EVALUATION OF COMBUSTION CHARACTERISTIC ON 2D CYLINDRICAL COMBUSTION CHAMBER FOR DIFFERENT OPERATING CONDITIONS AND USING ALTERNATIVE FUELS

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by

SIM SING MEI

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ENDORSEMENT

I, Sim Sing Mei hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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Date :

(Signature of Supervisor)

Name :

Date :

(Signature of Examiner)

Name :

Date :

EVALUATION OF COMBUSTION CHARACTERISTIC ON 2D CYLINDRICAL COMBUSTION CHAMBER FOR DIFFERENT OPERATING CONDITIONS AND USING ALTERNATIVE FUELS

ABSTRACT

The study conducted is on simulation of a two-dimensional (2D) case of a cylindrical combustion chamber. The objective of the study is to evaluate the effects of different operating conditions on the combustion characteristics of 2D cylindrical combustion chamber. The software used to perform this study is ANSYS Fluent. Research was done by using different operating conditions including fuel temperature, droplet sizes, fuel injectors and type of fuel. The fuels used were Jet-A which is the conventional fuel for aircrafts, and alternative fuels including Jatropha Bio-synthetic Paraffinic Kerosene (JSPK), Camelina Bio-synthetic Paraffinic Kerosene (CSPK), mixture of 50% JSPK with 50% Jet-A (50JSPK/50Jet-A) and mixture of 50% CSPK with Jet-A (50CSPK/50Jet-A). Droplets size were varied to study the effect of droplet-size distribution (DSD) on spray combustion processes. Results had proven that smaller droplet size will lead to high combustion rate and thus better efficiency. Effects of fuel temperature at 300 K, 400 K and 500 K were analysed. Higher fuel temperature produced better evaporation in the chamber. Besides, every fuel listed were simulated at different spray half cone angles, which are 30°, 40° and 50°. From the simulation, it is shown that higher spray half cone angle produced shortest penetration length and took shortest time for droplets to reduce in its diameter. 50JSPK/50Jet-A and 50CSPK/50Jet-A had the shortest time to evaporate where it indicated that both fuel mixtures have higher evaporation rate due to lower boiling point and density.

PENILAIAN TENTANG CIRI-CIRI PEMBAKARAN KEBUK PEMBAKARAN SILINDER 2D UNTUK KEADAAN BEROPERASI DAN BAHAN BAKAR ALTERNATIF BERLAINAN

ABSTRAK

Kajian ini adalah tentang simulasi kebuk pembakaran silinder 2D. Tujuan kajian ini adalah untuk menilai kesan-kesan penggunaaan keadaan pengoperasian yang berlainan terhadap kebuk pembakaran. Perisian yang digunakan untuk menjalani simulasi ialah ANSYS Fluent. Kajian ini dijalankan dengan menggunakan keadaan beroperasi yang berlainan termasuk suhu bahan bakar, saiz titisan bahan bakar, jenis percikan dan jenis bahan bakar. Bahan bakar yang digunakan adalah Jet-A iaitu bahan api konvensional untuk pesawat udara, dan bahan api alternatif termasuk Jatropha Bio-synthetic Paraffinic Kerosene (JSPK), Camelina Bio-synthetic Paraffinic Kerosene (CSPK), campuran 50% JSPK dengan 50% Jet-A (50JSPK/50Jet-A) dan campuran 50% CSPK dengan 50% Jet-A (50CSPK/50Jet-A). Saiz titisan bahan bakar divariasikan untuk mengetahui kesan saiz titisan tersebut ke atas proses pembakaran percikan. Simulasi telah membuktikan bahawa saiz titisan bahan bakar yang kecil memberikan kadar pembakaran yang tinggi dan cekap. Kesan suhu bahan bakar pada 300 K, 400 K dan 500 K telah dikaji. Suhu bahan bakar yang tinggi akan menghasilkan proses penyejatan yang cekap. Selain itu, setiap bahan bakar yang disenaraikan telah dimasukkan dalam simulasi dengan sudut percikan separuh kon yang berbeza iaitu 30°, 40° dan 50°. Simulasi ini membuktikan bahawa sudut percikan separuh kon yang paling tinggi menghasilkan penembusan yang pendek dan memerlukan masa yang singkat untuk mengurangkan saiz titisan bahan bakar. 50JSPK/50Jet-A dan 50CSPK/50Jet-A menggunakan masa yang paling singkat untuk proses penyejatan disebabkan kedua-dua campuran bahan bakar ini

mempunyai kadar penyejatan yang tinggi disebabkan takat didih dan ketumpatan yang rendah.

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Other than that, my sincere thanks also go to all my lecturers that had taught me for the last four years. They had providing guidance and knowledge which are very helpful throughout my degree life. Without them, this thesis would not have been possible.

Last but not the least, my final year project would have been impossible without the support from my family. I would like to thank my family, my parents and to my sister for supporting me spiritually throughout the project and my life in general.

DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

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(Signature of Student)

Date :

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LIST OF ABBREVIATIONS

CFD : Computational Fluid Dynamics

NOx : Nitrogen Oxide

DPM : DPM

JSPK : Jatropha Bio-synthetic Paraffinic Kerosene

CSPK : Camelina Bio-synthetic Paraffinic Kerosene

50JSPK/50Jet-A : Mixture of 50% JSPK with 50% Jet-A

50CSPK/50Jet-A : Mixture of 50% CSPK with 50% Jet-A

PDF : Probability Density Function

LIST OF SYMBOLS

c_p : Specific heat [J/kgK]

ρ : Density [kg/m^3]

θ : Spray half cone angle [°]

CHAPTER 1

INTRODUCTION

This chapter provides general introduction on research background, problem statement, research objectives and the thesis outline.

1.1 Research Background and Problem Statement

The International Civil Aviation Organization (ICAO) estimated that there will be an increment of air passengers from 3.0 billion in 2012 to 6.4 billion in 2030 (Yim et al., 2015). The increasing number of air passengers will lead to a situation where more airplanes are needed for transportation purpose. This situation will cause increases in gas emissions including pollutants that will be harmful for human health and lives (Yim et al., 2015). It is important to evaluate the effects caused by air transport due to the growing of the industry related. Emissions from aircrafts are one of the sources that lead to air pollution, which is similar with traffic emissions. Emissions from higher altitude in stratosphere will bring more impacts on climate change compare to ground emissions (Zhang et al., 2016). Air pollution becomes a serious issue all around the world. Failure in achieving high combustion efficiency represents a waste of fuel since it will transform into a form of pollutant emissions such as unburned hydrocarbons and carbon monoxide (Lefebvre, 1998).

Research shows that greenhouse gas emitted from air travel has an increment of 3.3% per year since the year of 1990, and the main cause of this increasing percentage of gases is the growing of traffic volumes (Elofsson et al., 2018). After the gases are emitted into the atmosphere, the gases will react with other chemicals to produce other pollutants.

To reduce the emission of the engines, scientists have been working on different strategies in solving this problem. There are few possible ways in reducing gas emissions, including the usage of alternatives fuels instead of the petroleum-based fuel, and to improve the efficiency by changing the operating conditions. Research related to engine combustion and alternative fuels are continuously conducted to provide new solutions in increasing efficiency of aircraft engine. The main requirement of the solution is to improve engine efficiency which is associated to the fuel properties and the combustion characteristics of the combustion chamber.

Biofuels become a good solution in providing more sustainable flight, since it is produced by renewable material. Biofuels can be divided into four generations, and each generation has its own characteristics and sources. First generation biofuels, it is normally produced from edible biomass, such as glucose and starches that went through fermentation using yeast (Lee and Lavoie, 2013). However, edible biomass will cause a competition between food crops and also high production cost (Alalwan et al., 2019). The other disadvantages of it are usage of more energy to cultivate crops, require big amount of fertiliser, water and also cropland (Alalwan et al., 2019). The examples of first generation biofuels are ethanol and biodiesel. Ethanol burns more effectively without producing huge amount of greenhouse gases. However, ethanol is not suitable in aviation as it tends to deteriorate aircraft engine components if those are made from rubber and aluminium. When contacting with rubber fuel storage, ethanol as an alcohol will dry out the rubber component and causes cracking of the rubber (Russell, 2018). Thus, it may cause the whole fuel storage system to fail. In older engines, it acts as a solvent where it dissolves the varnish and other deposits in tanks and being carried to injection system and clogs the orifices involved (Russell, 2018). Hence, ethanol is not the best choice since it can be a risk for the aircraft while flying.

Lee and Lavoie stated that second generation biofuels are those fuels which are produced from non-food biomass (Lee and Lavoie, 2013). Second generation of biofuels are from more efficient renewable sources compared to first generation of biofuels (Alalwan et al., 2019). Instead of foods, second generation of biofuels uses inedible biomass such as sawdust, low-priced woods, crop wastes and others. Unlike first generation biofuels, second generation biofuels are produced by more complicated process where it is more complex to be converted from solid waste. The complex process to produce second generation biofuels leads to the development of the next biofuel generation.

The source to produce third generation biofuels is algal biomass. For third generation biofuels, photosynthetic plant such as seaweed is used and being processed. Third generation of biofuels has few disadvantages such as low stability and higher cost. Low stability of the biofuel is caused by its highly unsaturated properties where it is volatile at higher temperature and tends to degrade. The latest generation, which is fourth generation of biofuels, is currently developing. This generation of biofuels use bioengineered algae which is altered to increase its carbon dioxide consumption from the environment while being consume or burned (Alalwan et al., 2019)

Aviation sector is consuming about 6% of the second generation biofuels (Yilmaz and Atmanli, 2017). In addition, the production of aviation biofuel is showing progress in which 30% of biofuel will be used in jet fuel by 2030, as predicted by International Air Transport Association (IATA). United States (USA) is targeting to substitute 20% of the transportation fossil fuel with biofuel (Alalwan et al., 2019). The Federal Aviation Administration (FAA) is now working on a way to enable the usage of one billion gallons alternative fuels per year in U.S, by the year of 2018 (Zhang et al., 2016). However, even though the usage of biofuels will be beneficial, there are still some improvements needed so that it can be widely used in every aircraft. According to Zhang, biofuels have lower energy density, poor high-temperature thermal stability, storage instability etc (Zhang et al., 2016). Therefore, many researches have been conducted to evaluate the performance of biofuels mixture in engine combustion. Turbine engines that operates with biofuels emits less carbon emissions without affecting other exhaust gases (Rochelle and Najafi, 2019) which leads to more sustainable flight.

Other than fuel properties, emission and combustion are also affected by operating conditions such as spray half cone angle, droplet size, droplet temperature, operation pressure and temperature. Different fuel injection pressures, injection timings, size number distribution and other spray characteristics are used to study on its effect on combustion (Agarwal et al., 2014). Simulation of spray vaporisation and penetration was done to investigate the vaporisation of alternatives fuel under different operating conditions (Azami and Savill, 2016). Vaporisation of alternative fuels is affected by its fuel properties and the operating conditions. Good vaporisation of fuels indicate that combustion occurs perfectly in engine and it achieves high combustion efficiency. Complete combustion does not produce pollutants such as hydrocarbons and carbon monoxide.

In previous study of Roslan, it mainly focuses on the study of combustion characteristics using alternative fuels and different spray cone angle (Roslan, 2018). Simulations were made by 5 types of fuels and 3 types of spray half cone angle. For her work, she did not include other operating conditions such as fuel temperature and droplet size. Basically, this work is the continuous work from the similar study by Roslan but with more operating conditions. To simulate the combustion process in an engine, modelling of fuel injection will be done by using different fuels and operating conditions including droplet temperature, droplet sizes and fuel injectors (spray half cone angle). The fuels involved in this study are Jet-A, JSPK, CSPK, 50JSPK/50Jet-A and 50CSPK/50Jet-A. In this work, combustion characteristics of a 2D combustion chamber will be evaluated through Computational Fluid Dynamics (CFD) simulation. The penetration length and the flame temperature will be observed and analysed respectively to the operating conditions.

1.2 Objectives

The objectives of this study are:

1. To simulate the combustion inside a 2D chamber under different operating conditions using alternative fuels.
2. To analyse the effects of fuel properties towards its penetration length and flame temperature under different operating conditions.
3. To discuss how the different combustion characteristic affects the engine efficiency.

1.3 Thesis Outline

This thesis contains of 5 chapters:

- First chapter includes the research background and problem statement of the study. The objectives of the study and the thesis outline are explained and presented in the chapter.
- Second chapter is the literature review of the study. Researches, simulation and experiments done by previous researchers on this topic are discussed.
- Chapter three will be focusing on the methodology which is basically on the setup of the simulation. Description and explanation about combustion chamber CFD modelling, set up of boundary conditions, solution and validation will be further discussed in this chapter.
- In chapter 4, results will be analysed and discussed according to the data obtained from ANSYS Fluent simulation. Simulation results will be shown and graph related will be plotted. Discussion will be done on the results and compared to others' work or researches.

- Finally, in chapter 5, it will be discussing on the conclusion of the findings. Recommendations will be stated and proposed so that others that do similar research can improve the simulation. Last but not least, future work will be discussed based on the understanding of the whole project.

CHAPTER 2

LITERATURE REVIEW

This chapter provides state-of-art on previous researches conducted on combustion characteristics. This chapter will be explaining on each of the operating condition and its roles in affecting combustion characteristics. There will be three subtopics on fuel spray design parameters, fuel properties and droplet size. For fuel spray design parameters, it will be touching on spray half cone angle and how it affects atomisation and evaporation of the fuel. Besides spray half cone angle, there are also other factors that affect combustion characteristics such as injection pressure and injector's location. On the other hand, rate of evaporation also depends on both physical and chemical properties of the fuels. Physical properties such as density, viscosity and chemical properties such as boiling point, volatility will be further discussed in the second subtopic. Third subtopic which is droplet size will be discussed and its effect on evaporation will be explained. All the operating conditions will be further explained according to the works and research by other scientists.

2.1 Fuel Spray Design Parameters

Spray half cone angle is the crucial part on an engine because it must be at a perfect angle so that the injection and the vaporisation of fuel will not be affected. Researchers have been doing different experiments to determine the most suitable spray half cone angle.

Kim et.al did an experiment on impact of fuel spray angles and injection timing on combustion and emission characteristics. Two spray half cone angles were used, which including 156° and 60°. The injection and the combustion were observed and analysed. Development of spray from injector with the narrow spray angle was longer than that from the injector with a conventional spray angle which is 156°. For conventional spray angle, the spray moves in radial direction and will strike on the cylinder wall. Injection that used 60° produced longer penetration length and it takes longer time to strike on the wall because the air-fuel mixing occurs along the penetration (Kim et al., 2016). Narrow entrance from injector which is lower spray half cone angle will increase the air-fuel mixing within the chamber and thus increase the combustion efficiency (Dimitriou et al., 2015). Anyway, research shows that NO_x emissions were larger at spray angle of 60° due to the fuel rich region. For narrow spray angle injector, it was suggested that the early injection strategy should be used so that the emission is reduced (Kim et al., 2016).

Besides spray half cone angle, investigation on various fuel spray design parameters such as injection location and direction was done by using a Eulerian-Lagrangian model. The location and direction of the injection should be chosen properly so that the fuel droplets are not trapped (Asgari and Amani, 2017). When the fuel droplets are trapped, the breakup process will be hard to occur and thus reducing the vaporisation and combustion efficiency. Slow progress of vaporisation and combustion process will leads the combustion to be drawn more toward low temperature at expansion stroke of and engine where it will cause incomplete combustion (Mousavi et al., 2016). The location should be optimised to ensure an effective droplets breakup process before it hits the walls.

On the other hand, injection pressure will also affect the combustion characteristics. A numerical study on the effect of cavitation phenomena on spray penetration length and Sauter main diameter (SMD) was done by using different injection pressures. Cavitation phenomena is when bubbles exist at the tip of the injector. Cavitation occurs in liquid fuel when the saturated vapor pressure of the fuel is higher than the statics pressure (Shervani-Tabar et al., 2013). SMD is defined as the volume of droplet fraction to total surface of the droplet (Shervani-Tabar et al., 2013). When cavitation occurs and there are bubbles produced, the bubbles tend to burst at the injector hole and cause turbulence flow. This leads to a situation where primary breakup occurred and the SMD decreases. Lower SMD indicates a better spray quality where the atomisation process occurs perfectly. Results show that the increases of injection pressure will increase the spray penetration length and reduce the SMD. It is stated that spray penetration is directly influenced by fuel injection pressures and spray chamber pressures (Agarwal et al., 2014). Vapor is distributed well when the drops are sprayed from high pressure because it can be divided into small droplets at each timestep and the small drops vaporize rapidly (Mousavi et al., 2016). When the fuel injection pressure increased, the spray tip penetration increased (Agarwal et al., 2014). Increasing the injection pressure enlarges the spray penetration length and to accelerate n-heptane fuel vaporisation process (Fajri et al., 2017). All these researches are focusing on the effect of fuel injection pressures on spray penetration length.

2.2 Fuel Properties

Fuel properties play an important role in combustion characteristics. Fuel injection can be affected by both the physical properties and chemical properties of the fuel used. For the physical properties, viscosity, surface tension and density will affect the injection in the penetration length. During the primary atomisation, the breakup of droplets is due to the unstable growth of surface wave which differs according to the fuel's surface tension (Jääskeläinen and Khair, 2017). Fuel with lower viscosity will have longer penetration length since the friction between fuel and injector nozzle hole surface is reduced. When the viscosity of a fuel is higher, the velocity of the injection will be reduced which it leads to larger droplet size (Chen et al., 2013). The higher the viscosity of a fuel, the harder the fuel to atomise (Lefebvre and R.Ballal, 2010). Fuel with lower surface tension will lead to better spray properties because the atomisation process occurs easily (Chen et al., 2013). When the surface tension is high, the atoms stick together and it will cause difficulties in breaking up into smaller droplets. This situation will reduce the combustion efficiency because it cannot evaporate perfectly.

In liquid fuel combustion, liquid droplets will be evaporated and the mixture will burn with the droplet evaporation rate (Wang et al., 2017). Chemical properties such as latent heat, specific heat, vapor pressure, volatility and boiling point will be affecting the atomisation of the fuel. Volatility is the opposite of the boiling temperature. High boiling point indicates less volatility and vice versa (Mazlan, 2012). It is stated that increased volatility affects combustion performance by improving stability and the efficiency of the combustion (Lefebvre and R.Ballal, 2010). Fuel with lower boiling point or higher volatility should have shorter droplet lifetime compare to those with higher boiling point (Mazlan, 2012). But, instead of only focusing on the boiling point of the fuel, other effects from fuel properties such as vapor pressure should be considered too.

Vapor pressure is very important where the temperature and the thermochemical properties of the fuel depends on each other (Azami and Savill, 2016). Higher vapor pressure is desirable as it ensures faster evaporation rate of fuel in primary combustion zone (Lefebvre and R.Ballal, 2010). All fuel including Kerosene (KE), Ethanol (ETH), Methanol (MTH), Microalgae biofuel (MA), Jatropha biofuel (JA), and Camelina biofuel (CA) show an increase in vapor pressure as the temperature increases until it achieves a certain limit (Azami and Savill, 2016). Even though the fuels have high vapor pressure, the slower vaporisation rate caused by its high vaporisation latent heat will make the temperature of the droplets maintained (Azami and Savill, 2016).

Besides, the temperature of the fuel itself will define the efficiency of the vaporisation. According to Lefebvre and R.Ballal, the temperature of fuel drop varies along its lifetime. There are two stages for the evaporation process which is heat up period and also steady-state period. First when the fuel droplet is injected at its initial temperature, the temperature increases during the heat up period. During this period, there is no mass transfer from the drop. When the temperature increases, fuel vapor will from at the surface and part of the heat will be transferred to furnish the heat of vaporisation of the fuel. After the droplets are heated up, it enters another period which is steady-state period where the temperature remains constant until evaporation is complete (Lefebvre and R.Ballal, 2010). Low gas temperature in surrounding of a diesel spray will cause the liquid droplets to evaporate late and far away from the injector, thus reduce the combustion efficiency (Mousavi et al., 2016). By increasing the initial temperature, the droplets particle slows down in high rate and the penetration length is reduced (Azami and Savill, 2016). The penetration is shorter due to the faster rate of complete vaporisation. High initial temperature and velocity are preferable since it increase the vaporisation rate. Vaporisation rate can vary according to its heat of vaporisation. It is shown that vaporisation does not only depends on the fuel's vapor pressure because it will react according to the temperature of surrounding. A study on vaporisation was done and it showed that even though ethanol has higher vapor pressure than gasoline, the heat of vaporisation of ethanol is three times higher than gasoline where it also needs three times more heat than gasoline to vaporise (Gu et al., 2012). Instead of only focusing on the vapor pressure, the heat of vaporisation is also an important parameter to optimise the engine. For example, when the fuel has higher heat of vaporisation, pre-heat process could be done so that even when it is injected to the lower temperature area, it still can be vaporised in suitable rate.

2.3 Droplet Size

Evaporation character of liquid droplets is important for both combustion chamber design process and simulation for high-accuracy of spray combustion (Wang et al., 2017). The changing of droplets size along the combustion chamber indicates the evaporation rate of the fuel droplets. When the fuel is injected from the injector, it will become completely turbulent and mix with the surrounding air (Jääskeläinen and Khair, 2017). Fuel droplets will go through primary and secondary atomisation in the combustion chamber.

All combustion chambers have a recirculation zone or primary zone, burning zone or secondary zone and dilution zone or tertiary zone. Primary atomisation or combustion occurs near the injector nozzle , where the liquid breaks into droplets and interact with the gas in the chamber (Jääskeläinen and Khair, 2017). In primary zone, the heat is provided so that the reaction and combustion between the fuel and oxygen occurs (Boyce, 2012). The reaction will produce carbon dioxide and water. This reaction is stoichiometric where a certain proportion of reactants react with enough amount of oxidizer molecules to complete the chemical reaction.

After primary atomisation, the droplets will go through secondary breakup process, where the size of the droplets keeps reducing as they penetrate into the air (Jääskeläinen and Khair, 2017). Before entering secondary zone, the fuel should be evaporated and partly burned so that it is ready for rapid combustion in burning zone (Boyce, 2012). It will be a combination between the droplets and evaporation to ensure that the size of droplets decreases along the path (Jääskeläinen and Khair, 2017). For a well-designed combustion chamber, all fuel should be burnt at the end of the burning zone. The fuel should be burnt so that the hot gas can be mixed with the dilution air in dilution zone. Lastly, the mixture should be leaving the chamber with an acceptable value of temperature and velocity distribution. To sum up, a combustion chamber should be designed well so that the droplet size reduces along the path and to ensure that there is sufficient time to evaporate completely.

In this work, combustion characteristics of a 2-dimensional cylindrical combustion chamber for different operating conditions will be evaluated through

Computational Fluid Dynamics (CFD) simulation. Research will be done by using different temperature, droplet sizes, fuel injectors and type of fuel. The penetration length and the flame temperature at each position will be observed and analysed respectively to the operating conditions. The analysis will then decide the efficiency of the combustion chamber and to find out the gas emission for every fuel.

CHAPTER 3

METHODOLOGY

Method on conducting this study will be described in detail in this chapter. The combustion chamber properties, combustion characteristics, fuels used, CFD setup including its meshing, boundary conditions, solution methods and the validation are further discussed.

3.1 Flow Chart

Figure 3.1 shows the flow chart of the whole research from the beginning to the end.

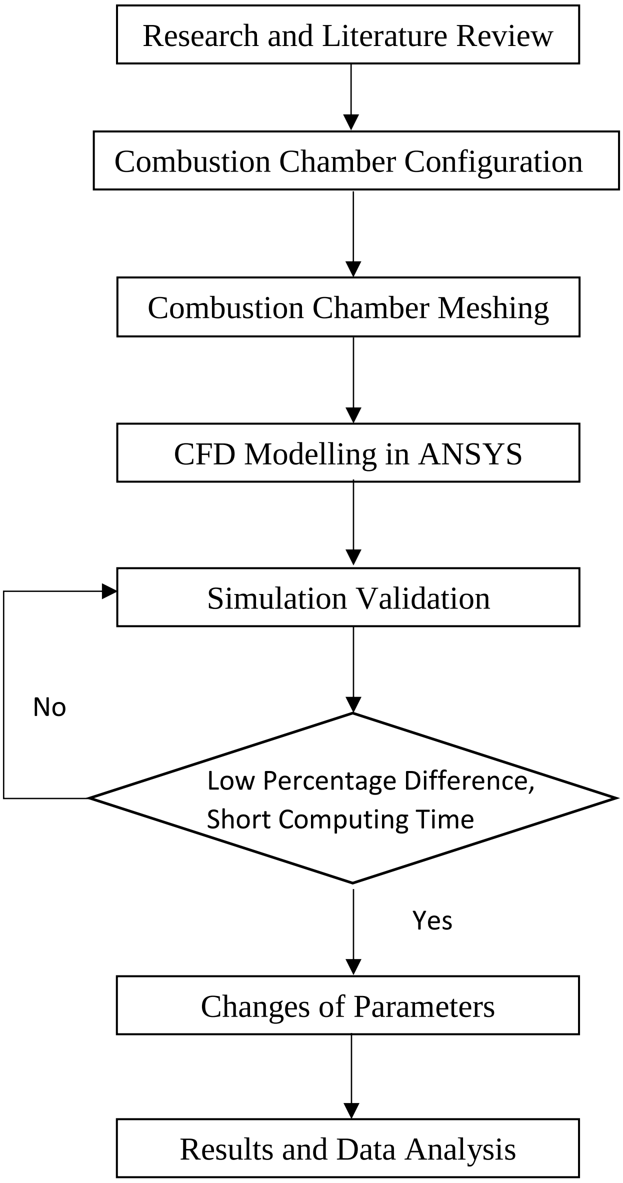

Figure 3.1: Flow Chart

At the beginning of the study, literature reviews and theoretical approach were done according to the similar topics and method used. At the same time, information on ANSYS was collected to ease the next processes. While doing literature review and research, combustion chamber configuration was set and the dimension of the combustion chamber was defined. Process continued with the meshing of combustion chamber where 5 different meshing were done. All the meshing was used to run same set of simulation and the results were recorded. This process was required to avoid dependency of the result with grid size. The result for each of the meshing was compared with the result from journal. The meshing was revised until the simulation result was closed with the reference value and did not affected by the grid size. The best meshing where its result converged was used in next process which is to substitute in the evaluated parameters. Simulation was continued by the same setups, but with the parameters included spray half cone angle, fuel temperature, droplet sizes and fuel properties. Last but not least, results and data from the simulation were analysed and further discussed in Chapter 4.

3.2 Combustion Chamber Configuration

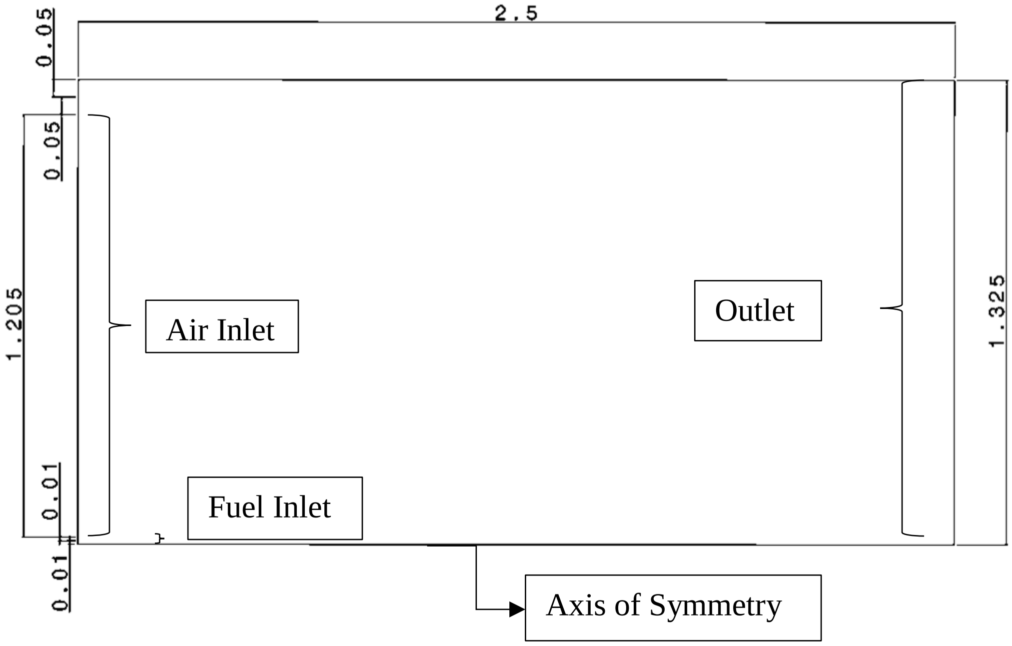

Figure 3.2 Combustion Chamber Configuration

The dimensions of the 2D combustion used in this simulation are shown in Figure 3.2. It is a 2D simulation where only the cross-section of a combustion chamber is considered. The combustion chamber has a 0.01 m fuel inlet, 1.205 m air inlet and 1.325 m for outlet. The total length of the chamber is 2.5 m. The total length of the chamber is 2.5 m. Figure 3.2 shows the upper part of the combustion chamber where the same dimensions will be reflected at the axis of symmetry. Basically, there was only upper half of the model is used for the simulation because it is assumed that the flow inside the combustion chamber is the same in every axis and direction.

3.3 Combustion Chamber Zones

Every combustion chamber is divided into primary zone, secondary zone and dilution zone in which each zone can be presented by calculation (Mark and Selwyn, 2016). The length for each of the zone can be calculated by Equation (3.1).

The similar approach suggested in Mark and Selwyn is used to calculate the zone length for this study. Table 3.1 shows the percentage and the length of the zones from related journal.

$$Zone\ Length\ Percentage\ (\%) = \frac{Zone\ Length}{Total\ Length} \times 100 \qquad (3.1)$$

Table 3.1: Percentage and Zone (Mark and Selwyn, 2016)

Zone	Percentage from Calculation
Primary Zone	25.24%
Secondary Zone	16.82%
Dilution Zone	57.94%

Calculation of zone lengths is done by using the percentage from the journal. Therefore, the zone lengths of combustion chamber considered in this study was calculated by substituting the total length of 2.5 m and the zone length percentage from journal. Table 3.2 shows the dimension of zones of the combustion chamber designed in this study.

Table 3.2: Length of Each Zone for Combustion Chamber Designed

Zone	Distance (m)	Length (m)
Primary Zone	0 – 0.631	0.6310
Secondary Zone	0.631 – 1.056	0.4205
Dilution Zone	1.056 – 2.5	1.4485
Total		2.5

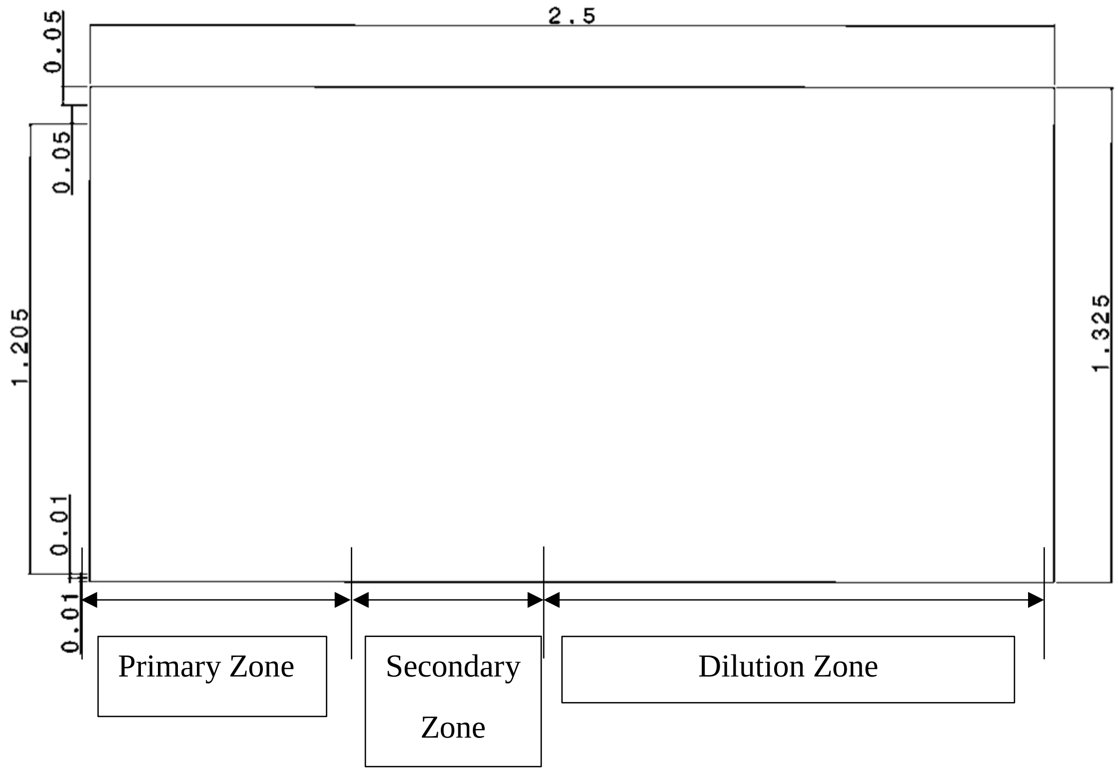

Figure 3.3: Zone Division of the Chamber

3.4 Meshing of 2D Combustion Chamber

Meshing of the designed combustion chamber, are performed in five types of meshing. For all the meshing, same boundary condition was set to run the flow simulation in the combustion chamber. Few considerations were taken in choosing the best meshing. First is the computation time, since different combustion characteristics will be used for each simulation, it is suggested that the mesh used should be accurate and at the same time do not have extremely long computation time. Next, the maximum temperature of simulation for each mesh will be taken to compare to similar journal. The one which is having the similar result will be chosen. The following tables and figures will be showing the mesh quality for each of the meshing.

For 2D coarsest,

Table 3.3: Mesh Quality

Nodes	1800
Elements	1716
Minimum Orthogonal Quality	0.966
Maximum Aspect Ratio	18.5345

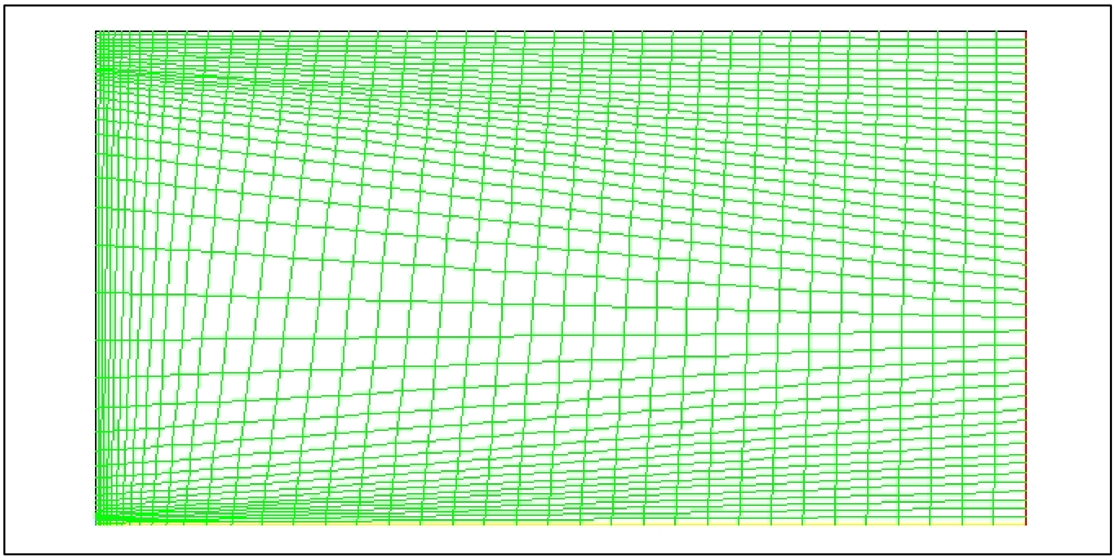

Figure 3.4: Coarsest Mesh

For 2D coarse,

Table 3.4: Mesh Quality

Nodes	2378
Elements	2280
Minimum Orthogonal Quality	1
Maximum Aspect Ratio	25.02

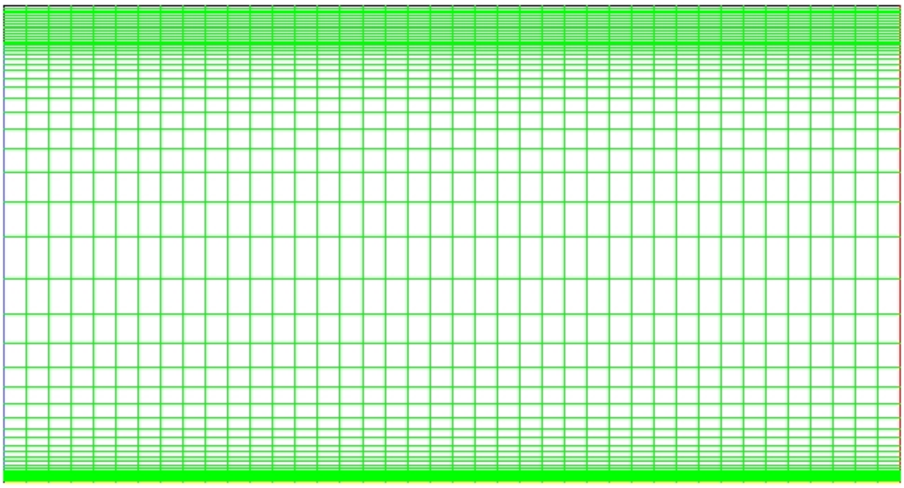

Figure 3.5: Coarse Mesh

For 2D fine,

Table 3.5: Mesh Quality

Nodes	18271
Elements	18000
Minimum Orthogonal Quality	1
Maximum Aspect Ratio	52.9442

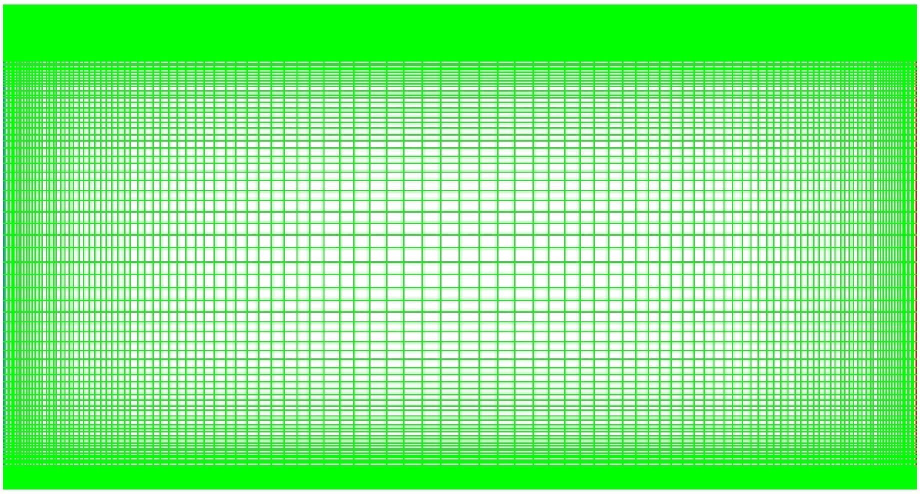

Figure 3.6: Fine Mesh

For 2D finer,

Table 3.6: Mesh Quality

Nodes	46431
Elements	46000
Minimum Orthogonal Quality	1
Maximum Aspect Ratio	44.4195

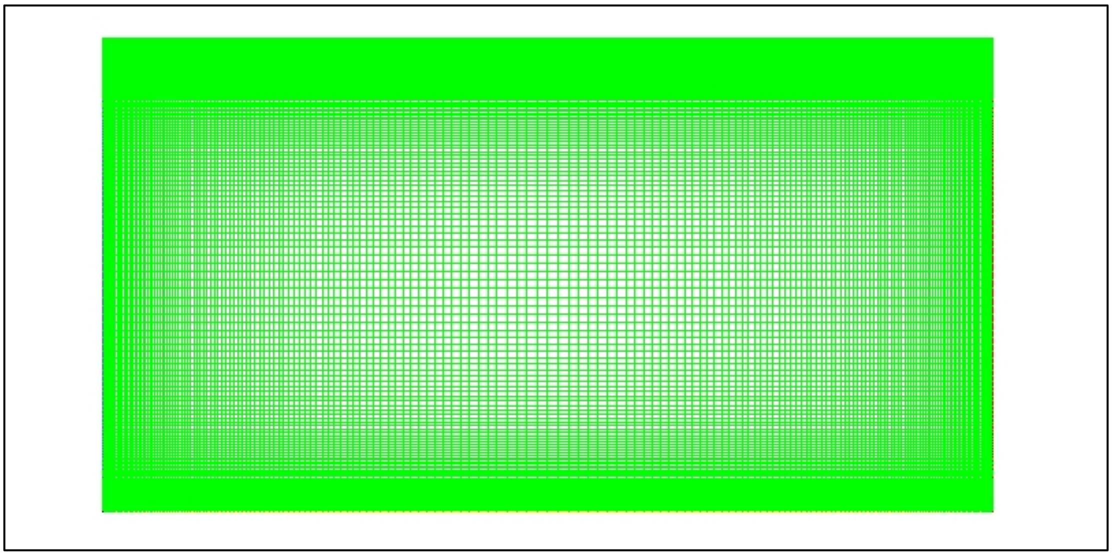

Figure 3.7: Finer Mesh

For 2D finest,

Table 3.7: Mesh Quality

Nodes	78061
Elements	77500
Minimum Orthogonal Quality	1
Maximum Aspect Ratio	47.4118

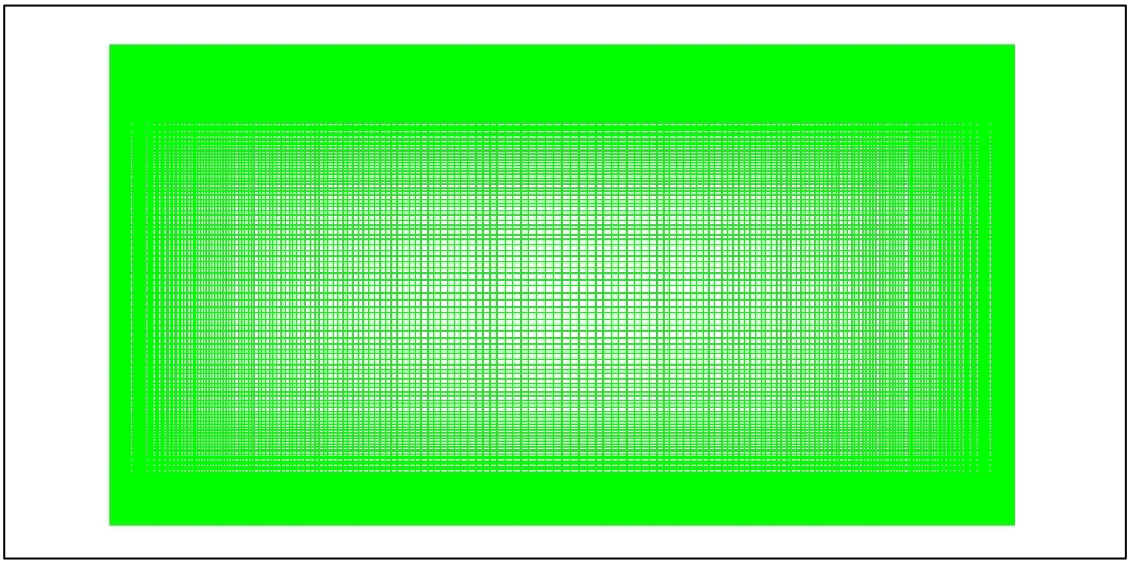

Table 3.8: Finest Mesh

3.5 Simulation Setup Parameters

In this study, few parameters will be used in the simulation setup in order to analyse the effect of different operating condition on the combustion characteristics. The parameters used in this study are spray half cone angle, fuel temperature, droplet diameters and type of fuels. Spray half cone angle that were chosen are 30°, 40° and 50°. Fuel temperature that were chosen are 300 K, 400 K and 500 K while the droplet diameters are varied at 20 µm, 30 µm and 40 µm. Fuels used in the simulation are Jet-A, JSPK, CSPK, 50JSPK/50Jet-A and 50CSPK/50Jet-A. 50JSPK/50Jet-A and 50CSPK/50Jet-A are the mixtures of 50% of JSPK with 50% Jet-A and 50% of CSPK with 50% Jet-A. The fuel properties of all the fuels are listed as the table below. Viscosity for the mixture of two fuels can be calculated by Equation 3.2 (Davidson, 1993), by summing viscosity (μ_i) of the fuels with their mole fraction (X_i).

$$\mu_{mix} = \sum(X_i \cdot \mu_i) \tag{3.2}$$