LEAN PREMIXED PRE-VAPORIZED COMBUSTION IN A SWIRL STABILIZED LIQUID FUEL BURNER

BY:

AHMAD FARIS BIN AHMAD NORDIN

(Matrix no: 144486)

Supervisor:

Dr. Khairil Faizi Mustafa

JULY 2022

This dissertation is submitted to
Universiti Sains Malaysia
As partial fulfilment of the requirement to graduate with honors degree in
BACHELOR OF ENGINEERING (MECHANICAL ENGINEERING)

School of Mechanical Engineering

Engineering Campus

Universiti Sains Malaysia

Acknowledgement

I would like to thank the following people, as without their support and help of these people the completion of this thesis would not be made possible. Foremost, I would like to express my sincere gratitude to my supervisor, Dr. Khairil Faizi B. Mustafa for the continuous support of my bachelor's study and research, for his patience, encouragement, and vast knowledge input. The problems faced are made easier due to his effective guidance and responsive feedback. Without proper guidance, I would have easily lost my way especially, during the writing process, thesis formats, and project development. Since this research was made during the COVID-19 pandemic, he always made time for me to answer my questions, set up meetings for discussion, and replied to my messages via WhatsApp. The sacrifice made is one of the key factors of this project being completed

I would also like to give special thanks to Dr Khaled Al Attab for teaching me the basis of combustion simulations using ANSYS Fluent. Since I have zero knowledge of combustion basics, he would help by giving me lessons on the fundamental. I appreciate his willingness to show and guide me throughout the research even though he was busy working.

Furthermore, I want to express my gratitude to the lab technician, En. Jamari for giving me access to the computer lab daily without fail. The facilities provided were always in good condition such as computers with high computing power and with his assistance several technical issues were able to resolve. This is essential for my simulation process to run with quality performance. Also, I am truly grateful to all the staff and lecturers who helped me in my 4 years journey at university.

Lastly, I would like to personally thank my family and friends for having my back and giving me their constant support. All those reminders and teachings given by them kept me motivated and determined in finishing this research paper. Sincerely, I thank you all for helping me finish this research paper.

Declaration

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed……………………………… (AHMAD FARIS B. AHMAD NORDIN) Date…………………………………

Statement 1: This journal is the result of my own investigation, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/ references are appended.

Signed……………………………… (AHMAD FARIS B. AHMAD NORDIN) Date…………………………………

Statement 2: I hereby give consent for my journal, if accepted, to be available for photocopying and for interlibrary loan, and for the title and summary to be made available outside organizations.

Signed……………………………… (AHMAD FARIS B. AHMAD NORDIN) Date…………………………………

Table of Contents

List of Tables

List of Figures

List of Graphs

List of Abbreviations

CAA	Clean Air Act
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
GT	Gas Turbine
HC	Hydrocarbon
HCNG	Hydrogen Compressed Natural Gas
JME	Jojoba Methyl Ester
LPP	Lean Premixed Prevaporised
MTBE	Methyl Tertyl-Butyl Ether
NO_x	Nitrogen Dioxide
PDF	Probability Density Function
PM	Particulate Matter
SI	Spark Ignition
ULPP	Ultra-Lean Premixed Prevaporized

Abstrak

Dilaporkan bahawa dari sektor pengangkutan mendapati bahawa penyumbang utama dalam pelepasan bahan pencemar udara adalah seperti NOx, CO, UHC, CO2 dan ia juga merupakan punca utama kemerosotan alam sekitar. Pembakaran pracampuran prawak dalam kondisi 'lean' telah mendapat perhatian terutamanya dalam kalangan komuniti saintifik kerana potensinya dalam mengurangkan pelepasan bahan pencemar udara. Di samping itu, rizab bahan api fosil pada masa ini semakin berkurangan disebabkan oleh eksploitasi manusia yang meluas dengan tujuan penjanaan kuasa, pengangkutan dan automasi. Etanol telah menarik perhatian meluas sebagai bahan api pengganti kepada bahan api konvensional kerana faedahnya yang seakan sama dengan bahan api konventional. Walaupun begitu, tiada langkah balas atau penyelesaian alternatif disediakan untuk aplikasi di negara membangun seperti Malaysia. Jadi, penyelidikan dan kajian sedemikian akan menjadi langkah besar untuk pengangkutan yang lebih bersih dan hijau dalam masa terdekat. Oleh itu, satu kajian telah dijalankan untuk menyiasat kebuk pembakaran LPP dengan pemutar yang berjalan pada campuran petrol-etanol. Beberapa komposisi adunan petrol-etanol iaitu E10(gasolin 90%/ etanol 10%), E20, E30 telah dibakar pada nisbah kesetaraan 0.9 dan 0.5. Berdasarkan eksperimen, pelaksanaan pemutar mendapati percampuran sengit antara udara dan bahan api sebelum pembakaran. Eksperimen ini dilakukan pada platform maya menggunakan ANSYS Fluent sebagai cara untuk mensimulasikan fenomena pembakaran dengan parameter operasi yang dikehendaki. Kadar aliran jisim dan nisbah kesetaraan terutamanya mempengaruhi pembentukan ciri nyalaan dan pelepasan bahan pencemar. Daripada keputusan tersebut, ia mencadangkan bahawa pada mod pembakaran ULPP mengurangkan lagi pelepasan NOx, CO dan CO_2 adalah mungkin kerana keadaan pembakaran. Walau bagaimanapun, apabila pemberat komposisi etanol meningkat dalam campuran campuran dan keadaan kurus, keluaran kuasa haba semakin berkurangan. Pastinya penemuan ini akan membantu sebagai input dalam usaha merealisasikan teknologi ini.

Abstract

From transportation sector alone is known to be major contributors to pollutant emissions such as NO_x, CO, UHC, CO_2 and the main cause of environmental degradation. Lean Premixed Prevaporised combustion has been gaining attention amongst scientific communities due to its potential in reducing pollutant emissions. Similarly, fossil fuel reserves currently are depleting due to extensive exploitation for power generation, transportation, and automation purpose. Ethanol has attracted wide attention as a replacement fuel for conventional fuels because of its lucrative benefits. Despite that, no countermeasures or alternative solutions are provided for application in a developing country such as Malaysia. Commercially, such research and studies would be a big step for towards a cleaner and greener transportation in the near future. Hence, a study was conducted to investigate the LPP combustion chamber with a swirler running on gasoline-ethanol mixtures. Several compositions of gasoline-ethanol blends which are E10(gasoline 90%/ ethanol 10%), E20, and E30 were burned at an equivalence ratio of 0.9 and 0.5. Based on the experiment, the implementation of a swirler articulates intense mixing between air and fuel before combustion. This experiment was performed on a virtual platform using ANSYS Fluent as means to simulate the combustion phenomena with the desired operating parameters. Mass flow rate and equivalence ratio mainly influence the flame characteristic formation and pollutant emission. From the results, it suggests that at ULPP combustion mode further lowering of emissions of NO_x, CO and CO_2 is possible. In addition, findings showed that the effect of swirl facilitates the high-speed mixing of air and fuel composition which also results in near-complete combustion situations. However, as the weightage of the ethanol composition increases within the blended mixture and under lean conditions, thermal power output is decreasing. Surely these findings would help as an input in efforts of realizing this technology.

Chapter 1 Introduction

1.1. Research Background

Reports have shown that the shortage of global fossil-fuel supply is critical due to the over-extensive exploitation of fossil fuels to power up various sectors such as power generation, transportation, and industrial purposes. It is reported that in the transportation sector alone, about 20% of the world's primary energy is consumed, and produces 14% of global emission of greenhouse gases and 23% of CO_2 emissions (Kalghatgi, 2018). These numbers are expected to increase at an alarming rate with the increased demand for global energy owing because of the ever-rising global population numbers. Fossil fuels are finite and they are non-renewable energy resources that give rise to harmful pollutants to cause natural disasters, global warming, and climate changes. These phenomena generally lead to food scarcity and health complications for millions of people around the world. Compared to fossil fuels, biofuels are readily available, environmentally friendly, and considered to be a renewable energy source because it is essentially made from biomass. Unlike conventional diesel, biodiesel is fairly advantageous since it is renewable and biodegradable, non-toxic, contains high cetane numbers, high flash points, and low emission of greenhouse gas (Attia et al., 2020). Bio-based fuel originated from vegetable oils, animal fats and includes waste or recycled oils (El-Zoheiry et al., 2020). Biofuels produce fewer pollutants, particulate matter, smoke, and unburnt hydrocarbon, and they are free of sulphur and aromatics, and have more oxygen molecules compared to conventional petrol diesel. Having A higher number of free oxygen ultimately leads to complete combustion and reduced emission. Biodiesel is safe to handle and has an inherent lubricity advantage over conventional diesel (Rajasekar et al., 2010)

The present energy crisis pushes the scientific community towards developing and exploring new alternative energy sources. Renewable energy sources such as solar, wind, and biomass have gained attention over the years as it provides readily available energy resources without having a negative environmental impact.

Ethanol has found its way as a prominent alternative to conventional fuel due to its environmentally friendly nature and superior physicochemical properties compared to other biofuels.

Furthermore, in a study conducted by Hill et al(2006), it is reported that energy produced by biomass sources does not contribute to the total net of CO_2 in the atmosphere as CO_2 from combustion is absorbed during biomass growth.

By blending a certain amount of alternative and conventional fuels is one method to replace conventional fuel. A good example is the biodiesel to diesel blend which becomes B20 (20% biodiesel /80 diesel) and B2(2% biodiesel/98 diesel). Also, the blends can be of two types of alternative fuels such as hydrogen and compressed natural gas (HCNG), which can be a combination of 20% hydrogen/80% CNG. Apart from attaining low levels of pollutants by utilizing biodiesel, further reduction of pollutants can be achieved with the help of lean premixed pre-vaporized combustion (LPP). Lean premixed pre-vaporized (LPP) combustion technology is a combustion technique that utilizes lean fuel mixture and good mixing of the air and fuel before the entrance to a combustion chamber. It can reduce the emission of nitrogen oxides (NOx) and carbon monoxide (CO).

NOx would influence the viral spread of infectious disease such as influenza as humans are made vulnerable in this state. The most severe effects on health occur when additional air contaminants are present. (Liaquat et al., 2010) .On contrary, environmental degradation from major NOx emissions poses a major threat to humans and the environment alike. Such environmental effects are acid rains (formation of nitric acid occurs), particulate matters 2.5 exists in tiny particles which give out ammonium nitrate. These PM2.5 not only sever the marine life ecosystems due to formation of eutrophication from excess nitrogen but also articulate hazy weather. This certainly has amounted to a devastating effect on agriculture and health. (Mauzerall et al., 2005)

Pre-vaporized is the method of converting liquid fuels into fine-sized droplets in a prechamber to produce a finer mixture of fuel and air. This, in return, provides a uniform supply of air and fuel which resulted in low levels of flame temperature and thus the reduction of thermal NOx. The lean premixed pre-vaporized flame produces a uniform spread of flames, and it forms a blue flame. However, LPP is commonly associated with combustion instabilities as it operates near the lean flammability limit.A profound parameter that is generally required for proper control and attention is the air-fuel ratio as it is the main driving force of LPP. Increasing the amount of supplied air produces lean-fuel combustion whereas decreasing the air content results in a rich fuel combustion. Because different fuels have various stoichiometric air-fuel ratios, it is conveniently expressed in terms of the equivalence ratio, Ø.

1.2. Problem Statement

Lean premixed pre-vaporized (LPP) combustion technology is one of the methods to reduce the pollutants such as nitrogen oxide (NOx) and carbon monoxide (CO). A constant supply of air and fuel facilitates the complete mixing of fuel and air prior to combustion. Hence, low flame temperature and less thermal NOx levels are achieved. However, LPP combustion suffers from several problems such as combustion instabilities and unsteadiness which is strongly influenced by the air-to-fuel ratio. Such combustion instabilities are produced by the reaction between fluctuating combustion heat release, pressure, and velocity fields. Some of which include a self-excitation oscillation that gradually becomes intense enough to break the combustor. (Dhanuka et al., 2011). Flame-flame interactions and shear layer vortex shedding in an LPP combustor are thought to be the source of combustion instabilities. By incorporating an LPP combustion system with a swirl burner, the combustion process generally attains better flame stability as it maximizes the benefits of recirculation which promotes better mixing of air and fuel. Therefore, this study will try to analyze the LPP combustion with different blends of gasoline-ethanol fuel blends. The ultra-lean premixed pre-vaporized (ULPP) with LPP will also be investigated to analyze the temperature, pressure, and pollutant emission variations of fuel blend.

1.3. Objectives

- To investigate the Lean Premixed Pre-vaporized conditions of several blends of gasoline-ethanol blends.
- To analyze the corresponding spatial and temporal temperature fluctuations for both LPP and ULPP.

1.4. Scope of work

Firstly, all the simulation and modelling performed in this study are by using ANSYS Fluent and Solidworks. This project is a simulation study which will look into solving the combustion problem using a theoretical model based on previous research and researching from other similar research papers. The fuel used is a mixture of ethanol and gasoline blends with different range of ethanol and gasoline compositions. The blends ranges from 10% to 30% of ethanol composition within gasoline-ethanol blend. Simulation is set in an enclosed cylindrical combustion chamber equipped with a swirl premixed chamber at the front exhaust outlet ending. The fuels are tested at equivalence ratio of Φ=0.9 and Φ=0.5. A conceptual prototype is not made available for this project since it does not require any fabrication or physical activities.

Chapter 2 Literature review

2.1. Alternative Fuel

Current crisis of global fossil fuel has resulted in an increase in the cost of living and unprecedented environmental disasters. Scientists all over the world have strived in search of a suitable alternative fuel. It is reported that 84% of harmful emissions such as carbon pollutant has been released into the atmosphere since the 1980s(Çelebi & Aydın, 2019).

Likewise, stricter emission regulations are now in place because of the depletion of fossil fuels and the rising expense of living(Nabi et al., 2021). In the United States, the implementation of stringent biofuel standards has resulted in the addition of 7.3 billion alternative fuel substitutes for gasoline which has significantly lessens the air pollution(Ridge National Laboratory, 2011). Based on recent studies, scientists have found several alternatives that have the potential to resolve this energy depletion problem.

One of the promising alternatives is called biofuels which are mainly oils extracted from organic matter such as biomass, vegetable oils, biodiesel, and biogas(Agarwal, 2007).

Alcohol has also been attracting wide attention as a candidate for fuel substitute. Alcohol fuels which are commonly found includes methanol, biodiesel, and ethanol, which offer an economic, easy, and safe way of production(Agarwal, 2007).

A study by (Kisenyi et al., 2018), reported that the use of oxygenates in the unleaded fuels showed a reduction in the emission and fuel consumption. A total of six European cars were studied with the addition of oxygenates such as ethanol and methyl tert-butyl ether (MTBE).

The results compared the exhaust emissions from each car with different blends of ethanol and MTBE concentrations. Based on the findings, 15% of MTBE added to the fuel showed the most significant reduction in emissions of CO (15-30%), NOx (1.3%-1.7%) and CO_2 (4%). Furthermore, the fuel consumption for each car improved by 3.5%, when one compares with the non-catalyst car.

2.2. Ethanol

A fuel substitute which suits the requirement of a sustainable fuel from renewable sources and environmentally friendly is ethanol. Due to its desirable physicochemical qualities, ethanol is one of the many options for renewable fuels that are widely utilized globally along with mixes of pure petroleum.(Iodice & Cardone, 2021a). Ethanol is currently the most popular biofuel used around the world as its usage is well accepted in the transportation sector.

Ethanol is derived from various types of plants including corn (maize), wheat, molasses, cassava root, and sugarcane which are collectively known as 'biomass'(Agarwal, 2007). Ethanol by nature is a colorless, flammable, and volatile liquid fuel. It also gives out a pungent smell. Ethanol exists via a synthetic or bio-based form, and it is understood that the chemical formula for ethanol is C_2H_5OH or C_2H_6O (Iodice & Cardone, 2021b; Mofijur et al., 2016). Ethanol also acts as a low-cost production oxygenate which has a weighted oxygen concentration which is 34% higher compared to that of water(Mofijur et al., 2016). The generation of ethanol originates from processed feedstocks such a sugar cane, maize, and sorghum(Prasad et al., 2007). It started with milling or grinding of the crops, liquefication (cook with water), fermentation (sugar breakdown), distillation, and lastly denaturation. During the winter seasons, certain countries use ethanol mixed with gasoline as an additive called oxygenates to boost combustion properties. This is supported by the Clean Air Act (CAA) 1990 which stated that it is mandatory for gasoline vehicles to add oxygenates during winter seasons(Piver, 1974). In recent years, it is common for petrol cars to be using ethanol-gasoline fuel blends, especially in the cosmopolitan parts of the country. This is because ethanol offers a reduction in harmful air emissions and is statistically proven to lower the production cost(Iodice & Cardone, 2021b).

Ethanol can be added to the gasoline mixture to increase the octane number and improve the emission qualities of gasoline(Ridge National Laboratory, 2011). Due to its high-octane value, numerous studies in the literature have evaluated the viability of using ethanol as an addition to gasoline fuel(Iodice et al., 2017).

(Kapil Karadia & Nayyar, 2017) , demonstrated the use of a spark ignition engine fueled with ethanol-gasoline blends. Using E0 (pure gasoline without ethanol) and up to E100 (100% ethanol) with intervals of 10% increasing content of ethanol added into gasoline fuel was tested and analyzed based on combustion performance and emission characteristics.

Their results reported that with the addition of ethanol to gasoline fuel, a positive impact on engine torque, power, and brake fuel consumption can be achieved. In terms of the emission, the CO, NOx, and HC emission were also reduced but limited to content of ethanol blend (E50) it produces better engine performance compared to SI engine, at high compression ratio. Oxygenates are fuel additives that contain oxygen and are typically found in the form of alcohol or ether. This fuel additive serves as an enhancement to improve the fuel combustion abilities influencing the reduction of toxic air emissions(Kumar et al., 2019).

The physicochemical properties of biofuels are almost identical to that of conventional fuels, which ensures better emission and combustion performance while fulfilling the emission standards. The combustion characteristics of ethanol are influenced by the thermophysical properties such as density, lower heating value, oxygen content, latent heat of vaporization, and oxygen content. Table 2.1 shows the physicochemical properties for ethanol, diesel, and gasoline. (Iodice & Cardone, 2021b; Masum et al., 2013)

Table 2.1 Physicochemical properties of ethanol, diesel, and gasoline

Properties	Ethanol	Diesel	Gasoline
Molecular Formula	C_2H_5OH	$C_{11}H_{23}$	C_7H_{16}
Density(kg/m^3)	0.785	0.856	0.737
Lower Heating Value (MJ/kg)	26.87	41.66	43.47
Octane Number	110	15-25	95
Oxygen Content (%)	34.7	0	0

2.2.1. Low Heating Value (LHV)

Ethanol has a LHV of approximately 27MJ/kg which is almost half the LHV of gasoline. This will generally result in an increased in the fuel consumption during combustion. However, lower LHV value does not result in reductions in engine power owing to the increasing content of ethanol fuel. The stoichiometric air/ethanol mixture holds the same amount of energy to the stoichiometric air/fuel mixture (Iodice & Cardone, 2021a)

2.2.2. Latent Heat of Vaporization:

Ethanol has a latent heat of vaporization of 910 kJ/kg which means it requires higher heat to vaporize compared to gasoline. Higher heat of vaporization will produce lower burning velocity and decreased combustion temperature paving the way for increased hydrocarbon (HC) and Carbon Monoxide (CO) emissions (Iodice & Cardone, 2021a)

2.2.3. Oxygen Content

Ethanol has a very high oxygen content which is 34.7% compared to other conventional fuels. High value of oxygen content helps to yield uniform and frequent combustion, especially in lean region of combustion. As a result, CO and HC emissions will be significantly reduced as lean combustion is associated to low-temperature combustion.

2.3. Research Paper

As we have discussed, the fundamentals of ethanol, its applications, and why it is considered the next best alternative fuel option out there, there have been several scientific studies over the last years that prove the following claims.

The use of low cetane number fuel suggests that it is better compared to current diesel fuels in CI engines as the ignition delay time could be increased. This results in low NOx emissions because longer time for air and fuel to mix prior to combustion. Greater octane fuels will have ignition issues at lower loads and higher exhaust gas recirculation levels, while lower octane fuels may start losing their advantage over diesel in terms of ignition delays.

(Mirhashemi & Sadrnia, 2020; Nabi et al., 2021; Qubeissi et al., 2021; Tibaquirá et al., 2018) have reported that adding ethanol to gasoline and diesel resulted in positive impact for the combustion performance and emission qualities. However, ethanol content added is limited to 15% only, because higher ethanol content requires significant engine modifications as ethanol exhibit corrosive behaviors which may damages the engine parts.

Combustion process from petroleum derivatives produces harmful gas emissions such as particulate matter (PM), nitrogen oxides (NOx), carbon monoxide (CO), carbon dioxide (CO_2), formaldehyde, benzene, toluene, sulfur dioxide (SO_2). These pollutants can be divided into two categories; regulated and unregulated pollutants.(Agarwal, 2007)

These pollutants lead to serious humans' health complications either in a long or short-term period. For instance, NOx causes breathing problems and irritation in respiratory tract whereas CO is very dangerous influencing the central nervous system which may lead to death at times (Agarwal, 2007).

2.3.1. Lean Premixed Prevaporized (LPP)

A breakthrough in an improved combustion technology is called Lean Premixed Pre-vaporized (LPP) combustion technique. The technique works by pre-mixing the fuel and air before the mixture enters a combustion chamber. (Dowling, 2003). The technique allows lean burning with a relatively higher air to fuel ratio. Consequently, cleaner combustion with low levels of pollutants such as NOx and CO can be achieved. Although LPP also suffers from combustion instabilities, the method is hugely beneficial. The instability issue can be solved by implementing a swirl burner in the system whereby the burner promotes a uniform supply of fuel and air prior to burning. The results from the experimental work of (Attia et al., 2020) demonstrated that burning fuels with LPP produced very low NOx emissions compared to the burning of natural gas (Attia et al., 2020).A lot of studies have showed that the LPP combustion with biodiesel could drastically reduce the levels of thermal NOx and facilitates clean combustion. The experimental work of (Attia et al., 2020), showed that the flame characteristics and emission are comparable with other studies by using blended fuels in different ratios with waste cooking methyl ester (WCOME) and Jet A-1 (B5, B10, B15 and B20). The addition of a swirl burner with the LPP combustor produces a stable flame with a Swirl Number equals to 0.55. This value denotes as High Swirl Burner (HSB).

Preheated air from the surrounding flows at a constant temperature of 250 °C and the tangentially blended fuel with Φ value of 0.75 was also trailed. The results showed that significant reduction of approximately 41% was achieved in the emitted CO and NOx of B20 fuel blend. This is significantly lower compared with pure Jet A-1 fuel. A reduction in the NOx caused by WCOME is related to biodiesel, with short hydrocarbon chains and consequently lower flame temperature. This has resulted in lower thermal NOx(Attia et al., 2020. It can thus be concluded that by introducing a partial blend of biodiesel into the fuel, the emitted pollutants such as CO and NOx can be reduced.

Another experimental investigation of LPP combustion with various blends of Jojoba biodiesel with jet A1 fuel was also carried out by (El-Zoheiry et al., 2020), with the aim of reducing the emission pollutants. The study was conducted to analyze the combustion and emission characteristics. Two mixture fuel ratios were used; 10% of Jojoba Methyl Ester (JME) with 90% pure jet fuel and 20% of JME with 80% pure jet fuel. Using a careful selection method of the design and parameters of the burner, the blend was effectively combusted. The level of thermal NOx decreased when the amount of JME was added. However, the CO and UHC formation was found to increase. Furthermore, JME can also be blended with pure jet fuel with the JME contents of up to 20% without modifications of current LPP combustor, particularly at lower equivalence ratio.

The main concept of LPP hinges on the combustor which can operate at low equivalence ratio. This results in low combustion temperature which avoids droplets combustion and produces less thermal NOx. The design of the LPP combustor is unique because it is different compared to other conventional combustors. In other words, LPP combustor can be designed with three distinct zones; the first zone is for fuel injection, the second zone is for fuel vaporization purpose, and third zone is for fuel-air mixing purpose. In principle, the aim of these zones is to facilitate complete fuel vaporization and complete fuel-air mixing prior to combustion.

There are also LPP combustors which are equipped with a swirl burner to aid the mixing of the air-fuel mixture. The swirl burner is equipped with vanes and injectors which spinning motion to draw the surrounding air and fuel mixture. This swirling flow creates a uniform tangential distribution of fuel and flame temperature which is important for low NOx emission(Imamura et al., n.d.). In a swirl-stabilized LPP combustion, many parameters such as flame temperature, fuel type, air-to-fuel ratio, fuel spray characteristics and combustion ratio have a strong influence on the level of CO, NOx, and UHC.

(El-Zoheiry et al., 2020; Yan et al., 2015a) , investigated the flow dynamics and fuel spray characteristics in LPP combustor using Particle Image Velocimetry. Low levels of air pollutants were achieved by manipulating the combustion characteristics. In addition, the research work of(Yan et al., 2015b) reported that there are other salient parameters which are important to determine the performance of the LPP combustor. In their experiment, the fuel allocation quantity and pilot atomizer position were continuously changed to study the fuel spray characteristics and flow fields using a staged LPP combustor.

By positioning the pilot atomizer toward the throat, superior spray characteristics were generated. In addition, the gap of the primary recirculation zone increased in the axial direction from the combustor inlet and decreased at a certain distance. The results conclude that the position of the pilot atomizer and fuel allocation play a major role toward increasing fuel flow rate and increasing the performance of the LPP combustor. The results also showed that the number and Sauter Mean Diameter of the fuels increased as fuel flow rate was increased.

In another study by (Sun et al., 2017), the combustion oscillation characteristics in the LPP combustor at different equivalence ratios and inlet velocities were experimentally investigated. The acoustic modal analysis was carried out to identify the acoustic eigenmodes in the LPP combustor. The results showed that there was a periodical process of a flame roll-up for the flame near the LPP combustor axis and separation with flame consolidation away from the LPP combustor axis. Spatial distribution of the normalized Rayleigh index in the LPP combustor was also calculated to determine the driving zones of the combustion oscillation.

Although LPP combustion promises low levels of NOx and soot, this combustion technique is also exposed to a huge problem related to the combustion instabilities, flashback, auto-ignition, and flame stability (Yan et al., 2015a). The combustion instabilities, for instance, should be suppressed because it is generally associated with extensive vibration, loud noise, and flame blowout which may cause structural damage and loss in power efficiency through combustor. Commonly, combustion instabilities in a combustor are highly sensitive towards various operating parameters, such as stratification ratio, equivalence ratio, inlet mass flow rate and temperature (Han et al., 2019). In fact, one study showed that the combustion instabilities triggered by air inlet temperature in terms of supercritical bifurcation (Han et al., 2021). Bifurcation is defined as sudden changes in the oscillation of amplitudes as the combustor operation exceeds some critical values. Tests results showed that heat release is severely fluctuated because of the oscillations of the equivalence ratio at the fuel injectors.

The main source of the combustion instabilities in an LPP combustor originates from the effects of flame-flame interactions and flame-shear layer interaction (Temme et al., 2014). In addition, there are other reasons which contribute to the combustion instabilities. These are the interaction between unstable combustion heat release and acoustic fields as acoustic pressure waves fluctuated in phase with the heat release disturbances. The pressure waves grow with the addition of energy and the amplitude of oscillation will increase drastically. In a study conducted by Han et al. (2017; 2019)

In a RP-3 fuelled LPP combustor, a thermoacoustic model and simulation method were categorized according to a staging ratio. Based on the results, an exceedingly sceptical intrinsic mode was identified as the main reason for low frequency oscillation at 50Hz-120HZ (Qin & Wang, 2021). An injection of a small amount of fuel prior to the mixing process between the air and fuel led to the creation of piloting region that promotes stable flame.

However, none of the reported works mentioned above looked into the LPP combustion technology with the use of several blends of gasoline-ethanol fuel where a swirler is also implemented together with the LPP combustor. Moreover, it is found that from the various sources only a limited number of studies has been made regarding ULPP combustion. Thus, an option of exploring ULPP combustion should be implemented for comparison purposes. This would result in a steady supply of fuel and air mixture which facilitates complete combustion in low flame temperature.

2.3.2. Ultra-Lean Premixed Pre-vaporized

In contrast to Lean Premixed Pre-vaporized technology (LPP), Ultra Lean Premixed Pre-vaporized (ULPP) combustion operates with a very high composition of air to fuel within the chamber. At ultra-lean operating conditions, promotes stabilization in flame due to a very uniform temperature distribution at exhaust regions. (Raghu Jarpala). With addition of swirler in the combustion chamber, a more intense mixing of fuel and air is developed giving rise to lower NOx emissions.

One of the benefits of running in a lean regime is the reduction in the pumping losses due to a wider opening of throttle control. (Raju Jarpala) investigated the effects of swirl intensity for ULPP configuration in gas turbine settings towards flame characteristics and pollutant emission. The study tested methane at two different swirl numbers S=1.59 and S=2.91 with varying equivalence ratio Φ (up to Φ=0.4). Results shows, intense swirling strengths aids in lesser NOx emission when compared to low swirling rate. This is such that higher swirling rates showcase increased mixing of fuel and air suggesting flame stabilization occurs at very low Φ.

However, ultra-lean regimes are generally associated with an excess of HC, NOx, and CO_2 emissions. An example of the application is a BMW company which has successfully run an efficiently gasoline engine in lean regimes. Similarly , in gas turbine (GT) machineries, it is found that lean-premixed technology (LP) is widely implemented as part of their combustion technology (Raju Jarpala).

Chapter 3 Methodology

In this chapter, the simulation process is thoroughly explained. Computational Fluid Dynamics (CFD) simulation was selected because the method is practically viable to analyze the LPP and ULPP combustion.

The CFD software depends on the type of models selected for the specific applications. To achieve the objectives for this project, ANSYS Fluent software was chosen due to its popularity and versatility in solving various engineering problems.

Prior to the simulation process, several parameters were determined to obtain the chemical equilibrium equation and the fuel-air equivalence ratio Φ.

3.1. Geometry Design

The combustor design is referred to a study conducted by (Stefanizzi et al., 2021). A 3D model geometry of the combustor was created using Solidwork. The model is referenced after having simple geometries and dimensions which ease the process of designing the combustion chamber. The referenced model shares similar features as to the desired model such as having a swirler and a premixed chamber at front. The model was then imported to ANSYS Fluent for mesh and combustion analysis. The details of the design and its dimensions are shown in Figure 3.1 and Figure 3.2.

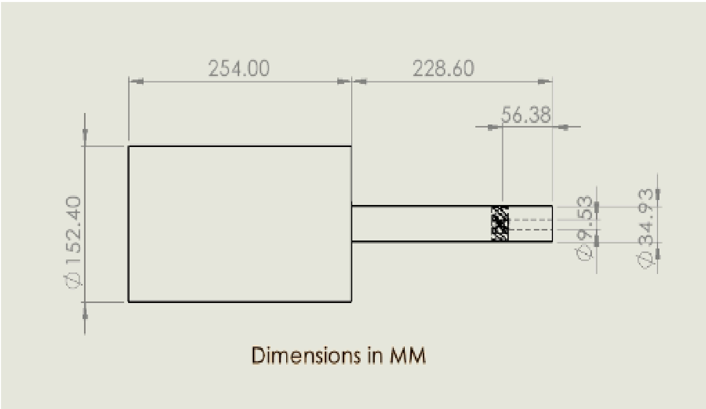

Figure 3.1 Dimension of combustion chamber

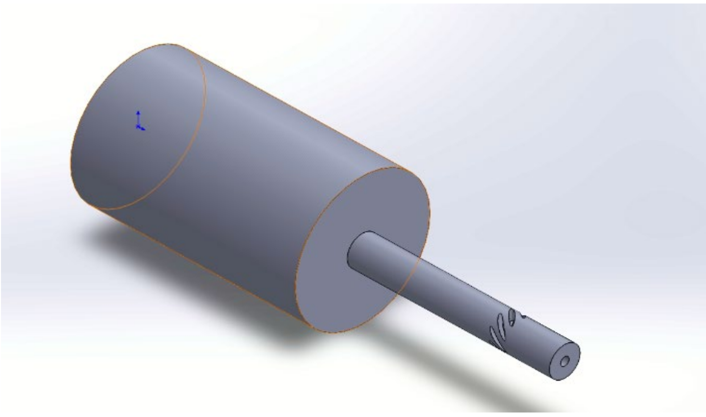

Figure 3.2 3-Dimensional model of combustion chamber

3.2. Mesh Generation

Mesh size is a very important parameter to achieve higher degree of accuracy during CFD simulation. In addition, a suitable mesh size will produce a solution with minimum error that could have affected the accuracy of the computation.

The cylindrical combustion chamber has one inlet port. The port contains both the air and fuel mixture. It has one outlet which is the exhaust region for the combustion. As shown in Figure 3.3, a swirler is located and positioned at a distance of 56.8 mm from the inlet. The swirler is location is referenced from a study(Stefanizzi et al., 2021)

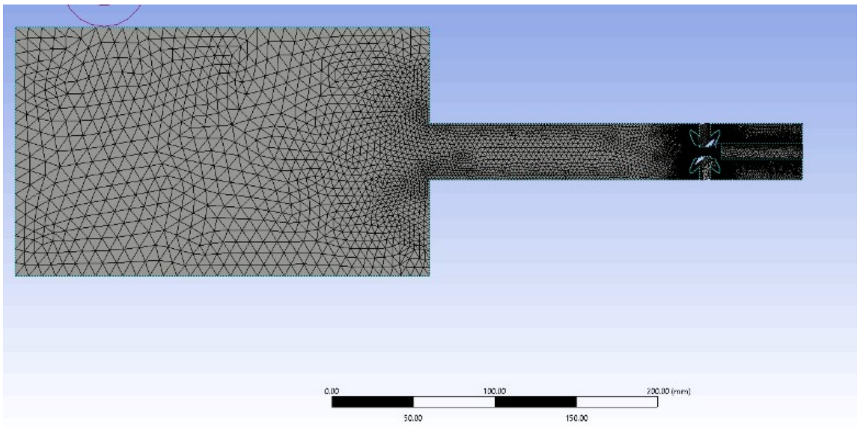

Figure 3.3 Side profile of mesh of combustion chamber

With a smaller mesh size would have resulted in greater computational power but with a longer computing time. In other words, opting for a fine mesh should not always be the case because only certain regions are focused. Therefore, complex geometrics regions such as the swirler and inlet have smaller refined mesh compared to the main chamber. Furthermore, tetrahedral elements are used in the formation of mesh since it is suitable for complex geometry especially within swirler regions.

3.2.1. Grid Independence Test

Grid independence test was performed to identify the most suitable and optimum mesh size based on the geometry, by considering the accuracy of the results and the computing time. Give that the scope of this study is to minimize the computing time without sacrificing too much computing accuracy, the element size for each mesh analysis was kept constant at 25mm. Each mesh was generated with increased levels of refinement to obtain an acceptable level of accuracy. Comparatively, Mesh 1 has a total of 0.68 million of elements, mesh 2 has a total of 1.6 million of elements and mesh 3 contains 2.3 million of elements. As a result, mesh 3 has the longest period of computing followed by mesh 2(1.5 hours) and mesh 1(0.75 hours)

Table 3.1 Mesh Parameter

Mesh	**Element Size**	**Refinement**	**Average Temperature(K)**	**Maximum Temperature (K)**	**Computing Time (Hour)**	**Number of Elements (M)**
1	25	1	309.44	625.66	0.75	0.68
2	25	2	308.22	737.9	1.5	1.6
3	25	3	306.86	595.68	4.5	2.3

From Figure 3.4, we can also observe that mesh 3 is more accurate compared to mesh 1 mesh 2. However, by giving considerable attention to the computational time, mesh 2 was selected as the most appropriate mesh for the combustion analysis in this project.

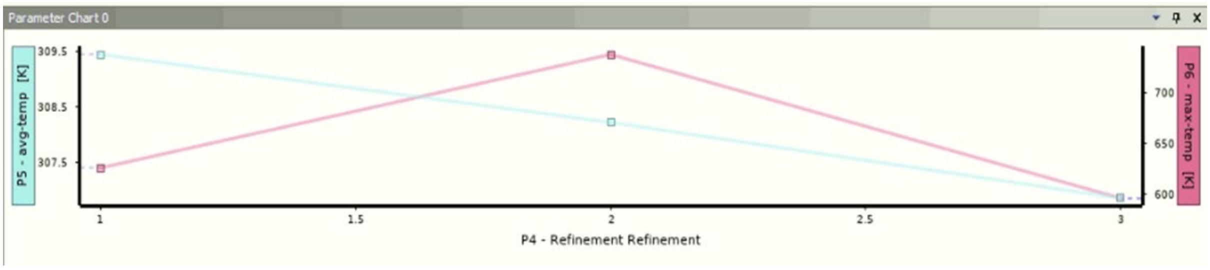

Figure 3.4 Parameter comparison of mesh 1, mesh 2, and mesh 3

3.3. Mathematical Model

3.3.1. Governing Equations

ANSYS Fluent uses the fundamental Navier-Stokes equation which consists of the continuity equation, momentum equation, and energy equation involving fluid flow problem (Mina, 2014). Species and energy transport equations were also computed specifically for combustion problems. The balances equations are listed here:

Continuation Equation

$$\left[\frac{\partial(\rho u_x)}{dx}+\frac{\partial(\rho u_y)}{dy}+\frac{\partial(\rho u_z)}{dz}\right]=0 \tag{1}$$

Momentum Equation

$$\frac{\partial}{\partial t}(pu_i)+\frac{\partial}{\partial x_i}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_i}+F_i \tag{2}$$

Energy equation

$$\frac{\partial}{\partial t}(\rho h)+\frac{\partial}{\partial x}(\rho u_i h)=\frac{\partial}{\partial x_i}\left[\frac{u}{\sigma_h}\frac{\partial h}{\partial x_i}+\left(\frac{1}{Sc_k}-\frac{1}{\sigma_h}\right)\sum_{k=1}^{N}h_k\frac{\partial Y_k}{\partial x_i}\right]+\frac{\partial p}{\partial t}S_{rad} \tag{3}$$

3.3.2. Viscous Model

The viscous k-epsilon model was used for the simulation because it can provide a good balance of computational effort and computational accuracy. This two-equation model was introduced by Jones and Launder (Zimmermann, 2009)

$$\mu_t = \frac{C_\mu \bar{\rho}\, k^2}{\varepsilon} \tag{4}$$

k is the turbulence kinetic energy and ε is defined as the variance of the fluctuations in velocity. k - ε model is suitable in a wide range of application (wall-bounded and free shear flows) and it is very cost efficient. Despite that, it is reported that this model is taught to excessively predict spreading rate of jet flows.

3.3.3. Species Transport Model (Partially Premixed Mode)

Basically, Partially Premixed Combustion (PPC) system combines both the concept of non-premixed model and premixed model in ANSYS Fluent. Combining these two models was straightforward. Hence, by utilizing both of their benefits while s would lead to partially premixed combustion (Zimmermann, 2009). The reaction progress variable c is used to track the location of the flame, called the flame front. To the left of the flame front at c = 0, the mixture is unburnt, and the mass fractions and other variables are computed using mixture from the precomputed mixture fraction of Probability Density Function (PDF). For your information, PDF is a mathematical formula used for discrete random variable's probability distribution (the likelihood of an outcome). Inside the flame, a combination of the two models was used. In the burnt area (to the right of the flame at c = 1), the equilibrium mixture fraction was computed, and it is the premixed reaction-progress variable functions. The position of the flame front during combustion was then determined. The parameter condition is summarized below:

$c = 1$ (Mixture is combusted using equilibrium or flamelet mixture fraction solution)

$c = 0$ (Parameters is calculated from mixed but unburnt mixture fraction)

$0 < c < 1$ (Combination of unburnt and burnt mixture is used)

3.3.4. Chemical Equilibrium Model

Mean scalars (Species fractions and temperature) were calculated from the probability density function (PDF) of f and c as:

$$\overline{\emptyset} = \int_{0}^{1}\int_{0}^{0} \emptyset(f,c)p(f,c)dfdc \tag{5}$$

The condition assumed thin flames, which means that unburnt reactants and burnt products exist. Calculation of the mean scalars were carried out using Eq. (6) :

$$\overline{\emptyset} = \int_{0}^{1} \emptyset_b\,(f)p(f)df + (1-\bar{c})\int_{0}^{1} \theta_u\,(f)p(f)df \tag{6}$$

Note: Subscripts of b and u is denoted as burnt and unburnt

Where:

$\emptyset_{\mathbf{b}}$ – burnt scalars

f – fuel

$(1-f)$ - oxidizer

To achieve equilibrium in mixture, burn scalars are used as a function of mixture fraction which are calculated by mixing mass. A mass of fuel, f with mass $(1-f)$ of oxides is determined for mixture to equilibrium.

3.3.5. Computational Process

The simulation begins by selecting double precision option and 2 for solver processes on the fluent launcher. The viscous model selected is k - ε model as discussed in sub-chapter 3.3.2. Side note, all the details on the computational process are provided in Appendix E

In this study, Partially Premixed Combustion (PPC) mode was selected as the species model. For fuel rich flammability limit, the PPC was set to be 1 because the stoichiometry fuel rich flammability is approximately 1. An ambient pressure of 101325 Pa (1 atm) and an ambient temperature of 300K were chosen for both the air and fuel.

Adiabatic flame and chemical equilibrium were selected because of the constant pressure condition. Furthermore, the fuel chosen was ethanol-gasoline blend and it can be altered in terms of the molar mass or mass fraction in the boundary tab. Here, the composition of the species can be added or reduced, depending on the user. An equivalence ratio and air-fuel stoichiometric ratio of the fuel must be calculated based on the composition blends of ethanol-gasoline fuel to obtain the right amount of air and fuel required for complete combustion. To get a clearer picture, the details of the species are provided in Appendix E. The boundary was set as mass flow inlet boundary and mass flow rate of 0.08kg/s was given.

Because there was no external or specified direction for the model, the direction specification method was set to be normal to boundary. The air inlet mean mixture variance was set to be 0 whereas for the fuel inlet mean mixture fraction was set to be 1. In this context, 0 indicates fully air content and 1 indicates fully fuel composition. The chosen value was 1 because there is presence fuel completely in the inlet with the addition air by which we confirmed during species modeling. The inlet temperature was set to be 300K and the turbulent intensity was 10%. The exhaust pressure outlet and the backflow progress variables were set to be 1.

NO_x formation option was turned on to determine the NO_x emission formed. The tab for prompt NO_x and fuel NO_x was selected since in this problem NO_x formation comes from fuel and surrounding atmosphere. Other parameters were set as default values in the ANSYS Fluent control menu.

SIMPLE solution was used as the solution method because it has the best convergence of up to 1e-6 whilst running the initialization step. This means value of calculated variable from one iteration to the next is around 0.000001. Once, the value calculated prompts into a unified value the solution is considered convergence. The solution was monitored by residual plot with convergence of 1E-3 because the problem involved transport and energy equations. Prior to the simulation, a hybrid initialization step was performed to ensure the solution could be achieved with the 1E-6 convergence. After several simulation tests, it was found that the solution converged after 2000 iterations. The iteration was set to be 2000 with an interval reporting profile of 1.

Chapter 4 Results and Discussion

4.1. Overall Result

Several blends of ethanol-diesel mixture were analyzed at two different equivalence ratios, Φ using the same operating parameters. An equivalence ratio, Φ of 0.9 was considered to be a lean combustion mode and at Φ = 0.5 was defined as an ultra-lean combustion mode. From table 4.1, the overall results are tabulated for various combustion parameters such as temperature, pressure, mole fraction of CO_2, CO and NOx at various blend compositions and equivalence ratios.

Table 4.1 Overall Result

`	**Equivalence Ratio, Φ=0.9**			**Equivalence Ratio, Φ=0.5**		
Blend	E10	E20	E30	E10	E20	E30
Max Temperature(K)	2270	2282	2271	1725	1676	1624
Average Pressure(kPa)	37.24	36.663	35.987	10.955	10.927	10.854
Mole fraction CO2	0.104	0.107	0.11	0.12	0.075	0.072
Mole fraction CO	0.032	0.021	0.013	2.44E-05	1.33E-05	6.49E-06
Mole fraction NOx	3.06E-06	9.04E-06	6.81E-06	1.22E-07	4.19E-08	1.31E-08