THERMAL ANALYSIS OF THE INTERNAL CLIMATIC CONDITION OF A HOUSE USING A COMPUTATIONAL MODEL

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A dissertation submitted to the faculty of Engineering and the Built Environment of the University of Cape Town in the fulfilment of the requirements for the degree:

MSc Mechanical Engineering

Department of Mechanical Engineering

University of Cape Town

December 2019

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ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to the following for their significant contribution during this research:

- Prof. Tunde Bello-Ochende, for all his advice, guidance and encouragement throughout this project.
- University of Cape Town's ICTS High Performance Computing team: hpc.uct.ac.za for providing the facilities where all numerical simulations were performed.
- Andrew Lewis for his guidance and assistance using the University of Cape Town's ICTS High Performance Computing facilities.
- Prof. Ryno Laubscher for his guidance and assistance using Ansys Fluent and the University of Cape Town's ICTS High Performance Computing facilities.
- Evan Smuts and Stephan Schmitt for their guidance in developing the computational model for this project.
- Priyesh Gosai and all staff part of the UCT Pecha Kucha team for helping me structure and present my research.
- My family for their continued support, guidance and motivation throughout the duration of my studies.
- To my digs mates, who reside at our digs formally known as The Workshop, for their enthusiastic support, motivation and excellent food throughout the duration of this project.
- My colleagues in the Mechanical Engineering Department Postgraduate Workspace for their advice, motivation and providing excellent working environment.
- The University of Cape Town Mechanical Engineering Department for their financial support and access to resources and facilities.
- The University of Cape Town Centre for Materials Engineering Department for their financial support and use of facilities.
- The NRF for their financial support

ABSTRACT

The internal thermal climatic condition of a house is directly affected by how the building envelope (walls, windows and roof) is designed to suit the environment it is exposed to. The way in which the building envelope is constructed has a great affect on the energy required for heating and cooling to maintain human thermal comfort. Understanding how the internal climatic conditions react to the building envelope construction is therefore of great value. This study investigates how the thermal behaviour inside of a simple house reacts to changes made to the building envelope with the objective to predict how these changes will affect human thermal comfort when optimising the design of the house. A three-dimensional numerical model was created using computational fluid dynamic code (Ansys Fluent) to solve the governing equations that describe the thermal properties inside of a simple house. The geometries and thermophysical properties of the model were altered to simulate changes in the building envelope design to determine how these changes affect the internal thermal climate for both summer and winter environmental conditions. Changes that were made to the building envelope geometry and thermophysical properties include: thickness of the exterior walls, size of the window, and the walls and window glazing constant of emissivity. Results showed that there is a substantial difference in indoor temperatures, and heating and cooling patterns, between summer and winter environmental conditions. The thickness of the walls and size of the windows had a minimal effect on internal climate. It was found that the emissivity of the walls and window glazing had a significant effect on the internal climate conditions, where lowering the constant of emissivity allowed for more stable thermal conditions within the human comfort range.

<u>Keywords:</u> Computational Fluid Mechanics, Heat Transfer, Building Envelope, Thermal Comfort, Buildings

NOMENCLATURE

°	Degree
°C	Degree Celsius
%	Percent
A	Area
CFD	Computational Fluid Dynamics
Cp	Specific Heat in constant pressure
Cv	Specific Heat in constant volume
g-value	Total solar energy transmittance
GB	Gigabyte
ISO	International Organisation for Standardisation
K	Kelvin
k	Coefficient of thermal conduction
kJ	Kilojoule
kW	Kilowatt
lux	illuminance
m	Metre
mm	Millimetre
N,S,E,W	Cardinal points
Q	Heat
R-value	Thermal Resistance
RDP	Rural Development Project
s	Conduction material thickness

SA	South Africa
SAWS	South African Weather Service
T	Temperature
t	Time
U-value	Thermal Transmittance
UCT	University of Cape Town
UDF	User Defined Function
W	Watt
WWR	Window to wall area ratio

α	Thermal Admittance
ε	Constant of emissivity
ρ	Density
σ	Stephan Boltzmann Constant
Ω	Angular frequency

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CHAPTER 1:

INTRODUCTION

1.1 Background

Human thermal comfort is essential for the inhabitants of a household to live comfortably. Human thermal comfort is defined as the environmental temperature and humidity range where human beings feel comfortable. When the environmental temperature and humidity fall outside of that range, then a state of discomfort sets in by feeling either hot or cold [1].

The human body can regulate its temperature through certain bodily functions. The body converts a large portion of the energy we consume in the form of food into thermal energy through a process of metabolism. The rate at which this conversion is done aids in the regulation of our body temperature to maintain a constant ideal body temperature of 37°C which is essential for proper bodily function. To aid in the regulation of our body temperature, the body can execute emergency functions such as shivering or sweating. If the metabolism process is not able to maintain our ideal core body temperature in cold conditions, the human body starts to shiver in order to raise the body temperature. In hot conditions, the human body excretes water in the form of sweating, which aids in decreasing the body temperature as it evaporates. Shivering and sweating are both signs of thermal discomfort and should be avoided in environments such as a household, where human beings should feel comfortable in.

There are actions that can be taken to control the environmental conditions to best suit human thermal comfort. Among these include, putting on a jersey or warm clothing to keep the human body warm when it is cold, or alternatively, open a window to let cool air into a house or building to keep it cool. However, it may not be practical to wear multiple layers of clothing, or there may not always be a window to open, in such case thermal techniques are commonly used to control the internal climatic condition of a house or building. Such techniques include electric heaters, air conditioning systems and wood burning fireplaces. These techniques are very effective at controlling the temperature to maintain human thermal comfort. However, the use of these techniques comes at a cost in the form of energy use.

In the average modern household, most of the energy consumed is used for heating and cooling of the internal climate. This is due to the techniques that are used to control the temperature of the internal climate. Most of these devices use electricity to operate which is commonly produced from unsustainable energy sources, such as coal in a coal fired powerplant or radioactive materials in a nuclear powerplant.

As the population of the world increases, the need for electricity increases, and there will come a point where the electricity supply does not meet the demand. This results in blackouts or load shedding which is currently implemented in South Africa. A solution to this, is to reduce our reliance on unsustainable energy sources used for the heating and cooling of houses and buildings.

Ideally, residential houses and buildings should be built in such a way to maintain their internal climatic conditions to best suit human comfort without the need for additional devices that make use of unsustainable energy sources. By utilising the free energy received from the sun to keep a house warm when required and optimising the insulating properties of the building envelope to control the rate of heat transfer between it and both the interior and exterior environments, the internal climatic condition can be controlled. This may be done by optimising the geometry and thermophysical properties of the building envelope to best suit a household's environment and achieve an internal thermal climate that maintains thermal comfort for the inhabitants.

Currently, most houses are not built with the aim of optimising the building envelope geometry and thermophysical properties to control thermal comfort. This is because the modelling process is computationally expensive and time consuming.

This project investigates how the building envelopes wall thickness, window size and thermophysical properties affect the internal climate of a simple house. A thermal analysis of a simple house is conducted using a computational model to analyse internal climate.

1.2 Research Objectives

The objectives of the research presented in this dissertation are:

- To create a computational model of a simple residential house with four walls, a single glazed window and an internal airspace that incorporates the necessary boundary conditions to simulate the exterior climate to determine its internal climatic conditions.

- To numerically solve for the internal climatic conditions of a simple residential house based on a set of realistic boundary conditions that best emulate the external climatic conditions of a house situated in Cape Town, South Africa.

- To alter the geometry and thermophysical properties of the building envelope and analyse how these changes may affect the internal climate with the goal to optimise the design of the house in order to maintain human thermal comfort and reduce the reliance on unsustainable energy use for climate control.

- To recommend improvements and additions to the research conducted that will aid in others pursuing research in the field of energy and buildings, and further the understanding of how the design and construction of the building envelope may affect the internal climate of a house to best maintain human thermal comfort.

1.3 Research Scope

The scope of this research is limited to the creation of a numerical model of a house with four walls, one single glazed window placed in the north façade, a floor and internal airspace using the Ansys software suit. The model would then be used to determine how the thickness of the exterior building wall, size of the window and thermophysical properties of the building materials effect on the internal climate of the house.

1.4 Dissertation Structure

The dissertation research conducted has been organised into eight chapters for ease of reading. This dissertation therefore consists of the following chapters:

- Chapter 2 – provides insight into the relevant published literature that relates to how heat is transferred through the building envelope and concepts that were put together to create a numerical model.
- Chapter 3 – provides background to the numerical modelling procedure and how it was applied in the creation of the numerical model for this project.
- Chapter 4 – explains the procedure in which the numerical model was used to generate results that may be used to explain the effects of the building envelope geometry and thermophysical properties on the internal climate of a house.
- Chapter 5 – explains the documented results obtained from following the numerical procedure and solving the computational model.
- Chapter 6 – discusses the results obtained in chapter 5 and how they relate to literature.
- Chapter 7 – states all the conclusions that can be drawn from the results obtained.
- Chapter 8 – provides recommendations on how the research conducted may have been improved and topics for future research.

CHAPTER 2:

LITERATURE REVIEW

2.1 Introduction

This chapter reviews literature relevant to construct the numerical model for this project and explains the thermal behaviour that occurs within the building envelope and how it may apply to the numerical model. The literature review also covers the background knowledge that the author feels the reader should know to fully understand the content of this dissertation.

2.2 Human Thermal Comfort in Buildings

Thermal comfort is defined as the perceived satisfaction that an individual has with their respective environment [1]. Thermal comfort is maintained when the heat generated by the human metabolism, is regulated so as to maintain thermal equilibrium within the body [2]. Any heat gain or loss beyond the point of equilibrium generates discomfort. This discomfort is felt in the form of feeling hot or cold. The human body reacts to thermal deviations (hot or cold) to attain thermal equilibrium [3][4]. Therefore, humans have the ability to survive in a range of environmental conditions.

There are six primary thermal comfort variables [2] that affect an individual’s thermal comfort:

- Ambient air temperature
- Relative Humidity
- Radiant temperature
- Air motion
- Metabolic rate
- Clothing insulation

The range in thermal properties can be seen in Figure 2.12.1:

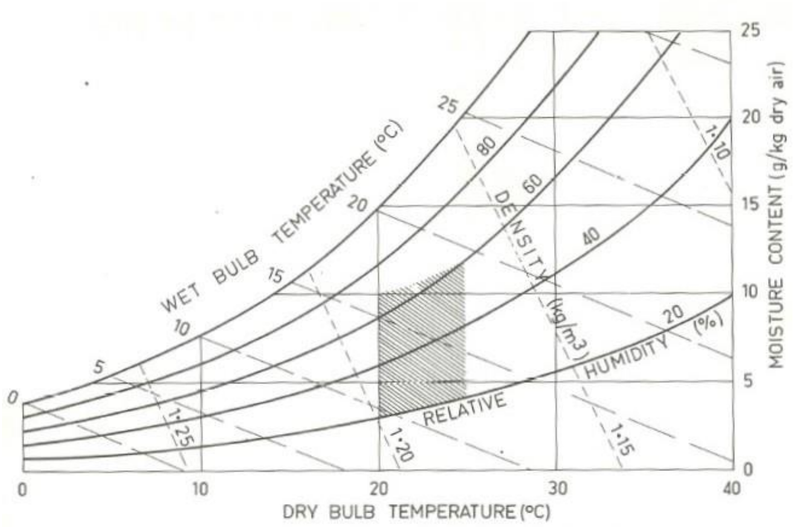


Figure 2.1 - Psychometric Chart Showing Comfort Zone [2]

Across the world, humans seem to favour conditions of clean air at about 20°C or slightly higher depending on the movement of air[5]. It has been found that inside a building, the temperature of the air, the temperature of the surrounding surfaces, the moisture content and the air movement across the human body contribute to thermal comfort[5][6].

An individual's health can also be affected by incorrect thermal comfort levels. If the relative humidity is too high, condensation may form on the walls or windows. Over time, this excess condensation can lead to bacteria or mould thriving in the environment. This mould and bacteria can effect an individual's health [1].

When the human metabolism is unable to regulate the body's temperature in a particular environment, humans tend to use heating or cooling devices to change the environment to achieve climate conditions that favour thermal comfort. Such devices include: air conditioners, electric heaters, wood burning fires, etc. These devices are very effective at maintaining the internal climate to favour human thermal comfort, however, they come at the cost of expending vast amounts of energy.

2.3 Household Energy Use

To perform daily household needs, energy is required. In most houses in South Africa, electricity is used to operate appliances, provide lighting, heating and cooling, etc. In some cases, alternate energy sources, such as solar and biomass, are used for water heating and household heating. Figure 1.2 presents the energy use distribution for the average household in South Africa [7]. Figure 2.2 shows that a majority of the energy used in the household is for heating and cooling of the environment via the use of both electrical and alternate energy devices.

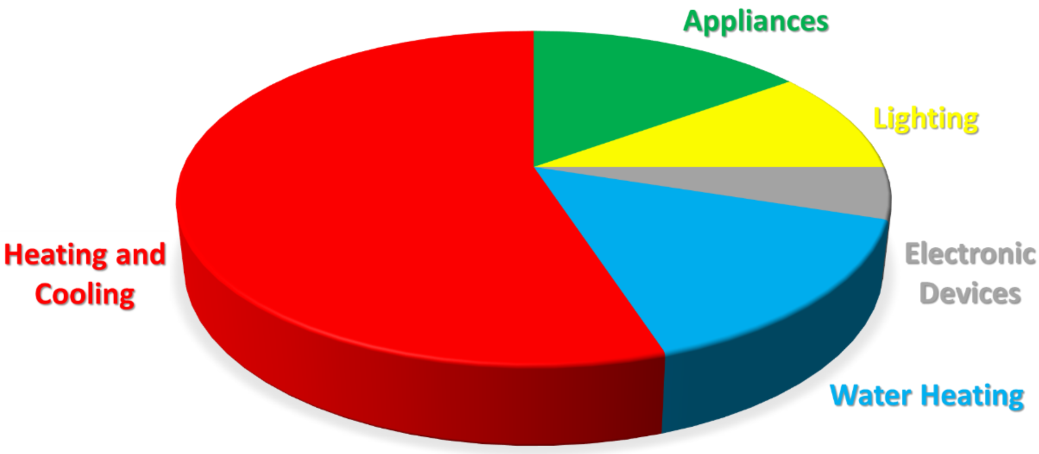


Figure 1.2 - Average Household Energy Use [7]

Since most of the energy used for the heating and cooling of the environment is produced from unsustainable sources, such as coal power stations and biomass, etc. This form of heating and cooling will not be sustainable for the future when considering the current worldwide population growth. To reduce the unsustainable energy use, methods of heating and cooling that rely on sustainable energy should be implemented.

One of such methods is designing a house or building that utilises solar radiation and the external climate to heat said house or building. An alternative method would involve relying on the correct choice of building materials and building geometry to maintain a stable internal climate that favours human thermal comfort. [8]–[10]

2.4 South African Low-cost Housing

In South Africa the Rural Development Program (RDP) has started a housing project, in which it aims to build low-cost houses. These houses are of masonry construction with a minimum floor area of 30 m^2. The walls of the houses are 2.4 m high and comprise of 230 mm thick burnt clay masonry, plastered on both sides. The floors are made of a concrete surface bed. Each house typically consists of a single bedroom, bathroom, entrance hall and one other habitable room. [11]

2.5 Heat Transfer in Buildings

Thermal comfort and heat loss should be considered when designing a building or residential house. The walls of a house have a large effect on the building's thermal properties. Wall thickness, window size and their material thermophysical properties influence heat gained and loss from a building. Windows allow solar radiation to penetrate the building envelope and allow heat to be lost through conduction during the cooling cycle[8], [12], [13].

The heat transfer from a wall between the surroundings on either side depends on three partially independent processes:

- Heat transfer to the wall from the surroundings on the outside of the house.
- Heat transfer through the wall material.
- Heat transfer from the wall to the surroundings on the inside of the house.

The building envelope of a simple house is always exposed to cyclic thermal conditions within a period of 24 hours. During daylight hours, solar radiation transfers thermal energy to object surfaces and the surrounding environment. During this time the internal climate of a house begins to heat up. When the sun sets in the evening, the thermal energy transfer is reduced and the thermal energy that the house has absorbed throughout the day begins to dissipate to the external environment. Consequently, the internal climate begins to cool down[14], [15]. The temperature profile of the internal climate theoretically looks like a sine wave as shown in Figure 2.2:

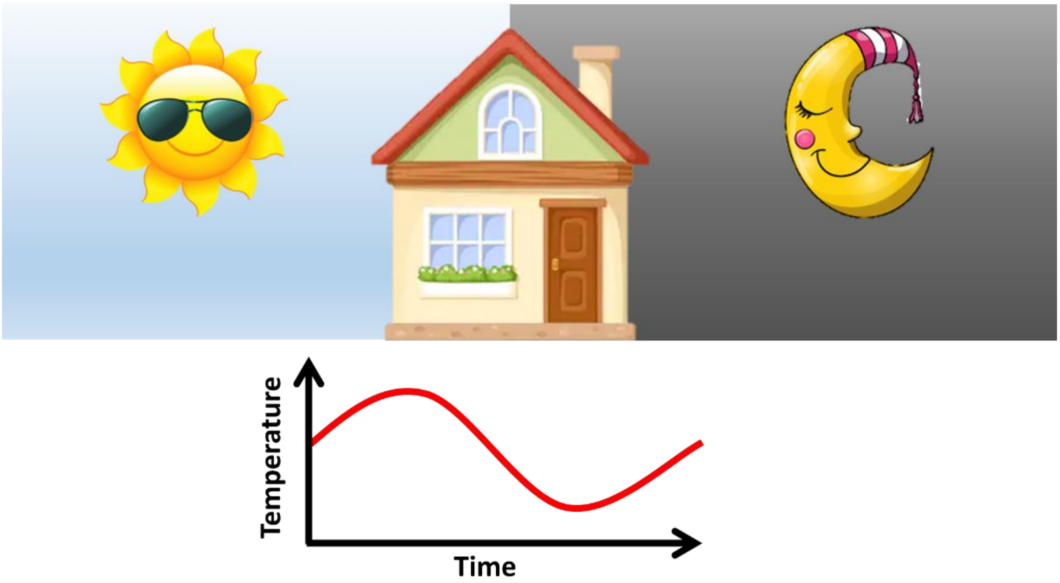


Figure 2.2 - Simple House Theoretical Internal Temperature Profile

Heat transfer in and around the building envelope takes place via conduction, convection and radiation, and the relative contribution of each depends on the thermal conditions that the building is experiencing. Heat is transferred from the air to the walls inside and outside the building by convective air currents set up by the temperature difference between the wall and the air, or due to wind or forced ventilation.[16]

At points near the surface of the wall, the air velocity is reduced, and the heat is transferred from these regions to the solid surface of the wall mainly by pure conduction through layers of air moving parallel to the wall.[16],[17]

In addition to the heat transferred to the air via convection and conduction, heat transfer via radiation takes place between the wall surface and its surroundings. The magnitude of the heat transferred is dependent on the absolute temperature, temperature difference and the characteristics of the surface of the wall and its surroundings.[16]

2.6 Thermophysical Properties of Walls

Heat transfer through solid walls takes place via conduction in the direction of temperature gradients only. The rate of heat transfer, as governed by Fourier's Law, is directly proportional to the temperature difference on the two surfaces of the wall, and further depends on the materials that the wall is constructed of [16]. The thermal conductivities of building materials generally increase with increasing temperature. Consequently, the wall resistance will decrease with increasing mean temperature of the wall [16].

In walls that contain voids, such as hollow brick type walls, convective heat transfer takes place inside these voids in addition to the conductive transfer of heat through the solid parts of the bricks[16]. It can be assumed that the corners and edges between windows and walls have only a small impact on heat flow.[5]

Thermophysical properties, such as thermal conductivity and volumetric heat capacity, can strongly influence the energy performance of the building envelope[18]. Different wall materials may have different thermal conductivity and volumetric heat capacity values; therefore, choosing the right building material is crucial to achieving good building energy performance.

Long and Ye [18] investigated the effects of thermophysical properties of wall materials on energy performance in an active building. In the study, a standard room with all potential wall materials was analysed to determine the relationship between thermal conductivity and volumetric heat capacity on energy performance. The standard room with of 240 mm and 100 mm thick exterior and interior walls respectively. The room was considered to have one exterior wall, 3 interior walls and no windows. It was further assumed that the temperature inside the room was maintained at 18 and 26°C in the summer and winter seasons, respectively. The temperature was maintained via ventilation and air conditioning facilities.

The findings for external walls from the study are as follows:

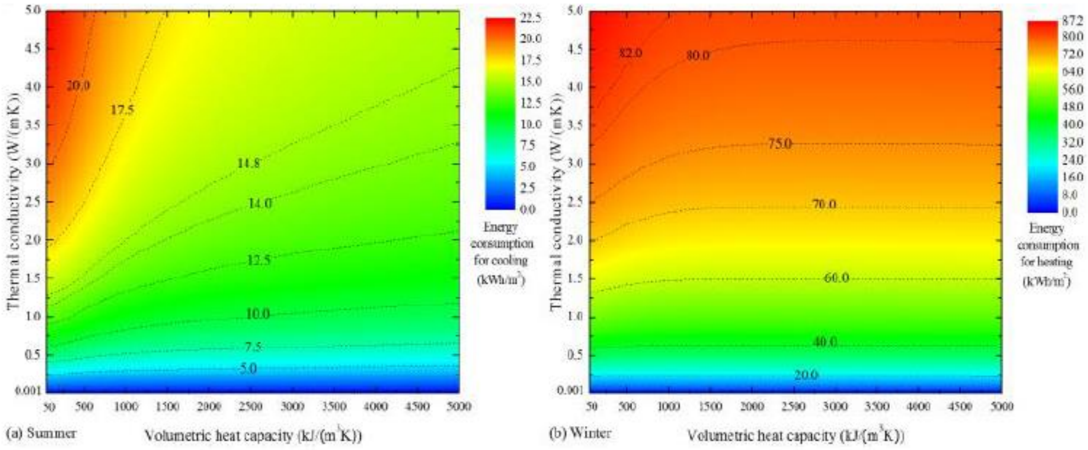


Figure 2.3 - Energy Consumption Contours Related to the External Walls in Summer and Winter[18]

From Figure 2.3 it can be seen that, the contours differ in heating and cooling seasons. In summer, with a material that has a low thermal conductivity (k value), the volumetric heat capacity (C_v) value has little effect on the energy consumption for cooling. As the k value increases, the C_v value has more of an effect as the gradient of the energy consumption contours increase. In winter, the general tendency is consistent with that in summer, however the slope of the contour lines is almost zero when the C_v value increases greater than 2000 kJ/(m^3K). This means the C_v value has limited influence in winter.

The findings for internal walls from the study are as follows:

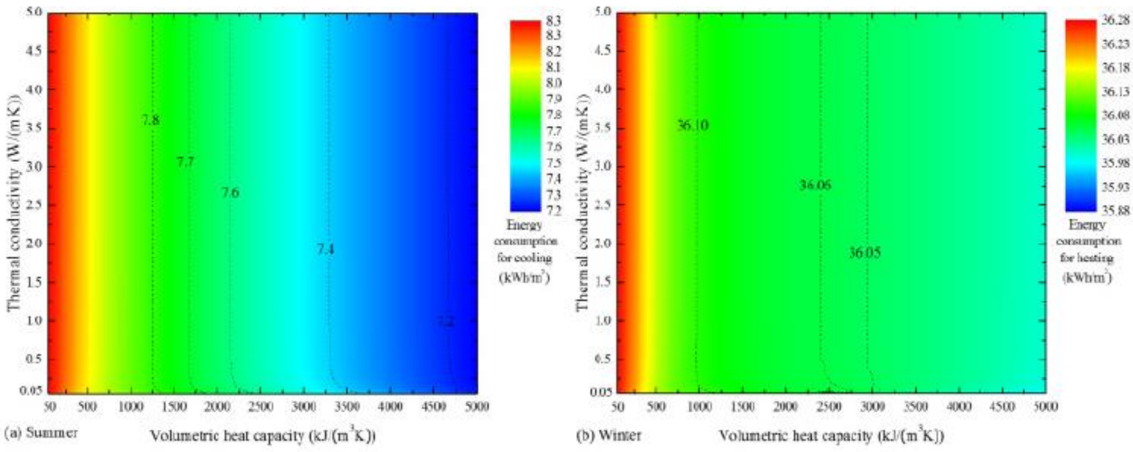


Figure 2.4 - Energy Consumption Contours Related to the Internal Walls in Summer and Winter [18]

As can be seen in Figure 2.4, the relationship between thermal conductivity and volumetric heat capacity varies for external and internal walls. This is to be expected since the internal walls are not subjected to the outside environment where the temperature gradient is larger. In both summer and winter periods, the C_v value has a large effect on energy consumption when the k value is greater than 0.5 W/ (m·K). However, the energy consumption is greater in winter than in summer. The corresponding energy consumption ranges in Figure 2.3 are much larger for the external wall, which means the role of the external wall is greater on energy consumption, meanwhile it has greater potential for improvement.

The study therefore concluded that, for an external wall, the thermal conductivity of the materials should be low, and the volumetric heat capacity of the materials should be high [18]. For internal walls, the volumetric heat capacity plays a significant role on the energy performance and should be kept as high as possible [18]. The thermal conductivity should also be high, but a k value of greater than 0,5 W/(m·K) is unnecessary [18]. These requirements of the materials hold for all climatic conditions [18].

Heat transfer also takes place via radiation in walls. Thermal radiation energy is both absorbed and emitted from the material that the wall is constructed from. Depending on the material used, the wall's constant of emissivity will change. The constant of emissivity of the material has an effect on the radiative heat transfer according to the following equation whereby the heat transferred is directly proportional to the constant of emissivity:

$$Q = \varepsilon\sigma A(T_2^4 - T_1^4) \qquad (2.1)$$

Much like the thermal conductivity constant described above, the constant of emissivity of the building material will affect the energy required for heating and cooling.

2.7 Free-Cooling and Free-Heating

Free-cooling is the ability to store outdoor "coolness" during the night and supply indoor cooling during the day in summer [19]. While free-heating is the ability to store the solar radiation received during the daytime and supply indoor heating during the night in winter [19]. In principle, by using free-cooling or free-heating, temperatures within the comfortable region can be achieved throughout the year if the thermophysical properties of the building envelope are in the desired range.

Factors that influence free-heating and free-cooling include [19]:

- Outdoor climatic condition
- Internal heat source intensity
- Building configuration
- Wall thermal performance
- Mode of ventilation

By utilising free-cooling and free-heating, the reliance on unsustainable energy used for climate control can be minimised while maintaining an internal climate that favours human thermal comfort.

2.8 Building Envelope Thermal Storage

When designing a building to have an internal environment that meets thermal comfort requirements, designers must consider the seasonal energy requirements for heating and what the maximum demand will be at any time[5]. It is generally accepted that temperatures are lower at night than in the day. It is also considered that average temperatures in winter are lower than average temperatures in summer.

During the day, heat flows from the outside surroundings to the inside of the building (Figure 2.5). As the air temperature and external wall surface temperature decrease at night, heat flows outward at a greater rate than it flows into the wall from the inside (Figure 2.5). The walls of a building store heat captured during the day. The heat flow to the outside air is maintained at the expense of this stored heat, and a steady state equilibrium condition is only established when the store of heat is exhausted [16]. The thicker the wall the more heat it can store due to its thermal mass, and the longer it will take for the steady state equilibrium to be established.

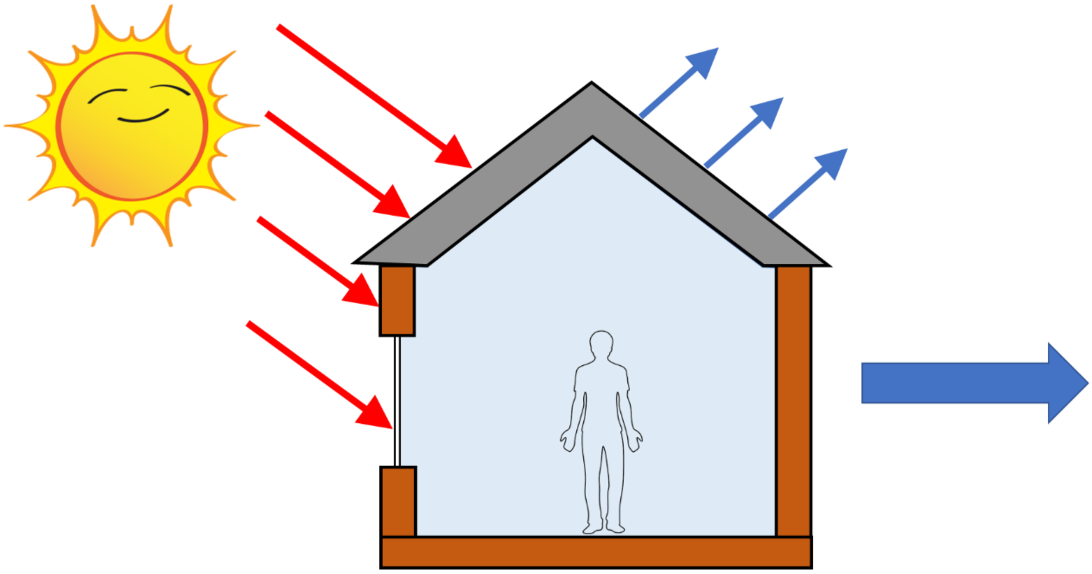


Figure 2.5 - Flow of Thermal Energy in a House

If the objective is always to maintain a uniform temperature indoors, the solid wall has a certain obvious advantage of a wall with small heat capacity. In the case of a thick solid wall, a constant heat supply will accomplish this objective. If a wall is constructed of hollow type bricks, its heat capacity will be lower than a solid wall and therefore may not be able to provide the necessary heat to maintain thermal comfort inside the building [16]. On the other hand, the building envelope can only absorb a finite amount of thermal energy during the day, so having a wall thermal storage capacity that exceeds this finite amount is inefficient.

The main objective of thermal storage in the building envelope is to balance the heat flux in and out of the house to maintain the temperature of the internal climate. An alternative way to maintain the temperature is by increasing the insulating properties of the building envelope. By adding insulation, the thermal energy gained, and thermal energy lost, is diminished thereby still maintaining the temperature of the internal climate to within the range for human thermal comfort. By combining the effect of thermal storage and insulation, optimum results can be achieved.

2.9 Dynamic Thermal Response

The energy demand on a building for heating and cooling is affected to some extent by its thermal stability, which is the ability to hold the internal temperature within a thermal range to achieve thermal comfort for its occupants. The buildings thermal stability is affected by the dynamic thermal response of its building envelope components, namely the exterior walls, internal walls, windows, roof, ceilings and floors. Solar radiation, external and internal temperature variations also influence a buildings thermal stability. The dynamic thermal response of these components is determined by their material thermal properties. [20]

The dynamic thermal characteristics of a building can be described by the thermal behaviour of its components when subjected to variable boundary conditions such as, variable heat flow rate or variable temperature on one or both sides of its boundaries [21]. As described in ISO 13786, these boundary conditions are only considered and applied as sinusoidal boundary conditions to emulate the natural cyclic temperature profile, when determining the thermal dynamic characterises of a building.

To relate cyclic heat flow rate to cyclic temperature variations, the properties of thermal admittance and thermal dynamic transfer are considered. Thermal admittance relates heat flow rate to temperature variations on the same side of a component [21]. Thermal dynamic transfer properties relate physical quantities on one side of a component to those on the other side [21]. From these properties of thermal admittance and thermal dynamic transfer, it is possible to determine the heat capacity of a given component and quantify the heat storage capacity of such component [21].

Thermal admittance can be used as an indicator of a material’s thermal storage capacity, or thermal mass. Absorbing heat from and releasing it to a house or room through cyclical temperature variations allows for the temperature variations on the inside of the house or room to be evened out, thus reducing the energy demand for air-conditioning systems [22].

To study the thermal response inside a wall, the theory of periodic thermal transfer is used [23]. Periodic heat transfer assumes that the temperatures of internal and external surfaces are simple harmonic waves with a period of 24 hours[23].

The dynamic thermal characteristics of building components that determine periodic heat transfer are admittance, transmittance and periodic thermal capacities. The periodic heat capacity is dependent on structure, thickness of masonry layers, surface resistance and the period of temperature variations.[20]

For thin walls of low thermal capacity, admittance and transmittance tend to the reciprocal of the total resistance for heat transmission through the wall. In very thick walls, transmittance tends to zero, and admittance tends to a constant value. Very thick walls are defined as walls that have a thickness of more than twice the periodic penetration depth. [20]

A study conducted on the effect of material composition and thickness on periodic thermal capacity of building components [20] has determined the physical properties, penetration depth and asymptotic value of the periodic heat capacity of various building materials. These findings can be seen in Figure 2.6 and Figure 2.7:

Material	λ [W/(m·K)]	ρ [kg/m^3]	c_p [J/(kg·K)]	δ [m]	χ_∞ [kJ/(m^2·K)]
Concrete	1.80	2400	1000	0.14	78.80
Brick	0.77	1800	880	0.12	62.96
Wood	0.16	550	2510	0.06	38.89
Cellular concrete	0.21	600	840	0.11	29.79
Polystyrene	0.04	30	1400	0.16	4.65
Mineral wool	0.04	90	750	0.13	5.85

Figure 2.6 - Physical Properties, Penetration Depth and Asymptotic Value of The Periodic Heat Capacity if Various Building Materials [20]

Where:
λ is the thermal conductivity coefficient.
ρ is the material density.
C_P is the material specific heat capacity.
δ is the periodic penetration distance from the surface of the wall.
χ_∞ is the periodic heat capacity for a very thick wall.

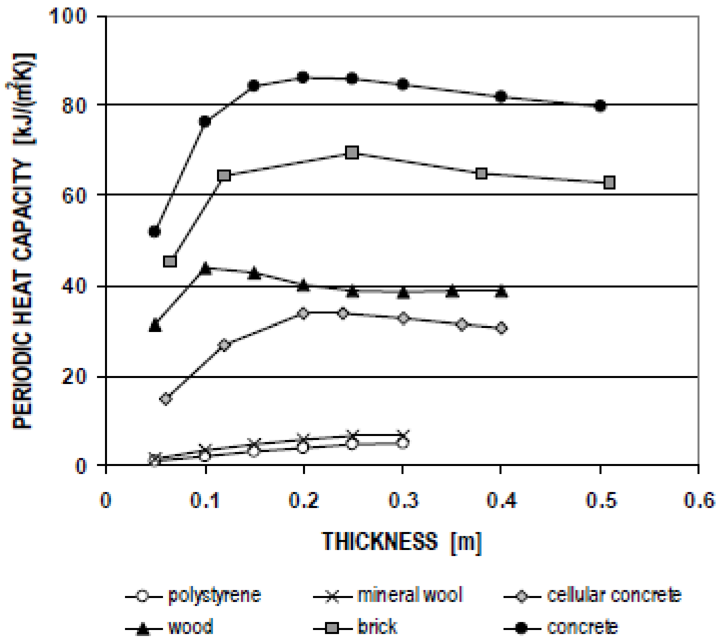


Figure 2.7 - Effect of Material Thickness Against Periodic Heat Capacity [20]

As can be seen from the results of the study, the type of building material that is used influences its periodic heat capacity. The thickness of the material also influences its periodic heat capacity. However, it is evident that the relationship between material thickness and periodic heat capacity is not simple. This relationship is dependent on the periodic penetration depth. The periodic heat capacity increases rapidly up until the periodic penetration depth, after which it plateaus and, in some cases, begins to decrease. This behaviour suggests that an optimum material thickness can be found for specific boundary conditions to maximise a components periodic heat capacity.

2.10 Insulation in Walls

To achieve thermal comfort for occupants in a residential house or building during cold winters and warm summers, insulation is an important factor. The insulation reduces unwanted heat loss or gain and therefore decreases the energy demand from heating and cooling systems. By decreasing the energy demand, it lowers both costs and emissions. Additionally, by reducing unwanted heat loss and gain, insulation extends the period of thermal comfort without the reliance on an air conditioning system.[24]

There are many types of insulation being used in houses or buildings. The insulation is typically used to insulate the roof and walls. The type of insulation, thickness and where it is located affects the magnitude of energy savings. Other factors that affect energy savings are the climatic conditions at which the building is located. One of the primary factors influencing the heat loss or gain is the insulating property of the material by which it reduces heat flow across it. [24]

Materials used in building insulation are chosen for their low thermal conductivity and ability to restrict heat flux through roofs and walls. The effect of insulation in a building is evaluated by its R-value. Materials with a high R-value reduce energy consumption for space heating in all climate zones, however, their impact is largest in climates with cold temperatures for many hours, and smallest in climates with a small number of cold hours per day. Materials with high R-values are also suited to enclosures that are exposed to direct solar radiation in hot climates.[24]

2.11 Wall Insulation Type, Thickness and Orientation

A study, on the thermal performance of different exterior wall structures based on wall orientation [25] was conducted. In the study, insulation models of opaque walls with different orientations and external, internal and sandwich insulation materials were numerically analysed in terms of their time dependent thermal behaviours. The one-dimensional transient heat conduction equation was solved via the implicit finite difference method for summer and winter conditions in northern, southern, eastern and western orientations.

Climate data from Izmir, a city in Turkey was used in the calculations. Izmir has a Mediterranean climate with summers that are generally hot and winters which are temperate. In this climate zone, cooling loads are as important as heating demand. The heat loss and heat gain for different insulation configurations and orientations can be seen in Figure 2.8:

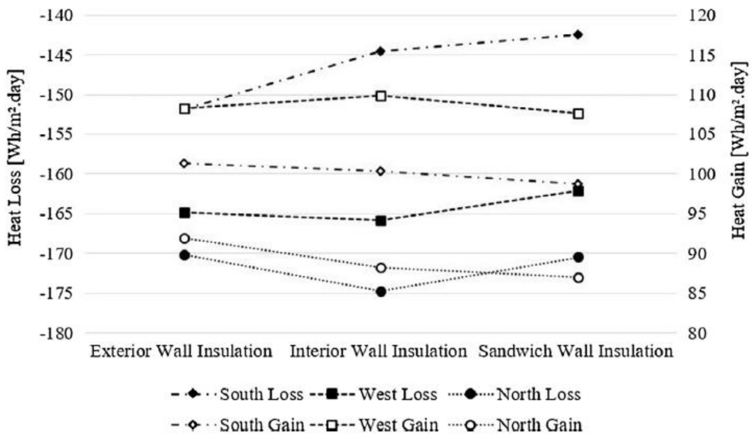
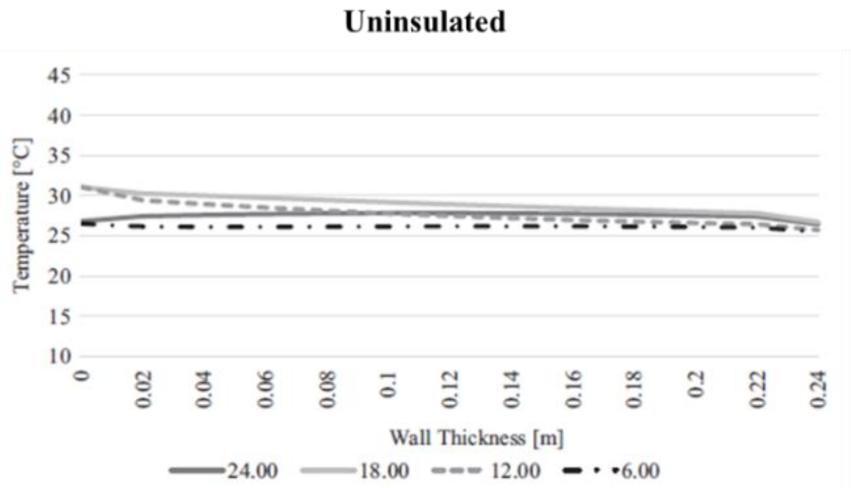


Figure 2.8 - Daily Total Heat Transfer for Different Insulation Types and Orientation [25]

These results represent the heat loss and gain through a $1m^2$ section of wall with different insulation configurations. Exterior wall insulation has insulation on the outside of a wall only. Interior wall insulation has insulation on the inside surface of the wall only. Sandwich wall insulation has an insulation layer inside the middle of the wall. As can be seen from these results, the sandwich wall type insulation preforms better than the other types for heat loss and heat gain. The way in which the walls are orientated has a large effect on their heat gain and loss.

The temperature distributions and heat transfer rates were calculated on a north facing wall in July (summer) at different times of the day for increasing wall thicknesses. Both uninsulated and sandwich insulation types of walls were used. These results can be seen in Figure 2.9:



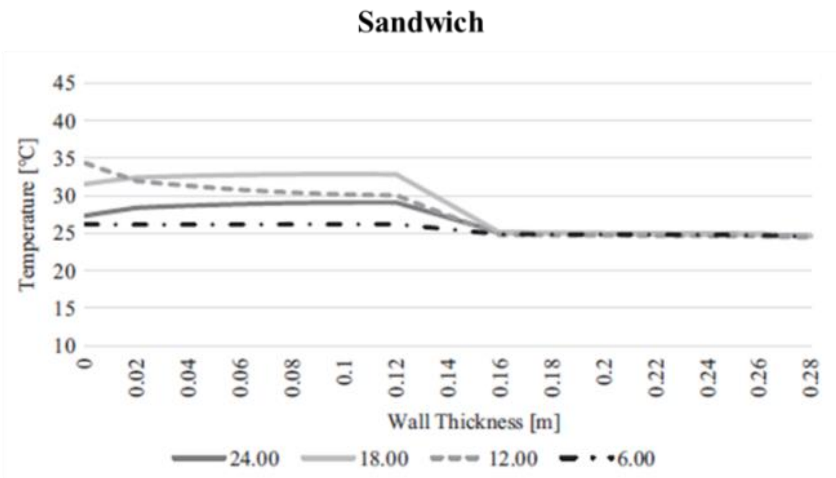


Figure 2.9 - Temperature Distributions for an Uninsulated And Sandwich Type Wall [25]

The result of the study shows that in both cases, when the wall thickness is small, the variation in temperature throughout the day is large. As the wall thickness increases this variation gets smaller. In uninsulated walls, the variation in temperature seems to converge to a value as the thickness increases. However, in sandwich insulated walls, the variation in temperature is greatly reduced at a wall thickness of 0,16 m and thereafter remains constant. This would suggest that a sandwich type wall has a critical thickness of 0.16 m.

2.12 Temperature and Humidity in Housing

A study was conducted on the indoor temperatures in low cost housing in Johannesburg, South Africa by [26]. In the study, the indoor temperature and humidity values were recorded inside different types of dwellings using a data logger over a period of four months from February to May. The types of dwellings used for the study were: formal housing, pre-1994 low cost housing, post-1994 low cost housing, apartments/flats, and informal settlement housing. Each type of dwelling is comprised of different building materials. A breakdown of these materials as obtained from the study can be seen in Figure 2.10:

Housing Type	Exterior Walls: Main Construction Material per House	Floor: Main Type of Flooring Used	Ceilings Type	Roof Material
Formal housing (Bertrams) *n* = 10	100% Bricks	10% cement 50% wood 40% tiles	100% ceiling boards	40% clay tiles 60% corrugated zinc roof (IBR) sheeting
Old pre-1994 low cost housing (Riverlea) *n* = 13	100% Bricks	31% cement 69% tiles	100% ceiling boards	15% corrugated zinc roof (IBR) sheeting 85% asbestos
Post-1994 low cost housing-RDP (Braamfischerville) *n* = 15	100% Bricks	67% cement 33% tiles	7% ceiling boards 93% no ceiling	100% asbestos
Apartments/Flats (Hillbrow) *n* = 13	100% Bricks	84% wood 8% tiles 8% vinyl	100% cement	100% Concrete
Informal settlement housing (Hospital Hill) *n* = 8	62% Bricks 25% Corrugated metal sheets 13% Dry wall	25% cement 12% tiles 38% vinyl 25% carpet	75% no ceiling 12% wood 13% boards	100% wood and corrugated zinc roof sheeting

Figure 2.10 - Building Materials per Housing Type [26]

The study theorised that the different building material compositions of these dwellings would influence the level of thermal comfort experienced in each dwelling. The results of the indoor temperature and relative humidity as recorded during the study can be seen in Figure 2.11 and Figure 2.12:

Month	February		March		April		May	
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Ambient	20.2 (0.7)	14.1–28.5	18.3 (1.4)	11.4–26.2	15.6 (1.7)	2.5–25.3	15.9 (2.3)	4.7–25.7
Braamfischerville (*n* = 15)	25.7 (4.2)	16.2–39.0	22.5 (3.7)	14.7–36.6	20.1 (4.5)	6.6–33.1	19.6 (4.7)	6.7–33.1
Riverlea (*n* = 13)	25.1 (2.2)	19.3–33.3	22.6 (2.2)	17.5–31.6	20.3 (2.8)	11.7–29.2	19.6 (3.1)	10.9–28.5
Hospital Hill (*n* = 8)	23.6 (4.3)	15.0–45.4	21.3 (3.9)	12.8–40.2	19.3 (4.8)	6.1–39.4	19.2 (5.2)	6.6–37.5
Bertrams (*n* = 10)	24.7 (2.1)	19.6–34.9	22.2 (2.1)	16.6–31.1	20.2 (2.2)	12.7–29.3	20.3 (2.2)	12.7–28.1
Hillbrow (*n* = 13)	24.4 (1.4)	19.3–28.7	22.5 (1.5)	17.4–30.3	21.5 (1.9)	15.9–28.5	22.3 (2.4)	16.9–30.7

Figure 2.11 - Monthly Indoor and Ambient Temperatures [26]

Month	February		March		April		May	
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Ambient	78.6 (8.1)	65.0–90.0	81.8 (10.3)	47.0–93.0	67.5 (16.9)	21.0–94.0	54.4 (17.2)	28.0–83.0
RDP houses (Braamfischerville, *n* = 15)	54.7 (11.3)	20.5–87.3	65.8 (13.1)	14.1–93.8	52.8 (13.2)	12.1–91.4	48.8 (12.9)	16.9–85.4
Low cost houses (Riverlea, *n* = 13)	54.9 (8.7)	27.9–79.7	65.5 (10.9)	21–93.9	52.1 (11.5)	14.3–92.4	47.6 (11.5)	14.3–93.5
Informal houses (Hospital Hill, *n* = 8)	61.5 (13.8)	18.3–87.9	69.4 (13.0)	16.2–93.4	54.7 (14.7)	10.1–88.4	47.4 (14.0)	13.1–84.2
Formal houses (Bertrams, *n* = 10)	54.1 (8.1)	21.7–73.4	63.4 (10.1)	19.9–84.5	49.0 (9.8)	15.2–75.8	41.7 (9.1)	13.3–66.4
Flats (Hillbrow, *n* = 13)	56.4 (6.6)	31.2–89.5	64.1 (8.9)	20.5–90.1	49.0 (10.1)	11.2–83.0	42.0 (10.0)	10.8–72.5

Figure 2.12 - Indoor and Ambient Relative Humidity [26]

As can be seen from these results, the mean indoor temperature exceeded that of the mean ambient temperature for all types of dwellings. This is to be expected due to the dwellings being able to absorb and retain heat from solar radiation. The result of interest is the range of temperatures inside the dwellings. The apartments in Hillbrow show the smallest range in temperature fluctuation with temperatures inside the thermal comfort range. This means that the indoor temperature is stable throughout the 24-hour periodic cycle. The informal houses on hospital hill showed the largest range in temperature fluctuation, with temperatures exceeding the thermal comfort range.

The results of the study show that the mean relative humidity for all dwellings is lower than the ambient mean. However, in all dwellings the range of relative humidity is large with all ranges exceeding the thermal comfort range of 30 – 65%. The greatest variation in relative humidity occurred in the informal houses and RDP houses.

The results of indoor temperature and relative humidity were then compared to the building materials used in the different types of dwellings. These results for wall materials can be seen in Figure 2.13:

Temperature

Wall Materials	February	March	April	May
Stone (n = 2)	24.7 (2.0) 19.3–30.2	22.5 (2.0) 17.6–29.7	20.1 (2.6) 11.7–24.9	19.6 (3.0) 12.4–25.2
Brick (n = 53)	24.9 (3.1) 15.5–45.4	22.4 (2.8) 13.5–40.2	20.5 (3.4) 6.4–39.4	20.4 (3.8) 6.6–37.5
Iron sheets (n = 2)	22.1 (4.8) 15–36.1	20.0 (4.4) 12.8–33.6	18.0 (5.8) 6.1–33.2	17.9 (6.4) 7.3–33.7
Dry wall (n = 1)	24.4 (1.8) 21.2–29.4	21.8 (1.6) 17.8–26.4	19.6 (1.9) 14.4–24.2	19.4 (2.2) 14.4–25.1

Relative Humidity

Wall Materials	February	March	April	May
Stone (n = 2)	55.3 (8.5) 31.2–70.5	65.3 (10.4) 24.4–91.6	51.8 (10.2) 18.7–78.8	45.0 (10.1) 15.7–67.5
Brick (n = 53)	55.6 (9.8) 18.3–89.5	65.2 (11.3) 14.1–93.9	51.3 (11.9) 11.2–92.4	45.6 (11.9) 10.8–93.5
Iron sheets (n = 2)	63.7 (16.8) 23.8–87.9	70.6 (16.2) 19.8–93.4	52.5 (18.7) 10.1–88.4	44.6 (18.0) 13.1–84.2
Dry wall (n = 1)	59.1 (6.9) 40.6–69.4	67.9 (7.2) 46.9–80.7	54.3 (7.7) 27.8–69.9	48.7 (8.5) 25.2–65.4

Figure 2.13 – Monthly Indoor Temperatures and Relative Humidity by Wall Material [26]

The results of the study show that the mean indoor temperature for all wall materials is very similar. However, the range of temperatures differs between the wall materials. Dwellings made from bricks have the largest temperature ranges, and dwellings made with dry wall have the smallest temperature range. As the RDP houses are constructed from hollow concrete bricks, large improvements can be made to the wall material of the house to increase thermal stability and improve thermal comfort.

The mean relative humidity results are also similar for all wall materials. Once again, bricks have the largest range in relative humidity readings, while dry wall have the most stable relative humidity range that is closest to the range required to achieve thermal comfort.

The bricks used in RDP houses are single wall thickness (150mm) and constructed from cement. This results in a high thermal conductivity between outdoor and indoor temperatures. The increased thermal conductivity and reduced thermal mass of the wall result in the dwelling being very sensitive to external temperature changes.

2.13 Windows

Window design in buildings and houses has a significant impact on the heating and cooling energy demand due to the heat loss or gain that enters through the building envelope. It is important that windows be designed to minimise the heat gain in summer and heat loss in winter. The orientation, size and thermal properties of the window frame material have an impact on the heating and cooling energy demand. [27]

The window is an important element in the building envelope that performs several functions which include: supplying daylight, providing outside views, and acting as a natural ventilation system. Additionally, it can play a part in the architectural appearance of the house or building. However, the window is considered the weakest thermal link in the building envelope for heat gain in summer and heat loss in winter [27]. Even though windows are a small percentage of the building envelope, they have the greatest effect on heat flow when compared to the walls, roof and floors. Therefore, by improving the design of windows, a large improvement can be made on decreasing building energy use.

The thermal performance of windows is specified by three factors [27]:

- Thermal Transmittance (U-value)
- Total solar energy transmittance (g-value)
- Air leakage (L)

These three factors are used to describe the heat flow through a window. The U-value is the heat transfer rate per temperature difference between the inside and the outside of the window per square meter [27]. The g-value is the total solar energy transmittance through a window. It is also known as the solar heat gain coefficient [27]. Air leakage increases the thermal performance of a building due to the incoming air heating or cooling the indoor air temperature [27].

The solar energy that enters through a window represents the largest source of heat gain and therefore, may increase the indoor temperature above the outdoor temperature. This increase occurs due to the radiant heat being trapped inside the building by the window glass. This is known as the greenhouse effect..

The amount of heat gained and lost through the windows is influenced by the location of the windows within the building envelope and the window to wall area ratio (WWR). The larger the area of the window, the more solar radiation and light is allowed in. The direction the window faces also affects the amount of solar radiation allowed in due to the orientation and path of the sun as it moves throughout the day. [28]

A study was carried out on the impact of the orientation, size, and glass material of windows on the heating and cooling energy demand of the Gaza Strip buildings [27]. The study conducted a computer simulation on a room model, varying the room orientation, window size and glass material. The simulated room can be seen in Figure 2.14:

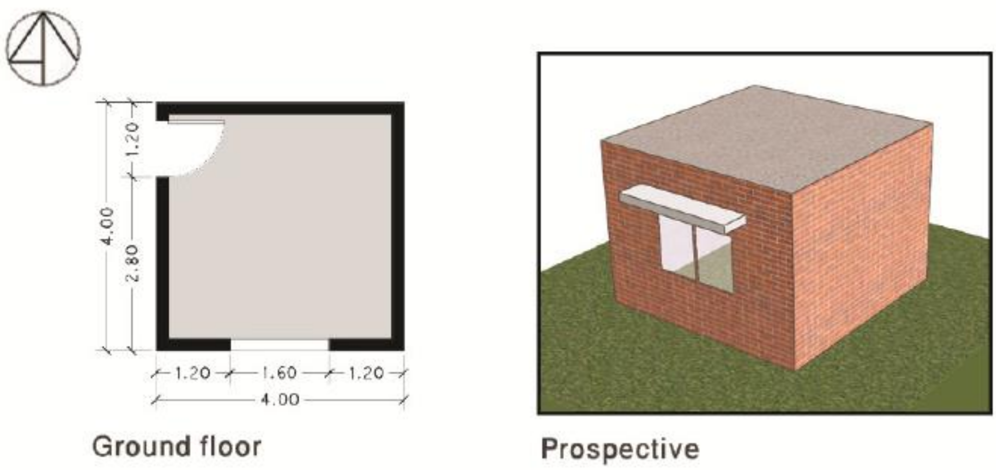


Figure 2.14 - Ground Floor and Perspective View of Room Model [27]

The climate of the Gaza Strip is hot and humid, which is similar to the hot and humid climate in South Africa, and more specifically Cape Town. It is located the same distance away from the equator as Cape Town, however, in the northern hemisphere. Therefore, the results from the study can be applied to some buildings constructed in South Africa.

The orientation of the room was changed from the façade facing East through 180° to face West. The orientation was changed in increments of 10°. Figure 2.15 shows how the orientation of the room was changed and includes the results of the simulation.

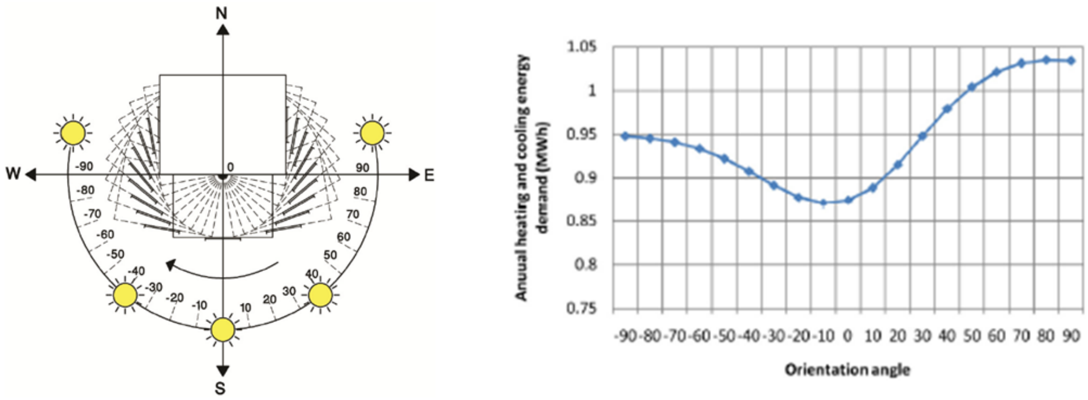


Figure 2.15 – Changing Room Orientation From East to West [27]

The results of the study show that to achieve the lowest annual heating and cooling energy demand, the room should be orientated with a south facing façade and the long axis of the room running from east to west. The heating and cooling energy demand is influenced mainly by the window position in relation to solar radiation and radiation intensity, according to sun azimuth and altitude angles. Therefore, the long axes of a building should preferably face north and south because they receive lower heat loads from solar radiation.

The window to wall ratio (WWR) was changed in the simulation to determine the effect of the WWR on the heating and cooling energy demand for a façade facing north, east, south and west. The WWR was varied from 0% to 90% in increments of 10% for each simulation. Windows in the vertical and horizontal orientation were also tested to see if it influenced the heating and cooling demand. The results for this study can be seen in Figure 2.16:

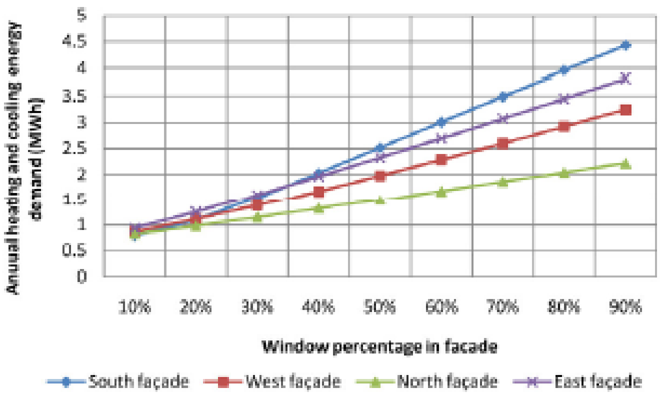


Figure 2.16 - Energy Demand for Different WWR [27]

The results of the study show that by increasing the window size in each façade, the heating and cooling energy demand increases. The direction in which the façade faces also influences the energy demand due to the variable amount and intensity of solar radiation which enters through the facades. The orientation of the window being vertical or horizontal did not have a significant on the results. Therefore, the WWR should be minimised to reduce the heating and cooling energy demand on the building. However, although minimising the window size reduces the energy load, it also reduces the amount of natural light inside the room.

Furthermore, the study evaluated the effect of window size on the amount of natural light inside the room. For residential spaces, the acceptable range of light intensity is between 100 and 300 lux to maintain visual comfort. To achieve a light intensity in this range, the study concluded that a WWR of 10% is sufficient in most scenarios.

The thermal properties of glass material were analysed in the study. It was found that the material does influence the heat loss and heat gain through the window. Six types of glass materials were used in the simulation and the energy demand for heating and cooling was analysed. The six types of materials and their thermophysical properties can be seen in Figure 2.17:

	U-Values ($W/m^2.k$)	Transparency (0-1)	Solar Heat Gain Coeff. (0-1)
U1: Double glazed with timber frame, emissivity of 0.10	2.26	0.92	0.75
U2: Double glazed with aluminum frame, emissivity of 0.10	2.41	0.92	0.75
U3: Double glazed with timber frame	2.90	0.92	0.75
U4: Translucent skylight	5.00	0.81	0.78
U5: Single pane of glass with timber frame	5.10	0.92	0.94
U6: Single pane of glass with aluminum frame (no thermal break)	6.00	0.92	0.94

Figure 2.17 - Thermophysical Properties of Different Materials [27]

The study concluded that there is a direct correlation between the U-Value and energy demand. As the U-Value increases, the energy demand increases. It is therefore recommended that a material with the lowest U-value be chosen to reduce the heating and cooling energy demand.

2.14 Types of Windows

There are three main materials that are used to construct the window frames in residential houses. These materials are plastic, aluminium and wood [29]. Each material has its own advantages and disadvantages.

Plastic window frames are durable against all meteorological conditions, especially in high humidity. They require very little maintenance due their sealed seams and joints, and do not require additional finishes to protect the frame. Plastic is by its nature an insulating material; and therefore, reduces the noise inside the room by providing acoustic insulation. It is also a good thermal insulator which allows the room to retain heat for longer.[29]

Aluminium window frames are incredibly durable due to their high strength properties when compared to plastic and wood. Aluminium has a high strength to weight ratio which results in a frame that is of lightweight construction. Aluminium has a good resistance to corrosion, and therefore, it does not require any maintenance. The cost of aluminium windows is relatively high due to the energy intensive and costly process of producing them. Aluminium has a high thermal conductance, which results in a great deal of heat loss from the room. [29]

Wooden window frames are also very durable, however, in harsh weather conditions they may require a large amount of maintenance or special attention. The wood used may contain defects, such as cracks, that compromise the strength of the material. However, wood does have an excellent strength to weight ratio which results in lightweight construction of the frames. Wooden frames in most parts of the world are considered to be aesthetically pleasing due to the attractive appearance of natural materials. Wood has low thermal and acoustic conductivity resulting in lower noise inside the building, and the ability for the space to remain warmer for longer. [29]

A study on appropriate window types concerning energy consumption for heating [30] was done. This study compared the calculated values of the daily average hourly heat loss per unit area of building envelopes having different window types was conducted. Double glazed wooden and plastic sashes were used in the comparison.

Firstly, the study determined the optimum values of the thermophysical properties (overall heat transfer coefficient and transparency ratio) of the building with different window types. Secondly, the values of daily average hourly heat loss per unit area of the building envelope related to the optimum values of the thermophysical properties was determined. Finally, based on the average hourly heat loss per unit area of the building envelope, these values were compared for each window type to determine the window with the least heat loss.

The results from the study show that the plastic window type has a lower U-Value than the wooden type window for all transparency ratios in all orientations. The results also show that the daily average hourly heat loss is lower for the plastic type windows than the wooden type windows.

2.15 Solar Load

Solar radiation emitted from the sun enters the Earth's atmosphere and transfers thermal energy to objects that it interacts with. The largest parts of the energy from the sun can be found in the visible, infrared and ultraviolet spectrum. The incoming radiation is responsible for the fluctuating daily temperatures and changes in season [31].

The Earth revolves around the sun while the Earth also rotates on its own axis. This results in the 24-hour day to night cycle where a specific location on the surface of the earth experiences sunlight for a certain number of hours during the day, while receiving no sunlight at night-time. The Earth's centre axis is not parallel to the sun's centre axis, which results in the change of seasons as shown in Figure 2.18.

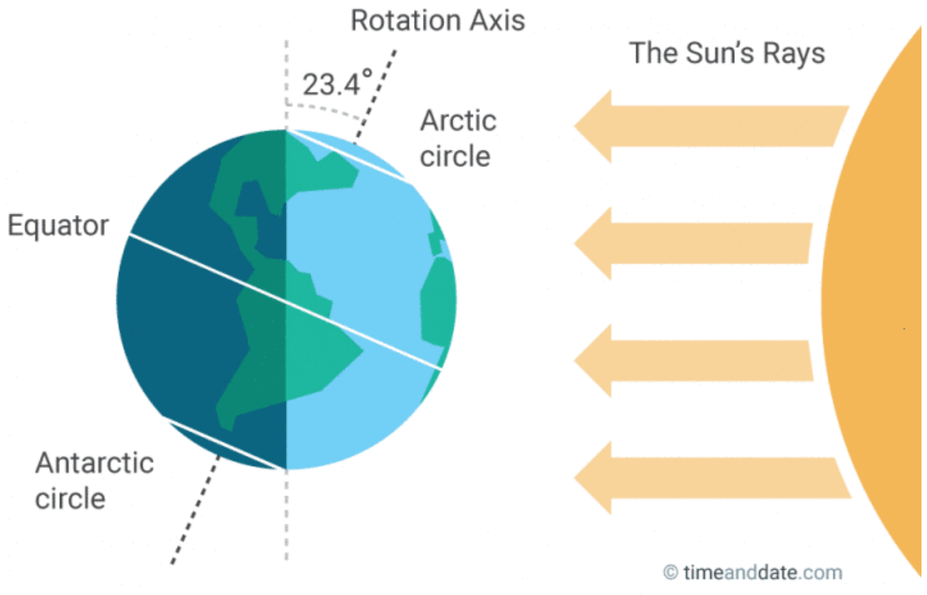


Figure 2.18 - Earth's Axis of Rotation [32]

The offset in angle of rotation changes the angle between the path of the sun and the horizon as the earth rotates around the sun as shown in Figure 2.19. This results in a change in the amount of sunlight hours and solar radiation intensity [33]–[38].

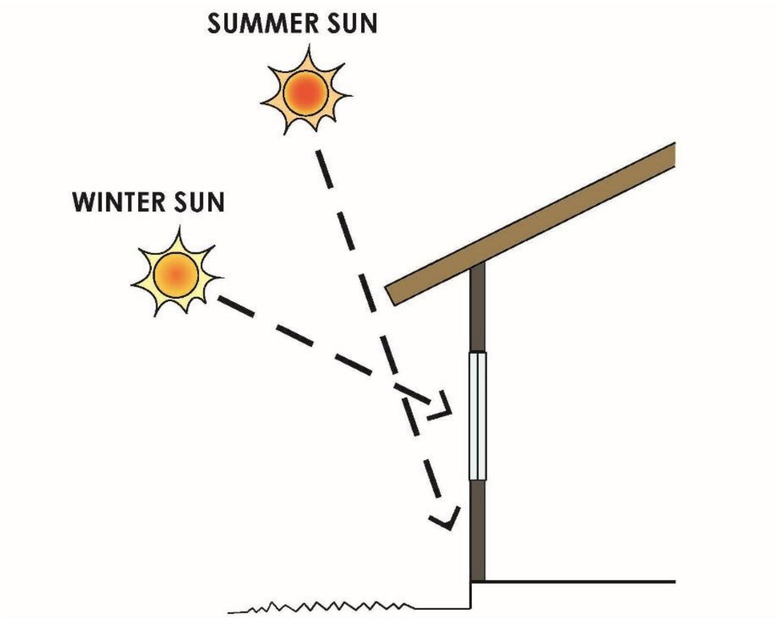


Figure 2.19 - Summer and Winter Sun [39]

The angle between the sun and Earth's surface is known as the altitude angle. As the altitude angle changes throughout the year, the solar loading changes on solid surfaces. For example, in South Africa, the north facing wall of a house receives more direct sunlight in winter than in summer due to the altitude angle approaching that of the walls normal vector [40].

Not all the solar radiation emitted from the sun reaches the surface of the Earth. Approximately 30% is reflected off the atmosphere, 17% is absorbed by the atmosphere and 53% reaches the Earth's surface [31], [36]–[39]. When calculating the total solar load experienced by an object on the surface of the earth, these losses should be taken into account.

2.16 Emissivity

The types of building materials used in the construction of residential houses and buildings have demonstrated great potential for controlling the heat transfer properties of the building envelope as a whole [42]. The thermophysical properties of these materials ultimately affect the heat transfer properties and consequently affect the internal climatic conditions.

Low-emissivity materials can be used in both opaque and transparent areas of the building envelope to reduce heat transfer through thermal radiation [43]. Depending on the weather conditions, a reduction in the radiative heat transfer may lower the cooling needs in summer and lower the heating needs in winter [43]. This can be achieved by reducing the amount of heat transferred via radiation through the building envelope in summer and reducing the amount of heat allowed to radiate out of the house in winter.

For transparent areas in the building envelope, such as window glazing, a coating can be applied to lower its constant of emissivity, and in some cases be selective in the electromagnetic wavelength that is allowed through [43][44]. These coatings may be applied by the manufacturer during the manufacturing process, or after the installation of the window.

Opaque parts of the building envelope may have low-emissivity foil products or spray coatings applied to them to reduce their emissivity. By applying these solutions to opaque areas, it has been found that the heat transfer has reduced significantly [43].

2.17 Shading Devices

The most effective way to reduce solar load on a building's windows is to intercept the direct radiation from the sun before it reaches the glass [45]. Shading devices, such as overhangs, side fins, external roller shades and blinds, can influence the solar energy on a window and the transmitted energy within a room which has entered through the window [45].

Well-designed shading devices can reduce the heat transfer and cooling requirements of buildings. They can also improve the user visual comfort by controlling glare and reducing contrast ratios. Shading devices can also have an aesthetically pleasing effect on the exterior of the building and allows the opportunity of differentiating one building façade from another.[45]

All exterior shading devices need to allow for air to move freely to carry away heat absorbed by the shading and glazing materials [45]. Energy transferred through the window depends on many parameters, such as the type of window, overhands and side fins, and selecting the optimum window is very difficult.

A study on the effect of external shading and window glazing on energy consumption of buildings in Bangladesh was conducted by [45]. The study made use of computer simulation on a simple single-story building constructed of masonry walls and a single 1 m^2 window. The type of shading and window configuration was altered for each simulation and the coefficient of performance (cp) was calculated by using equation (2.2):

$$cp = 100 \times \frac{E_a - E_b}{E_a} \tag{2.2}$$

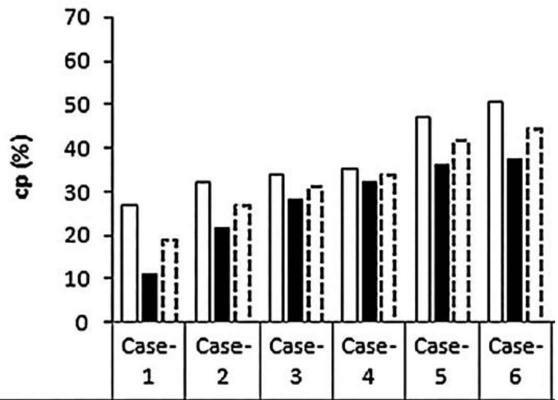
Where E_a is the total energy that is transferred into the building from a single clear pane glazing without overhangs or side fins. E_b is the total energy that is transferred into the building from the new simulated window.

Six different cases were simulated, each with different configurations of overhang above the window and side fins alongside the window. For each case a window with single clear glazing was used. Figure 2.20 shows a description of the cases:

Case	Overhangs (m) Width	Depth	Distance above the window (m)	Side fin with 1 m width: Depth of the right side (m)	Depth of the left side (m)
1	1.1	0.5	–	–	–
2	1.1	1	–	–	–
3	2	1	–	–	–
4	2	1	0.2	–	–
5	2	1	–	1	–
6	2	1	–	–	1

Figure 2.20 - Overhang and Side Fin Configurations [45]

The results from the simulations are as follows:



	Case-1	Case-2	Case-3	Case-4	Case-5	Case-6
Cooling Period	26.8	32.19	33.93	35.43	47.14	50.62
Heating Period	11.01	21.56	28.35	32.12	35.89	37.40
Year	18.90	26.88	31.14	33.78	41.52	44.01

Figure 2.21 - Coefficient of Performance for Each Case

Results of the study show that, shading devices increase the windows ability to save energy by a minimum of 18.90% over a year. As the amount of shading increases, so does the cp value, which is to be expected due to the decreased solar radiation that enters the window. It is important to ensure that the size of the shading device used does not restrict the amount of natural light in the room or effect visual comfort.

2.18 Natural Convection

Natural convection is described as the movement of particles due to the interaction of the density difference with the gravitational or some other body force. A density difference is caused due to a temperature difference that exists between the particles of a medium. [46]

In the case of a vertical wall in a dwelling, with the wall having a surface temperature T_s and the air having a temperature T_a. If the wall surface temperature is greater than the surrounding air temperature, the fluid adjacent to the wall becomes heated, consequently becomes lighter, and rises. Fluid from the neighbouring areas rushes in to take place of the rising fluid and so the process continues. If the temperature difference was reversed and the wall was colder than the surrounding air, the fluid layer adjacent to the wall will become cooled, consequently become heavier, and sink. [46]

The heat transfer from the vertical wall surface may be expressed in terms of a linear relationship between the heat transfer rate Q and the temperature difference between the wall surface and surrounding air. The equation for this linear relationship is as follows:

$$Q = hA(T_s - T_a) \tag{2.3}$$

Where h is termed the convective heat transfer coefficient and A is the total surface area of the vertical wall. The convective heat transfer, h is dependent on the flow configuration, fluid properties, dimensions of the heated body and the temperature difference.

It is important to note that the fluid velocity at the wall surface becomes zero due to the no-slip condition with demands that there be no relative motion between the wall surface and fluid layer directly adjacent to it. The mode of heat transfer from the wall surface to the fluid in its immediate vicinity is therefore by conduction.

A velocity profile whereby the further away from the wall, the faster the fluid velocity becomes, up until the point of maximum velocity is reached and the velocity decreases once again to zero as the temperature difference in the ambient air becomes zero.

CHAPTER 3:

NUMERICAL MODELLING

3.1 Introduction

This chapter gives an overview of how Computational Fluid Dynamics (CFD), a numerical modelling method, can be used to model engineering problems that involve fluid flow and energy transfer. CFD uses digital computers to produce quantitative predictions of fluid flow phenomena based on the conservation laws governing fluid motion. CFD involves discretising geometry or spatial domain into a mesh of cells which have a finite volume and solving the governing equations over these cells to numerically determine the fluid or energy flow over the entire spatial domain.

This numerical modelling technique was used in this work to model a simple house and solve for the internal climatic conditions experienced inside, as well as fluid flow data. The process required to create a numerical model that will determine the effect of the building envelope geometry and properties on the internal climatic condition of a simple house is shown in Figure 3.1:

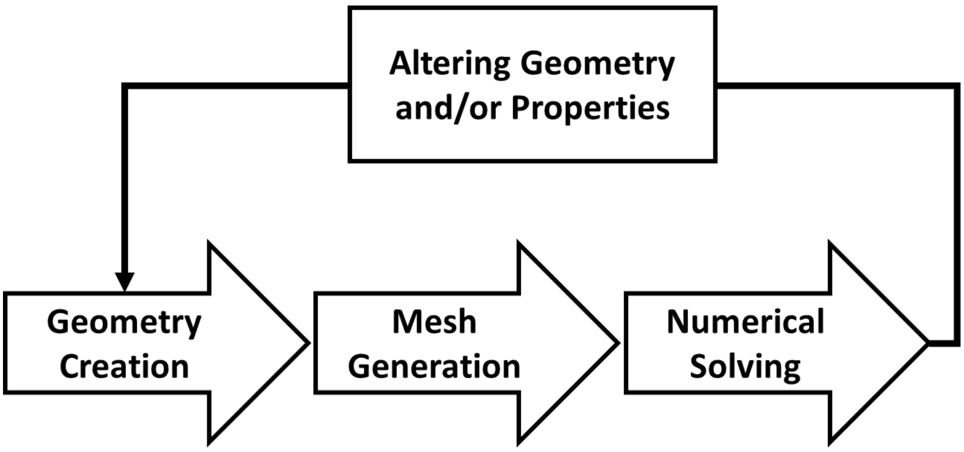


Figure 3.1 - CFD Numerical Modelling Process Flow Path

3.2 Geometry

To numerically solve how the geometry of the walls and windows of a simple house effect the internal climatic condition, a geometric model of a simple house was created to analyse the wall and window geometry.

The geometric design of the house was based on a standard low-cost brick house typically found in the rural areas of South Africa. The basic internal dimensions (Figure 3.2) of the house measured 7 x 7 x 2.4 m, excluding the height of the roof. It was decided that the internal volume of the house should remain constant to keep the volume of air inside, that is to be heated and cooled, constant.

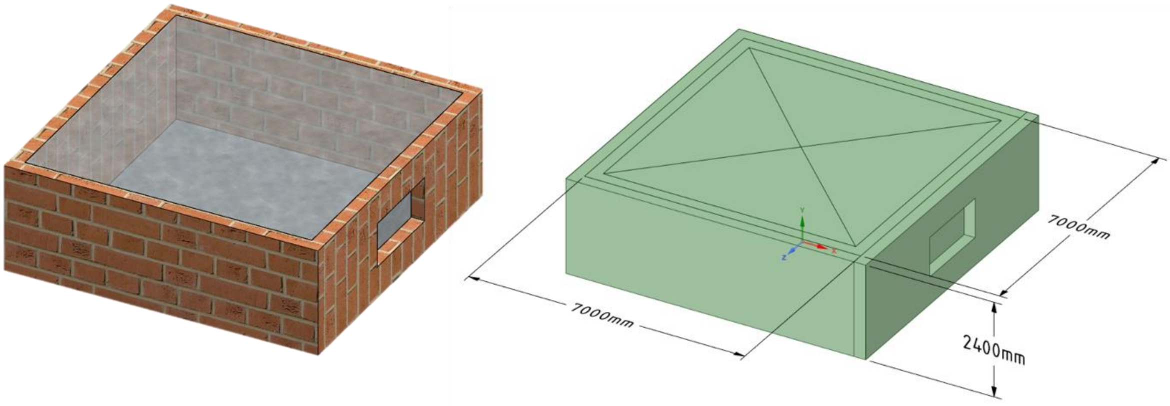


Figure 3.2 - House Internal Basis Dimensions

The building geometry consists of four walls, a single window with single glazing and an internal air space. The fluid domain that contains the air was split into five sections: 4 prisms that allow for a swept mesh to be created, and a boundary air space that can contain a finer mesh with inflation layers to best describe the flow of air in the boundary layer.

The thickness of the walls and size of the window were configured so that they can easily simulate various building envelope geometries as described in CHAPTER 4 - NUMERICAL PROCEDURE.

3.3 Mesh

To numerically solve the governing equations using the finite volume method, the geometry of the model needs to be broken up into finite cells called a mesh. The mesh of the geometry described in section 3.2 is displayed in Figure 3.3.

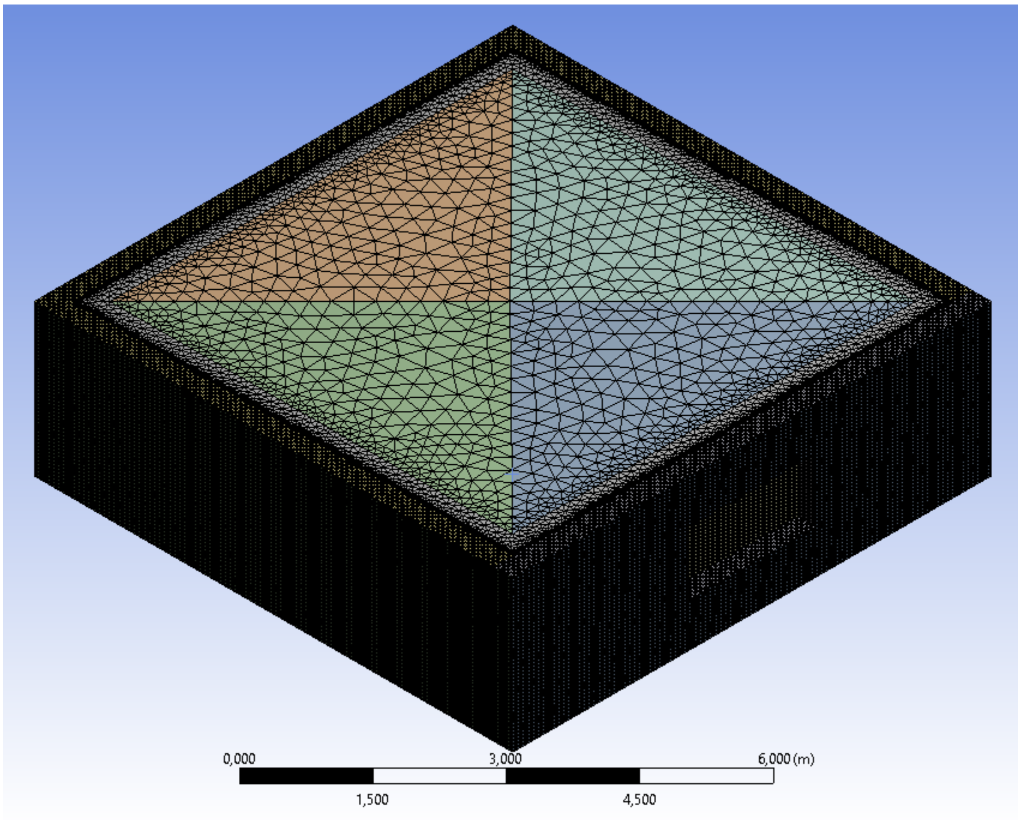


Figure 3.3 - Geometry Mesh

The mesh has been created using the Ansys Fluent meshing package. The mesh has been refined in such a way to analyse the heat transfer through the building envelope, heat transfer from the building envelope to the fluid domain and the behaviour of the boundary layer of air near the building envelope. Therefore, a fine hexahedral mesh has been applied to the walls, and inflation layers have been applied where the fluid domain meets the solid domain.

To reduce the computational requirements, a coarse mesh has been applied to the prism fluid domain sections. The fluid movement and boundary interactions in this area are of a lesser importance, therefore the mesh can be coarse.

3.4 Governing Equations

To solve an engineering problem where the characteristics of fluid flow and heat transfer are of interest, the nonlinear governing equations of conservation of mass, momentum and energy are used to describe these characteristics.

3.4.1 Conservation of Mass

In the Eulerian specification of fluid flow, the principal of conservation of mass states that the rate of change in mass of a control volume must be equal to the net flow rate of mass into the control volume. The integral form of the conservation of mass equation is given as:

$$\frac{\partial}{\partial t}\int_V \rho dv = -\oint_S \rho \boldsymbol{u} \cdot \boldsymbol{n} ds \tag{3.1}$$

3.4.2 Conservation of Momentum

The conservation of momentum equation is a statement of Newton's Second Law and relates the sum of the forces acting on a finite volume of fluid to its acceleration or rate of change in momentum. The integral form of the conservation of momentum equation is given as:

$$\frac{\partial}{\partial t}\int \rho \boldsymbol{u} dv = \int \rho \boldsymbol{f} dv + \oint \big(\boldsymbol{nT} - \rho \boldsymbol{u}(\boldsymbol{u} \cdot \boldsymbol{n})\big) ds \tag{3.2}$$

3.4.3 Conservation of Energy

The law of conservation of energy states that the total energy of an isolated system remains constant because energy is not destroyed but is transformed from one form to another. In CFD, only mechanical and thermodynamic energy contributions are described using the integral form of the conservation of energy equation given as:

$$\frac{\partial}{\partial t}\int \rho \left(e + \frac{1}{2}u^2\right) dv = \int \boldsymbol{u} \cdot \rho \boldsymbol{f} dv + \oint \boldsymbol{n} \cdot \left(\boldsymbol{uT} - \rho \left(e + \frac{1}{2}u^2\right) - \boldsymbol{q}\right) ds \tag{3.3}$$

3.5 Numerical Solution Schemes

The solutions of the mass, momentum and energy conservation equations was achieved through numerical approximation scheme. The purpose of any discretisation method is to transform one of the more partial differential equations into a system of linear algebraic equations. The discretisation process comprises of two components; the discretisation of the computational domain by creating a mesh of the geometry and the discretisation of the governing equations as described by the finite volume method and solving algorithm.

3.5.1 Finite Volume Method

Ansys uses the Finite Volume Method to solve the governing equations of fluid flow. This method is based on discretising the integral form of the governing equations over each control volume. Based in a fixed Cartesian coordinate system, the governing equations can be solved at specific spatial locations on a mesh that does not change. The control volumes can be of any polyhedral shape and have a variable number of neighbouring control volumes creating a structured mesh. This method can be applied to both steady-state and transient calculations.

3.5.2 The Coupled Algorithm

In Fluent, flow problems can be solved using a pressure-based solver in either a segregated or coupled manner. The coupled scheme obtains a robust and efficient single-phase implementation for steady-state flows. For transient flows, where the quality of the mesh is poor or large time steps are used, the use of the coupled algorithm is necessary.

The coupled algorithm solves the momentum and pressure-based continuity equations together which results in more stable and faster convergence of the solution compared to the segregated algorithm.

3.5 Boundary Conditions

Once the geometry and mesh have been created, boundary conditions need to be applied to the mesh. These boundary conditions provide information to the solver when solving the governing equations.

When simulating a simple house and analysing the effect of the building envelope on the internal climatic conditions, the following boundary conditions needed to be applied. All boundaries not mentioned are set to adiabatic boundary conditions.

3.5.1 Exterior of Building Envelope

The exterior of the building envelope includes the surfaces of the walls and window glazing on the exterior of the house. A mixed boundary condition was applied to the exterior building envelope that incorporated radiation to simulate solar loading, temperature to simulate outside air temperatures and convection to simulate heat being lost to the outside air through convection.

3.5.2 Interior Building Envelope

The interior of the building envelope includes all the surfaces of the walls and window glazing on the interior of the house. A coupled boundary condition was applied to these surfaces to allow the transfer of thermal energy between the solid and fluid domain.

3.5.3 Floor

The floor of a house acts as a constant thermal sink. Therefore, a constant temperature boundary condition was applied to the floor.

3.6 Solar Load Model

To set boundary conditions for solar loading on the building envelope of a house, a solar load model needs to be applied. Unfortunately, Fluent does not have a built-in solar load model for transient state simulations. Therefore, a solar load model for a transient state simulation needed to be created and applied in Fluent.

3.6.1 Model Overview

Fluent has a built-in solar load model for steady state simulations which takes inputs of location and the time of day, to calculate the magnitude of direct solar radiation, and then applies it to the model. The same approach was taken when creating a solar load model for the transient state in this study.

To calculate the magnitude of direct solar load, a solar load calculator w created as seen in APPENDIX A – Solar Load Calculator. The calculator takes inputs of the date, time of day and location, and outputs the magnitude of direct solar radiation on vertical surfaces for each cardinal point.

Once the magnitude of direct solar radiation for each cardinal point is calculated, a transient table was created by calculating the direct solar radiation magnitude every 60 seconds for a 24-hour period. The transient table (.ttab file) is a suitable format to be inputted into Fluent. Fluent can extract the solar radiation magnitude from the table for a specific time step in the simulation and apply it as a specified boundary condition.

3.6.2 Solar Boundary Condition

Once the magnitude of the solar radiation is calculated, it is applied as a boundary condition to the model. There are various methods in which the solar radiation can be applied as a boundary condition, and these methods are investigated and discussed in APPENDIX B – Solar Boundary Condition Investigation.

From the investigation it can be concluded that the Semi-Transparent Film Boundary method should be used. This method uses a 1mm film that covers the total surface area of the exterior wall. This film is set to be semi-transparent and the incident solar radiation is then applied to the film using a radiation boundary condition.

This method was chosen because it most accurately replicated the mechanism in which solar radiation transfers thermal energy to the building envelope in a real-world environment. The film is heated by the solar radiation and the heat generated is transferred to the building envelope via conduction.

3.7 Temperature Function

The outdoor environment air temperature fluctuates throughout the day due to solar radiation interacting with it and other objects in the environment that transfer thermal energy to the air. During daylight hours the air temperature increases until the sun sets, after which the air temperature decreases. The temperature function plotted against time looks like a sinusoidal function in the theoretical ideal case as shown in Figure 3.4.

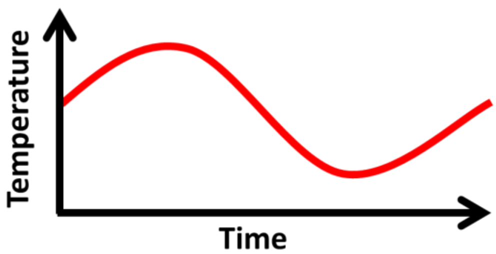


Figure 3.4 - Temperature vs Time Function

To incorporate this variation of outdoor air temperature into a simulation, a user defined function (UDF) needed to be created to apply the temperature function as a boundary condition. The mathematical procedure in creating the UDF is detailed in APPENDIX C – Sinusoidal Temperature Function, and the actual code used in writing the UDF is detailed in APPENDIX D – Temperature UDF.

Once the UDF is coded it could be interpreted in Fluent and the appropriate boundary conditions could be set to simulate the temperature fluctuations over a 24-hour period.

3.8 Natural Convection

The mechanism of thermal energy transfer between the building envelope and the air inside of the house is by convection, or more specifically, natural convection. Natural convection is caused by thermal energy being transferred to the boundary air layer, which causes the temperature of the air in the boundary layer to increase which results localised reduction in the air. This localised reduction in density of the air causes the affected warm air to rise. As this warm air in the boundary layer rises, cool air rushes in to replace it. The new cool air that enters the boundary layer heats up and so the cycle continues causing a continuous natural flow of air. A visual description of natural convection as shown in Figure which shows how a hot egg interacts with the air surrounding it [47].

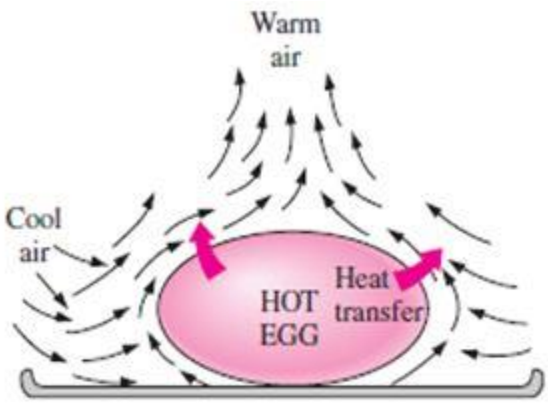


Figure 3.5 - Visual Description of Natural Convection [47]

The movement or flow of air caused by natural convection aids in the distribution of thermal energy throughout the inside of the room.

To simulate the effect of natural convection in Fluent, the fluid domain needs to be set up in a very specific way. The effect of gravitational acceleration was turned on to allow the change in density of the air to influence its buoyancy. The density properties of air were changed from constant to Boussinesq which enables its density to change as a function of temperature. These two changes to the fluid domain allow for natural convection to be simulated.

3.9 Output Parameters

Once the governing equations have been solved and the solution has stabilised for one timestep, certain output parameters are recorded that can be analysed in post processing. The output parameters that are important to determining the effect of the building envelope geometries on the internal climatic conditions of a house include: the average air temperature inside of the house, and the magnitude of average heat transfer to and from the house.

The average air temperature gives an indication as to how the building envelope geometry performs when comparing the temperature profile results from simulations of varying geometry. Knowing the average room temperature also provides information that can be used to validate the model.

The magnitude of average heat transfer to and from the house gives an indication on the thermal state of the house, i.e. is the house gaining or losing heat? Knowing this output parameter also provides information that aids in validating the model.

A temperature contour plot of the solid and fluid domain was also created to give a visual representation of the temperature. This temperature contour plot was recorded for each timestep and then animated to show how temperature varies with time within the house. This animation is very important in validating the model as it confirms whether the set boundary conditions are correct, and it visually shows the thermal energy being dispersed throughout the house.

CHAPTER 4

NUMERICAL PROCEDURE

4.1 Introduction

This chapter outlines how each element of the building envelope was modelled and simulated to determine its effect on the internal climatic conditions of a simple house as outlined in Chapter 3. The model of the simple house was created using Ansys, the simulation was executed in Fluent solver and the results were recorded for analysis.

4.2 Weather Conditions

To simulate the model of a simple house, the environmental conditions to which the house is exposed to needs to be incorporated into the simulation. Weather factors that influence the temperature of an object placed into an environment include: ambient temperature, windspeed, humidity and solar intensity. For the purpose of this study, the effects of windspeed and humidity have been omitted due to their complexity in modelling. Modelling windspeed and humidity is challenging due to the capabilities of Ansys Fluent and would exceed the complexity required of a master's dissertation.

The location of the house influences these weather factors, since climates may change with location. For the purpose of this study, Cape Town, South Africa has been chosen as the location. In all the calculations carried out the longitude, latitude and time zone are required as inputs, the respective values for Cape Town were used.

In this study, typical weather conditions from summer and winter were used as inputs to the model since they accounted for conditions on either end of the seasonal spectrum. The dates 15 June and 15 November were chosen as inputs to use for the solar load calculator since they represent a typical day in winter and summer respectively. Based on the temperature data acquired from the South African Weather Service (SAWS) [48], a user defined function was made to create a time dependant temperature function that was used as an ambient temperature boundary condition for summer and winter.

4.3 Wall Thickness

As described in [12 – 15], the thickness of the exterior walls of the building envelope may influence the internal climatic condition depending on the thickness of the wall, material of which it is comprised of and the outside environment to which it is exposed to. For the purpose of this study the walls are to be constructed from fly ash. The following material and thermophysical properties for fly ash were used as inputs to Fluent when creating the numerical model [49]:

$$\rho = 1200 \frac{kg}{m^3} \tag{4.1}$$

$$Cp = 857 \frac{kJ}{kg \cdot K} \tag{4.2}$$

$$k = 0.36 \frac{W}{m \cdot K} \tag{4.3}$$

Fourier's Law is an expression of conductive heat transfer. Since the method of heat transfer within the wall is conduction, Fourier's Law is applied. The equation states that the thickness of the material is conversely proportional to the rate of heat transfer, i.e. the thicker the material, the lower the rate of heat transfer:

$$Q = \left(\frac{k}{s}\right) A \Delta T \tag{4.4}$$

Where s is the thickness of the material through which condition takes place.

To determine the effect of building envelope wall thickness. Wall thicknesses ranging from 100 – 400mm were selected to represent thin walls to thick walls. Numerical models were solved in 100mm increments. The output variables obtained from the simulation include the average temperature of the fluid domain inside of the house (average room temperature) for each timestep, and the average rate of heat flux entering the fluid domain inside the house.

The average room temperature can be compared for each increment of the wall thickness to determine whether the wall thickness effects the internal climate temperature range, global average and general profile. The average heat transfer rate can be used to determine the effect that the insulating properties have on the changing temperature of the internal climate.

4.4 Window Size

As described by [12 – 15], the size of the window installed into the building envelope influences the potential for thermal energy transfer between the environment and the interior of a house. This is achieved by allowing solar radiation to penetrate the building envelope through the window, and creating a point in the building envelope that has a great potential for thermal conduction.

For the purpose of this study, only single clear glazed windows was used. This is because single glazed windows are most commonly used in South Africa. Double or multi glazed windows are only used when required. To simplify the model and isolate the effect of the size of a window on the internal climate, only a single window situated on the north façade was used. The north façade was chosen as the location of the window due to the zenith angle of the sun having the greatest effect on north facing vertical surfaces when transitioning between summer and winter seasons.

Standard 6 mm thick window glass was used as specified by the SANS 10400 Building Regulations. The material and thermophysical properties of window glass that were used as inputs to Fluent are:

$$\rho = 2500 \frac{kg}{m^3} \tag{4.5}$$

$$Cp = 0.8 \frac{kJ}{kg \cdot K} \tag{4.6}$$

$$k = 1.0 \frac{W}{m \cdot K} \tag{4.7}$$

To determine the effect the size of a window has on the internal climatic condition of a simple house, three variations in window size were created in the numerical model: 1x1 m, 1x2 m and 1x3 m. Where rectangular windows were used, they were in the landscape orientation. The average temperature of the fluid domain inside of the house (average room temperature) for each timestep was computed as a numerical output.

The average room temperature can be compared for each window size to determine its effect on the internal climate of the house. Summer and winter conditions was simulated to determine how the sun's zenith angle effects the amount of solar radiation that penetrates the building envelope, and consequently, the change in average room temperature.

4.5 Emissivity

In thermodynamics, the rate of radiation heat transfer is directly proportional to the material's constant of emissivity:

$$Q = \varepsilon\sigma A(T_2^4 - T_1^4) \quad (4.8)$$

Where ε is the material's constant of emissivity.

This relationship can be used to control the radiative heat transfer to and from the building envelope. Therefore, as literature suggested, if the constant of emissivity is decreased and the consequent radiative heat transfer is decreased, then the average room temperature inside of a house or building will decrease.

For this project the emissivity of the exterior walls and window glazing was altered to determine their effect on the internal climate of a simple house. To test these effects the standard numerical model with an exterior wall thickness of 300mm and a single 1x2m single glazed window on the north façade was simulated. The external constant of emissivity of the exterior surfaces of the wall and glazing material were then altered.

4.5.1 Wall Emissivity

To determine the effect the exterior wall constant of emissivity has on the internal climate of a simple house, the external constant of emissivity was increased at a time step of 0.25 in a range of 0.25 – 1 each time the numerical model is solved.

Only the exterior surface of the exterior wall will have the external constant of emissivity altered. The walls' interior surface external emissivity remain unchanged at 1. This is because the study is interested in determining the effect that solar radiation has on the changing constant of emissivity and not the radiation on the inside of the house.

The average room temperature was recorded for each timestep and the average room temperature profile for each constant of emissivity will be compared to determine the effect of the constant of emissivity on the internal climate.

4.5.2 Window Emissivity

To determine the effect the window glazing constant of emissivity has on the internal climate of a simple house, the external constant of emissivity will be incremented by 0.25 in a range of 0.25 – 1 each time the numerical model is solved.

Commercially available low emissivity glass has a nano film of silver on its exterior surface which reduces its emissivity. The same effect was simulated in the numerical model by only altering the external constant of emissivity of the exterior surface of the window glazing.

In Fluent, the solid domain that comprises the window glazing, has been set to be semi-transparent. This means that the radiation was coupled to the solid cells.

The average room temperature was recorded for each timestep and the average room temperature profile for each constant of emissivity was compared to determine the effect of the constant of emissivity on the internal climate.

CHAPTER 5:

NUMERICAL RESULTS

This chapter presents the results obtained from the computational simulations performed using Ansys Fluent. These results are analysed and discussed to conclude their significance.

5.1 Solar Load

The term solar load is used to describe the radiation energy that penetrates the atmosphere and can interact with bodies. The solar load describes the energy from the sun that is applied to a surface of the building envelope. Using the solar load calculator in Appendix A, the solar loads applied to each exterior wall surface have been calculated. The resulting solar load profiles for both summer and winter are presented in Figure 5.1 and Figure 5.2:

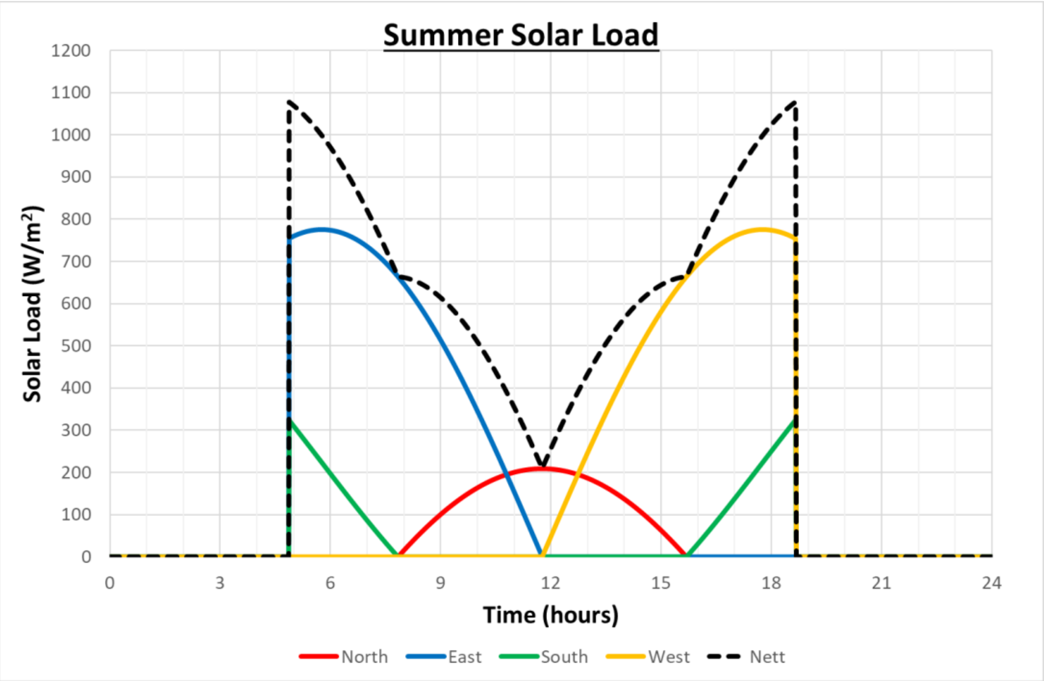


Figure 5.1 - Summer Solar Load Profile

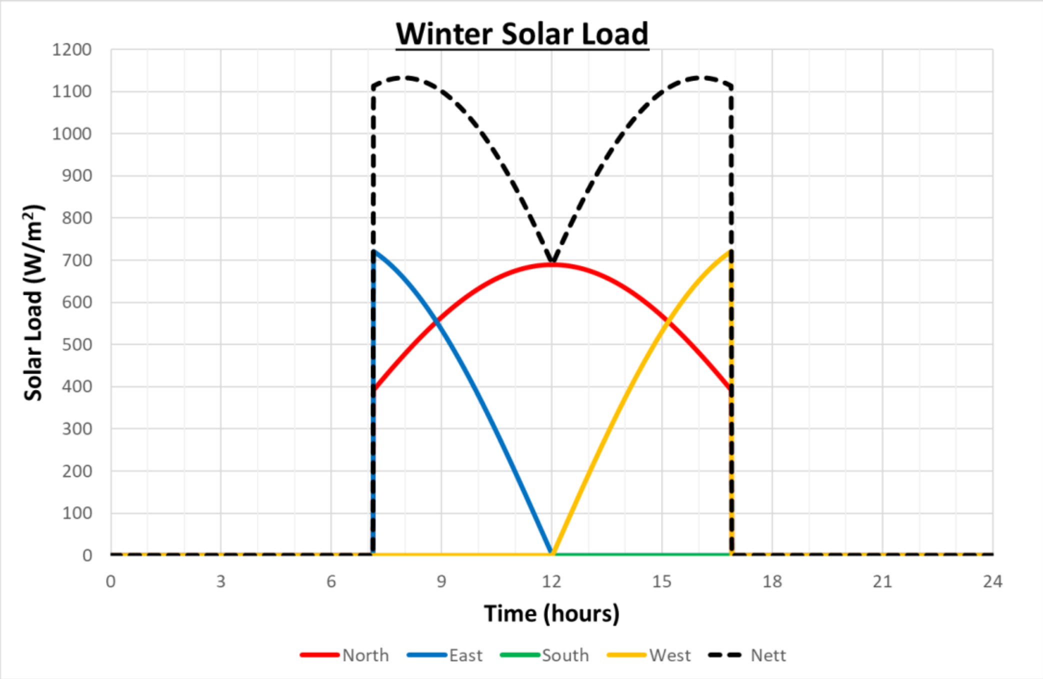


Figure 5.2 - Winter Solar Load Profile

As expected, the solar loading profiles are different for summer and winter. This is due to the change in sun angle and light hours. In figure 5.1 and 5.2, the broken black line indicates the nett solar load the house experiences at any given time. The area under these nett solar load curves quantifies the total solar energy the house receives throughout the 24-hour cycle. The magnitude of total solar energy was calculated using an integral sum to determine the area under the nett solar load curve (Figure 5.2). Therefore, during summer, a simple house will receive a total of 9320 W/m^2 of solar energy and in winter will receive 9780 W/m^2 on its exterior walls.

The amount of solar energy received by the walls is greater in winter than in summer, even though summer has more light hours. This is due to the sun angle allowing for more direct solar radiation on the walls in the wintertime. Therefore, there is more scope for the exterior walls to play a role in absorbing solar energy in winter.

5.2 Model Validation

To ensure the accuracy the results outputted from the simulations, the model needs to be validated. The model may be validated against empirical data, or specific test conditions with a known analytical output that the designed model should be able to replicate as close as possible. The accuracy of the model is a measure of how close the outputted results are compared to the empirical data or expected analytical results. The model created for this project was validated in three stages:

5.2.1 Solid Wall with Sinusoidal Boundary Condition

To validate the Fluent heat transfer model in the unsteady state, a test was performed whereby an isentropic and homogeneous solid wall was considered to have infinite length was subjected to a sinusoidal temperature pattern on one of its sides. The top and bottom surfaces are considered as adiabatic. The temperature of the walls centre of mass was recorded and compared to the analytical model.

The solids material has been set to be aluminium characterised by:

$\sigma = 2719$ kg/m^3 (5.1)

$c_p = 871$ J/(kgK) (5.2)

$\lambda = 202.4$ W/(mK). (5.3)

The sinusoidal boundary condition has been made equal to the equation:

$$T_{sin} = 298.15 + 5\sin\left(1.73 \times 10^{-5} t\right) \tag{5.4}$$

T_{wall} has been set to 298.15 K.

The geometry of the solid is presented in Figure below. Since the geometry is very simple, a mesh with a structured grid comprised of 10 500 hexahedral cells has been chosen.

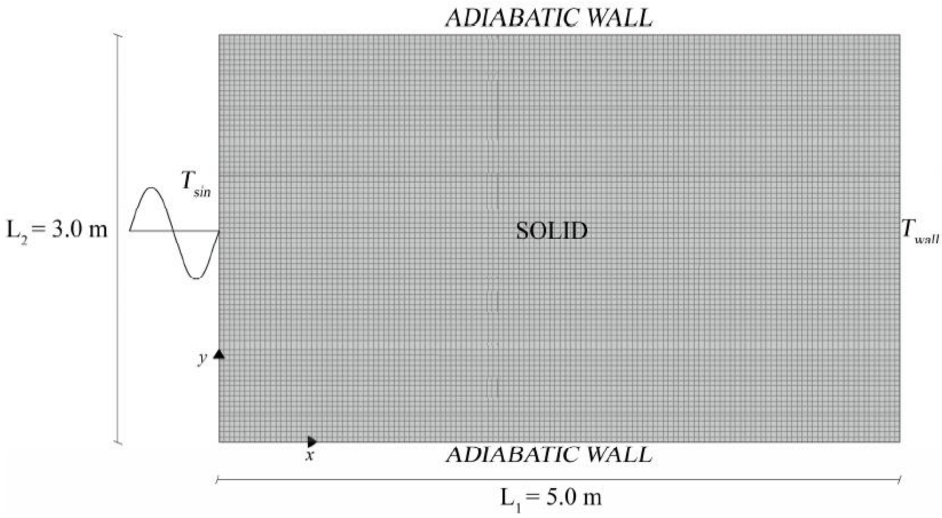


Figure 5.3 – Geometry of Solid Wall for Sinusoidal Boundary [48]

An article titled Computational Fluid Dynamic Modelling of Thermal Periodic Stabilized Regime in Passive buildings [48] conducted a similar simulation and obtained results seen in Figure 4, which can be used to validate the model created in Ansys Fluent.

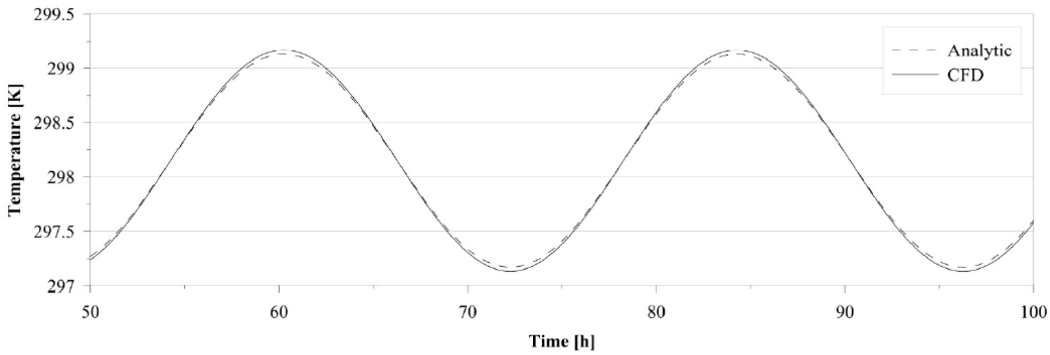


Figure 5.4- Results Achieved by [48]

The following results were achieved in Ansys Fluent and compared to that of the previous study:

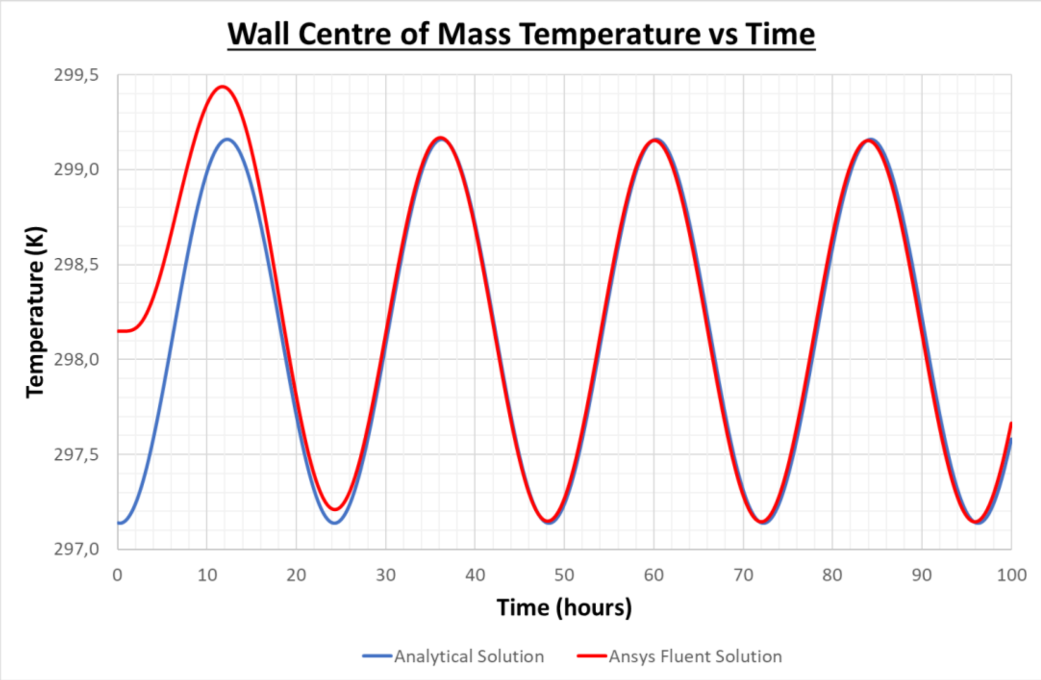


Figure 5.5 - Wall Centre of Mass Temperature vs Time

The results in Figure 5.5 show that the CFD solution matches the analytical solution very well. The results obtained also match the values and trend from the previous study by [48]. The CDF solution does take one cycle to stabilise, however this was expected. It should be noted however, that in the final simulation, adequate time should be given for the solution to stabilise so as not to skew the results.

Since the results from the Ansys Fluent model compare well to the previous study, the boundary conditions and setup used in this model may be applied to the model where the different elements of the building envelope are modelled to determine their effect on the internal climate of a simple house.

5.2.2 Heat Transfer from Solid to Fluid Domain

To validate the convective heat transfer and viscosity Fluent models in the unsteady state, a test was performed whereby a geometry consisting of a solid and fluid domain is subjected to an initial temperature boundary condition and then allowed to reach thermal equilibrium as time progresses.

The dimensions and layout of the geometry used in the test is shown in **Error! Reference source not found.** below:

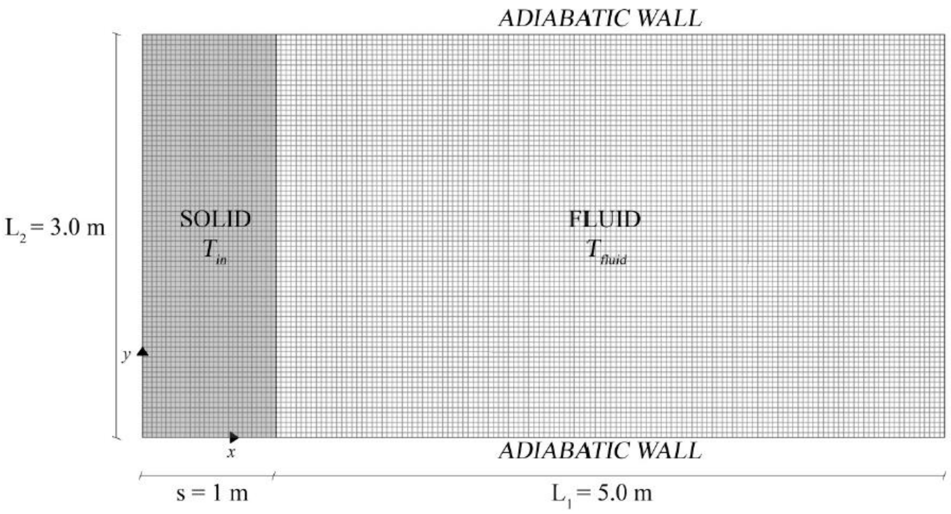


Figure 5.6 – Geometry and Layout of Solid and Fluid Domain

The temperature of the fluid domain has been kept constant with $T_{fluid} = 215.15\ K$ and the solid domain has been given an initial temperature of $T_{in} = 293.15\ K$. The heat transfer coefficient of the solid material has been set such that the rate of heat transfer is equal to 10 W/(m^2K). Both the top and bottom edges have been assumed to be adiabatic.

Since the geometry is simple, a structured grid has been composed with a cell size of 0.035 m, resulting in a mesh size of 12,700 hexahedral cells.

The temperature of the solid domain was determined by measuring the temperature of the solids centre of mass. Natural convection has been assumed as the method of heat transfer between the solid and fluid domains. To allow natural convection to be simulated, gravity was turned on and a Boussinesq model was applied to the density of air. A coupled solver was then used to solve the model.

Results from a similar study conducted previously titled Computational Fluid Dynamic Modelling of Thermal Periodic Stabilized Regime in Passive buildings [48] can be seen in Figure 5.7 below:

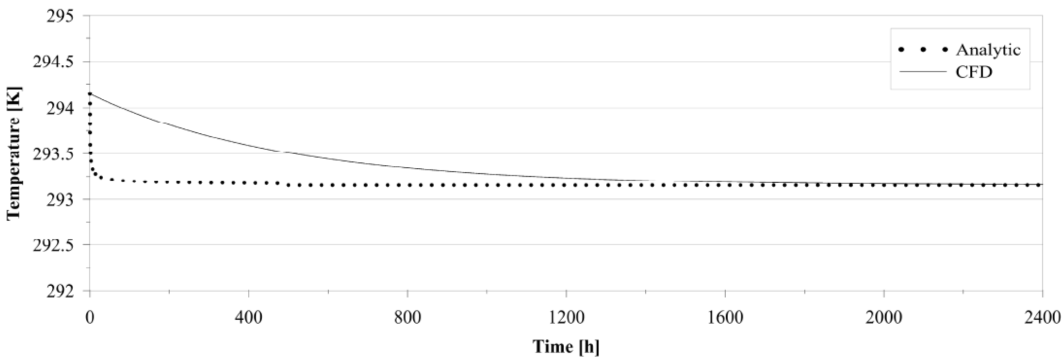


Figure 5.7 – Solid and Fluid Domain Results Achieved by [48]

The following results were achieved in Ansys Fluent and compared to that of the previous study:

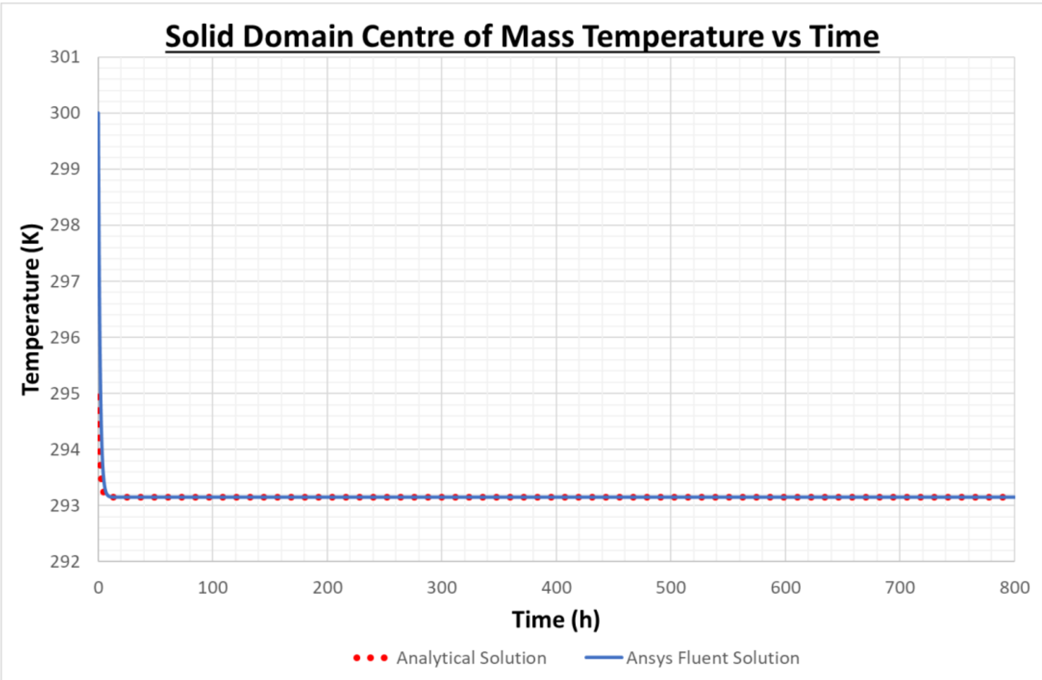


Figure 5.8 – Solid Domain Centre of Mass Temperature vs Time

As can be seen in Figure 5.8, the Ansys Fluent solution follows the analytical solution. The CFD solution does have a higher initial starting temperature, but this is due to the hybrid initialisation, and after a few time steps follows the analytical solutions temperature.

Since the results from the Ansys Fluent model compare well to the previous study, the boundary conditions and setup used in this model may be applied to the model where the different elements of the building envelope are modelled to determine their effect on the internal climate of a simple house.

5.2.3 Solar Load Model

To validate the transient solar load model that has been created for the purpose of this project, it has been compared to the solar load model that is built into Fluent. The inbuilt Fluent solar load model can only be used for steady state simulations, so to validate the new model, the steady state solutions from the Fluent model and new model will be compared.

First the solar radiation magnitude is compared between the two models. The surface normal solar load experienced by all vertical surfaces is presented as follows:

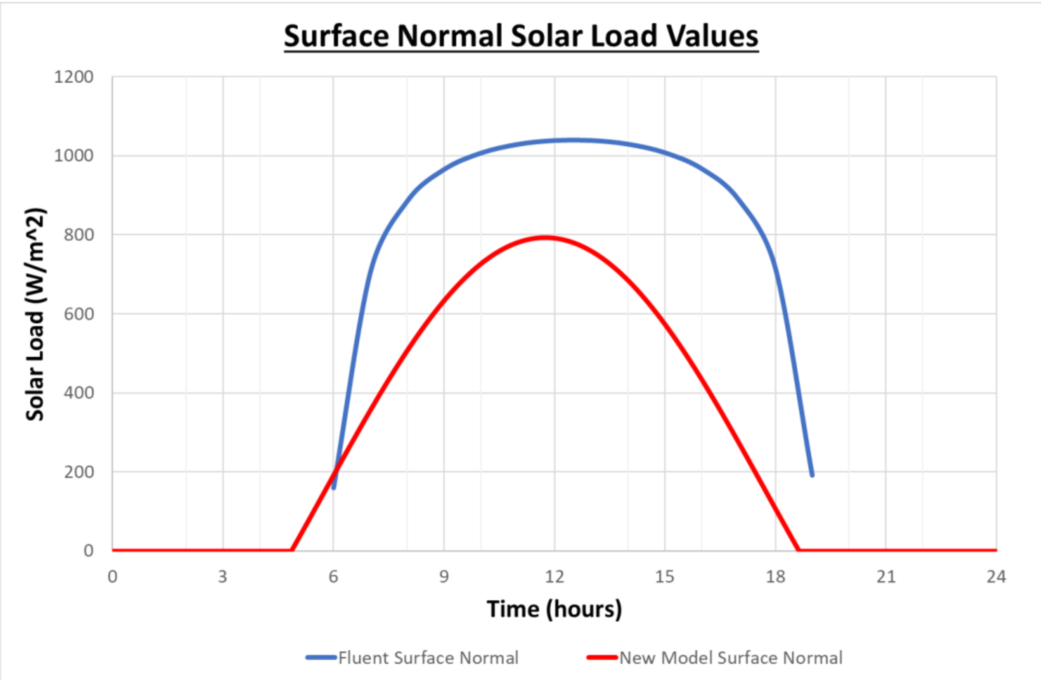


Figure 5.9 - Surface Normal Solar Load Comparison

As can be seen in Figure 5.9, the general shape of the two graphs is similar, however the Fluent model seems to have been smoothed out. The average magnitude of the New model is less than that of the Fluent model. This is due to a conservative approach being taken in the new model and possible undisclosed inputs to the Fluent model.

Next, the steady state solutions for both models were evaluated during daylight hours between 06:00 and 18:00 during summer using a simple house model with 300mm thick walls and window omitted. A fluid domain enclosure comprising of air was placed around the Fluent solar load model case to simulate the convective heat transfer between the environment and exterior wall. This was done because a mixed boundary condition could not be set when using the Fluent solar ray tracing algorithm.

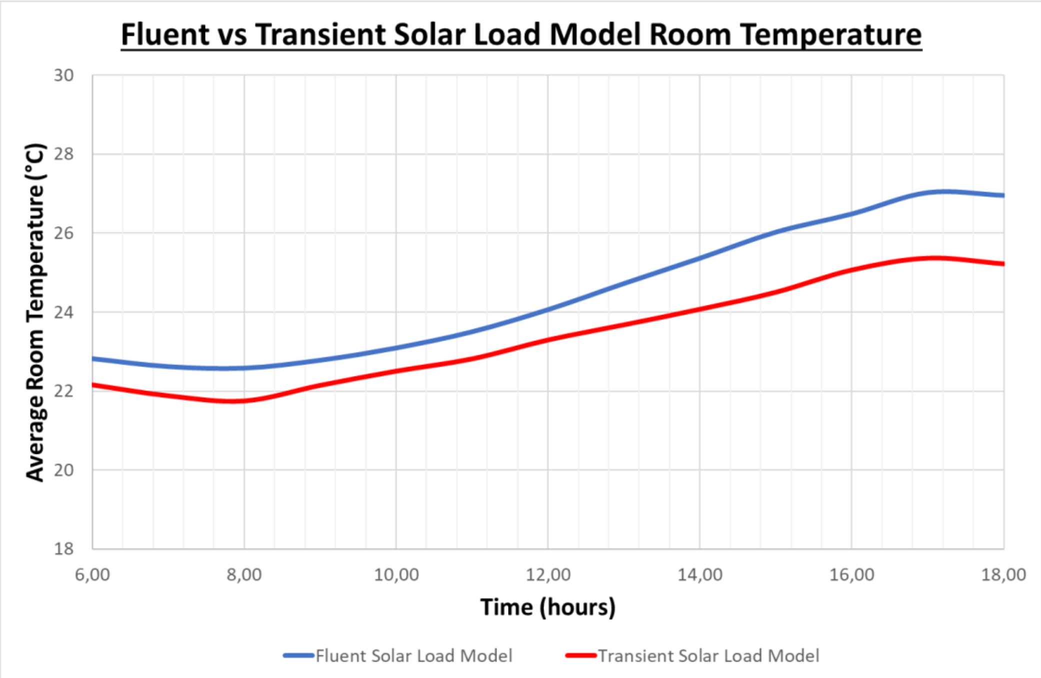


Figure 5.10 - Fluent vs Transient Solar Load Model Average Room Temperature Comparison

As can be seen in Figure 5.10, the trend is very similar to the graph comparing solar radiation loads in that the overall shape of the curves are similar. The average temperature for the Fluent model is higher than the New model, however this is to be expected since the same was found for the solar radiation loads.

Since the results from the Ansys Fluent model compare well to the new transient solar load model, the boundary conditions and setup used in this model may be applied to the simple house model where the different elements of the building envelope are modelled to determine their effect on the internal climate of a simple house.

5.3 Baseline Results

To analyse the effect of the applied boundary conditions on the internal climatic condion of a house, a baseline case of a simple house with 300mm thick walls and a single 1x2m north facing window was simulated for both summer and winter conditions:

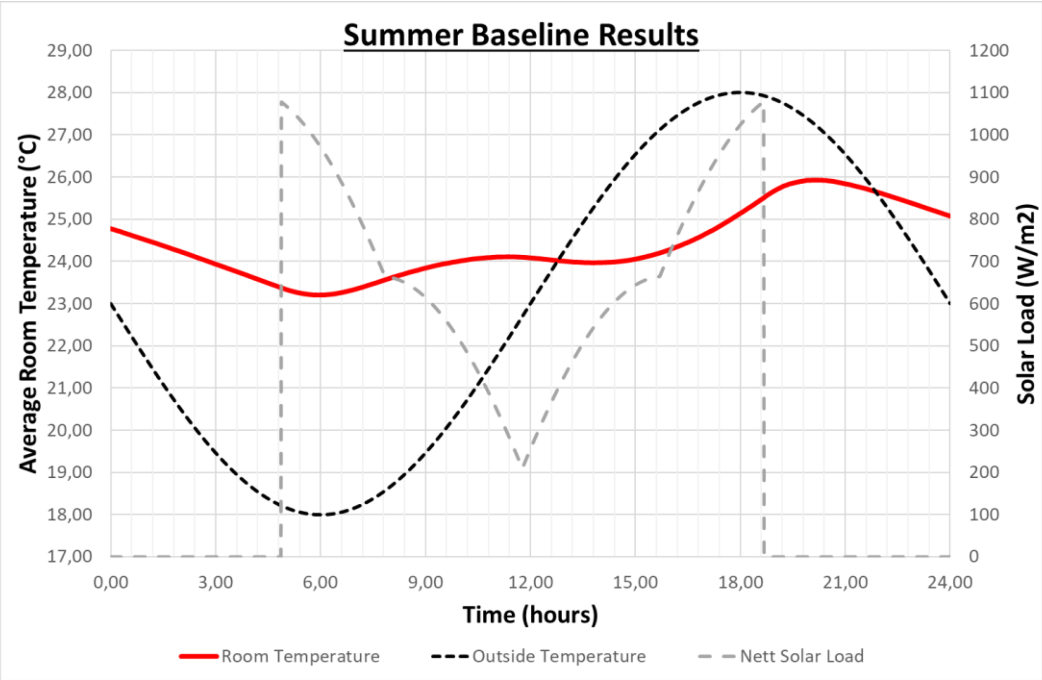


Figure 5.11 - Summer Baseline Results

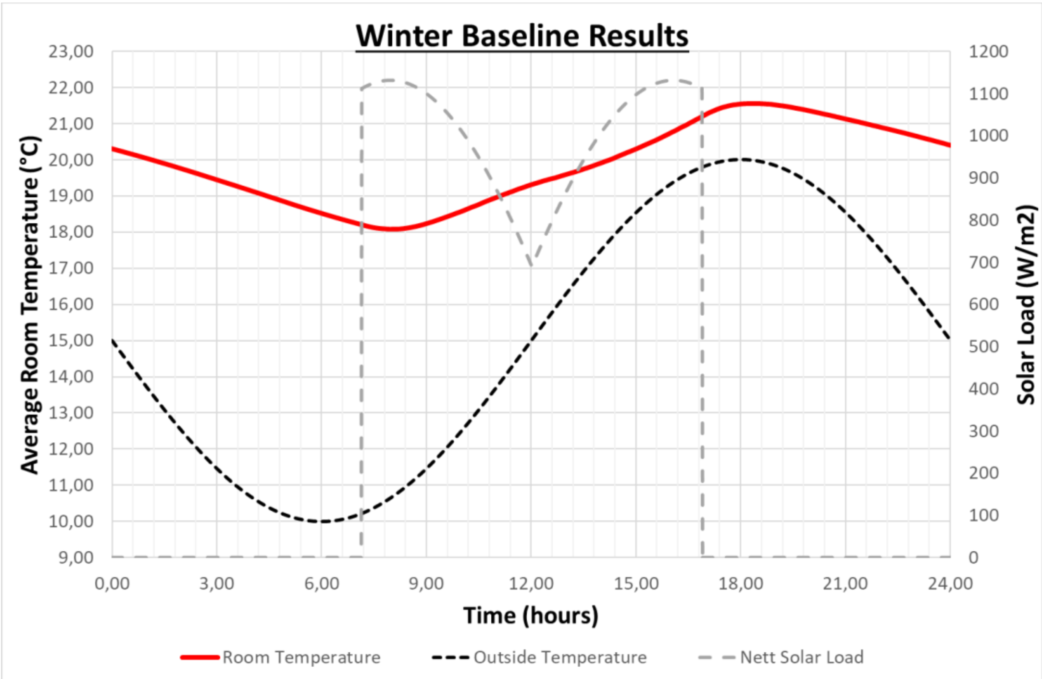


Figure 5.12- Winter Baseline Results

Figure 5.11 and Figure 5.12 show the applied boundary conditions of the outside temperature and solar load, and the resulting average room temperature. By looking at the profile of the average room temperature plot in both summer and winter cases, it can be seen that the general trend follows that of the outside temperature plot. The solar load does also affect the trend of the average room temperature profile, however these effects are smaller than the that of the outside temperature. This would indicate that the outside temperature effects the inside temperature of the house more than the solar load on the exterior of the house.

The summer baseline average room temperature results are closer to the average outside air temperature when compared to that of the winter baseline average room temperature results. This is due to the boundary condition applied to the floor being the same in both cases. In this study, it was assumed that the temperature of the earth underneath the house would remain the same for both summer and winter seasons. The temperature of the earth was set to 18°C.

5.4 Wall Thickness

As presented in Chapter 4, the effect of the building envelope wall thickness was analysed by running multiple simulations and varying the wall thickness. Figure 5.13 and Figure 5.14 show the average room temperature inside a simple house during summer and winter conditions:

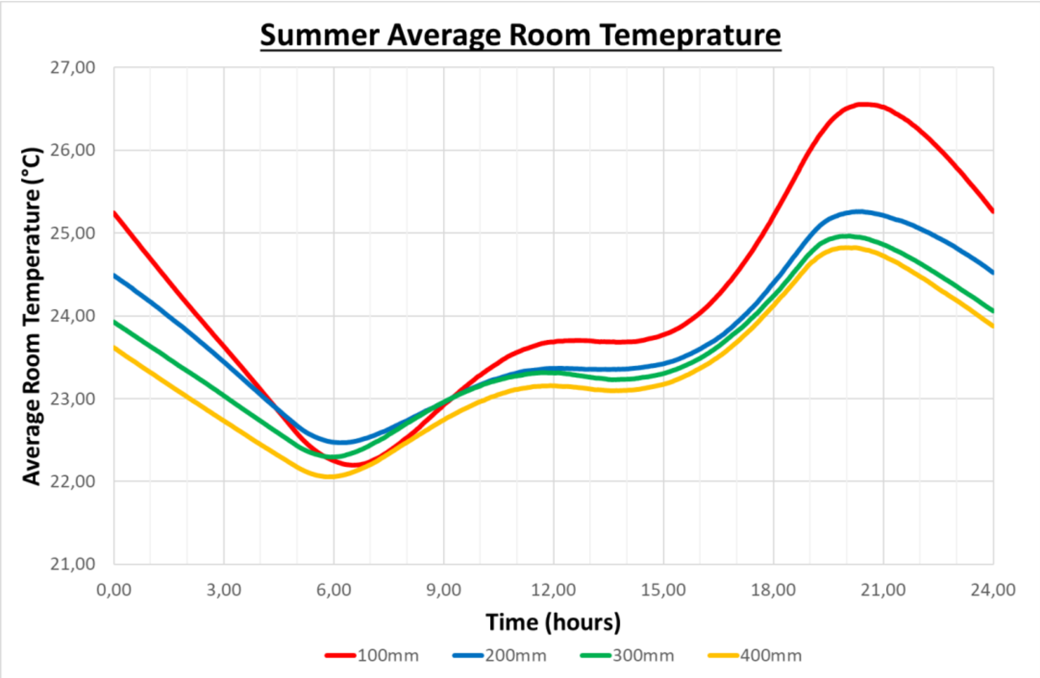


Figure 5.13 - Summer Average Room Temperature for Varying Wall Thickness

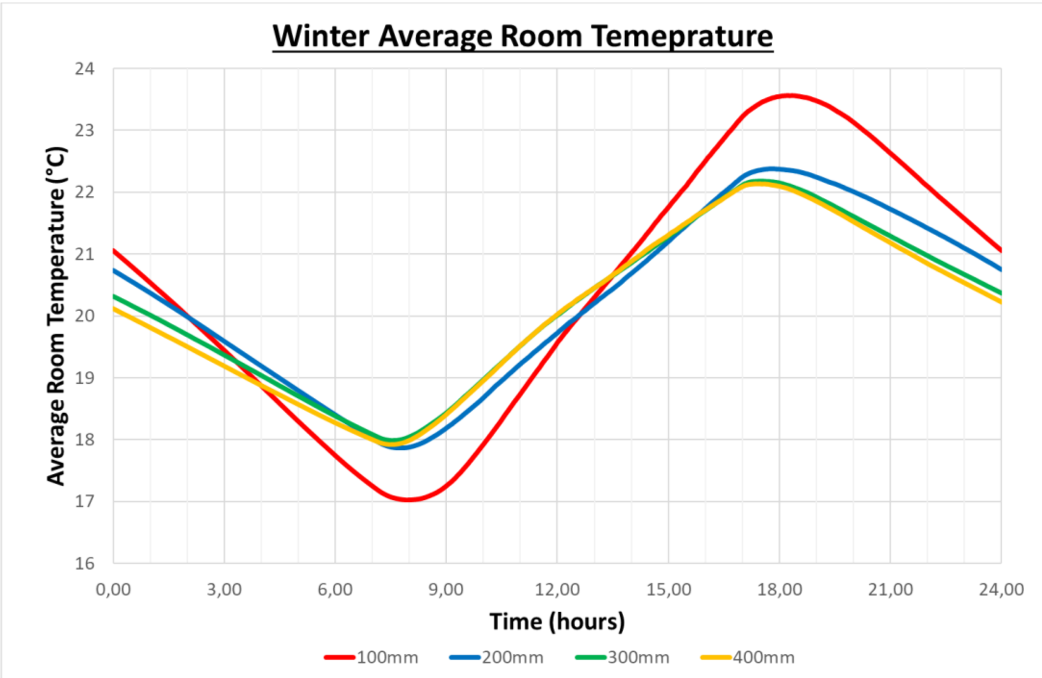


Figure 5.14 - Winter Average Room Temperature for Varying Wall Thickness

From Figure 5.13 and Figure 5.14 it is evident that the wall thickness of the building envelope does have an effect on the internal climate of a simple house. In both summer and winter cases, as the wall thickness is increased, the overall average temperature decreases. However, it is evident that this relationship is not linear. For relatively thin walls at 100mm there is a large difference in overall average temperature compared to the next size up, 200mm. This difference is larger than the overall average temperature difference between a 200mm and 300mm thickness.

This means that creating a house with very thick walls >400mm is not very efficient since the effect the increase in thickness will have on the internal climate will be insignificant compared to a house that has a building envelope wall thickness of between 200mm and 300mm.

By looking at the average heat transfer rates to and from the internal air in the house, the effect the wall thickness has on the internal climate can be explained further. These average heat transfer rate results can be seen in Figure 5.15 and Figure 5.16:

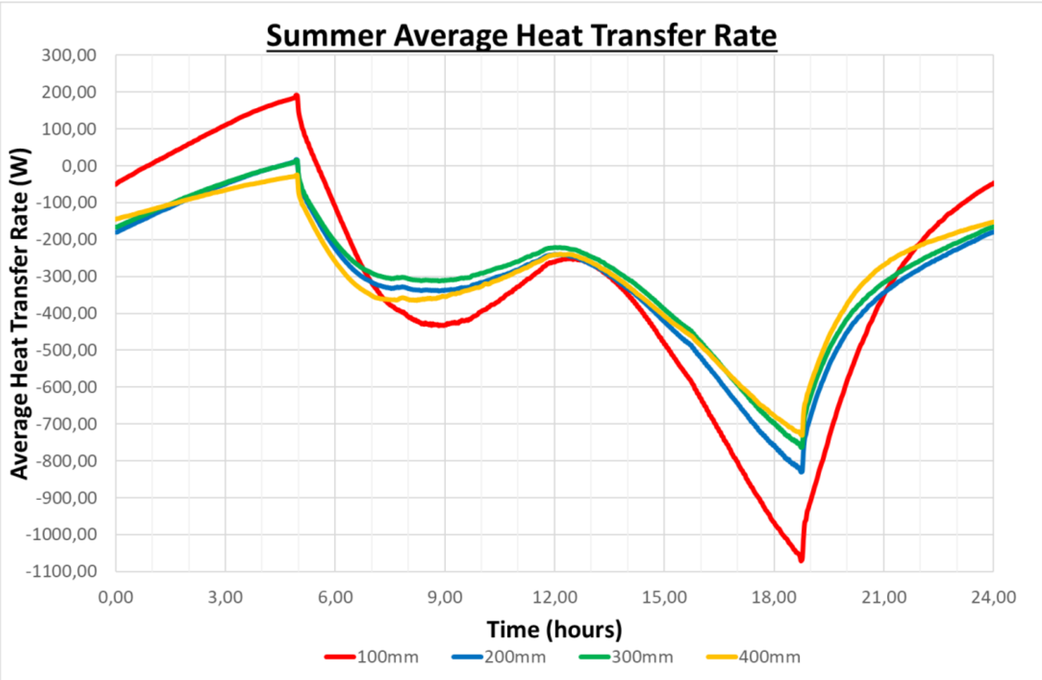


Figure 5.15- Summer Average Heat Transfer Rate for Varying Wall Thickness

It is evident from Figure 5.15 and Figure 5.16 that as the building envelope wall thickness increases, the nett heat transferred decreases. This reduction in nett heat transfer explains the decrease in average room temperature amplitude as the wall thickness increases.

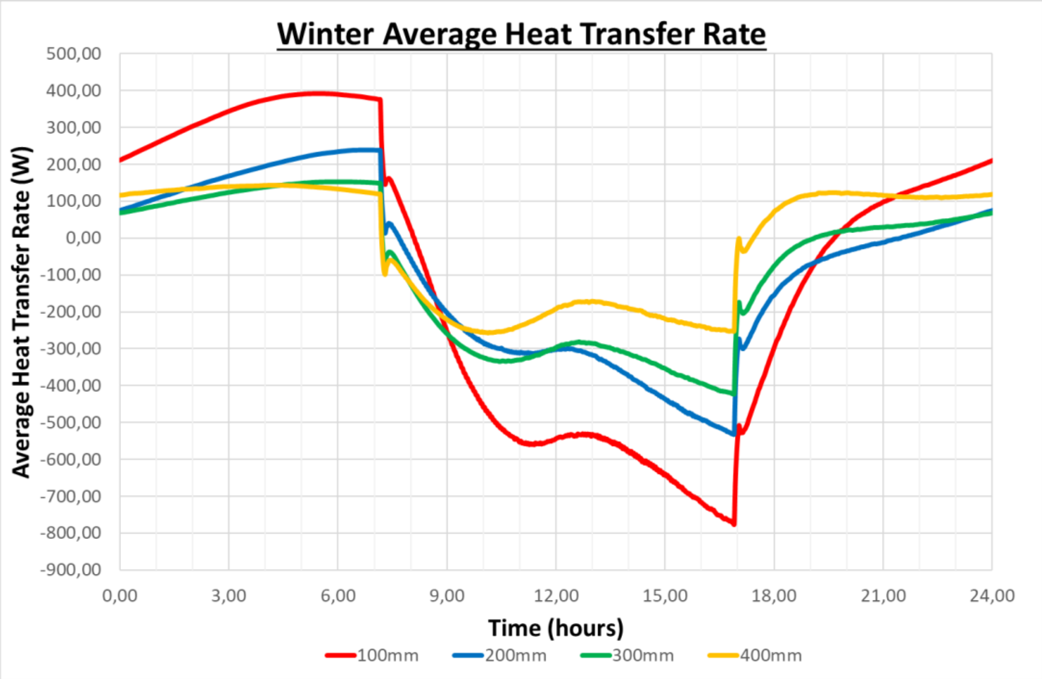


Figure 5.16 - Winter Average Heat Transfer Rate for Varying Wall Thickness

5.5 Window Size

As presented in Chapter 4, the effect of the window size on the internal climatic condition of a house was analysed by running multiple simulations, each time changing the size of the single north facing window. The results from the simulations as presented in Figure 5.17 and Figure 5.18:

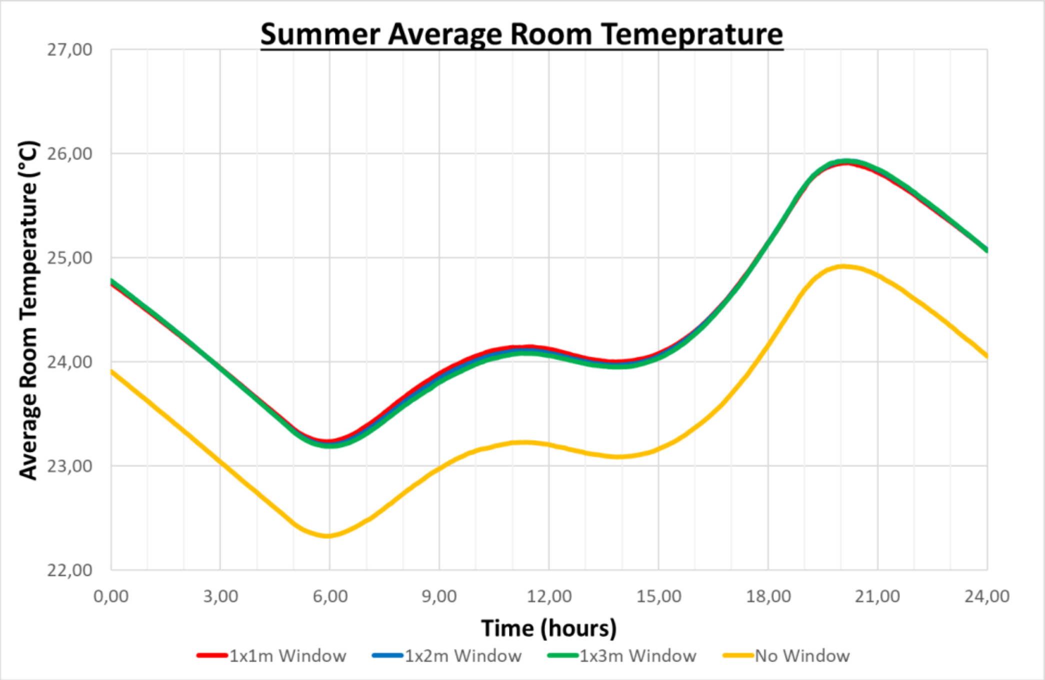


Figure 5.17 - Summer Average Room Temperature for Varying Window Sizes

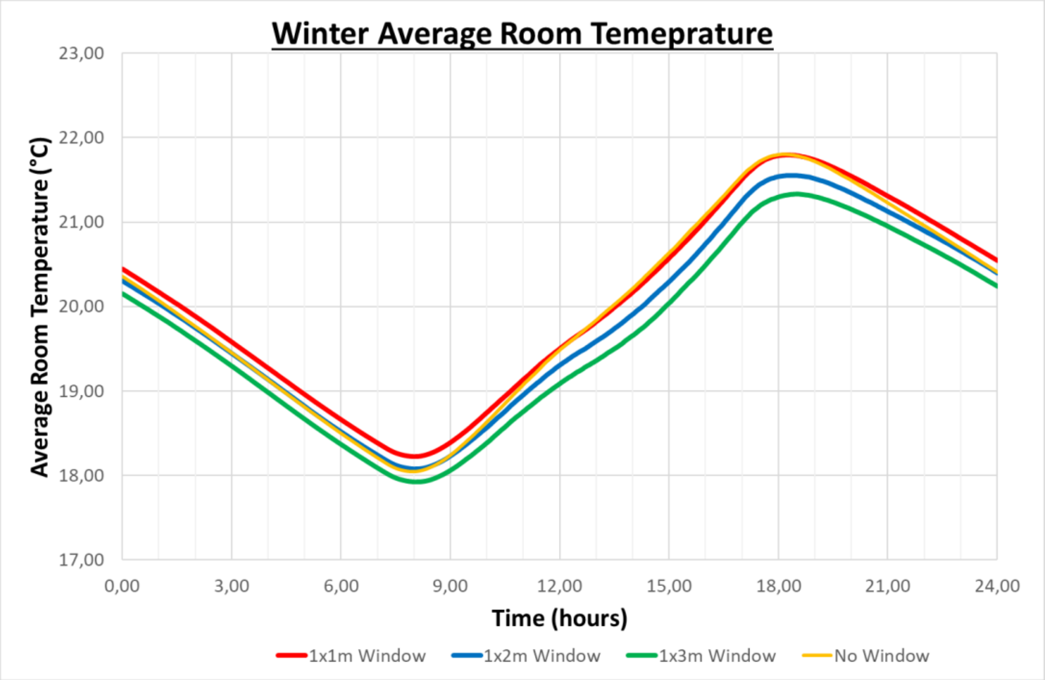


Figure 5.18 - Winter Average Room Temperature for Varying Window Sizes

From Figure 5.17, it can be seen that the change in the size of a window in a simple house has a negligible effect on the internal climatic condition during summer. There is however a difference between a house with a window and without a window. The general trend is that the internal temperature of the house increases when a window is added.

The windows in the building envelope allow for solar radiation to penetrate the building envelope and heat up the inside of the house. However, they also cause a thermal “weak spot” in the building envelope that allows thermal energy to escape.

When a window is added in the summer simulation, the influx of solar radiation increases the average room temperature. However, the increase in the size of the window does not increase the temperature further because the thermal energy leaving the building envelope is almost equal to the additional thermal energy introduced into the house.

From Figure 5.18 it can be seen that there is a small effect on the internal climatic condition of the house for a varying window size. In winter, the sun angle causes the sun to be lower in the sky in comparison to summer. This results in more direct solar radiation entering the house through the window. As the window size is increased, more solar radiation can penetrate the building envelope. However, the larger the size of the window, the more potential there is for thermal energy to be lost to the environment. Furthermore, it is evident that increasing the size of a north facing window in winter will decrease the average room temperature inside of a simple house.

5.6 Wall Emissivity

As presented in Chapter 4, the external constant of emissivity of the material comprising the walls of the building envelope was altered to determine its effect on the internal climatic conditions of a simple house. The results from the summer and winter simulations are shown in Figure 5.19 and Figure 5.20:

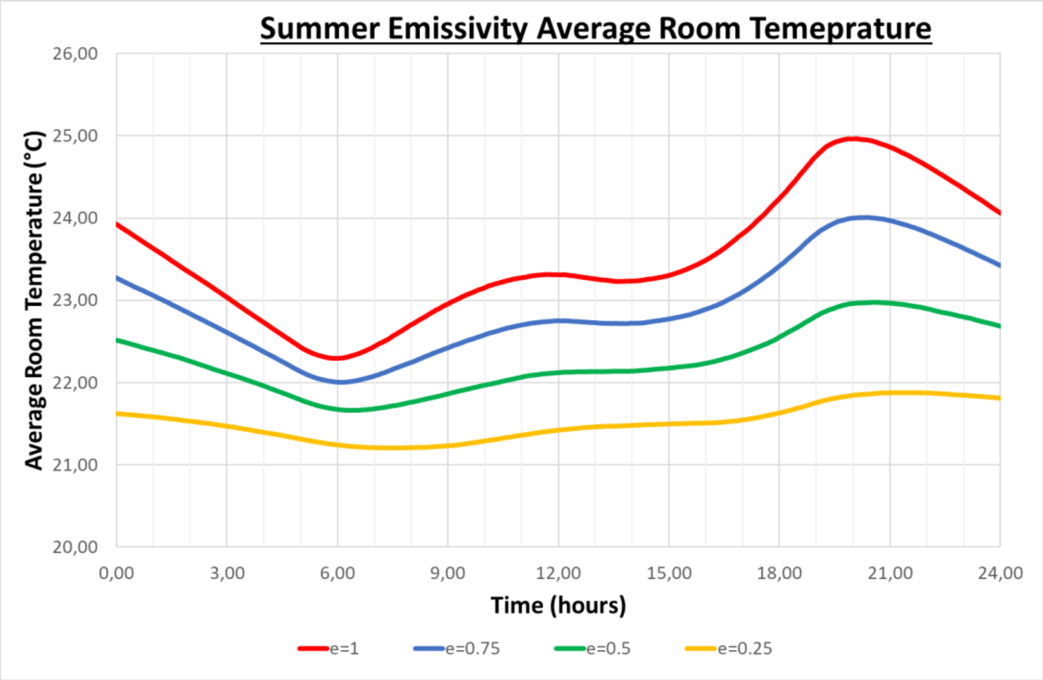


Figure 5.19 - Summer Average Room Temperature vs Time for Varying Emissivity

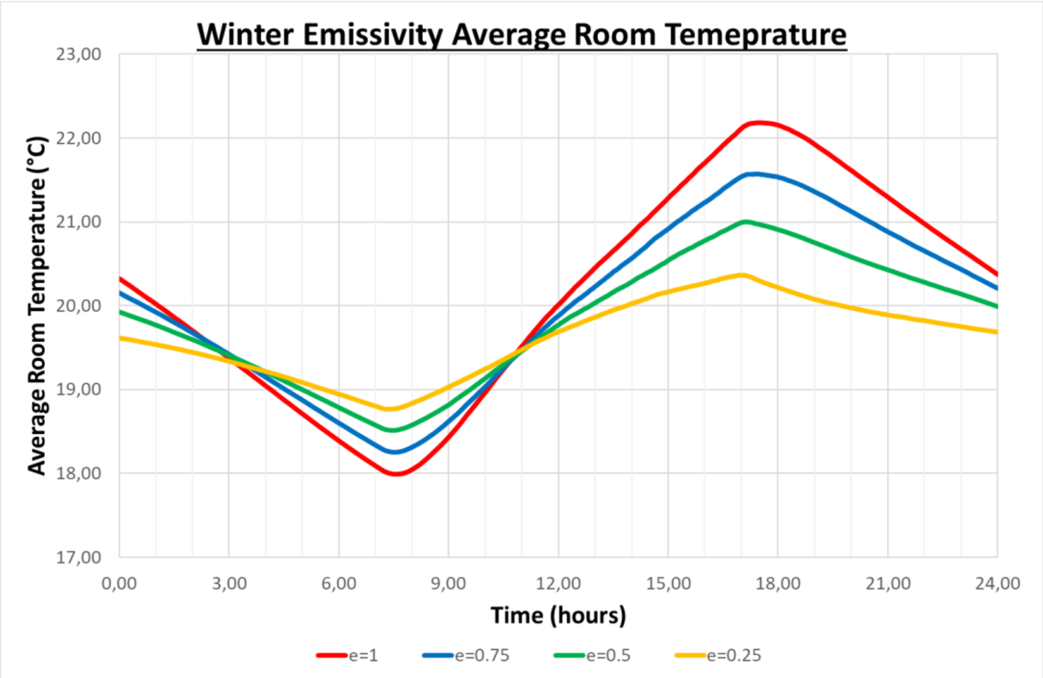


Figure 5.20 - Winter Average Room Temperature vs Time for Varying Emissivity

Immediately, it can be seen that changing the external constant of emissivity of the wall material has a substantial impact on the internal climatic condition of the simple house in both summer and winter conditions. This result therefore proves that the internal climatic condition can be changed simply by choosing a material with a different emissivity property.

In both the summer and winter cases, reducing the constant of emissivity of the material decreases the amplitude of the average room temperature daily fluctuation pattern. The constant of emissivity is directly proportional to the amplitude. In terms of human thermal comfort, this means that the temperature inside a house can remain stable by reducing the constant of emissivity of the wall material.

The effect of wall's material constant of emissivity on the internal climate is further backed up by the results of the average heat transfer rate between the interior surface of the walls and internal air. The results presented in Figure 5.21 and Figure 5.22, show that the average heat transfer rate amplitude decreases as the constant of emissivity decreases.

It can therefore be stated that as the constant of emissivity decreases, it decreases the amount of thermal energy that is transferred to the internal air through the building envelope, which in turn decreases the rate at which the internal temperature changes. This results in a more stable internal climatic condition.

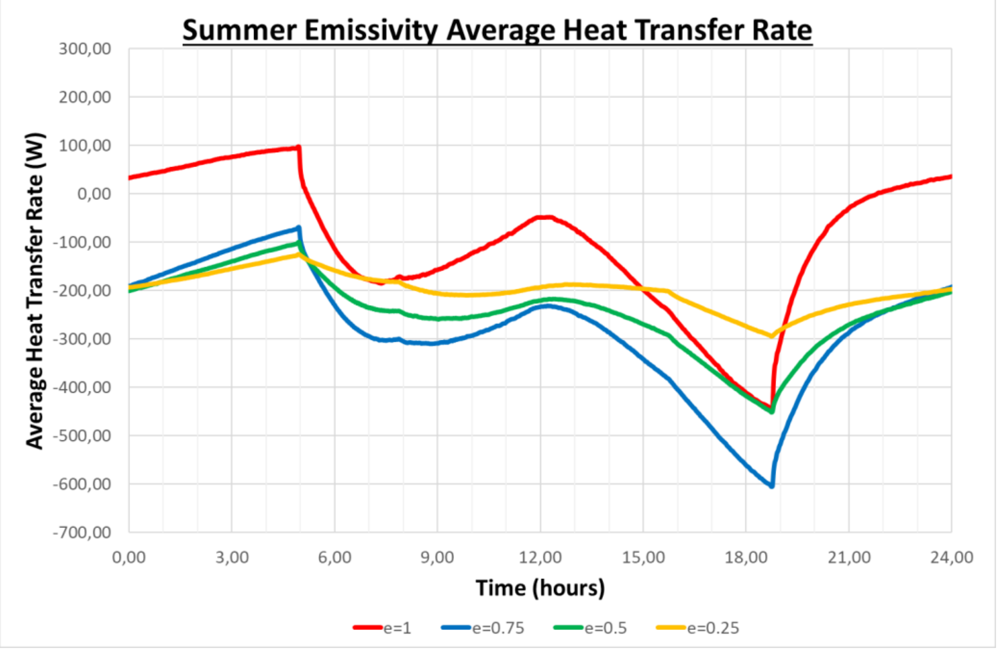


Figure 5.21 - Summer Average Heat Transfer Rate vs Time for Varying Emissivity

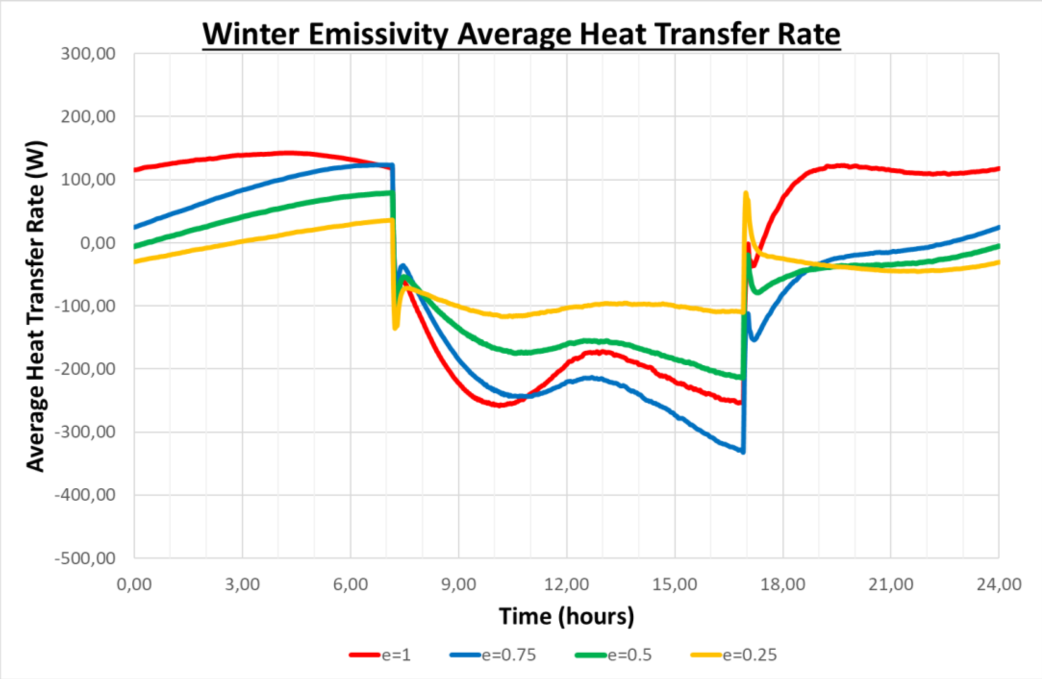


Figure 5.22 – Winter Average Heat Transfer Rate vs Time for Varying Emissivity

5.7 Window Emissivity

As presented in Chapter 4, the external constant of emissivity of the window glazing was altered to determine its effect on the internal climatic condition of a simple house. The results from the summer and winter simulations are presented in Figure 5.23 and Figure 5.24:

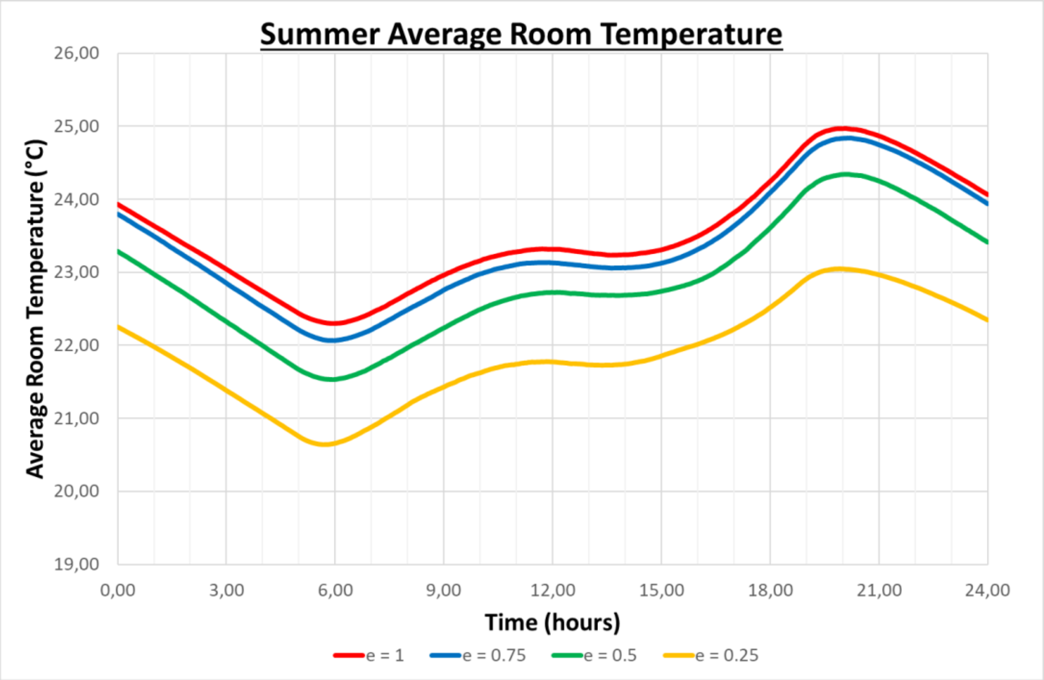


Figure 5.23 - Summer Average Room Temperature vs Time for Varying Window Emissivity

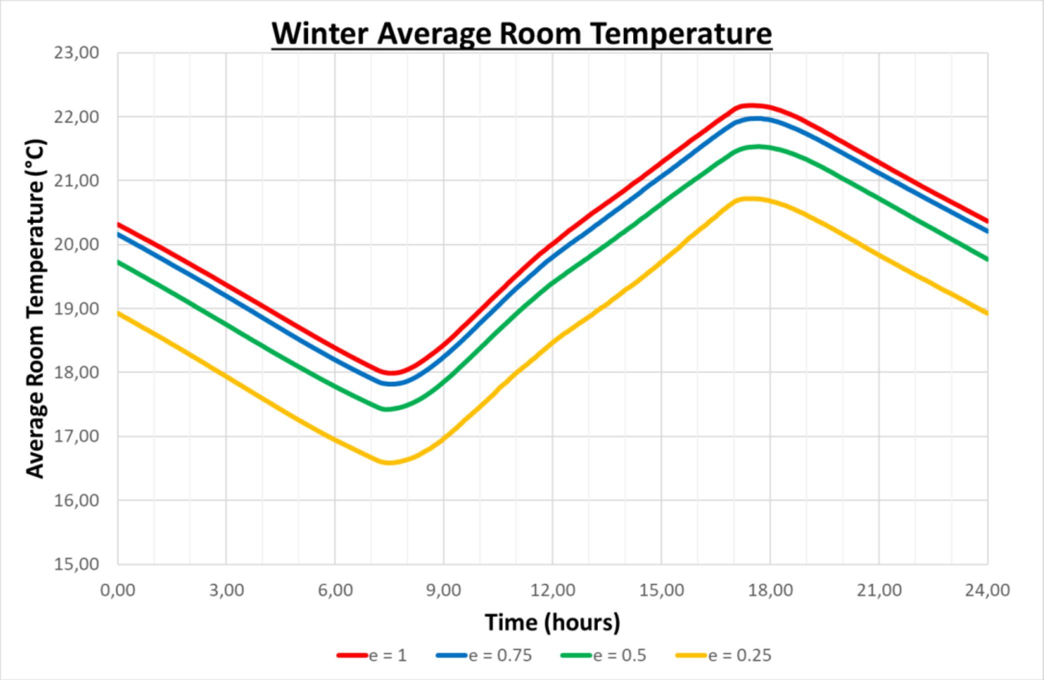


Figure 5.24 - Winter Average Room Temperature vs Time for Varying Window Emissivity

From figures 5.23 and 5.24 it can clearly be seen that the external constant of emissivity of a single glazed window does influence the internal climate of a house. This result is similar in behaviour to the results obtained in Section 5.6 – Wall Emissivity, in that decreasing the constant of emissivity results in a decrease in average room temperature.

However, the relationship between the external constant of emissivity and average room temperature is not linear for the window glazing in contrast to the walls. Changing the external constant of emissivity does not change the amplitude of the average room temperature profile, instead it decreases the overall average of the profile.

CHAPTER 6:

DISCUSSION

There are several factors that influence the internal thermal climate of a house or building. These factors are mainly the composition of the building envelope, i.e. thickness of the exterior walls, number and size of windows, and thermophysical properties of the building materials. The key to maintaining thermal comfort inside of a household while reducing unsustainable energy usage is to optimise these factors when designing a house. The building envelope should be designed in such a way as to reduce heat transfer into the building during summer, and reduce heat transfer out of the building during winter. Additionally, the building envelope should be designed to best utilise “free” thermal energy sources, such as solar radiation, to regulate the internal climatic copndition so that it is maintained within the thermal comfort range without relying on unsustainable energy usage for climate control. This chapter aims to discuss the numerical model developed for this dissertation and the results obtained to research the effect of these aforementioned factors, their effect on the internal climatic conditions of a simple house, and how they may affect the future construction of such a simple house.

6.1 Numerical Model

As highlighted in Chapter 3, a numerical model was created in Ansys Fluent to simulate the effect of the building envelope on the internal climatic conditions of a simple house. The numerical model was designed to best approximate the real-life conditions of a typical brick house that is found in Cape Town, South Africa. However, there have been numerous simplifications made in the design of the model to keep this project within its scope while still being able to output the desired result from the simulations. This project has successfully created a basic numerical model that can be expanded upon in further research which will have the potential to investigate additional elements in the building envelope and add complexity to the design.

6.1.1 Boundary Conditions

Applying the correct boundary conditions is essential to creating a numerical model that will output the desired result that is numerically accurate. The boundary conditions applied to this model are introduced in Section 3.5 - Boundary Conditions.

The most complicated boundary condition applied to the model was that of the exterior wall surface. A method of simulating the effects of solar radiation on a solid domain when conducting a transient simulation did not exist for use in Ansys Fluent, so a novel method was designed and created. The process in which this method was created is explained in APPENDIX A – Solar Load Calculator and APPENDIX B – Solar Boundary Condition Investigation. The method created aimed to simulate the warming effect caused by solar radiation when it is exposed to a solid domain. This was achieved by creating a semi-transparent film connected to the exterior wall of the house. Radiation was applied to this film according to the output of the solar load calculator, which resulted in the film being heated as presented in Figure 6.1:

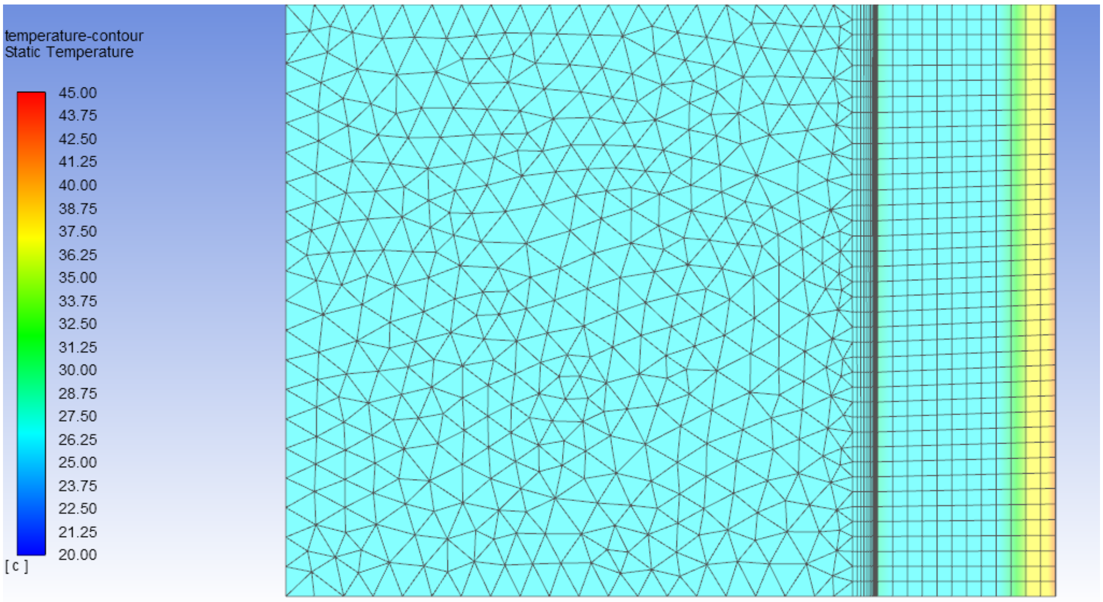


Figure 6.1 - Exterior Wall Heated by Solar Radiation

The heat generated in the film was then allowed to transfer to the external wall via conduction. Additionally, a convective boundary condition was applied to the film to simulate heat being lost to the air surrounding the house from the exterior walls. The boundary condition does not take the effect of the wind blowing over the house into account as it adds additional complexity to the model, which is out of scope of this project. It is however, recommended that in the further development of this model that the effect of wind causing forced convective heat transfer from the external walls to the surrounding air be investigated. The effect of the outside temperature was simulated by changing the temperature of the free stream fluid surrounding the exterior of the house to vary according to the temperature UDF as explained in Section 3.7 - Temperature Function.

The interior wall used a natural convective boundary condition to simulate the exterior walls transferring heat to and from the air inside of the house. This was achieved by activating the effect of gravitational acceleration and the effect of temperature changing the density properties of air. This resulted in a flow of air inside of the house caused by the natural convection effect. This air flow caused by natural convection aided in mixing the internal air and evenly distributing the temperature within the house as presented in Figure 6.2:

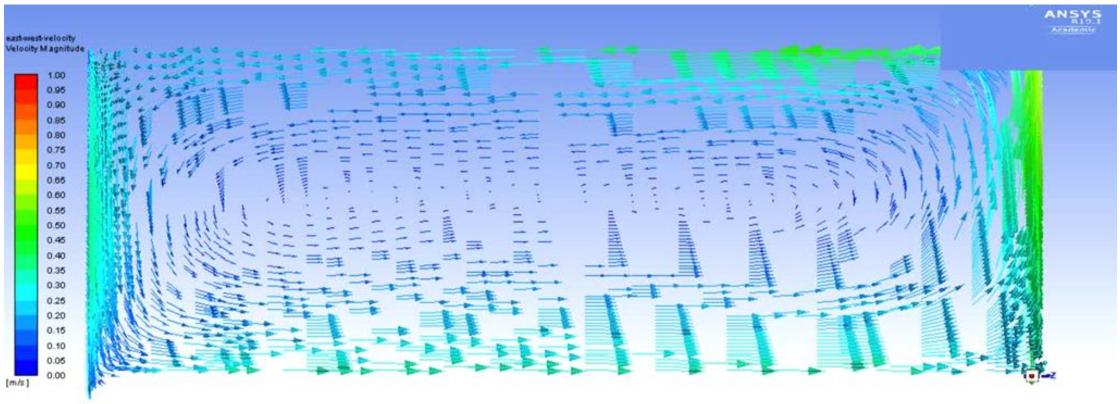


Figure 6.2 - Natural Convective Flow Velocity Vector Plot

To simulate the effect of the solar radiation penetrating the window of a house and adding heat to the internal air space, said radiation was applied over the top surface area of the floor. In reality, sunlight shines through a window into a house where a dynamic field of sunlight falls on a small section of the floor and or wall depending on the sun angle and time of day. Adding the effect of the dynamic sunlight field is complex and out of scope of this project, so the effect was simplified by distributing the solar radiation caused by the sunlight penetrating through the window over the entire top surface area of the floor. Performing this simplification will create an error in the temperature distribution within the house but will not affect the accuracy of the average room temperature.

The single glazed north facing window had a mixed boundary condition applied to its external surface to simulate the effect of outside temperature and convection in creating heat flux. The internal surface of the window had the same boundary condition as the internal wall surface applied to it in order to simulate natural convective heat transfer.

A simple temperature boundary condition was applied to the base of the floor to simulate heat loss to the earth’s surface. The earth’s surface was considered an infinitely large thermal sink, thus allowing the temperature boundary to remain constant. It was also assumed that the thermal sink temperature remained constant through the change in seasons.

The air-ceiling interface was considered to have an adiabatic boundary condition since the effect of the roof on the internal climatic condition was out of the scope of this project. It was assumed that the roof of the house is perfectly insulated so there could be no heat flux.

6.1.2 Mesh

The mesh of the geometry created for this model is robust. A mesh dependency test was performed to compare three different mesh sizes: course, medium and fine. There was a limit set to how fine the mesh could be by the 8GB memory of the computer used. The numerical model was then solved for all three mesh sizes and the results of the average room temperature are presented in Figure 6.3:

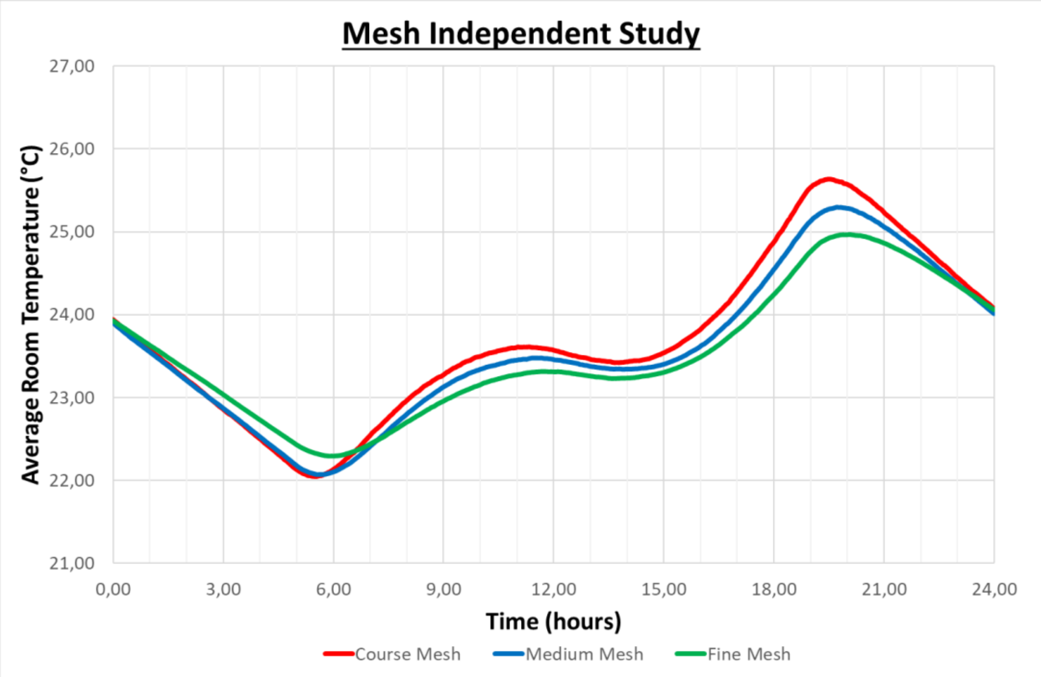


Figure 6.3 - Mesh Independent Study

As can be seen in Figure 6.3, there is a difference in results between the mesh sizes. Since the result would seem to converge towards the finer mesh size, the fine mesh size was used for all numerical simulations.

It should be noted however, that refining the mesh further could lead to more accurate results. Given more memory and computing power, a more refined mesh should be explored.

6.1.3 High-Performance Computing

A high-performance computing (HPC) cluster was used to solve all numerical simulations. The University of Cape Town HPC cluster was used for this project. Using HPC, numerical simulations could be executed, and results achieved quickly. The typical simulation time achieved was less than 10 hours. Therefore, there was no need to optimise the mesh to reduce computing power as the time taken to generate results was manageable.

6.1.4 Realism

The results achieved from the numerical model fall within the expected range for human thermal comfort. However, due to the simplification of certain aspects of the model, these results may not be completely realistic. The interest and scope of this project is to determine and analyse the effect of certain elements of the building envelope on the internal climatic condition. Therefore, the results achieved do not need to be completely realistic because only the resulting behaviour of changes to the building envelope are important. If the results from this project were to be applied in actual design and construction of houses and buildings it is recommended that the model be refined and improved upon to achieve more realistic results.

Such improvements may include: improving the solar loading model to output results that more accurately replicate that of the steady state solar load model built into Fluent, incorporating a roof which would affect the total solar loading experienced by the building envelope, and providing additional thermal pathways which may affect the internal climatic temperature profile.

6.2 Solar Load Model

The accuracy of the solar load model and how the boundary condition is applied can have a large effect on the internal climate's temperature profile. The solar load model as supplied by Fluent is known to be validated. Therefore, by using the average room temperature outputs when performing a simulation on the simple house using this solar load model, the Transient Solar Load Model that has been developed could be validated and compared.

6.2.1 Fluent Solar Load Model

Fluent's built in solar load model's ray tracing algorithm is used to predict the incident solar radiation from the sun by using the sun's position vector and illumination parameters and applying it to a specified boundary. The global position, date and time are inputted into the algorithm to determine the sun position vector. The heat flux calculated by the solar ray tracing algorithm is used as a source term in the energy equation. Heat sources are then added directly to computational cells that border on the specified boundary.

The solar ray tracing algorithm allows the option to include the effects of direct solar and diffuse solar radiation in the model. The algorithm can create a two-band spectral model that accounts for visible and infrared spectrum bands.

The algorithm also accounts for internal scattered and diffusive loading. Any reflected direct solar irradiation is tracked, and the internally scattered energy is applied as radiative heat flux to surfaces that participate in the solar load calculation.

The solar load model does not account for surface to surface radiation transfer, it only accounts for the radiation emitted from the sun. To ensure this surface to surface radiation is included, a radiation model needs to be used in conjunction with the solar load model.

While the Fluent solar load model is versatile and applicable to a large variety of scenarios, it is not applicable to time dependant models. In time dependant models, the simulation time determines the sun vector, and the Fluent model does not have a way to alter the sun vector in a transient case.

6.2.2 Transient Solar Load Model

Much like the built-in solar load model in Fluent, the transient solar load model also takes inputs of global position and date in order to calculate the sun vector. However, the transient solar load model is able to calculate the sun vector at finite intervals over a 24-hour period. This results in multiple time dependant solar load outputs that may be inputted into Fluent to simulate a transient case.

The Fluent solar load model can accurately solve steady state or moment in time simulations. However, in the real-world, time does not stand still and the instantaneous temperature inside of a house is not dependant on current exterior conditions, but rather on the exterior conditions that the house has experienced previously over time as literature suggests. Therefore, to get a more accurate idea as to the behaviour of the internal climate of a house, the house should be modelled in the transient case. It is for this reason that this project performed transient simulations over a cyclic 24-hour period to determine the effect of elements in the building envelope on the internal climate of a simple house

Based on the average room temperature results achieved from the solar load model validation study in Figure 5.10, and comparing them to the average room temperature results achieved from the summer baseline simulation in Figure 5.11, it can be seen that the behaviour of these graphs profile is different. This shows that there is a difference between the steady state and transient solution. To further validate the model, empirical results would need to be captured by creating an actual model of a house and measuring the average room temperature.

6.2.3 Limitations

In the ideal case, the simulation of a house would incorporate solar load boundary conditions that perfectly emulate that of the environment. Since this is not possible due to the simplifications required to reduce computational requirements, it is important to identify some of the limitations that have been placed upon the solar load model and how they affect the results of the simulations.

In both solar load models, fair weather conditions are applied. The fair-weather conditions method imposes greater attenuation on the solar load which represents atmospheric conditions that are fair but not completely clear, i.e. some cloud cover [50]. The amount of cloud cover can change drastically throughout the day which would influence solar loading.

Since this project focuses mapping the behaviour of how the elements comprising the building envelope influence the internal climate, using a solar load model that applies fair weather conditions is sufficient. The fair-weather conditions model imposes a standard average that can be used as a comparison.

The transient solar load model does not account for reflected solar radiation from objects that may surround the solid domain of the numerical model since it does not incorporate solar ray tracing. The steady state Fluent model does have solar ray tracing built into its solar load model. However, in the case of this study, accounting for reflected solar radiation is not applicable since the boundaries that have solar loading applied to them as a boundary condition are situated on the limits of the computational domain. It should be noted however, that the solar loading should increase if the reflected solar radiation were to be taken into account.

6.3 Wall Thickness

When a house or building is constructed, the material and thickness of its walls may vary depending on their position, loading conditions, resources and cost. In South Africa, the average house is made from brick and cement with loadbearing walls having a thickness of 380 mm and non-loadbearing walls having a thickness of 180 mm. While the type of loading dictates the thickness of a wall, there is still scope to adjust the wall thickness in certain areas of the house to adjust the internal thermal climate.

Low cost housing constructed in South Africa by the Rural Development Program utilises single wall hollow concrete bricks when building the houses. The reason these bricks are used instead of clay bricks and cement is due to the lower cost of hollow concrete bricks. The loading conditions on the walls are also relatively low which means the exterior load bearing walls can be thinner.

As seen in the results chapter, the thickness of the walls has a marginal effect on the internal climate of a house. The wall thickness does begin to affect the internal climate when the walls are very thin, i.e. less than 100mm. The thinner the walls become, the less insulating properties they provide to the internal airspace and the result therefore means that the internal climate behaves more like the external environment.

Building thin walls into a house can be utilised in rooms that are utilised for only specific events or occasions, such as a sunroom. Sunrooms are designed to provide a place of warmth in the late afternoon or evening. By looking at Figure 5.13 and 5.14, it can be seen that the 100mm thick wall provides great warmth to the house in both summer and winter during the late afternoon and evening.

Overall it is not feasible to vary the thickness of the walls of a simple house to adjust the thermal climate, since there is not a significant effect on the internal climate for different wall thicknesses, except in cases of very thin walls. In most cases, constructing large sections of a house out of thin walls is not feasible because they would not be able to carry the load to support the roofing structure and integrity of the house.

The thin and hollow brick walls in low cost housing can be improved upon by increasing their thickness or density to increase thermal mass and insulation to better maintain thermal comfort and reduce energy usage.

6.4 Window Size

The windows in the building envelope play the role of primarily allowing natural light into the room and as a result allow the occupants to see outside the house or building. The windows also allow for a source of cooling and airflow because they may be opened to allow air from the outside environment into the house. If the outside air is at a lower temperature than the inside of the house or building, then it may also provide cooling.

By allowing natural light (sunlight) into the house or building through the window, it results in an increase in solar radiation thermal energy entering through the building envelope. This solar radiation provides a source of heat to the internal environment which in turn increases its temperature.

Additionally, installing the windows in the building envelope create a thermal weak point due to the insulating properties of a single glazed window being inferior to that of the wall material. These thermal weak points allow for increased heat transfer between the internal and external environments.

As mentioned in [27], as the amount of solar radiation that is allowed to penetrate the building envelope increases, the temperature of the internal climate will increase. While this is true, to increase the amount of incoming solar radiation, the size of the window needs to be increased. This increase in window size increases the potential for heat transfer between the inside and outside environment, which would potentially decrease the temperature inside of the house if the internal thermal potential is greater than the external.

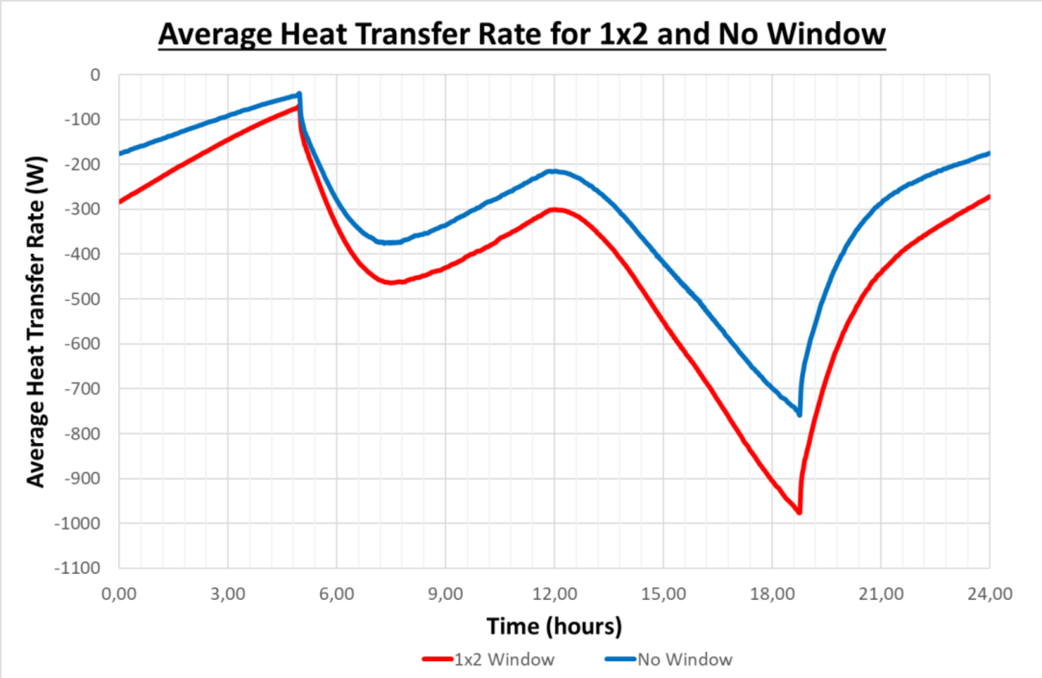


Figure 6.4 - Average Heat Transfer rate for 1x2 and No Window Comparison

As can be seen in Figure 6.4, the magnitude of heat transferred through the building envelope is greater when a window is introduced.

It can be seen from the results in Section 5.5 Window Size, the size of the window on a north facing façade does not make a significant impact on the temperature of the internal climate. Therefore, it can be said that changing the size of the windows in the building envelope does not aid in controlling the internal thermal climate of a simple house.

This project only looks at a single glazed window on the north façade. More investigation can be done into double glazed windows and introducing multiple windows into the building envelope. A double-glazed window has better insulating properties than a single glazed window due to insulating space between the panes of glass. Increasing the windows insulating properties will create less of a thermal weak spot in the building envelope and will trap more heat inside due to less heat transfer between the internal and external environments. Increasing the number of windows installed in the building envelope will increase the amount of thermal radiation and depending on which direction the window is facing the angle of the sun will have an effect on the amount of radiation that passes through the window. Placing windows in different facing walls will influence the time of day at which the house receives the most solar radiation.

6.4 Emissivity

Based on the results presented in Section 5.6 - Wall Emissivity and Section 5.7 – Window Emissivity it can be said that the external constant of emissivity of the walls and windows have a significant effect on the thermal properties of the building envelope. The external constant of emissivity should therefore be an important consideration when selecting building materials to construct a house or building.

The external constant of emissivity of the walls can be changed by using different building materials. For example, red bricks have an external constant of emissivity of 0.93, while cement cinderblocks have an constant of emissivity of 0.54. These are two building materials that are commonly used in the construction of a house or building. The external constant of emissivity can also be altered to a certain degree by changing the surface finish of the wall. The paint colour on the exterior surface of a wall can change the external constant of emissivity. Black paint for example which has an constant of emissivity of close to 1 will result in a wall that has the potential to absorb large amounts of solar radiation. On the other hand, painting the surface white will decrease the constant of emissivity and radiation will be reflected. The emissivity of a wall constructed from red bricks can be reduced by covering the surface of the bricks in a layer of cement. This reduces the overall surface constant of emissivity of the wall.

The external emissivity of window glazing can also be changed by applying a surface film to the glass. Low emissivity glass is a type of window glazing that is commonly used in buildings and houses. It has a silver coating thinner than a human hair that prevents infrared and ultraviolet radiation while still allowing visible light through the window [44]. The infrared radiation spectrum is primarily responsible for the transfer of radiative thermal energy. Infrared radiation coming from the sun is considered as short-wave infrared, while the infrared radiation that is emitted from objects is considered long wave radiation.

There are two types of low emissivity glass, passive and solar controlled. Passive low emissivity glass primarily blocks long wave infrared radiation from being transmitted through the glass. This therefore allows solar radiation in but prevents emitted radiation from escaping the house or building, thus trapping in the heat. Passive low emissivity glass is ideal for cooler climates where a house or building can benefit from retaining the heat supplied from the sun. Solar controlled low emissivity glass prevents the short-wave infrared radiation from penetrating though the glass. This is ideally suited in applications where the climate is mild to hot. By preventing the short-wave infrared radiation from penetrating the building envelope, it eliminates the additional thermal energy that would be allowed through the windows into the house or building, thus preventing the internal room temperature from rising. The solar controlled low emissivity glass can be effective when used in conjunction with air conditioning systems.

Standard window glass that is commonly used in single glazed windows has an emissivity of 0,84 while low emissivity glass typically has an emissivity of 0,02 which is significantly lower [51]. Based on the results in Section 5.7 – Window Emissivity, it can be seen that the emissivity of the window glazing can significantly influence the internal climate. Reducing the constant of emissivity reduces the overall average temperature inside of the house.

Currently, the constant of emissivity of the walls and windows can only be permanently set during the construction of the house or building. In South Africa, the climate is such that the summer is hot with temperatures reaching >30°C, and winter with average temperatures in the range of 17°. In such a climate the passive low emissivity glass would be greatly beneficial in winter, but in summer they would not be beneficial. If the constant of emissivity of the walls and window glazing could be varied based on the season and environmental conditions, then the internal climate could be optimised based on the external conditions.

6.6 Prediction Model for Optimisation

In the ideal situation, houses are designed, modelled and simulated to optimise their design to best suit their environment and climate in the location where they are built. Unfortunately, to perform a rigorous simulation of a house it requires a large amount of computing power, time and modelling work to complete. This is largely impractical and would result in the construction of a new house becoming very expensive and taking a long time to complete.

Taking the design of a standard brick house that is commonly found in South Africa, such as the one seen in Figure 6.5, and building it in another part of the world, such as England would result in a completely different internal climate profile. This is due to the environment and external climate being completely different. Therefore, it can be said that a house needs to be built differently in England to achieve a similar internal climate than the house built in South Africa.

Figure 6.5 - Typical South African Brick House

By understanding how the design of the different components that compose the building envelope affect the internal climatic condition of a house, designers can tailor these components to achieve a desired internal climate based on the location, environment and climate in which the house is to be built. The results achieved from this project have helped to understand how the thickness of the walls, size of the windows and thermophysical properties of the building envelope material’s effect the internal climate of the house.

By understanding this behaviour, the characteristics of the internal climatic conditions may be predicted and applied to the design of a house without the need to perform rigorous simulations each time a house is constructed. Being able to tailor the design of the house to its environment to achieve an internal climate that best achieves human thermal comfort will drastically reduce the unsustainable energy that is required to power devices used for climate control.

To create an accurate prediction model for how the internal climate of a house reacts to certain building envelope geometry inputs, a machine learning algorithm may be used. By collecting multiple data points of different building materials and geometries, and their effect on the internal climate, a machine learning algorithm may be created. By inputting the building envelope geometry, materials used, location, environment and climate, the algorithm can output the expected internal climate characteristics based off the library of data points it has previously received. The design of the house may then be changed as necessary and the algorithm run again to fully optimise the house to its environment and reduce the need for additional energy use for heating and cooling of the internal environment. The use of a machine learning algorithm will reduce the computing power required while reducing the time it takes to complete the simulation.

CHAPTER 7:

CONCLUSION

Based on the results obtained from this research, the following conclusions can be made:

- Numerically solving for the internal climatic conditions of a simple house based on external climatic conditions applied as boundary conditions using a computational model is an effective method in determining the effect of the building envelope geometry and thermophysical properties on the internal climate.
- The building envelope geometry, namely the thickness of the exterior walls and size of the single glazed north facing window, and the building envelope thermophysical properties, namely the constant of emissivity of the exterior walls and window glazing, were successfully altered and simulated to determine their effect on the internal climatic condition of a house.
- By altering the thickness of the exterior walls in the building envelope, the effect on the internal climatic condition of the house is minimal. There is only a significant difference when the thickness of a very thin wall (<100mm) is increased.
- The size of the windows on the north facing façade has no significant effect on the internal climatic conditions in summer. In winter, when the north facing façade receives more solar loading, there is a small effect of the size of the window on the internal climatic condition. However, the effect is not large enough to control the internal climatic conditions.
- Altering the constant of emissivity of the building envelope has a significant effect on the internal climatic condition of a house. By changing the constant of emissivity of the exterior walls and window, the internal climate can be controlled. When optimising the design of the building envelope to best suit its environment it would be advisable to adjust the constant of emissivity to do so.

CHAPTER 8:

RECOMMENDATIONS

To further the research in the field of reducing energy use for heating and cooling in a household, specifically by creating a computational model to determine the effect of changes to the building envelope on the internal climate, the following recommendations are suggested:

- Further develop the numerical model created in this project to incorporate a roof structure. The roof structure should also interact with the solar loading boundary conditions, in which case the transient solar load model should be further developed to calculate the solar load experienced by surfaces at a specific angle. By including a roof structure to the building envelope, the thermal energy input into the computational domain is increased while the potential for thermal energy transfer within the building envelope and the environment is also increased. This adds additional complexity to the model, while creating a more realistic model.

- Another research topic may be to determine the effect of roof insulation material on the internal climate of a house. This project has confirmed that the rate of heat transfer between the building envelope, internal airspace and external environment affect the internal climate of a house. By changing the thermophysical properties of the building envelope, the internal climate can be controlled. A study to determine how roof structures with different thermophysical properties, either due to the material it is constructed from or type of insulation used, affects the internal climate may aid in the further understanding of how to control the internal climate.

- Further research into the internal wall structure design would be beneficial to optimising the cost and performance of the building envelope to best achieve thermal comfort inside of a house or building. The internal structure of a wall may change the thermophysical properties of said wall depending on its design. For example, insulating materials may be sandwiched between layers of bricks to improve the insulating properties of the wall to reduce the rate of heat transfer within the building envelope. The use of phase changing materials may also be incorporated into the internal structure of the wall to increase thermal storage. This may be beneficial to houses situated in climates where maximum and minimum daily temperatures have a wide range.

- Simulating different wall materials, other than the fly-ash material used in this project, will be beneficial to understanding how the internal climates of houses built from different materials are affected. Although research is being pursued in the construction of houses and buildings from fly-ash as it is perceived to be a material that will aid in use of waste materials from coal fired powerplants, traditional building materials are still widely used and are predicted to be used in the future. As such, clay bricks, hollow concrete bricks and other traditional constructions materials should be simulated to aid in the construction of houses and buildings that use these materials to decrease their reliance on unsustainable energy use for heating and cooling of the internal climate.

- The computational model created in this project simulates a simple house over a transient 24-hour period. There was found to be evidence of the thermal storage within the building envelope influencing the internal temperature profile when compared to the steady state simulation. The effect of thermal storage on the internal climate should be further researched. This may be done by varying the thermal mass of the building envelope and performing simulations of the house over a longer period that involves the environmental conditions changing. For example, simulating over a 48-hour period where the house experiences a hot day followed by a cold day and analysing how the thermal energy gained by the building on the hot day carries through to influencing the internal climate on the cold day.

- The accuracy and capabilities of the transient solar load model should be improved and expanded upon. In this project, the transient solar load model created was proven to follow the general performance of the steady state solar load model built into Fluent when comparing both models in the stead state condition. However, further improvement can be made to increase the transient solar load model to improve its performance and better replicate that of the Fluent solar load model. It may also be beneficial to include ray tracing into the model to improve its capabilities for use in more complicated numerical simulations where reflected radiation is included. Being able to alter the weather conditions and determine its effect on solar loading will aid in simulating houses and buildings that are exposed to varying climatic conditions. For example, the solar load model should be able to account for cloud cover and its effects on the solar load experienced by solid objects in the computational domain. Since Ansys Fluent does not have the option of a built-in solar load model for transient simulations, developing a transient solar load model for use in Fluent will not only benefit this field of research, but also other fields of research.

- The technology incorporated in buildings to control the internal climate to best suit human thermal comfort is continuously developing. Technologies, such as phase changing materials, smart windows that work to condition air, window shading devices, etc, play a role in controlling the internal climate. Such technologies may be incorporated into the computational model of a house or building to determine their effects on the internal climate when used in conjunction with each other and certain building envelope geometries. Doing so will also aid in the development of these technologies and innovate the design of new technologies.

- Generate empirical data that may be used to further validate the numerical model and transient solar load model that was created in this project.

CHAPTER 9:

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APPENDIX A – Solar Load Calculator

Determining the day of the year:

Month	n for the Day of the Month, D	Month	n for the Day of the Month, D
January	D	July	181 + D
February	31 + D	August	212 + D
March	59 + D	September	243 + D
April	90 + D	October	273 + D
May	120 + D	November	304 + D
June	151 + D	December	334 + D

January := 0
February := 31
March := 59
April := 90
May := 120
June := 151
July := 181
August := 212
September := 243
October := 273
November := 304
December := 334

month := December — Month of the year

D := 21 — Day in the month

n := month + D = 355 — Day of the year

Determining the declamation angle:

$$d := 23.45\sin\left[\frac{360}{365}(284 + n)\cdot deg\right] = -23.45$$ Degrees

Determining the Local Solar Time:

$CT := \frac{t}{6}$ — Clock Time (hours)

$L_{std} := -30\cdot\frac{\pi}{180} = -0.524$ — Standard meridian for the local time zone (radians)

$L_{loc} := -18.4241\cdot\frac{\pi}{180} = -0.322$ — Longitude of actual location (radians)

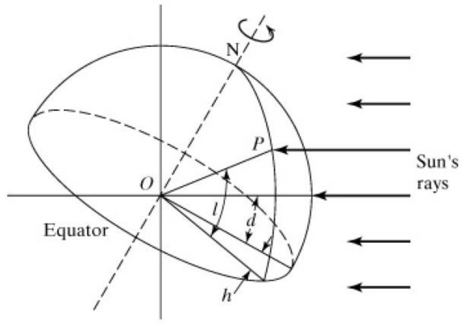
$DT := 0$ — Daylight Saving correction time (hours)

$B := \frac{\pi}{180}\cdot 360\frac{(n - 81)}{364} = 4.73$ — Radians

$$E := 0.165\sin(2B) - 0.126\cos(B) - 0.025\sin(B) = 0.017$$

$$LST := CT + \left(\frac{1}{15}\right)\left(L_{std} - L_{loc}\right) + E - DT$$

Basic Earth-Sun Angles:

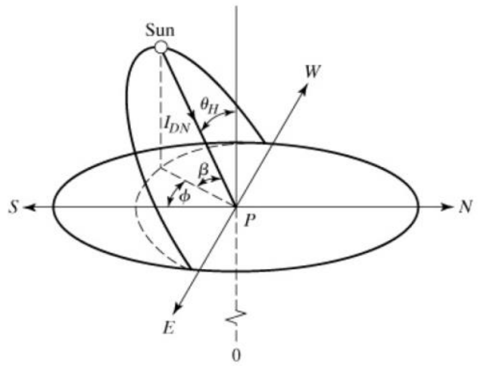


$h := 15(LST - 12)\cdot\frac{\pi}{180}$ Hour Angle (radians)

$lat := -33.9249\cdot\frac{\pi}{180} = -0.592$ Latitude (radians)

$d_{rad} := d\cdot\frac{\pi}{180} = -0.409$ Declamation angle (radians)

Derived solar angles:



$\theta_H := acos\left(\cos(lat)\cos(h)\cos\left(d_{rad}\right) + \sin(lat)\sin\left(d_{rad}\right)\right)$ Zenith angle (radians)

$\beta := 90\cdot\frac{\pi}{180} - \theta_H$ Altitude angle (radians)

$\phi := acos\left(\frac{\sin\left(d_{rad}\right)\cos(lat) - \cos\left(d_{rad}\right)\cos(h)\sin(lat)}{\cos(\beta)}\right)$

Azimuth angle (radians)

$\phi_{deg} := \phi\cdot\frac{180}{\pi}$

$\phi_{act_i} := if\left(h_i \le 0, -1, 1\right)\cdot\phi_{deg_i} = ...$

$\phi_{act.rad} := \phi_{act}\cdot^{c}$

Determining the magnitude of terrestrial solar radiation:

$G_{ET} := 1367 \frac{W}{m^2}$ Mean extra-terrestrial radiation

$\alpha := 25\%$ Percentage atmospheric losses

$G_T := G_{ET} \cdot (1 - \alpha) = 1.025 \times 10^3 \frac{W}{m^2}$ Terrestrial Radiation

Determining Cartesian components of terrestrial solar radiation:

$G_{Tx_i} := -G_T \cdot \cos\left(\phi_{act.rad_i}\right) \sin\left(\theta_{H_i}\right)$ X Component

$G_{Ty_i} := -G_T \cdot \sin\left(\phi_{act.rad_i}\right) \sin\left(\theta_{H_i}\right)$ Y Component

$G_{Tz} := -G_T \cdot \cos\left(\theta_H\right)$ Z Component

Sunrise and Sunset Time:

$$h_{noon} := \frac{acos\left(-\tan(lat)\tan\left(d_{rad}\right)\right)}{15°}$$

$h_{noon} = 7.131$ Hours before and after local noon

$LST_{rise} := 12 - h_{noon}$ Sunrise at local solar time

$LST_{set} := 12 + h_{noon}$ Sunset at local solar time

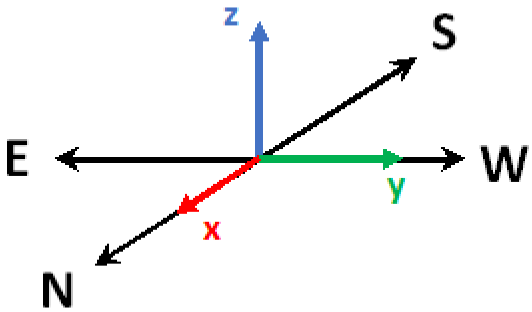
$$T_{rise} := LST_{rise} - \frac{1}{15}\left(L_{std} - L_{loc}\right) - E + DT$$

$T_{rise} = 4.865$ Sunrise local time

$$T_{set} := LST_{set} - \frac{1}{15}\left(L_{std} - L_{loc}\right) - E + DT$$

$T_{set} = 19.127$ Sunset local time

Cardinal Components of Terrestrial Solar Radiation:

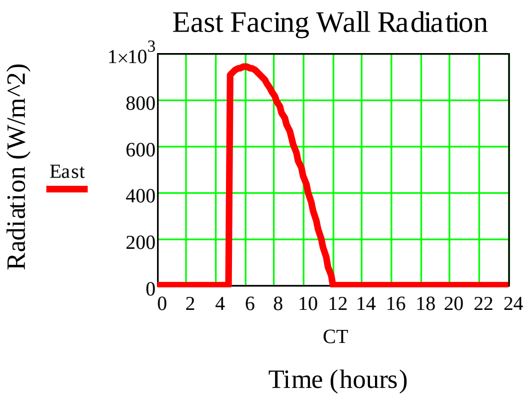


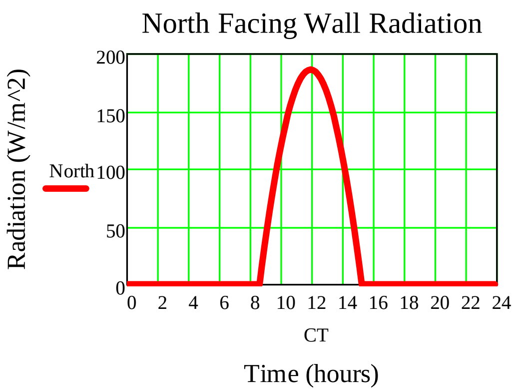
$$North_i := \text{if}\left(T_{rise} \le CT_i \le T_{set}, \text{if}\left(G_{Tx_i} \le 0, -1, 0\right)\cdot G_{Tx_i}, 0\right)$$

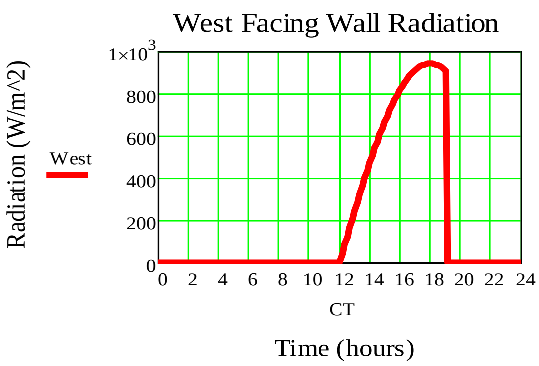
$$East_i := \text{if}\left(T_{rise} \le CT_i \le T_{set}, \text{if}\left(G_{Ty_i} \ge 0, 1, 0\right)\cdot G_{Ty_i}, 0\right)$$

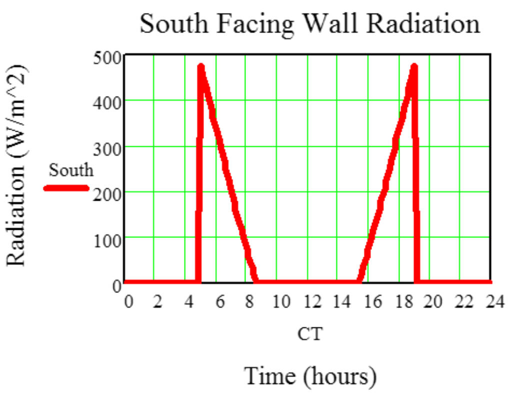
$$South_i := \text{if}\left(T_{rise} \le CT_i \le T_{set}, \text{if}\left(G_{Tx_i} \ge 0, 1, 0\right)\cdot G_{Tx_i}, 0\right)$$

$$West_i := \text{if}\left(T_{rise} \le CT_i \le T_{set}, \text{if}\left(G_{Ty_i} \le 0, -1, 0\right)\cdot G_{Ty_i}, 0\right)$$









APPENDIX B – Solar Boundary Condition Investigation

Solar Load Models Applied to a Simple Room Geometry in Ansys Fluent for a Transient Simulation:

The purpose of this report is to investigate different solar load models and how they are applied to a simple room geometry in Ansys Fluent in a transient simulation. The Fluent solar load model can accurately be used to simulate the effect of solar radiation on geometries, however this may only be done in the steady state case. Therefore, a novel way of applying a solar load to geometries needs to be designed for transient state simulations.

Objectives:

- Research methods of applying solar load in the transient state.
- Apply these methods as boundary conditions for a simple room geometry.
- Compare the temperature results of each model to realistic results.

Solar Load Models:

Each model takes its inputs from the Solar Radiation Calculator (APPENDIX A – Solar Load Calculator**Error! Reference source not found.**) and applies them as boundary conditions to the exterior walls of the room.

1. **Heat Generation Film:**

To simulate the heat generated by the incident solar radiation, a heat generation film was created on the exterior surface of each wall. The film is 1mm in thickness and covers the full area of the exterior wall. The heat generation power was calculated based on the volume of the heat generation layer, and the total incident radiation received by the surface.

This heat generation was applied as a mixed condition boundary layer in Fluent whereby apart from the heat generation, convection was also enabled for the vertical wall.

Results and Discussion:

The heat generation film resulted in average room temperatures that were in the range of 50°C to 150°C which are not accurate when compared to realistic results. It was determined that the exterior surface temperature of the wall exceeded 250°C.

It is theorised that the heat generation film method overestimated the amount of solar radiation that is converted into thermal energy. In this way, all of the incoming solar radiation is converted directly into thermal energy and is then transmitted through the wall.

However, what is correct about this model is that the incident solar radiation only heats the exterior surface of the wall.

2. **Semi-transparent Wall:**

In the case of the heat generation film, the wall is set to be opaque which means there is no interaction between the wall and radiation. In this model the wall was set to be semi-transparent whereby the solar radiation would be allowed to penetrate the wall and heat would therefore be generated.

This boundary condition was applied by setting the incident radiation value in Fluent to that calculated by the solar load calculator. A mixed boundary condition was also applied to the wall where convection was enabled for the vertical wall.

Results and Discussion:

The average room temperature results are more accurate than the heat generation film model and track very closely to the realistic results. However, looking at heat map profile it can clearly be seen that the method in which the wall is heated by solar radiation is incorrect.

The heat map shows that the internal core of the wall is at a higher temperature than the exterior of the wall. This would be similar to the case of microwave radiation, whereby it heats the whole geometry as one. It does not heat the exterior layer of the wall and allow conduction to transfer the heat through the wall.

3. **Semi-transparent Film:**

This method combines aspects from both the heat generation film and semi-transparent methods whereby a 1mm film that covers the total surface area of the exterior wall is created and is set to be semi-transparent. The incident solar radiation as calculated by the solar radiation calculator is applied to the semi-transparent film. This allows for the film to heat up and then transfer heat to the wall via conduction.

Results and Discussion:

The average room temperature is similar to results from the semi-transparent wall case. These results are very realistic as they follow the realistic case, and the temperature range falls within the human comfort range.

By looking at the heat transfer map, it can also be seen that the exterior surface of the wall heats up first, and the heat is then allowed to transfer through the wall via condition to then interact with the air inside of the room via natural convection.

Conclusion:

By comparing all three methods of applying solar load to a transient simulation in Ansys Fluent, it is clear the at the semi-transparent film method is the most realistic due to the average room temperature range falling within the temperature range for human comfort, and the way in which the heat is transferred through the wall is realistic.

APPENDIX C – Sinusoidal Temperature Function

The basic equation for the sinusoidal temperature function is as follows:

$$T(t) = -Asin(\omega t) + C$$

Where:

A is the amplitude

C is the mean y-intercept

ω is the angular frequency

t is a point in time

During a 24-hour day and night cycle the outdoor temperature fluctuates according to a sinusoidal pattern. This pattern can be modelled and applied as a boundary condition in Fluent. To determine the temperature equation, the daily temperature range needs to be decided. For the purpose of this model a temperature range of 18 – 28°C will be used. The period in which the temperature fluctuates is 24 hours.

The sinusoidal temperature function for this model is therefore:

$$T(t) = -5\sin(7{,}272 \times 10^{-5}t) + 23$$

APPENDIX D – Temperature UDF

```
/**********************************************************************
   unsteady.c
 UDF for specifying a transient temperature profile boundary condition
 **********************************************************************/

 #include "udf.h"

 DEFINE_PROFILE(unsteady_temperature, thread, position)
 {
    face_t f;
    real t = CURRENT_TIME;
    begin_f_loop(f, thread)
      {
        F_PROFILE(f, thread, position) =  -5*sin(0.00007272*t)+(15+273.15);
      }
    end_f_loop(f, thread)

 }
```