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MECHANICAL ENGINEERING

The Design of a Combustion Test Facility for Synthetic Jet Fuel Research

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Declaration

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Executive Summary

Background

With the relatively recent emergence of non-petroleum-derived aviation gas turbine fuels, it was appropriate to review the complete list of jet-fuel specifications to assess whether they were sufficiently robust to ensure fit-for-purpose within the new paradigm. Although this has been an industry-wide endeavour, there were some particular research areas that were identified for special in-house attention by Sasol, as the world's first commercial producer of approved and certified semi-synthetic and fully synthetic jet fuel. The project described in this report formed part of one of these research areas, which pertained to ignition and combustion stability in gas turbines and the role played by various fuel attributes and properties. The project was conducted at the Sasol Advance Fuels Laboratory based at the University of Cape Town.

Objectives

The project entailed the design and construction of a combustion test facility for conducting synthetic jet fuel research. The primary intended focus of the facility was the investigation of ignition and combustion stability behaviour of various test fuels, ranging from commercial jet fuel to single component model fuels. The scope of the project also included the design of both a basic homogeneous and a heterogeneous combustor which served to verify the facility's suitability for investigating the influence of fuel chemistry and combustor inlet conditions on ignition and combustion stability limits.

Test facility design

Design criteria, such as the required test condition range, facility scale, cost and safety, were considered during the generation of design concepts and the selection of the final facility design. The facility design was approached as a number of integrated subsystem designs. The final facility design employed a single positive displacement blower that allowed testing to be conducted under both vacuum and pressurised combustor inlet conditions depending on the configuration of the flow control valves.

An absolute pressure range of 70kPa to 150kPa was attainable over a temperature range of 263K to 340K. The fuel system allowed primary zone equivalence ratios of 0.3 to 1.5 over the full air mass flow range of 0.85kg/min to 18kg/min.. This allowed the study of both temperature and pressure influences on ignition and combustion stability limits.

A homogeneous and a heterogeneous combustor were designed to allow the study of both fuel chemistry influences in isolation and in conjunction with mixing and evaporation effects.

Test programme

As the sign-off acceptance criterion for the commissioning of the test facility, a test programme was conducted with a small selection of single component model fuels and some petroleum-derived Jet A-1. These tests were used to provide not only proof of the facility's capabilities, but also to confirm the sensitivity of the equipment to detect and measure the expected influence of autoignition chemistry on threshold combustion performance.

Tests with single component model fuels were performed using the premixed homogeneous combustor to assess the measurement capability of the test facility in terms of the influence of autoignition chemistry on lean ignition and lean blowout behaviour. This was followed by tests with petroleum-derived Jet A-1 in the heterogeneous combustor to assess the temperature and pressure dependence of ignition and combustion stability behaviour. Finally in order to determine how the results obtained in the homogeneous combustor translated to a heterogeneous environment, the lean blowout behaviour of two single component model fuels were compared with that of petroleum-derived Jet A-1.

Conclusions

The test programme provided conclusive evidence of the successful commissioning of the test facility. The results of the pressure and temperature influence evaluation clearly illustrated the repeatability of test results and the suitability of the test facility and the heterogeneous combustor design for investigating the ignition and extinction behaviour of practical synthetic jet fuel alternatives.

The results of the fuel autoignition chemistry evaluation, using both combustor designs, revealed evidence of the influence of fuel chemistry and physical property effects. These results were seen to validate the motivation for designing and constructing a facility that would enable further study of the influence of fuel chemistry on ignition and extinction behaviour, and its particular relevance to synthetic gas turbine fuel formulation.

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Nomenclature

A	combustor constant / area	[m^2]
B	combustor constant / mass-transfer number	
B_g	geometric blockage ratio	
b	plate width	[m]
C_a	ambient velocity	[m/s]
C_p	specific heat at constant pressure	
D	droplet diameter	[μm]
D_{32}	Sauter mean diameter (SMD)	[μm]
d_q	quenching distance	[μm]
E	Young's modulus	[N/m^2]
f_f	fuel fraction vaporised in combustion zone	
g	gravity	[m/s^2]
H	lower calorific heating value	[J/kg]
L	vertical temperature gradient	[K/m]
M	molar mass	[kg/mol]
$\dot{m}$	mass flow rate	[kg/s]
P	pressure	[Pa]
q	fuel-air ratio by mass / tank pressure	[Pa]
R	universal gas constant	[J/(mol.K)]
S	burning velocity	[m/s]
S_L	laminar burning velocity	[m/s]
S_T	turbulent burning velocity	[m/s]
T	temperature	[K]
t	plate thickness	[m]
U	velocity	[m/s]
V	volume	[m^3]
z	altitude	[m]
α	plate constant / thermal diffusivity	[$k/c_p\rho$]
β	plate constant	
γ	ratio of specific heats	
Δ	difference	
δ_L	laminar flame thickness	

μ	dynamic viscosity	[kg/ms]
η_c	combustion efficiency, isentropic compressor efficiency	
η_i	isentropic intake efficiency	
λ	evaporation constant	[m^2/s]
ρ	density	[kg/m^3]
σ_{max}	maximum plate stress	[N/m^2]
σ	surface tension	[kg/s2]
ϕ	equivalence ratio	

Subscripts

A	air
a	altitude value
BO	blowout value
c	combustion zone value
eff	effective value
g	gas
h	hole value
h,eff	total effective liner hole value
j	jet value
L	liner value / liquid value
LBO	lean blowout value
LLO	lean lightup value
pz	primary zone value
r	relative value to JP4 value
ref	reference value
st	stoichiometric value
sl	sea level value
WE	weak extinction value
0	initial value, stagnation value
2	compressor inlet plane value
3	combustor inlet plane value

1. Introduction

1.1. Background

It has always been an acknowledged feature of gas turbine engines that they are essentially “omnivorous” in terms of their fuel requirements. This fortuitous characteristic helped to facilitate the gas-turbine’s evolution to become the aviation engine of choice. However, the wide range of ambient operating conditions, coupled with the ever growing demand for improved efficiency, has forced the designers to constrain the engine’s fuel tolerance. Fuel handling and the associated stringent safety requirements has imposed further restrictions on the range of permissible fuel properties and all of this has evolved into a very explicit jet fuel specification that is, of necessity, a global, consensus agreement.

With the relatively recent emergence of non-petroleum-derived aviation gas turbine fuels, it was appropriate to review the complete list of jet-fuel specifications to assess whether they were sufficiently robust to ensure fit-for-purpose within the new paradigm. Although this has been an industry-wide endeavour, there were some particular research areas that were identified for special in-house attention by Sasol, as the world’s first commercial producer of approved and certified semi-synthetic and fully synthetic jet fuel [1].

One of these identified research areas pertained to ignition and combustion stability in gas turbines and the role played by various fuel attributes and properties. The project described in this report formed part of that particular research study. The project was conducted at the Sasol Advance Fuels Laboratory based at the University of Cape Town.

One particular distinction between petroleum-derived fuel and synthetic fuel that has possible relevance is that the latter can potentially comprise a single class of hydrocarbon species such as n-paraffins, iso-paraffins, olefins, aromatics, etc. The synthetic fuel plant can of course be designed to produce and blend these streams as required but, in terms of this particular project, it was hypothesised that that the autoignition characteristics of the different fuel classes found in jet fuel could, in isolation, behave differently in the extent to which they impact on the engine performance under marginal combustion circumstances, such as during ignition and close to the point of extinction. This is a unique condition where the chemical timescales are not insignificant as is generally the case in normal gas-turbine combustion and operation. It was speculated that synthetic fuels could possibly be formulated to perform differently under these conditions than is the norm for petroleum fuels.

The current jet fuel specification list does not contain any property parameter that addresses combustion propensity (such as octane or cetane rating as found in automotive specifications). It was inferred that feedstock, production processes and jet fuel specifications have traditionally conspired to result in the production of petroleum-derived jet fuels that did not specifically accentuate the possibility of autoignition characteristics being of interest. The emergence of synthetic jet fuels has raised the possibility for selectively tuning the autoignition chemistry of the final product though the use of different class-specific blend streams. It is possible that the hypothesised autoignition distinction between the petroleum and the synthetic fuel was not detected as such during the early proving evaluations on account of the interplay between temperature, evaporation and autoignition which may have masked the role played by differences in reaction chemistry. All of which highlights the need to study the influence of fuel chemistry in general, and autoignition chemistry in particular, on gas turbine combustion, ignition and extinction behaviour.

1.2. Project scope

The scope of this project entailed the design and construction of a combustion test facility for conducting synthetic jet fuel research. The facility was primarily designed to be employed in the investigation of ignition and combustion stability behaviour of various test fuels, ranging from commercial jet fuel to single component model fuels. These fuels would be used to evaluate specific evaporative and autoignition chemistry effects. The possibility of utilising the facility for future alternative test programmes (such as combustion instability or additives or bio-derived fuels) was identified and borne in mind as a consideration throughout the design and construction of the facility.

The scope of the project included the design of both a basic homogeneous and a heterogeneous combustor which would serve to verify the facility's suitability for investigating the influence of fuel chemistry and combustor inlet conditions on ignition and combustion stability limits. Tests with a small selection of single component model fuels and some petroleum-derived Jet A-1 tests would be used to provide not only proof of the facility's capabilities, but also to confirm the sensitivity of the equipment to detect and measure the expected influence of autoignition chemistry on threshold combustion performance. This would constitute the sign-off acceptance criterion for the construction of the test facility.

1.3. Report structure

This report starts with a discussion of the theoretical context which provided the motivation for designing and constructing the test facility and the planned basis for the interpretation of the test results. This provides the foundation for the test facility design which follows, including the development of the design criteria and their influence on the design of the various subsystems. The operation of the facility is discussed with emphasis on accuracy, repeatability, and pertinent safety considerations. The second stage of the project relates to the test programme, and is divided into two sections based on the combustor designs (homogeneous or heterogeneous) being employed. The test results are discussed and interpreted against the context of theoretically predicted behaviour. Based on the operation of the facility and the test results, a number of conclusions were drawn and these are summarised together with recommendations for further development of the test facility and future test programmes.

2. Historical and Theoretical Background

2.1. Gas turbine fuels

While gas turbines have generally acquired the reputation of being “omnivorous” of fuels, the restrictive requirements of aviation have limited the range of suitable jet fuel formulations. Energy content and combustion quality are accepted to be key performance properties in aviation gas turbine fuels. Other significant performance properties include thermal stability, lubricity, volatility, non-corrosivity and cleanliness. Jet fuel specifications are performance specifications, and allow any combinations of hydrocarbons that satisfy the required performance. The development of gas turbine fuel specifications since the 1940s has concentrated primarily on aspects of distillation, volatility, freeze point, thermal stability and volume yield [2], [3]. It is of interest to note that no direct or indirect specifications of fuel autoignition characteristics have been introduced. This is presumably due to the argument that over a wide range of operating conditions the chemical reaction timescales are so short, in comparison with the time required to produce an adequate quantity of fuel vapour in the ignition zone, that it can be ignored [4]. The literature does however acknowledge that chemical reaction rates play an important role under threshold operating conditions, such as encountered during ignition and blowout [5]. Exploring this area of research, and the implications for jet fuel formulation, was the primary motivation for establishing the combustion test facility that formed the focus of this project.

Volatile crude oil prices, “peak oil”, energy supply security and lifecycle environmental considerations are some of the drivers that have incentivised the quest for, and commercialisation of, alternatives to petroleum-derived jet fuel. Alternative aviation gas turbine fuels have been investigated since the early days of engine development with cryogenic fuels like liquid hydrogen and boron compounds being studied in the 1950s and 1960s. Alternative fuel sources received considerable attention in the 1970s due to the energy crisis, and various alternative feedstock avenues such as biomass, tar sands, coal and oil shale were researched. Prominent current alternative jet fuel sources that are being investigated include fossil fuel sources, such as natural gas, shale oil, coal and tar sands, biomass-derived fuels such as bio-ethanol and biodiesel, Fisher-Tropsch synthetic fuels utilising either bio or fossil feedstock, and cryogenic fuels such as methane and hydrogen [2], [6]. Regardless of the technology involved there are a number of key areas of consideration that need to be addressed by all jet fuel alternatives. Combustion quality, ignition and combustion stability are of primary concern. The gravimetric and volumetric energy content of a potential jet fuel are important due to their impact on payload (maximum take-off weight – MTOW) and flight range, respectively. Any jet fuel alternative also needs to exhibit thermal stability and material compatibility behaviour comparable to that of conventional petroleum-derived jet fuel. To date, jet fuel has remained virtually exclusively petroleum-derived, with the only commercially certified alternative fuels in the world being the semi-synthetic and fully-synthetic Fischer-Tropsch Jet A-1 formulations, produced by Sasol to supply OR Thambo International Airport (ORTIA) [1]. The process of formulating generic certification criteria for synthetic jet fuels could potentially benefit from further study of the influence of variable chemical reaction rates on threshold combustion.

2.2. Combustion fundamentals

Combustion in continuous flow combustors can be classified as either premixed or diffusion controlled, depending on whether the fuel and oxidant are evaporated prior to combustion or mixed in the combustion zone by diffusion. The specific category of diffusion controlled combustion is determined by the initial physical states of the fuel and oxidant. If both are in the gaseous state the flame is referred to as a diffusion flame. If the fuel and oxidant are in different initial physical states the process is called heterogeneous combustion. Both premixed and diffusion flames can be classified as either laminar or turbulent, depending on the prevailing flow conditions [7].

2.2.1. Laminar burning velocities

The laminar burning velocity is defined as the velocity, relative to and normal to the flame front, at which unburned gas moves into the thin flame front and is transformed to products under laminar flow conditions. In the case of laminar flames in homogeneous premixed systems the rate of chemical reactions in the flame front and the rate of heat and mass transfer from the flame to the unburned gas are considered to be rate controlling. The flame front consists of a pre-heat zone and a reaction zone. The temperature of the unburned mixture is raised in the preheat zone by heat transfer from the reaction zone. The heat transfer occurs mainly by diffusion which, at a molecular level, is related to conduction. The ratio of the thermal diffusivity over the mass diffusivity (conduction/ diffusion), represented by the Lewis number, is often taken as unity for flame analysis. The laminar flame velocity can be expressed as [8]:

$$S_L = \frac{\alpha}{C_p \rho \delta_L} \tag{2.1}$$

Where α represents the thermal diffusivity, C_p the specific heat at constant pressure, ρ the density, and δ_L the laminar flame thickness. Laminar premixed burning velocities are thus primarily governed by equivalence ratio, temperature and pressure. The influence of equivalence ratio or mixture strength on flame speed roughly corresponds to its influence on flame temperature, with a maximum value in most instances being attained at an equivalence ratio of 1.05 to 1.10 [7], [9], [8].

Dugger and Heimel [10] investigated laminar flame speed response to initial mixture temperature. Mixtures of methane, propane and ethylene with air were studied and shown to exhibit increases in maximum flame speed with increased initial mixture temperature.

The relatively slow laminar flame speeds (less than 0.6m/s) of fuels traditionally employed in gas turbines are reported to exhibit a pressure dependence that can be expressed as shown in Equation 2.2 [7]. The laminar burning velocity (S_L) is related to pressure (P) with exponent x ranging from 0.1 to 0.5.

$$S_L \quad \propto \quad P^{-X} \tag{2.2}$$

2.2.2. Turbulent burning velocities

Damkohler [11] originally proposed that turbulent flames exhibited similar structures to laminar flames and attributed the increased burn velocities of turbulent flames to a wrinkling of the flame front increasing the specific area available to consume fresh mixture. Subsequent theories embodied the wrinkled flame concept, but offered different explanations to relate turbulence to flame surface increases. Results of an experimental study by Ballal and Lefebvre [12] were in agreement with Damkohler's theory of a wrinkled laminar flame surface at low velocities, but at very high turbulence levels the theory was shown not to apply. The large number of small eddies that were observed at high turbulence velocities were unable to wrinkle the flame surface, but rather created a thick matrix of burned gasses and eddies of unburned mixture, resulting in a very large total flame surface and associated increased flame speed.

2.2.3. Heterogeneous burning velocities

In non-premixed systems where mixing occurs rapidly relative to chemical reaction rates, the combustion rates may still be considered in terms of homogeneous processes alone. However, in systems where the mixing of fuel and oxidant is slow relative to the chemical reaction rates, physical mixing is considered to be burn rate controlling. Diffusion flames fall into this category with the fuel and oxidant mixing in the reaction zone through molecular and turbulent diffusion.

Ballal and Lefebvre [13] proposed a model for flame propagation through quiescent heterogeneous fuel-air mixtures that was based on the rate of flame propagation being such that the quench time of the reaction zone equals the sum of the evaporation and chemical reaction times. Assuming monodisperse sprays of fuel droplets in air, the equation simplifies to:

$$S = \left[\frac{D^2}{\alpha_{air}\lambda} + \frac{1}{S_L^2}\right]^{-0.5} \qquad (2.3)$$

Where S represents the burning velocity, S_L the laminar burning velocity, D the droplet diameter, α_{air} the thermal diffusivity of air, and λ the evaporation constant of the fuel. The authors concluded that the flame propagation rate is therefore determined by an evaporation rate term that is dependent on fuel volatility, mean droplet size and vapour fraction, as well as a laminar burning velocity term that provides an indication of the rate of chemical reaction. (As mentioned in Section 2.2.1, laminar burning velocity is also considered to be influenced by the rate of heat and mass transfer from the flame to the unburned mixture, in addition to the chemical reaction rate. This point is revisited in Section 2.6.) If the evaporation time is greater than the chemical reaction time, the flame speed is increased by reducing the mean droplet size and increasing the gas density, fuel volatility and vapour concentration. If the chemical reaction time scales are rate controlling, the burning velocity tends to the laminar burning velocity under fully evaporated mixture conditions.

In cases where the chemical reaction timescales are short relative to the time required for evaporation, the model predicts that flame speed is inversely proportional to mean droplet size. Experimental results of Myers and Lefebvre [14] that confirmed this, showed an inverse linear relationship between turbulent burning velocity (S_T) and droplet mean diameter over a wide range of diameter values. (Figures 2.1 and 2.2)

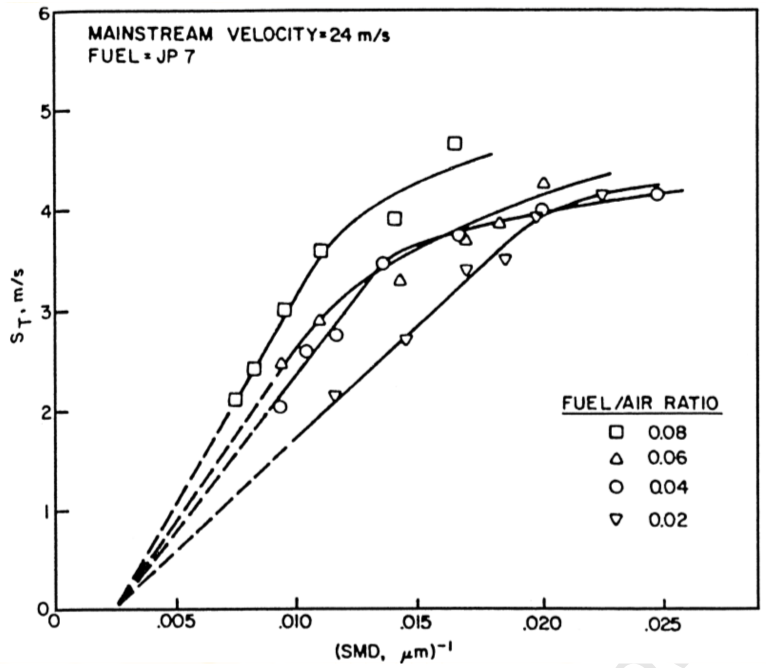

Figure 2.1 Influence of fuel-air ratio and SMD on flame speed (mainstream velocity 24m/s) [14].

The most often used mean diameter parameter is the Sauter mean diameter (SMD or D_{32}), which corresponds to the diameter of a drop that has the same volume to surface ratio as that of the whole spray. While, theoretically, the burning velocity is expected to approach zero as the mean droplet diameter approaches infinity, there always exists a practical limit to the maximum droplet size at which the burning velocity reaches zero. Myers and Lefebvre found this limit to be approximately 400µm.

Burning velocity generally increases with a reduction in mean droplet size, up to a critical value beyond which the curves in Figure 2.1 flatten out due to the chemical reactions becoming rate controlling in preference over the rates of evaporation. In the case of kerosene-type fuels this critical value is approximately 50 to 70µm. These observations confirm the relevance of chemical reaction rates under highly atomised conditions where evaporation timescales are short. The influence of atomisation quality on reaction rates was of particular relevance during the design of the test facility fuel system, the selection of the appropriate fuel atomisers and the interpretation of the heterogeneous combustor test results.

The flow velocity dependence of the burning velocity indicated by Figure 2.2 is primarily due to the resultant turbulence intensity that enhances both flame speed, through increased flame surface area, and evaporation rates.

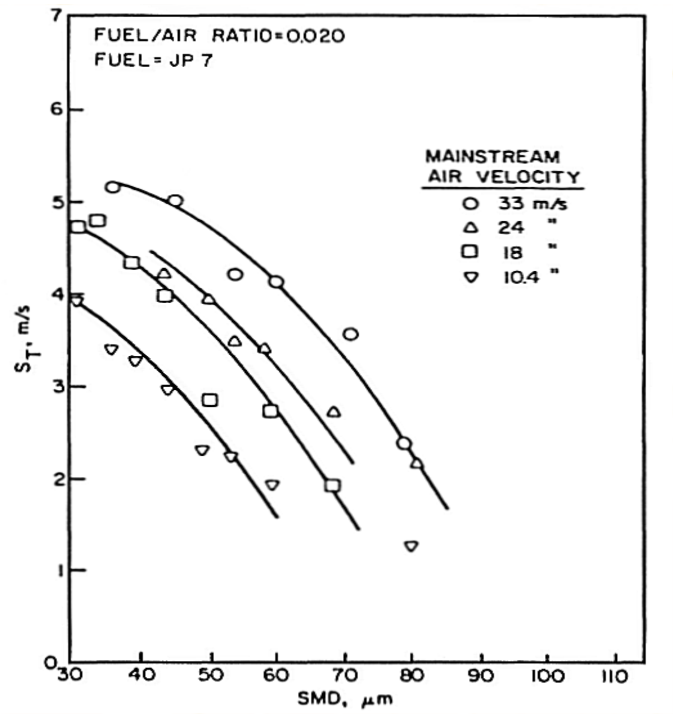

Figure 2.2 Influence of mainstream velocity and SMD on flame speed [14].

Taking these influences into account, Equation 2.3 can be modified to be applied to turbulent mixtures of fuel droplets in air. The evaporation constant is replaced by the effective evaporation constant λ_{eff} and S_T represents the turbulent burning velocity [15].

$$S = \left[\frac{D^2}{\alpha_{air}\lambda_{eff}} + \frac{1}{S_T^2} \right]^{-0.5} \qquad (2.4)$$

In conventional gas turbine combustion applications the physical processes of heat transfer, mass transfer, thermodynamics, gas dynamics and fluid dynamics are considered to influence overall reaction rates to a much greater extent than the chemical processes. While chemical reaction rates are acknowledged as essential they are considered to be relatively rapid and not rate controlling in high temperature flames and are therefore largely disregarded. Emphasis is placed on the rate of interdiffusion of fuel and air and large scale mixing as the rate controlling steps. In the combustion of conventional petroleum derived gas turbine fuels the literature does however acknowledge that chemical reaction rates play an important role in pollutant emission formation as well as the lean lightoff and lean blowout limits attained at high altitudes [5], [3], [16]. The potential to influence the chemical reaction rates of synthetic jet fuel formulations to a larger degree than is possible with petroleum-derived jet fuel therefore warrants investigation of the influence of chemical reaction rates on, not only emission formation, but also threshold combustion.

2.3. Combustion stability

Aircraft combustors need to be able to sustain stable combustion over a broad range of temperatures and pressures and at fuel–air ratios that can lie outside the normal limits of flammability for hydrocarbon–air mixtures. An example of a typical stability loop is shown in Figure 2.3. The measure of combustion stability refers to two separate properties that contribute to the overall stability performance of the system: the equivalence ratio burning range and the maximum blowout velocity (U_{BO}).

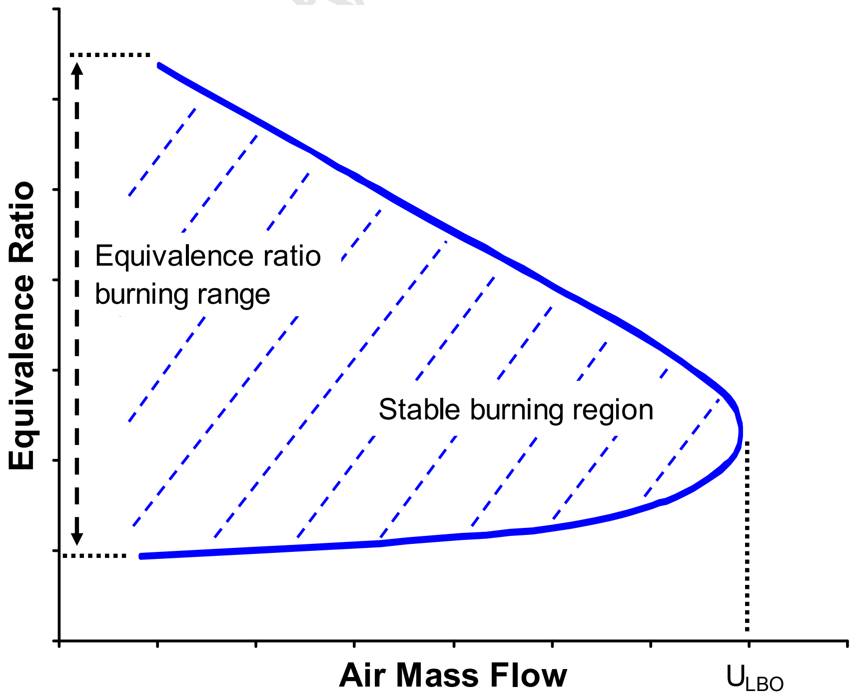

Figure 2.3 A typical combustion stability loop at constant combustor inlet pressure and temperature conditions.

In gas turbine combustors the range of fuel–air ratios over which stable burning is possible is considered to be of prime importance. Experimental premixed combustor studies on the other hand often concentrate on maximum blowout velocities [17]. Ballal and Lefebvre [18], [19] investigated the effects of inlet air pressure, temperature, velocity, turbulence, fuel volatility and mean droplet size on the lean extinction performance of both homogeneous and heterogeneous mixtures stabilised utilising bluff body stabilisers. They found that stability limits are extended by:

- reduced inlet velocity
- increased inlet temperature
- increased gas pressure
- reduced turbulence intensity
- change in equivalence ratio towards unity
- increased flameholder size
- increased flameholder base-drag coefficient
- reduced flameholder blockage ratio.

Heterogeneous mixture stability was also found to be improved by increased fuel volatility and mean droplet size reduction down to a critical SMD value. Droplets with diameters below the critical value evaporated completely within the combustion zone, which then effectively operated as a homogeneous stirred reactor [20]. These findings were of direct relevance to the design of the various test facility subsystems including the charge air supply system, pressure and temperature control systems, fuel system, and both combustor designs that were employed. The influence of critical droplet size is revisited in the discussion of test results that were generated using the heterogeneous combustor (Section 6.2).

Ballal and Lefebvre [18], [19] proposed a model of the bluff-body combustor reaction zone as a homogeneous chemical reactor with constant chemical composition and temperature distribution. They proposed that flame extinction occurs when the required heat to ignite the fresh mixture entering the wake region of the flame holder just exceeds the heat provided by combustion in the reaction zone.

$$\phi_{WE} \propto \left[\frac{U}{P^{0.25}T_0 \exp(T_0/150) D_c (1-B_g)}\right]^{0.16} \tag{2.5}$$

It is evident from their proposed relationship that weak extinction equivalence ratio (ϕ_{WE}) is affected primarily by initial temperature (T_0), to a lesser extent by velocity (U), and significantly less by pressure (P). Increasing the characteristic dimension of the flameholder (D_c) improves the weak-extinction performance as long as it is not accompanied by a blockage ratio (B_g) increase. It should also be noted that the true characteristic dimension governing a flameholder's stability is not the geometric blockage ratio (B_g) but the corresponding aerodynamic value (B_a). The ratio of the aerodynamic to geometric blockage ratio is determined by the forebody shape, with more streamlined forebody shapes resulting in lower B_a to B_g ratios [21]. These observations provided guidance during the design and evaluation of the different bluff body flameholders that were employed by the homogeneous combustor design.

Equation 2.5 can also be applied to heterogeneous fuel-air mixtures if the fuel evaporation rate is sufficiently high to guarantee that the fuel is fully vaporised within the primary combustion zone. In cases where the evaporation rate is slower, the relationship can be modified to take into account the fact that the effective fuel-air ratio would be lower than the nominal value. (Equations 2.6 & 2.7)

$$\phi_{WE}(heterogeneous) = \frac{\phi_{WE}(\mathrm{hom}ogeneous)}{f_f} \tag{2.6}$$

and

$$f_f = \frac{8\rho_g V_c \lambda_{eff}}{f_{pz}\dot{m}_A D_0^2} \tag{2.7}$$

The gas density is represented by ρ_g, the combustion zone volume by V_c, the effective evaporation constant by λ_{eff}, the air mass flow rate by $\dot{m}_A$, and the initial droplet diameter by D_0. If the calculated value of f_f (the fraction of fuel vaporised in the combustion zone) exceeds unity it indicates that the time available for evaporation is greater than the time required for evaporation. A value of unity is then assigned to f_f, with the heterogeneous and homogeneous weak extinction equivalence ratios being equal [19].

The amount of fresh mixture entrained into the recirculation zone of a combustion chamber can be controlled to a much greater degree than in the case of bluff-body flameholders. The primary zone acts as the major heat release zone of the combustor. Air enters the primary zone through various apertures in the liner wall and causes recirculation of burned and burning gasses that mix with incoming fuel and air to establish and sustain combustion over wide velocity, pressure, temperature and fuel-air ratio ranges. The number, size, position and type of apertures determine the stability limits of the primary zone. A general rule that applies to the primary air recirculation holes is that a smaller number of larger holes provide the maximum stability due to the larger holes producing larger jets of air that aid large scale recirculation. However, this has to be balanced against the required air mass flow rate to determine the optimal number of holes required [22].

While lean extinction or blowout limits are usually expressed in terms of equivalence ratio for bluff-body flameholders, overall fuel-air ratio is most common for gas turbine combustors. Lean blowout limits are critical during marginal flight conditions such as during aircraft decent through inclement weather. Under such conditions, overall combustor air-fuel ratios (AFR) of around 120 can be encountered, while typical lean blowout air-fuel ratios of around 250 are specified to provide a safety margin for potential engine and fuel variations as well as the possibility of water and ice ingestion.

Apart from the atomisation quality, the fuel distribution of different atomiser designs plays a cardinal role in lean blowout limits. Simplex and duplex pressure-swirl atomisers are known to exhibit poor fuel distribution, resulting in some combustion taking place at mixture strengths that are significantly richer than the average value. While this leads to performance problems like high rates of soot formation it also results in good lean blowout performance with overall combustor air-fuel ratios in excess of 1000 AFR being attained. In contrast, the much more uniform mixing achieved by airblast atomisers results in lean blowout limits of around 250 AFR [3], [22].

Lefebvre [3], [22] studied the lean blowout performance of a number of combustion chamber designs with a range of test fuels and derived the following equation for determining lean blowout fuel-air ratios (q_{LBO}):

$$q_{LBO} = \left[\frac{A}{V_{pz}}\right]\left[\frac{\dot{m}_A}{P_3^{1.3}\exp(T_3/300)}\right]\left[\frac{D_r^2}{\lambda_r H_r}\right] \tag{2.8}$$

The first term contains the primary combustion zone volume (V_{pz}) and combustor specific constant (A) dependence. The second term addresses the combustor operating conditions of pressure (P_3), temperature (T_3) and air mass flow rate ($\dot{m}_A$). The third term deals with the fuel property dependent properties of droplet size (D_r), effective evaporation constant (λ_r) and the lower calorific value (H_r) of the fuel relative to that of JP4. While the physical properties of the fuel influence lean blowout behaviour through droplet size and evaporation effects, the lower heating value of the fuel is proposed to be the only fuel chemistry dependent parameter to influence lean blowout performance for the particular range of test fuels that was considered. This appears to be contradicting the observation that chemical reaction rates can be relevant under lean blowout conditions. The need to investigate the influence of chemical reaction rates on combustion stability was therefore reaffirmed and contributed to the motivation for constructing a test facility that would enable research in this field.

2.4. Ignition

Gas turbine ignition is of cardinal importance both during ground starting lightup and, in the case of aircraft gas turbines, during rapid relighting after an in-flight flameout. Ignition loops similar to the one shown in Figure 2.4 reflect the limits of possible ignition for combustors over ranges of fuel-air ratios and air mass flow rates at fixed combustor inlet pressures and temperatures.

As discussed in Section 2.5, these loops are used to determine the altitude relight behaviour of a combustor. The same flow properties that influence combustion stability govern ignition behaviour and one might therefore expect the limits to coincide. The difference between stability and ignition behaviour can be ascribed to heat loss differences. Ignition is associated with colder liner temperatures and thus greater heat loss, which results in the lean lightup equivalence ratio (ϕ_{LLO}) always being richer than the lean blowout (ϕ_{LBO}) equivalence ratio [23].

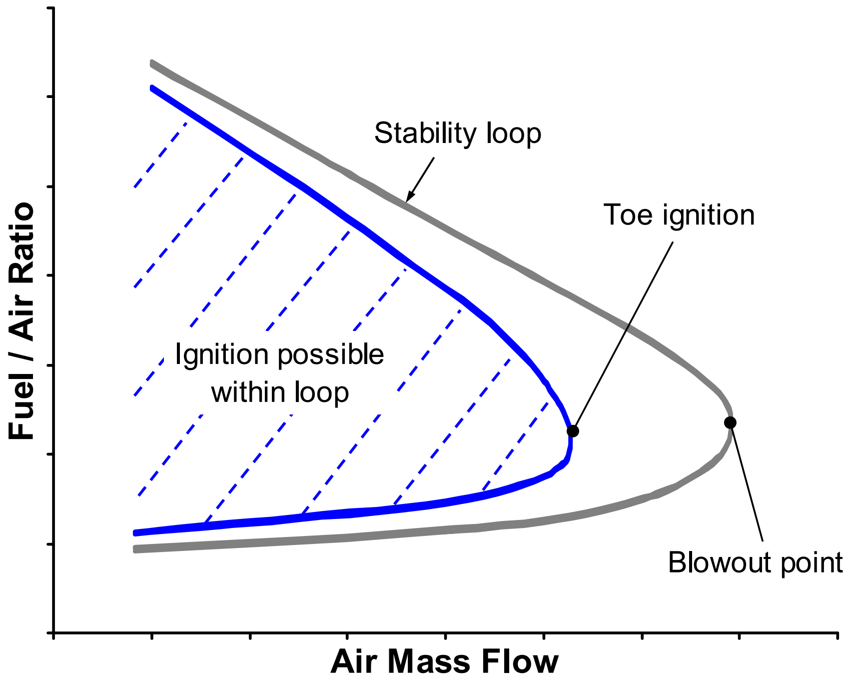

Figure 2.4 A typical combustor ignition loop at constant combustor inlet pressure and temperature conditions.

The majority of gas turbine ignition systems employ spark ignition to ignite highly turbulent heterogeneous fuel-air mixtures flowing at velocities of the order of 25m/s. Theoretical and experimental studies have yielded correlations between operating variables and ignition performance that are in agreement with general practical experience namely:

- increased pressure, temperature and spark energy improves ignition
- increased velocity, turbulence intensity and fuel droplet size impairs ignition.

The ignition performance of liquid fuels is markedly affected by the fuel properties, primarily through their influence on the concentration of fuel vapour in the immediate vicinity of the igniter plug and throughout the primary zone during lightup. The influence of volatility on evaporation rates and viscosity on mean droplet size are traditionally seen to be the key drivers [23].

The lean lightup behaviour of numerous combustion chambers using a range of test fuels was studied by Lefebvre who proposed Equation 2.9 for determining lean lightup fuel-air ratios (q_{LLO}) [3], [23].

$$q_{LLO} = \left[\frac{B}{V_c}\right]\left[\frac{\dot{m}_A}{P_3^{1.5}\exp\left(T_3/300\right)}\right]\left[\frac{D_r^2}{\lambda_r H_r}\right] \qquad (2.9)$$

The combustor specific constant (B) was determined by the geometry, mixing characteristics of the combustion zone and the relative quantity of air employed in the primary combustion zone. Apart from having a higher pressure dependence ($P^{1.5}$ vs $P^{1.3}$), Equations 2.8 and 2.9 for q_{LBO} and q_{LLO} are virtually identical. The same observations regarding the influence of combustor operating conditions and physical and chemical fuel properties apply, and again the lower heating value of the fuel was proposed to be the only fuel chemistry dependent parameter to influence lean lightoff. As mentioned before, the influence of fuel chemistry on reaction rates appears to have been ignored and was seen as a motivation for further research.

2.5. Altitude relight

The ignition performance of an aircraft gas turbine combustor is typically quantified by the range of flight conditions over which combustion can be re-established after flameout occurs. Windmilling is a phenomenon that occurs when airflow through an unlit engine causes spool rotation. During windmilling, ram pressure results in the combustor inlet pressure (P_{30}) and temperature (T_{30}) being higher than the ambient conditions. The combustor inlet conditions are dependent on the windmilling characteristic, also known as "windmilling carpet", of the engine. As shown by the windmilling characteristic and constant combustor inlet condition schematic in Figure 2.5, the combustor inlet pressure and temperature decreases with increasing altitude and increases with increasing flight Mach number.

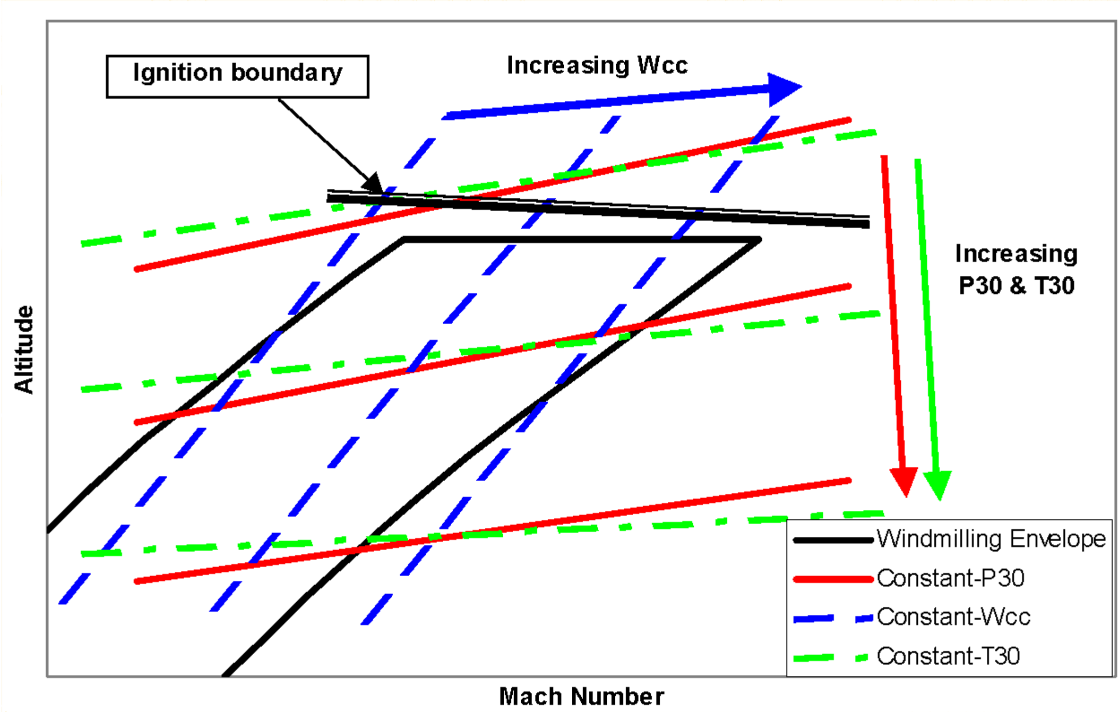

Figure 2.5 A Schematic windmilling characteristic [24].

Unlike high altitude engine test facilities or flying test beds that can simulate actual relight and blowout performance, altitude combustor test facilities can only be used to determine ignition and extinction performance. For such testing different regions of the Mach number-altitude plot are selected, which usually means that tests are conducted along a constant P_{30} line. For each P_{30} line, the ignition and extinction loops (similar to Figure 2.4) are determined. The ignition loop consists of a weak ignition boundary, rich ignition boundary and toe ignition point at the highest mass flow where ignition is still possible. The extinction limits and blowout point can be defined similarly.

During relight, combustion is initiated at a certain fuel flow that can be represented by a fuelling line on the equivalence ratio versus air mass flow plot. The intersection of the fuelling line and the ignition loop represents the maximum combustor mass flow where ignition is possible. By plotting the maximum combustor mass flow at various pressure levels in the altitude-Mach number graph, a relight envelope can be constructed. A typical combustor relight envelope is shown in Figure 2.6.

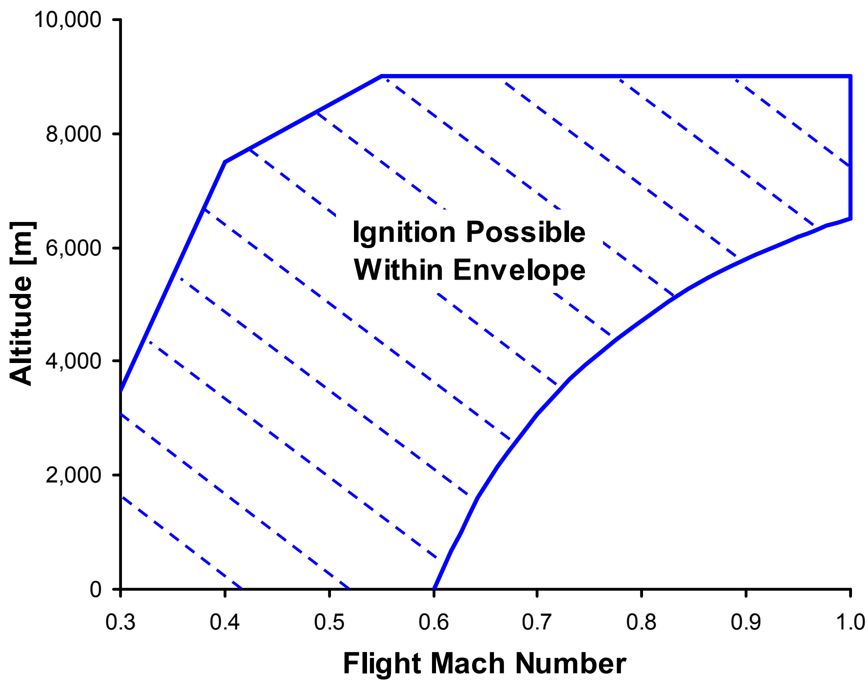

Figure 2.6 A typical combustor relight envelope.

Gas turbine ignition is not a single-step event, but occurs in two or more phases [23]. The first phase entails the formation of a flame kernel large enough to propagate. The second phase entails the actual propagation of the flame from the kernel into the entire primary zone. A third phase applies to can-annular and tubular combustor designs where the flame spreads from a lit liner to the adjacent unlit liners. The relative position of stability and ignition loops can be used to determine in which phase the ignition failure occurs. The significance of phase 3, for example, is illustrated by cases where the altitude relight capability predicted by rig tests employing a sector from a multi-tube combustor do not agree with in-flight relight performance test results. As discussed in Section 6.2, the influence of igniter positioning on phase one ignition failure was encountered during the commissioning of the heterogeneous combustor.

2.6. Fuel property effects on gas turbine combustion

Literature highlights the difficulty in investigating fuel property effects on gas turbine combustion since the classical approach to experimental research of quantifying the effects of varying a single independent parameter while maintaining all others constant is precluded to a large extent due to the interrelated nature of various fuel properties. Furthermore, different hardware designs have been shown to respond differently to fuel property variations. A notable example is the liner temperature response to the carbon-hydrogen (C/H) ratio variation of combustors with either lean or rich primary combustion zones. In the case of rich primary zones heat transfer to the liner wall is primarily due to radiation, which is governed by flame emissivity, which in turn is influenced by the C/H ratio. Heat transfer from a lean primary combustion zone to the liner wall occurs mainly by forced convection, where the gas temperature is dominant and relatively insensitive to C/H ratio changes [3].

A number of engine-hardware-oriented studies have been conducted that focused on investigating the influences of gas turbine fuel properties on combustion. In many instances the net effect of fuel variations on a specific combustor parameter were analysed, while in others attempts were made to isolate fuel effects into categories.

Venkataramani [25] investigated the influences of fuel properties on altitude relight performance and focussed on isolating fuel volatility effects from atomisation effects. The focus of the study was on separating the influences of physical fuel properties, and chemical property differences were not explored. The four test fuels (JP-4, Jet A, Jet A/2040 solvent blend, and Diesel 2) covered a wide range of volatilities, while fuel specific effects on atomisation were eliminated by employing injection equipment that maintained equivalent SMD values (50±10μm) for all test fuels at equal design flow rates. It was found that fuel volatility assumed a secondary role in initial (first-cup) lightoff. Slightly poorer blowout performance was recorded due to decreased volatility. Full-propagation and first-cup-blowout were found to be independent of fuel volatility. Due to chemical difference between the test fuels having been ignored, the potential influence of different chemical reaction rates was not taken into account. This was in spite of the previously mentioned acknowledgement that chemical reaction time scales can be significant under threshold conditions such as encountered during altitude relight. In line with previous findings, airblast atomisers were found to exhibit poorer ignition performance and showed a stronger volatility dependence than pressure atomisers. This observation was relevant to the design of the test facility fuel system, as discussed in Section 3.4.6.

Lefebvre [3] analysed a large body of data from studies conducted by the USAF, Army, Navy and NASA that were aimed at anticipating the combustion performance effects of future fuel formulations. Thirteen test fuels which included a JP4, JP8, five blends each of JP4 and JP8, as well as a No. 2 diesel, were intended to achieve three levels of hydrogen content, namely 12, 13 and 14 percent by mass. The results were analysed to determine fuel formulation influences on combustion efficiency, lean blowout limits, ignition performance, liner wall temperature, emissions and pattern factor.

It was concluded that hydrogen content and/or aromatic content had a significant influence on flame radiance, liner wall temperature and smoke emissions. Physical fuel properties that influenced atomisation quality and evaporation rates were found to affect ignition, lean blowout, combustion efficiency and CO emissions. Liner wall temperature, NOx and smoke emissions did not show a fuel physical property dependence. Fuel chemistry was found to have a small effect on combustion efficiency, lean blowout, ignition and CO and NO_x emissions that was attributed to the influence of slight variations in lower calorific value on combustion temperature. Pattern factor was not influenced by fuel chemistry. It should be noted that the carbon to hydrogen (C/H) ratio was taken to be representative of the fuel chemistry differences and no metric representative of ignition delay, such as laminar flame speed, was measured or reported. Physical properties had an appreciable effect on pattern factor at low power conditions but this effect decreased to be very small at high power settings where pattern factor effects on vane life are typically most significant.

From evidence obtained by Rao and Lefebvre [26] it was concluded that the sole determining criterion for ignition of mixtures of fuel droplets in air, is sufficient fuel vapour in the ignition zone. Ignition will ensue automatically if the passage of the spark creates sufficient thermal energy to produce the required amount of fuel vapour. This argument is based on the understanding that, over a wide range of operating conditions, the chemical reaction time is so short in comparison with the time required to produce an adequate amount of fuel vapour in the ignition zone, that for all practical purposes it can be ignored. This is in direct contrast to ignition of homogeneous mixtures which are dominated by chemical reaction rates. Based on these considerations, Ballal and Lefebvre [27] proposed theoretical models for quench distance and minimum ignition energy in liquid fuel sprays. The quenching distance is defined as the critical spark-kernel size for which the rate of heat loss at the kernel surface is balanced by the rate of heat release, due to the instantaneous combustion of fuel vapour, throughout the volume of the kernel. The kernel must attain this size in order to propagate unaided. The minimum ignition energy is defined as the amount of energy required from an external source to attain the quenching distance [4].

In a subsequent study, Ballal and Lefebvre [28] extended the abovementioned model to include the influence of finite chemical reaction rates, which are known to be significant for well atomised fuels at low pressures and low equivalence ratios, and the presence of fuel vapour in the mixture entering the ignition zone. They derived Equation 2.10 for calculating quenching distance (d_q) to cover all conditions likely to be encountered in practical combustion systems. The model provided a good fit with experimental data over a range of SMD values from 40 to 150μm.

$$d_q = \left[\frac{\rho_F D_{32}^2}{\rho_A \phi \ln(1+B_{st})} + \left(\frac{10\alpha}{S_L} \right)^2 \right]^{0.5} \tag{2.10}$$

The first term of the root sum square equation deals with fuel evaporation, where ρ_F and ρ_A represents the fuel and air density, D_{32}, the Sauter mean diameter, ϕ equivalence ratio, and B_{st} the stoichiometric mass transfer number. The influence of fuel chemistry is contained in the second term where α represents the thermal diffusivity and S_L represents the laminar flame speed of the fuel. With reference to Equation 2.1, by dividing the thermal diffusivity by the laminar flame speed, the second term in Equation 2.10 effectively reduces to the product of the specific heat at constant pressure (C_p), density (ρ) and laminar flame thickness (δ_L), with the laminar flame thickness being a reflection of the chemical reaction rate.

It can be concluded that the relevance of chemical reaction timescales is acknowledged by literature, for well atomised fuels at low pressures and lean equivalence ratios and under threshold combustion conditions such as encountered during altitude relight and blowout. Various previous research programmes have however both acknowledged and ignored chemical reaction rates, which highlighted the possibility and need for further examination. The emergence of synthetic jet fuel formulations, and the related opportunity to influence chemical reaction rates to a greater degree than traditionally possible in the case of petroleum-derived jet fuel, further highlighted the need for conclusive research being conducted in this field. The design and commissioning of the test facility, that formed the focus of this project, was intended to enable such research being conducted at the Sasol Advanced Fuels Laboratory (SAFL).

3. Test Facility Design

3.1. Design Criteria

The primary purpose of the combustion test facility was the investigation of the ignition and combustion stability of different synthetic test fuel formulations. A range of design criteria were considered during the generation of concepts and selection of the final facility design. The following main design criteria were identified and are discussed in greater detail under the design of the various subsystems:

- The test conditions that needed to be simulated in order for the test facility to meet its design requirements were of primary importance. These included the pressure, temperature, velocity and equivalence ratio ranges that needed to be attained.
- The combustor designs had to enable the study of both the physical and chemical property effects of different synthetic test fuel formulations on ignition and combustion stability.
- The test facility needed to be constructed on a laboratory scale in order to minimise its physical size, test fuel volume requirements, and subsystem power requirements.
- Capital expenditure needed to be minimised.
- Best practises in terms of health, safety and environment had to be adhered to at all times.

3.2. Test conditions

The combustion test facility was designed to enable the investigation of the ignition and combustion stability of different test fuels over a range of continuous flow test conditions. Equivalence ratio, temperature and pressure influences on these limits were of primary interest. The following test conditions were set as design criteria for the test facility.

3.2.1. Temperature and pressure

The influences of temperature and pressure on the combustion stability of the test fuels at various equivalence ratios were to be investigated. Conditions representative of those encountered during altitude relight operation were of specific interest. The maximum relight altitude for civilian aircraft is typically 10,000 meters at airspeeds of approximately 650km/h, while military requirements are slightly lower in altitude and higher in air speed [29]. The maximum simulated altitude attainable by the test facility was determined by air compressor performance and air conditioning requirements, as discussed below. The infrastructural requirements of simulating temperature and pressure conditions representative of altitudes of around 10,000 meters were found to be prohibitively costly. It was decided that generating realistically attainable test conditions representative of a lower altitude, would provide significant insight into potential differences between test fuels. Results could be extrapolated with care and could possibly be verified and investigated further by contracting commercial test facilities capable of simulating greater altitude conditions if deemed necessary.

As discussed in Section 2.5, it should be borne in mind that the combustor inlet conditions, and not the absolute ambient conditions, were to be simulated by the test facility. The charge air velocity reduction and resultant ram pressure and temperature rise at the inlet to the combustor translates into the minimum attainable facility pressure and temperature being representative of a higher altitude than if the temperature and pressure was representative of ambient conditions.

The so-called "International Standard Atmosphere", ISA, employs the following equations for calculating the theoretical altitude dependences of temperature and pressure in mid-latitudes in the temperate climate zone [30].

$$T_a = T_{sl} + zL \tag{3.1}$$

$$P_a = P_{sl}\left(1 + \frac{zL}{T_{sl}}\right)^{\frac{-gM}{RL}} \tag{3.2}$$

The temperatures and pressures at altitude (z) and sea level are represented by T_a, T_{sl}, P_a, and P_{sl}, respectively. The molar mass of air is represented by M, and the universal gas constant by R. The model assumes a temperature of 15°C and pressure of 101.325kPa at sea level taking gravity (g) as 9.807ms^{-2}. It further also assumes dry air of a constant composition at all levels and a constant vertical temperature gradient (L) of –6.5x10^{-3}K/m for the troposphere (0 to 11km).

The charge air supply and conditioning units that were selected were capable of maintaining a minimum temperature of 263K and minimum absolute pressure of 70kPa, over the full design flow range. These conditions would allow the simulation of ambient conditions representative of an altitude of up to 3000m. In order to equate the minimum pressure and temperature capabilities of the facility to theoretical flight Mach number and altitude values, Equations 3.3 to 3.5 [31] were used in conjunction with the ISA equations to determine stagnation temperature and pressure conditions at the combustor inlet.

$$P_{03} = P_a \left(\frac{P_{03}}{P_{02}} \right) \left(1 + \eta_i \frac{C_a^2}{2C_p T_a} \right)^{\frac{\gamma}{(\gamma - 1)}} \qquad (3.3)$$

$$T_{02} = T_a + \frac{C_a^2}{2C_p} \qquad (3.4)$$

$$T_{03} = T_{02} + \frac{T_{02}}{\eta_c} \left[\left(\frac{P_{03}}{P_{02}} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right] \qquad (3.5)$$

The stagnation temperatures and pressures at the compressor and combustor inlet are represented by T_{02}, T_{03}, P_{02}, and P_{03}, respectively. The specific heat at constant pressure, ratio of specific heats, and ambient velocity are represented by C_p, γ and C_a. In order to calculate combustor inlet conditions at a given altitude and Mach number, the isentropic intake efficiency (η_i), isentropic compressor efficiency (η_c) and compressor pressure ratio (P_{03}/P_{02}) had to be estimated for a representative engine. Assuming windmilling conditions to result in a compressor pressure ratio of 1 and an intake efficiency of 93%, the facility temperature and pressure capabilities would allow the simulation of combustor inlet pressures and temperatures representing relight conditions of up to 5,900m at Mach 0.8.

The primary considerations regarding the maximum required pressure and temperature were that sufficiently large temperature and pressure ranges should be attainable in order to establish temperature and pressure dependency trends, that the facility should be able to accommodate future expansion of the research scope, and that safety should not be compromised. A maximum pressure of 150kPa and maximum temperature of 340K were deemed to satisfy these requirements.

3.2.2. Density

Due to its influence on the blower size and cost, the charge air density range required to satisfy the test programme objectives had t be minimised. It was therefore decided to evaluate the pressure dependence of the test fuels' ignition and combustion stability at high temperature and their temperature dependence at ambient and low pressure. For the purposes of specifying the test facility performance it was deemed acceptable to assume the charge air to be an ideal gas when calculating the density range corresponding to the range of test pressures and temperatures. As shown in Table 3.1, the resultant density range required from the facility was calculated to be 0.73 to 1.57kg/m^3.

Table 3.1 Test density range [kg/m^3]

Absolute pressure [kPa]	**Combustor inlet temperature**		
	265K	**300K**	**340K**
150	-	-	1.54
101	1.33	1.18	1.04
70	0.92	0.81	0.72

3.2.3. Equivalence ratio

The equivalence ratio and air mass flow ranges required in order to establish the boundaries of stable burning regions for different test fuels needed to be determined. For many fuels, the ignition and sustainable flammability limits fall between a weak equivalence ratio of around 0.5 and a rich equivalence ratio of around 3. Increasing pressures above atmospheric conditions results in a widening of flammability limits, with most of the widening occurring at the rich extinction limit. This pressure dependence is however reported to be less pronounced between 10kPa and 5MPa. Similarly, temperature increase is also reported to widen flammability limits but this effect is usually not as great as in the case of pressure [5].

The lean extinction limit of a fuel is of particular interest since it is a critical parameter of typical operating conditions. Lefebvre [20] reviewed experimental findings of the effects of flameholder geometry, inlet air temperature, main air stream velocity, fuel droplet size (Sauter mean diameter, SMD), fuel volatility and gas pressure on bluff-body flame stabilisation. These results suggested that the test facility should be designed to attain a minimum equivalence ratio of 0.3 in order to fully investigate lean extinction limits.

Lefebvre [32] noted that establishing rich extinction limits often proved to be problematic due to the risks of overheating, especially at elevated pressures. Combustion stability results obtained in test facilities using nitrogen and water injection techniques provided guidance in specifying the required equivalence ratio range. These facilities rely on a reduction in the global reaction rate through reduction of reaction temperature being more or less equivalent to the global reaction rate reduction caused by a reduction in reaction pressure. A typical equivalence ratio range for such a facility was found to be 0.75 to 1.25 [32], [33]. Initially a maximum required equivalence ratio of 1.5 was chosen for this study with the potential for it to be increased if future test programmes identified a need to do so.

3.2.4. Velocities

While the velocities associated with extinction limits in the test facility combustor were dependent on, and could be tailored by, modifying the design of the combustor or flame holder, it had been decided that the system should be designed to accommodate combustor designs that yielded extinction velocities of similar magnitudes to those achieved by conventional gas turbine combustors. Results from an investigation by Ballal and Lefebvre [19] into the factors governing lean blow-out limits of bluff-body stabilised flames reported lean blow-out velocities ranging from 15 to 75m/s. Baxter and Lefebvre [34] conducted studies of fully-vaporised kerosene-air mixtures' weak extinction limits at velocities between 10 and 16m/s. It was reported that even large-scale test facilities were usually unable to achieve peaks of stability loops due to their being unable to supply sufficient air flow at sub-atmospheric conditions. This is generally not seen as a serious drawback due to the fact that the lean blow-out limit is usually considered to be of primary concern [20]. Based on these guidelines, the maximum and minimum air flow velocities attainable by the test facility were chosen to be 50m/s and 5m/s respectively.

3.2.5. Test facility sizing

The primary test facility design specifications, that determined the design and sizing of the various subsystems and facility as a whole, are summarised in Table 3.2. Due to the design interdependence of the various test facility subsystems primary specifications were set for each subsystem and the test facility was optimised as a whole prior to finalising the detailed design of individual subsystems. The minimum size and design of most of the subsystems were either directly or indirectly determined by the minimum fuel flow range attainable by the fuel injection system.

Table 3.2 Primary test facility design specifications

	Minimum	**Maximum**
Pressure [kPa]	70	150
Temperature [K]	263	340
Equivalence ratio	0.3	1.5
Velocity [m/s]	5	50
Fuel flow [kg/h]	1	110
Air mass flow [kg/h]	51	1087

3.3. Test facility layout

A schematic diagram of the test facility layout is provided in Figure 3.1. The test facility consisted of an air handling system, temperature control system, fuel system, combustor, and quench system. A continuous flow arrangement was chosen over a blow-down configuration in order to allow extended periods of testing at pressures both above and below atmospheric pressure.

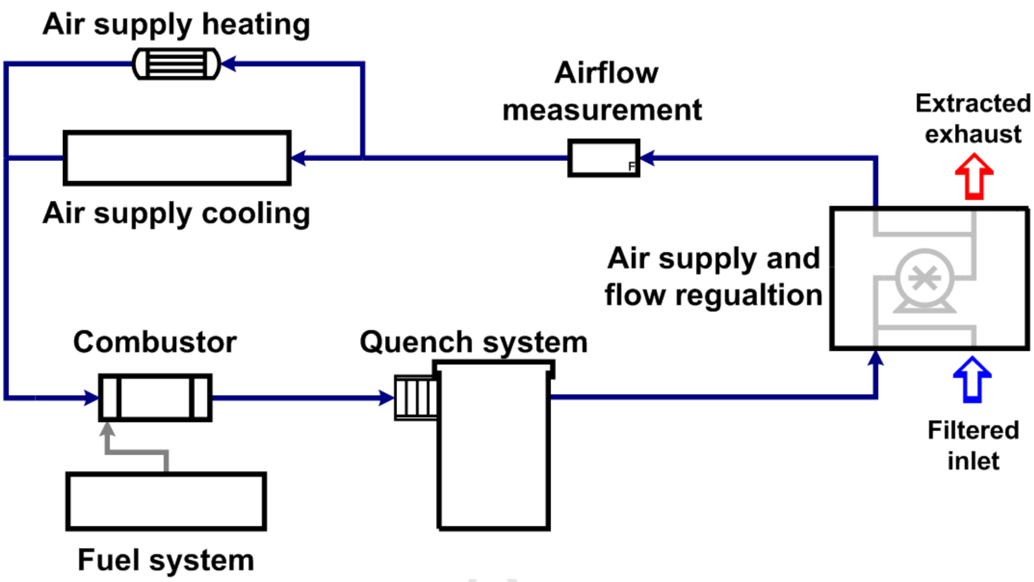

Figure 3.1 Schematic diagram of test facility layout.

The air supply and extraction was performed by a single positive displacement blower that could provide either pressurised or vacuum test conditions. This was achieved through the appropriate setting of flow directional control valves as discussed in Section 3.4.3. Two interchangeable combustor designs were developed. A combustor utilising direct fuel injection was used to evaluate conventional and potential alternative jet fuels. A premixed fuel injection system with a bluff-body flame holder was used for testing the ignition and combustion behaviour of single-component "model fuels" which allowed the investigation of specific fuel chemistry effects in isolation. The premixed configuration minimised combustor geometric influences however, it was only possible to test under fully evaporated conditions since the flameholders caused accumulation of fuel droplets, which lead to inconsistent air-fuel ratios. This limited the air-fuel ratio range and minimum temperature at which less volatile fuels could be evaluated.

3.4. Subsystem design

Due to the design interdependence of the various test facility subsystems primary specifications were set for each subsystem and the test facility was optimised as a whole prior to finalising the detailed design of individual subsystems. Examples of subsystem design drawings are provided in Appendix F.

3.4.1. Air supply

In order for the required fuel–air ratio range to be attained over the specified air flow, temperature, pressure and density ranges (as summarised in Table 3.2) an air supply of 0.014 to 0.3kg/s needed to be delivered to the combustor over an absolute pressure range of 70 to 150kPa and temperature range of –10 to 60°C. As discussed in Section 3.3 a continuous flow arrangement was chosen in order to permit extended periods of testing at pressures both above and below atmospheric pressure. This was achieved by employing a single positive displacement blower that was able to operate in both a pressurised and vacuum configuration. The resultant additional system design and construction complexity was justified by the cost saving realised through eliminating the need for two separate air handling units. The transmission of pressure pulsations produced by conventional two-lobe Roots-type blowers to the combustor could possibly have resulted in unstable test conditions. The 30kW Aerzen GM 25S unit that was selected employed a patented three-lobe design in order to achieve positive cancellation of pressure pulsations, which ensured a constant pressure delivery to the combustor in both pressurised and vacuum mode operation.

3.4.2. Airflow measurement

An orifice plate was used to measure air mass flow. Orifice plate flow measurement incurs a larger pressure loss than venturi flow measurement but was selected due to its relative simplicity of manufacture and ease of orifice exchange, to accommodate a wide range of flow rates as required by the test facility. Exchanging orifice plates during tests that required broad air mass flow rate ranges proved to be laborious. As discussed further in Section 8.1, design modifications might be justified if such testing were to be conducted regularly. The device was designed in accordance with the American Society of Mechanical Engineers (ASME) standard ASME MFC-3M-2004 [35].

3.4.3. Airflow control

Two methods of air volume flow regulation were considered. Valve-regulated flow control was chosen over blower speed control, based on cost. Schematic diagrams of the airflow control system in pressurised and vacuum configurations are shown in Figures 3.2 and 3.3, respectively. The valve system was designed to prevent the possibility of unsafe operating modes arising from incorrect valve positions being selected by accident. Valves 5 and 6 and valves 7 and 8 were linked to operate in pairs for three-way flow selection with minimal pressure losses being incurred.

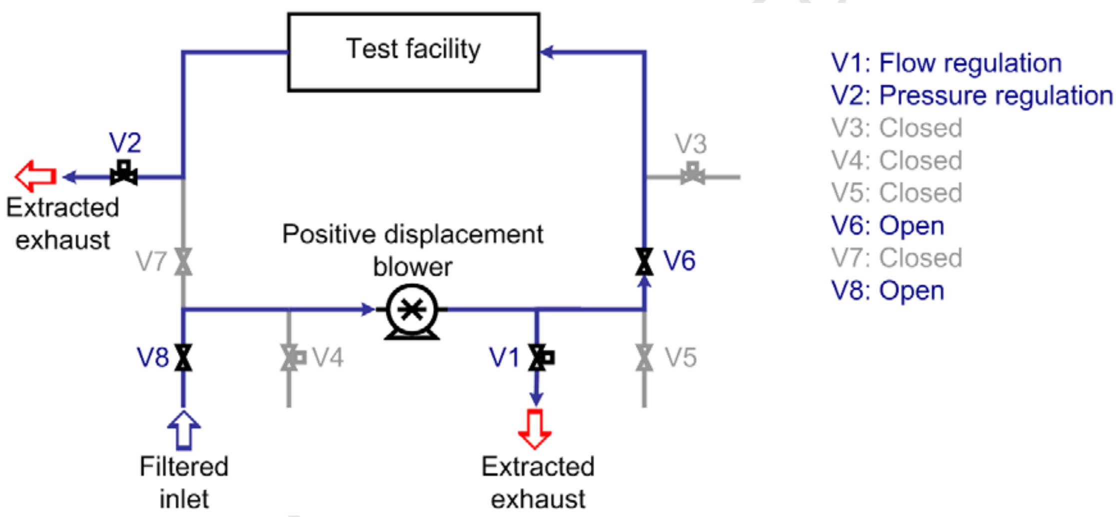

Figure 3.2 Schematic diagram of the air supply system being operated in pressurised configuration.

Two electro-pneumatic valves (V1 & V4) with position feedback control by the data acquisition system were used to regulate the airflow to set point values. During pressurised operation excess air was bled from the system, through Valve 1, with airflow feedback control maintaining a constant set flow rate through the test sector. In vacuum operation mode additional air was allowed into the system, through Valve 4, from the atmosphere in order to maintain the flow rate set point.

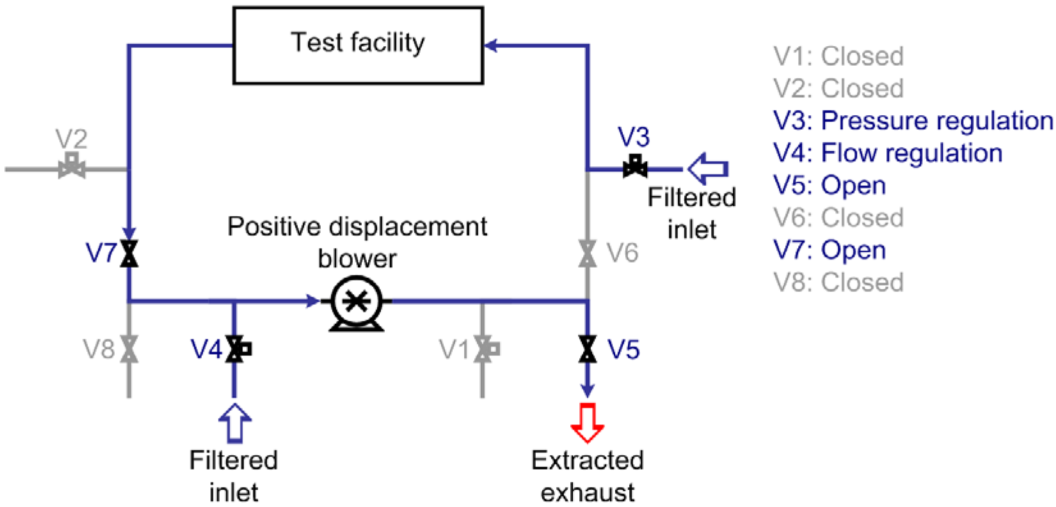

Figure 3.3 Schematic diagram of the air supply system being operated in vacuum configuration.

Similarly, a further two electro-pneumatic pressure control valves (V2 & V3) regulated the pressure drop over the inlet and outlet to the system during vacuum and pressurised operation, respectively. The two modes of operation and associated valve control are discussed in detail under Section 4.2.

3.4.4. Air supply cooling

Air supply temperatures were controlled to set-points between –10 and 60°C independent of air flow rate or pressure. The cooling and heating of the air stream were managed by two separate subsystems; two butterfly valves were used to select the appropriate subsystem. The design and manufacture of the air supply cooling system was subcontracted to an industrial air conditioning specialist, Heat Pump International, Cape Town South Africa (HPI), but considerable design input was retained due to the relatively unusual operational requirements.

Both chilled water cooling coils and direct expansion cooling coils were used for cooling of the air supply while a resistance heater bank was used to “trim” temperatures to set point values. A Carel IR32A unit was used to control a 0–10V solenoid valve in the chilled water supply and a 0–10 V current valve that regulated the power supply to the heater bank. The direct expansion cooling was activated progressively in three steps by manually operating two unequally sized compressors individually or concurrently.

It was anticipated that during sub-zero temperature operation moisture in the supply air would gradually deposit as ice on the direct expansion cooling coils. This would necessitate the periodic thawing of the cooling coils, as dictated by monitoring the air flow rate and pressure drop between the orifice plate and combustor. In order to expedite thawing, especially during vacuum operation in the absence of the heat of compression, the resistance heater bank was designed to be installed upstream of the direct expansion cooling coils. The unit casing was also equipped with two ball valves for draining condensate during thawing.

3.4.5. Air supply heating

The heating requirements of the various potential operating modes were calculated in order to determine the specifications of the air supply heating system. A maximum heating requirement of 8kW would be encountered during maximum air mass flow conditions and vacuum operation in the absence of the additional heat of compression. The heating system was based on a 10kW Leister 10000S resistance heater. The heating element of the unit was removed and modified to be incorporated into the air supply system. The control and safety systems of the Leister unit were retained and the wiring extended to allow remote operation. The modified unit was sealed to withstand operation under pressurised and vacuum conditions. Detailed design drawings of the air supply heating system are provided in Appendix F.

3.4.6. Fuel system

The minimum size and design of most of the subsystems were either directly or indirectly determined by the minimum fuel flow range attainable by the fuel injection system. The primary requirements of the fuel injection system were the ability to provide consistent atomisation over the full range of required fuel flow rates and atomisation being relatively insensitive to fuel property variations that can be expected when comparing different test fuels.

A number of potential fuel atomisers were considered, including air-assisted, air-blast and pressure atomised configurations. From these options a system that is normally used in industrial package burners employing simplex pressure-swirl atomisation was selected. The nozzles are designed to deliver finely atomised spray cones at atmospheric conditions, which approximate the injection conditions encountered in the test facility. It should be noted that, as discussed earlier in Section 2.3, pressure-swirl atomisers are known to exhibit poor fuel distribution, resulting in some combustion taking place at mixture strengths that are significantly richer than the average value. While this leads to performance problems like high rates of soot formation it also results in better lean blowout performance than that achieved by airblast atomisation.

In order to ensure consistent atomisation that was relatively independent of the fuel flow rate it was decided to control fuel flow rates by exchanging atomiser nozzles while keeping the fuel supply pressure constant. This approach yielded an attainable fuel flow range of 0.5 to 250kg/h at an injection pressure of 15bar. A spray cone angle of 45° was selected (over an alternative option of 60°) to reduce the minimum duct diameter (homogeneous combustor) and combustor diameter (heterogeneous combustor) that would be required to minimise the impact of fuel spray impinging on duct and combustor walls.

In the light of the effects of fuel viscosity, surface tension and density on pressure-swirl atomisation, it was recognised that SMD and droplet size distribution measurements would need to be conducted for each of the test fuels and all atomiser nozzles, in order to isolate fuel property influences on atomisation when comparing the combustion limit results obtained in the heterogeneous combustor with different test fuels. This requirement was not applicable to the homogeneous combustor due to sufficient time being allowed for evaporation to render relative differences in atomisation irrelevant.

Some tests were conducted with the heterogeneous combustor at both variable and fixed air mass flow rates and employing a single fuel atomiser nozzle. By adjusting fuel flow rate through adjusting the fuel supply pressure, the fuel atomisation quality, and thus ignition and stability thresholds, were influenced. The atomisation quality of air-assisted and airblast atomisers are expected to be less sensitive to fuel flow rate reductions and should be considered for conducting tests under these conditions.

The premixed homogeneous and direct injection heterogeneous combustor configurations shared all fuel system hardware with the exception of the atomiser holders. A fuel lance was employed to position the injection nozzle at the centre of the duct in the premixed configuration while the direct injection combustor employed a shorter 90º angled removable nozzle holder. Both combustor designs allowed atomiser nozzles to be interchanged with ease during testing. The fuel system layout is shown in Figure 3.4.

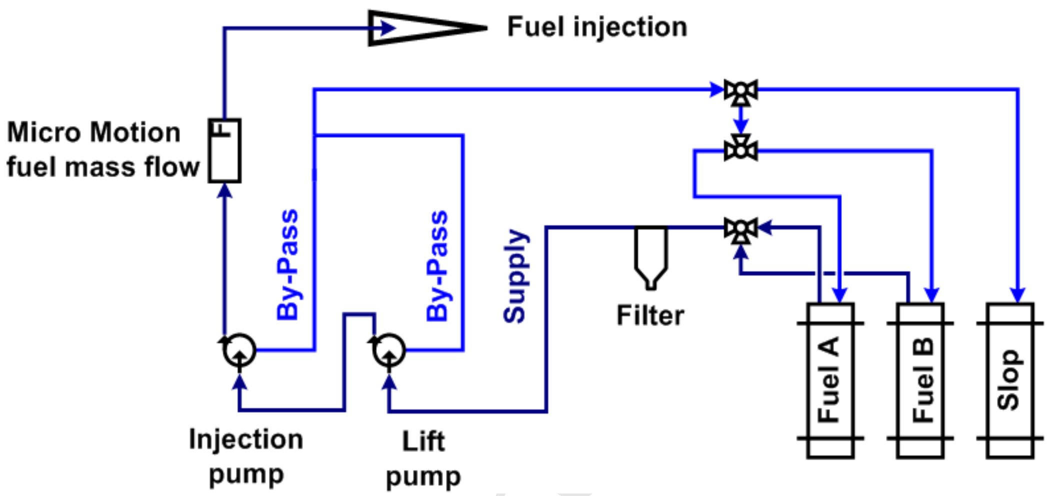

Figure 3.4 Schematic diagram of test facility fuel supply system.

Two sixty-litre fuel reservoirs and three three-way valves allowed the fuel supply to be changed between two test fuels in order to facilitate back-to-back comparison of fuels under identical test conditions. A third sixty-litre reservoir was provided to accommodate fuel that was purged during fuel changeovers in order to avoid any cross contamination of the test fuels.

The fuel injection pump that was selected is normally employed in industrial package burners where fuel is supplied to the pump gravimetrically at a gauge pressure of between 0.2 and 0.4bar. Due to the fuel system configuration not being suited to the use of a header tank and the additional pressure drop incurred by the use of three-way valves in both supply and return lines, a lift pump and check-valve bypass system was used to regulate the supply pressure to the injection pump. Fuel line diameters and flow rates were matched to the requirements of the fuel lift and injection pumps. A Separ 2000/5 unit consisting of a water trap and 30-micron fuel filter was installed in the fuel supply line to protect the two fuel pumps and injection nozzles from contamination.

Fuel mass flow was measured using a MicroMotion D6 flow meter and RFT9712 flow transmitter, which transmitted a 4–20mA flow rate signal to the data acquisition system. The entire fuel system was contained in a ventilated enclosure and supplied with a 130-litre containment tray. The fuel system, as installed in the test facility, is shown in Figure 3.5.

Figure 3.5 Test facility fuel supply system.

3.4.7. Combustors

Two combustor configurations were designed for conducting tests employing either homogeneous premixed pre-vaporised fuel injection or heterogeneous direct fuel injection, which allowed the study of combustion processes involving premixed flames or diffusion flames, respectively.

3.4.7.1. Homogeneous combustor

The homogeneous premixed combustor was designed to minimise the influence of combustor geometry effects on combustion stability limits and to remove evaporation and mixing time scales from the overall ignition delay. This allowed the study of fuel chemistry influences on ignition timescales. As in the case of the heterogeneous combustor, the size of the homogeneous combustor was dictated by the required equivalence ratio range, minimum fuel flow rates attainable by the fuel injection system and required airflow velocity range. A combustor diameter of 0.07m satisfied these requirements. A model of the homogeneous combustor design including the premixed fuel injection sector, is shown in Figure 3.6 and a photograph of the combustor as installed in the test facility is shown in Figure 3.7.

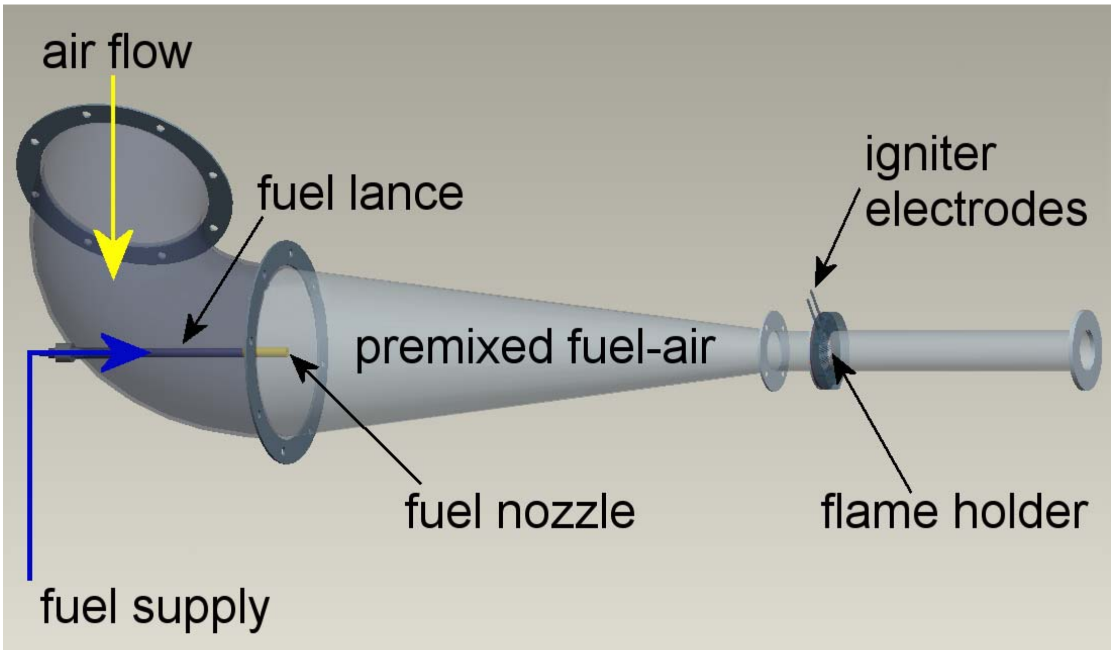

Figure 3.6 Model of the homogeneous combustor design.

A number of different bluff-body flameholder geometries were investigated. These included simple baffle plates and baffles with conical forebody shapes, providing ranges of blockage ratios. As discussed previously, the characteristic dimension governing a flameholder's stability is not the geometric blockage ratio (B_g) but the corresponding aerodynamic value (B_a). The relationship between aerodynamic and geometric blockage is governed by the flameholder forebody shape. The less streamlined the forebody shape the higher is the ratio of aerodynamic to geometric blockage [36]. Different forebody shapes and baffle plates (three of which are shown in Figure 3.8)

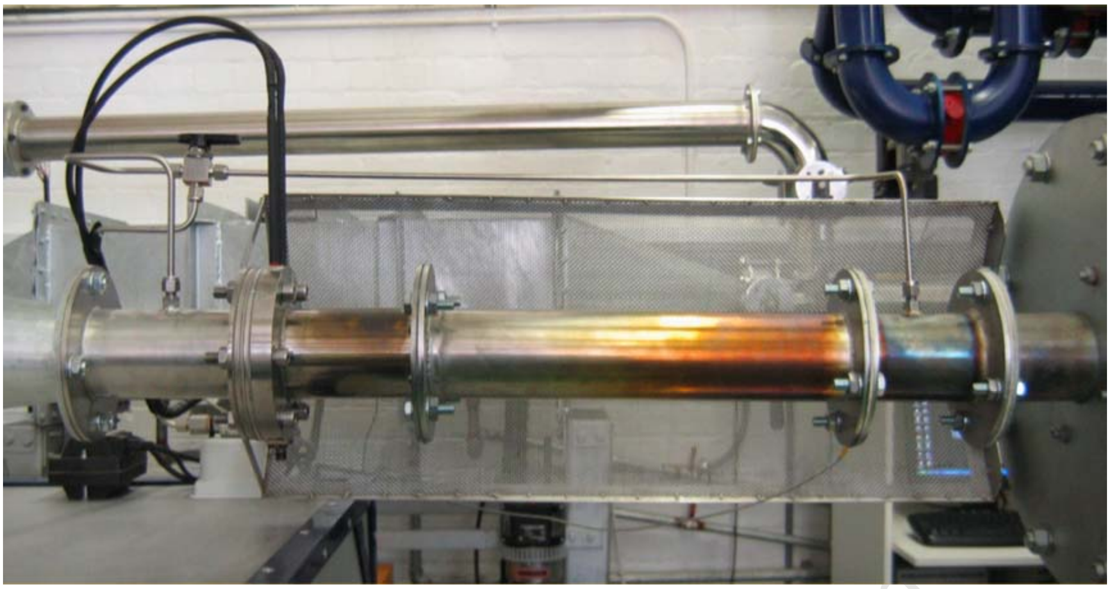

Figure 3.7 Homogeneous premixed combustor installed in the test facility.

were employed to investigate the influence of different aerodynamic blockage ratios. A maximum geometric blockage ratio of 33% was chosen since literature indicated that greater higher ratios result in a decline in weak-extinction performance [36]. Perforated plates with different hole sizes and spacing, resulting in different blockage ratios, were also investigated. A blockage ratio of 45% obtained using 4.5mm-diameter perforations resulted in a broad stable operating range, which was used during the investigation of combustion stability limits of a number of test fuels. .

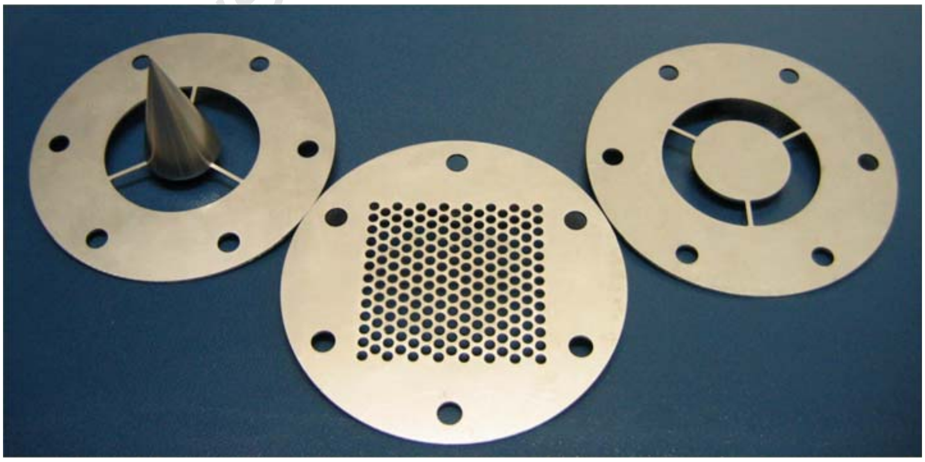

Figure 3.8 Examples of some of the flameholder designs that were evaluated for use in the homogeneous combustor.

3.4.7.2. Heterogeneous combustor

Many different airflow patterns are employed in the design of heterogeneous combustors to establish stability in the primary zone. A feature that all designs share is the creation of a toroidal flow reversal that entrains hot combustion products and recirculates it to mix with incoming fuel and air. The flow reversal is established and refreshed by holes in the liner, and, in most cases, supplemented by airflow through flare-cooling slots, air employed in atomisation and through swirlers. The use of swirlers in the dome around the fuel injector is known to provide excellent recirculation in the core region and rapid mixing rates due to high turbulence and strong shear zones [37].

The design of the heterogeneous combustor was roughly based on the primary zone of an Allison T63-A-700 combustor that was scaled according to the fuel and air supply systems as well as the required ranges of test conditions. The main purpose of the tests conducted using this combustor was to study ignition and combustion stability behaviour. Aspects such as emissions and combustor pattern factor that are governed by the intermediary and dilution zones were not intended to be investigated using this particular combustor design. The intermediary and dilution zones were thus omitted with the aim to simplify accurate control of primary zone stoichiometry.

Air was introduced to the primary zone of the test combustor through two concentric “rings” of vaned counter swirling slots in the dome and primary recirculation holes in the liner. The combustor liner was film cooled by airflow that was directed along the liner through holes around the edge of the dome. A model of the heterogeneous combustor design is shown in Figure 3.9.

The relationships provided by Lefebvre [38] for calculating liner pressure loss (Equation 3.6) and jet velocities (Equation 3.7) were used in combination with the facility flow capabilities, combustor geometric constraints, and relative effective area of the T63 combustor liner perforations to predict the appropriate size and number of the airflow holes and slots. This resulted in

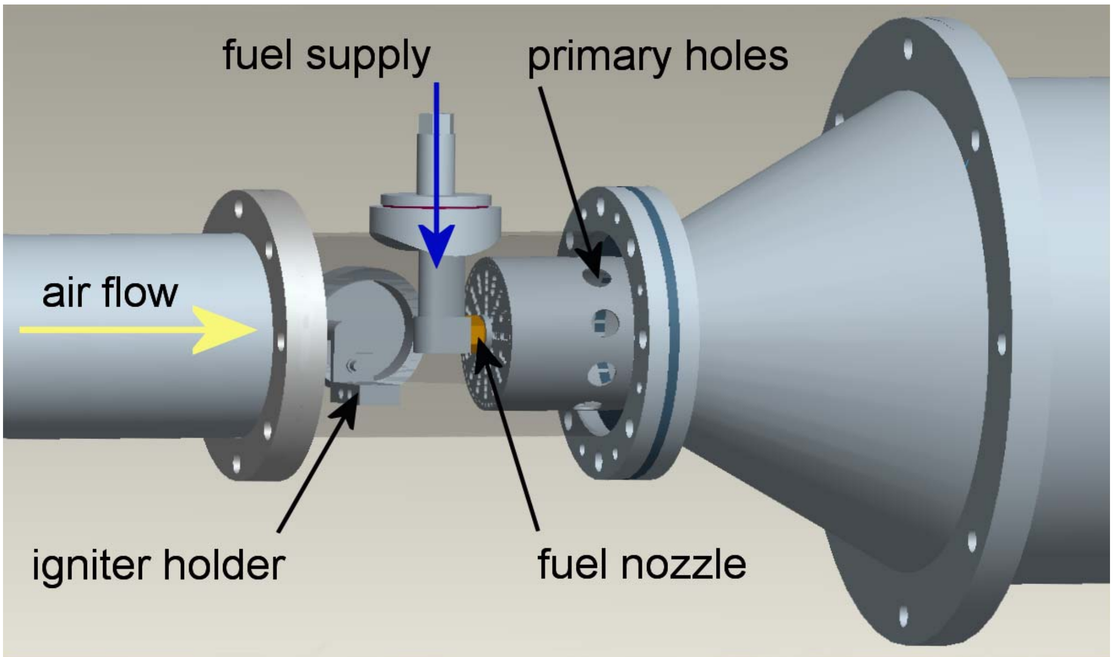

Figure 3.9 Model of the heterogeneous combustor design.

approximately 14% of the total airflow entering the primary zone through the counter swirling slots while the primary recirculation holes accounted for approximately 75% of the total airflow. Approximately 10% of the total airflow was directed along the liner, through the film cooling holes. An estimated maximum liner pressure loss of 30kPa was calculated to occur during maximum air mass flow test conditions.

$$\Delta P_L = \left(\frac{A_{ref}}{A_{h,eff}}\right)^2 \frac{\sigma_3 \dot{m}_3^2}{2\rho_3^2 A_{ref}^2} \qquad (3.6)$$

$$U_j = \left(\frac{2\Delta P_L}{\rho_3}\right)^{0.5} \qquad (3.7)$$

ΔP_L represents the liner pressure difference and U_j represents the airflow jet velocity. A_{ref} and $A_{h,eff}$ represent the combustor reference area and total effective liner hole area, respectively. The air mass flow rate and air density in the combustor inlet plane are represented by $\dot{m}_3$ and ρ_3.

The design of the combustor provided ease of exchange of fuel nozzles, adjustable igniter positioning and optical access. Detailed design drawings of the combustor are included in Appendix F. A photograph of the combustor as installed in the test facility is shown in Figure 3.10.

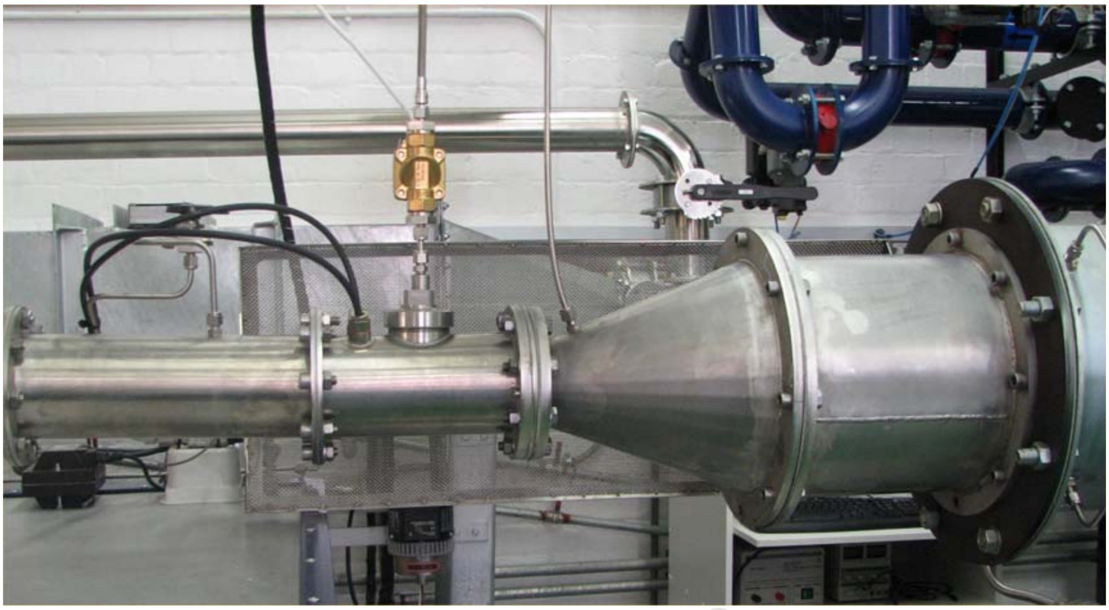

Figure 3.10 Heterogeneous combustor installed in the test facility.

3.4.8. Ignition system

The ignition system used in both combustor designs was based on a system normally employed by industrial package burners. It consisted of a transformer delivering a 14kV secondary voltage to sustain a pulsed AC arc between two electrodes. The exact location of igniter electrodes within a combustor has a controlling influence on igniter life and ignition performance [39]. The hot kernel of gas created by the ignition arc needs to be returned upstream by the gas stream flow reversal and therefore the igniter tip needs to be in the primary zone. Although immersion of the electrode into the hot gas stream improves ignition performance it reduces its life. It has been shown that by exposing the electrode tips to temperatures in excess of 900K the expected life of a conventional gas turbine igniter is rapidly decreased [39].

Both combustor designs used a common ignition system, with only the igniter electrodes being dedicated to each combustor. The design of the homogeneous combustor allowed for the position of the electrode tips relative to the flameholder, and resultant primary zone, to be adjusted axially by exchanging a series of spacer plates, and radially by adjusting the penetration depth of the electrodes. Similarly, the design of the igniter holder employed in the heterogeneous combustor allowed independent radial and axial adjustment of the electrode tips.

Figure 3.11 shows the electrode arc with a perforated plate flameholder in the homogeneous combustor at low and high airflow velocities, illustrating the effect of increased air velocities on the stretching of the arc.

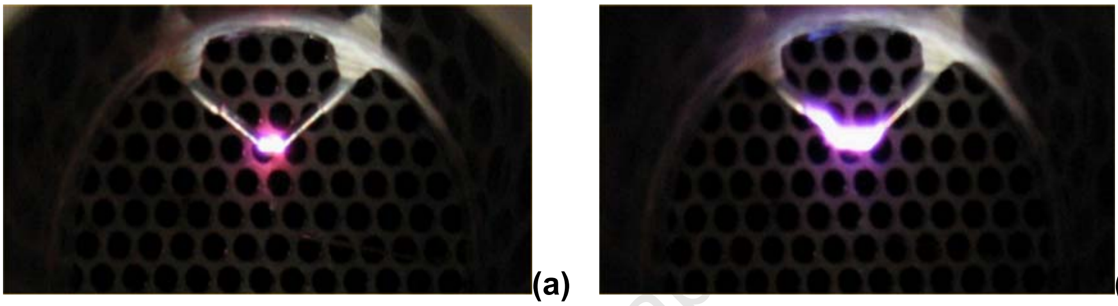
(a) (b)

Figure 3.11 Igniter arc with perforated plate flameholder at air velocities of (a) 2m/s and (b) 20m/s.

3.4.9. Quenching system

Gas flowing from the combustor sector ejected into a quenching system that was designed to extinguish combustion, cool the combustion products and “scrub” any unburnt fuel from the gas stream. A model of the quenching system is shown in Figure 3.12

The first stage of the quenching system consisted of eight water nozzles and a series of baffles that increased gas residence time in the water spray. The minimum required quench water flow rate was calculated such as to cool the gas stream to temperatures below 320K under all operating conditions. Combustion products were assumed to be at the maximum adiabatic flame temperature (AFT) attainable under test facility operating conditions. As shown by the modelled results in Appendix A, a maximum AFT of 2290K was calculated to be attained by Jet A-1 at an equivalence ratio of 1.05 and combustor inlet pressure and temperature of 1.5bar and 333K, respectively.

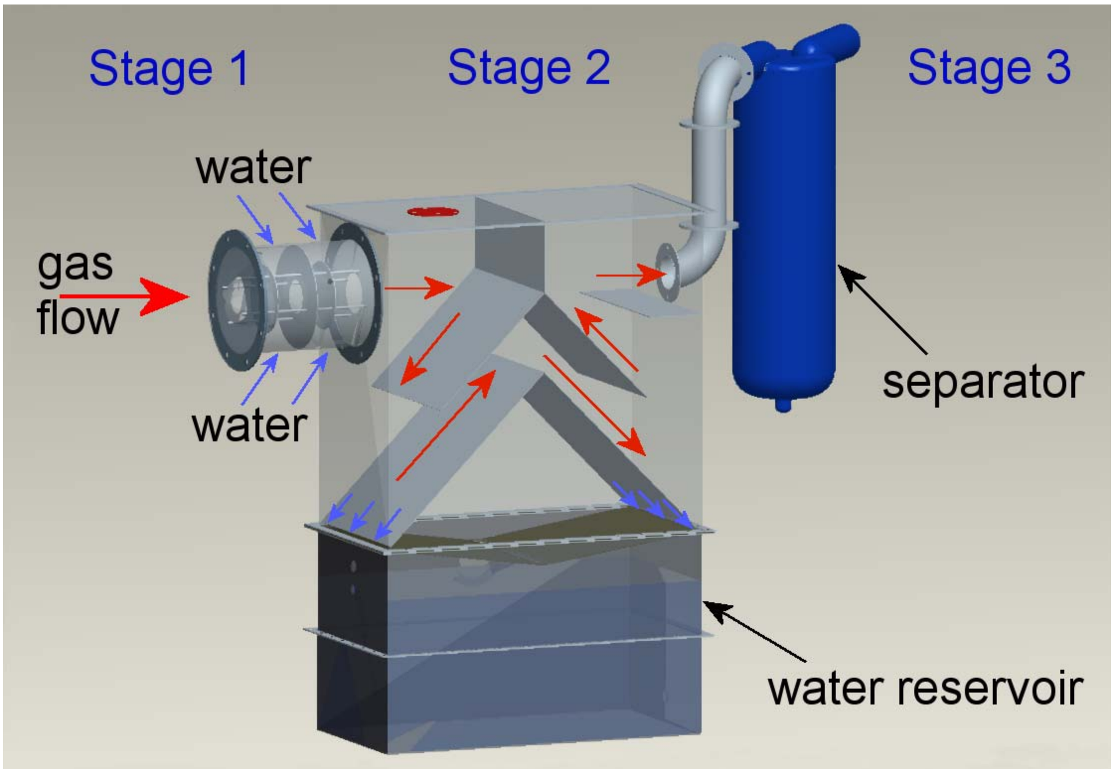

Figure 3.12 Model of the quenching system.

The corresponding specific heat of combustion of the combustion products was calculated as 1.45kJ/kgK. Assuming a maximum combustion product mass flow of 0.33kg/s, 950kW of heat needed to be rejected by the gas stream. Assuming this heat rejection to be achieved entirely through evaporation of the quench water (and ignoring the relatively small contribution made by heating the water), a minimum required flow rate of 26L/min was calculated. The quench pump was chosen to be capable of delivering 30L/min at 5bar to the eight quench nozzles, each of which allowed fully atomised flow rates of up to 5L/min at 5bar.

From the first quench stage the gas flow ejected into a tank where a ninth water nozzle provided a final quenching spray before the gas stream was guided through a series of baffles that enforced four flow direction changes to allow shedding of free water and fuel droplets. The geometry of the tank was designed to restrict velocities to a maximum of 5m/s during high flow rate testing in order to assist droplet shedding. Due to it being a closed system, the water and unburnt fuel stripped from the gas stream accumulated in the reservoir that fed the water spray supply pump. The system relied on the density separation of fuel and water to avoid recirculation of fuel through the quench nozzles. The water reservoir volume was circulated every six minutes and therefore the safe operation of the system relied on regular monitoring of both the water level and the accumulation of fuel in the reservoir through an optical access point on the side of the tank, as discussed under Section 4.1. A dedicated ball valve was provided to drain fuel from the tank while topping up the water supply. A separate ball valve was used to drain water from the bottom of the tank. Two zinc sacrificial anodes provided corrosion protection inside the tank.

The quench system and entire test facility was a continuous flow apparatus and was thus not legally required to conform to pressure vessel design codes. It was however still subjected to significant pressure gradients that needed to be taken into account. The tank was considered to consist of a selection of rectangular plates with applied uniform loads. In such a configuration, if deflections are restricted to less than half the plate thickness, stresses in the Y direction can be assumed to be insignificant and Timoshenko's formulas for flat plates can be used [40], [41]. Both freely supported (Equation 3.8) and clamped edge (Equation 3.9) configurations were considered in the calculation of maximum plate stresses.

$$\sigma_{\max} = \frac{\beta q b^2}{t^2} \qquad y_{\max} = \frac{-\alpha q b^4}{E t^3} \tag{3.8}$$

$$\sigma_{\max} = \frac{-\beta_1 q b^2}{t^2} \qquad y_{\max} = \frac{\alpha q b^4}{E t^3} \tag{3.9}$$

The maximum plate stress and maximum plate deflection are represented by σ_{max} and y_{max}, respectively. The plate dimensions and support modes determine constants α and β. The plate width, plate thickness, and tank pressure are represented by b, t, and q, respectively and E is the Young’s modulus.

In order to protect the test facility as a whole and the quench tank in particular against unforeseen over-pressure conditions, a burst diaphragm was provided in the lid of the quench tank. A chimney ensured that in the case of the diaphragm rupturing the blast and associated debris would be directed in a safe direction.

The final stage of the quench system was a centrifugal separator that ensured that all free water and fuel had been removed from the gas stream. This is of particular importance during vacuum operation when the gas stream is ingested by the blower. A photograph of the quenching system as installed in the test facility is shown in Figure 3.13.

Figure 3.13 Photograph of the quench system installed in the test facility.

3.4.10. System control and data capturing

The different operating modes (vacuum vs. pressurised and cooled vs. heated) were selected by means of manual valve adjustments. All other mass flow, temperature and pressure control measures were automated. The automated control systems and data capturing functions were managed by a USB-based National Instruments DAQ system operated through a LabVIEW 8.5 user interface. This allowed operating range definition of control inputs as well as intelligent interlocking and alarming of system outputs in order to aid safety and data integrity. Safety critical aspects such as the main facility emergency stop were hardwired and not managed by the DAQ system software. Power supply to the facility subsystems was only enabled once the DAQ system was online to preclude the facility from being operated in an uncontrolled fashion. A diagram of the instrumentation and control systems employed in the facility is provided in Appendix B.

3.4.11. Subsystem integration and final layout

The individual subsystem designs were integrated and the facility layout was optimised to allow for ease of operation and safety while minimising pressure loss through the system as a whole. A schematic diagram of the integrated subsystems is provided in Figure 3.14. A model of the facility design and a photograph of the final installation are shown in Figures 3.15 and 3.16, respectively.

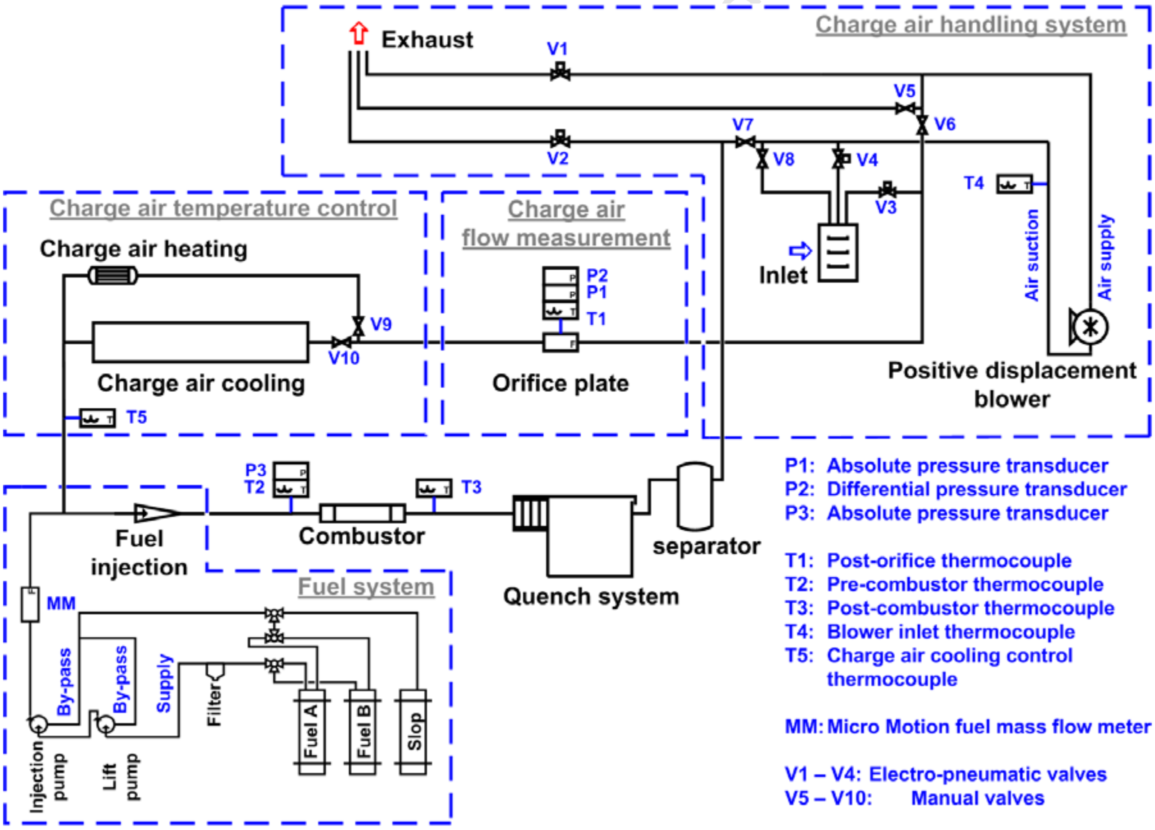

Figure 3.14 Schematic of test facility layout showing subsystem integration (homogeneous combustor configuration).

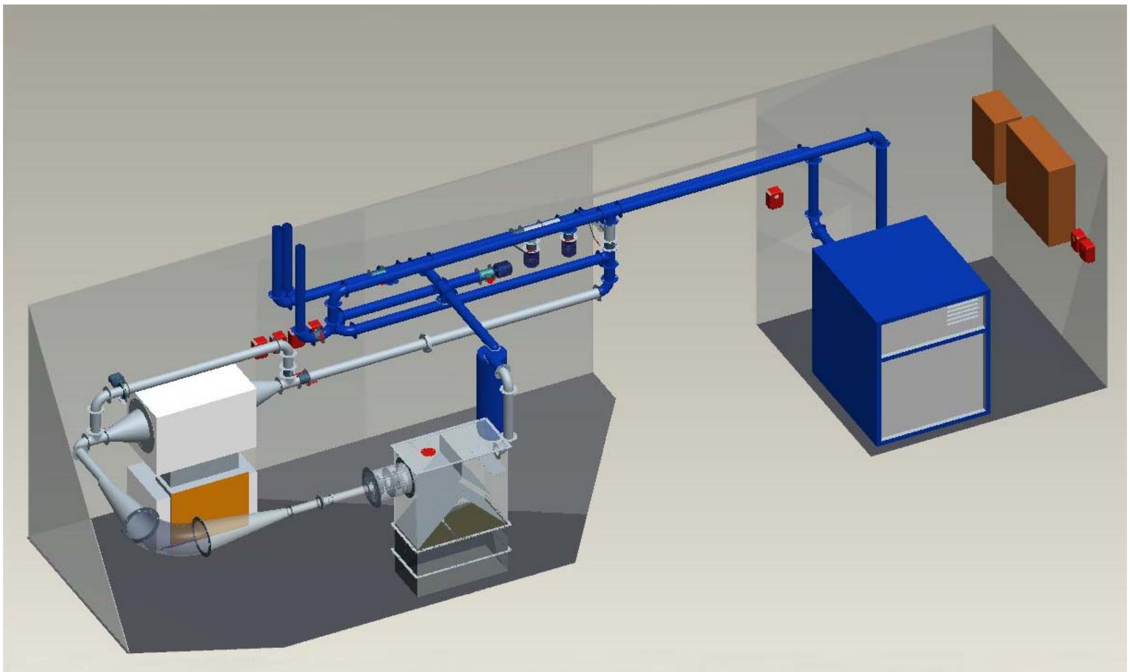

Figure 3.15 Model of the test facility design layout (with homogeneous combustor).

Figure 3.16 Photograph of the test facility installation (with homogeneous combustor).

4. System Operation and Safety

In the interest of safety and test result integrity, a number of mandatory procedures were adhered to when operating the test facility. Safety concerns as well as the systems employed to address these concerns are discussed below. This is followed by a discussion of the system operating procedures which consist of general pre-test checks that needed to be performed prior to commencing with any testing as well as test condition specific controls that applied to the two primary modes of operation – "pressurised" and "vacuum" operation. The facility commissioning procedure and emergency shutdown procedure are summarised in Appendices C and D.5, respectively. The subsystem maintenance requirements are summarised in Appendix E.

4.1. Safety

During the design phase a Hazard and Operability (HAZOP) study was conducted, with critical input provided by an independent specialist. The study was revisited and updated during the commissioning phase. The following potential safety and operability concerns were identified by the HAZOP and were addressed for the subsystems and the test facility as a whole.

4.1.1. Test facility extraction and ventilation

The test facility relied on a ventilation system that it shared with a gas turbine test cell to extract hot air, combustion products and fuel vapour from the test facility outlets and fuel enclosure. Failure of the system to operate optimally could result in build-up of harmful and potentially flammable gasses and vapour in the test facility and laboratory.

Potential modes of failure that were identified included inadequate extraction due to blockages in the system, incorrect positions of the ventilation slide valve and test cell inlet cover, incorrect setting of the extraction fan speed control, failure of the extractor fan or power supply failure. The following measures were implemented to address these potentially hazardous operating conditions:

- The test facility and gas turbine test facility were not to be operated simultaneously.
- Mandatory confirmation of ventilation slide valve and test cell inlet cover position and extractor fan speed was included in the operating procedure and check lists.
- An airflow switch in the extraction duct detected low-flow conditions and activated a warning indicator.

4.1.2. Air supply and flow regulation system

Airflow was provided by a positive displacement blower that was able to operate in both a pressurised and vacuum configuration. Test conditions were controlled by six manually operated and four electro-pneumatic butterfly valves that regulated the airflow rate and pressure through the combustor. Failure or incorrect operation of the system could result in both airflow rates and pressures outside the design levels, which would compromise test result integrity as well as test component and operator safety.

Potential modes of failure included mechanical failure of the blower, failure of the power supply to the blower and/or electro-pneumatic valves, failure of the electro-pneumatic valve control system or compressed air supply, and inappropriate operation of both the electro-pneumatic and manually operated butterfly valves. These potentially hazardous operating conditions were addressed by implementing the following safety measures:

- The blower was quipped with an internal overpressure bypass mechanism.
- A burst diaphragm was installed at the blower outlet to protect the test facility against overpressure operation.
- An overriding facility emergency stop was installed to interrupt the power supply to the blower.
- The blower power supply was not provided unless the control system was fully operational.
- The blower inlet temperature was monitored to not exceed 333K.

- o The electro-pneumatic valves were configured to open fully when power supply was interrupted either due to power supply failure or control system failure. Pneumatic supply failure resulted in the valves maintaining their position, which allowed the test facility to be shut down safely.
- o The control system restricted the actuation ranges of the electro-pneumatic valves according to the operation mode and orifice plate size (and thus air mass flow range) that had been selected.
- o The handles of the manually operated valves were linked to operate in pairs, which, in conjunction with the overall facility layout design, ensured that closed loop operation and unsafe system pressures were avoided.
- o The operating procedures and checklists included mandatory confirmation of the appropriate operation mode and orifice plate selection.

4.1.3. Fuel system

The fuel system was designed to minimise the risk of fuel spillage and fire. The following safety features were included in the fuel system:

- o The system was contained in a ventilated enclosure.
- o A containment tray, with a volume exceeding the volume of the two supply drums, was provided for fuel leakage.
- o Fuel flow was regulated by two solenoid valves that provided redundancy on fuel shut-off. Both solenoids defaulted to the closed position when the power supply was interrupted.
- o The facility emergency stop interrupted the power supply to both fuel pumps and the fuel solenoids.
- o Drain valves upstream of the combustor, at the flameholder of the homogeneous combustor, and downstream of the heterogeneous combustor allowed draining of unburnt fuel from the facility.
- o Electrical connections of the fuel pumps and fuel flow measurement device were safeguarded through the use of the appropriate sealing glands.

4.1.4. Quench system

The gas flow from the combustor sector ejected into a quenching subsystem that was designed to extinguish combustion, cool the combustion products and “scrub” any unburnt fuel from the gas stream. The water and unburnt fuel stripped from the gas stream accumulated in a reservoir that fed the water spray supply pump.

Potential modes of failure that were identified included the following: insufficient quench water supply due to quench pump failure, nozzle failure or low quench water reservoir level, recirculation of fuel due to excessive accumulation of unburnt fuel in the quench tank and structural failure of the quench tank due to an over-pressure situation caused by a facility failure or ignition of a combustible mixture of unburnt fuel and charge air accumulated in the quench tank.

These potentially hazardous operating conditions were addressed by including the following safety measures:

- The quench water pump power supply was not provided unless the control system was operational and the facility emergency stop, when engaged, interrupted the power supply.
- A window in the quench tank provided optical access to monitor quench water and fuel levels.
- The quench tank outlet temperature was monitored.
- A flow switch detected low-flow conditions in the quench water supply.
- A burst diaphragm was installed in the quench tank lid. A chimney ensured that, in the case of the diaphragm rupturing, the blast and associated debris would be directed in a safe direction.
- A centrifugal separator was installed to ensure that any potential free water and unburnt fuel was removed from the gas stream exiting the quench system.
- The operating procedures and check lists included mandatory confirmation of the quench system condition.

4.1.5. General safety measures

Acoustic damping measures were installed for both the blower enclosure and the charge air inlet to minimise noise levels, however, sound pressure level measurements at the test facility indicated the need for hearing protection to be worn at all time. The use of eye protection and safety boots were also mandatory and signage indicating the appropriate personal protection equipment (PPE) were provided. Access to the laboratory was restricted during testing and signage communicating the fact was provided at all entrances.

A number of surfaces in the air conveyance system and combustor sector reached temperatures well in excess of safe skin contact levels. Hot surfaces were indicated by signage while heat shields and insulation provided additional protection, where appropriate.

In addition to the blower, fuel system and quencher, power supplies to the heater, air conditioning and ignition systems were wired through the facility emergency stop.

4.2. System operation

The safe and accurate operation of the test system depended on a combination of safety systems and adherence to strict operating procedures. These procedures were designed to minimise potential risks, both in terms of safety as well as test result integrity, by avoiding potential dangers such as pressurising the system beyond its design specifications or allowing the accumulation of gas and fuel vapour. Appendix D contains check lists that were compiled to address pre-test checks and test condition specific checks and controls. The sequence of operational steps as dictated by the checklists played a key role in avoiding unsafe and unstable operating conditions.

Appendix D.1 contains the pre-test checklist of the electrical, airflow, extraction, quench and fuel systems that had to be completed prior to any testing in order to ensure testing accuracy and safety.

The test condition specific checklists in Appendices D.2 and D.3 address the startup and shutdown procedures that followed the pre-test checks for pressurised and vacuum operation, respectively. In both operating modes the basic sequence was that the appropriate orifice plate was selected, the positive displacement blower was started and the flow condition was set, followed by the test temperature and pressure set-points being established. While the operating conditions stabilised the quench, ignition and injection systems were started in sequence.

Once testing was ready to be commenced the igniter was energised, fuel injection was started, and ignition and combustion were regulated and recorded. Fuel injection duration and minimum ventilation times between injection periods were regulated to minimise the volume of unburnt fuel liquid and vapour accumulating in the system.

For the majority of the tests that were conducted, the fuel flow rate was varied by changing atomiser nozzles, while keeping the fuel supply pressure constant. This was done to ensure consistent fuel atomisation, independent of the fuel flow rate. The effective air–fuel ratio for each fuel atomiser nozzle size was adjusted by controlling the charge air mass flow rate. This resulted in characteristic nozzle curves relating air mass flow to equivalence ratio as shown in Figure 4.1.

Test fuel lean ignition limits were investigated by establishing stable combustor inlet conditions prior to activating the ignition and fuel injection systems in order to attempt ignition. Successful ignition points were repeated whilst incrementally increasing the air mass flow rate in order to determine the lean ignition threshold at the lowest possible equivalence ratio and decreasing air mass flow rate to determine the rich ignition threshold at the highest possible equivalence ratio. Failed ignition points were re-tried while reducing or increasing the air mass flow rate for lean and rich ignition limits, respectively. Experiments at marginal test points were repeated at least three times to verify results.

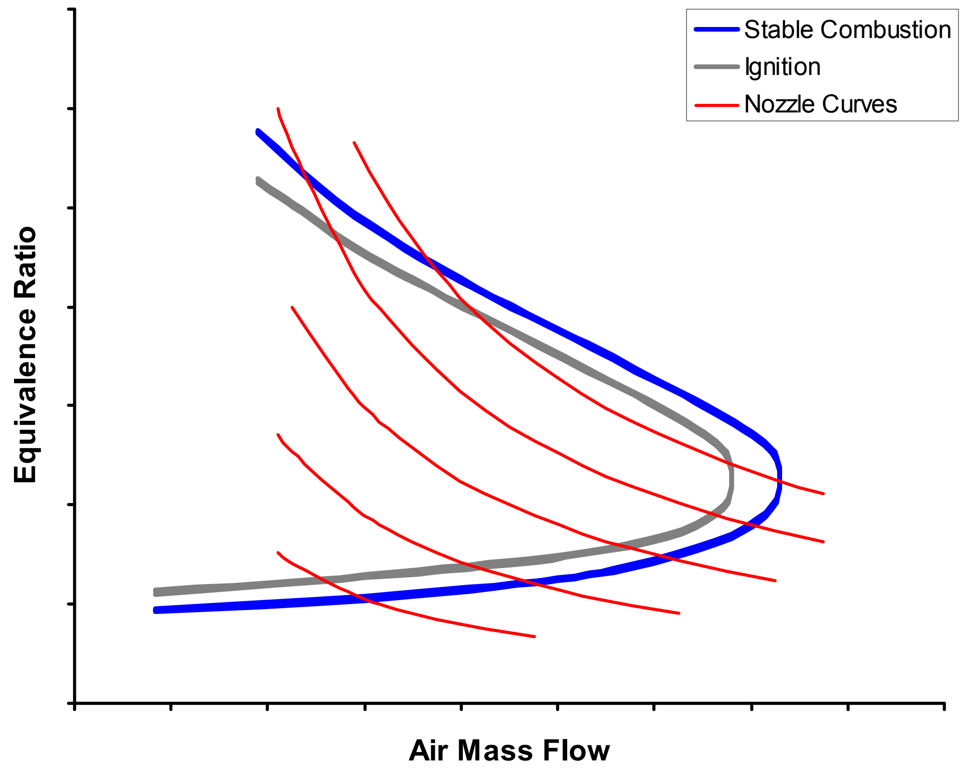

Figure 4.1 Ignition and combustion stability loops constructed by varying air mass flow while keeping fuel mass flow rate constant for each nozzle size, resulting in characteristic nozzle curves.

Test fuel lean blowout limits were established by igniting the mixture well within the ignition "envelope" and incrementally increasing the air mass flow until the blowout occurred. Conversely, rich extinction limits were established by decreasing the air mass flow rate until blowout occurred. Experiments at each blowout condition were conducted at least five times.

Some heterogeneous combustor tests were conducted with a single fuel atomiser nozzle size. The fuel flow rate was changed by adjusting the fuel supply pressure and thereby varying the fuel mass flow rate. As discussed in detail under Section 6.2, this approach is known to influence the atomisation quality of the fuel spray and thus also the ignition and stability thresholds.

The shutdown sequences were designed to minimise unburnt fuel accumulation, allow adequate ventilation of the entire system, and to minimise thermal stressing of the resistance heater and air-conditioning units.

5. Test Programme

Once the construction of the test facility was completed, a series of commissioning tests were conducted to verify the safe operation of all subsystems and that the required test conditions could be attained. This was followed by a number of tests, using both combustor designs, which were intended to demonstrate the facility's capabilities, and confirm the sensitivity of the equipment to detect and measure the expected influence of autoignition chemistry on threshold combustion performance. Tests with a small selection of single component model fuels were performed using the premixed homogeneous combustor configuration to investigate the influence of autoignition chemistry on lean ignition and lean blowout behaviour. This was followed by tests with petroleum-derived Jet A-1 in the heterogeneous combustor to investigate the temperature and pressure dependence of ignition and combustion stability behaviour. Finally, in order to determine how the results obtained in the homogeneous combustor translated to a heterogeneous environment, the lean blowout behaviour of two single component model fuels were compared with that of petroleum-derived Jet A-1.

5.1. Facility commissioning tests

Subsequent to the satisfactory commissioning of all subsystems, the following facility commissioning tests were performed to verify the capabilities of the system as a whole and to investigate the stability of test condition set-points:

- commissioning and calibration of control, measurement and data capturing systems
- facility pressure testing
- verification of valve actuation and control strategies for pressure and flow range control
- quench system operation and free droplet removal testing
- verification of charge air cooling and heating range and control
- ignition and blowout testing of various combustor designs

The premixed homogeneous combustor was commissioned using 95RON unleaded petrol (ULP) since the volatility of this fuel is comparable to the single component “model fuels” that were to be tested in the combustor. Commissioning involved the evaluation of various flameholder designs and optimising the igniter positioning. A series of atmospheric ignition and blowout tests were conducted with the combustor opened (while taking appropriate safety measures) in order to evaluate the combustor performance. A lean blowout event during one of these tests (employing a 45% blockage ratio perforated plate), is shown in Figure 5.1. All commissioning fuel and test fuel specifications are provided in Appendix G.

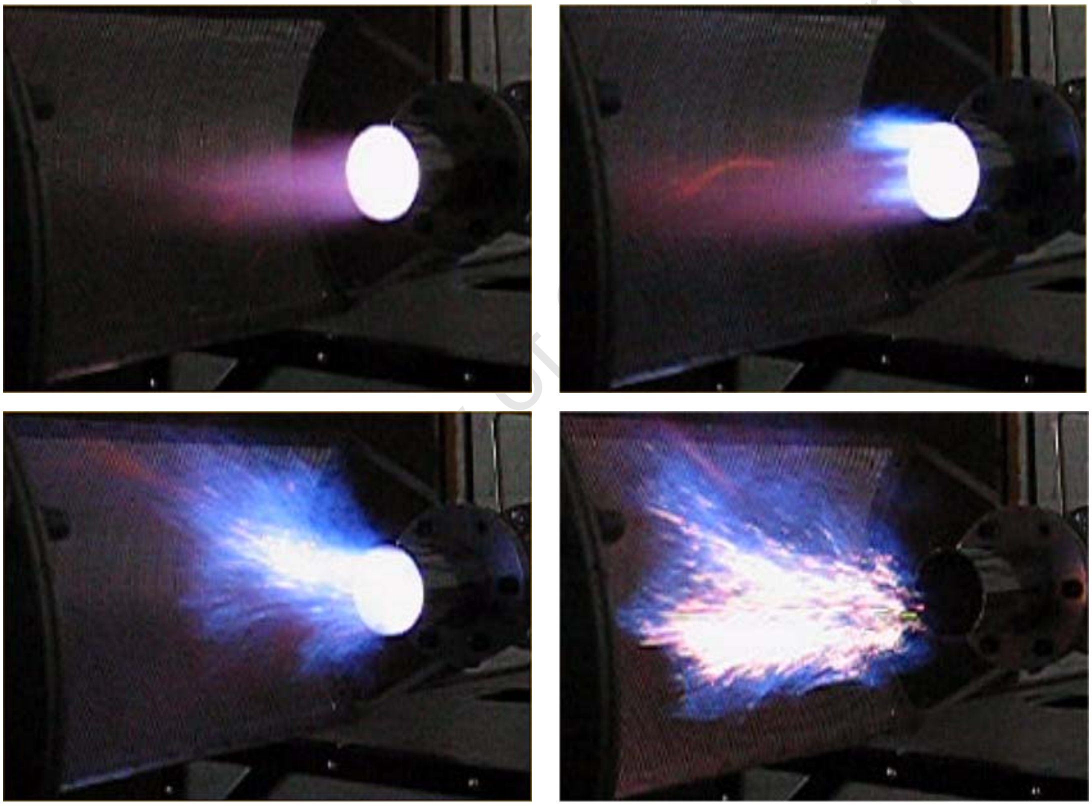

Figure 5.1 Blowout event during commissioning testing of a homogeneous combustor with the combustor opened to atmosphere.

Commissioning of the direct injection heterogeneous combustor was conducted with conventional crude-derived Jet A-1. Similar to the homogeneous combustor, a series of ignition and combustion stability test were conducted to optimise positioning of the igniter and to verify combustion quality and repeatability. Photographic captures of a blowout event occurring in the combustor during commissioning tests are shown in Figure 5.2. Ignition tests during commissioning revealed a considerable difference between the stability and ignition performance, which was attributed to stage 1 ignition failure. The ignition performance was improved considerably by optimising the igniter position (as discussed in Section 6.2).

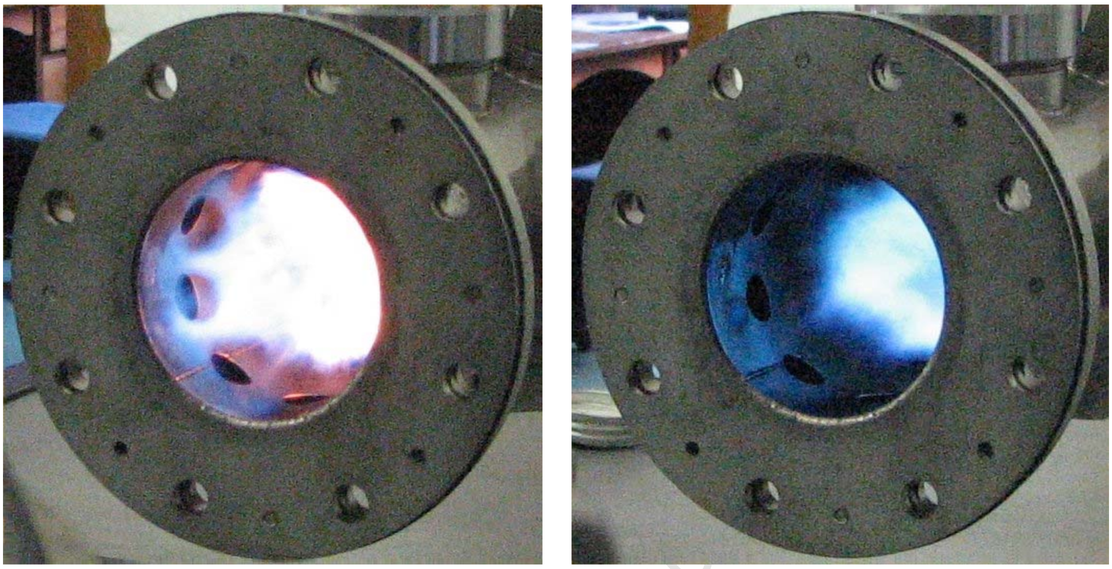

Figure 5.2 Blowout event during commissioning testing of a heterogeneous combustor.

5.2. Homogeneous combustor test programme

As discussed in Section 2.2, it is accepted that the total combustion time is equal to the sum of the times required for fuel evaporation, mixing and chemical reaction. Under normal combustion conditions, emphasis is placed on evaporation and mixing since chemical reaction times are short by comparison. However, under marginal conditions of threshold ignition and blowout, the chemical reaction times are expected to be of more prominent importance.

The influence of fuel autoignition chemistry on the threshold equivalence ratio values of lean ignition and blowout in a continuous combustion environment was investigated by employing four reference fuels in the premixed homogeneous combustion configured test facility. Thus, by moving the atomisation, evaporation and mixing events outside the combustor, the chemical reaction timescales were dominant within the primary combustion zone. The combustor pressure was maintained at 101kPa. In order to ensure a consistent combustor inlet temperature of 298K, the charge air temperature set-point was adjusted to compensate for differences between the different test fuels in evaporative cooling effects. Empirical correlations (Equations 2.8 and 2.9) provided by Lefebvre [23] were used to compensate for slight differences in inlet temperature. A bluff-body flameholder design was employed.

Each test fuel was evaluated at four fixed fuel mass flow rates (atomiser nozzle sizes) while varying the air mass flow rate according to the testing procedure, as discussed in Section 4.2. The lean light-up limits were determined by establishing stable combustor inlet conditions prior to activating the ignition and fuel injection systems in order to attempt ignition. A regimented procedure was followed to aid repeatability. Successful ignition points were followed by incrementally increasing the air mass flow rate, resulting in a simultaneous decrease in the equivalence ratio. Conversely, failed ignition points were followed by reducing the air mass flow rate. Experiments at marginal test point conditions were repeated at least three times to verify results. The lean blowout limits were established by igniting the mixture well within the ignition "envelope" and incrementally increasing the air mass flow until the blowout occurred. Experiments at each blowout condition were conducted at least five times.

The test fuels iso-octane, n-heptane, toluene and ethanol were chosen because of their similar boiling points but significantly different autoignition delay characters. Some of the relevant test fuel properties are summarised below in Table 5.1. Iso-octane and n-heptane were chosen as representative of paraffinic hydrocarbons with nearly identical boiling points but very different autoignition characteristics. The autoignition delays of both fuels exhibited negative temperature coefficient (NTC) behaviour, which is also to be found in paraffinic jet fuel components. Toluene represents an aromatic class of organic compounds, known to exhibit single stage autoignition chemistry and relatively long ignition delays. Ethanol is also a single-stage autoignition fuel, but with high temperature autoignition timescales that are closer to those exhibited by iso-octane and n-heptane.

Table 5.1 Relevant properties of homogeneous test fuels

Test Fuel	Boiling point [°C]	Research octane number	Approximate cetane rating	h_{fg} [kJ/kg]
n-Heptane	98.4	0	~54	364.7
Iso-octane	99.2	100	~12	307.5
Toluene [42]	110.6	120	~0	412.3
Ethanol [43]	78.5	108.6	~10	855

As discussed in Section 6.1, the significance of the lean ignition and lean extinction test results were evaluated with the assistance of results from detailed chemical kinetic modelling, spherical combustion bomb laminar flame speed measurements and high temperature atmospheric combustion bomb ignition delay measurements for the four test fuels.

5.3. Heterogeneous combustor test programme

The heterogeneous combustor was used to conduct two test series. The first series evaluated the influence of pressure and temperature on the ignition and combustion stability performance of conventional petroleum-derived Jet A-1. The second series of tests investigated the influence of autoignition chemistry on lean blowout behaviour in the heterogeneous combustor to determine how the results obtained in the homogeneous combustor translated to a heterogeneous combustion environment. Test fuel properties that were of relevance in the interpretation of the test results are provided in Table 5.2.

Table 5.2 Relevant properties of heterogeneous test fuels (at 20ºC)

Test Fuel	Density [kg/m^3]	Dynamic viscosity [kg/ms]	Surface tension [mN/m]
n-Heptane	686	0.41×10^{-3}	20.3
Iso-octane	695	0.51×10^{-3}	18.8
Jet A-1	796	1.83×10^{-3}	24.2

5.3.1. Pressure and temperature evaluation

The ability of the test facility to investigate the influence of pressure and temperature on the combustion stability limits of test fuels was evaluated using Jet A-1 as test fuel in the heterogeneous combustor. The tests were primarily intended to establish confidence in the capability of the test facility and combustor design to study the relative ignition and combustion stability performance of different alternative jet fuel formulations.

A baseline lean ignition test was conducted followed by three sets of lean blowout tests: a baseline test, a pressure dependence test and a temperature dependence test. The baseline test served as the reference for the ignition test and pressure and temperature dependence tests and was conducted at inlet conditions of 320K and 105kPa. The pressure dependence of the test fuel's combustion stability performance was evaluated at an inlet temperature of 320K and inlet pressure of 125kPa. In order to examine the temperature dependence, the lean blowout limits were determined at an inlet temperature of 290K and inlet pressure of 105kPa. Equation 2.8 was again used to correct slight differences in inlet temperature and pressure.

Each test condition was evaluated at four fixed fuel mass flow rates that were obtained by operating a single fuel nozzle at four different fuel supply pressures. The lean ignition and blowout limits were determined by varying the air mass flow rate as described in Section 4.2. Experiments at each blowout condition were conducted at least five times. The results were interpreted against the predicted temperature and pressure dependence.

5.3.2. Fuel autoignition delay evaluation

The influence of autoignition chemistry on lean blowout behaviour was investigated in the heterogeneous combustor to determine how the results obtained in the homogeneous combustor translated to a more conventional gas turbine combustion environment. The results from the baseline Jet A-1 test were compared with results obtained with the two paraffinic primary reference fuels, n-Heptane and iso-Octane, that were also employed in the homogeneous combustor test programme. All three fuel tests were conducted at inlet conditions of 320K and 105kPa.

Similar to the temperature and pressure evaluation, each fuel test was conducted at four fixed fuel mass flow rates while varying the air mass flow rate. As before, the lean blowout limits were established by igniting the mixture well within the ignition “envelope” and incrementally increasing the air mass flow until the blowout occurred and experiments at each blowout condition were conducted at least five times

6. Test Results and Discussion

6.1. Homogeneous combustor test programme

The homogeneous combustion configured test facility was used to investigate the influence of fuel autoignition chemistry on the threshold equivalence ratio values of lean ignition and blowout in a continuous combustion environment. Iso-octane, n-heptane, toluene and ethanol were used as test fuels.

6.1.1. Test results

The lean ignition results of the four test fuels in the homogeneous combustor are presented in Figure 6.1. The pre-injection inlet conditions were controlled to compensate for differences between test fuels in evaporative cooling and provide constant combustor inlet temperature conditions. The results were further corrected to compensate for slight combustor inlet temperature variations using the equations (2.8 and 2.9) proposed by Lefebvre [22], [23]. Apart from the difference in pressure dependence ($P^{1.3}$ vs $P^{1.5}$), the two equations are virtually identical. For a given combustor geometry, inlet pressure, air mass flow rate, fuel type and atomisation quality, the temperature dependence of both lean blowout and lean lightoff equivalence ratios (q_{LBO} and q_{LLO}) can therefore be expressed as shown in Equation 6.1.

$$q_{LBO}\ , q_{LLO} \propto \left[\frac{1}{\exp(T_3/300)}\right] \qquad (6.1)$$

Except for the results obtained with ethanol, the ignition results exhibited a clear ranking between the four test fuels that appeared to reflect their high temperature autoignition delay ranking. The results of the lean blowout threshold limits are depicted in Figure 6.2. As indicated by the error bars, repeatability was relatively poor, and it was not adequately discerning to enable the author to confidently establish a trend with respect to air mass flow rate. The variability of the results was attributed to differences in the time required to achieve blowout, which possibly resulted in variable combustor temperatures at the point of extinction. In spite of this observed variability in the individual tests, the average lean blowout equivalence ratio results exhibited a ranking that again appeared to reflect the test fuel autoignition delay ranking, as discussed below.

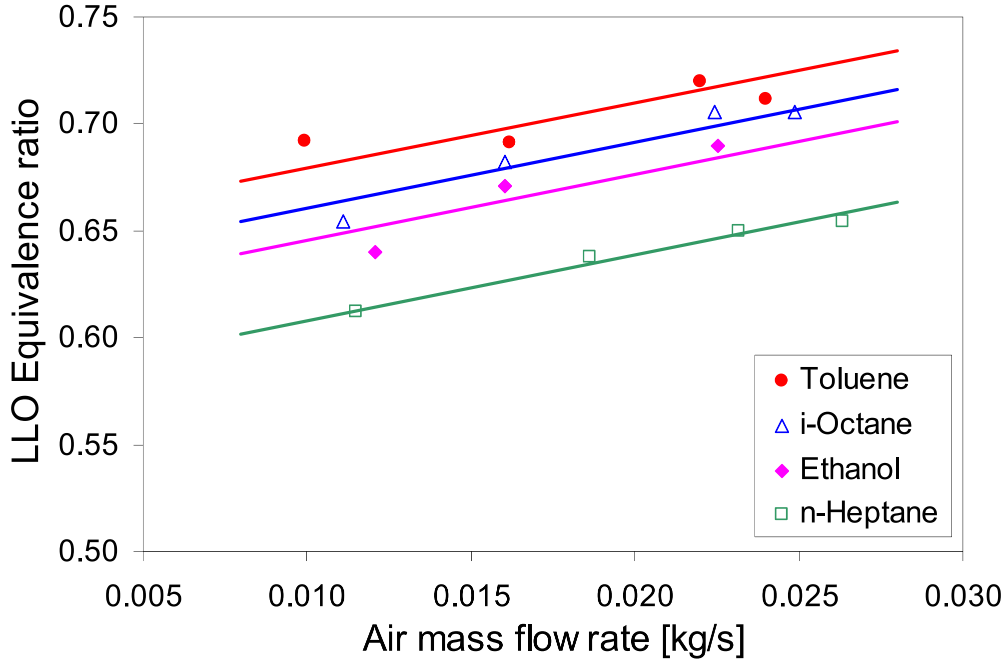

Figure 6.1 Lean ignition threshold limits of four test fuels in the homogeneous premixed combustor (101kPa, 298K).

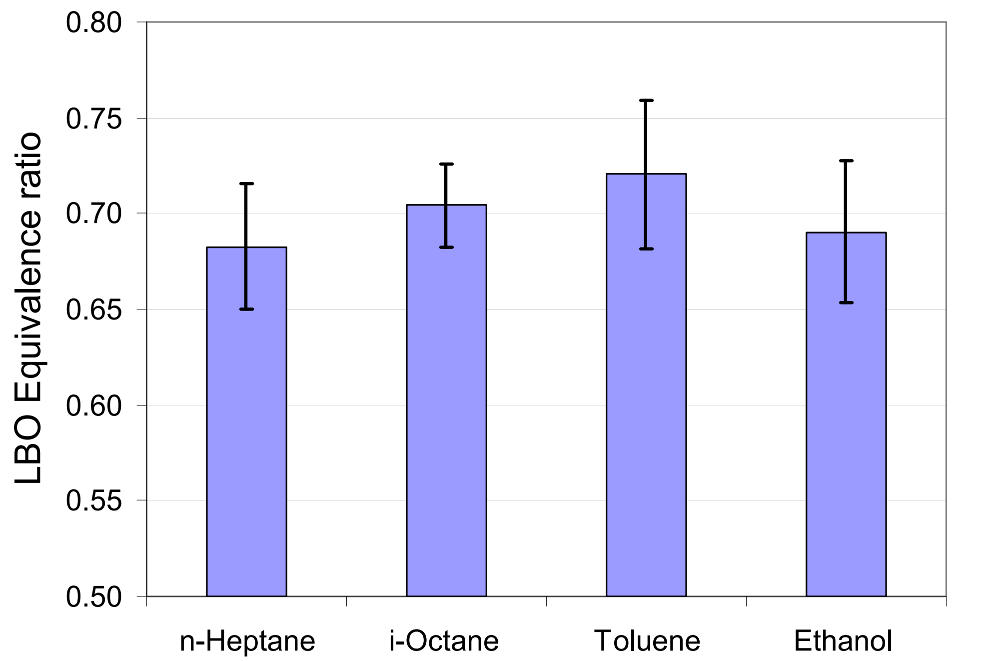

Figure 6.2 Lean blowout threshold limits of four test fuels in the homogeneous premixed combustor (101kPa, 298K).

6.1.2. Discussion of test results

The lean ignition results appeared to reflect the high-temperature autoignition delay ranking of the test fuels, with the exception of ethanol falling between n-heptane and iso-octane rather than below n-heptane as its high-temperature autoignition ranking would suggest. It was speculated that, considering the high latent heat of vaporisation of ethanol and the significantly different stoichiometry, the evaporation of this fuel may have been incomplete which could possibly have accounted for the anomalous result. Figure 6.3, taken from Burger et al. [44], depicts the chemical kinetic prediction of autoignition delays for stoichiometric, adiabatic, constant-pressure simulations at 1bar over a range of temperatures.

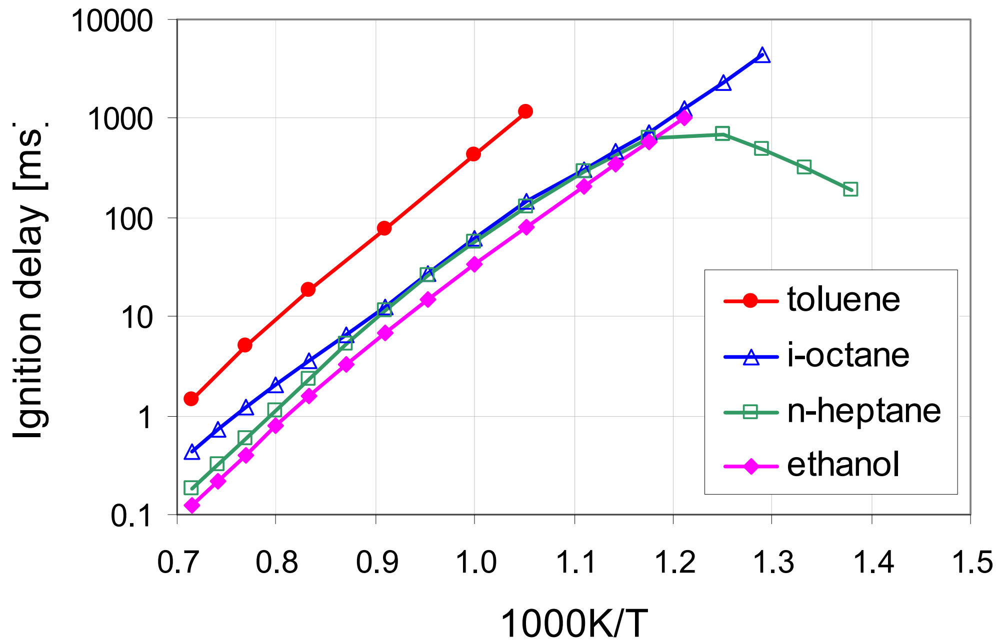

Figure 6.3 Chemical kinetic prediction of the autoignition delays of the four test fuels for stoichiometric, adiabatic, constant pressure simulations at 1bar [44].

The ignition threshold results were in direct agreement with laminar flame speed measurements reported by Burger et al. [44], which also reflect the high temperature autoignition delay ranking of the test fuels, except for ethanol again falling between n-heptane and iso-octane. The correlation between the ranking of the laminar flame speed, and ignition results are in agreement with Equation 6.2, as proposed by Ballal and Lefebvre [28], that relates quench distance, d_q, to evaporation, thermal diffusivity, α, and laminar flame speed, S_L. (discussed in Section 2.6)

$$d_q \quad \propto \quad \left[f(evaporation) + \left(\frac{\alpha}{S_L} \right)^2 \right]^{0.5} \tag{6.2}$$

Although this was a very simple flame holder design, it was estimated that the re-circulating flow ignition process would correspond to timescales of the order of about 1 ms to 2 ms. It was evident that high temperature chemical timescales are relevant during ignition in a recirculating flow regime. In a non-premixed environment, such as found in a conventional gas turbine combustor, fuel volatility differences would influence the relight envelope but the overall envelope could be expected to be delineated by the underlying fuel chemistry.

In spite of the variability of the results of the individual blowout tests, it was observed that the average lean blowout equivalence ratio results for the four test fuels, similarly to the ignition behaviour, appeared to reflect their high temperature autoignition chemistry. The lean blowout results were, yet again, in direct agreement with laminar flame speed measurements.

6.2. Heterogeneous combustor test programme

Experience gained from the homogeneous combustor tests and the subsequent optimisation of the test procedure ensured that the repeatability of the ignition and blowout test results obtained with the heterogeneous combustor were improved considerably compared to the homogeneous test results. Initial results however revealed a considerable difference between the stability and ignition performance. This was attributed to stage 1 ignition failure and was improved considerably by optimising the igniter position, as illustrated by the lean ignition and extinction results shown in Figure 6.4. These tests were conducted with petroleum-derived Jet A-1 at inlet conditions of 320K and 105kPa and show the baseline lean blowout results and lean ignition before and after adjusting the igniter position.

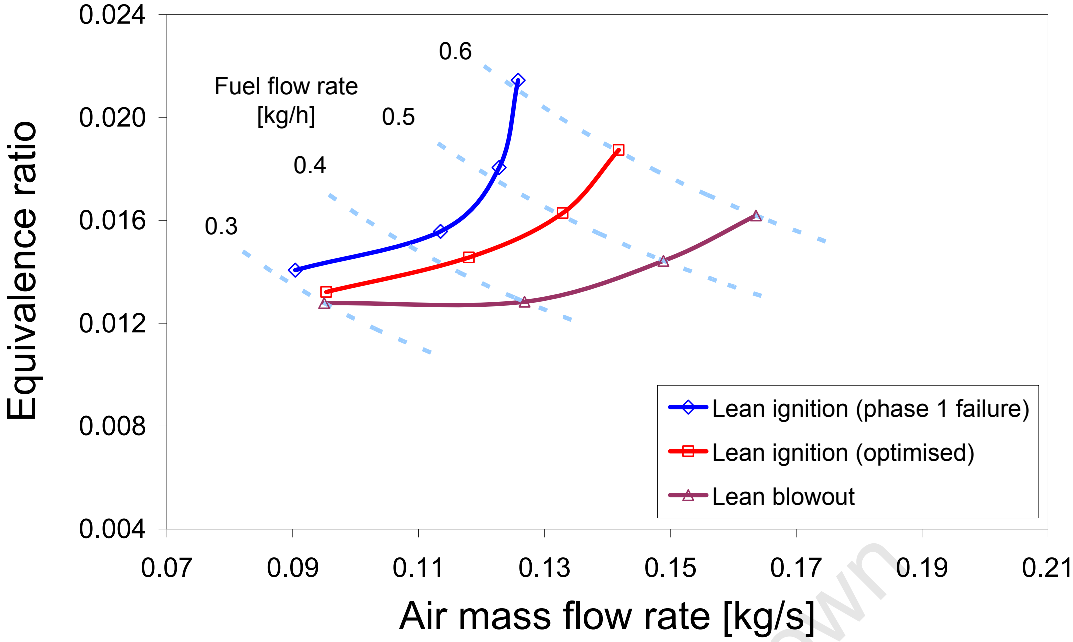

Figure 6.4 Baseline lean ignition and extinction performance of Jet A-1 in the heterogeneous combustor (105kPa, 320K).

It should also be noted that the very lean overall equivalence ratio values recorded at ignition and extinction are indicative of the large quantity of air that bypassed the primary combustion zone. The combustor was also expected to exhibit good stability since it was modelled on a rich primary zone combustor design and it employed pressure atomisation.

6.2.1. Test results: Pressure and temperature evaluation

The results of the investigation into the influence of pressure and temperature on the blowout performance of the heterogeneous combustor are shown in Figure 6.5. The pressure dependence tests, conducted at 125kPa and 320K, and temperature dependence tests, conducted at 105kPa and 290K, were compared to baseline tests that were conducted at 105kPa and 320K. All three test results were again corrected for small deviations from temperature and pressure set-points, as proposed by Lefebvre [23]. Applying Equation 2.8, for a given combustor geometry and fuel type, and assuming that the atomisation quality and air mass flow rate at the test point are relatively insensitive to small inlet temperature and pressure variations, the pressure and temperature dependence of the lean blowout equivalence ratio (q_{LBO}) can be expressed as shown in Equation 6.3.

$$q_{LBO} \quad \propto \quad \left[\frac{1}{P_3^{1.3}\exp(T_3/300)}\right] \tag{6.3}$$

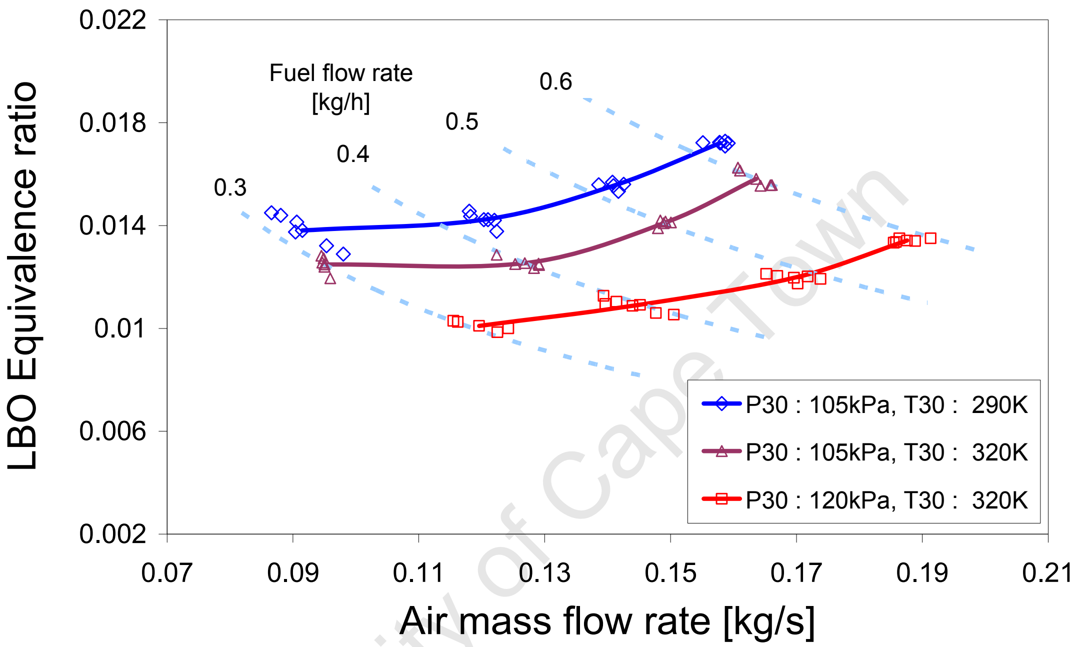

Figure 6.5 Pressure and temperature dependence of lean blowout performance of Jet A-1 in the heterogeneous combustor.

6.2.2. Discussion of test results: Pressure and temperature evaluation

The test results showed acceptable repeatability and were in agreement with the theoretical directional influence of pressure and temperature on lean blowout limits, as discussed in Section 2.3. In order to determine whether the pressure and temperature influence was also quantitatively in agreement with the theoretical dependence, the two data sets were adjusted to the baseline inlet conditions, using Equation 6.3. The results of these adjusted blowout limits are presented in Figure 6.6. At lower air mass flow rates the corrected results were in close agreement with the baseline data. The adjusted pressure dependence data set deviated slightly from the baseline and adjusted temperature dependence trend, at air mass flow rates above 0.15kg/s, but the agreement was still considered to be acceptable. It should also be mentioned that the assumption that atomisation quality and air mass flow rate were not influenced by the correction is only valid for small pressure adjustments, since droplet size and air mass flow rate is combustor pressure dependent.

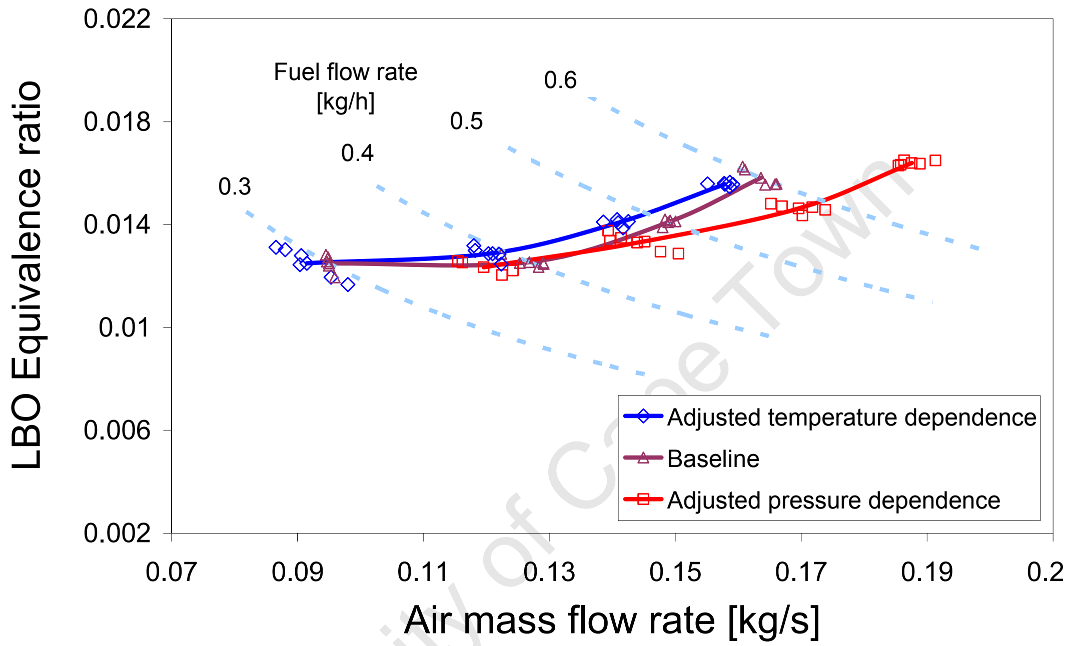

Figure 6.6 Pressure and temperature dependence lean blowout tests adjusted to baseline inlet conditions of 105kPa and 320K.

6.2.3. Test results: Fuel autoignition delay evaluation

The results of the evaluation of fuel autoignition delay influences on the heterogeneous combustor lean blowout performance are shown in Figure 6.7. All three test fuels were evaluated at combustor inlet conditions of 105kPa and 320K and Equation 6.3 was again used to correct the test results for small deviations from temperature and pressure set-points. Blowout points were determined by varying the air mass flow rates at fixed fuel flow rates that were obtained with a single fuel nozzle that was operated at different fuel pressures. Due to the lower density and viscosity of the two single component model fuels (see Table 5.2), similar fuel supply pressures resulted in fuel flow rates that were between 75 and 80% of those obtained with Jet A-1.

The lean blowout results of the two single component model fuels appeared to reflect their high-temperature autoignition delay ranking, which was in line with the results obtained in the homogeneous combustor. n-Heptane exhibited a greater resistance to lean blow out than iso-octane. At higher fuel flow rates the Jet A-1 results ranked between the model fuels, falling closer to the n-heptane than the iso-octane blowout limits. At the lower fuel flow rates the Jet A-1 stability limits appeared to be impaired (slightly at the 0.4kg/h fuel flow test point and considerably more at the 0.3kg/h test point). This trend was ascribed to the fuel atomisation being impaired and SMD values starting to exceed the critical value at lower fuel supply pressures, as discussed below.

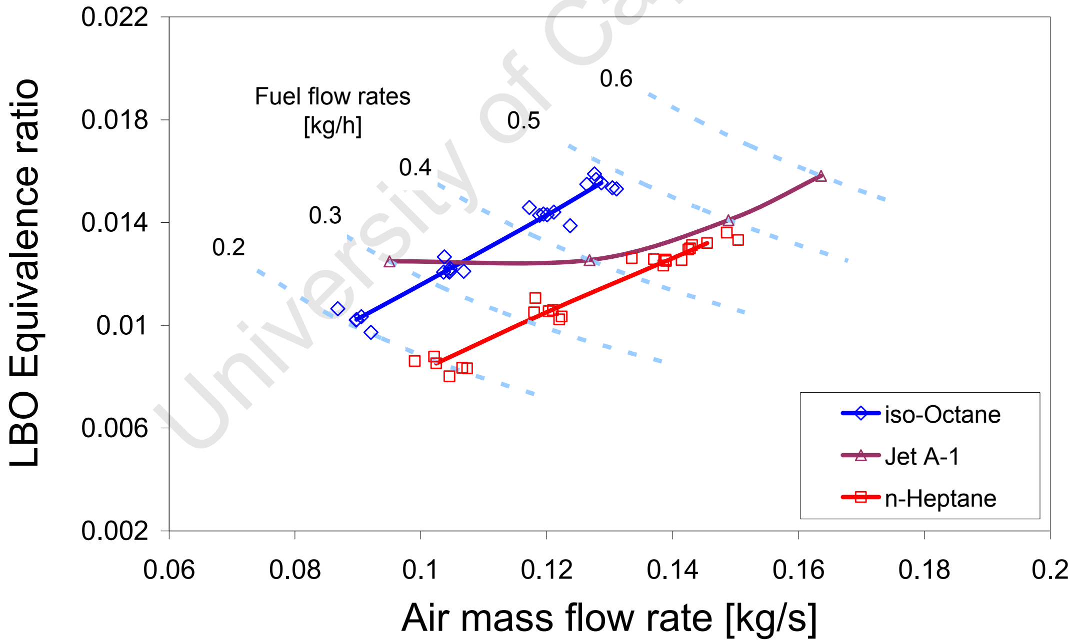

Figure 6.7 Heterogeneous fuel autoignition delay evaluation results.

6.2.4. Discussion of test results: Fuel autoignition delay evaluation

In order to interpret the test results it was essential to take into account the effect of fuel atomisation of the different test fuels at the various fuel flow rates. It was not possible to conduct fuel spray characterisation at SAFL at the time of this test programme. Off-site droplet size measurements were thus conducted (using a Malvern Insitec 97) with the specific fuel nozzle employed during these tests and Jet A-1 as test fuel. An SMD of 35μm was measured at a fuel supply pressure of 10bar. Lefebvre [45] proposed the following empirical equation (6.4) for mean droplet sizes.

$$SMD = 2.25\sigma^{0.25}\mu_L^{0.25}\dot{m}_L^{0.25}\Delta P_L^{-0.5}\rho_A^{-0.25} \quad (6.4)$$

Where σ represents the surface tension, μ_L the dynamic viscosity, $\dot{m}_L$ the fuel mass flow, ΔP_L the pressure differential across the fuel nozzle and ρ_A the density of the charge air. For the same fuel at a given fuel temperature, and therefore constant surface tension, density and dynamic viscosity, and assuming the charge air density to be constant, the relative SMD values are a function of fuel mass flow rates and supply pressure that can be expressed as follows in Equation 6.5.

$$SMD \propto \dot{m}_L^{0.25}\Delta P_L^{-0.5} \quad (6.5)$$

Using this relationship with the measured SMD value at 10bar fuel supply pressure, SMD values were calculated for the different fuel flow rates and fuel supply pressures that were measured during the blowout testing with Jet A-1. These results are summarised in Table 6.1. As discussed in Section 2.2.3, Myers and Lefebvre [14] found that there is a critical droplet size beyond which heterogeneous burning velocities change from being chemical reaction rate controlled to being evaporation rate controlled. From Figure 2.1, the critical SMD for kerosene-type fuels, at air-fuel ratios that would be encountered in the primary combustion zone during lean blowout, is approximately 50 μm. The calculated SMD values revealed that the atomisation at test points 3 and 4 approached this critical droplet size.

Table 6.1 Calculated relative SMD values for Jet A-1

	Fuel pressure [bar]	**Fuel flow rate [kg/h]**	**SMD [μm]**
Test point 1	15	0.62	30
Test point 2	10	0.51	35 *
Test point 3	6	0.40	43
Test point 4	3	0.29	55

***** measured reference SMD value at 10bar

From Equation 6.4, the atomisation of n-heptane and iso-octane relative to that obtained with Jet A-1 can be expressed as follows in Equation 6.6, for each fuel supply pressure.

$$SMD \quad \propto \quad \sigma^{0.25}\mu_L^{0.25}\dot{m}_L^{0.25} \tag{6.6}$$

This yielded SMD values that were 61 to 64% of those obtained with Jet A-1, depending on the fuel type, mass flow rate and supply pressure. The maximum SMD values at test point 4 (with the minimum fuel supply pressure and mass flow rate and hence poorest atomisation) were calculated as 36 and 34 μm for iso-octane and n-heptane, respectively. This meant that the critical droplet size was not exceeded and resulted in the apparent difference in the blowout trends recorded with Jet A-1 and the model fuels.

The finding that the autoignition delay characteristics of the test fuels were relevant under lean, finely atomised conditions was in line with literature acknowledging the significance of chemical reaction rates for well atomised fuels at low pressures and low equivalence ratios.

7. Conclusions

On completion of the project a number of conclusions could be drawn about the design and performance of the test facility and its suitability for being employed in studying the influence of fuel chemistry in general, and autoignition chemistry in particular, on gas turbine ignition and extinction behaviour. The test programmes that were used as the sign-off criterion for the successful completion of the test facility, yielded results that provided insight into the influence of fuel autoignition delay on combustion stability and ignition. It also validated the motivation for constructing a facility that would enable further study of this phenomenon and its relevance to synthetic gas turbine fuel formulation.

7.1. Test facility

The gas turbine combustion test facility was designed, constructed and commissioned for the investigation of the ignition and combustion stability of different test fuels over a range of test conditions. The commissioning programme indicated that the facility was able to achieve the design test conditions. Pressures and temperatures representative of theoretical combustor inlet conditions up to an altitude of 5900m above sea level at Mach 0.8 were attainable.

Two combustor designs were developed, constructed and tested in order to evaluate specific combustion ignition and combustion stability phenomena. A homogeneous combustor was designed and used in a series of tests aimed at investigating the influence of fuel autoignition chemistry on the threshold equivalence ratio values of lean ignition and extinction in a continuous combustion environment. By moving the atomisation, evaporation and mixing events outside the combustor the chemical reaction timescales were dominant within the primary combustion zone.

A heterogeneous combustor was designed to investigate the ignition and extinction behaviour of practical synthetic jet fuel alternatives. The combustor design was signed-off by the successful execution of tests that investigated the influence of pressure and temperature on the extinction behaviour of Jet A-1, as well as tests that investigated the influence of autoignition chemistry in a heterogeneous combustion environment.

7.2. Test programme

7.2.1. Autoignition chemistry evaluation

The influence of autoignition chemistry was evaluated using both the homogeneous and heterogeneous combustors. The results of the evaluation in the homogeneous combustor revealed that the lean ignition threshold limits of the four test fuels exhibited a clear relative ranking that appeared to reflect their high temperature autoignition delay ranking. The lean blowout equivalence ratio results of the four test fuels exhibited some variability but similar to the ignition behaviour also appeared to reflect their autoignition chemistry.

It was shown that, in the absence of fuel evaporation effects, normal paraffins were likely to exhibit the greatest resistance to lean blowout and ignited most easily due to relatively short high-temperature ignition delays and hence relatively fast laminar flame speeds. Conversely, fuels that exhibit a strong iso-paraffinic structure or fuels with a single-stage autoignition character such as toluene, appeared to exhibit a relatively longer high-temperature ignition delay, which manifested as a slower laminar burn speed, less resistance to blowout, and a greater difficulty to ignite. While the laminar flame speed, ignition and combustion stability results obtained with ethanol were in agreement, these results were not in absolute agreement with the theoretical ignition delay ranking. This may have been due to incomplete fuel evaporation.

While it is known that fuel evaporation and mixing timescales can exert an overriding influence in a practical, gas turbine application, it was concluded that the fuel's autoignition chemistry also plays a significant role in threshold operational situations. Discussion of the implications of these observations was considered to be beyond the scope of this project. Interested readers are referred to [44].

The heterogeneous combustor was used to investigate how the results obtained in the homogeneous combustor translated to a more conventional gas turbine combustion environment where fuel evaporation and mixing timescales can be dominant. The influence of autoignition chemistry was shown to be relevant to the lean extinction behaviour of two single component model fuels in the heterogeneous combustion environment, which was in line with literature acknowledging the significance of chemical reaction rates for well atomised fuels at low pressures and low equivalence ratios. The results highlighted the role of atomisation quality and droplet size relative to the critical SMD value in determining whether the evaporation and mixing timescales or chemical reaction timescales dominated lean blowout behaviour. The results were shown to be in line with literature results and theory and confirmed the need for accurate SMD measurement in order to interpret test results accurately.

The results from both test series validated the motivation for designing and constructing a facility that would enable further study of the influence of fuel chemistry on ignition and extinction behaviour, and its particular relevance to synthetic gas turbine fuel formulation.

7.2.2. Pressure and temperature influence evaluation

The heterogeneous combustor design was used to determine the temperature and pressure influences on the lean blowout performance of Jet A-1. The temperature and pressure dependence was shown to be in agreement with the behaviour predicted by literature [23], with stability limits being extended by increased combustor inlet gas temperature and pressure. It was concluded that the results of the pressure and temperature influence evaluation clearly illustrated the repeatability of test results and the suitability of the test facility and the heterogeneous combustor design for investigating the ignition and extinction behaviour of practical synthetic jet fuel alternatives.

8. Recommendations

8.1. Test facility

During the commissioning phase of the test facility and the subsequent test programmes a number potential modifications and improvements were identified and, in most cases, implemented. The following changes that were not implemented could potentially have improved the operability of the facility and the test results obtained from it.

- A fuel conditioning unit should be incorporated in the fuel system to provide more accurate control over the fuel supply temperature.
- In order to further study the influence of fuel atomisation on ignition and stability results, it is recommended that a combustor employing air-assist atomisation be designed and constructed to complement the existing heterogeneous and homogeneous combustor designs.
- It is recommended that the air mass flow measurement device be modified to either ease or avoid the exchange of orifice plates during tests spanning large air mass flow ranges. Possible solutions include employing a quick-release clamping device for the orifice plate holders or switching between two measurement sections with individual orifice plates.
- The procedures that the operator had to adhere to in order to ensure repeatability of test results could become cumbersome during the execution of test programmes that involved large numbers of test points. It is recommended that test sequences be automated (specifically the blowout sequence) to ensure repeatability of critical aspects such as the rates of fuel and air mass flow rate change. The existing measurement and control systems lend themselves to such a modification.
- A hydrocarbon sensor could be installed in order to detect excessive levels of unburnt fuel in the gas stream exiting the quench tank.

8.2. Test programme

Consideration of the two test programmes that were conducted resulted in the following recommendations.

- Thermal stabilisation of the facility and the combustor in particular was shown to be critical in ensuring accurate and repeatable results. This was particularly evident when establishing extinction limits. Intelligent feedback control should therefore be incorporated in the test sequence automation that is recommended above.
- The test programmes that were conducted were designed to avoid the requirement of accurate atomisation measurement. It was shown that comparison of different fuel formulations in the heterogeneous combustor would require accurate SMD measurement of each fuel and each atomiser nozzle. It is recommended that a dedicated droplet sizing device be used to quantify atomisation quality of all test fuel, nozzle size and flow rate combinations while conducting heterogeneous test programmes.
- The results obtained with the heterogeneous combustor suggested that the influence of fuel autoignition chemistry on lean ignition and blowout is relevant. It is recommended that this be studied over a greater equivalence and air mass flow rate range in order to investigate the phenomenon beyond the lean limit range to include toe ignition and blowout conditions.
- The test results produced by the test facility can be extrapolated with care to provide an indication of the expected behaviour of different test fuels under altitude blowout and relight conditions. However, in order to validate these extrapolations it would be necessary to compare it with results obtained within a conventional altitude test facility. It is therefore recommended that a test programme be conducted in the test facility, employing test fuels that have been evaluated in a conventional altitude test facility and have shown a significant measurable difference in performance.

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