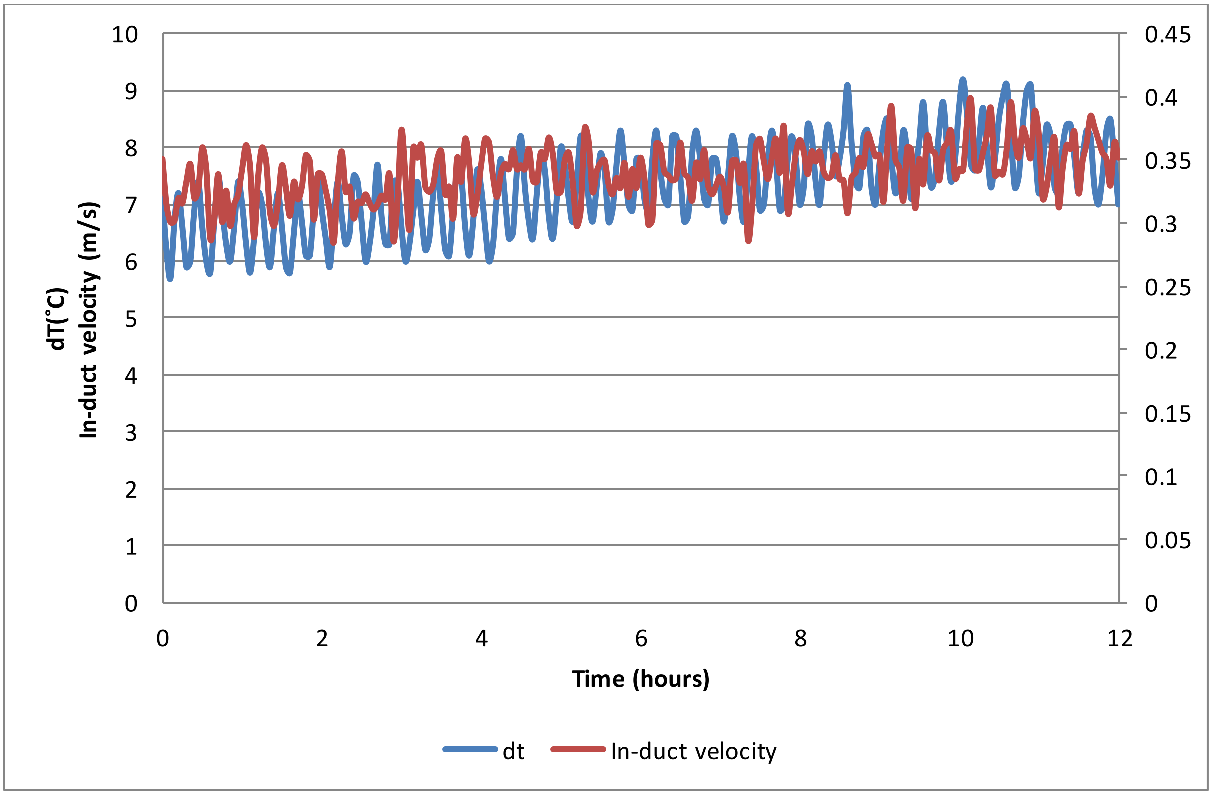

Figure 77: V_{ID} **though the turbine ventilator in buoyancy test 2**

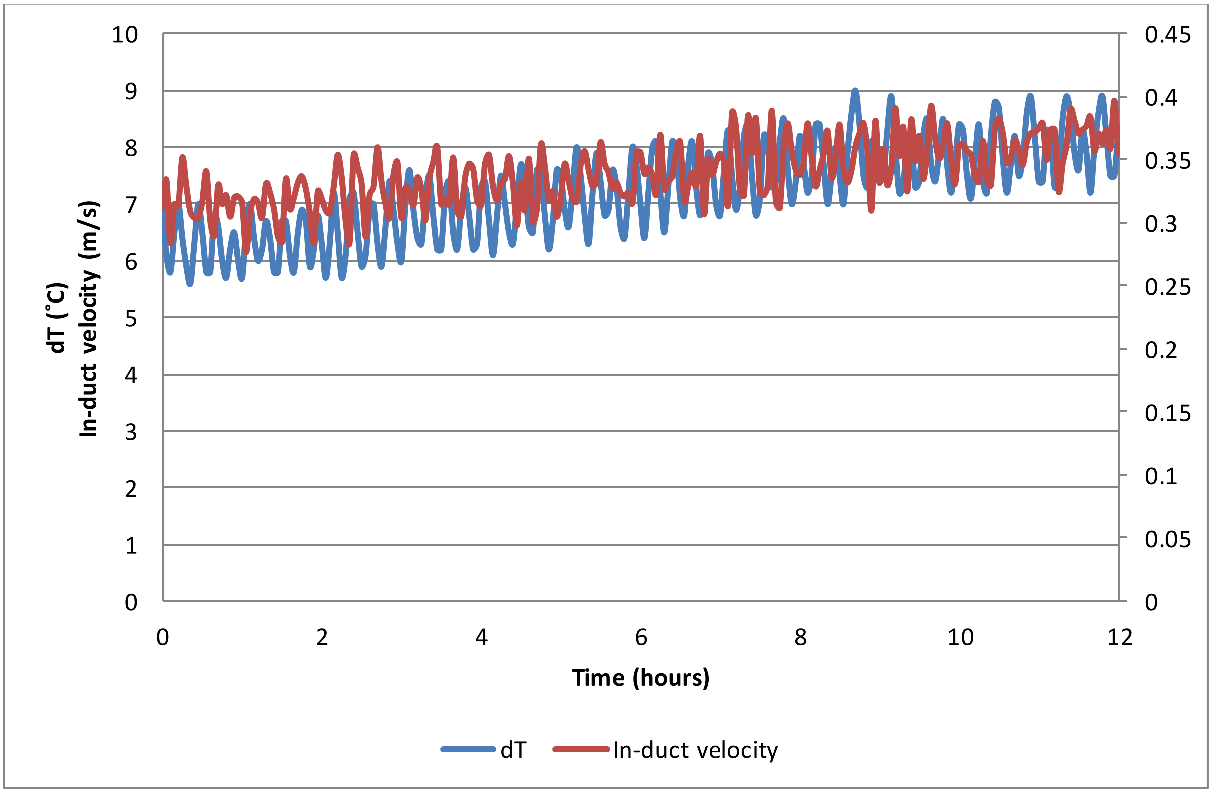

Figure 78: V_{ID} **through the turbine ventilator in buoyancy test 3**

From Figures 76, 77 and 78, it can be seen that as dT increases, V_{ID} increases. Once the temperature inside the control volume is near 30˚C, thermostatic control intervenes and the heating element is switched off. The temperature differential then decreases. As dT decreases, V_{ID} decreases. V_{ID} fluctuates around the fluctuating dT . Average, maximum and minimum values of the three tests are presented in Table 23. The time-averaged V_{ID} , and the minimum and maximum V_{ID} of each of the three tests are of similar magnitude.

Table 23: Extracted data from buoyancy tests

	Min dT (˚C)	Max dT (˚C)	Mean dT (˚C)	SD dT (˚C)	Min V_{ID} (m/s)	Max V_{ID} (m/s)	Mean V_{ID} (m/s)	SD V_{ID} (m/s)
Test 1	5.50	9.30	7.20	0.84	0.26	0.40	0.33	0.03
Test 2	5.70	9.20	7.30	0.77	0.29	0.40	0.34	0.02
Test 3	5.60	9.00	7.20	0.80	0.28	0.40	0.34	0.03

A temperature differential has to be established before the air flows through the turbine ventilator, i.e. dT "peaks" before V_{ID} "peaks". It was noted that a dT of 7˚C was required for the turbine ventilator to rotate in the absence of any wind. Because of the fluctuating dT and fluctuating V_{ID} , it is difficult to establish the direct relationship between dT and V_{ID} in these experiments. In the analysis of these results, all V_{ID} for a given dT was pooled, and averaged. It was found that the average V_{ID} through the turbine ventilator appeared to be independent of dT . It was anticipated that an increase in dT would result in an increase in V_{ID} . The data was then time shifted by one time step (three minutes), so that, in most cases, the peak dT corresponded to the peak V_{ID} . The corresponding graphs are presented in **Appendix F**. All V_{ID} for a given dT were again pooled, and averaged, and are presented in Figure 79.

The density difference can be calculated from Equation 12 ((CIBSE, 2005):

$$\Delta\rho_0 = \frac{\rho(T_{out} - T_{\text{int}})}{(T_{out} + 273.15)}$$ … **Equation 12**

Where:

$\Delta\rho_0$ is the pressure difference

T_{out} is the outside temperature (of the workshop)

T_{ins} is the temperature inside the box

Using Equation 12, with a temperature of 23°C in the workshop, a temperature differential of 5.5°C, the density difference would be 0.02 kg/m^3. At a temperature differential of 9.3°C, the density difference is 0.04 kg/m^3. It is this resulting density differences which contribute to the fluctuations in wind speed in V_{ID}.

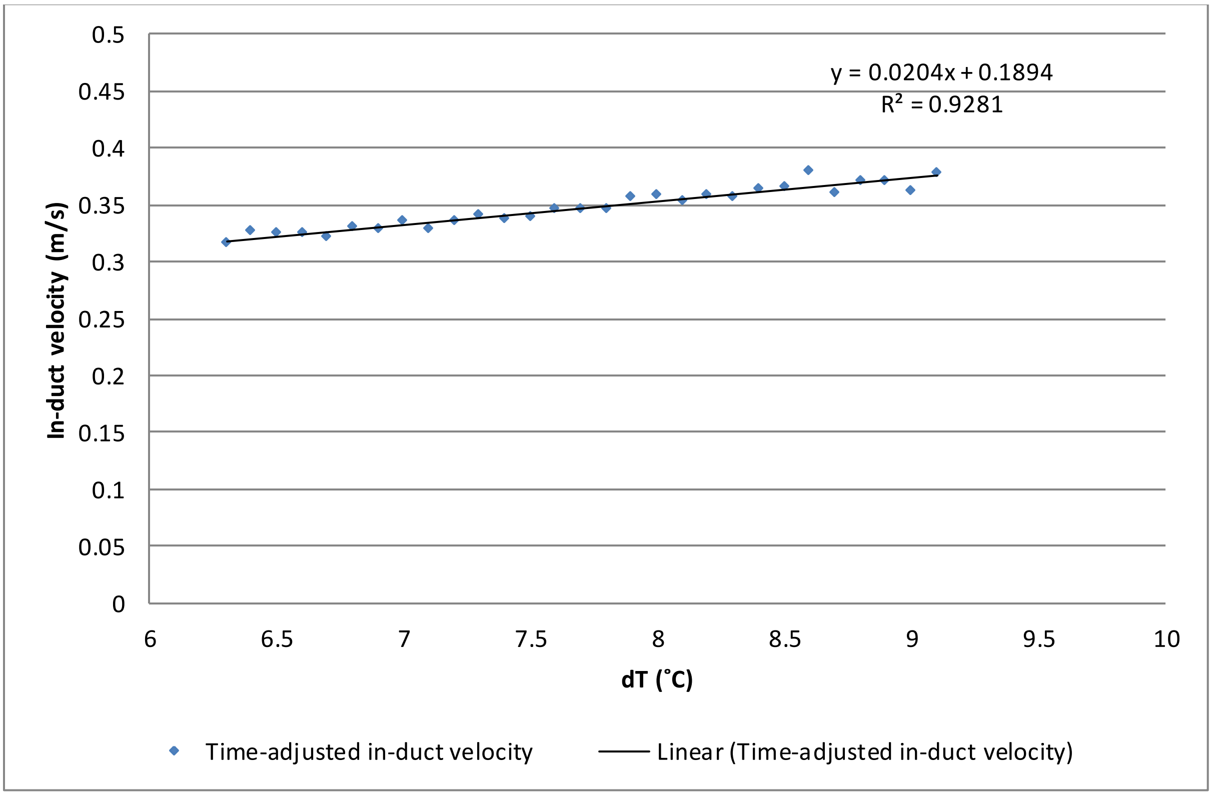

Figure 79: V_{ID} through the turbine ventilator as a function of dT (time-adjusted)

The centreline velocities $V_{0.5D}$, V_D and $V_{1.5D}$ were measured and recorded. $V_{0.5D}$ and V_D were undetectable at all points across all tests, and $V_{1.5D}$ fluctuated throughout each of the three overnight tests. The measured data for $V_{1.5D}$ in the three tests are presented in the form of a histogram, as shown in Figure 80. In Figure 80, the histogram presents the total count of how many times $V_{1.5D}$

recorded a detectable value. Table 24 shows how many times during the 12 hour test period the value of $V_{1.5D}$ were detected or undetected. An undetected value of $V_{1.5D}$ was reported between 48 and 57%. This could imply one of two things. The first explanation is that the velocity was in fact undetectable. It could alternatively imply that, because the probe is directional and recorded only the upward component of $V_{1.5D}$, there exists a turbulent region where air may be moving both upwards and downwards across the sensor.

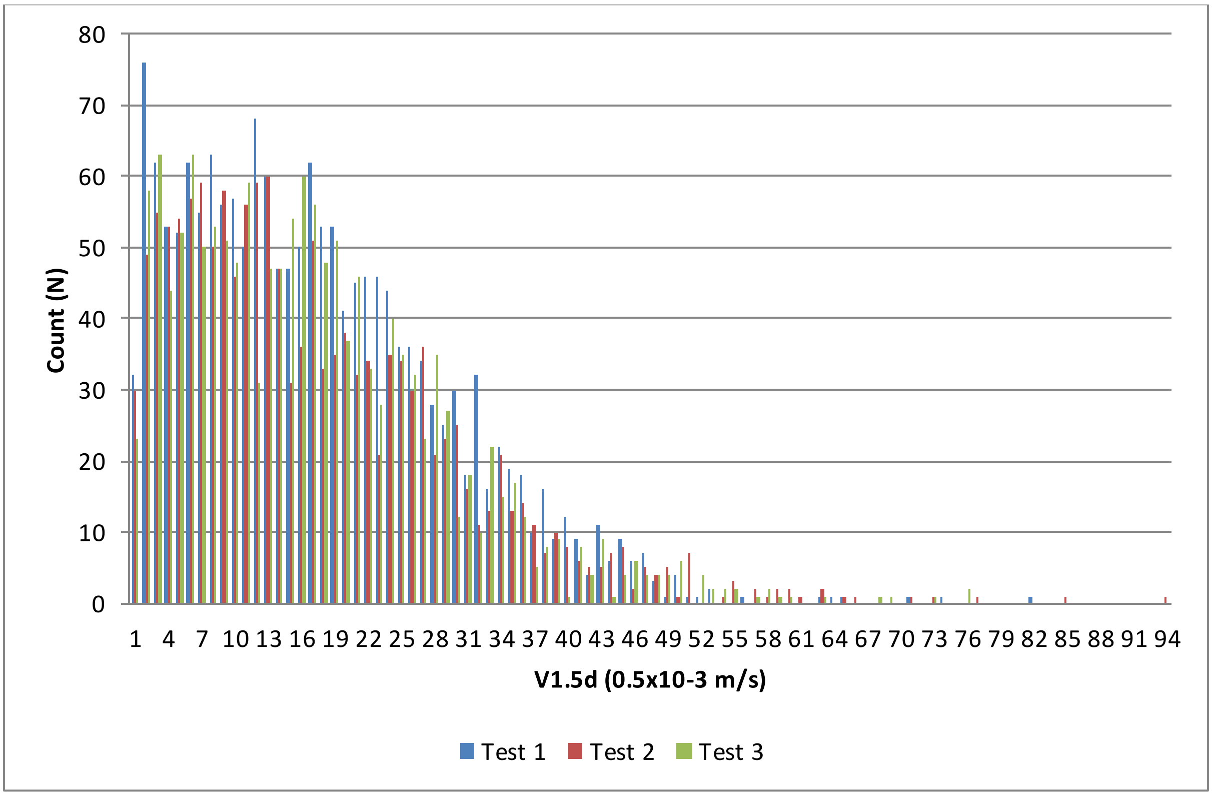

Figure 80: Distribution of measured data for $V_{1.5D}$ in buoyancy tests

Table 24: Detectable and undetectable counts of measured data for buoyancy tests

	Undetectable	Detectable	Total	% Detectable
Test 1	1642	1236	2878	43
Test 2	1442	1434	2876	50
Test 3	1390	1487	2877	52

The detectable mean centreline $V_{1.5D}$ for Sets 1, 2 and 3 was 0.06, 0.07 and 0.08 m/s, respectively.

6.3 The combined effect of wind and buoyancy forces on the turbine ventilator

The results of the combined wind speed and buoyancy forces tests are presented in Figures 81, 82 and 83 as Set 1, Set 2 and Set 3, respectively. Set 1 is performed in two parts. The first two tests, 1a (v_w of 0.2 m/s) and 1b (v_w of 0.3 m/s) are performed consecutively in the late afternoon, and the last two tests, 1c (v_w of 0.4 m/s) and 1d (v_w of 0.5 m/s) are performed the following morning. The time-averaged results of Set 1 are tabulated below.

Table 25: Extracted data from Set 1 of the combined wind speed and buoyancy forces test

Test	Min dT (˚C)	Max dT (˚C)	Mean dT (˚C)	SD dT (˚C)	Min V_{ID} (m/s)	Max V_{ID} (m/s)	Mean V_{ID} (m/s)	SD V_{ID} (m/s)
1a	5.9	8.0	6.9	0.59	0.22	0.33	0.26	0.02
1b	6.0	8.3	7.2	0.55	0.20	0.30	0.25	0.02
1c	7.4	9.5	8.4	0.59	0.22	0.34	0.27	0.02
1d	6.9	9.4	8.1	0.61	0.21	0.32	0.26	0.02

In 1a the fan speed is set to deliver a v_w of 0.2 m/s. The graph of this test shows that as dT increases and decreases, so too does V_{ID} through the turbine ventilator. In 1b, the fan is set to deliver a v_w of 0.3 m/s. The temperature differential range in 1b is similar to that of 1a; however, in 1b the measured V_{ID} is lower than that of 1a.

1c and 1d are performed in the early hours of the morning and a higher dT range, of similar magnitude, was achieved. V_{ID} of 1c was higher than V_{ID} of 1b, and so too was its dT . V_{ID} of 1c was slightly higher than V_{ID} of 1d, for a similar range of dT .

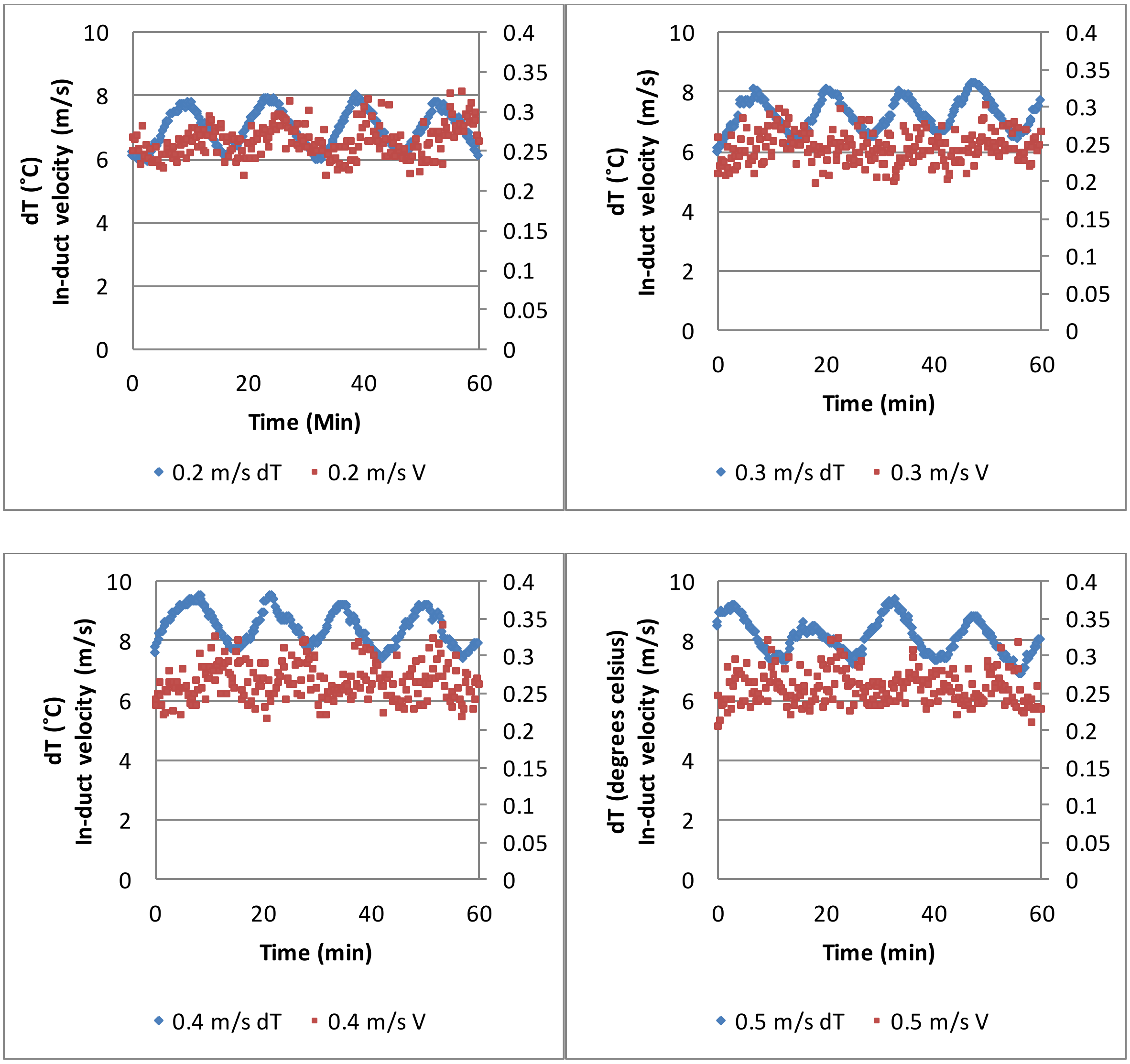

Figure 81: The effect of wind speed and buoyancy forces on the turbine ventilator - Set 1

Set 2, presented in Figure 87, was also performed in two parts. The first two tests, 2a (v_w of 0.2 m/s) and 2b (v_w of 0.3 m/s) are performed consecutively in the late afternoon, and the last two tests 2c (v_w of 0.4 m/s) and 2d (v_w of 0.5 m/s) are performed the following morning. The time-averaged results of Set 2 are tabulated in Table 22.

V_{ID} of 2a is lower than V_{ID} of 2b. From the first two tests of Set 2 it appears as though the increase in v_w in the combined wind speed and buoyancy forces test reduces V_{ID} through the turbine ventilator.

Table 26: Extracted data from Set 2 of the combined wind speed and buoyancy forces test

Test	Min dT (˚C)	Max dT (˚C)	Mean dT (˚C)	SD dT (˚C)	Min V_{ID} (m/s)	Max V_{ID} (m/s)	Mean V_{ID} (m/s)	SD V_{ID} (m/s)
2a	5.6	7.4	6.6	0.47	0.20	0.29	0.24	0.02
2b	6.0	7.7	6.8	0.45	0.13	0.22	0.17	0.02
2c	7.8	9.9	8.9	0.57	0.22	0.34	0.29	0.02
2d	7.6	9.8	8.6	0.53	0.22	0.35	0.28	0.02

2c and 2d are performed in the early hours of the morning and a higher dT range, of similar magnitude to each other, was again achieved. V_{ID} of 2c was higher than V_{ID} of 2d, for a similar dT range. These results agree with 2a and 2b, where it appears as though the increase in v_w in the combined wind speed and buoyancy forces test reduces the V_{ID} through the turbine ventilator.

Resource constraints did not allow for Sets 1 and 2 to be performed consecutively. However, the results of Set 1 and 2 indicated that Set 3 would have to be recorded consecutively to see if the suspected trends were the same. The time-averaged results of Set 3 are shown in Figure 83, and presented in Table 27. The results of 3a, 3b, 3c and 3d shows a steady decrease in V_{ID} as v_w is increased, from an average of 0.30 m/s in the 3a test to 0.25 m/s in the 3d.

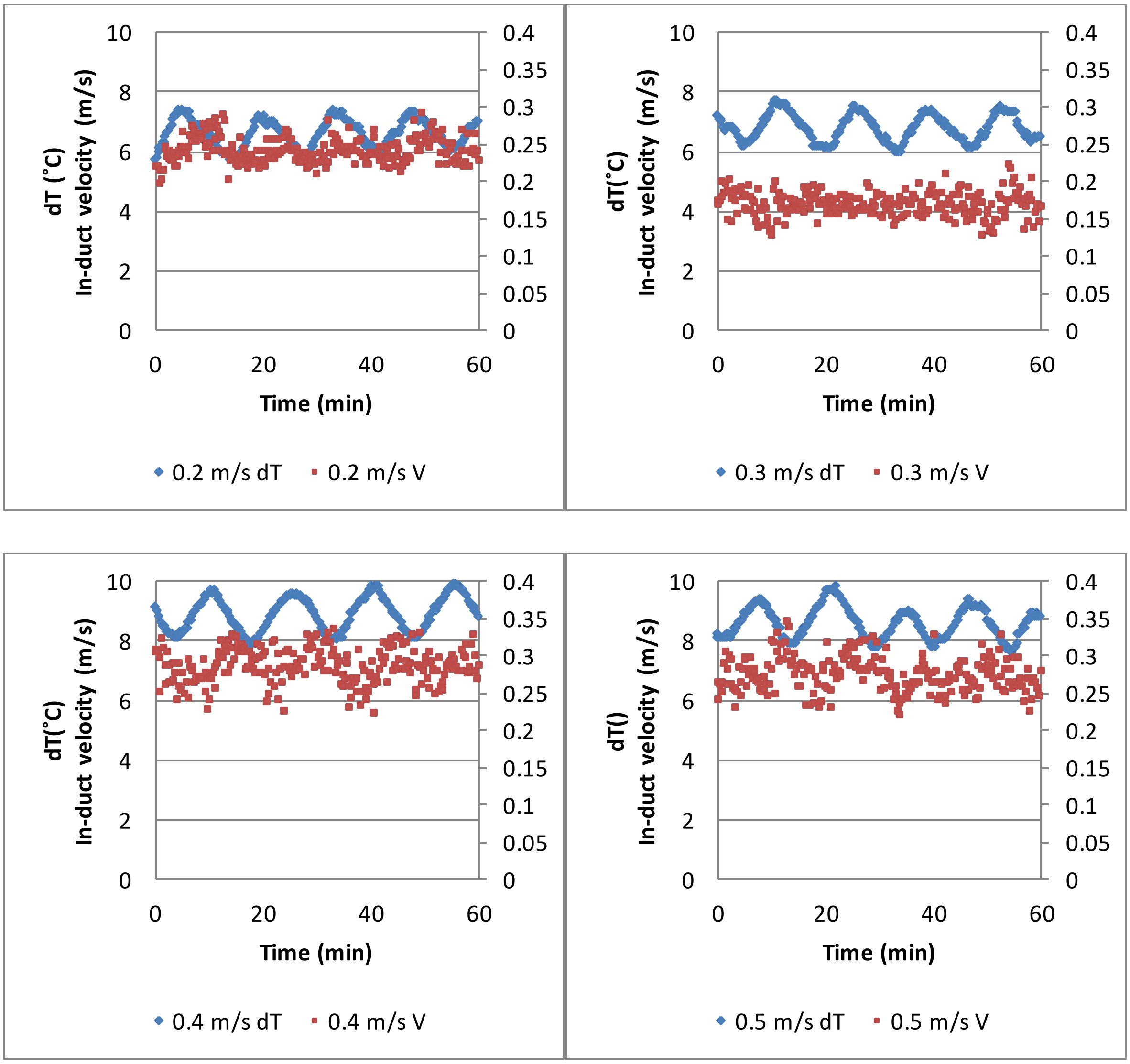

Figure 82: The effect of wind speed and buoyancy forces on the turbine ventilator – Set 2

Table 27: Extracted data from Set 3 of the combine wind speed and buoyancy forces test

Test	Min dT (˚C)	Max dT (˚C)	Mean dT (˚C)	SD dT (˚C)	Min V_{ID} (m/s)	Max V_{ID} (m/s)	Mean V_{ID} (m/s)	SD V_{ID} (m/s)
3a	6.8	8.9	7.9	0.53	0.24	0.35	0.30	0.02
3b	6.8	9.3	8.0	0.61	0.21	0.33	0.27	0.02
3c	6.8	8.8	7.8	0.50	0.20	0.31	0.25	0.02
3d	6.4	8.6	7.4	0.51	0.20	0.31	0.25	0.02

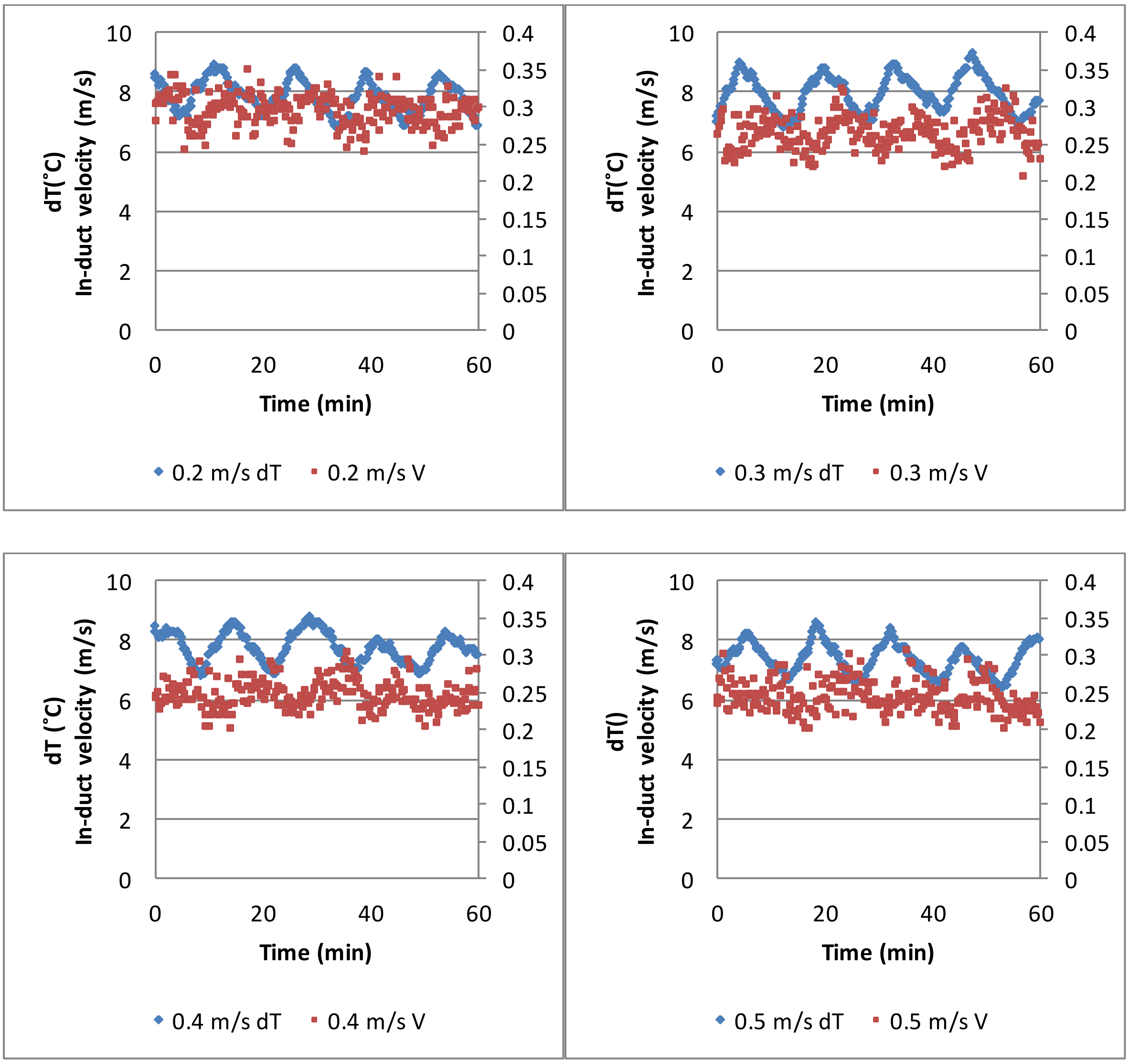

Figure 83: The effect of wind speed and buoyancy forces on the turbine ventilator - Set 3

As Set 3 was considered to be most representative of the results of the combined effect of wind and buoyancy on the turbine ventilator, the results of Set 3 was used in the analysis of the combined effect of wind and buoyancy on the turbine ventilator. As with the buoyancy tests' analysis, V_{ID} is time-shifted such that the peak V_{ID} corresponds to the peak dT . The analysis is performed on one minute intervals in 3a, 3b, 3c and 3d and is presented in Figure 84.

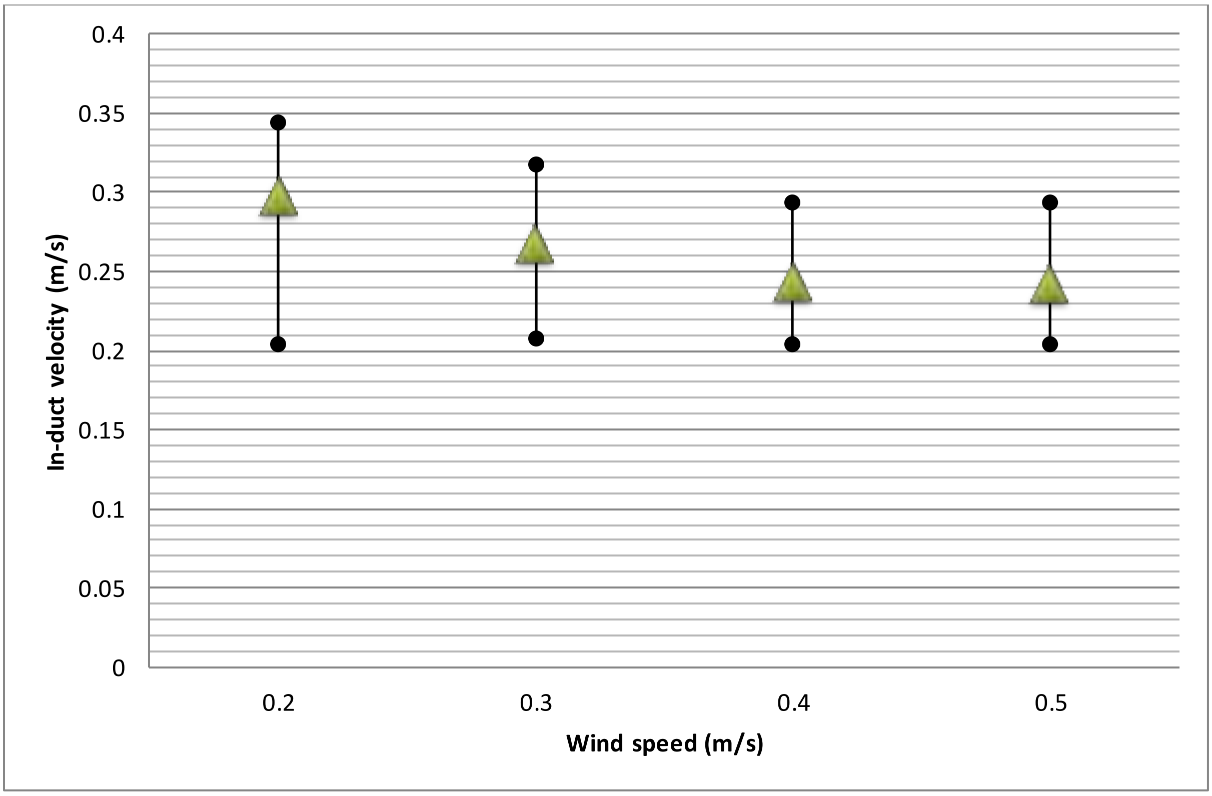

Figure 84: Average V_{ID} through the turbine ventilator as a function of dT (time-adjusted) in the combined wind speed and buoyancy tests

In Figure 84 the green triangle presents V_{ID} for the given v_w, and the black dot on either end represents the minimum and maximum reported value. From Figure 84, the decrease in V_{ID} for an increase in v_w, at a set dT, can be seen. Whilst V_{ID} increases with an increase in dT for a given v_w, as this given v_w increases, V_{ID} decreases. This decrease in V_{ID} is more pronounced in the lower wind speeds, but is almost identical in the 0.4 and 0.5 m/s tests.

The centreline velocities $V_{0.5D}$, V_D and $V_{1.5D}$ were measured and recorded. $V_{0.5D}$ and V_D was undetectable at all points across all tests, and $V_{1.5D}$ fluctuated throughout each of the three tests. Similarly, as in the analysis of $V_{1.5D}$ in the buoyancy forces tests, Table 28 shows how many times during a Test 3 the value of $V_{1.5D}$ were either detected or undetected.

Table 28: Undetectable and detectable counts of measured data for wind and buoyancy Test 3

	Undetectable	Detectable	Total	% Detectable
3a	169	72	241	29.9
3b	172	69	241	28.6
3c	205	36	241	14.9
3d	223	18	241	7.5

In Test 3, an undetectable value for $V_{1.5D}$ occurred between 60.1% in the 0.2 m/s test and 92.5% in the 0.5 m/s test. This result is significantly different to what was obtained in the buoyancy forces tests. In the combined forces tests, there appears to be a decrease in turbulent fluctuations with an increase in wind speed.

6.4 Comparison of effect of wind speed, buoyancy and a combination of wind speed and buoyancy on the turbine ventilator

When comparing the response of the turbine ventilator to the varying parameters, it is important to point out the scope to which these comparisons are made. The parameters of these tests were low wind speeds in the range of 0.2 to 0.5 m/s, variable temperature differentials in the range of 6 to 9.3 ˚C, and a combination of these wind speeds and temperature differentials. The time-averaged V_{ID} is used to compare the performance of the turbine ventilator under the different parameters, as this was the most consistent parameter measured. V_{ID} for wind, buoyancy and combination of wind and buoyancy forces are plotted on the same graph in Figure 85.

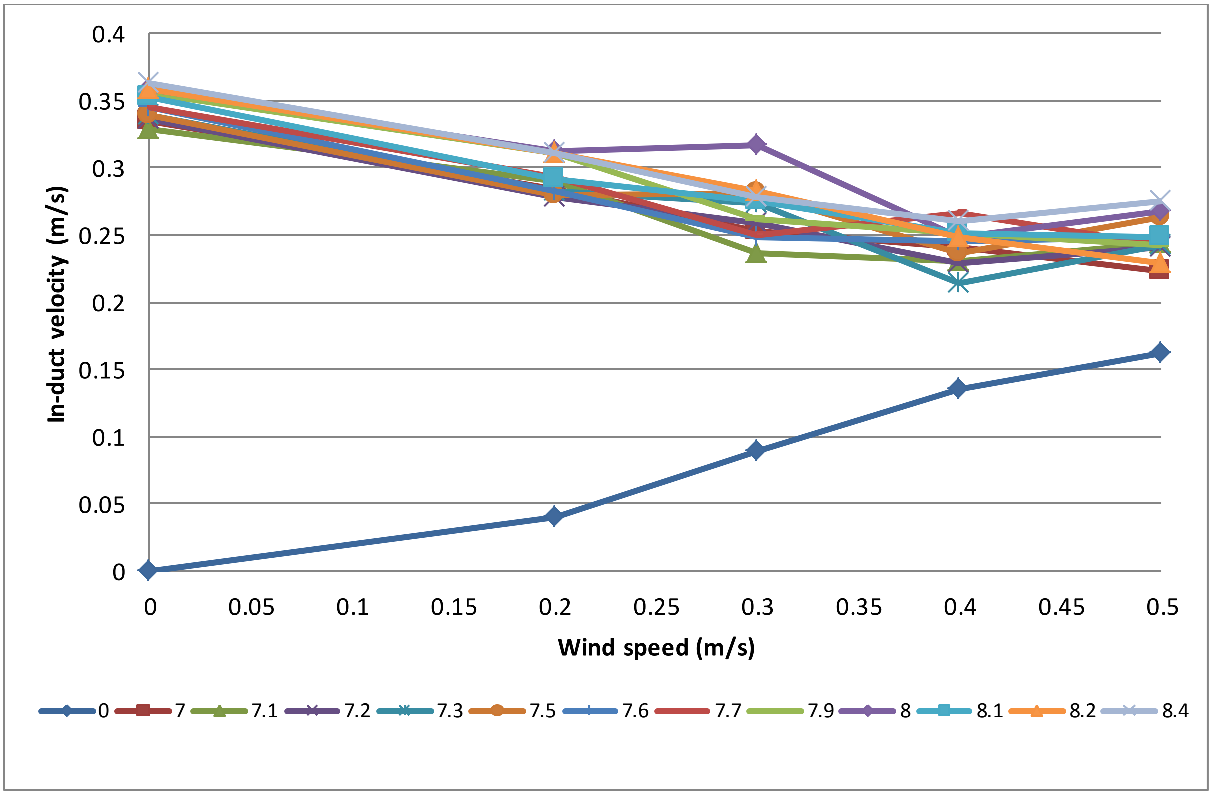

Figure 85: In-duct velocities of wind, buoyancy and combined wind and buoyancy forces

In Figure 85, V_{ID} as a function of v_w, are presented for varying dT. These graphs are a collation of the data presented in **Sections 6.1 to 6.3**, and are presented on the same graph to compare the performance of the varying parameters. Three things are highlighted in this graph:

1. On the y-axis, where $v_w = 0$, V_{ID} increases with an increase in dT.
2. In the wind speed tests, where $dT = 0$, V_{ID} increase with an increase in v_w. V_{ID}, although increasing, were lower than V_{ID} in the buoyancy forces tests. This may be true for low wind speeds only.
3. For a given dT, an increase in v_w results in a decrease in V_{ID}. This relationship appeared to plateau between 0.4 and 0.5 m/s, where in most dT plots, V_{ID} increases at 0.5m/s.

The results and comparisons presented here will be used to inform local flow behaviour of the turbine ventilator in the discussions of **Chapter 7**.

7. DISCUSSION

The performance of a turbine ventilator has been investigated in a field study and a laboratory environment. The results of these tests have been presented in **Chapters 5 and 6**, respectively. These results are discussed here, and the performance of the turbine ventilator is assessed in both scenarios, ultimately looking to its potential to reduce the concentration of airborne TB particles in a room.

In Chapter 5, the following blanket statement was made concerning the field study results: "***The results presented here are under the specific environmental conditions and ventilation strategy at the time of the test, and are not generalisable.***"This blanket statement is extended to the discussion of these results, unless otherwise stated.

Another point to bear in mind is that the results from these tests reflect the decay due to the ventilation system at the measuring points. This data is then used to calculate the ventilation flow rate, MAA and air change efficiency at these points, and are presented as a reflection of the ventilation system in the room. The results are specific to the test conditions.

The WHO (WHO, 2009) recommends a minimum hourly-averaged ventilation rate of 160 l/s/p for airborne precaution rooms, and a minimum hourly-averaged ventilation flow rate of 60 l/s/p for general wards and outpatient departments. In bedroom 2 of the reference house, considering a single occupant, this would result in a recommended ventilation flow rate of 34.4 ACH and 12.9 ACH, respectively. In reality, patients who receive the correct treatment become non-infectious after a short period of time. Adopting the recommendation of 60 l/s/p for general wards and outpatient departments, as in (Cox, et al., 2012), appears appropriate for bedroom 2 of the reference house.

Considering the ventilation flow rates achieved in both the baseline and turbine ventilator tests (see **Section 5.1.3**), cross-ventilation (CV) was the only test configuration which exceeded 12.9 ACH, a mean ventilation flow rate of 16.9 ACH in the baseline tests and a mean ventilation flow rate of 17.7 ACH in the turbine ventilator tests. In the CV tests, it cannot be concluded that the installation of the turbine ventilator increased the ventilation flow rate in bedroom 2. The results of the CV configuration, however, highlight the potential of natural ventilation for TB infection, prevention and control (IPC). By simply opening all the windows of the reference house, and opening the door of bedroom 2, a cross-ventilation stream was able to deliver greater than 12.9 ACH.

In the infiltration/leakage (IL), single-sided ventilation case 1 (SS1) and single-sided ventilation case 2 (SS2) configurations, the ventilation flow rates were well below 12.9 ACH, in all baseline and turbine ventilator tests. The mean ventilation flow rates in the baseline tests for IL, SS1 and SS2 were 0.6, 8.1 and 7.5 ACH, respectively. The mean ventilation flow rates in the turbine ventilator tests for IL, SS1 and SS2 were 1.8, 5.4 and 9.4 ACH respectively. While it does not appear that the turbine ventilator increased the ventilation flow rate for CV, the installation of the turbine ventilator appeared to affect the ventilation flow rates in all other configurations. For IL and SS2, the installation of the turbine ventilator increased the mean ventilation flow rates while for SS1, the mean ventilation flow rate decreased.

For the IL configuration, the installation of the turbine increased the mean ventilation flow rate by 1.2 ACH. The theoretical model described by the Wells-Riley Equation suggests that, when ventilation rates are low, any additional air changes make a significant difference in contaminant reduction in the room. Consider the case of IL where, in the baseline test a ventilation flow rate of approximately 0.6 ACH was achieved. According to the Wells-Riley model, under the model's assumption of steady-state conditions, the first air change removes 63% of contaminants in the room. The second air change removes 63% of the contaminants which are left in the room, i.e. after the second air change the initial contaminant concentration was reduced by 87%. By introducing the turbine ventilator into IL, an additional ACH was achieved, theoretically removing at least 63% more contaminants than the case without the turbine ventilator.

Additionally, in the IL configuration (see **Section 5.2.2**), by comparing the tracer gas decay at the turbine ventilator to the tracer gas decay in the room (Figure 59) the decay at the turbine ventilator was significantly faster than the decay in the room. In the morning and noon tests, the tracer gas decays to the background concentration in fewer than 60 minutes. After 60 minutes the concentration of tracer gas at the turbine ventilator started to increase, and the tracer gas concentration in the room was (still) decreasing. This suggests that the tracer gas from the room was travelling to the turbine ventilator. After 60 minutes, air inside the room would be warmer than it was at the beginning of the test, and started to rise. This result suggests that the air from the room was moving to the turbine ventilator due to natural convection, and not necessarily due to the rotation of the turbine ventilator. This finding suggests that a passive exhaust port on the roof may facilitate ventilation by natural convection in a similar manner.

In the baseline SS1 tests (see **Section 5.3.1**), the reported ventilation flow rates varied, between 6.8 and 9.3 ACH. The configuration of baseline SS1 is such that air exchange in bedroom 2 occurs at the window of bedroom 2. Air exchange can happen in two ways across the window. The window can act as both an inlet and exhaust as the wind pressure fluctuates across the building envelope. The wind pressure fluctuations create a pressure differential between bedroom 2 and the outside, which may be positive, in which case air moves into the room, or negative, in which case air will move out of the room. Air exchange may also occur due to the stack effect across tall windows. Cool air enters the room at the lower part of the window and exhaust stale warm air at the upper part of the window. The second case is more relevant in still wind conditions. The SS1 turbine ventilator tests reported a decrease in ventilation flow rates across all turbine ventilator tests. This could be due to the effect of the turbine ventilator on single-sided ventilation systems. The predominant wind direction in all tests was from the North Easterly direction. This results in bedroom 2 lying on the leeward side of the house, where the wind may work against exhaustion via the turbine ventilator.

In presenting the field study results, the accuracy of the instrumentation and its role in confidence in the results, should be expressed. The CO_2 sensor reported an accuracy of ± 50 ppm in the 0 – 5000 ppm range, which corresponds to 1% of the upper end and 10% at 500 ppm. The upper and lower limits of all field study tests were calculated to determine the deviation of the measured ventilation rates. In the baseline tests, this difference was calculated to be between 0 – 20% in IL, 7.4 – 13% in SS1, 5.8 – 13% in CV and 5.4 – 8.9% in SS2. In the turbine ventilator tests, this difference was calculated to be between 0 – 6.3% in IL, 5.3 – 7.7% in SS1, 3.8 – 6.5% in CV and 3.5 - 5.0% in SS2.

(WHO, 2009) recommends that the overall airflow should bring air from the contaminant source to areas of sufficient dilution, and preferably be exhausted to the outside. This recommendation is difficult to achieve in natural ventilation designs because the driving forces are constantly changing.

In baseline tests for the SS1 configuration (see **Section 3.4.6**), the air will be exhausted directly to the outside. In the SS2 configuration (see **Section 3.4.8**), the potentially contaminated air will leave bedroom 2 through the door of bedroom 2, to diffuse with air in the rest of the house, and be exhausted at the leeward side of the house. While this scenario is not ideal, it is also of lower risk. The same number of contaminants present in bedroom 2 is now incrementally moved to a bigger volume, thereby reducing the concentration of contaminants in bedroom 2, but increasing contaminant concentration in the rest of the house. The presence of a cross-ventilation stream in the house allows for fresh air to constantly enter the house, dilute the contaminant concentration by mixing with air inside the house, and exhaust contaminated air as it leaves the house. Contamination of corridors and adjacent rooms is therefore a risk, particularly on completely wind-still days (Escombe, et al., 2007).

In the turbine ventilator tests, for the IL and SS1 configurations, the air will be exhausted directly to the outside, in IL by the turbine ventilator, in SS1 either via the window or the turbine ventilator. For the SS2 configuration, the potentially contaminated air will either follow the same path of as the baseline tests, or the potentially contaminated air will leave bedroom 2 through the turbine ventilator. The latter aligns with the WHO recommendation, while the risks associated with the former have been discussed.

In CV, a North Easterly wind results in bedroom 2 being at the leeward side of the house and as such, the cross-ventilation stream through the house allows the potentially contaminated air to be exhausted directly to the outside. In the baseline test, air was exhausted at the window of bedroom 2, and in the turbine ventilator test, air was exhausted at both the window of bedroom 2 and the turbine ventilator. Wind directions are variable, and the airflow direction may change, which would result in the risk posed by SS2.

Air change efficiency is a good indicator of indoor air quality when there are many sampling points in the room. This will identify the variability of the air change efficiency in the room and highlight where the contaminants may go. As the air change efficiency is derived from only one measuring point in the room, the results here should not be misinterpreted. In the baseline tests, the air change efficiency of the IL, CV and SS2 configurations ranged between 52 and 60%. SS1 reported air change efficiencies in the range of 61 to 70%. These results indicate that the IL, CV and SS2 configurations allow for the air in the room to be well mixed. The SS1 configuration, which is subjected to wind pressure fluctuations, reduces the potential for mixing in the room. In the turbine ventilator tests, the air change efficiency of all test configurations ranged between 54 and 60%. The addition of the turbine ventilator to SS1 appears to allow for greater mixing in the room, and the SS1 configuration now approached the well-mixed condition.

While CRE could not be assessed in these tests, and the limitations of air change efficiency has been acknowledged, a comparison between the tracer gas decay in the room and the tracer gas decay at the turbine ventilator were presented. In IL, there was a distinct difference between the decay in the room and the decay through the turbine ventilator. The tracer gas decayed at the turbine ventilator steadily decayed to the background concentration, and stabilised, while the tracer gas decayed slowly in the room. After approximately an hour, the air in the room was at a higher temperature than it was at the beginning of the test, and begins to rise, due to natural convection, towards the opening at the turbine ventilator. The rising air reduced the tracer gas concentration in the room, and was transferred to the tracer gas concentration through the turbine ventilator. In SS1 and SS2, some tests displayed erratic decay through the turbine ventilator, and steady decay in the room, in the same test. This occurred in some and not all tests. This would suggest that the ventilation at the turbine ventilator and the ventilation in the room are separate, where the ventilation at the turbine ventilator is influenced by the rotation of the turbine ventilator and the ventilation in the room is due to single-sided ventilation across the window of bedroom 2. In CV, the decay rate at the turbine ventilator and in the room was similar.

The two previous studies which are most relevant for comparison and discussion of the field study are (Escombe, et al., 2007) for the baseline and turbine ventilator tests; and (Cox, et al., 2012) for the turbine ventilator tests. These studies have been extensively presented in **Chapters 2 and 3**. In investigating the determinants of natural ventilation, (Escombe, et al., 2007) found that increased natural ventilation (m^3/h and ACH) and decreased risk of TB transmission were significantly associated with the area of open windows/doors, placement of windows/doors on opposite sides of walls, ceiling height, floor area, and wind speed. The results were consistent in all three measurements, except for ceiling height in ventilation flow rate measured in ACH, where ceiling height was only statistically borderline significant. Temperature and relative humidity were also measured, but did not qualify for inclusion in being a determinant for measurements. In the field study of this research project, the ambient temperature and directional wind speed varied across the tests. In all baseline configurations, save SS1, and all turbine ventilator configurations, the ambient temperature and fluctuating wind speed did not greatly affect the ventilation performance of the configuration. All baseline configurations, save SS1, reported similar ventilation flow rates. All turbine ventilator configurations reported similar ventilation flow rates. This finding highlights that the ventilation flow rate in this field study was more dependent on the test configuration, and hence openable area, than on the environmental conditions. Results of the field study concur with (Escombe, et al., 2007) where the ventilation flow rate (in ACH) was more dependent on openable area, than environmental conditions. Results of this field study differ from (Escombe, et al., 2007) where wind speed was not a determinant in ventilation flow rate.

The limitations of the field study of this research project have to be acknowledged. The number of tests was limited to three per configuration, and hence, extensive statistical analysis was not performed. All tests per configuration were also tested on the same day. While this has allowed for the diurnal evaluation of the ventilation system across a typical Pretoria summer day, these tests have not evaluated the ventilation performance across different seasons in the year. The aim of these tests was to evaluate the turbine ventilator performance in the naturally ventilated system on hot still days, which was achieved; however, due to time and seasonal constraints, the sample size had to be limited. The turbine ventilator study differs from (Cox, et al., 2012), in that (Cox, et al., 2012) compared the installation of the turbine ventilator to that of natural ventilation whereas this study evaluated the performance of the naturally ventilated system supplemented by a turbine ventilator.

The performance of the turbine ventilator is evaluated in a laboratory environment under a set of parameters. The in-duct velocity and the centreline velocity profile at the base of the turbine ventilator are measured under these parameters to establish the suction created by the turbine ventilator. The centreline velocity would then be used to relate Dalla Valle's Equation and Stoke's Law to a contaminant whose properties are defined.

The wind speeds and temperature differentials parameters were low. The parameters were low enough to cause some air movement through the turbine ventilator, even in the absence of turbine ventilator rotation. The tests were performed to mimic a climate of high temperatures and low wind speeds. At low wind speeds, the in-duct velocity through the turbine ventilator is very low. A mean in-duct velocity between 0.07 m/s at a wind speed of 0.2 m/s to 0.16 m/s at 0.5 m/s were reported. In the wind speed range 0.2 – 0.5 m/s, there is a clear increase in in-duct velocity with an increase in wind speed.

In the buoyancy forces tests, a mean in-duct velocity of approximately 0.34 m/s was achieved, across all tests. This in-duct velocity is significantly greater than the in-duct velocities achieved in the low-wind speed tests. However, if this scenario were to be expanded to a physical case, it implies that the upper-room needs to be at least in the range of 7.0 to 9.3˚C warmer than the outside to experience ventilation rates of this magnitude. For the turbine ventilator to consistently exhaust air at approximately 0.34 m/s, the temperature differential would also have to be maintained in some way, to maintain that flow rate.

In the combined wind speed and buoyancy forces tests, the results show that for a given temperature differential range, an increase in wind speed, at low wind speeds, result in a decrease in in-duct velocity, within limits. This effect appears to plateau at a wind speed between 0.4 and 0.5 m/s.

At the commencement of this study, no literature was found on the performance of the turbine ventilator under wind, buoyancy and a combination of wind and buoyancy forces, in a laboratory environment. To date, the only known study to investigate such performance was that performed by

(Nguyen, Nguyen, & Ha, 2012). The study was published in the International Journal of Engineering; more than a year after the laboratory apparatus of this research project was constructed. As such, the study of (Nguyen, Nguyen, & Ha, 2012), summarised in **Appendix G**, is used for comparison, and does not form part of the literature review of **Chapter 2**, nor the literature pertaining to the development of the laboratory apparatus design presented in **Chapter 4**.

There are similarities and differences between the laboratory experimental set-up of this project and the laboratory experimental set-up of (Nguyen, Nguyen, & Ha, 2012)). (Nguyen, Nguyen, & Ha, 2012) experimental set-up was the size of a small room, with a single low level opening. The experimental set-up in this research projects is smaller, with low level openings on two sides of the control volume. Wind speed was created similarly, using fans and airflow straighteners, however (Nguyen, Nguyen, & Ha, 2012) wind speed range, and fan capacity, was greater. To establish a temperature differential, (Nguyen, Nguyen, & Ha, 2012) used heat flux from light bulbs, increasing the temperature differential by increasing the number of light bulbs. In this way, the temperature differential could be controlled. The laboratory apparatus in this research project used a heating element with thermostatic control to establish a (fluctuating) temperature differential.

A comparison between the results of this research project, Figure 85, and the results obtained by (Nguyen, Nguyen, & Ha, 2012) can be made, within limits. This comparison can be made on general trends, but specifically in the 0 to 0.5 m/s range, highlighted in Figure 98. The results of (Nguyen, Nguyen, & Ha, 2012) showed that an increase in wind speed resulted in an increase in air speed through the turbine ventilator. This relationship was also previously reported in (Lai, 2003) and (Khan, Su, Riffat, & Biggs, Performance testing and comparison of turbine ventilators, 2008). There was also an increase in air speed through the turbine ventilator with an increase in heat flux in the room. The air speed induced in the turbine ventilator due to wind was substantially lower than the air speed induced in the turbine ventilator by the buoyancy forces, and combination of wind and buoyancy forces.

In terms of comparative performance, the laboratory experiments of this research project can be directly compared only to the wind speed range of 0 to 0.5 m/s. While the heat fluxes of (Nguyen, Nguyen, & Ha, 2012) experiments cannot be translated to the temperature differentials reported in this research project, the general trends can be compared. The most notable comparison to be made in this highlighted region is the combined wind speed and heat flux results. At 0.0 m/s, at heat fluxes of 1, 2 and 3 kW, the induced air speed through the turbine ventilator was approximately 0.50, 0.68 and 0.85 m/s, respectively. At 0.5 m/s, at heat fluxes of 1, 2 and 3 kW, the induced air speed through the turbine ventilator was approximately 0.48, 0.69 and 0.83 m/s, respectively. This trend is similar to what was achieved in the laboratory study, where, at low wind speed, the in-duct velocity through the turbine ventilator decreased with an increase in wind speed. In the study of (Nguyen, Nguyen, & Ha, 2012), beyond 0.5 m/s, the induced air speed in the turbine ventilator increased with an increase in wind speed, for a given heat flux. This is similar to the trend realised in this research project, where for some temperature differentials plotted in Figure 85, at 0.4 to 05 m/s, the decrease in in-duct velocity plateaus. At the low wind speed parameters investigate in this research project, the total in-duct velocity does not conform to the relationship described by Equation 22.

Having determined the rates at which air flows through the turbine ventilator under the different parameters, the effect that the in-duct velocity has on producing a centreline velocity was investigated. In the wind speed tests, the velocity measured at $V_{0.5D}$, V_D and $V_{1.5D}$ were undetectable in all tests. The velocity at the base of the turbine ventilator is so low the thin film sensors cannot measure the centreline velocities produced by the turbine ventilator. Following from Figure 75, at $V_{0.5D}$, the expected velocity is reduced to 32% of V_{ID} in the 0.05 m/s test. This is the limit of detection of the thin film sensor. At low wind speeds, the turbine ventilator does not produce a centreline velocity which extends to the measured domain, and therefore cannot be characterised by the Dalla Valle Equation in this experimental set-up.

In the buoyancy forces tests, the centreline velocities $V_{0.5D}$ and V_D, were undetectable across all tests. The centreline velocity $V_{1.5D}$ recorded both undetectable and detectable values. The distribution of the detectable velocities were recorded, and it was found that, the value of $V_{1.5D}$ was detectable for 43 to 52% of the measurements in the three sets of tests. The distribution indicated that the ratio of undetectable to detectable values for $V_{1.5D}$ was so close to one, the possibility of bi-directional flow across the thin film sensor may be very likely. The thin film sensors used in these tests were directional, and were used to establish the upward centreline velocity component. If air did flow in the opposite direction across the thin film sensor, the recorded centreline velocity would be zero. The distribution indicated that in the vicinity of $V_{1.5D}$ there exists a turbulent region, in which the air passing through $V_{1.5D}$ fluctuates, in both magnitude and direction. The mean centreline velocity $V_{1.5D}$ (upward component) for the three sets of tests is 0.06, 0.07 and 0.08 m/s for Sets 1, 2 and 3 respectively. Because $V_{0.5D}$ and V_D were undetectable, and $V_{1.5D}$ fluctuates in both the upward and downward direction, a centreline velocity described by Dalla Valle's Equation cannot be established. Additionally the mean centreline velocity $V_{1.5D}$ is much higher than what would be predicted by Dalle Valle at 1.5 D. While this outcome cannot be used to evaluate the capture envelope of the turbine ventilator under buoyancy forces, it has highlighted the turbulent environment near the turbine ventilator.

In the combined wind speed and buoyancy forces tests, similar behaviour was observed at 1.5D. An evaluation of Test 3 of the combined wind and buoyancy forces test showed that an undetectable value for $V_{1.5D}$ was obtained between 60.1% in the 0.2 m/s test and 92.5% in the 0.5 m/s test. In this instance, it cannot simply said that (1) the downward component of $V_{1.5D}$ is now more significant, or that (2) the increase in wind speed reduces the turbulent fluctuations at $V_{1.5D}$. What is apparent is that increasing wind speeds affect the local flow dynamics around the turbine ventilator. In the combined wind and buoyancy forces tests, V_{ID} decreased with an increase in wind speed, and there is a significantly lower percentage of measured upward $V_{1.5D}$.

Particles sized 1-5 µm, have terminal velocities of 0.3 to 8 mm/s in still air (Hinds, 1999). According to Stoke's law (**Appendix D**), an upward velocity (stream), greater than this terminal velocity would be required to carry the particle to the turbine ventilator.

When addressing the question of "**are turbine ventilators able to remove particles of specified mass and size under a set of defined parameters?**" the results and discoveries of the field study and laboratory are aligned.

In the field study, the IL test showed that the flow from the room through the turbine ventilator was due to natural convection, and not necessarily due to the rotation of the turbine ventilator. The other three configurations, SS1, CV and SS2, showed that were two distinct and separate ventilation rates between the room and the turbine ventilator.

The laboratory experiments showed that, at low wind speeds, a centreline velocity described by Dalla Valle's equation could not be produced, as the velocities were too low to be detected by the thin film sensors. The laboratory experiments also showed that, under buoyancy forces only, the region near the turbine ventilator is turbulent, resulting in mixing near the turbine ventilator. The combined wind speed and buoyancy forces test showed that this turbulent region still exists; however, the increasing wind speed reduced the turbulent fluctuations.

When (Cox, et al., 2012) evaluated the performance of the turbine ventilator, the resulting natural ventilation system had a low-level inlet (air intake grille) with a high-level, negative pressure exhaust (turbine ventilator). The design of the turbine ventilator installation in (Cox, et al., 2012) allowed for the room to be ventilated as the air exhausted at the turbine ventilator had to be replenished with fresh air from the air intake grille. In this research project, a turbine ventilator was supplemented to the (existing) natural ventilation system. The turbine ventilator did not produce a pressure differential strong enough to move the air from the room to the turbine ventilator. In this study, the turbine ventilator did not change the airflow strategies of SS1 and SS2, such that the window/door of bedroom 2 served as an inlet and the turbine ventilator as the exhaust. The presence of the turbine ventilator only increased the ventilation flow rate in IL by a single air change, and did not increase the ventilation flow rate in CV.

8. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

This chapter will conclude the findings of this research project in terms of the objectives and research questions set out in **Chapter 1**. These objectives were broken down into six tasks, which aimed to determine if the turbine ventilator was able to reduce the number of airborne particles of specified mass and size from a room. This chapter concludes with a list of recommendations for future study.

The conclusions presented here are derived under the specific parameters of the laboratory study and environmental conditions of the field study, and are not generalizable. This statement applies to all conclusions drawn.

8.1 Conclusions

In the field study, four natural ventilation system configurations, all of which included the installation of the turbine ventilator, were investigated to determine if the turbine ventilator would increase the ventilation flow rate in a room. The following findings were obtained:

1. The ventilation flow rate in the room was dependant on the natural ventilation configuration, and hence openable area to the room. Wind speed and temperature were not the determinant factors in the ventilation flow rate.
2. The installation of the turbine ventilator did not increase the ventilation flow rate in the IL configuration; however, this increase in ventilation flow rate was attributed to natural convection, where the turbine ventilator facilitated the exhaustion of warm air.
3. The installation of the turbine ventilator did not increase the ventilation flow rate in all natural ventilation configurations. In the case of single-sided ventilation (SS1), the ventilation flow rate decreased. In the case of IL and SS2, the ventilation flow rate increased. As CV produced high ventilation rates in the baseline tests, and similar ventilation rate in the turbine ventilator tests, it cannot be concluded that the installation of the turbine ventilator increased the ventilation flow rate in CV.
4. Results of the baseline CV test highlight the potential of cross-ventilation to adequately ventilate a room according to (WHO, 2009) guidelines.

In the laboratory experiment, the ventilation flow rate and centreline velocity profiles were investigated under wind, buoyancy and a combination of wind and buoyancy forces. The following findings, which relate to the tested experimental parameters only, were obtained:

1. An increase in wind speed resulted in an increase in in-duct velocity through the turbine ventilator.
2. An increase in temperature differential resulted in an increase in in-duct velocity through the turbine ventilator. However, there is a time difference between these processes, as the temperature differential has to be established first before the turbine ventilator starts to rotate.

3. An increase in wind speed, for a given temperature differential, resulted in a decrease in in-duct velocity through the turbine ventilator. This result applies only to the parameters tested.
4. A centreline velocity profile was not established at the base of the turbine ventilator in the wind speed tests. The low-wind speed did not produce a capture envelope, detectable by the thin film sensors, which extended to 0.5D.
5. In the buoyancy forces test, a turbulent environment at $V_{1.5D}$ was realised, where air fluctuates in both magnitude and direction.
6. In the combined wind and buoyancy forces tests, the turbulent environment at $V_{1.5D}$ was again observed. The magnitude and frequency of fluctuations was significantly lower than that of the buoyancy forces tests.

In **Chapter 1**, the thesis statement was presented as:

"Turbine ventilators are able to reduce the concentrations of particles of specified mass and size from a room, within specified performance parameters."

The aim of research project was to investigate whether the above statement was true or false. It is hereby concluded - by investigation through a field study and laboratory experiments - that at, at the parameters presented in (a) and (b) below, turbine ventilators cannot simply be supplemented to natural ventilation systems to increase ventilation flow rates and reduce the concentration of TB particles in the room.

(a) low wind speeds , 0.1 to 0.5 m/s for the laboratory experiments, and 0.38 to 1.72 m/s in the field study; and
(b) high temperatures differentials, 7.0°C to 9.3°C for the laboratory experiments.

8.2 Recommendations for further study

This section provides some recommendations for further study on this topic:

1. In this field study, summer (hot and still) conditions were tested. Wind and temperature conditions will change throughout the year. It is recommended that tracer gas (concentration decay) tests are performed throughout the year to get a true picture of seasonal variability and its relation to (changing) ventilation flow rates and airflow patterns for a given room. This could be extended to several sites across regions with different climatic conditions, to investigate the potential local climate has on ventilation flow rates and airflow patterns.
2. A complete computational fluid dynamics (CFD) study should be performed on the field study of this research project. In this way, the experimental results could be used to calibrate the numerical model. Any further interventions, and changing weather conditions, could then be numerically modelled, as opposed to physically tested.

3. In the laboratory experiments, a constant heat flux should be used to create the temperature differential to quantify the relationship between temperature differential and flow rates.
4. In the laboratory apparatus, a fan with greater capacity can be installed to provide a higher range of wind speeds.
5. CRE should be investigated in the field study by using a more suitable tracer gas technique, e.g. constant generation tracer-gas method.
6. To effectively quantify the ventilation flow rate, MAA, and air change efficiency of the room, additional sampling points should be considered. The locations of these sampling points should be considered carefully, and may include, sitting position, planes in the habitable zone, vertical planes to reflect the effect of thermal stratification, amongst others.
7. The selection of instrumentation should completely characterise a parameter, e.g. anemometers and air-flow instrumentation should measure wind speed and direction.

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APPENDICES

APPENDIX A – Specifications of the 300mm Windmaster Tornado turbine ventilator (Windmaster)

Coverage Area:

Void	76 m^2
Open	38 m^2

Tested air removing capacity at:

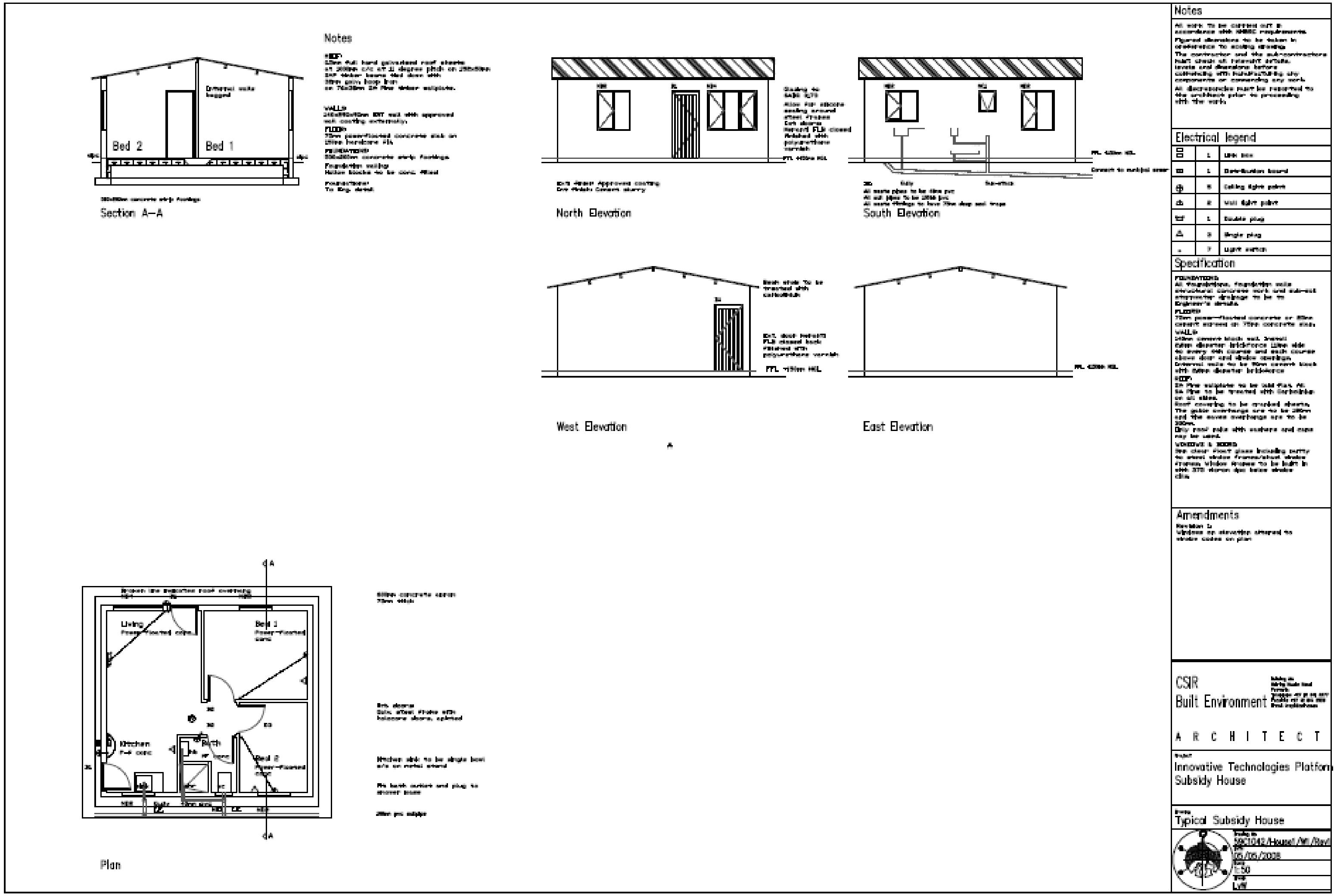
15 km/h	1489 m^3/h
25 km/h	2184 m^3/h

Sealed bearings in housing	2
Number of blades	20
Dome height	270 mm
Dome Width	430 mm
Total height	510 mm
Mass	6.3 kg

Note:

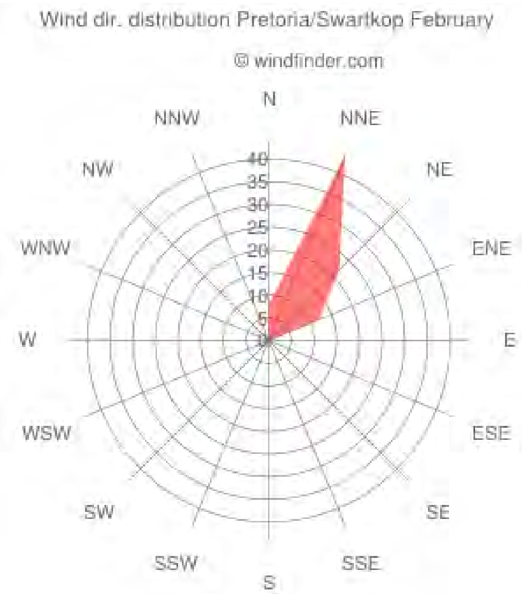
1. Air removing capacity figures shown have been calculated at an average roof height (heat stack) of 5 meters above working level. Average wind speed of 15 km/h.
2. Total height and mass exclude container and chimney champ products.

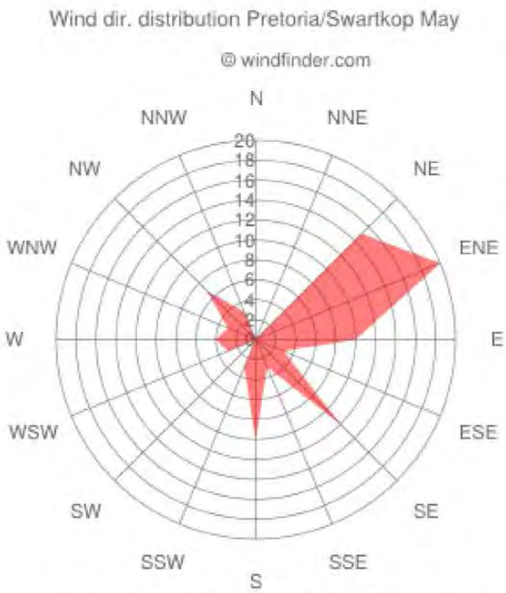
APPENDIX B – Architectural drawing of the reference house



APPENDIX C – Wind roses for Pretoria (Swartkop)

The following weather data for Pretoria has been recorded at Swartkop, which is approximately 15 km from the test site. The data has been statistically presented on (Windfinder, 2012) for 7AM to 7PM daily, for the period May 2010 to October 2012. All data presented here remains the copyright of (Windfinder, 2012).




Wind dir. distribution Pretoria/Swartkop May
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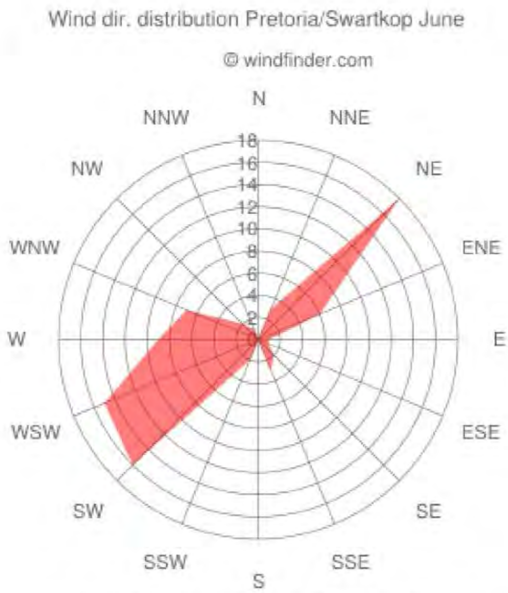
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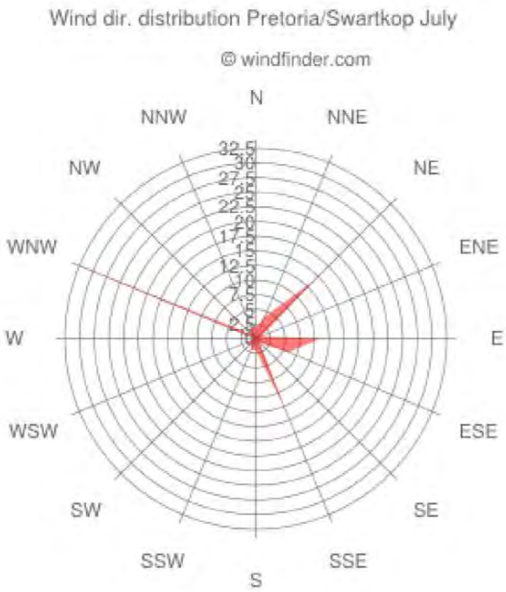
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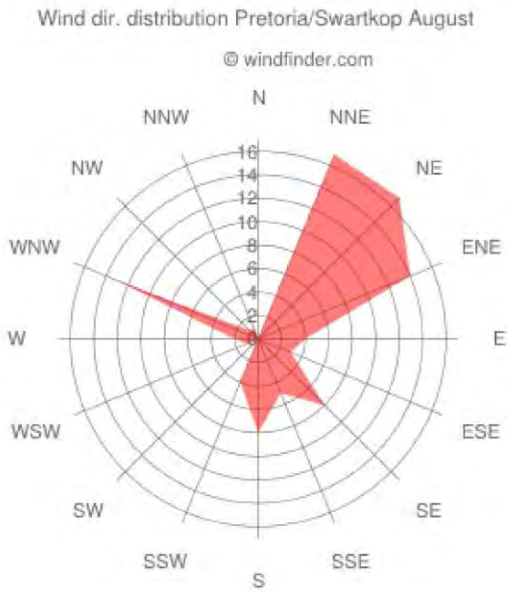
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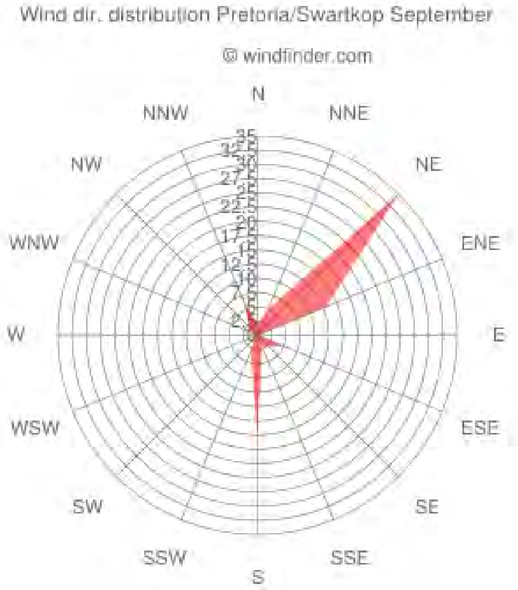

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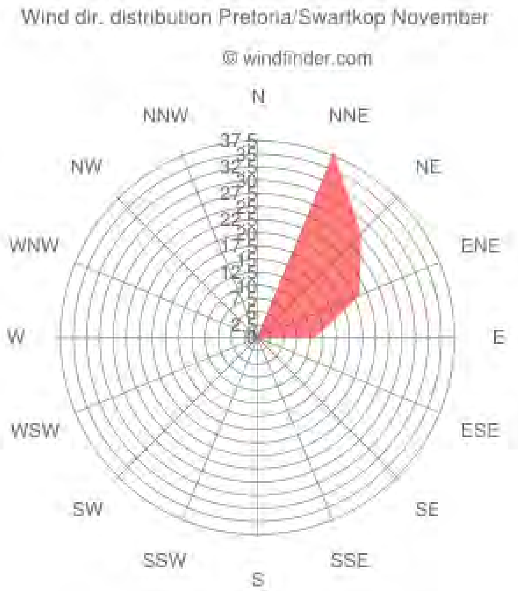

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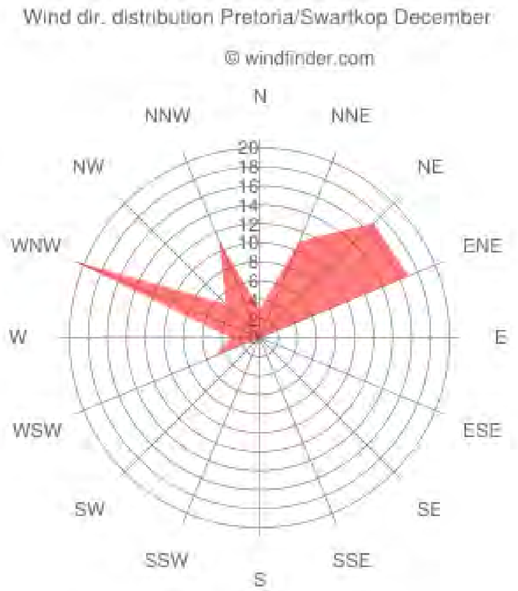

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APPENDIX D - Literature review relating to the concept formation of the laboratory apparatus design

D.1 AS/NZS 4740:2000 Natural Ventilators – Classification and Performance

AS/NZS 4740:2000 Natural Ventilators – Classification and Performance is a joint Australian and New Zealand standard which specifies minimum requirements for ventilators which operate solely by natural forces. These ventilators are divided into four groups:

Type 1 – Fixed grilles and louver panels

Type 2 – Fixed roof ventilators, hoods and ride vents

Type 3 – Wind directional vane ventilators

Type 4 – Turbine ventilators

This standard includes performance test methods for each of the different groups of ventilators. The classification and performance of turbine ventilators includes effective aerodynamic area, coefficient of discharge, flow coefficient, and rain and wind resistance. While the standard stipulates that all ventilators should have their effective aerodynamic area and coefficient of discharge established, the flow coefficient of the ventilator is of most interest here, as it characterises the performance of the turbine ventilator under simulated conditions. The flow co-efficient is the ratio of exhaust air, drawn through the ventilator, to the air passing over the ventilator (AS/NZS 4740, 2000). The flow coefficient is established using the apparatus shown in Figure 86.

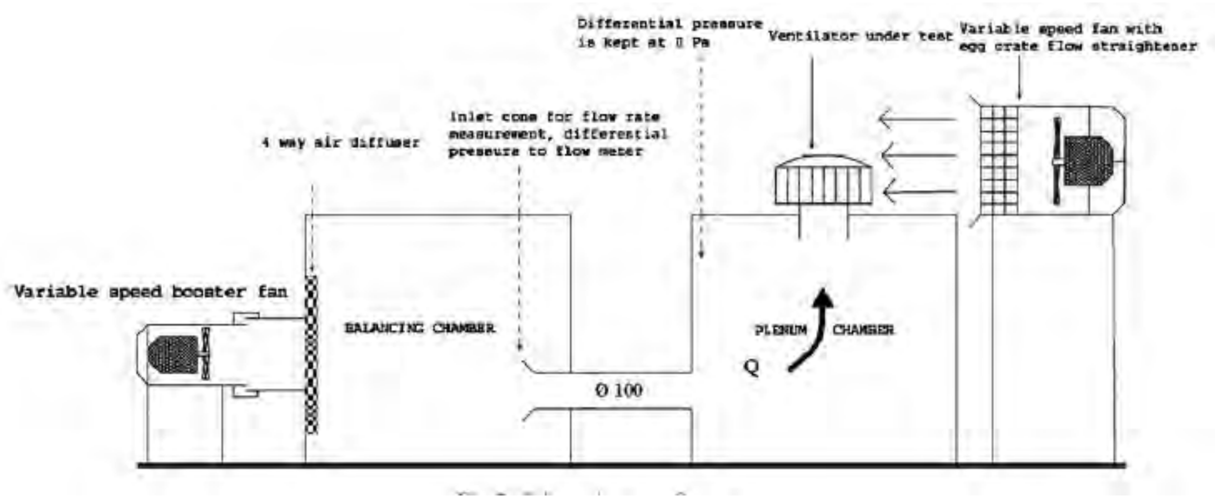


Figure 86: Test apparatus described in AS/NZS4740:2000 to establish the flow coefficient of turbine ventilators (Khan, Su, Riffat, & Biggs, Performance testing and comparison of turbine ventilators, 2008)

(Khan, Su, Riffat, & Biggs, Performance testing and comparison of turbine ventilators, 2008) describe the operation of the test apparatus: The turbine ventilator is positioned on top of the plenum chamber, where it is subjected to winds via a variable speed wind blower. The blower is placed behind an egg-crate flow straightener. When the wind blower was set to the predetermined wind speed, the turbine ventilator started to rotate, inducing a negative pressure inside the plenum chamber. A variable speed booster fan was then used to adjust the negative pressure to atmospheric pressure. The airflow from the booster fan passes through a four-way air diffuser into the balancing chamber, which has a conical face of the inlet cone inside. The other end of the inlet cone is attached to a duct, connecting the balancing chamber to the plenum chamber. In this way a differential pressure of 0 Pa is maintained between the plenum chamber and the balancing chamber. A probe anemometer is placed in this connecting duct to measure the air velocity, and hence, flow rate. The flow coefficient is a measure of the airflow induced through the ventilator by a known or simulated wind speed, and is given by Equation 13 (AS/NZS 4740, 2000):

$$C_f = \frac{V_V}{V_i}$$ **… Equation 13**

where:

V_v = velocity through the ventilator in m/s

V_i = free field velocity incident on the ventilator in m/s

This standard provides a method of calculating the airflow performance of natural ventilators under assumed conditions. Airflow due to wind siphoning, buoyancy and a combination of these forces may be calculated. The pressure due to buoyancy is calculated from Equation 14 (AS/NZS 4740, 2000):

$$P_B = \frac{\rho g h \Delta T}{T_{out}}$$ **…Equation 14**

where:

P_B = pressure due to buoyancy in Pa

ρ = density of air at ambient temperature in kg/m^3

g = gravitational acceleration in m/s^2

h = stack height in m

ΔT = temperature differential between the intake and exhaust air in K

T_{out} = outside ambient temperature in K

The wind siphoning pressure of the ventilator is given by Equation 15 (AS/NZS 4740, 2000):

$$P_W = \frac{\rho(C_f v_w)^2}{2}$$ **… Equation 15**

where:

P_w = wind siphoning pressure in Pa

C_f = flow co-efficient across the ventilator

v_w = wind velocity in m/s

The airflow through the ventilator is given by Equation 16 (AS/NZS 4740, 2000):

$$Q = F\sqrt{\frac{2P}{\rho}}$$ **… Equation 16**

Where:

Q = ventilation flow rate through the ventilator by either wind or buoyancy forces in m^3/s

F = effective aerodynamic area of the turbine ventilator in m^2

P in Pa is either P_B or P_w, given by **Equations 14 and 15** respectively

The combined effect of the wind and buoyancy forces can be calculated by Equation 17 (AS/NZS 4740, 2000):

$$Q_C = F\sqrt{\frac{2\sum P_C}{\rho}}$$ **… Equation 17**

Where:

Q_c = Combined ventilation flow rate

$\sum P_C = P_B + P_W$

AS/NZS 4740:2000 provides a means to classify natural ventilators in a standard method, thereby allowing a standardised comparison method across ventilators of the same group. It does not however characterise the ventilator in terms of its flow dynamics, and its potential to remove contaminants from the ventilated space.

D.2 Hood capture velocity

In industrial applications, the implementation of extraction hoods is standard practice to remove contaminants from the breathing zone of employees. A typical hood design, related to Dalla Valle's Equation (discussed below), is shown in Figure 87. A typical hood design includes a hood, which may be open or flanged, connected to a duct, which has a fan situated in-duct upstream from the hood opening. As the fan rotates, a suction force is produced and contaminants will move towards the hood, where it is channelled through the duct, and transported to be exhausted.

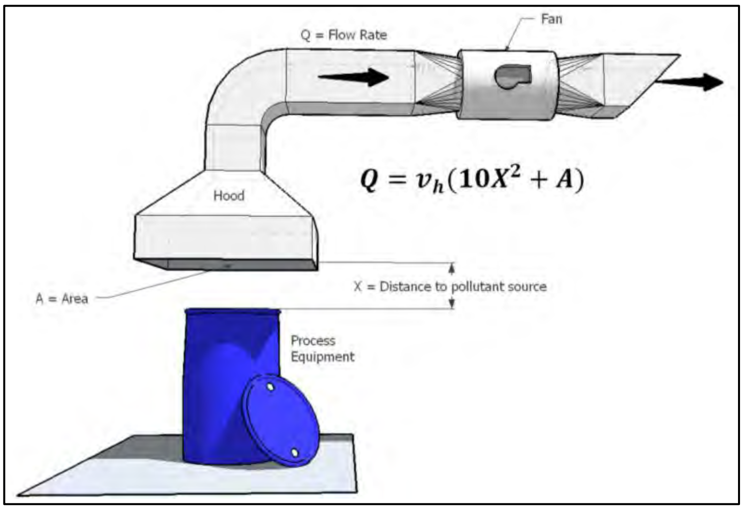


Figure 87: A typical hood design based on Dalla Vall 's Equation (Tobias van Reenen)

Hoods are designed to remove contaminants from a room. In order to remove contaminants, the suction force should be strong enough to capture particles. This gives rise to the concept of hood capture velocity. Capture velocity is a fundamental concept for the capture and removal of airborne contaminants by local exhaust ventilation (Garrison, 1981). Capture velocity is defined as the velocity at any point in front of a hood necessary to overcome opposing air currents and capture the contaminated air by causing it to flow into the hood (ACGIH, 2005). This implies that contaminated air at some point in front of the hood must, at least, be travelling at the capture velocity in order to be drawn into the hood (Fume hood capture velocity).

The Dalla Valle Equation calculates the exhaust flow rate needed to produce a specified capture velocity, and is given by (Fume hood capture velocity):

$$Q = v_h(10x^2 + A)$$ **… Equation 18**

Where:

Q = Required ventilation flow rate in m^3/s

x = Distance from the hood to the farthest point of contaminant release in m

v_h = Hood capture velocity at distance x in m/s

A = Area of the hood opening in m^2

Equation 18 is only valid for unflanged hoods, and is limited to x being less than or equal to 1.5 times the hood diameter (Fume hood capture velocity).The installation of turbine ventilators onto a surface results in the surface acting as a flange, and hence, Equation 18 does not apply. Dalla Valle's Equation for flanged hoods, having the same variables as Equation 18, is described by Equation 19 (Garrison, 1981):

$$Q = 0.75v_h(10x^2 + A)$$ **… Equation 19**

The concept of capture velocity can be expanded to capture envelope. Theoretically, ignoring the effects of dispersion, all contaminants inside the capture envelope should flow and be attracted into the hood opening (Huang, Sir, Chen, Yeh, Chen, & Chen, 2001). The flow field, the capture envelope in particular, is representative of the capture performance of a hood (Huang, Sir, Chen, Yeh, Chen, &

Chen, 2001). Figure 88 is an illustration of the capture envelope as depicted by Dalla Valle's Equation near the base of the hood.

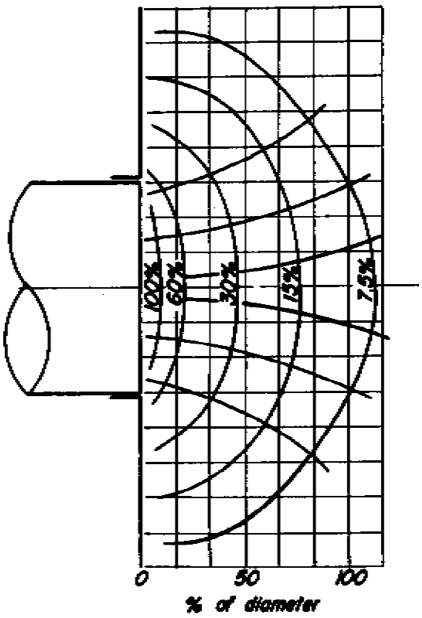


Figure 88: Velocity contours expressed in percentages of opening Velocity and streamlines for circular openings (ACGIH, 2005)

The vacuum created by a hood does not create equal velocity lines or points (Fume hood capture velocity). From Figure 88 it can be seen that there is a rapid decrease in velocity with an increase in distance from the hood (ACGIH, 2005). This result correlates with the relationship displayed in Dalla Valle's Equation, where velocity is inversely proportional to the square of the distance.

Dalla Valle measured centreline velocities as a function of pressure difference using a modified pitot-static pressure probe (Garrison, 1981). The pitot-static pressure probe was designed to measure slightly elevated differential velocity pressures at a point in the exhaust airflow stream, using a Whalen gauge manometer (Garrison, 1981). The centreline velocities were determined by traversing the centreline axis in front of the inlet opening (Garrison, 1981). The "Approximate" Dalla Valle's Equation for centreline velocity gradient for a circular flanged hood is given by Equation 20 (Garrison, 1981):

$$Y = \frac{133}{12.7(XDW)^2 + 1.0}$$ **...Equation 20**

where:

Y = percentage centreline velocity gradient

XDW = Non-dimensional centreline distance

Equation 20 may be used to establish the percentile velocity with respect to the hood face velocity at some distance in front of the hood. Dalla Valle noted that centreline velocities for flanged inlets are generally 30-40 % higher than that of plain inlets, and a 33% increase was applied to the "Approximate" expression for flanged inlets (Garrison, 1981). This is evident in Equation 20. From Equation 20, the percentage centreline velocity gradient for 90%, 50 % and 10% of the face velocity corresponds to 0.19D, 0.36D and 0.98D, respectively, from the inlet.

D.3 Stok 's Law

Stoke's law is an expression for the drag force experienced by particles when inertial forces are negligible compared to viscous forces (Hinds, 1999). At low Reynolds numbers (Re), the inertial effect of particles may be considered negligible, and the steady-state Navier-Stokes Equation may be simplified by omitting the inertia term.

By expressing the simplified Navier-Stokes equation together with the Continuity Equation in polar coordinates, and using the boundary condition that all velocity components are zero at the surface of a spherical particle, Stokes obtained a solution for drag (Douglas, Gasiorek, Swaffield, & Jack, 2005):

$$D = 6\pi\mu R U_{\infty}$$ **...Equation 21**

Where:

D = drag force on the spherical particle in N

μ = dynamic viscosity of the fluid in Ns/m^2

R = radius of the spherical particle in m

U_{∞} = free stream velocity of the fluid in m/s

In practice, Stoke's law is only used in applications where the particle's $\mathrm{Re}\langle 0.1$ (Hinds, 1999), but may be used with negligible error up to Re=0.2 (Douglas, Gasiorek, Swaffield, & Jack, 2005). Stoke's formula forms the basis for the determination of viscosity of oils (Douglas, Gasiorek, Swaffield, & Jack, 2005). If a sphere of known diameter is allowed to fall freely in oil, after the initial acceleration, the sphere will attain terminal velocity (Douglas, Gasiorek, Swaffield, & Jack, 2005). This terminal velocity is reached when the external drag on the sphere's surface plus the buoyancy force is equal to the gravitational acceleration of the sphere (Douglas, Gasiorek, Swaffield, & Jack, 2005). The terminal velocity of the sphere may be calculated from Equation 22 (Douglas, Gasiorek, Swaffield, & Jack, 2005):

$$v_t = \left(\frac{d^2}{18\mu}\right)(\rho_P - \rho)g$$ **… Equation 22**

where:

v_t = terminal velocity in m/s

d = diameter of the sphere in m

ρ_P = density of the particle in kg/m^3

ρ = density of the fluid in kg/m^3

g = gravitational acceleration in m/s^2

To illustrate the effect of terminal velocities for particles of different sizes, Figure 89, extracted from (WHO, 2009) is presented. Under normal conditions, Well's found that particles smaller than 100µm would completely dry out, before travelling 2m towards the ground. Particles in the order of 1-5 µm, evaporate instantaneously and remain suspended in the air, having to travel a long distance to the ground. As the particle increases in size, the evaporation time is longer, and the fall to the ground is shorter.

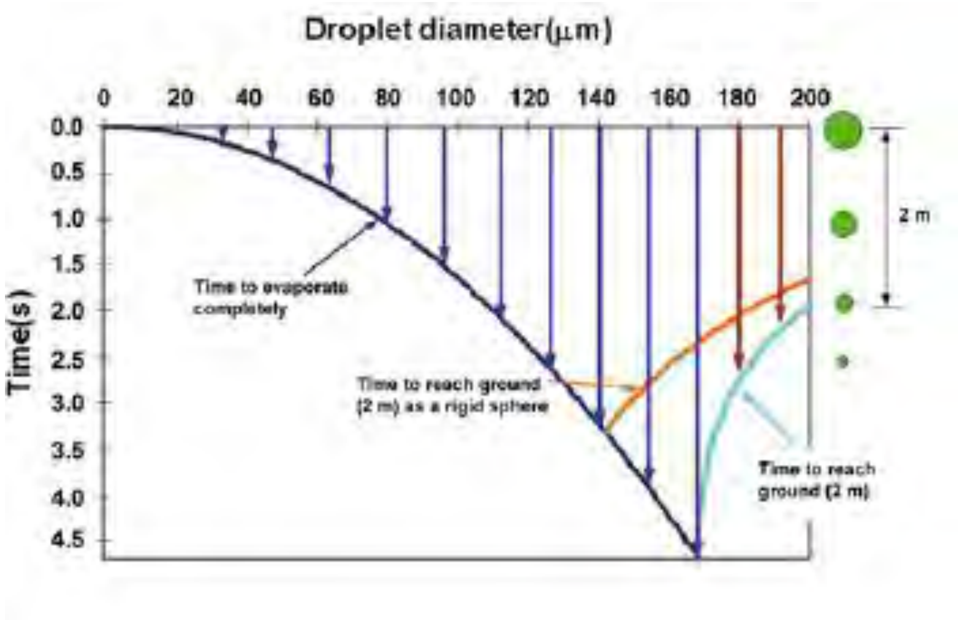


Figure 89: An illustration of particles evaporation and falling according to W ll's quation (WHO, 2009)

Terminal velocity is important in particle mechanics, as it forms the basis of operations such as settling and sorting. Consider Figure 90, where a spherical particle is introduced into a vertical fluid stream (Douglas, Gasiorek, Swaffield, & Jack, 2005).

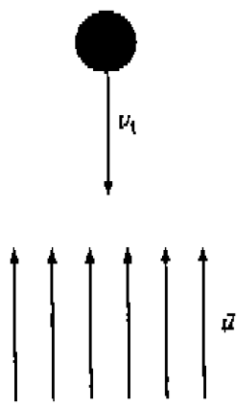


Figure 90: Spherical particle falling into a vertical fluid stream (Douglas, Gasiorek, Swaffield, & Jack, 2005)

If the fluid was stationary, i.e. $\bar{u} = 0$, the particle would attain constant terminal velocity, v_t and descend at this velocity (Douglas, Gasiorek, Swaffield, & Jack, 2005). If the fluid is moving vertically upwards at a velocity of $\bar{u}$, then 3 possibilities may exist (Douglas, Gasiorek, Swaffield, & Jack, 2005):

1. When $\bar{u} < v_t$ the particle will descend with an absolute velocity of $v = v_t - \bar{u}$. The term v_t is now the relative velocity between the fluid and the particle.
2. When $\bar{u} = v_t$ the particle will remain suspended in the fluid, and has an absolute velocity of $v = 0$.
3. When $\bar{u} > v_t$ the particle will move upwards with the fluid with an absolute velocity of $v = \bar{u} - v_t$.

By establishing the terminal velocity, v_t, the required stream velocity, $\bar{u}$ to capture particles of specified mass and size, can be determined. (Nardell & Macher, 1999) report that particles of 1-5 µm, have terminal velocities in the range of 0.3 to 8 mm/s in still air.

With the exception of specially designed cleanrooms, air does not travel in vertically upward streams. In natural ventilation, air in a room is often partially or fully mixed. This implies that air enters the room, circulates within the room according to pressure profiles in the room, and will be exhausted after some time. With low-level inlets, and high level exhausts, the net air flow pattern may be upward, but the air may circulate several times in the room, before it reaches the exhaust.

APPENDIX E – Code used to run data logger for laboratory experiments

```
\' PROGRAM VIR "PUNCH TESTS" SAAM MET Faatiema
                      \'
                      \'  D=2/12/2010 " SO WORD DIE DATUM REG
GESTEL"
RESET
\W5                   \' Timer for 5sec
CLEAR
                      \'  Set Time
P39=0                 \' TIME IN HH:MM:SS.5
T=\t                  \' GET TIME FROM COMPUTER
P39=0                 \' TIME IN HH:MM:SS
\'P39=2               \'TIME IN DECIMAL HOURS
P31=2                 \' DATE IN MM-DD-YYYY
D=\d                  \' GET DATE FROM COMPUTER
P31=1                 \' DATE IN DD-MM-YYYY
\'P15=1               \' SLEEP MODE PAGE 15 IN MANUAL
/n/u                  \' Disable Channel ID & Units
/N/S/E
P22=44                \'32= SPACE BETWEEN DATA (32 is Space
delimiter)
                      \'STATUS
                      \'TEST
BEGIN
\'   /T/D              \'Time & Date stamp

 P16=200
  RA4S
     1+TJ             \' Termo No 1 Tipe J
     2+TJ             \' Termo No 2 Tipe J
          3+TK        \' Termo No 3 Tipe K       4#I
          4+TK        \' Termo No 4 Type K
          5+TK        \' Termo No 5 Type K
               6#I    \' AIR 1
```

```
                7#I   \' AIR 2
                8#I   \' AIR 3
                9#I  \' AIR 4
LOGON
END
```

APPENDIX F – Time-adjusted data for buoyancy forces tests and combined wind and buoyancy forces tests

In Figures 91 – 93, only the first six hours of the test is presented.

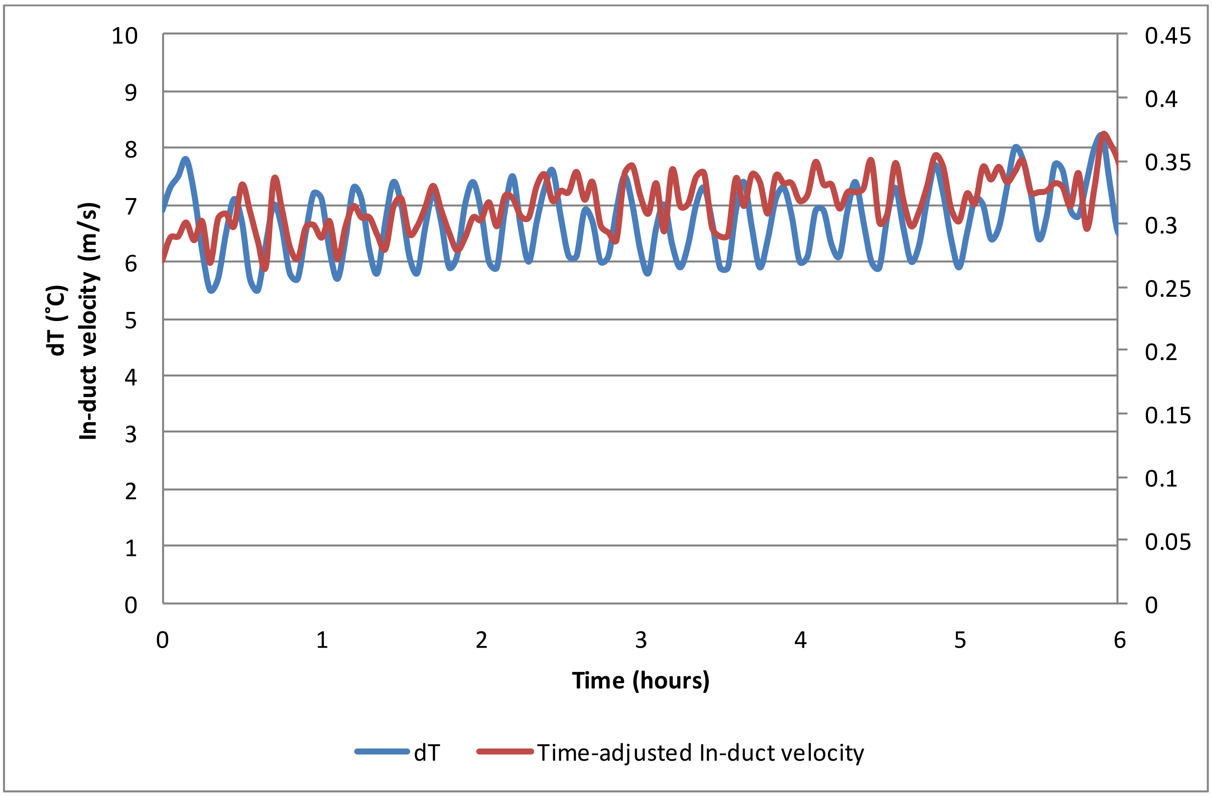


Figure 91: Time-adjusted data for buoyancy forces tests, Set 1

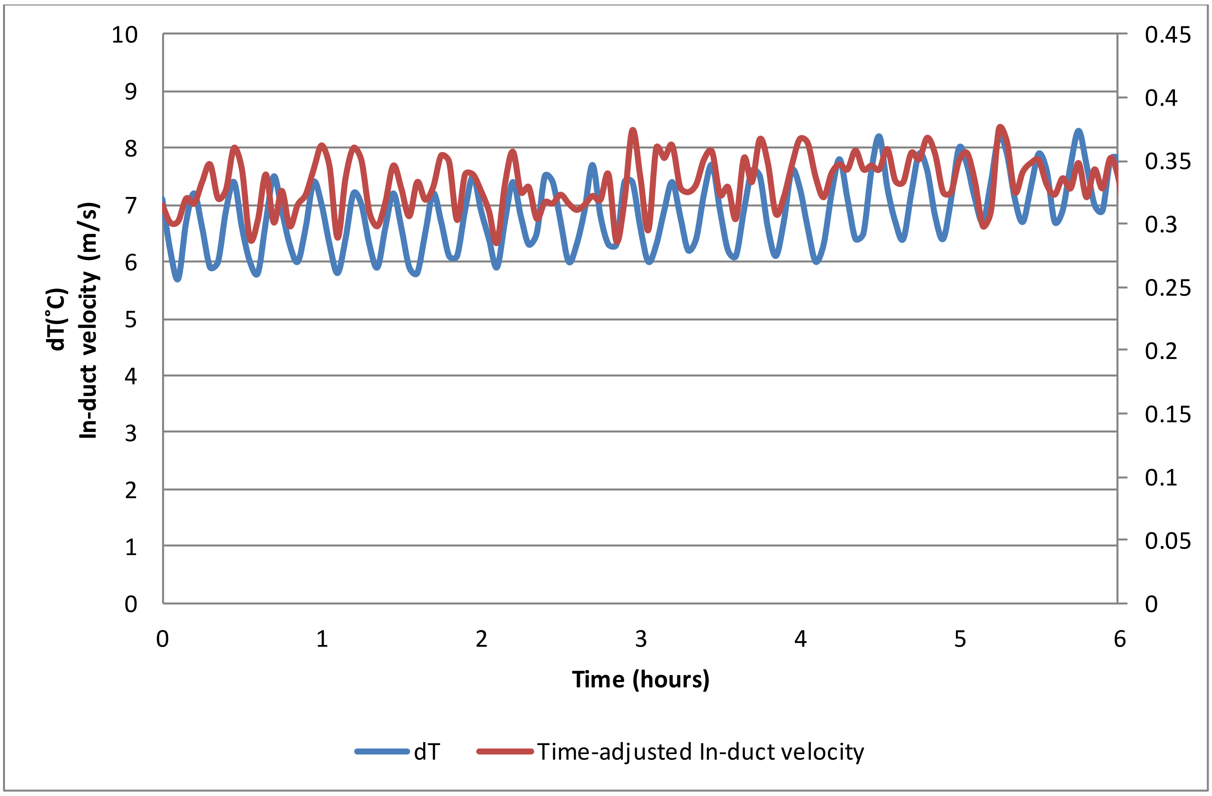


Figure 92: Time-adjusted data for buoyancy forces tests, Set 2

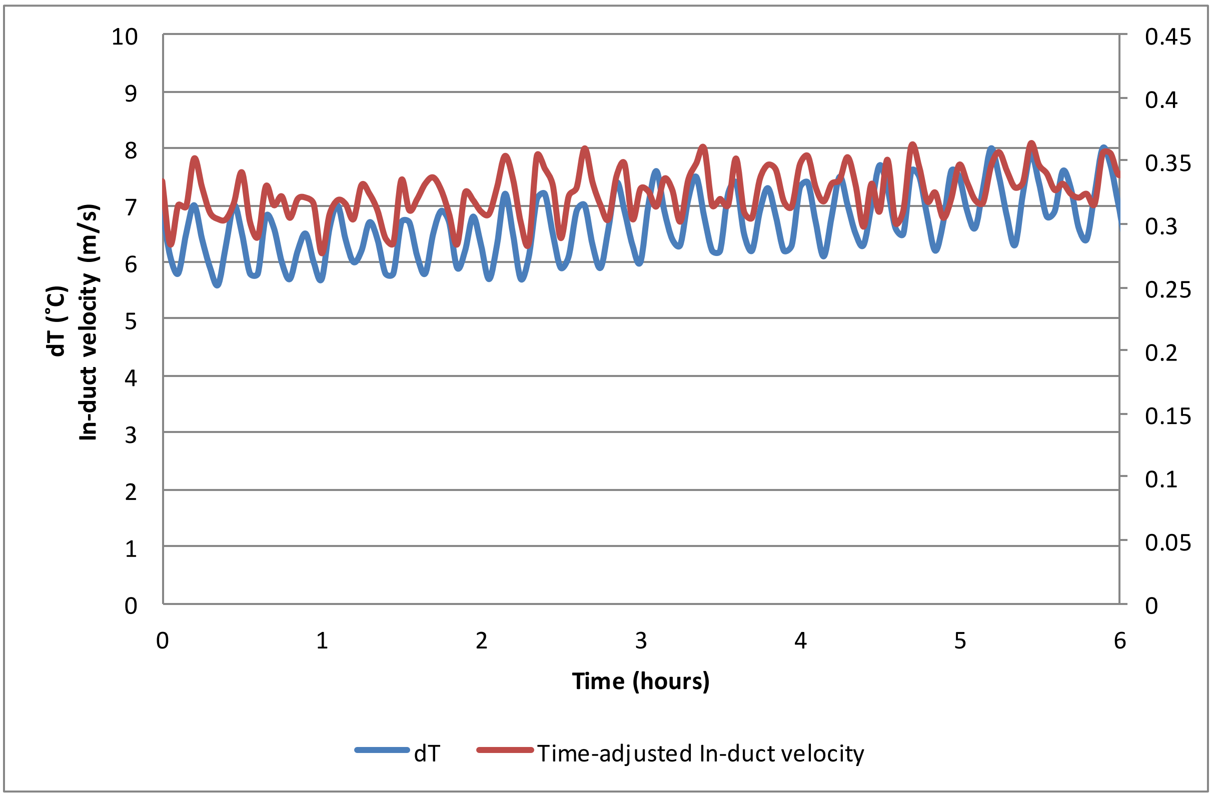


Figure 93: Time-adjusted data for buoyancy forces tests, Set 3

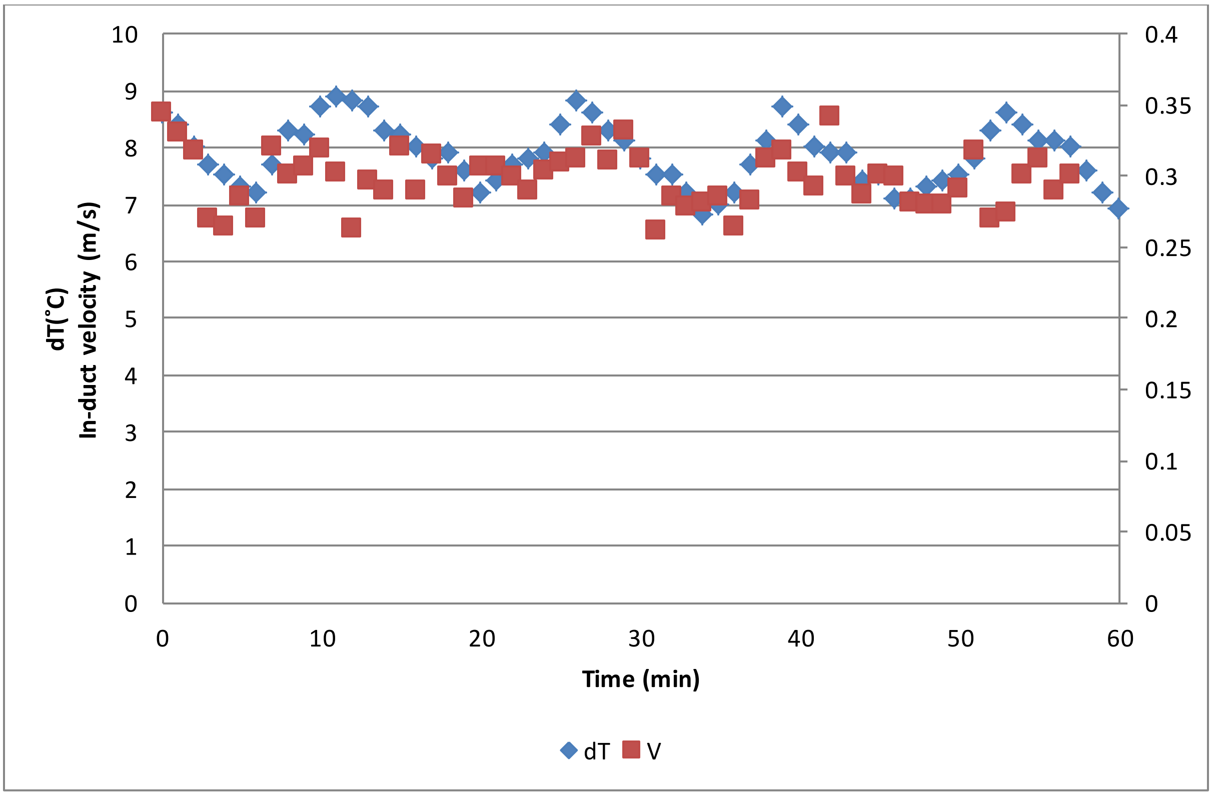


Figure 94: Time-adjusted data for combined wind and buoyancy forces test for v_w of 0.2 m/s

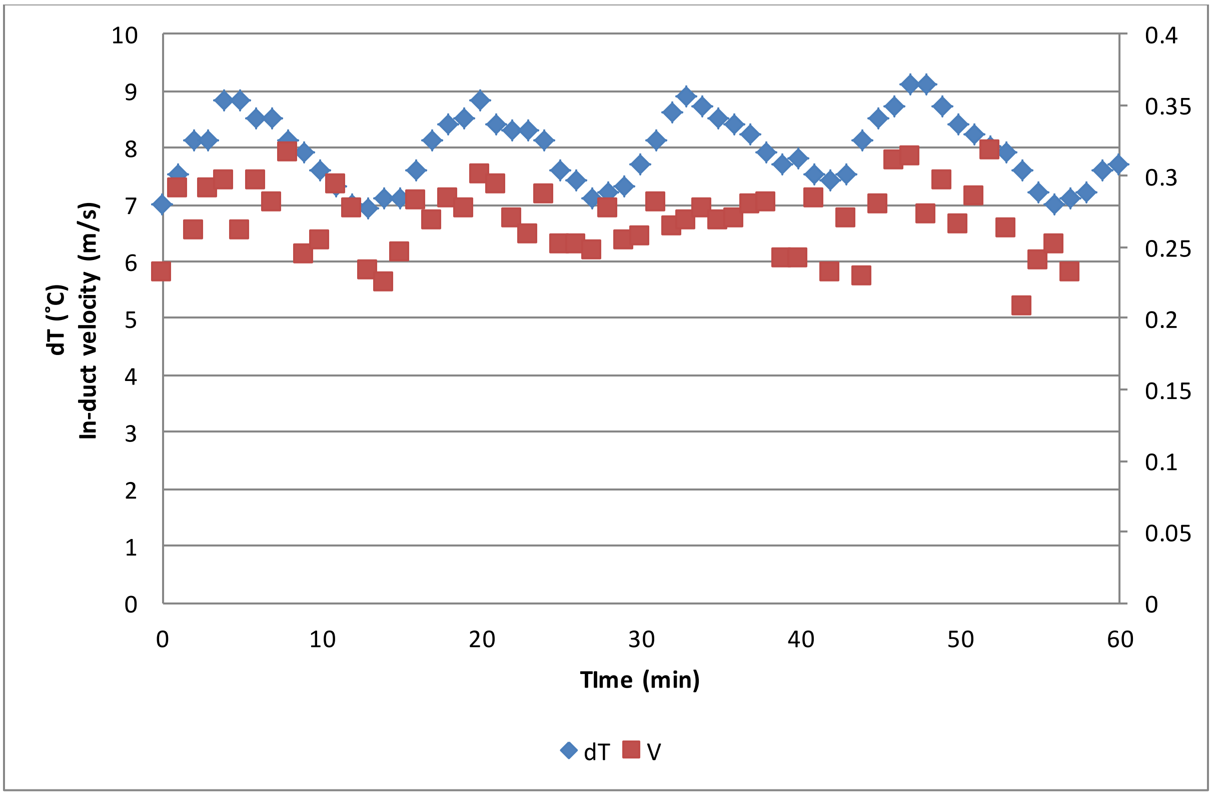


Figure 95: Time-adjusted data for combined wind and buoyancy forces test for v_w of 0.3 m/s

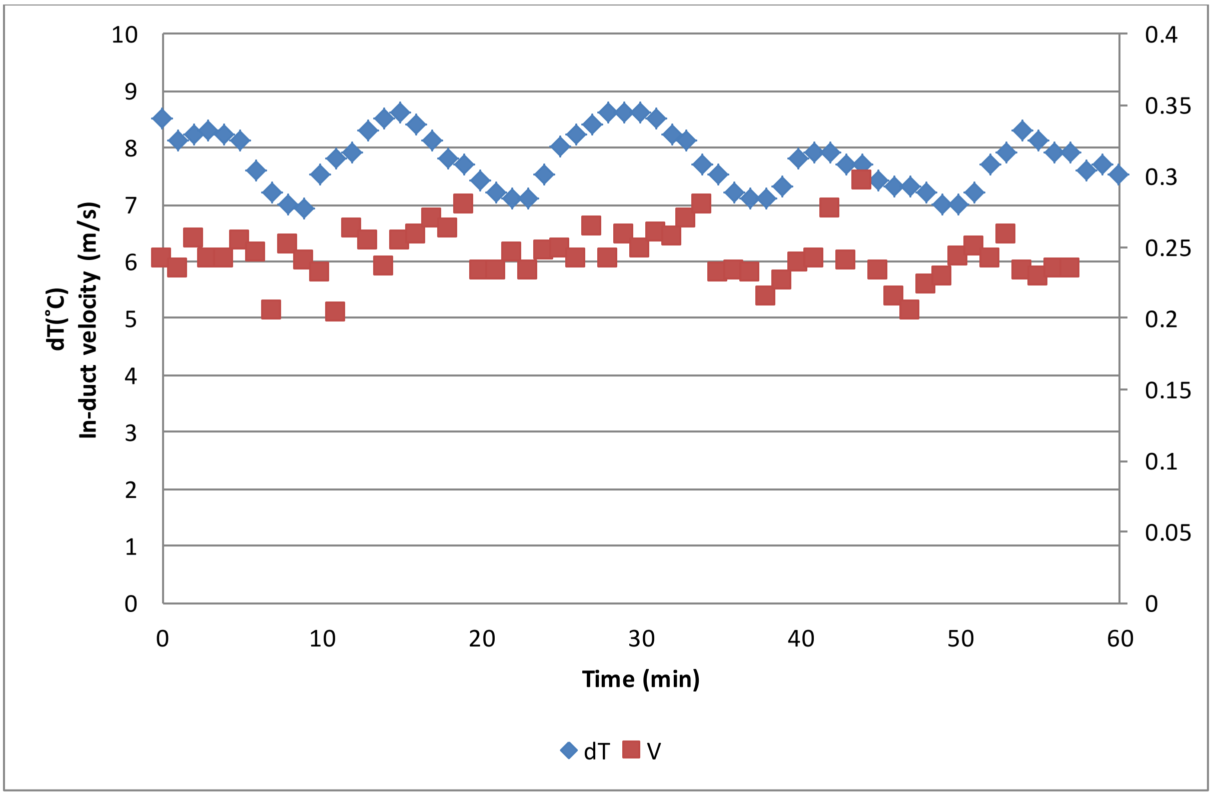


Figure 96: Time-adjusted data for combined wind and buoyancy forces test for v_w of 0.4 m/s

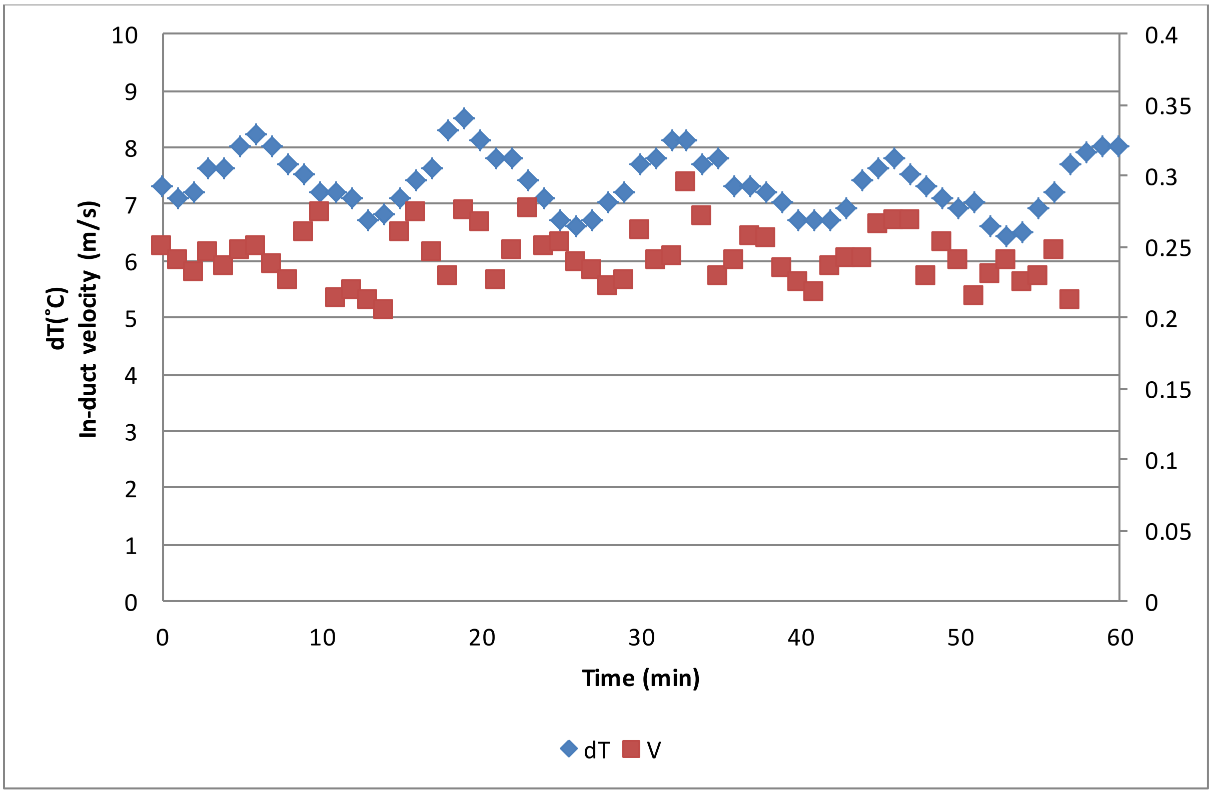


Figure 97: Time-adjusted data for combined wind and buoyancy forces test for v_w of 0.5 m/s

APPENDIX F – Summary of study performed by (Nguyen, Nguyen, & Ha, 2012)

The study of (Nguyen, Nguyen, & Ha, 2012) aimed to assess the ventilation performance of the turbine ventilator, and to compare its performance to a simple vent column and a specially made device which is a combination of the vent column and turbine ventilator, under both wind and buoyancy forces. Their experiments aimed to simulate a practical ventilation scenario of a turbine ventilator placed on top of a building or room, for ventilation. To model the room, a 3000mm X 1500mm X 3000mm room was constructed of wood. An air inlet was provided at one side with dimensions of 800mm X 600mm. Air would be exhausted through the test device. The experimental set-up is shown in Figure 98.

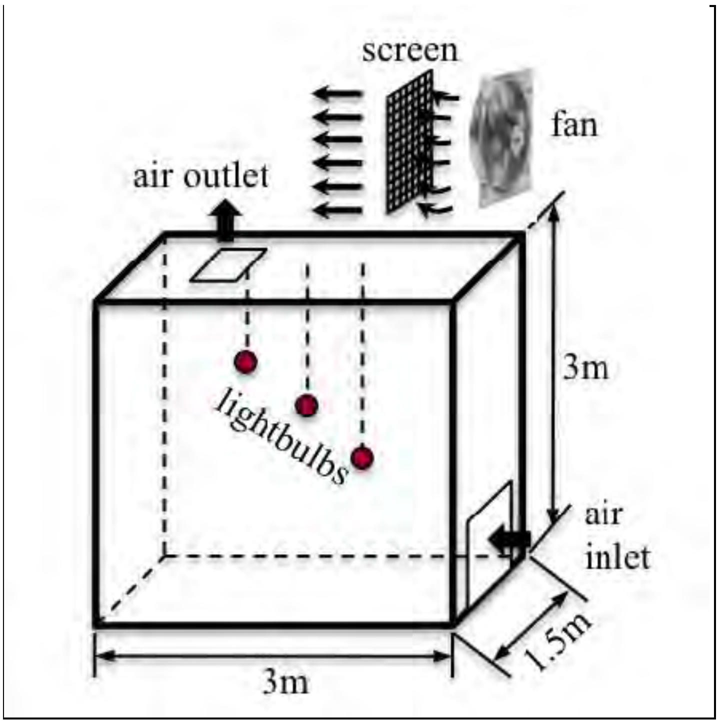


Figure 98: Experimental set-up of (Nguyen, Nguyen, & Ha, 2012)

Wind is simulated using a 400mm 50W diameter electrical fan. The fan was positioned on top of the model room, so that wind would flow over the tested device, but not over the whole façade of the room. A metal screen is placed between the fan and test device to reduce the rotating velocity component of the fan in an attempt to increase the airflow uniformity. The wind speed is adjusted by adding electrical resistances serially to the fan, and/or adding more screens. To create the buoyancy effect, electric light bulbs of 200W each are installed in the central plane on the room. The heat flux was controlled by the number of light bulbs switched on during the experiment. The apparatus is able to produce a maximum wind speed of 3.6 m/s and a maximum heat flux of 3kW, which resulted in a temperature differential of about 15˚C.

(Nguyen, Nguyen, & Ha, 2012) investigated three ventilation devices, one of which was a 300mm spherical turbine ventilator, similar to the 300mm Windmaster Tornado of this research project. The velocity and temperature of the air through the turbine ventilator was measured at the centre of the throat of the device, under three conditions. These conditions include external wind only, internal heat flux only, and a combination of wind and internal heat flux. The external wind speed was measured 200mm in front of the test device. The ambient temperature ranged from 26˚C to 34˚C, and the internal heat of the model room ranged from 26˚C to 50˚C.The results of the airflow through the turbine ventilator under the various test conditions are shown in Figure 99.

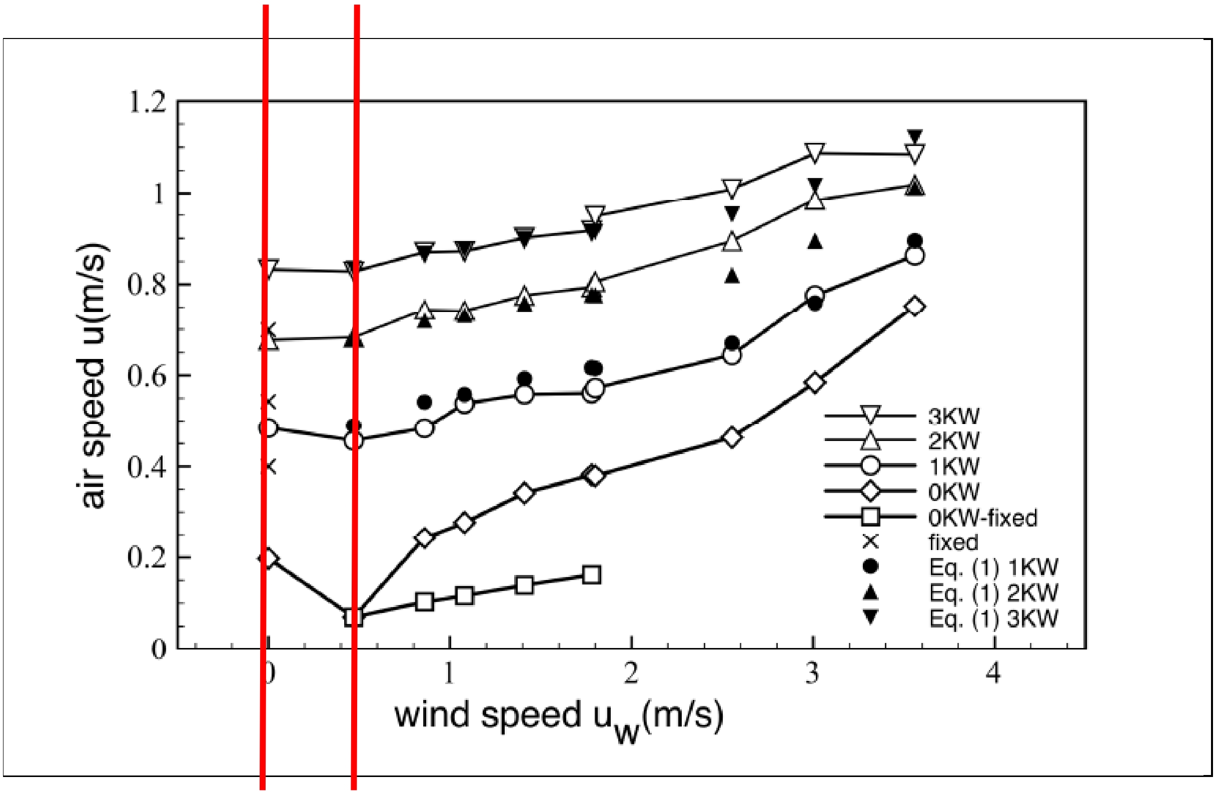


Figure 99: Air speed through the turbine ventilator (Nguyen, Nguyen, & Ha, 2012)

From Figure 99 it can be seen that the airflow through the throat of the turbine ventilator increased with an increase in wind speed (0kW test) and increased with an increase in heat flux. In the 0kW test the turbine ventilator did not rotate at 0m/s and 0.5 m/s. In the cases of heat fluxes (1kW, 2kW and 3kW) and no external wind (0 m/s) the turbine ventilator was able to rotate due to the airflow induced through the turbine ventilator by the internal heat source.

The combined wind and buoyancy effect, show that, for a given heat flux, the airflow through the turbine ventilator increased with an increase in wind speed. A proposed empirical formula to describe the combined effect of wind and buoyancy was given by Walker and Wilson, as presented in (Nguyen, Nguyen, & Ha, 2012) as:

$$u = \sqrt{u_w^2 + u_B^2}$$ **… Equation 22**

Where:

u Velocity through the turbine ventilator due to the combined effect of wind and buoyancy

u_w Velocity through the turbine ventilator due wind effects

u_B Velocity through the turbine ventilator due to buoyancy effects

Equation 22 was used to estimate u for the 1kW, 2kW and 3kW tests for the non-zero wind speeds of u_w of the 0kW test and u_B at 1kW, 2kW and 3kW with zero wind speed. These estimates are also shown on Figure 99. From Figure 99 it appears as though Equation 22 closely approximates the measured data.

The Revision and Resubmission of:

An Investigation into Turbine Ventilators as a Potential Environmental Control Measure to Minimise the Risk of Transmission of TB

Author: Faatiema Salie

Supervisor: Mr Mladen Poluta

Date: 5 March 2014

Contents

1. Introduction

The aim of this document is to formalise the revision and resubmission of the dissertation, ***"An investigation into turbine ventilators as a potential environmental control measure to minimise the risk of transmission of TB"***. The document begins by discussing all the major changes in the revised submission. It then follows with a response to the comments made by the Examiner 1 and Examiner 2. As Examiner 1's comments were quite comprehensive, it is presented first, and where Examiner 1 and Examiner 2's comments are coincident, the response is referred to Examiner 1's comment.

In this revision and resubmission, the following recurring terms are defined:

1. The "Author" refers to myself, Faatiema Salie.
2. The "Examiner" refers to the respective examiner, either Examiner 1 or Examiner 2.
3. The "original dissertation" refers to the first submitted dissertation for examination.
4. The "revised dissertation" revised to the accompanying revised and resubmitted dissertation.

When addressing the comments of the Examiners, some comments made by the examiners were not necessarily critical, but made to provide more information, or in some instances complimentary. In these cases, the response has been "This comment has been acknowledged by the Author. No change has been made."

2. Major Changes

This section provides an overview of the major changes made in the revised submission. Details about these changes, as well as comprehensive detail about these changes, are documented when addressing the Examiner's comments. The following major changes have been made to the dissertation:

1. The content of the dissertation has been narrowed to turbine ventilators only. Subsequently, the title of the dissertation has changed. In the original dissertation, characterising the performance of active wind-driven ventilation techniques was investigated. In the revised dissertation, the focus is now only on turbine ventilators. This changed results in the omission of the literature review related to active wind-driven ventilation devices (Section 2.3.3) in the revised dissertation completely.
2. In the Glossary, primary references have been sourced. This has resulted in some of the definition of terms being streamlined. These terms include Ethambutol, Isoniazid, Pyrazinamide, Quantum and Rifampicin.
3. The presentation of the work of (Escombe et al., 2007) in the literature review has been extended to provide more detail about the physical layout of the experiments, and the statistical analysis of the results.
4. Figure 7 – Operation of a turbine ventilator has been redrawn to show an optimally positioned turbine ventilator.
5. The factors affecting the performance of turbine ventilator, according to the literature, were listed in point form, to highlight each factor. These factors were picked up in the Field Study and Laboratory Experimental protocols to highlight the way in which the literature had influenced the study designs.
6. All graphs of the Field Study results have had their axes changed to be aligned with the reported values for the respective test.
7. The advantages and limitation of air change efficiency and contaminant removal effectiveness are discussed in Section 3.6 Quantifying the ventilation performance of the system.
8. A section on how the field study design compares to previous studies has been added (3.7 How does the field study of this research project differ from previous studies?)
9. The methodology of assessing the natural ventilation system according the questions raised in (WHO, 2009) has been abandoned in the revised dissertation. This has changed the approach presented in the Discussion Chapter of the original dissertation.
10. A discussion of accuracy related to the instrumentation of the field study has been added. This extends to creating Upper and Lower limits for ventilation flow rates.
11. Wind roses for Pretoria have been added to Appendix C, to show the correlation in wind speeds in the field study to available weather data.
12. The limit of detection of the thin film sensors is 0.05 m/s. It cannot detect velocities below this. In the original dissertation, undetectable values were simply set to zero. In the revised dissertation, the undetectable values have been omitted from calculations. In the 0.2 m/s wind speed only test, the data has been presented in point form in Figure 70, as the data was largely discontinuous.

13. A discussion of accuracy related to the instrumentation of the laboratory experiments has been added. This extends to creating Upper and Lower limits for measured in-duct velocities.
14. Dalla Valle predictions for centreline velocities for wind speeds tests in the laboratory experiments have been added.
15. In the buoyancy forces tests and the combined wind and buoyancy forces tests of the laboratory experiments, zero and non-zero data sets were presented at $V_{1.5D}$ in the original dissertation. In the revised dissertation, this has been changed to undetectable and detectable data sets. The undetectable data was then omitted from the calculations.
16. The Discussion Chapter has been revised. In the revised dissertation a discussion of the results, and its relation to previous studies, is presented. In the original dissertation, the Discussion was presented in a response to questions from the (WHO, 2009) assessment of natural ventilation.

3. Addressing the comments of Examiner 1

General Comments: (To be updated once all other sections have been updated)

1	Turbine ventilator vs. active wind-driven ventilation devices vs. turbine. The thesis presents some background information of "active wind-driven ventilation devices;" however, the work focuses on turbine ventilators. Hence, consideration should be given to narrow the title to the actual work that was performed.	The phrase "Active wind-driven ventilation devices" has been removed from the Glossary section and has been replaced several times in the new document with the phrase "Turbine Ventilators": (1) The title (2) The closing paragraph to Section 1.1 (3) The first paragraph of Section 1.2 (4) On two instances in Section 1.3 (5) On six instances in Section 1.4 (6)The closing paragraph of Section 2.2.2 (7) Additionally, the entire Section 2.3.3 has been removed, except for Figure 5. Subsequently, the removal of Figure 6, changes all subsequent Figure numbers. (8) The concluding paragraph of Chapter 2
1.b.	Tuberculosis vs.Tb vs. TB	The term Tuberculosis is introduced in in Section 1.1 and parenthesised to TB. All subsequent "tuberculosis" has been changed to TB. This occurs in the following instances: (1) Paragraph 2 of Section 1.1 . The conversion from Tuberculosis to TB has not been made where tuberculosis is used in the term *M.tuberculosis,* or in any references document, and in the names of the referenced papers in the Reference Chapter. The conversion from Tb to TB is made on several occasions : (1) The definition of Ethambutol in the Glossary (2) On one instance in Section 2.3.2 (3)
1.c.	Global replace "ventialation" with "ventilation" (occurs in several spots)	The reference (Lien & Ahmed, Wind driven ventilation for enhanced indoor air quality, 2011) was the source of the error. Once the source had been corrected, all citations were updated.
1.d.	Definitely need to spell check; I obviously did not find all	The following words have been corrected :

	typos/misspellings (e.g. “rectangular” and “Inddor”)	(1) "Myobacterium" (2) "venitlator" (3)"EnergyPlus" (4)"louvre"
2.a.i.2.a	Need to be consistent!!! Yes, some papers are in SI and some in Imperial units. Makes sense to stick with one or use both. i For example: 1. Referenced paper gives velocity in terms of cm/s a. Simply (and correctly) convert to m/s. 2. Referenced paper gives velocity in terms of fpm a. Simply (and correctly) convert to m/s b. Or take the converted value and parenthetically include the fpm value (“1.5 m/s (300 fpm)”)	The graph of Figure 4 has been converted to l/s/p which was more appropriate to the data presented.
2.b.	Why use ppm for concentration when mg/m^3 is a much more appropriate unit of measurement?	The unit ppm is chosen over mg/m^3 because both references cited in the field study, (REHVA, 2004) and (Nordtest, 1985), of this research project uses ppm. Also, ppm is an easy concept to grasp. It presents the amount of gas as a fraction of air.
3.a.	Significant Figures : Using the above example, I converted 1.5 m/s to 300 fpm. Technically, the calculator gave me 295.27559055 fpm. Why did I round up to 295.3? Well, there are two significant figures in my 1.5 m/s measurement. Therefore, any other use or units should also have no more than two significant figures. Hence, I rounded to 300.	Significant Figures have been addressed in all data sets of the field study and laboratory experiments. The only exception to the significant figure rule has been applied to Table 5, where the presented data corresponds to the figures dialled into the variable speed drive of the fan to deliver the required wind speed.
4.a.	Building selection and design: Was this building used because it was available or was it designed to	The low-income house used in this study was used because it was available. Additionally, the design of this house is the design of a typical low-income house in South Africa. It referred to as the “reference” house in this

	meet some IPC criteria? While mentioned in the beginning, all of the editorial comments that follow ignore the fact that neither the building nor the turbine ventilator design were ideal. SO that the conclusions and comments are not misinterpreted, additional qualifiers should be made throughout the thesis.	dissertation because it is the baseline house at the CSIR Built Environment, to which additions and interventions to improve thermal comfort and energy performance of low-income infrastructure are compared to.
4.b.	From WHO 2009: i. "Three major design elements of natural ventilation ii. Designing natural ventilation requires more than just estimating vent and window sizes – it also requires innovative design and significant attention to detail. Priolo (1998) presented a comprehensive design guideline for natural ventilation. This section gives a brief overview of the three layers of the design process related to natural ventilation design: 1. Site design – building location, layout, building orientation, landscaping; 2. Building design – type of building, building function, building form, envelope, natural ventilation strategy, internal distribution of spaces and functions, thermal mass, heating, ventilation and air-conditioning if it exists; and 3. Vent opening design – position of openings, types of openings, sizing of openings, control strategy."	This information has been incorporated into Section 2.3, immediately after Figure 3: "Designing natural ventilation systems is systematic, and involves a multi-layered approach. These include [(WHO, 2009)refers to (Priolo, 1998): 1. Site design, which extends to building location, site layout, building orientation and landscaping. 2. Building design – The form and function of the building, the building envelope and natural ventilation strategy, thermal mass, heating, ventilation and air-conditioning (if present). 3. Vent opening design – Positioning of openings, type of opening, size of opening, and a control strategy." The discussion is limited in this dissertation, as the work is performed in an existing low-income house.
5.a.	Miscellaneous:	This comment is extensively dealt with in the comments of Chapter 5 – Results of the Field Study.

	Graphs should be meaningful and comparable	
5.b.	Use similar units	All units are now SI units, and data presented in different units to the base units (m/s, m^3/s, etc) are parenthesised.
5.c.	Minimise "dead space" in graphs (for example, if the maximum concentration in a test was 5000 ppm, why go to 10 000 ppm?)	This comment is extensively dealt with in the comments of Chapter 5 – Results of the Field Study.
5.d.	Several places mention inserting a reference	All associated references have been referred to in the revised dissertation. A global search of the dissertation in the end has ensured that this mistake is not repeated in the revised dissertation.

Abstract: (To be updated once all other sections have been updated)

1.	For more detailed discussion of Valle's equation and application, see: Garrison (1981) : Centreline velocity gradients for plain and flanged local exhaust inlets, American Industrial Hygiene Association Journal, 42:10, 739-746	A detailed discussion of Dalla Valle's equation and application is presented in Appendix D.
2.	Buoyancy Theory … The difference in dP between 6.0 and 9.3C would be (To-Ti)/(To+273.15). If To=, then dP=to or a % increase/decrease. So how would this affect volumetric flow rate?	The following text has been added : "The density difference can be calculated from Equation 12 ((CIBSE, 2005): $\Delta\rho_0 = \frac{\rho(T_{out} - T_{\text{int}})}{(T_{out} + 273.15)}$ … **Equation 12** Where: $\Delta\rho_0$ is the pressure difference T_{out} is the outside temperature (of the workshop) T_{ins} is the temperature inside the box

		Using Equation 12, with a temperature of 23°C in the workshop, a temperature differential of 5.5°C, the density difference would be 0.02 kg/m^3. At a temperature differential of 9.3°C, the density difference is 0.04 kg/m^3. It is this resulting density differences which contribute to the fluctuations in wind speed in V_{ID}."
3.	Wind speeds of 0.0-0.5 m/s = 0- _ km/h = 0-_mph (I need to do this to put in perspective with "normal" wind speeds)	The km/h conversion (0.0 – 1.8 km/h) has been parenthesised. The text now reads : "The wind speeds were low, ranging from 0.0 to 0.5 m/s (0.0 to 1.8 km/h), and the temperature differential tested was in the range of 5.5 to 9.3˚C."
4.	ACH is not a direct measurement of ventilation flow rate; however it is sometimes used in this manner, though not preferred.	While ventilation flow rate is presented in ACH in this dissertation, it is also presented in l/s/p in Chapter 5 – The Results of the Field Study.
5.	The first set of ACH data are 0.58, 8.11, 16.9 and 7.49. Can you actually measure or detect 0.01 ACH? Is 0.01 ACH significant? See general comment about significant figures.	All ventilation flow rates (in ACH) are given to one decimal point. The text now reads: "In the field study baseline tests, IL, SS1, CV and SS2 mean – and range of - ventilation flow rates of 0.6 [0.5 – 0.6], 8.1 [6.8 – 9.3], 16.9 [14.7 – 19.0] and 7.4 [7.0 – 7.9] ACH, respectively, were reported."
6.	In reference to the above ACH, the presentation of these data indicate great accuracy (bias and precision) and no variability. In know the sample size is only three (though not stated here), either the range or the 95% CLM (n=3) should be presented.	The range of flow rates for each test has been parenthesised, as in 5 above.
7.	"For given temperature differential, an increase in wind speed resulted in a decrease in in-duct velocity." While this may be true for the narrow set of conditions of the laboratory study, the implication is this is a generalizable comment.	This comment has been incorporated. The text now reads: "The results of the laboratory experiments are specific to the parameters tested, and are not generalizable." Additionally, the following statement concerning the field study tests are also made: "The results of the field study are specific to the environmental conditions at the time of the test, and are not generalizable."
8.	The second-to-last paragraph is a bit confusing to me. What is the expected centreline velocities at 0.5D & 1.5D given the measured centreline velocities? How does this calculation compare to the random	According to Dalla Valle's equation, the centreline velocities are expected to be reduced to 32% of V_{ID} at $V_{0.5D}$, 10% of V_{ID} at V_D and 4.5% of V_{ID} at $V_{1.5D}$. In the wind speed tests, the expected centreline velocities were beyond the limit of detection of the thin film sensors. In the buoyancy forces test, the mean of the

	air currents?	detectable upwards velocities of $V_{1.5D}$ is between 0.06 and 0.08 m/s. The predicted velocity at1.5D is 0.02 m/s which would be undetectable by the thin film sensors.
9.	"This turbulent region suggest that the flow beneath the turbine ventilator under … forces would entrain, rather than exhaust bioaerosols." Why? Could it be as simple as incorrect/improper installation? I believe the results are a result of this particular building design and/or inlet design.	The text has been edited, and now reads: "This turbulent region was again observed in the combined wind and buoyancy forces tests, though the magnitude was smaller and occurrence less frequent." The discussion of entrainment and exhaustion has been abandoned in the revised dissertation as the experiments were not designed to derive these conclusions.
10.a.	I have major problems with the concluding paragraph: "By correlating the field study, laboratory experiments, and … adding a turbine ventilator to natural ventilation system will not reduce the concentration of contaminants in the occupied zone of the room." I agree with this statement if it were modified to say something like "As installed for this particular study" and "these results are not generalizable.	The paragraph has been edited, and now reads: "By correlating the field study, laboratory experiments, and previous (similar) studies, it was concluded, that, under the tested conditions, adding a turbine ventilator as a supplement to natural ventilation system will not reduce the concentration of contaminants in the occupied zone in a room. "
10.b.	"The upper-room was found to be ventilated by the turbine ventilator and the lower room according to the natural configuration. What is the "boundary" between upper and lower? While this may be true for this particular installation, if it had been installed as part of a system, it would have gotten different results.	The boundary cannot be established as the tests were not designed to make this deduction. This sentence has been removed.
10.c.	"The turbine ventilator did not produce a suction force strong enough to encourage air from the occupied zone in the room to be drawn to or through the turbine ventilator." How does one "encourage" air to move? The issue is creating a pressure gradient (you mention this later). How much "suction" or resistance" can a turbine ventilator overcome without	This sentence has been removed. The presentation of this sentence in the Abstract was inferred from the Discussion chapter. Specific Comment 39.d.xix (below) discusses this comment.

	a large drop in airflow rate? Hint: Think fan curves! Finally, the turbine ventilator was doomed for failure as it was installed as part of a system.	

Glossary:

1.	Need clarification of the "active wind driven ventilation device" definition. Why? Because density differences ARE pressure differences!!!	The definition has been removed as the title (and context) of the revised dissertation has been updated.
2.	Ideally, you should always use primary references for definitions and not secondary (reviews and guidelines)	The following definitions have been updated to reflect primary references: (i) Droplet nuclei - Particles one to ten μm in diameter, implicated in the spread of airborne infection; the dried residue formed by evaporation of droplets coughed or sneezed into the atmosphere or by aerosolisation of infective material (Medical Dictionary); (ii) Ethambutol - An antibacterial drug used in combination with other drugs, in the treatment of pulmonary TB (The American Heritage Medical Dictionary, 2007); (iii) Infiltration - The unintentional or accidental entry of air into a building (ASHRAE, 2007); (iv) Isoniazid - An antibacterial compound used in the treatment of TB (Miller-Keane Encyclopaedia and Dictionary of Medicine, Nursing and Allied Heath, 2003); (v) Pyrazinimide - An antibacterial, derived from nicotinic acid, used in the treatment of TB (Miller-Keane Encyclopaedia and Dictionary of Medicine, Nursing and Allied Heath, 2003); (vi) Quantum - A quantity or an amount (The American Heritage Medical Dictionary, 2007); and (vii) Rifampicin - A derivative of rifamycin which is an antibacterial and antifungal agent used in the treatment of mycobacterial infection, actinomycosis and histoplasmosis (Saunders Comprehensive Veterinary Dictionary 3rd Edition, 2007).

Specific Comments:

1.a.	Need a reference for XDR TB in the first paragraph	The original dissertation refers to (CDC, 2006) as a reference.
1.b.	Have you requested permission from the author/journal to use the photo in Figure (as well as a few other subsequent figures)?	In consulting the Department of Biomedical Engineering, the following response, originally attributed to the Registrar of the Doctoral and Master's Committee, has been presented here: "Reproducing other peoples work and attributing it is not plagiarism; reproducing other people's work that is subject to copyright may or may not infringe copyright; it may well fall into the fair use category which copyright law allows. "Using figures without adaptation while making it clear where it came from, i.e. with the references being cited". This is not plagiarism. It is acceptable practice, and it stands in sharp contrast to what is sometimes found (namely the use of another's figure, adapted to disguise the fact an without attribution) which is plagiarism an is unacceptable. Limited use of such figures, with attribution, in a dissertation will fall within the fair use provisions even if the work is under copyright; what constitutes acceptable limited use is not easily defined. Where in doubt the author(s) can be applied to for permission to reproduce. "
1.c.	"When compared to mechanical ventilation, natural ventilation generally offers higher ventilation rates for little or no (running) cost, and is free of maintenance (Escombe et al)". This statement is NOT true as written. A well-designed, simple natural ventilation system may offer higher ventilation rates; however, there ARE maintenance and operation issues. Are the windows open? can they open? Is the climate amenable to natural ventilation 24/7/365?	The text has been changed to : "When compared to mechanical ventilation, natural ventilation generally offers higher ventilation rates, however, in many cases the efficacy of the natural ventilation system is dependent on an amenable climate, openings on the façade, and on the user (i.e. the day to day opening of windows and doors)."

2.a.	Why "active wind-driven ventilation devices" and not "turbine ventilators" in the actual hypothesis?	The text has been changed to : "Turbine ventilators are able to reduce the concentrations of particles of specified mass and size from a room, within specified performance parameters."
2.b.	While I agree with the qualifying statement ("If this statement is to hold true, it should be in the worst case scenario too."), this and the fact that the turbine ventilators are not designed/installed as part of a system led to the rejection of the hypothesis. Also, the design of the wind-driven (horizontal) natural ventilation aspect of the "reference house" was good (not perfect); however you are comparing a good design with a condition of poor design (addition of the turbine ventilator).	The performance of the turbine ventilator is tested at the lower end of the performance scale in the field study and laboratory tests. While the turbine ventilator was added as a supplement to natural ventilation, the field study design considered separating/isolating the infectious patient, and the potentially contaminated air from reaching the rest of the house. This is an important administrative control measure. The addition of a turbine ventilator to either increase the ventilation flow rate, or change the resulting airflow pattern in the room, was investigated in the field study. No change has been made here.
3.a.	Throughout the document the terms "quanta" and "quantum" are not used in a consistent manner.	Refer to Specific Comment 3.b. below
3.b.	1 quantum does not equal 1 M.Tuberculosis bacillus does not equal 1 droplet nucleus. A quantum is a probability function (Poisson) of an infectious dose.	The original dissertation describes the use of the word quantum. The text (Section 2.1) in the original dissertation reads : "In 1955, Wells developed the concept of a "quantum". A "quantum" represents the required dosage of a pathogen needed to cause infection. It is based on Poisson's Law of small chances, where a "quantum" is the average number of microorganisms needed to infect approximately 63% of susceptible individuals (Nardell & Macher, 1999)." In this research project, the term quanta means many/more than one quantum. The term quanta is only used in Section 2.3.2, where it reflects the plural of the definition described here.
4.a.	An additional benefit of environmental controls is the containment (physical structure or negative pressure differential) or protection (physical structure or positive pressure differential)	A third broad stream has been added: "3. Control measures which contain pathogens to a space. An example would be negatively pressurised airborne infection isolation rooms."

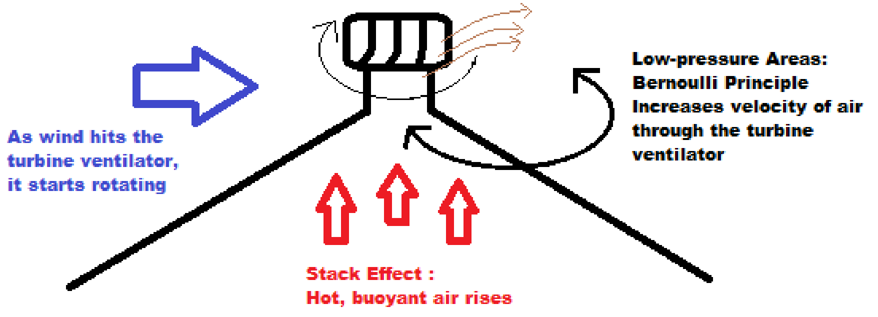
5.a.	WHO 1999 is not a primary reference	(WHO, 1999) is used in two instances in this section. In the first instance, the WHO reference has been replaced by consulting the "3M Health Care Particulate Respirator and Surgical Mask" guide. In the second instance, the reference has been omitted and changed as in Specific Comment 5.b. below.
5.b.	"The use of a surgical face mask does not protect healthcare workers…". Suggest "does not significantly protect" or some other waffle wording. There are now published data showing that there may be up to 50% for droplet nuclei-sized particles.	The text now reads: "The use of a surgical face mask does not significantly protect healthcare workers, patients or visitors against TB infection, however, it can be worn by TB patients to reduce the number of aerosolised TB particles in the room (OSHA, 2009)."
6.a.	Buoyancy forces ARE pressure forces	The phrase "wind pressure" has been changed to "wind".
6.b.	Figure 2 … Permission?	Refer to Specific Comment 1.b.
7.a.	The purpose of WHO 2009 was two- fold: (i) "to promote natural ventilation design for infection control in health care (part 1); and" (ii) "to describe the basic principles of how to design, construct, operate and maintain an effective natural ventilation system for infection control (Part 2)."	The original text: "This document provides broad design guidelines for architects, engineers and clinicians involved in the design and construction of health-care facilities. It also provides details about the rationale for specifying these guidelines. This section provides details about the specifications made in these guidelines, as well as the science behind these specifications." has been replaced with "The document is divided into two parts. Part 1 promotes the natural ventilation design for infection prevention and control in healthcare facilities. Part 2, describes the basic principles of natural ventilation systems to design, construct, operate and maintain an effective natural ventilation system."

7.b.	The CDC 2005 guidelines were preceded by the CDC 1994 guidelines. The "change" occurred in 1994; hence, facilities built (or had major renovations) after October 28, 1994 should comply with the 12 ACH recommendation. The "2001" was to align the 2005 guidelines with the change in recommendation of the AIA. This is a very minor point and made more as an FYI.	While the examiner notes the "This is a very minor point and made more as an FYI", the point has been noted in the new text, as the point raised by the examiner provides more clarity. The text of the original dissertation: "Guidelines released prior to (WHO, 2009) set the minimum ventilation rate to 12 ACH for airborne infectious isolation rooms in healthcare facilities built post 2001, and a minimum ventilation rate of 6 ACH for airborne isolation rooms built pre-2001 (CDC, 2005). This guideline is extracted from (CDC, 2005), and applies to airborne infectious isolation rooms which are maintained at negative pressure relative to adjacent rooms." is replaced with : "The (CDC, 2005) guidelines replaces the (CDC, 1994) guidelines, in which the minimum ventilation rate for airborne infectious isolation rooms are set to 12 ACH. Facilities built, or majorly renovated, post (CDC, 1994) were to comply with a minimum ventilation rate of 12 ACH, and facilities built prior to (CDC, 1994) were to comply with a minimum ventilation rate of 6 ACH. "
7.c.	The third rationale for 12 ACH was not clearly stated … It's based on feasibility and economics	Section 2.3.2 discusses the (WHO, 2009) guidelines on Natural Ventilation for Infection Control. These guidelines explicitly mention that the rationale for 12 ACH is based on TWO main aspects. Those aspects are discussed in Section 2.3.2.
7.d.i.	Escombe used MEDIAN and not MEAN!	The term "mean" has been changed to "median" on two instances in Section 2.3.2
7.d.ii.	The "modern" facilities were built 1970-1990 (not 1970-1900)	1970-1900 has been changed to 1970-1990

7.d.iii.	The discussion here as well as in Escombe 2007 is a bit misleading. For example, there is a difference in volume of the rooms for modern vs. old-fashioned buildings. For instance, the median volumetric flow rates were 1,174 and 3,769 m3/h respectively. Is the difference due to size of the openings? Is the difference due to orientation of the building?	The objective of (Escombe, 2007) was to investigate the rates, determinants, and effects of natural ventilation in health care facilities. Natural ventilation was evaluated by certain architectural and environmental features, including, open windows and doors, presence of open windows or doors on opposite walls to facilitate cross-ventilation, ceiling height, floor area, elevation of room above ground level, temperature, relative humidity, and wind speed. (Escombe, 2007) performed a large number of tests. The data of all these tests were pooled, and assessed statistically. In this method of assessment, it is difficult to assess the performance of each room configuration/situation, i.e. it is difficult to assess how each room performed under a specific wind speed for a specific openable area (windows and door fully or partially opened) of that room. While (Escombe, 2007) mentions that 80% of the experiments performed all of the naturally ventilated room experienced some degree of cross-ventilation, this was the only indicator to assess the position of a room and its windows in relation to the prevailing wind. The following text has been added : "Statistically, (Escombe, et al., 2007) found the driving determinants of natural ventilation to be the area of openable windows and doors, placement of windows on opposite walls (cross ventilation), floor area and wind speed at the window. The significant difference in median volumetric airflow rates between modern and old-fashioned volumetric flow rate can therefore not be explicitly contributed to openable area to the room. The orientation of the building, and the position of respective room in that building, also plays a role."
7.d.iv.	See 3.3.1 of WHO 2009. The 12 ACH was equated to 80 l/s (260 m^3/h) for a 4x2x3m patient room (i.e. 8m^2/patient in an "old fashioned" room with a 3m ceiling). The recommendation is a minimum of 80 l/s/patient (260 m^3/h) with an hourly averaged ventilation rate of 160 l/s/patient (580 m^3/h). Both the old-fashioned and the modern facilities met the minimum volumetric airflow rates IF there was at least 8m2/patient.	This comment has provided clarity when considering the patient loading comment of 7.d.vi. However, no change has been added to the text.

7.d.v.	Most sections in this thesis use m^3/s ... Constantly changing units in the thesis (mainly because the referenced and other documents used other units) is confusing and probably does not meet University requirements. Generally, one would convert to a consistent unit and put the original author's #s & units in parenthesis.	All values which were given in m^3/h have been converted to m^3/s, and the m^3/h values have been parenthesised.
7.d.vi	What was the relative volume of old-fashioned vs modern facilities (m3/m3)? What was the patient loading of old-fashioned vs modern facilities (m3/patient; m2/patient)?	The relative volume and patient loading of old-fashioned and modern naturally ventilated buildings have been added to the text. The following text has been added to Section 2.3.2: "Compared to modern naturally ventilated building, old-fashioned naturally ventilated buildings were larger (85m^3 vs. 60m^3), had higher ceilings (4.2m vs 3.0m), had bigger windows (6.6m^2 vs. 3.4m^2), and were more likely to have windows and doors on opposite walls (56% of rooms vs. 19% of rooms)." AND: "The patient loading (floor area per patient) for old-fashioned and modern natural ventilated buildings was 9.2m^2 vs. 9.3m^2, respectively."
7.d.vii.	Add Levin's correspondence to PLOS Medicine regarding Escombe 2007	Levin's correspondence highlights three key points. The first is that ventilation through an open window is a function of window size, number, and location in a room as modified by indoor-outdoor temperature differences and wind direction and velocity. The following text has been added : "The significant difference in median volumetric airflow rates between modern and old-fashioned volumetric flow rate can therefore not be explicitly contributed to openable area to the room. The orientation of the building, and the position of respective room in that building, also plays a role. A response by (Levin, 2007) to (Escombe, et al., 2007) points out that the ventilation rate through windows is a function of the window size, the number and location of windows, and the indoor-outdoor temperature differences and the wind velocity." The second point is that the ventilation rates were measured and that infection rates were CALCULATED. The term "calculated" has been added in two places in Section 2.3.2. The text now reads:

		"Using the Wells-Riley model (Equation 1), under the assumption of 24 hour exposure, and 13 quanta of infectious agents per infectious TB patient, the calculated median estimated risk of TB transmission was 97% for all naturally ventilated facilities with windows and doors closed. The patient loading (floor area per patient) for old-fashioned and modern natural ventilated buildings was 9.2m^2 vs. 9.3m^2, respectively. The calculated median estimated risk of TB transmission was, with all windows and doors opened, 33% in modern naturally ventilated facilities and 11% in old-fashioned naturally ventilated facilities." The third point is that the results presented in (Escombe,2007) cannot be generalised. The following text has been added : "The results and discussion presented here of (Escombe, et al., 2007) are specific to the study conducted in Lima, Peru, and are not generalizable (Levin, 2007)."
7.d.viii.	How might Escombe's and your conclusions change if volumetric airflow rates and air exchange rates were normalised?	In (Escombe, 2007), the results for ventilation flow rate and wind speed were significantly skewed, and median data was presented in quartiles of wind speed. (Escombe, 2007) was able to establish the determinants of natural ventilation based on the parameters which became statistically significant. The number of experiments was large, and good confidence intervals were achieved. However, (Levin, 2007) still highlights that the results are not generalizable. In the field study of this research project, only three tests per configuration were tested, and results in trends and observation under the specific environmental conditions, are reported and discussed. The number of tests does not allow for confident, generalizable statements to be made. Normalising volumetric flow rates would not add value here. The cannot exclusively say that it would have added value to (Escombe, 2007) as the results presented in (Escombe, 2007) were statistically significant.
8.a.	"These devices may rely on wind or buoyancy forces." Should this be "and/or" as opposed to "or"?	As the content of the dissertation has been changed from "Active wind-driven ventilation devices" to "Turbine ventilators", the entire section 2.3.3 has been removed
9.a.	Figure 7 shows a poor installation design	The Figure has been redrawn to illustrate the correct installation:

		 Figure 6: Operation of a turbine ventilator, adapted from (How it Works)
9.b.	Figures 10 & 11 clearly show the point about the Fan Laws. Would be nice if simple regression was performed on the variants. Since some overlap, the data might be best given in a table. This could also include r^2 as well as ratio/slope. Should use consistent units. Wind velocity is given in m/s and volumetric airflow rate is given in m^3/s in most sections of the thesis.	The axes of Figure 10 have been changed to m/s on the x-axis and m^3/s on the y-axis. Since overlapping only occurs in the 250 mm straight vane turbine ventilators, the data has been kept as a graph. The author feels that the graph best presents the relationship displayed in turbine ventilators of the same size. The data previously presented in Figure 11 had been extracted from a table in (Khan et al, 2008). Figure 11 has been removed, and the table has been inserted. The table includes a column of percentage difference between the measured and calculated values.
9.c.	So, what's the significance of the info from Figures 10 & 11? Is there a reason for presenting this? Did you measure RPM along with volumetric airflow rate?	Section 2.4 provides details about previous studies performed on turbine ventilators. The information presented in Figure 10 compare the performance of different size and types of turbine ventilators under increasing wind speeds. Figure 11 presents measured and calculated data, and shows that the turbine ventilator appears to follow fan law. While this may not be relevant to the study of this dissertation, it is presented here to show that this theory exists. In the study of this dissertation, RPM was not measured.
9.d.i.	So, how does it relate to your work? Most of their work was at 10 m/s (20+ times the test conditions of the experiment presented in the thesis) See Figures 15-17.	The work of (Lien and Ahmed, 2011) was one of the very few scientific studies available at the onset of the experimental phase of this dissertation, and provided some guidance in the laboratory experimental phase. From Figure 15, the decision to test the turbine ventilator on a flat surface was derived, and from Figures 16 and 17 (along with Figures 7 and 8), airflow through and around the turbine ventilator is more

		clearly understood. The work is presented here because it is a viable source of information.
9.d.ii.	Again, a lot of figures were cut-and-pasted from the reference without clear indication of permission.	Refer to 1.b.
9.d.iii	What are the manufacturer's recommendations for installation. Seems that the Lien and Ahmed 2011 chapter is an academic evaluation. Is it reasonable to have the turbine ventilator below the apex of the roof?	The manufacturer, Windmaster (www.windmaster.co.za) provides installation instructional videos for tiled and zinc roof installations. In their installation instructions, the manufacturer does not mention that the turbine ventilator should be installed above the apex of the roof. However, the installation videos always show the turbine ventilator to be exposed above the apex of the roof. It would be inefficient to install the turbine ventilator below the apex of a roof as the turbine ventilator would not be exposed to the maximum available wind.
9.d.iv.	Conclusion implies that 4 m/s (for the roof inclination study) is a low velocity; however, is 4m/s really low? The conditions in the thesis are much lower than 4 m/s. Is it reasonable to extrapolate?	The Author assumes this comment is related to the text : "From Figure 14 it can be seen that this point is more noticeable at higher wind speeds, suggesting that the roof inclination angle has little effect of the total mass flow extracted by the turbine ventilator at low wind speeds." This has been concluded in the study by (Lien and Ahmed, 2011) as 4 m/s was at the lower end of their experimental range. At this point, no extrapolation is made, merely a presentation of Lien and Ahmed's conclusions.
9.d.v.	Figure 18 actually shows a poor installation of a turbine	The author agrees with this statement; however, this is the way it had been installed at the facility and is presented here for illustrative purposes only.
9.e.	Page 28 … Reference missing on second sentence	The square brackets ([]) have been removed. The intended reference was (WHO,2009).
9.f.i.	10.1 km/h = 2.8 m/s	This conversion has been made and the 10.1 km/h has been parenthesised

9.f.ii.	Figure 19 … Without reading the original paper, Q1, Q2, Q3 & Q4 are meaningless	The values of Q1, Q2, Q3 and Q4 are never explicitly given in (Cox, 2012). However, the median and interquartile range (IQR) is given, and Q1, Q2, Q3 and Q4 can be calculated. The following text has been added: "The ventilation flow rate and wind speed data of all four rooms were pooled, and assessed in terms of quartiles of wind speeds [Q1 : 0.28 – 1.90 m/s (1.0 -6.8 km/h); Q2 : 1.90 – 2.81 m/s (6.8 – 10.1 km/h); Q3 : 2.81 – 3.72 m/s (10.1 – 13.4 km/h) and Q4 : 3.72 – 13.90 m/s (13.4 – 50.0 km/h)], as presented in Figure 17."
9.f.iii.	Table 2. Print is very small. Recommend larger font. What does IQR stand for?	The table has been enlarged. The text is now more legible. IQR stands for inter-quartile range
9.g	Page 31, 1st paragraph … I previously discussed this with Helen. Is a balometer/airflow capture hood appropriate for such measurements? What effect will the balometer have on the airflow rate through a wind turbine? Have you ever seen a "fan curve" for a wind turbine?	The author does not believe that the balometer/airflow capture hood is appropriate for the measurements of (Cox et al, 2012) as it significantly affects the airflow pattern in the room. The presentation of the work by (Cox et al, 2012) is not an endorsement of the methodology, but merely a presentation of the manner in which the experiments were performed. This point is highlighted in a new section, Section 3.7 How does the field study of this research project differ from previous studies? The author has not seen a "fan curve" for a turbine ventilator from a manufacturer of a turbine ventilator.
9.h.	Page 31, 1st paragraph …"These measurements … the mean ventilation flow rate through the turbine ventilator was 71% in room 1, …" I do not understand this sentence. Isn't this 71% the fraction of total estimated airflow that goes through the wind turbine?	The Examiner's understanding is correct. The sentence has been changed to : "From Table 2 it can be seen that the fraction of the total estimated mean ventilation flow rate through the turbine ventilator was 71% in room 1, 61% in room 2, 49% in room 3 and 40% in room 4, and 58% for all rooms combined."
9.i.	Page 31, 2nd paragraph … One missing but critical parameter is the location of the wind turbine relative to the peak or highest point of the building/roof.	This parameter has been added. Furthermore, the second and third paragraphs have been morphed to conclude this Chapter and present the following chapters. The text now reads: "In this chapter, airborne infection control to minimise the risk of transmission of airborne pathogens was discussed. Dilution, via natural ventilation, was considered as an environmental control measure, the aim

		of which is to reduce the number of airborne pathogens, thereby minimising the risk of airborne transmission. The limitations of natural ventilation were discussed, and turbine ventilators were presented as a potential solution to increase the ventilation rate and compromise control of internal airflow in buildings. From the literature discussed in this section, the factors affecting the performance of turbine ventilators are: 1. The presence of wind and buoyancy forces 2. The shape of turbine ventilator blades 3. The diameter of the turbine ventilator 4. Roof inclination angle 5. Location of the turbine ventilator relative to the apex of the roof 6. Openings in the room In the following chapters, the performance of the turbine ventilator will be investigated in a Field Study and Laboratory Experiments.”
10.a	Need to define "air change efficiency"	A definition for "air change efficiency" has been added to the glossary: Air Change Efficiency - A rating given to a ventilation system to express how efficient the ventilation system is at replenishing exhausted air with fresh/cleaner air.
11.a.	Are the cement blocks solid, hollow, or insulated?	The cement blocks are solid, and this has been included in the text : "The external walls are made of 140 mm solid cement block, and the internal walls of 90 mm solid cement block"
11.b.	Figure 22 … Suggest adding the location of the wind turbine	The location of the turbine ventilator has been included in Figure 25, in Section 3.4, which deals with the field study design. This has not been added to Figure 20 (previously Figure 22) as the baseline tests were performed in the reference house before the turbine ventilator was installed.

11.c.	Figure 23 (or somewhere in the text) ... What are the prevailing winds?	The prevailing winds at the test site were from the north east. This has been included in the paragraph following Figure 21 (previously Figure 23) : "The prevailing winds at the test site were from the North Eastern direction." Additionally, wind roses for Pretoria have been included in Appendix C.
11.d.	Page 37, 1st paragraph ... How does radiant heat affect air temperature? Figure 24 basically shows the difference between the gain of radiant energy ("Reference House") vs insulation or "blocking" of radiant in the "Well Insulated House"? How does radiant heat gain contribute to stratification of air temperature? What would the effect of a mixing fan be? Also, where was the "indoor temperature" taken? Was there significant horizontal and vertical variability? Could you give a range of measurements?	In (Osburn, 2010), no indication is given where temperature is measured. Osburn does however speak of the habitable zone and the zone between the roof and ceiling (in the insulated house). It is the author's deduction that the measurements are taken in the habitable zone, however, the exact location is not known. The discussion presented about (Osburn, 2010) is about the work presented in (Osburn, 2010). The questions raised by the examiner are beyond those detailed in (Osburn, 2010). The point the Author is trying to make by presenting the work of (Osburn, 2010) is that the thermal performance of the low-income house is considered to be very weak, i.e. high gains in summer, and low gains in winter.
11.e.	Page 38, 2nd paragraph ... The last sentence is not supported by data and does not take into account radiant heat gain or heat gain due to what may be generated in the house. Because this is really a heat balance issue, either a large discussion of heat balance should be made here or this sentence deleted.	The Author agrees with the comment of the Examiner, and the sentence has been deleted.
12.a.	Page 38 ... "The data from these tests can be used to calculate the ..." While literally true, the test is an estimate of the average decay in one location and the ventilation flow rate, MAA, and air change efficiency are estimated and only apply to that one location under those specific conditions.	The text has been edited to accommodate the points raised by the Examiner, and now reads : "The data from these tests reflect the decay due to the ventilation strategy at those specific points in the room. These points are then used to calculate the ventilation flow rate, mean age of air (MAA) and air change efficiency of the ventilation systems. The results are specific to the test conditions."
12.b.	Page 39, last paragraph ... Suggest adding "Historically" to the beginning of the first sentence. CO2 is a very common tracer gas and has been for at	The last paragraph now reads : "Historically, the most commonly used tracer gases were Nitrous Oxide (N_2O) and Sulphur Hexafluoride

	least 10 years ... I've used it for over 20 years.	(SF_6) (REHVA, 2004). Carbon Dioxide (CO_2) may be used if the background concentration is constant (REHVA, 2004). The tracer gas used in this field study was CO_2. "
12.c.	Table 3 ... Suggest adding a row with the properties of air. Since one of the recommendations is similar density, it would be nice to show readers the data.	The air density of Pretoria is presented as 1.02 kg/m3.
12.d.	Figure 26 ... Please note safety issue of unsupported CO2 bottle	A fine print has been added to the caption of Figure 24 (previously Figure 26) : "***Please note that the cylinder of CO_2 in Figure 26 is for illustrative purposes. Cylinders of CO2 must always be secured and supported, as in Figure 27 (right)."
12.e.	Page 41 ... Perhaps this is covered later. Yes, the probe is directional. Did you line it up parallel to the wind?	The probe was not lined up parallel to the wind, as wind speed and direction varies. The sensor was positioned as described in Section 3.4.3.
13.a.	"By introducing the turbine ventilator into the bedroom, the bedroom should, in theory, be at negative pressure relative to the adjacent rooms and hallways, ..." While on the surface this appears to be a true statement, we must remember that pressure differential is a function of both airflow rate and leakage area. So, if there were NO wind, there would be NO pressure differential with a door and/or window open.	The Author does not completely agree with this comment. The turbine ventilator may be driven with a pressure differential developed by buoyancy. This is evident in the laboratory phase of this dissertation.
13.b.	Since the wind turbine was located in the smaller bedroom (#2), were the indoor temperature measurements also taken in bedroom #2?	Yes. This is mentioned in Section 3.4.3 in the original dissertation.
13.c.	Figure 27 ... Is the entire turbine above the peak of the roof? How much above the roof? Do/will the trees block the prevailing wind?	Figure 25 (previously Figure 27) clearly shows that the turbine of the turbine ventilator is positioned entirely above the peak of the roof. The presence of trees will impede the prevailing wind, however, it did not completely block wind at the turbine ventilator. In all tests of the field study, save one, the turbine ventilator was rotating due to the wind.
14.a.	Table 4 ... Are the temperature measurements "dry bulb" measurements? Would WBGT be more appropriate?	The temperature measurements are dry bulb measurements. While WBGT would be a more appropriate measurement, the SENTRY ST372 was to serve as both the temperature and velocity measuring device,

		and does not measure global thermometer temperature for the WBGT deduction. The temperatures in Table 4 have dry bulb parenthesised to clearly indicate that the temperatures were dry bulb temperature measurements.
14.b.	Page 43, 1st paragraph … Why standing height? Why not sitting height? Need a sentence on rationale for sampling location. The base of the turbine ventilator is a commonly used sample location; however I am not certain how to interpret or apply those data.	Standing height was chosen over sitting height (1.1m) for two reasons. Standing height is closer to the geometric centre point of the room, and may therefore be more representative of the room. The standing height sampling point lies between the windows, doors and turbine ventilator, and may capture the air from the room through the turbine ventilator better. The following text has been added: "The criterion of standing height was selected over sitting height (1.1m above the ground) for two reasons. The first is that standing height was closer to the geometric centre of the room vertically, and may be more representative of the room. The second reason is due to the potential separation of flow streams in the room, the standing height may favour the flow between the window/door and the turbine ventilator." Concerning point B, the following has been added to provide clarity: "As the infrared sensors require air to pass through the sensor to measure the concentration, this sensor is positioned at the base of the turbine ventilator where air flows across the sensor into the turbine ventilator."
14.c.	Page 43, last paragraph … Suggest adding ", shown in Figure 27" at the end of the first sentence.	The change has been made as recommended by the Examiner.
14.d.	Page 44, top of page … I do not understand the rationale for the wind speed location and method. What is the prevailing wind? The wind speed AT the wind turbine is independent of direction. The orientation of the prevailing wind to the openings of the building/house IS critical and we are interested in the maximum wind speed. The anemometer probe	The rationale for the wind speed location was to find a position on the test site in which wind had been developed without much interference from other houses/constructions at the test site. This can be seen in Figure 27. The prevailing wind is from the North East, however, wind speed and direction change, especially considering that some of these tests ran for up to two hours. The probe was not aligned to this prevailing wind direction. Additionally, the probe was directional, and was positioned to measure the

	should be aligned. How did the trees and other buildings affect the wind veloity at the houses? Do you have similar information for the Well Insulated House for comparison in the earlier section.	component of wind which would most influence ventilation in the house (in the absence of the turbine ventilator). The trees do serve as interference, thereby reducing the measured wind speed. The well-insulated house presented earlier in Osburn 2010 was a simulation, which used a Johannesburg climate file, made available through United States Department of Energy.
15.a.	Page 44, bottom of page … Please describe "flow ribbon"	The following text has been added to provide clarity : " A flow ribbon essentially serves the same purpose as a smoke tube. The flow ribbons used in this research project were made of tissue paper, and were each approximately 10mm x 150mm."
15.b.	Figure 30 … How will the window design affect efficiency of airflow into the reference house? This is NOT the ideal window!	A better description of the windows has been added to Section 3.2.2. The following text concerning windows now appear : "Windows are located on the northern and southern facades, and doors on the southern and western facades. The windows of the reference house are not efficient in delivering the maximum available air for natural ventilation to all areas of the house. The windows of bedroom 1 and 2, and the living room and kitchen are side-hung windows which open to the outside. The window in the bathroom is a top-hung window which also opens to the outside. The openable window area on the northern façade is 1.92 m^2, and 1.62 m^2 on the southern façade. Openable window area is an important parameter because it is directly related to the amount of air which can enter and leave the house. Side-hung and top-hung windows greatly reduce the effective openable area of windows."
16.a.	Figure 31 … Looks like the door to bedroom 1 was open and the kitchen door was closed.	The paragraph following Figure 28 highlights this point. It reads : "In all tests, the doors on the northern and western facades of the reference house were closed, and the doors of bedroom 1 and the bathroom were open."
16.b.	Figure 32 … Looks like the door to bedroom 1 was open and the kitchen door was closed.	See Specific Comment 16.a.
16.c.	Page 47, outcome 1 … With an open window on the windward side, the room will most likely be at greater pressure than the rest of the house.	Outcome 1 has been changed to : "1. If bedroom 2's window was on the windward side of the house, air would flow through the window,

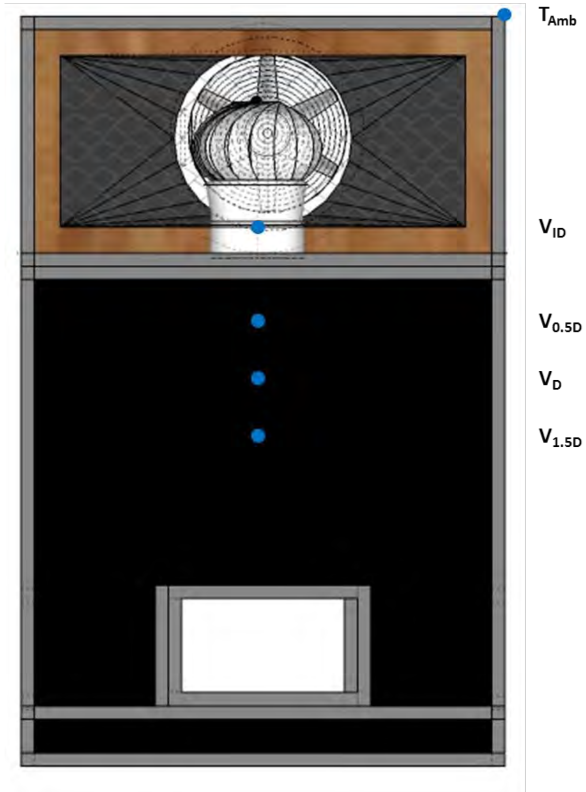
		and bedroom 2 would most likely be at greater pressure relative to the rest of the house. Air would be exhausted via the turbine ventilator."
16.d.	Page 47, outcome 2 … Plausible	The Author acknowledges this comment. No change has been made.
16.e.	Page 47, outcome 3…. Plausible	The Author acknowledges this comment. No change has been made.
17.a.	Page 47 … Add "All interior doors were opened".	The following text has been added : "All interior doors were opened"
17.b.	Page 48, outcome 1 … Plausible, but highly dependent on wind speed.	The Author acknowledges this comment. No change has been made.
17.c.	Page 48, outcome 12… Plausible, but highly dependent on wind speed.	The Author acknowledges this comment. No change has been made.
18.a.	Page 48 … All interior doors were open	The following text has been added: "All interior doors were opened" The following text has been removed: "Bedroom 2's door were opened"
18.b.	Page 48…Is this really one-sided ventilation? The living room room/kitchen is cross-ventilated. Bedroom 1 is single-sided.	Single-sided ventilation relies on ventilation occurring on only one side of the room/space. In this case, in the absence of a turbine ventilator (and other leakages) air will enter and exhaust Bedroom 2 through the door of Bedroom 2. For this reason, the room is referred to as single-sided ventilation.
18.c.	Page 49, outcome 1 … With the open door, there would be no measurable pressure differential between bedroom 2 and the rest of the house.	The Author acknowledges this comment. However, the airflow, due to the cross ventilation in the rest of the house, replenishes the air in bedroom. No change has been made.
18.d.	Page 49, outcome 2 … See above comment.	See Comment 18.d. above.
19.a.	Page 50, #8 …"on minute" should be "one minute"	The text has been changed to "one minute"
19.b.	Page 50, last sentence … See earlier comment … While literally true, the test is an estimate of the decay in one location and the ventilation flow rate, MAA, and air change efficiency are estimated and apply only to that	Similarly to Specific Comment 12.a., the text has been edited to include the points raised in the Examiner's comments. The text now reads : "The data from these tests reflect the decay due to the ventilation system at the measuring points. This

	one location under those specific test conditions.	data is then used to calculate the ventilation flow rate, mean age of air (MAA) and air change efficiency at these points, and are presented as a reflection of the ventilation system in the room. The results are specific to the test conditions"
20.a.	Figure 35 … Why go out to 120 minutes? Would 40 minutes be more appropriate? Does the graph have to go all the way to 10,000ppm?	The x-axis has been adjusted to 40 minutes, and the y-axis to 6,000 ppm
20.b.	Figure 35 … Did the concentration remain at 5,000 ppm? Did it go above and eventually decay to 5,000 ppm? Would be nice to see data of equilibrium. How did you block the wind turbine during the equilibrium portion of the study? Perhaps a photo should be added to the earlier section so that the reader has a better understanding of how the wind turbine was installed from the interior.	Chapter 5 will present many more of these graphs. As the time interval between measurements is 2 minutes, the equilibrium phase is not really captured. The 5,000 ppm in Figure 33 (previously Figure 35) is the first reading once the fan has been switched off. Beyond this point, all measured data is due to the ventilation strategy at play. The turbine ventilator was not blocked off for the equilibrium phase as it was not accessible from outside the room to be opened on commencement of the study.
20.c.	Figure 36 … Why was this not a straight line?	The graph presented in Figure 34 (previously Figure 36) is a straight line.
20.d.	Figure 36 …Why go out to 120 minutes and not 40? 40 minutes would be more appropriate.	The x-axis has been adjusted to 40 minutes.
20.e.	Figure 36 … Vertical axis … This is really be labelled the natural logarithm of the concentration. Please note that LN(5000) = 8.5 and LN (500) = 6.2. SO why use 1-10 scale? Would be best to expand (perhaps 5-10)	The y-axis label has been changed to "The Natural Logarithm od Concentration (ppm)" and the y-axis range has been changed to the range 5-10
20.f.	Page 52 … So, what does MAA tell you? How will you use it? Is it consistent throughout the house?	The following text has been added : "The mean age of air (MAA) is the average time required to replenish a pocket of air in the room with fresh air." MAA will be used to describe, in time, the effect of the different ventilation strategies. As data was only recorded in bedroom 2, conclusions about the rest of the house are not made.
20.g.	Figure 37 … DO you really believe this is a fully mixed room?	In hindsight, No, the Author does not believe this to be reflective of a fully mixed room. The figure has been removed.

20.h.	Figure 38 … This is an example of a mechanically ventilated room and the air will not necessarily follow the arrows. The conclusion is OK.	The text preceding Figure 35 (previously Figure 38) now reads: "When the contaminant sources are not uniformly distributed in the room, the position of the contaminant source influences the CRE (REHVA, 2004). Figures 35 and 36 illustrate the effect of the position of the contaminant source on the exhaust concentration in a mechanically ventilated room."
20.i.	Figure 39 … This is an example of a mechanically ventilated room and the air will not necessarily follow the arrows. The conclusion is OK.	Refer to Specific Comment 20.h.
20.j.	Page 56, last paragraph … Since the MAA is not investigated, why go through all the background as well as including it in the protocol?	The MAA is in fact investigated. This was an oversight in the original dissertation. The text has been changed to : "In the field study, the ventilation flow rate, MAA and air change efficiency of the natural ventilation will be investigated."
20.k.	Page 56, last paragraph … Limitations of CRE (both in mechanically and naturally ventilated systems should be mentioned in more detail earlier).	The following text has been added: "(Novoselac & Srebric, 2003) compared air change efficiency and CRE as performance indicators for indoor air quality. Air exchange efficiency is an indicator of air distribution quality because it quantifies how good the airflow pattern is. CRE is an indicator of the contamination level in the room. Air change efficiency considers the size and intensity of recirculation in the room, by comparing the room airflow pattern to the airflow pattern of piston flow. CRE is dependent on the airflow pattern, intensity, area and positions of contaminant sources in the room. For well-known positions of contaminant sources, CRE provides good indication of air quality, and provides more informative results. However, in the space where contaminants are unknown, the air exchange is a more useful indicator because it provides a general indication of air quality independent of contaminant source positions. In natural ventilation, steady-state conditions are unlikely to be reached, as the airflow in the varies with the environmental conditions. For this reason, CRE cannot be evaluated by tracer gas concentration decay testing. Air change efficiency is considered to be a more appropriate indoor air quality indicator in this

		research project. "
20.l.	Page 56, last paragraph ... I found it a bit of a let-down to read all the background and methods to find out that not everything discussed was evaluated. Will you or someone else look at the data to further investigate MAA and CRE? If yes, then simply state that.	The MAA is investigated. CRE is not investigated here as steady-state conditions are unlikely in natural ventilation.
21.a.	Figure 40 ... Contrary to the cited references, the experimental set-up simulated a wind turbine at the highest point of a roof.	The experimental set-up simulates a wind turbine on a flat-roof. One of Lien and Ahmed's conclusions were that, at low wind speeds, the inclined roof has very little effect on the performance of the turbine ventilator. This data has been extrapolated here for very low wind speeds.
22.a.	So, is the measurement point close to the wind turbine? Unlike the wind, air coming from a flanged orifice decreases with distance from the orifice. The "box" helps direct the airflow. Was there uniform velocity both across the cross-sectional area of the box as well as from measurement point to the wind turbine? I am just a little confused here.	The measurement point is taken midway between the diffuser and the turbine ventilator. This corresponds to 375 mm away from the diffuser, and 225 mm in front of the turbine ventilator. Figure 42 has been added to provide clarity. The measurements taken at the measuring point to simulate the wind speed are in the absence of a turbine ventilator. This was done to establish the question of "how would the turbine ventilator perform at the given wind speed?". The introduction of the turbine ventilator significantly changed the airflow pattern and velocity across the cross-sectional area of the box, creating a three dimensional flow field, near the turbine ventilator, and behind the turbine ventilator.
22.b.	Equation 9 ... Significant figures? Only one significant figure for the slope and three for the intercept?	The Equation has now been reduced to one significant figure. Equation 8 (previously Equation 9) now reads y=0.0001x-0.03
22.c.	Equation 9 ... Is this correct? If I assume 1000/2000/3000 rpm, then y(wind speed) should be approximately 0.067/0.17/0.27 m/s.	Equation 8 is correct. This is evident in correlating Figure 44 (y-axis has been adjusted) to Table 5. The author has tested the examiner's assumptions and concluded that the sensitivity of the gradient in Equation 8 may lead to the results the examiner had deduced.
22.d.	Figure 46 ... The equation is valid within the parameters tested (300-3900 rpm) and should not be extrapolated beyond that. Should this be a linear relationship? Probably yes, once you overcome the initial friction and	The following text has been added to the paragraph after Equation 8 : "Equation 8 is only valid within the parameters tested, i.e. 300 – 3900 rpm."

	inertia. As it spins faster, the friction loss is less (or the momentum and winds are greater).	
22.e.	Table 5 … Significant Figures!	The rule of significant figures has been overlooked for Table 5 as Table 5 presents the actual corresponding input needed to deliver a specific wind speed.
23.a.	Page 66, 1st paragraph … "wind pressure"? Should probably be velocity pressure.	"wind pressure" has been converted to "velocity pressure"
23.b.	Table 6 … A diagram would help the reader better understand where measurements were taken. Was an adjustment made to the velocity because it was a centreline velocity measurement? 100 mm is 1/3 the duct diameter … Is this sufficient for a "good" measurement? How uniform was the velocity profile (cross-sectional)?	Figure 46 has been included to show the location of the measuring points. No adjustment was made to the centreline velocity. The measurement was made at 100 mm above the base of the turbine ventilator as the bearings are housed inside the duct also (above the measuring point) , and will affect in-duct velocity also.

		 Figure 1 : An illustration of the position of measuring points in the laboratory apparatus
23.c.	Equation 10 … dry bulb does not account for radiant energy	No, the hot-wire anemometer was not placed in the shade. As a result, the temperature data may be affected by solar radiation effects. This has been acknowledged in Section 5.1.1 after Equation 10 : "As the hot-wire anemometer was positioned at Point C (see Figure 27), and point C was not shaded, the outside air temperature may be affected by solar radiation effects. "
24.a	Should include something about accuracy of instrumentation … For	The following text has been added:

	example, the manufacturer states that the accuracy of the Sentry ST 732 is : i. +- (0.03 + 3%) m/s ii. +-2 degrees Celsius.	"The manufacturer reports an accuracy of ±(0.03+3%) m/s for the air velocity measurements (SENTRY Optronics Corporation, 2010)."
25.a.	Equation 11 ... I do not quite understand this equation and its application. Basically, this equation states that the outside temperature equals the average of the inside temperature. Is that what was intended? Does that seem reasonable?	Equation 10 (previously Equation 11) has been corrected to be the average of the OUTDOOR temperature readings.
25.b.	Equation 12 ... What is the "x-direction"?	The text prior to Equation 11 (previously Equation 12) now reads: "The average wind speed component, perpendicular to the reference house (x-direction), is given by Equation 11:"
25.c.	Table 7 ... Should repeat the color-coding or legend (green=open, red=closed)	This has been incorporated into the heading of Table 7, which now reads : "Table 7: Test configurations (Green = Open; Red = Closed)"
25.d.	Tables 8 & 9 ... Why not simply present measured inside and measured outside temperatures?	The measured inside temperatures at the start of each test have been added to Tables 8 and 9. In the text, the following has been added to Section 5.1 : "The temperature, $T_{i,A}$ of Bedroom 2 is measured at Point A (See Figure 26), at the start of each test." AND : "In most instances, the average outside temperature, T_{out} , was higher than the measured inside temperature, $T_{i,A}$, at the start of the test. This differs from the simulations of (Osburn, 2010) for two reasons. The first is that (Osburn, 2010) assumed an accommodation schedule of the house which accounted for heat generation due to occupants and appliances. In the field study, the low-income house was empty, aside from the test equipment. Secondly, (Osburn, 2010) assumed that air exchange was due to infiltration/exfiltration. In the field study, between each test, all the windows and doors were left open so that all the CO_2 could be removed from the reference house. "

25.e.	Tables 8 & 9 … The wind velocity was +-50% within a day.	Yes, this observation is correct. No changes have been made.
26.a.	Seems that the +-50% wind speed variability would lead to NOT seeing a difference.	Yes, this observation is correct. No changes have been made.
26.b.	In looking at Figures 50 & 51, the stunning difference is the difference in the IL condition. What would explain this and how would you expect this change in test configuration affect the results in the other three test conditions?	The difference has been attributed to natural convection. The discussion of this difference precedes Figure 59: "There is a distinct difference between the decay in the room and the decay through the turbine ventilator in all three tests. As the turbine ventilator rotated, tracer gas in the close vicinity of the turbine ventilator was removed, reducing the concentration of tracer gas in the air near the turbine ventilator. As the test progresses, the decay rate at the turbine ventilator stabilised. After approximately 50 – 60 minutes, the air in the room was at a higher temperature than it was at the beginning of the test, and begins to rise, due to natural convection, towards the opening at the turbine ventilator. The rising air reduced the tracer gas concentration in the room, and was transferred to the tracer gas concentration through the turbine ventilator." The results of IL may not extend to other test configurations, as the SS1, CV and SS2 tests are significantly shorter IL, and natural convection is not established.
26.c.	Figures 50 & 51 i. Recommend mg/m^3 ii. ii. Recommend shortening the x-axis (horizontal) to 80 or 100 minutes (nothing will be lost in Figure 50) iii. iii. Recommend shortening the y-axis (vertical) to 10 000 mg/m3 (5500ppm)	i. Refer to General Comment 2.b. ii. The x-axes have been shortened to 120 minutes iii. The y-axis have been shortened to 6000 ppm
27.a.	Caution must be used when comparing data to norms and standards. It	The author feels that the Examiner's comments do not respond to the work presented here. The MAA is

	looks like the simple MAA is used. We know there is great variability. During my NIOSH days, we used exposure data in two ways. i. Calculated the lower 95% confidence limit about the mean and compared it to the OSHA exposure limit. If the lower 95% CLM was greater than the OSHA exposure limit, the company would be cited. This gave the employer the opportunity to not be charged with an over exposure when there was a chance there was not over exposure. ii. ii. Calculated the upper 95% confidence limit about the mean and compared it to the OSHA exposure limit and determine whether or not action was needed. If the upper 95% CLM was greater than the OSHA occupational exposure limit, we would recommend additional sampling if there was huge variability and huge confidence limits. If the variability was small, then we would recommend corrective actions as small changes in processes or work practices could lead to changes (good or bad) in exposure.	used as a tool to illustrate to the audience the effect of the ventilation flow rate of the natural ventilation system in terms of time. The comment appears to be made as more of a background context, than the specifics presented here. No changes have been made.
28.a.	Figure 53 is a bit misleading. While it does present the mean ACH (without any statistics), this building was NOT designed to any of the references sited. Hence, one needs to be very careful the findings for specific conditions and configurations tested are not generalised and misinterpreted!!!	The following text has been added to the beginning of Chapter 5: "At the outset of the presentation of the field study results, the following blanket statement is made for ALL results presented here: ***The results presented here are under the specific environmental conditions and ventilation strategy at the time of the test, and are not generalisable.*** This statement will not be repeated at every point, but most certainly, does apply."
29.a.	2nd sentence: "This implies that, in most instances, the window of	The sentence now reads :

	bedroom 2 would lie on the leeward side of the house." i. Good observation ii. This point should also be emphasised in concluding statements ... That the turbine ventilator was tested under worst-case scenario and performance can be better improved by better designing the air inlet to bedroom 2. iii. Finally, please consider adding something like "and work against the turbine ventilator" to the end of the sentence.	"In all baseline tests, and the majority of turbine ventilator tests, the predominant wind direction was from the north east with regard to the reference house, as shown in Figure 53. This implies that, in most instances, the window of bedroom 2 would lie on the leeward side of the house, and would work against the turbine ventilator."
29.b.	Is there local meteorological data (Airport?Weather Station?) that can be used to show that stability or variability of wind speed and direction?	Wind roses have been appended (Appendix C) to show the wind speed and direction of Pretoria.
29.c.	Figure 54. Please identify the test house.	Figure 53 (previously Figure 54) has been edited to highlight the location of the reference house.
29.d.	Figure 55. i. I disagree with the two sentences immediately preceding this figure. ii. Since statistical analyses were not performed (but could easily have lead the author to a different conclusion), I simply drew a vertical line across both figures at 20 & 30 degrees. iii. One sees a definite shift to the right (.i.r. temperature MAY be a factor.	The Author feels that the Examiner may have misinterpreted the way the data has been presented in Figures 54 and 55. The indicator to consider the ACH is the SIZE OF THE BUBBLE. The turbine ventilator tests were performed after the baseline tests, and subsequently, were performed at higher temperatures. This did not necessarily lead to an increase in bubble size. The following text has been added to the paragraph preceding Figure 55 : “In Figure 55, all the bubbles of a test have similar size, e.g. the orange bubbles of SS2 are all of similar size, and the blue bubbles of CV are also of similar size, but the blue bubbles of CV are bigger than the orange bubbles of SS2, implying that the ventilation flow rate of CV is greater than that of SS2. This implies that each of the morning, noon and afternoon tests of the test configurations all achieved ventilation flow rates of similar magnitude. From Figure 55, it appears that this magnitude does not depend on the directional wind velocity or the temperature at which the test is performed. The ventilation flow rate is more dependent on the openable area of bedroom 2. “

30.a.	While I thought I mentioned this earlier, I now see that I did not. Air change efficiency is a good if one has many sampling points so that two things may be identified : i. Variability of ACE in the room ii. Where the contaminants might go (i.e. out the window, out the door) other than through the exhaust (wind turbine, in this case). Average ACE is often misinterpreted.	The points raised by the examiner have been incorporated into the Discussion in Chapter 7. The text now reads: "Air change efficiency is a good indicator of indoor air quality when there are many sampling points in the room. This will identify the variability of the air change efficiency in the room and highlight where the contaminants may go. As the air change efficiency is derived from only one measuring point in the room, the results here should not be misinterpreted. In the baseline tests, the air change efficiency of the IL, CV and SS2 configurations ranged between 52 and 60%. SS1 reported air change efficiencies in the range of 61 to 70%. These results indicate that the IL, CV and SS2 configurations allow for the air in the room to be well mixed. The SS1 configuration, which is subjected to wind pressure fluctuations, reduces the potential for mixing in the room. In the turbine ventilator tests, the air change efficiency of all test configurations ranged between 54 and 60%. The addition of the turbine ventilator to SS1 appears to allow for greater mixing in the room, and the SS1 configuration now approached the well-mixed condition. "
30.b.	So, without statistical analyses, how do we know that 61% & 70% are statistically significantly different? The statements need to be softened. "It appears…""and more data are needed to conclude.."	See Specific Comment 30.a.
31.a.	Figure 57 … Same general comment (different words this time) as other graph … Why have such large axes? It really dilutes your point. Also, very difficult to see the three lines of each graph.	The y-axis of Figure 56 (Previously Figure 57) (left) have been changed to maximum 5000 ppm, and the y-axis of Figure 56 (right) has been changed to a range of 5-10.
31.b.	"The resulting ventilation flow rate is between 0.54 and 0.6 ACH." The manufacturer of the Sentry ST 303 states its accuracy is +- 50 ppm. i. Is that significant? ii. Probably not when the concentration is 4000 ppm; however	This comment has been addressed in two parts. The first part is addressed in Section 5.1.1 where a description of the method for accounting for accuracy is presented. This addition is a page long and the examiner is referred to the document to note the change. The second part is presented in Section 5.1.3, where the accuracy has been incorporated into the ventilation flow rates results. This addition spans more

	when the concentration is 1500 ppm, the error could be +- 3.3%. iii. Now, add the variability of the reading, and the confidence limits may get even larger. iv. Is there really a difference between 0.56 and 0.6 ACH? v. I think NOT! How about between 0.5 and 1.0 ACH? vi. The issue here is showing data without presenting accuracy information let alone giving it a reality check.	than a page, and the examiner is referred to the Section to note the change.
32.a.	Figure 58 and 59 … Same point as Figure 57 and others.	The y-axis of Figure 57 (previously Figure 58) has been changed to maximum 6000 ppm and the x-axis has been changed to maximum 100 minutes. The y-axis of Figure 58 (previously Figure 59) has been changed to a range of 5-10, and the x-axis has been changed to maximum 100 minutes.
32.b.	Table 12 i. Please add a column with airflow rate (L/s) ii. Why? There is diversity among folks on how to express ventilation rates for patients. Some only recommend ACH. Some only recommend L/s/patient. Some use one and calculate the other (as did WHO 2009). iii. Now, compare this column to "160 l/s/patient (hourly average ventilation rate) for airborne precaution rooms (with a minimum of 80 L/s/patient) (note that this only applies to new healthcare facilities and major renovations. iv. Also note that a TB patient will NOT remain infectious very long once placed on treatment. One non-infectious "60 L/s/patient" for general wards and out-patient departments" is recommended by (WHO, 2009).	A l/s column has been added to Tables 13 -20. The conversion of 160 l/s/p for the volume of bedroom 2 corresponds to 34.4 ACH, and of 60 l/s/p corresponds to 12.9 ACH. This comparison has been made throughout the presentation of the data in Chapter 5, and the Discussion in Chapter 7. Concerning the comment of the difference between 1.6 ACH and 2.0 ACH, the following text, presented in the Discussion, is presented here for emphasis: "For the IL configuration, the installation of the turbine increased the mean ventilation flow rate by 1.2 ACH. The theoretical model described by the Wells-Riley Equation suggests that, when ventilation rates are low, any additional air changes make a significant difference in contaminant reduction in the room. Consider the case of IL where, in the baseline test a ventilation flow rate of approximately 0.6 ACH was achieved. According to the Wells-Riley model, under the model's assumption of steady-state conditions, the first air change removes 63% of contaminants in the room. The second air change removes 63% of the contaminants which are left in the room, i.e. after the second air change the initial contaminant concentration was reduced by 87%. By introducing the turbine ventilator into IL, an additional ACH was achieved, theoretically removing at least 63% more contaminants than the case without the turbine

	v. Is there really a difference between 1.6 ACH and 2.0 ACH?	ventilator.”
32.c.	This may also be a location to mention alternative methods for low ACH would include constant generation test.	“While tracer gas (concentration decay) testing provides detail about the ventilation flow rates, MAA and air change efficiency of the room, and through the turbine ventilator, it cannot calculate CRE, and a true reflection of the contaminant sources leaving the turbine ventilator cannot be established. For the IL configuration, a constant injection tracer gas test, could have determined the CRE in the room, as steady state would have likely been reached. “
32.d.	Figure 60 i. Again, a lot of wasted space … Condense the axes.	The x-axis has been set to maximum 100 minutes, and the y-axis has been set to maximum 6000 ppm.
33.a.	In considering estimation error, remember that at 500 ppm, the accuracy if +- 50ppm (10%)!	See Specific Comments 31.b.
33.b.	Figure 61 …axes	The x-axis of Figure 60 (previously Figure 61) (left and right) has been set to maximum 35 minutes. The y-axis of Figure 60 (left) has been set to maximum 6000 ppm, and the y-axis range of Figure 60 (right) has been changed to 4-10.
33.c.	Table 13 … Add L/s column	A l/s/p column has been added to Tables 13 -20
34.a.	Turbine ventilator SS1 See above	The Author assumes the Examiner is raising the same points about Accuracy, figure axes and l/s/p column, as in Comment 33 above. See Specific Comment 31.b. Also, the axes of Figure 60 have been edited to be more representative of the decay of the respective test. A l/s/p column has been added to Table 14.
34.b.	Figure 64 … Things are really crammed together here … Difficult to see anything. The graphs are meaningless on this scale.	The x-axis of Figure 64 has been set to maximum 40 minutes. The y-axis of Figure 64 has been set to maximum 7000 ppm.

35.a.	Figure 65 … These graphs are absolutely meaningless … cannot see what's going on.	The x-axis of Figure 64 (previously Figure 65) (left and right) has been set to a maximum of 15 minutes. The y-axis of Figure 64 (left) has been set to a maximum of 6000 ppm, and the y-axis of Figure 64 (right) has been set to a range of 4-10.
35.b.	Table 15 i. Is 14.6 really different from 19.0 ACH? ii. Based on wind variability, is 3.7 different from 4.5 m/s? iii. Add L/s column	i. At this high air change exchange, in the volume of bedroom 2, the relationship between risk of infection and ventilation flow rate described by the Wells-Riley Equation, would likely have reached diminishing returns. ii. The data has been misquoted by the Examiner. The 3.7 and 4.5 are in minutes, not m/s. No change has been made here. iii. A l/s/p column has been added.
35.c.	"The similarity in ventilation flow rates achieved …" and "It cannot be concluded at this point if the turbine ventilator increases the ventilation rate in CV's configuration." i. The experimental design did not include testing these two hypotheses in these two sentences. ii. The sentences may be misinterpreted. iii. Recommend you stick to the facts.	These two sentences have been deleted from the text.
35.d.	Figure 67 and Table 16 i. Same comments as previous sections.	A l/s column has been added to Tables 13 -20
37.a.	The accuracy stated by the manufacturer was +-0.03 m/s; so, a 0.1 m/s reading could have a range from 0.07-0.13 m/s. A reading of 0.03 m/s could have a range from 0.00 - 0.06 m/s.	As stated in Section 4.5.2: "Delta OHM HD2903T thin film sensors were used in this research project to measure the velocity profiles at the base of the turbine ventilator $V_{0.5D}$,V_D, and $V_{1.5D}$, as well as the in-duct velocity, V_{ID}. The output of Delta OHM HD2903T was 4 to 20 mA signal, and was set to a measure an air speed range of 0.05 to 1 m/s, with a reported accuracy of ±0.04 m/s + 2% of the measurement." From the data presented by the manufacturer, the limit of detection is assumed to be 0.05 m/s. Hence, in

		Figures 70 to 73, the non-zero points are always greater than 0.05 m/s.
37.b.	The inaccuracy at this low end of the instrument is probably much greater than 0.03 m/s!	Plausible, but the author only has the manufacturer's data to go on. The manufacturer reports an accuracy of +-0.04 m/s + 2% of the measurement.
37.c.	Conclusion?	See Specific Comment 37.a. above.
37.d.	What's missing from the manufacturer's information is the limit of detection or lower limit of this instrument. i. One of the hot-wire anemometers I use is a TSI VELOCICLC® Air Velocity Meter, Model 9555 Series ii. TSI states "The accuracy statement of +-3.0% of reading or +- 3ft/min (+-0.015 m/s), whichever is greater, begins at 30 ft/min through 9999 ft/min (0.15 m/s through 50 m/s) iii. So, they are basically saying that the accuracy is unknown below 0.015 m/s for this instrument. iv. Hence (I believe I mentioned this earlier), a table with instrument specifications would be a great addition!	See Specific Comment 37.a. The limit of detection for this instrument was 0.05 m/s. Section 4.4 presents all information associated with the instrumentation used in the laboratory study. All accuracies concerning instrumentation are presented here.
37.e.	Figure 71 i. Based on the above discussion, I would suggest concluding that these data are not usable either … Measurements are most likely below the LOD for your instrument	Based on the discussion presented in Specific Comment 37.a., a limit of detection consideration has been included. The opening paragraph of Section 6.1 now reads : "The protocol of Chapter 4 sets out to test the performance of the turbine ventilator under wind velocities of 0.1, 0.2, 0.3, 0.4 and 0.5 m/s. When performing the 0.1 m/s test $V_{0.5D}$, V_D and $V_{1.5D}$ recorded no detectable readings, i.e. readings ≥ 0.05 m/s, for the full hour of the test. Consequently, no further 0.1 m/s wind speed tests were performed." Also, Figure 70 has been edited, as all the values reading "0" have been omitted. The chart type has also been changed, to reflect data points, not continuous fluctuations in velocity, though this may very likely be the case. Additionally, the text following Figure 70, now reads :

		"In the 0.2 m/s tests, the turbine ventilator remained stationary for the duration of the tests. As the thin film sensors detect velocities from 0.05 m/s upwards, only readings from greater than 0.05 m/s were presented here. As such, the number of readings presented per set varies. The undetectable readings were not simply set to zero, as the velocity may be anywhere between 0.00 and 0.05 m/s. The 0.2 m/s tests revealed that V_{ID} was not always detectable by the thin film sensors, and that air was moving through the turbine ventilator, even in the absence of turbine ventilator rotation."
37.f.	Figure 72 i. Looks like this might be systematic instrument error for Sets 2 and 3. Not sure about Set 1.	The Author is unclear about what systematic error the Examiner refers to. However, Figure 71 has been edited to omit data points (previously 0.0m/s) below 0.05 m/s.
37.g.	Figure 73 and 74 i. Note that as Vid increases, the variability approaches +-3%	This observation has not been made by the Author. The Author acknowledges the comment, but no changes have been made.
37.h.	Figure 75 i. There's plenty of data here for some simple statistics on velocity. ii. How valid do you think the Vid measurements are below 0.1m/s? How about 0.15m/s?	i. Figure 74 (previously Figure 75) has been updated accordingly with Figure 71, to account for the undetectable data. The mean and standard deviation of the three sets of data has been calculated, and is presented in Table 22. ii. See Specific Comment 37.a.
37.i.	Figures 76 & 77 i. Since the manufacturer states the accuracy is +-2 degrees Celsius, these graphs seem reasonable.	The Author acknowledges this comment. No change has been made
37.j.	Figures 78 & Table 19 i. Y-axis (vertical) on right not labeled. Would also be nice to have a consistent two decimal places. ii. SO, if the instrument error is +-0.03m/s and the range of Vid was from 0.28 to 0.34 m/s, is there really a difference between the two extremes (minimum and maximum)? is this simply a trend?	Graphs which employ the right-hand axis as a secondary axis are labelled on the left-hand side axis, second. So, in Figures 76 to 78, the In-duct velocity (m/s) appears first (primary axis) and the temperature differential (°C) appears below it (secondary axis). No changes have been made to the Figures. All values in Table 23 (previously Table 19) have been changed to two decimal figures.

37.k.	Figure 79 i. Recommend only displaying dT of 6-10 degrees … ii. Could a simple regression be performed to show the relationship? This could later be compared to theory.	i. The dT range has been changed to 6-10 degrees Celsius ii. A linear trend has been included. The R^2 value is also reflected.
37.i.	Figure 80 i. Description on top of page 104 ii. The third reason for this may be the instrument itself … again, the instrument most likely is extremely inaccurate below 0.1 m/s … what if the analysis were repeated with 0.1 m/s as the cut-point and not 0.0 m/s?	Following from Specific Comment 37.a. the text has been changed to : "In Figure 80, the histogram presents the total count of how many times $V_{1.5D}$ was a detectable value. Table 20 shows how many times during the 12 hour test period the value of $V_{1.5D}$ were detected or undetected. An undetected value of $V_{1.5D}$ was reported between 48 and 57%. This could imply one of two things. The first explanation is that the velocity was in fact undetectable. It could alternatively imply that, because the probe is directional and recorded only the upward component of $V_{1.5D}$, there exists a turbulent region where air may be moving both upwards and downwards across the sensor." This correction is extended to Table 24.
38.a	Figure 84 & discussion i. Nice figure and discussion; however , additional clarification is needed ii. What are the dotted lines above/below each data point? Should be in the legend iii. Is there really a difference between any of these three conditions? DO the results better match the buoyancy only or wind-driven only conditions?	i. The Author acknowledges this comment. ii. The following text has been added immediately after Figure 84 :" In Figure 84 the green triangle presents V_{ID} for the given v_w, and the black dot on either end represents the minimum and maximum reported value." iii. The results better match the buoyancy forces tests. The in-duct velocities of the wind speed tests are significantly lower than that of the buoyancy forces only test.
38.b.	Table 24 and discussion i. So, are former assumptions about the percentage of zeros incorrect?	No, the former assumptions still hold. In the revised dissertation the following text has been edited and now reads: "In Test 3, an undetectable value for $V_{1.5D}$ occurred between 60.1% in the 0.2 m/s test and 92.5% in the 0.5 m/s test. This result is significantly different to what was obtained in the buoyancy forces tests. In the

		combined forces tests, there appears to be a decrease in turbulent fluctuations with an increase in wind speed.”
38.c.	What do the manufacturers say about minimum wind velocity and performance?	Refer to Specific Comment 37.a.
38.d.	Figure 85 i. While I am a bit tired, I have no clue how to read this figure ii. A clearer description is needed.	The text immediately preceding Figure 85 reads : " V_{ID} for wind, buoyancy and combination of wind and buoyancy forces are plotted on the same graph in Figure 85. " The text immediately following Figure 85 reads: "In Figure 85, V_{ID} as a function of v_w are presented for varying dT. These graphs are a collation of the data presented in Sections 6.1 to 6.3, and are presented on the same graph to compare the performance of the varying parameters." No change has been made.
39.a.	Are there any data to support the statement that a properly designed room with 34 ACH would be draughty and work against thermal comfort?	The Author is not aware of a study to support this claim, and the statement has been removed. Additionally, the paragraph has been changed, as in Specific Comment 39.b below.
39.b.	In reality, the person has lived in the house for a long time. They will become non-infectious after being put on proper treatment. Hence, 60 L/s is reasonable for patients under proper treatment. The 160 L/s was for infectious patients in a healthcare facility. Again, the statement seem a bit incorrect or misleading.	The paragraph has been changed to : "The WHO (WHO, 2009) recommends a minimum hourly-averaged ventilation rate of 160 l/s/p for airborne precaution rooms, and a minimum hourly-averaged ventilation flow rate of 60 l/s/p for general wards and outpatient departments. In bedroom 2 of the reference house, considering a single occupant, this would result in a recommended ventilation flow rate of 34.4 ACH and 12.9 ACH, respectively. In reality, patients who receive the correct treatment become non-infectious after a short period of time. Adopting the recommendation of 60 l/s/p for general wards and outpatient departments, as in (Cox, et al., 2012), appears appropriate for bedroom 2 of the reference house."
39.c.	Don't forget about significant figures!!! Is 17.68 any different than 17.7 ACH? For sure no.	17.68 ACH has been changed to 17.7 ACH

39.d.	The statements in this discussion need to clearly state that the results should NOT be generalised … Rather, you are reporting on a limited number of data points. Here are two specific examples: i. "In the CV tests, it cannot be concluded that the installation of the turbine ventilator increased the ventilation flow rate in bedroom 2" 1. Plausible 2. How will this wording be interpreted? 3. How should this be interpreted? ii. And what do you think about this statement (my words, not yours): "In CV tests, it cannot be concluded how often a mean ventilation flow rate of 16.9 ACH will actually be achieved." 1. Plausible. 2. It puts doubt on CV as well 3. Discussion and conclusion wording must be carefully chosen. iii. Page 114, 2nd paragraph a. Good discussion of Wells-Riley equation	The Discussion has been changed significantly, with several additions and major editing at parts. To address the comment on generalising results, the following text has been added: "In Chapter 5, the following blanket statement was made concerning the field study results: "***The results presented here are under the specific environmental conditions and ventilation strategy at the time of the test, and are not generalisable."*** This blanket statement is extended to the discussion of these results, unless otherwise stated. " i. The author believes that, by considering the blanket statement at the beginning of the discussion, the wording would be interpreted that , in the CV tests of this field study, under the specific environmental conditions, it cannot be concluded that the installation of the turbine ventilator resulted in an increase in ventilation flow rate in bedroom 2. ii. In the original dissertation, this sentence was followed immediately by the two sentences below, to eliminate any doubt on CV: "The results of the CV configuration, however, highlight the potential of natural ventilation for TB infection, prevention and control (IPC). By simply opening all the windows of the reference house, and opening the door of bedroom 2, a cross-ventilation stream was able to deliver greater than 12.9 ACH." iii. The Author acknowledges this comment. No change has been made. iv. These two paragraphs have been edited significantly, and the contents have been incorporated into

	iv. Page 116, top two paragraphs 1. Is "the system" defined earlier? 2. The thesis title includes wind-driven ventilation devices … doesn't say anything about cross ventilation 3. The experiments were NOT designed to answer this question 4. Due to the limited locations sampled, this question cannot be answered.	the following paragraph: “Air change efficiency is a good indicator of indoor air quality when there are many sampling points in the room. This will identify the variability of the air change efficiency in the room and highlight where the contaminants may go. As the air change efficiency is derived from only one measuring point in the room, the results here should not be misinterpreted. In the baseline tests, the air change efficiency of the IL, CV and SS2 configurations ranged between 52 and 60%. SS1 reported air change efficiencies in the range of 61 to 70%. These results indicate that the IL, CV and SS2 configurations allow for the air in the room to be well mixed. The SS1 configuration, which is subjected to wind pressure fluctuations, reduces the potential for mixing in the room. In the turbine ventilator tests, the air change efficiency of all test configurations ranged between 54 and 60%. The addition of the turbine ventilator to SS1 appears to allow for greater mixing in the room, and the SS1 configuration now approached the well-mixed condition.”
	v. Page 116, 5th paragraph 1. "A time-averaged in-duct velocity between 0.04 m/s …" a. Can you actually measure 0.04 m/s? b. Weren't the data from <0.1 m/s omitted? 2. "In the wind speed range tested …" a. Re-state the wind speed test!	v. The text now reads: “A mean in-duct velocity between 0.07 m/s at a wind speed of 0.2 m/s to 0.16 m/s at 0.5 m/s were reported. In the wind speed range 0.2 – 0.5 m/s, there is a clear increase in in-duct velocity with an increase in wind speed.”
	vi. Page 116, last paragraph 1. Are these statements true? 2. The statistics do not support these statements.	vi. The omission of results of the 0.1m/s wind speed test should not be confused by In-duct and centreline velocities which are less than 0.1 m/s. The Author believes the Examiner is referring to the statement :

	vii. Page 117, top of page 1. I found this whole discussion of temperature differential confusing and incorrect 2. If the outside temperature remains constant, and the inside temperature remains constant, then increasing the wind speed over the turbine ventilator will NOT result in a change in the temperature differential. viii. I should have asked earlier ... What are the specifications, including accuracy, for he thin film sensors? ix. Page 118, sentence beginning with "there are four possible reasons for this:" 1. "The velocity at the base ... is so low ..." a. The specifications, including accuracy, should confirm this statement.	"The laboratory experiments show that for a given temperature differential range, an increase in wind speed, at low wind speeds, result in a decrease in in-duct velocity, within limits." This statement follows from Figure 85. In the revised dissertation, the statement has been edited, and reads: " In the combined wind speed and buoyancy forces tests, the results show that for a given temperature differential range, an increase in wind speed, at low wind speeds, result in a decrease in in-duct velocity, within limits. This effect appears to plateau at a wind speed between 0.4 and 0.5 m/s." vii. The discussion of temperature differential has been removed. viii. .The specifications of the thin film sensors are discussed in Specific Comment 37.a. ix. This comment has also received some revision, and now reads: "Having determined the rates at which air flows through the turbine ventilator under the different parameters, the effect that the in-duct velocity has on producing a centreline velocity was investigated. In the wind speed tests, the velocity measured at $V_{0.5D}$, V_D and $V_{1.5D}$ were undetectable in all tests. The velocity at the base of the turbine ventilator is so low the thin film sensors cannot measure the centreline velocities produced by the turbine ventilator. Following from Figure 75, at $V_{0.5D}$, the expected velocity is

	2. "At low wind speeds, the turbine ventilator does not produce a centreline velocity …" a. This could be true. b. Also, it could be that the distance between the moving portion of the turbine ventilator and the centreline measurements is not sufficient (long enough) to develop laminar flow and a representative centreline velocity. 3. "The turbine does not produce a capture envelope under the presence of wind forces only." a. Wasn't smoke testing performed? b. This statement seems very unlikely to be true. 4. "The possibility of negative flow, though unlikely, cannot be detected by the thin film sensors in this experimental set up, under any velocities" a. Again, wasn't smoke testing performed? b. Why is negative flow unlikely? x. Page 118, last paragraph 1. Discussion is a little bit confusing and somewhat contradicts the immediately preceding paragraph.	reduced to 32% of V_{ID} in the 0.05 m/s test. This is the limit of detection of the thin film sensor. At low wind speeds, the turbine ventilator does not produce a centreline velocity which extends to the measured domain, and therefore cannot be characterised by the Dalla Valle Equation in this experimental set-up." Reasons 3 and 4 have been removed. x. As in Chapter 6, where zero/non-zero were values changed to undetectable/detectable values in the buoyancy forces and combined winds speed and buoyancy forces tests, this change has been extended to the discussion. The text now reads: "In the buoyancy forces tests, the centreline velocities $V_{0.5D}$ and V_D, were undetectable across all tests. The centreline velocity $V_{1.5D}$ recorded both undetectable and detectable values. The distribution of the detectable velocities were recorded, and it was found that, the value of $V_{1.5D}$ was detectable for 43 to 52% of the measurements in the three sets of tests. The distribution

		indicated that the ratio of undetectable to detectable values for $V_{1.5D}$ was so close to one, the possibility of bi-directional flow across the thin film sensor may be very likely. The thin film sensors used in these tests were directional, and were used to establish the upward centreline velocity component. If air did flow in the opposite direction across the thin film sensor, the recorded centreline velocity would be zero. The distribution indicated that in the vicinity of $V_{1.5D}$ there exists a turbulent region, in which the air passing through $V_{1.5D}$ fluctuates, in both magnitude and direction. “
	xi. Page 119, top 1. "Because ... a centreline velocity described by Dalla Valle's Equation cannot be established." a. How large of an envelope would there be at 0.1 m/s and this size duct? b. b. A diagram would help! c. Specifically, what percentage of in-duct velocity would you expect, using Dalla Valle's equation, at the 1.5D location?	xi. The centreline velocity $V_{1.5D}$ is reduced to approximately 4.5% of the in-duct velocity at 1.5D in Dalla Valle’s Equation. Diagrams for Dalla Valle’s predictions for wind speed tests are presented in Figure 75.
	xii. Page 119, 3rd paragraph 1. While Nardell & Macher (1999) mention settling velocities,	xii. The reference has been changed to (Hinds, 1999). The deletion has been made, as no data to support these statements are presented.

	a primary reference would be either an aerosol book or an early aerosol paper. a. Recommendation: Hinds, WC. Aerosol technology: Properties, behaviour and measurement of airborne particles. Wiley, New York, 1999. 2. Everything after "... to carry the particle to the turbine ventilator" should be deleted! a. This part of the paragraph shows a lack of understanding of general and natural ventilation. b. What data have you to support the hypothesis that entrainment, rather than exhaustion, occurs near the turbine ventilator?	
	xiii. Page 120, top 1. This would be a great spot to give a bit more detail i. How did the openable areas of your configurations compare with Escombe?	xiii. Additional detail and comparisons were presented in a new section, Section 3.7 How does the field study of this research project differ from previous studies?
	xiv. Page 120, 2nd paragraph 1. "...because the room was small, it was considered to be representative of the general flow in the room." a. Yes, this was stated earlier. b. Based on your data now, and re-review of the data, do you still believe this? c. What recommendations would you make for future studies?	xiv. At the beginning of the Discussion chapter, the following statement is made after the blanket statement: "Another point to bear in mind is that the results from these tests reflect the decay due to the ventilation system at the measuring points. This data is then used to calculate the ventilation flow rate, MAA and air change efficiency at these points, and are presented as a reflection of the ventilation system in the room. The results are specific to the test conditions." There is a distinct difference in the flow in the room and the flow through the turbine ventilator, such that a single measuring point in the room may not adequately reflect the airflow in the room. The following recommendation has been made in Chapter 8:

	xv. Page 120, Last paragraph 1. For comparison purposes, add the range of wind speed for Lima (Escombe) 2. For comparison purposes, add the ranges of wind speed for each quartile (Cox) 3. Levin wrote a letter to the editor regarding Escombe's paper ... Talked about wind in Lima	"To effectively quantify the ventilation flow rate, MAA, and air change efficiency of the room, additional sampling points should be considered. The locations of these sampling points should be considered carefully, and may include, sitting position, planes in the habitable zone, vertical planes to reflect the effect of thermal stratification, amongst others." xv. This paragraph of the Discussion has been removed, as it is presented earlier in Section 3.7: "The analysis of data in this field study is different to the previous studies. (Escombe, et al., 2007) and (Cox, et al., 2012) presented their data similarly, where the ventilation flow rates achieved were statistically interpreted as a function of quartiles of wind speed. (Escombe, et al., 2007) ventilation flow rate results were presented in terms of two wind speed quartiles as less than 0.56 m/s (2 km/h) and greater than 0.56 m/s (2 km/h) . (Cox, et al., 2012) results were presented in four quartiles of wind speed, from lowest to highest where the highest recorded wind speed was 13.89 m/s (50 km/h). These wind speed ranges are dependent on both the measuring point, and the probability of wind at the test location. As only three tests per configuration will be tested in this field study, only simple statistics of the data will be performed". Refer to Specific Comment 9.f.ii for details of the quartiles of wind speeds in (Cox, 2012). Levin's correspondence was presented in Specific Comment 7.d.vii.
	xvi. Page 121, 1st full paragraph 1. "The aim of these tests was to evaluate the turbine performance in the naturally ventilated system on hot still days."	xvi. The Author agrees with this comment, however, the low-end parameters are acknowledged in Chapter 1, at the hypothesis. The title has been changed to "An investigation into turbine ventilators as a potential environmental control measure to minimise the risk of transmission of TB", as in General Comment 1.

	a. This whole research effort was very focused on the lower end performance of on particular turbine ventilator and compare performance to a sub optimally designed natural ventilation building. b. Should the title be modified to reflect what was actually done? c. The title implies a much broader piece of work. xvii. Page 121, 3rd paragraph 1. The evidence does not support this paragraph 2. This set of experiments was not designed to give the answers to make such a statement. xviii. Page 121, 4th paragraph 1. Please see earlier comments (page 119 above) about these statements. xix. Last three sentences of this Discussion section 1. "In this research project, the upper-room an room were exhausted by two separate systems"	xvii. The paragraph has been edited and now reads: "In the field study, the IL test showed that the flow from the room through the turbine ventilator was due to natural convection, and not necessarily due to the rotation of the turbine ventilator. The other three configurations, SS1, CV and SS2, showed that were two distinct and separate ventilation rates between the room and the turbine ventilator. " xviii. The paragraph has been edited, and now reads: "The laboratory experiments showed that, at low wind speeds, a centreline velocity described by Dalla Valle's equation could not be produced, as the velocities were too low to be detected by the thin film sensors. The laboratory experiments also showed that, under buoyancy forces only, the region near the turbine ventilator is turbulent, resulting in mixing near the turbine ventilator. The combined wind speed and buoyancy forces test showed that this turbulent region still exists; however, the increasing wind speed reduced the turbulent fluctuations." xix. The last three sentences of the discussion has been revised, and now reads: *"In this research project, a turbine ventilator was supplemented to the (existing) natural ventilation system. The turbine ventilator did not produce a pressure differential strong enough to move the air from the room to the turbine ventilator. In this study, the turbine ventilator did not change the airflow strategies of SS1 and SS2, such that the window/door of bedroom 2 served as an inlet and the turbine ventilator as the*

	a. The research was not designed to determine this nor do the data support this conclusion. b. In reality, there are probably three areas … lower room, mid-room (transition area) and upper room. Again, the study was not designed to prove/disprove this. 2. "The upper room is ventilated by the turbine ventilator, and the lower room is ventilated according to the natural ventilation system configuration." a. The research was not designed to determine this nor do the data support this conclusion. b. In reality, there are probably three areas … lower room, mid-room (transition area) and upper room. Again, the study was not designed to prove/disprove this. 3. "the turbine ventilator did not produce a suction force strong enough to encourage air from the room to be drawn to, or through , the turbine ventilator. " a. This statement shows a lack of understanding of ventilation. One would NEVER expect an exhaust grille in a mechanical ventilated room to produce sufficient suction force strong enough to encourage air from the room to be drawn toward the exhaust grille. b. Next time someone has a birthday party, try to suck out the flame instead of blowing it out. c. Good ventilation design would have a well-designed inlet (location and size are critical) as well as an exhaust (turbine ventilator in this	*exhaust. The presence of the turbine ventilator only increased the ventilation flow rate in IL by a single air change, and did not increase the ventilation flow rate in CV. "*

	case). This is why there was no difference in the IL tests with or without the turbine ventilator. d. The research was not designed to determine this nor do the data support this.	
40.a.	Conclusions. Need to be very clear in the statements here that the conclusions are only for the configurations and conditions tested and are not generalizable. I will not repeat this for each and every statement.	At the beginning of Chapter 8, the following statement is made: "The conclusions presented here are derived under the specific parameters of the laboratory study and environmental conditions of the field study, and are not generalizable. This statement applies to all conclusions drawn. "
40.b.	Look at #3 of the first list. "It cannot be concluded that the installation of the turbine ventilator increased the ventilation flow in CV." i. Is this true under all possible situations? ii. What can be concluded?	The sentence has been edited to : "As CV produced high ventilation rates in the baseline tests, and similar ventilation rate in the turbine ventilator tests, it cannot be concluded that the installation of the turbine ventilator increased the ventilation flow rate in CV". The statement presented at the beginning of the Chapter clarifies that conclusions can only be drawn for the environmental conditions present at the time of the field study test.
40.c.	Look at #3 of the second list. "An increase in wind speed, for a given temperature differential, resulted in a decrease in in-duct velocity through the turbine ventilator." i. Is this true under all possible situations? ii. Is this true only under the very narrow conditions in the laboratory studies?	The statement presented at the beginning of the Chapter clarifies that conclusions can only be drawn for the parameters of the laboratory experiments. This however has been reinforced in #3: "An increase in wind speed, for a given temperature differential, resulted in a decrease in in-duct velocity through the turbine ventilator. This result applies only to the parameters tested. "
40.d.	Look at #4 of the second list. "It is possible … which extended to 0.5D." i. Very good statement and should be mentioned earlier as well.	#4 has been edited slightly to: "A centreline velocity profile was not established at the base of the turbine ventilator in the wind speed tests. The low-wind speed did not produce a capture envelope, detectable by the thin film sensors, which

	ii. What does the Dalla Valle's Equation predict?	extended to 0.5D." The Dalla Valle's Equation predictions have been addressed in Specific Comment 39.d.ix.
40.e.	Look at #5 of the second list "…entrain, rather than exhaust …" i. See comments regarding this phase earlier. ii. Were the experiments designed to test this hypothesis?	As the laboratory experiments were not designed to make this statement, the statement has been edited according to the facts deduced in the experiments: "In the buoyancy forces test, a turbulent environment at $V_{1.5D}$ was realised, where air fluctuates in both magnitude and direction. "
40.f.	Last paragraph i. I totally disagree with this paragraph and will dissect it: 1. "It is hereby concluded by investigation through a field and laboratory experiments – that low wind speeds and high temperatures turbine ventilators …" i. Each parameter must be defined. ii. Low wind speed 1. Xx-xx m/s for laboratory experiment 2. Xx-xx m/s for field experiments iii. High temperatures need to be defined 1. X°C for laboratory experiments 2. X°C for field experiments iv. What about temperature differentials? Isn't that the driving force?! 2. "… turbine ventilators cannot simply be supplemented to natural ventilation systems to increase ventilation flow rates and reduce the concentration of Tb particles in the room."	The last paragraph has been changed to incorporate the points raised by the Examiner: "The aim of research project was to investigate whether the above statement was true or false. It is hereby concluded - by investigation through a field study and laboratory experiments - that at, at the parameters presented in (a) and (b) below, turbine ventilators cannot simply be supplemented to natural ventilation systems to increase ventilation flow rates and reduce the concentration of TB particles in the room. (a) low wind speeds , 0.1 to 0.5 m/s for the laboratory experiments, and 0.38 to 1.72 m/s in the field study; and (b) high temperatures differentials, 7.0°C to 9.3°C for the laboratory experiments." In response to point 3: In the field study design, separation (and possible isolation) of an infectious patient was considered. The design of the field study evolved around that concept. Subsequently, a range of possible configurations were developed (as presented in Figures 29 to 32). Potential airflow patterns were developed in terms of

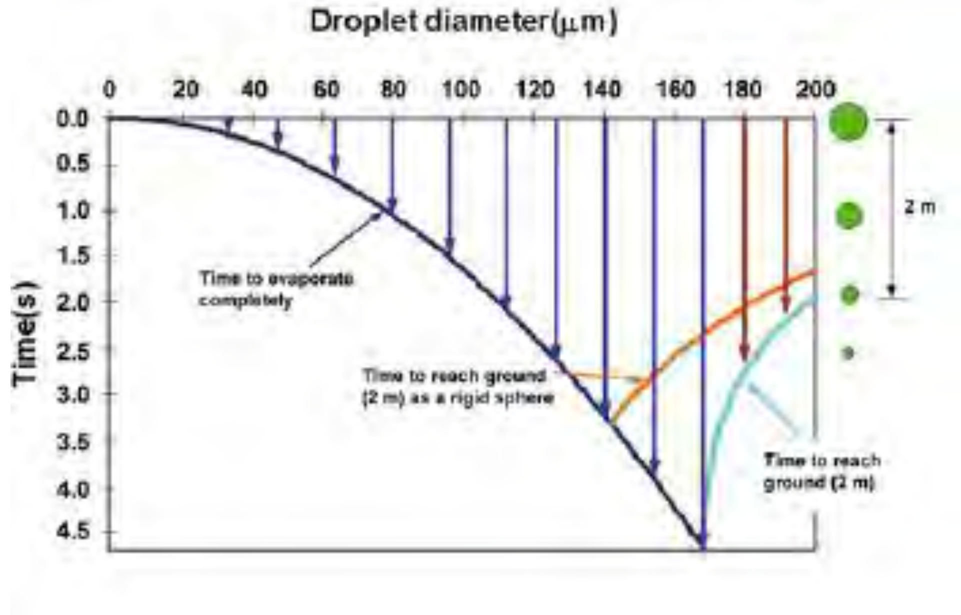
	a. I agree with this portion of the statement. b. The building has to be designed. c. The systems (natural ventilation and turbine ventilator) need to be properly designed. 3. So, what you've proven is that just sticking a turbine ventilator into a room, without proper design, is doomed for failure. 4. How might the results differ had the installation/design been done properly?	the configurations. Comment 4 has been addressed by referring to the work done by (Cox, 2012) at the end of the Discussion: *"When (Cox, et al., 2012) evaluated the performance of the turbine ventilator, the resulting natural ventilation system had a low-level inlet (air intake grille) with a high-level, negative pressure exhaust (turbine ventilator). The design of the turbine ventilator installation in (Cox, et al., 2012) allowed for the room to be ventilated as the air exhausted at the turbine ventilator had to be replenished with fresh air from the air intake grille. In this research project, a turbine ventilator was supplemented to the (existing) natural ventilation system. The turbine ventilator did not produce a pressure differential strong enough to move the air from the room to the turbine ventilator. In this study, the turbine ventilator did not change the airflow strategies of SS1 and SS2, such that the window/door of bedroom 2 served as an inlet and the turbine ventilator as the exhaust. The presence of the turbine ventilator only increased the ventilation flow rate in IL by a single air change, and did not increase the ventilation flow rate in CV. "*
41.a.	8.2 Recommendations for future study. These four recommendations are nice.	The Author acknowledges this comment.
41.b.	Based on comments thus far, I believe you should be able to add a few more. i. Constant generation test method. ii. Location of sampling points iii. Number of sampling points iv. Selection of equipment v. Refine questions and experimental design to be able to	The following additional recommendations have been made: 5. CRE should be investigated in the field study by using a more suitable tracer gas technique, e.g. constant generation tracer-gas method. 6. To effectively quantify the ventilation flow rate, MAA, and air change efficiency of the room, additional sampling points should be considered. The locations of these sampling points should be considered carefully, and may include, sitting position, planes in the

	answer questions. vi. Et al	habitable zone, vertical planes to reflect the effect of thermal stratification, amongst others. 7. The selection of instrumentation should completely characterise a parameter, e.g. anemometers and air-flow instrumentation should measure wind speed and direction.
42.a.	References: ACGIH (1986) has been superseded MANY times.	The document now refers to (ACGIH, 2005), which is the latest copy the author had access to.
42.b.	"CSR Edmunds (n.d.)" So how does one get a copy of this reference? If it's not available to the public like any other book or paper, then it does not belong here.	CSR Edmunds was a reference used in Section 2.3.3, which has been removed in the revised dissertation. Consequently, CSR Edmunds as a reference has also been removed.
42.c.	Escombe et al 2007 listed twice	(Escombe et al, 2007) is now only listed once in the revised dissertation.
42.d.	National Department of Health (2007) listed twice	(National Department of Health, 2007) is now only listed once in the revised dissertation.
42.e.	There are actually two WHO (2009) documents … The natural ventilation document and the TB IPC policy	The WHO 2009 TB IPC policy is not referred to in this dissertation. This policy would be transcribed in (National Department of Health, 2007) and (National Department of Health, 2009).
43.a.	Appendix A : Please give source of information	The specifications of the turbine ventilator are available on the manufacturer's website (Windmaster), and are presented in the References Chapter.
44.a.	Give units for all variables!!!	The units of all variables in Appendix D have been defined following their respective equation. This occurs in Equations 14, 15, 16, 17, 18, 19, 20 and 22.
44.b.	Figure 86 i. One annotation is differential pressure ii. What does this mean? Between the balancing chamber and plenum chamber?	I and ii. The annotation refers to the differential pressure between that balancing chamber and plenum chamber. The following text has been added for clarity to the paragraph immediately after Figure 86:

	iii. How sensitive is a wind ventilator to resistance? 1. Can a slight, barely measurable pressure in the balancing chamber significantly affect the flow through the wind ventilator? 2. How about the converse? iv. For the term T_{out}, is the ambient temperature in °K or °C? v. How does Figure 87 relate to the studies at hand? 1. If you're proposing that a wind ventilator is and capture hood, then there's a fatal flaw here? 2. This design is for a hot process (see ACGIH 1986) 3. If you want to demonstrate the application of Dalla Valle's Equation, then do it! Show the hood and the constant velocity contour lines. 4. What is the difference between local ventilation and general ventilation? vi. How does Dalla Valle deal with round vs rectangular ducts?	"In this way a differential pressure of 0 Pa is maintained between the plenum chamber and the balancing chamber." iii. A turbine ventilator has a cut-in speed, i.e. the wind has to be traveling at a certain velocity to overcome the resisting forces of the turbine ventilator to cause rotation of the turbine ventilator. This was discussed in the presentation of the work of (Lai, 2003). In the laboratory experiments of this research project, the cut-in speed for the turbine ventilator used was found to be between 0.2 and 0.3 m/s. This cut-in speed resulted in a measurable in-duct velocity, which in a closed system of Figure 86, would be measurable. iv. T_{out} is in °K v. Figure 87 is an illustration of a typical hood design, showing the components to create suction, and the contaminant source to show where ventilation is required, and why. It provides a relatable context to this dissertation, where a contaminant has to be removed from a space. The Dalla Valle's equation constant contour lines were presented in Figure 88. The aim of local (exhaust) ventilation systems are to remove the contaminants at its source so that it does not spread to the rest of the space. The aim of general ventilation is to supply and remove air from a space so that contaminant levels, humidity and temperature levels can be maintained in a space (ASHRAE, 2007). vi. The Dalla Valle's Equation presented in this dissertation is for circular ducts, and so, Equation 18 and 19 apply. For rectangular ducts, bound by a plane surface at one end, the duct is considered to be twice its actual size, and then corrected, as in the following Equation, *from Wang, LK, Pareira, NC, Hung Y-T Handbook of Environmental Engineering, Volume 2, 2005* :

		$$Q = \frac{V_x\left(2A + 10X^2\right)}{2}$$ As rectangular ducts were not considered in this dissertation, it has not been discussed, and has subsequently not been incorporated into the dissertation. No additions/changes have been made.
44.c.	Equations 18, 19 and 20 : i. It should be "hood effective diameter" 1. What is the diameter of a rectangular hood?	i. The Equations presented in this dissertation relate to circular ducts. The Equation relating to a rectangular duct is shown in Specific Comment 44.b. above. Equations 18, 19 and 20 may not apply to rectangular ducts, and so the extension of "hood effective diameter" is not made here. No change has been made.
44.d.	Figure 88 i. Finally!!! This is what I was looking for earlier!!! ii. A table would be good as well 1. Question: Why does it look like 100% is outside of the flanged inlet? Generally, if one takes the centreline velocity, they will just adjust it (0.9X) as it will be higher in the centre than the sides 2. Back to the table 3. What is the percentage of the opening velocity at 0.5D, 1.0D and 1.5D? 4. What is the fraction of diameter (XD) that yields 90%, 50% and 10% of the opening velocity?	i. The Author acknowledges this comment. ii. The Author acknowledges the Question and Answer comment. No change has been made. The percentage velocity at 0.5D, 1.0D and 1.5D is 32%, 10% and 4.5% of the in-duct velocity. This has been added to the text immediately preceding Figure 75 (Section 6.1): "The centreline velocities are expected to be reduced to 32% of V_{ID} at $V_{0.5D}$, 10% of V_{ID} at V_D and 4.5% of V_{ID} at $V_{1.5D}$." The following text has been added to the paragraph following Equation 20: "From Equation 20, the percentage centreline velocity gradient for 90%, 50 % and 10% of the face velocity corresponds to 0.19D, 0.36D and 0.98D, respectively, from the inlet. "

44.e.	Equation 20 i. Based on this equation, please develop a table as explained.	i. As very little data would be presented, the variables were calculated as described by the Examiner, and added to the text following Equation 20. This has been presented in Specific Comment 44.d. above.
44.f.	Equation 22 i. Please apply this equation and develop a table with settling velocities for several particle sizes.	To illustrate the point of settling velocities of different particle sizes, Figure 89 , which is the Well's evaporation-fall curve, has been added to the dissertation, with an accompanying paragraph: To illustrate the effect of terminal velocities for particles of different sizes, Figure 89, extracted from (WHO, 2009) is presented. Under normal conditions, Well's found that particles smaller than 100µm would completely dry out, before travelling 2m towards the ground. Particles in the order of 1-5 µm, evaporate instantaneously and remain suspended in the air, having to travel a long distance to the ground. As the particle increases in size, the evaporation time is longer, and the fall to the ground is shorter.

		 Figure 2: An illustration of particles evaporation and falling according to Well’s equation (WHO, 2009)
44.g.	Figure 89 and discussion i. This is a simple theory. In the thesis, it’s mentioned that these are well-mixed rooms; hence the air will not be vertically upward. The rooms were not designed for vertically upward air. Please add a paragraph discussing what happens in reality.	The following text has been added: “With the exception of specially designed cleanrooms, air does not travel in vertically upward streams. In natural ventilation, air in a room is often partially or fully mixed. This implies that air enters the room, circulates within the room according to pressure profiles in the room, and will be exhausted after some time. With low-level inlets, and high level exhausts, the net air flow pattern may be upward, but the air may circulate several times in the room, before it reaches the exhaust. “
45.a.	Appendix E Figure 90-96	

	i. Please fix the x-labels ii. Consider shrinking the x-axis a bit so we can better see the data. It's crammed into a small space.	i. The x-labels read "Time (hours)" for Figures 91 - 93, and "Time (min)" for Figures 94 -97. ii. In Figures 90 – 92, only the first six hours of the test is presented. This has made the graphs more legible.
46.a.	Appendix F a. Nice addition. b. How does this research relate to yours? c. How applicable is Equation 22 to your research results.	a. The Author acknowledges this comment. b. This work has been discussed in the Discussion chapter of the revised dissertation, and refers the reader to Appendix F. The laboratory experiments is similar to the work by (Nguyen et al, 2012) in that (Nguyen et al, 2012) also tested a turbine ventilator is tested under wind speed and buoyancy forces in a controlled environment. c. In the Discussion Chapter, the following statement was made: "At the low wind speed parameters investigated in this research project, the total in-duct velocity does not conform to the relationship described by Equation 22. "

4. Addressing the comments of Examiner 2

Relevant Literature:

	The absence of coefficients in Equation 1 strikes me to be odd. It might be coincidence that the parameters brought into relationship is described in this fashion, where multiplying coefficients are all 1, however it would have been hoped that the candidate would investigate slightly deeper. The general trend given by this equation is still of great use.	The Examiner's point is well received. The point raised by the Examiner can be seen in Equation 2. Equation 2 is another form of Equation 1, where the relationship between the initial concentration and the concentration at time t is normalised.
	ON page 20 where different ventilator sizes are considered in a literature reference, the candidate should have indicated that it would be important for the differently sized ventilators to be geometrically equivalent before they can be compared in the fashion which they were. If the literature reference did not supply this information, the candidate should have commented on the omission.	The point raised by the examiner has been incorporated into the discussion of (Lai, 2003) results: "Results of Lai's (Lai, 2003) second set of experiments are shown in Figure 8. Three turbine ventilators, of sizes 150 mm (6 in), 360 mm (14 in) and 500 mm (20 in) were tested. The results indicate that the bigger the size of the turbine ventilator, the bigger the ventilation rate it induces, though the difference between the 0.36 m (14 in) and 0.5 m (20 in) turbine ventilators were not significant. The sizes of the turbines differ, and are not geometrically equivalent. In the third set of experiments, (Lai, 2003) showed that inner vanes increase the induction of flow, though not significantly."
	On page 24 where the roof inclination angle is considered in terms of the ventilator performance by a literature reference, one would have hoped the candidate would have elaborated/mentioned that the positioning of the ventilator from the roof edge or apex is of importance. (In her field test it does, however, seems as if this was taken in consideration.)	At the conclusion of Chapter 2 in the revised submission, the following list is presented, highlighting the importance of the roof inclination angle as a performance parameter: "From the literature discussed in this section, the factors affecting the performance of turbine ventilators are: 1. The presence of wind and buoyancy forces 2. The shape of turbine ventilator blades 3. The diameter of the turbine ventilator

		4. Roof inclination angle 5. Location of the turbine ventilator relative to the apex of the roof 6. Openings in the room”

Research Methods:

	The measurement accuracy of the various test Equipment is not described, nor is it mentioned if they have been calibrated.	Accuracy of instrumentation and the effect on the results of the field study and laboratory experiments is a major change from the original dissertation to the revised dissertation. Concerning Accuracy, please see the response to Specific Comments 24.a, 31.b, 37.a and 37.b of Examiner. Concerning calibration, all laboratory instrumentation was performed prior to testing. All field study instrumentation had been bought for the field study tests, and was new, and have been factory calibrated.
	Were field test ambient temperatures taken in the shade to prevent solar radiation effects?	No, the hot-wire anemometer was not placed in the shade. As a result, the temperature data may be affected by solar radiation effects. This has been acknowledged in Section 5.1.1 after Equation 10 : “As the hot-wire anemometer was positioned at Point C (see Figure 27), and point C was not shaded, the outside air temperature may be affected by solar radiation effects. “
	On page 41, the procedure that was used to obtain the wind velocity is not described. Generally, an anemometer is to be placed in line with the airflow direction in order to achieve accurate measurements. It does not necessarily measure the wind component correctly. Did the candidate check this?	The process of measuring the wind speed is described in Section 3.4.2 immediately after Figure 26, in the revised dissertation: “T_{out} and v_w are measured at Point C, shown in Figure 27. Point C is located away from the reference house, at a height of 1.5m, to determine the wind speed and temperature at the site. In this way, the effect of the building envelope on the airflow around the house does not influence the wind speed and temperature measurements. The hot-wire anemometer used in this field study had a directional probe, i.e. it was only able to

		measure wind speed in one direction. For the purposes of this field study, the chosen direction was the plane perpendicular to the northern façade of the house. It was assumed that this component of the wind velocity would play the biggest role in ventilating the house, as it is the component perpendicular to windows of the house." The anemometer was not aligned with the dominant wind direction, as the wind speed and direction constantly fluctuated. This has also been addressed in Specific Comments 14.d and 29.a. of Examiner 1's comments.
	On Page 44, why was the reference wind direction selected to be North –South? It would have been better to give the wind velocity and the direction thereof. Depending on where the turbine ventilator is installed, its operation is not sensitive to the wind direction, but rather the magnitude of the wind velocity.	See above comment. (Cox,2012) raises the following point, presented in Chapter 2: " (Cox, et al., 2012) highlighted that the advantage of turbine ventilators over windows in their study is likely related to variability of wind, as turbine ventilators will rotate regardless of wind direction if positioned optimally on roof apexes, whereas ventilation via windows, especially single-sided ventilation in their case, was very subjective to changes in wind direction. " The decision of wind speed direction, for the availability of a single instrument, was chosen to be North-South, as this would be the component which would have the most impact on the ventilation configuration in the reference house.
	Did the candidate check/investigate the air tightness of roof structure in the field test? Would this have played a role?	Yes. Low-income houses, like the reference house, have corrugated roofs positioned on wooden beams structures to secure the roof to the house. This has created gaps in the building envelope, especially around the beams, on the upper sloped part of the wall, where building material erodes from around the beam. From the results of the IL tests in the field study, the air exchange due to infiltration and leakage in bedroom 2 is very low.
	Why was more than one type of thermocouple used? K-type thermocouple would have been suitable in the entire measuring range.	Type J thermocouples were placed onto the metal plate above the heating element, to measure the surface temperature of the plate. The Author acknowledges, in hindsight, that Type K thermocouples could have been suitable for both air temperature and surface

		temperature.
	Could the temperature in the lab experiment not be controlled more tightly?	The temperature control in the laboratory experiment could not be controlled more tightly by the Author, with the current thermostatic control. The heating element selected for the laboratory apparatus had a built in thermostat, which could deliver the required temperatures needed in the design phase of the experiments. The temperature range could have been more tightly controlled if a new thermostat was programmed heating element.

Presentation:

	The nomenclature should be given in alphabetical order. It was very difficult to make use of the nomenclatures in the current form.	The "Symbols" (nomenclature have been presented in alphabetical order in the original dissertation.
	On Page 11: Infection vs ACH: I was only able to get the reduction to be about 40% and not 50%.	By relooking at the presented data, the Author agrees with the Examiner. The text has been edited: "From Figure 4 it can be seen that doubling the ventilation rate reduces the number of infected individuals by up to 40%..This study assumes a well-mixed room, and does not account for variability in occupancy and contaminants in the room."
	On page 12: 1970 – 1900 should rather be 1970 – 2000?	See Specific Comment 7.d.ii of Examiner 1.
	Page 25: Cp is not defined in the nomenclature	This has been added to "Symbols"
	Some graphs which have dual axes, are not fully defined. Example 57.b – What do the two vertical axis represent?	See Specific Comment 37.j of Examiner 1
	Use the same alignment in the columns of tables. Example: Tables ... 16 & 17 .... Etc is difficult to read because column values are not	This level of formatting has been extended to all tables in the revised dissertation.

	below each other / below the heading.	
	If possible, adjust the scales of the horizontal axes to make the trends more visible (see Fig 65). Most readers will be able to understand that there was a reduction in the time taken for the concentration to drop.	The axes of all graphs of the field study have been adjusted to be more aligned to the decay of their respective tests.