# PERFORMANCE OF COMBUSTION CHAMBER FOR MICRO GAS TURBINE (MGT) APPLICATION RUNNING ON PALM OIL

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| APU | Auxiliary Power Unit |
| CAD | Computer-Aided Design |
| CFD | Computational Fluid Dynamics |
| CHP | Combined Heat and Power |
| DPM | Discrete Phase Model |
| LHV | Low Heating Value |
| LPG | Liquefied Petroleum Gas |
| MGT | Micro Gas Turbine |
| ORC | Organic Ranking Cycle |
| PPM | Parts Per Million |
| RET | Recycle Tube |
| RQL | Rich Combustion, Quick Mix, Lean combustion |
| SVO | Straight Vegetable Oil |
| TIT | Turbine Inlet Temperature |
| USM | Universiti Sains Malaysia |

# PRESTASI KEBUK PEMBAKARAN UNTUK APLIKASI TURBIN GAS MIKRO TUNGGAL (MGT) YANG DIJALANKAN DI ATAS MINYAK SAWIT

## ABSTRAK

Malaysia merupakan sebuah negara yang kaya dengan biojisim yang mendahului permintaan global yang tinggi untuk menggunakan sumber tenaga yang boleh diperbaharui dalam turbin gas untuk memastikan persekitaran hijau yang mampan. Unit penjanaan haba dan kuasa (CHP) gabungan berdasarkan Turbin Gas Mikro (MGT) adalah serba boleh dan dapat dipercayai untuk aplikasi di tapak dan mereka direka bentuk dengan mempunyai struktur yang kecil dan padat yang membolehkannya lebih terdedah kepada kebocoran dalaman berbanding dengan turbin gas yang berat tugas. Dalam kertas kerja ini, ujian permulaan pada prestasi aplikasi kebuk pembakaran turbin gas mikro tunggal berjalan pada minyak sawit telah dijalankan. Ubat pada reka bentuk ruang pembakaran untuk turbin gas mikro telah dilakukan dengan menggunakan perisian Reka Bentuk Berbantu Komputer (CAD), SOLIDWORKS kemudian dioptimumkan oleh perisian simulasi dinamik bendalir pengiraan (CFD), ANSYS-FLUENT diikuti dengan kerja permulaan pada persediaan MGT dan proses percubaan. Bahan api yang digunakan dalam MGT ialah minyak sayuran yang diklasifikasikan sebagai bahan api bio boleh diperbaharui gred rendah. Tambahan pula, kerja permulaan tentang pencirian pembakaran untuk MGT peringkat tunggal telah dijalankan. Pemerhatian terhadap prestasi MGT peringkat tunggal semasa operasi percubaan permulaan diperolehi termasuk prestasi penyejatan dan pengabusan biofuel, prestasi nyalaan dan prestasi turbin. Selain itu, hasil simulasi telah dilakukan dan dibangunkan berdasarkan beberapa parameter seperti jumlah suhu, pecahan mol CO, pecahan mol NOx pencemar, dan aras kuasa akustik. Untuk tahap kuasa akustik, lapan satah kedudukan yang berbeza telah ditetapkan di sepanjang kebuk pembakaran. Keputusan menunjukkan tahap kuasa akustik tertinggi ialah 100.153 dB pada kedudukan x=0.1m manakala tahap kuasa akustik terendah ialah 40.5497 dB pada kedudukan x=0.4m. Mikrofon disyorkan untuk diletakkan pada kedudukan x=0.1m untuk menyelesaikan isu bergema. Beberapa cadangan kerja masa depan telah diberikan untuk memanfaatkan dan meningkatkan prestasi kebuk pembakaran MGT peringkat tunggal.

# PERFORMANCE OF COMBUSTION CHAMBER FOR MICRO GAS TURBINE (MGT) APPLICATION RUNNING ON PALM OIL

## ABSTRACT

Malaysia is a country that rich in biomass which leads a high global requirement for utilizing renewable energy resources in gas turbines to ensure a sustainable green environment. Combined heat and power (CHP) generation units based on Micro Gas Turbines (MGT) are versatile and reliable for on-site applications and they are designed to have a small and compact structure which allows them more vulnerable to internal leakages compared to other heavy-duty gas turbines. In this paper, a start-up test on performance of combustion chamber of single stage micro gas turbine application running on palm oil has carried out. A modification on design of a combustion chamber for micro-gas turbine was performed by using Computer-Aided Design (CAD) software, SOLIDWORKS then optimized by computational fluid dynamics (CFD) simulation software, ANSYS-FLUENT program followed by start-up test on MGT setup and trial process. Fuel that has used in MGT is vegetable oil which classified as low-grade renewable biofuel. Moreover, a start-up test on combustion characterization for the single stage MGT was carried out. Observations on performance of single stage MGT during start-up trials operation are obtained which include performance of biofuel evaporation and atomization, performance of flame and performance of turbine. Besides, simulation results were performed and developed based on several parameters such as total temperature, mole fraction of CO, mole fraction of pollutant NOx, and acoustics power level. For acoustic power level, eight different position planes were set along the combustion chamber. The results showed that the highest acoustic power level is 100.153 dB at position x=0.1m while lowest acoustic power level is 40.5497 dB at position x=0.4m. The microphones are recommended to be placed at position x=0.1m to solve the reverberation issues. Several recommendations of future work were given to utilise and improve the performance of combustion chamber for single stage MGT application.

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview of Project

Micro gas turbine (MGT) engine shows a growing trend of popular technology which used widely in the commercial aviation and hobby industries [1]. Normally, the implementation of MGTs can be found in small electricity generating plant (combined heat and power) applications, hybrid electric vehicles and as auxiliary power units (APUs) for modern aircraft. The characterisation of MGTs is usually determined by lower efficiency and higher specific cost [2]. Micro Gas Turbines (MGTs) have played a main role for decentralised renewable energy generation due to their excellent environmental, potential applications and energetic performance [3], [4]. Generally, MGTs can be defines as versatile and reliable units for on-site combined heat and power production (CHP) [5]. CHP units depend on MGTs provide various advantages such as the high power-to-weight ratio, compactness, the lower pollutant emissions and high maintenance costs. On the other hand, some specific model of gas turbine has greater fuel flexibility than diesel engines since the fuel is not mixing with lubricating oil and it can burn continuously under high temperature of environment. For example, single stage turbines which in both radial and axial flow configuration, are invented specifically according to each significant fluid to explore the mounting chance for the Organic Ranking Cycle (ORC) expander directly on the gas turbine with high-speed shaft [6]. MGT was characterised successfully with diesel and then examined with low-grade biofuels which is vegetable oil under the framework of the EU-Russian Federation FP7 cooperative and specifically the Bioliquids-CHP project.

Implementation of renewable fuels can partially solve the problem of the potentially high specific cost of energy produced by means of an MGT. Renewable fuel or known as biofuels can be in gaseous form which are biogas and syngas or liquid form which are biodiesel or straight vegetable oil SVO. Regarding to these liquid biofuels or vegetable oil, the fuels can be either become raw products or transformed into biodiesel which known as transesterification process. To study the use of vegetable oil for power generation, several research works has been done along some years ago. The research works are mainly focused on problems of biooil combustion process and the performance of energy systems fuelled by biooils in terms of conversion efficiency, power, and pollutant emissions [2], [7]–[11].

To adapt MGT to biofuels such as kerosene, natural gas, diesel oil or even clean biogas, these biofuels can be directly implemented in MGTs without major improvements or modifications. On the other hand, few issues had been found to adapt MGT to biofuels which from biomass thermo-chemical conversion or very raw liquid biofuels such as vegetable oil since these liquid biofuels require more significant re-design on the combustion chamber and high variation of standard technologies before being used [5]. These low-grade renewable fuels or biofuels consists of some critical aspects which mainly related to their unfavourable chemical and physical characteristics, such as high viscosity, low Lower Heating Value (LHV), and poor atomization which contributes several issues. Moreover, the chemical–physical characteristics of low-grade biofuels or vegetable oils tend to decay during storage and fouling on the mechanical moving parts. For example, properties of the spray during injection are mainly affected by viscosity. The increasing of mean droplet size diameter and decreasing angle of spray cone will contribute poor combustion quality and rising of spray penetration. Vegetable oil is replacing a low-grade renewable fuel, and its use essential a deeper adaptation of the MGT given its physical properties and chemical composition. The palm oil or vegetable oils' chemical and physical characteristics are different from fossil diesel oil and gas turbine liquid fuels, not only in terms of LHV and kinematic viscosity, but also as regards other issues as ignition properties, contaminant levels and composition, fuel cold properties and others. Thus, particular observation and attention should be focused to the evaporation and atomization phases, as these are the most critical steps to achieve stable and efficient long-term operation. [12]

MGTs can achieve a steady flame during the combustion process which this feature provides a flexibility to implement alternative fuels. Thus, several researchers have investigated and studied the usage of various types of liquid biofuels in gas turbine. Start-up test is needed to carry out on the MGTs that run with biofuels such as vegetable oils to study MGT performance. The start-up test illustrated the MGT operated with palm oil or low-grade biofuels and the performance of MGT application is studied which include few parameters. The experiences obtained on the operation of MGT on low-grade biofuels will serve as a basis for MGT's modification and sustainability.

## 1.2 Problem Statement

Regarding the previous research about relevant topic that have been discussed, there are some limitations on the performance of combustion chamber of Single Stage MGT when it runs on low-grade biofuel such as palm oil. This include the lower heat value compared to diesel, additional to fuel atomization and evaporation issues leading to longer evaporation time resulting in difficulties in controlling turbine as the flame propagation is delayed and shifted to the exit of the chamber. This also causes other issues such as the elevation in turbine inlet temperature (TIT) and the higher emissions due to incomplete combustion. One of the proposed solutions in literature is the fuel preheat. However, fuel partial pyrolysis and carbonization at the hot spots of the heating coils is the major issue which can cause fouling and blockage in the fuel supply line. Therefore, this work will test a novel MGT combustion chamber design that overcome the low-grade fuel atomization, evaporation and combustion difficulties by implementing an internal fuel pre-evaporation with internal exhaust gas recycling.

## 1.3 Objectives

1. To modify the existing combustion chamber of single stage MGT system by using CAD software SolidWorks and CFD software ANSYS-FLUENT programs to determine the combustor characteristics including emissions, temperature profile and acoustic profile.

2. To modify combustion chamber of single stage MGT system via start-up test which can overcome atomization issues of biofuels.

3. To characterize the combustion chamber start-up behaviour via start-up test with liquid biofuels such as palm oil.

## 1.4 Scope of Project

The scope of this project is to carry out a research work to study the performance of combustion chamber for single stage Micro Gas Turbine application especially on combustion chamber with liquid biofuels (vegetable palm oil). This research work also involves modify and simulate the combustion chamber model with the aid of CAD software, SOLIDWORKS and CFD software, ANSYS-FLUENT program.

## 1.5 Limitations of Study

This research work is focusing on the low-quality biofuels which are vegetables oils only. There is a limitation on the performance of combustion chamber application when it runs by other fuels. All the parameters that have studied are different between low-quality biofuels and other fuels. Moreover, the current research work is evaluated in short term according to the periods given in the course. Therefore, the design and the results might change due to the new modification on this project which is done by other researcher in future.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Liquid Biofuels

In this competitive society, the quality of vegetable oil plays a significant role for its successful use as biofuel in engines [12]. An open issue is considered to the meaning of a widely agreed quality standard. According to the chemistry understanding, vegetable oil (VO) can be defined as a mixture of free fatty acid, di- and triglycerides, glycerol, phosphorus compounds and waxes [5]. The fatty acids vary in their carbon chain length and number of double bonds present in their molecular structure. Vegetable oils consists of 1 to 5% of free fatty acids, carotenes, phospholipids, phosphatides, tocopherols, sulphur compounds and traces of water [13], [14]. The ratio between two fatty acids which are linoleic and oleic acid are of paramount importance in the implement of diesel engine. This is due to linoleic acid is a measure of the degree of saturation such as the amount of double bound in the chain. If there is an excessive number of double bonds in the oils, it may cause the formation of deposits in engine hot parts especially valves. On the other hand, a very low number of double bonds in oils will lead the oil becomes solid at ambient temperature. Vegetable oil that consists of acid fats according on the seed specific type. Novaol which come from Italy has supplied refined vegetable oil from rapeseed in April 2010.

High viscosity and poor volatility of straight vegetable oils have become a major problem on itself as large molecular weight and bulky molecular structure. Vegetable oils have higher viscosity compared to mineral diesel which cause to inappropriate pumping and fuel spray characteristics. The injector nozzle will inject larger size fuel droplets instead of a spray of fine droplets leads to some problems such as lower volatility, inadequate air fuel mixing, poor atomization and incomplete combustion due to inefficient mixing of fuel with air. This results an increment in higher particulate emissions, combustion chamber deposits and gum formations [13].

Straight Vegetables Oil (SVO) can be extracted from a different type of plants such as chestnut, palm, tobacco, jatropha, castor, sunflower jojoba, karanja, rapeseed, soybean and candlenut [15]. The content of oil for these plants typically range from 20 to 60 % wt. SVOs from rapeseed, sunflower, palm, peanut and sesame are slightly more viscous (>35 $mm^2/s$) compared to jatropha, soybean, safflower, and coconut

(<35 mm$^2$/s). The major constituents of straight vegetable oils and fatty acid can be classified into two types which are saturated and unsaturated types. For saturated-chain fatty acids, there is no double bond linked between the carbon atoms while unsaturated chain fatty acid contains double bonds. The degree of unsaturation is one of the primary factors that influence the overall physical properties of SVO [16], [17]. Generally, higher degree of unsaturation consists of more double bonds in the chain contribute to lower viscosity of the oil. The presence in liquid form of oil with lower viscosity can be explained by the presence of double bonds in the fatty acid which it will bend the chains [18]. Table 2-1 shows the density of straight vegetable oil (SVO) which can be correlated to the degree of unsaturation. Based on Table 2-1, density below than 915 kg/m3 indicates higher unsaturation degree of SVO (>1.3) while density greater than 915 kg/m3 indicates lower unsaturation degree of SVO (<1.3) such as palm and coconut.

Table 2-1: Comparison of Physical Properties of Vegetable Oil [15]

| Feedstock | Density (kg/m$^3$) at 15°C | Kinematic Viscosity (mm$^2$/s) at 40°C | Cetane Number | Calorific Value (MJ/kg) | Flash Point (°C) | Pour Point (°C) | Sulphur(%wt) | Mass average chain length | Mass average unsaturation degree |
|---|---|---|---|---|---|---|---|---|---|
| Coconut | 915–918 | 27–28 | 40–42 | 35–38 | 228–298 | 23–24 | 0.01 | 13.0 | 0.1 |
| Jatropha | 940 | 33–34 | 39 | 38–39 | 225 | 3–5 | 0.01 | 17.7 | 1.1 |
| Palm | 918 | 39–41 | 42 | 39.5 | 267 | −1 to 4 | 0.01 | 16.7 | 0.5 |
| Sunflower | 916–918 | 33–36 | 37–38 | 39.6 | 274 | −18 to −15 | 0.01 | 18.0 | 1.5 |
| Peanut | 903 | 39–40 | 41 | 39.8 | 271 | −6.7 | 0.01 | 18.1 | 1.1 |
| Corn | 909–910 | 30–35 | 37–38 | 39.5 | 277 | −40 | 0.01 | 17.8 | 1.4 |
| Safflower | 914–915 | 31–32 | 40 | 39.5 | 260 | −7 to −6 | 0.01 | 17.9 | 1.6 |
| Soybean | 913–914 | 28–33 | 37–38 | 39.6 | 254 | −12 | 0.01 | 17.9 | 1.5 |
| Castor | 955 | 251–252 | 40 | 37.4 | 229 | −33 | 0.01 | 18.5 | 1.1 |
| Sesame | 912–914 | 36 | 39 | 39.4 | 260 | −14 to −12 | 0.01 | 17.8 | 1.3 |
| Rapeseed | 912 | 35–37 | 40 | 39.7 | 246 | −32 | 0.01 | 18.0 | 1.4 |

## 2.2 Combustors Design

In this research work, the combustor of the MGT is an annular combustion chamber with a configuration of a RQL (Rich Combustion, Quick Mix, Lean combustion) as shown as Figure 2-2 and Figure 2-3 [19]. In early of 1980, RQL Combustion chambers were invented as a strategy to consist of NOx emissions in combustion systems for gas turbine especially in aeronautical applications. The RQL combustor technology is of earning popularity in stationary applications for their effectiveness in treating fuels with complex composition. Primary zone (A) has a rich combustion can improves the stability of the combustion reaction through the production and maintaining a high concentration of hydrogen and hydrocarbon radical species as shown as Figure 2-3. Furthermore, it lowers the nitrogen oxides production due to low oxygen intermediates between species and its relatively low temperature. Effluents from the rich zone have a high concentration of hydrocarbon species, hydrogen and carbon monoxide, partially oxidized and partially pyrolyzed which require an additional supply of oxygen. The supply of oxygen can be obtained by injecting a high amount of air through the secondary air jets, in the Quick mix zone (B). Lastly, a dilution air, in the Lean burn zone (C) reduces the temperature to prevent the spoiling of the integrity of the turbine blades. Ideally, this will lead to the emission of an effluent comprising the main combustion products (CO2, H2O, N2, O2) and an almost zero concentration of pollutants (NOx, CO) [18], [20]. Dam walls separates rich and the lean zones where the secondary air holes and the rapid mixing area are located. The fuel is injected into the combustion rich zone through 12 injectors placed inside the mixing tube. Figure 2-3 illustrates an injection zone completely. The axis of the injector is tilted compared to that of the mixing tube to allow the fuel to interfere with the inner wall of the tube and to mix with air before entering the combustion rich zone.


Figure 2-1: Combustion Chamber of MGT

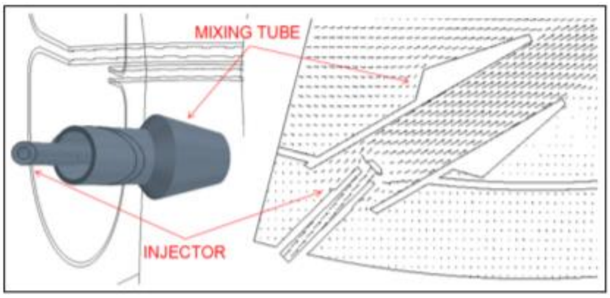


Figure 2-2: Injector and Mixing Tube

## 2.3 Combustion of Liquid Biofuels

Combustion is a process or chemical reaction which can be explained that if the fuel under current conditions either in solid or liquid phase, it will be evaporated into gas phase. For gas turbines, the flame is confined within metal surfaces in a combustion chamber and the chamber far end merges into the turbine inlet. At the moment, the hot gases in chamber need to achieve a sufficient temperature which not to hurt the vanes and turbine blades. The continuous flow combustion process with steady flame can be done in gas turbines [21]. This advantage allows clean combustion carried out and utilise the use of different fuels, robust mechanical design, moderate compression ratios and versatile combustor. The biofuels properties have effect on combustion design, efficiency and NOX emissions of gas turbines. Palm Methyl Ester (PME) as ideal fuel for gas turbines has illustrated combustion characteristics are similar to those of diesel fuel with reduced NOX emission [22]. At the same time, the combustion performance of biodiesel, vegetable oil and animal fat are slightly higher for CO emissions than diesel. There is another study focused on the catalytic contribution in a hybrid lean combustion for gas turbines, where rise both NOX emissions and lean combustion stability [23]. Furthermore, studying the thermodynamic performance of a lean burn catalytic combustion in gas turbine reveals a higher thermal efficiency for lower regenerator effectiveness at lower pressure ratios.

There are plenty of investigations have been done previously on MGT of ultra-low NOx combustor designs. To ensure NOx emissions can be under control, there are various techniques were implemented such as multi-stage premixed chambers with preheated air [24] as well as recuperation and exhaust gas recycling [25]. Besides, the techniques such as flameless premixed combustion with an annular nozzle[26], and the MILD combustion[27] have been carried out to lower emission of NOx. Furthermore, there are other significant considerations on reduction of NOx emission such as effects of number and location of stabilizer jets on the combustion characteristics.

Oxy-fuel flames reached a higher stability compared to normal air-fuel flames according to an experimental analysis of combustion behaviour in gas turbine combustor [28]. There are various studies on liquid biofuel in gas turbine have obtained better combustion stability by using atmospheric diffusion of oxy-combustion flame, low swirl fuel nozzle [29] and fuel-air mixture [30]. Different radiation models have predicted the enhanced thermal radiation in oxy-fuel combustion. The method of fuel preheating can improve the effect of spray quality on combustion of viscous biofuel in MGT. Apart from there, an expectation in reducing pollutant emission is demonstrated by the case of lean premixed pre-vaporised (LPP) combustor [31]. The study on gas turbines illustrated a stable combustion can be achieved with alternative fuels using air assisted pressure swirl atomiser for Jatropha oil and Jatropha methyl ester [32].

The exploitation of refuse derived fuels can be achieved by optimised fuel injection nozzle, regenerative thermodynamic cycles and high fuel preheat temperatures [33]. Furthermore, emission formation, rate of mixture formation and droplet penetration depth of liquefied spruce wood were significant affected by different parameters such as temperature, velocities, and flow conditions [34]. Nevertheless, an unique and innovative type of combustion is used for inter stage combine combustor which is trapped-vortex combustion technology to increase the gas turbine efficiency [35]. The impact of vortex generator in swirl combustor on combustion and emission characteristics was studied and the results revealed that the vortex generator had a positive effect on characteristic of emission and combustion [36].

## 2.4 MGT with Liquid Biofuels

Several past research works on the combustion of liquid biofuels such as straight vegetable oil in micro gas turbines have found that related to the present research work. The researchers Habib and others had tested several liquid biofuels or vegetable oil-based biodiesels, biofuel derived from animal and their 50% blends with Jet A fuel in an unmodified 30 kW gas turbine [37]. The engine performance and gas emissions of the 30kW gas turbine are recorded and reported. Unfortunately, there was no any information is obtained about the injection system and fuel injection temperature of the gas turbine. For next group researchers, they studied the performance of a Solar T-62T-32 micro gas turbine fed by blends of different concentrations of diesel and liquid biofuel [38] from 5 % to 100 % of SVO. All the experiment tests were tested by imposing the opening of the fuel flow valve to ensure the shaft rotates at nominal speed during MGT is fed by fuel. All experiment tests remained same opening with the exception of 100 % SVO feeding, since there is no any verification for self-sustaining condition. The experimental results obtained from this micro gas turbine highlighted some negative effects of different fuels on performance of MGT and emission of pollutant, such as carbon monoxide (CO) and nitrogen oxides (NOx). The operation of MGT with 100 % straight vegetable oil did not highlight any particular problems such as the noise created by combustion. The pure straight vegetable oil feeding, the measured pressure of injection was almost twice the injection pressure in the case of diesel.

Furthermore, there are some researchers carried out experiments with several fuels such as diesel, biodiesel and vegetable oil in a Garrett GTP 30-67 micro gas turbine equipped with a pressure swirl atomizer [5]. From the experiments, the temperature of preheating fuel required at least 120°C during combustion of pure vegetable oil and its blends with diesel. The combustion process could not be sustained even at this temperature at idle conditions. According to their experiment results, the carbon monoxide emissions were reduced via preheating the biofuels. The experiment was concluded that the efficiency of combustion for vegetable oil at 120°C which is similar to diesel at standard conditions. On the other hand, the next searchers implemented air-assist atomizers to inject SVO at three different temperatures [12] in modified Capstone C30 micro gas turbine. Based on their experiment results, an increasing of temperature of preheating biofuel contribute a decreasing of carbon monoxide emission especially at low load conditions. Viscosity is the most significant parameter to be controlled for affecting the performance of combustion engine.

Moreover, there are researchers from University of Twente conducted the combustion experiments with the multifuel micro gas turbine setup [39]. This experiment setup is mainly focusing for testing alternative fuels or biofuels at various fuel injection temperatures and loads. The experiment setup consists of five main components which are micro gas turbine, fuel supply system, generator, resistive load and a control unit. Data are collected by using various sensors during the experiments. DG4M-1 was selected as the micro gas turbine for the experiment setup which was formerly used as auxiliary power unit. A pressure-swirl atomizer is equipped on reverse-flow combustion chamber to burn biofuel in a single silo. The hollow cone spray with an angle of 90° to 100° can be supplied by the atomizer. The experiment test was started by preheating the alternative biofuel in the tank and by adjusting appropriate two fuel circuits pressure. The operating conditions are set to correlate the planned test case after start-up of the MGT. Next, the measurement steps were continued for at least another minute to ensure a stable and constant condition can be achieved once all data were reported by all sensors which in constant. The MGT ran stably in all tested or operation conditions and no flame extinction happened during the experiment tests. In the end, it was found that preheating of the fuel is an effective method to fully restore the combustion quality for viscous fuels. The emission of carbon monoxide was affected by temperature of fuel and viscosity according to results thus carbon monoxide level depends on the equivalent ration based on combustion experiments at different loads. The experimental that run with vegetable oil indicated for the application of pyrolysis oil in MGT, a more advanced biofuel with high viscosity. Although the burning characteristics and combustion performance are different for these biofuels, the limited tolerance to higher fuel viscosity measured in this research work considers the potential of pyrolysis oil combustion in the present setup configuration.

## 2.5 Overall Comparison and Comments

Table 2-2: Overall and Comparison of Literature Review

| Literature Review | Main Points |
|---|---|
| Liquid Biofuels | • Various types of liquid biofuels for combustion.<br>• Chemical and physical properties of liquid biofuels. |
| Combustor Design | • Previous combustor design in a combustion chamber.<br>• The configuration of a RQL (Rich Combustion, Quick Mix, Lean combustion) in combustor.<br>• Working steps of the combustion. |
| Combustion of Liquid Biofuels | • Ideation of combustion of liquid biofuels.<br>• The findings and output from combustion liquid biofuels such as emission of CO and NOx, stability of flame produced and others. |
| MGT with Liquid Biofuels | • Past research or experiment works on MGT that run with liquid biofuels.<br>• Demonstrated methodology or experimental setup.<br>• Major findings throughout experiment such as properties of biofuels, preheating fuel, CO emissions and others. |

There are 4 literature reviews have studied as shown as Table 2-2. According to these literature review, they address and highlight the information of liquid biofuels, information of combustor, the possible problems can be occurred such as atomization issues and injector fuel spray problem, the experiment setup and the finding or output of the experiments. All these information can indicate an awareness or contribute an idea to carry out a research work to study performance of single stage MGT running with liquid biofuels.

# CHAPTER 3

# RESEARCH METHODOLOGY

## 3.1 Introduction

In this chapter, the methodology of the research works on study performance of combustion chamber for single stage MGT application will be discussed. The research works can be classified into two types which are simulation work and MGT start-up test. Simulation work is mainly done by CAD and CFD software while MGT start-up test is done by hand-on work. Both simulation and start-up test are done simultaneously on the single stage MGT to obtain results. The overall flow chart of modification and simulation on combustion chamber is illustrated as shown in Figure 3-1.

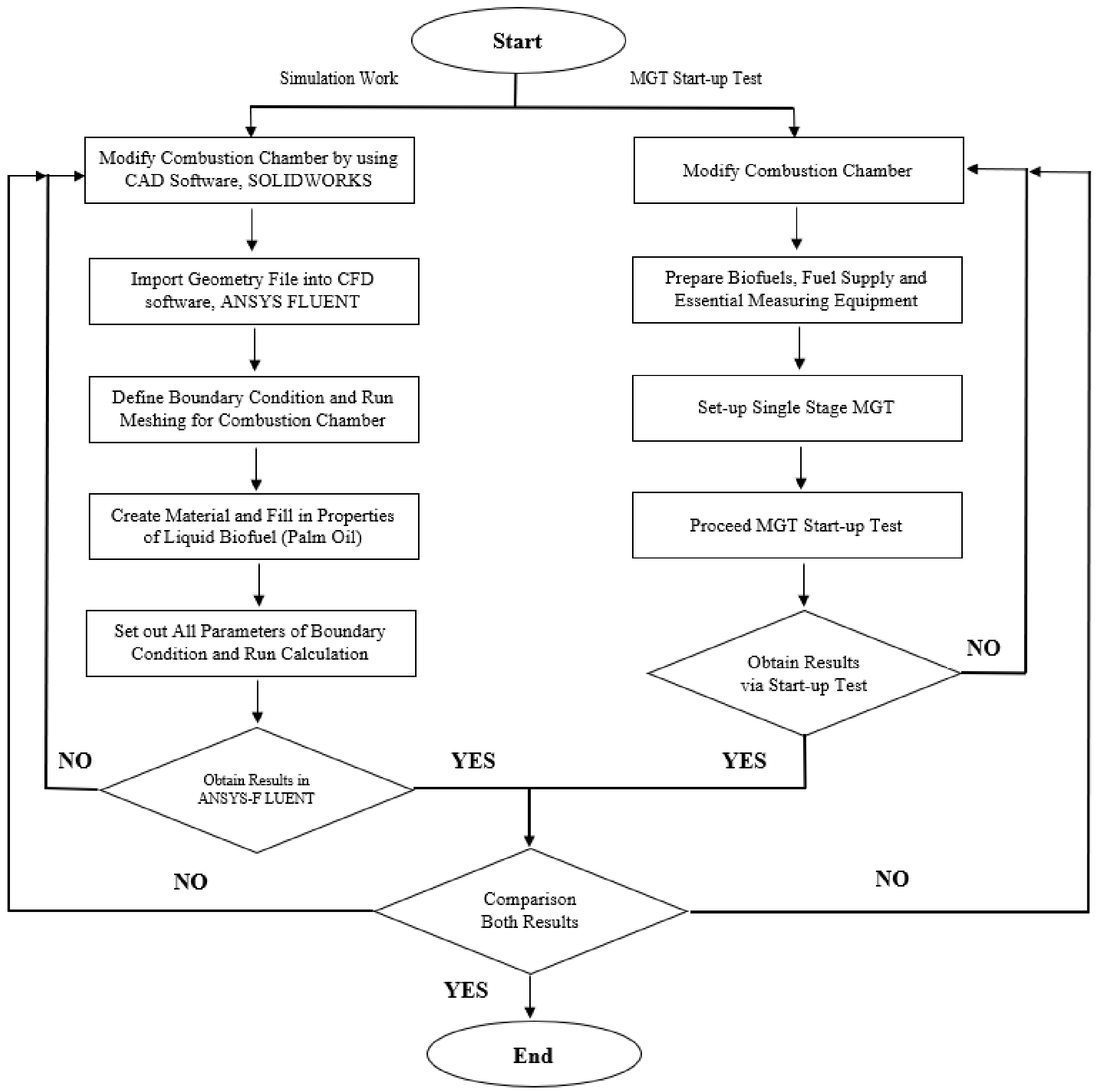


Figure 3-1: Overall Flow Chart of Simulation and Modification on Combustion Chamber

## 3.2 3D Modelling of Combustion Chamber by SOLIDWORKS

CAD software, SOLIDWORKS has been used for 3D modelling of combustion chamber for modification or improvement. Initially, combustion chamber consists of three parts which are chamber, recycling exhaust tube and flame tube. There are some challenges on the combustion chamber design such as flame stability, emission control and temperature limitations. Therefore, a plate with height of 245mm inside extension part is added on the side surface of combustion chamber. The complete assembly for all parts of combustion chamber is as shown as Figure 3-2. The diameter of fuel inlet of chamber is 50mm which in cylindrical shape. This is the entrance where the biofuel will flow inside the chamber and burned under high temperature. The fuel inlet is attached to the chamber zone with height of 560mm. The exit of the chamber is designed in square shape with dimension 100mm x 100mm. The total height of combustion chamber can reach to 725mm. The details drawing for assembly of combustion chamber can refer **Appendixes A**.

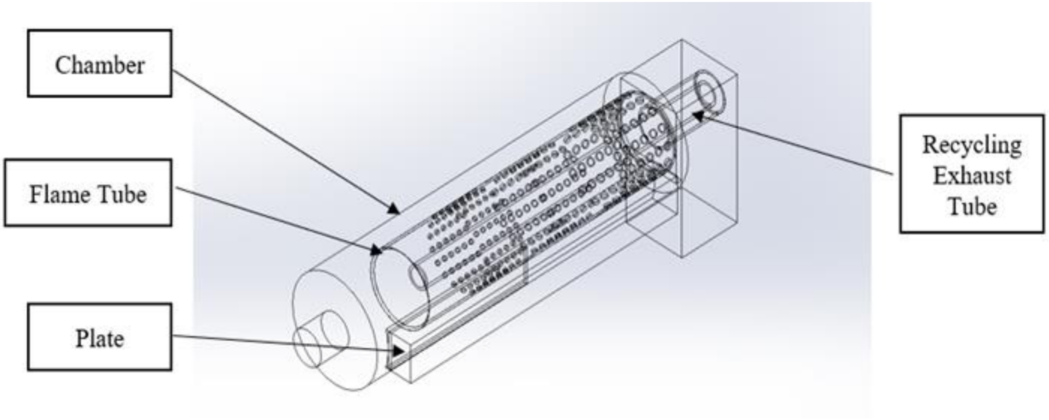


Figure 3-2: Schematic Diagram of Combustion Chamber

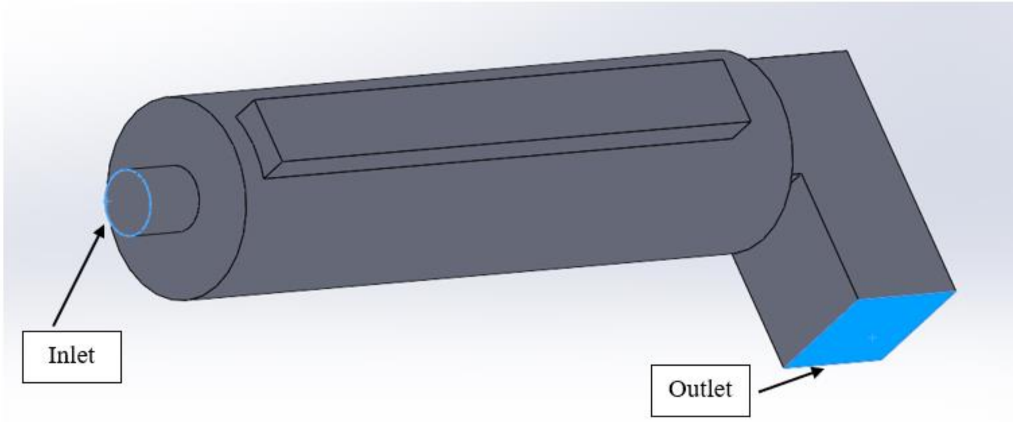


Figure 3-3: Inlet and Outlet of Combustion Chamber

The combustion chamber consists of flame tube with its length is 443 mm. The inner and outer diameter of flame tube is 100mm and 106mm respectively. There are several rows of holes on the flame tube which indicates and identifies three zones which are premix zone, primary combustion zone and dilution or cooling zone as shown as Figure 3-4. Each zone has constant rows number of 6 with a certain number of holes on each row with space between zones. In premix zone, there are 19 holes in each row and each hole has diameter of 6mm and distance of 12mm between each other. Premix zone has narrower reaction zone compared to other zone therefore the holes in premix zone have smaller diameter. In primary combustion zone, the number of holes in each row are 16 with diameter of 8mm. The distance between each hole is 14mm. Lastly, dilution or cooling zone has the least number of holes which is 14 but each hole has largest diameter which is 10mm. The distance between each hole is 16mm. The details drawing of flame tube can refer **Appendixes A**. Flame tube was assemble in the centre of the chamber with a recycling exhaust tube. The length of recycling exhaust tube is 520mm and its inner and outer diameter is 26mm and 33mm respectively. The recycling exhaust tube consists of recycle tube and recycle tube shell. The further information of recycling exhaust tube will be discussed in section 3.4.5.2.

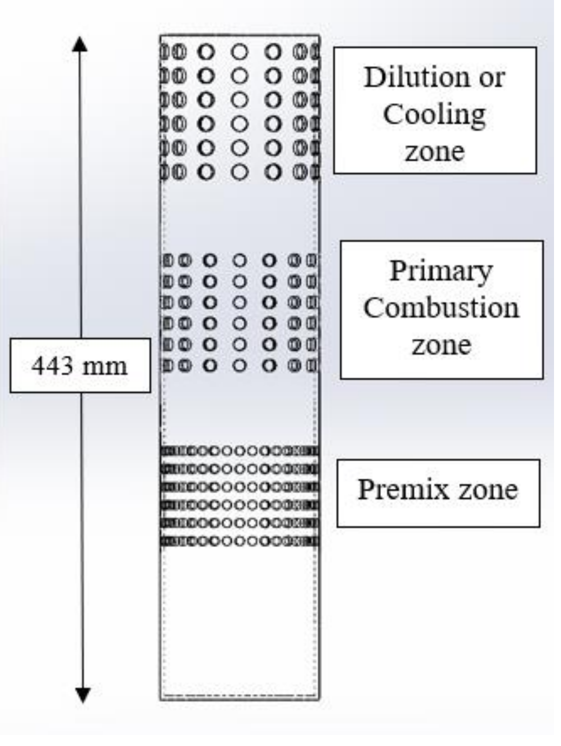


Figure 3-4: Schematic Diagram of Flame Tube

## 3.3 Simulation Model by ANSYS-FLUENT Software

Combustion chamber geometry was optimized by using CFD software, ANSYS-FLUENT program to carry out simulation. CFD simulation provides a virtual laboratory to perform investigation in the early stages which can reduce the time spent and cost. CFD modelling can conduct simulations by using commercial or own software with the same base. The other reason of use of CFD analysis techniques is it can provide a good prediction and improve combustion performance and pollutant emissions.

The model in ANSYS-FLUENT are focused on fluids flow and chemical reactions, including a very good model to run a first-approach simulations of combustion systems. In the workbench, there are five categories in ANSYS-FLUENT which are Geometry, Mesh, Setup, Solution and Results. The explanation of main characteristic of performing way a simulation by using ANSYS-FLUENT will be discussed in next section. The explanation includes mesh strategy or creation, models setup and run calculations.

The combustion chamber geometry which is designed by CAD software was save in parasolid file (.x_t) and then imported to the Design-Modeller tool in category of Geometry. There is total five parts in the body of combustion chamber. For the chamber body, it is set as fluid body while other parts remain as solid body for simplify meshing operation as shown as Figure 3-5.

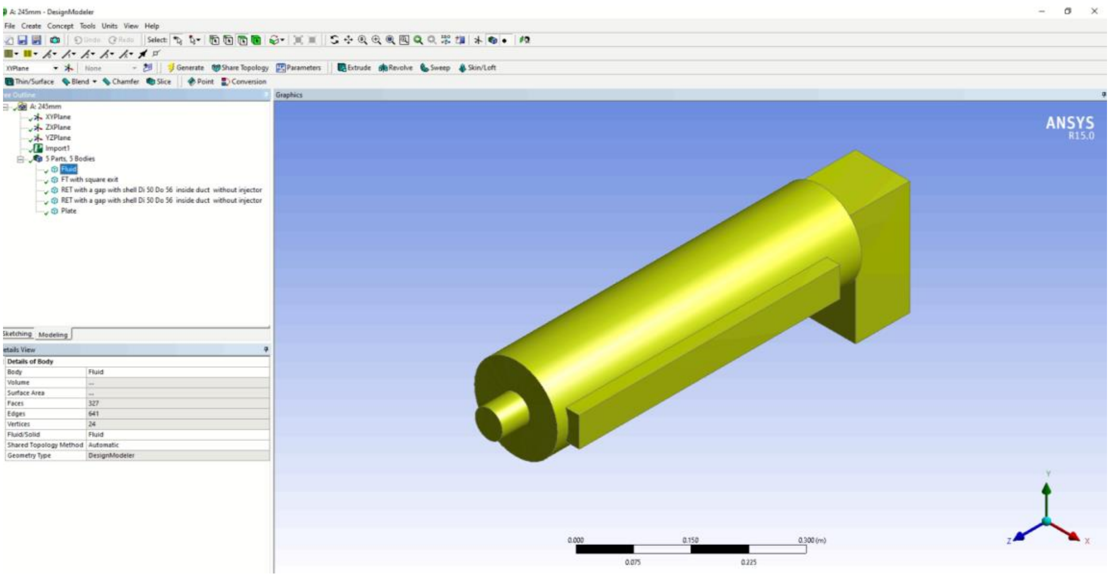


Figure 3-5: Combustion Chamber in Design Modeler

### 3.3.1 Meshing Strategy

After done the setting in Geometry, the next category is Mesh. Generally, the purpose of a meshing tool is to create the mesh and test its quality. There are three boundary conditions were named in combustion chamber which are Inlet, Wall and Outlet as shown as Figure 3-6. The size of elements in meshing is 0.003m. Normally, the elements size must be reduced to become smaller and denser to improve solution accuracy especially there is a zone where intense chemical reactions or high energy turbulences are occurring. In this combustion chamber, the mesh was refined all long near the center of chamber and near to inlet as shown as Figure 3-7 since there is location where the combustion reaction starts to occur.

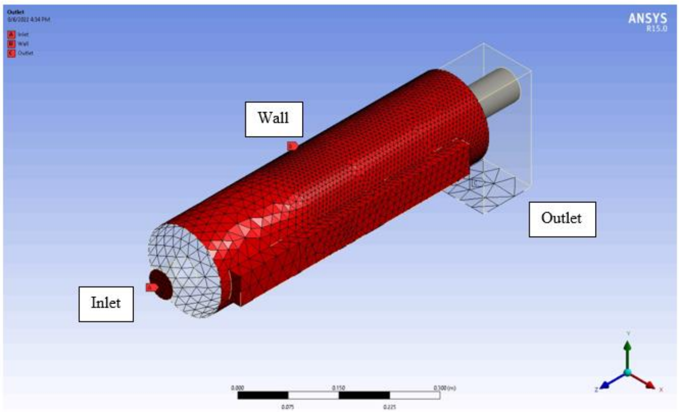


Figure 3-6: Boundary Conditions of Combustion Chamber

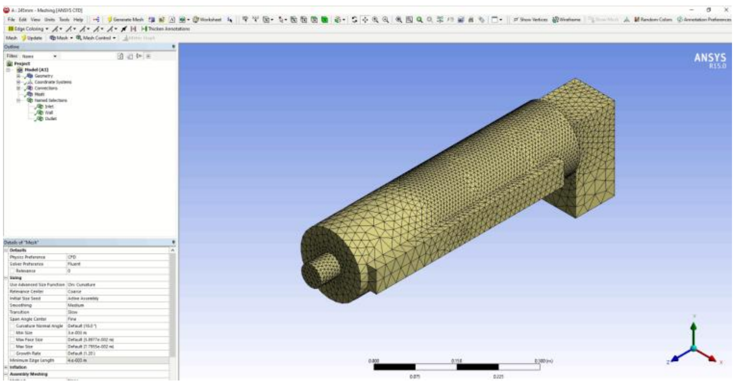


Figure 3-7: Meshing Results of Combustion Chamber

The statistic of element quality of combustion chamber is illustrated as Figure3-8. The statistic displays a bar chart of number of elements against element metrics. Generally, zero element metric indicates there is no quality on the geometry and cannot be simulated. Based on Figure 3-8, it can be observed that the range of element metric was started from 0.07 or 7%. Most of the elements were concentrated between 75% and 88% where the elements located are significant to affect the simulation results.

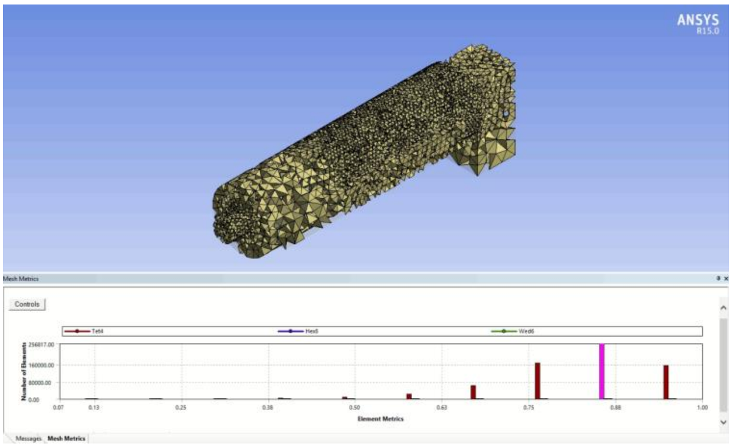

Figure 3-8: Statistic of Element Quality

### 3.3.2 Simulation Setup

After updating mesh, the category of Setup was opened. Double Precision and Serial processing were selected. The simulation setup is the step to allow the models are assigned to the design modelled in the previous parts. This is also a reason for selecting ANSYS-FLUENT since it can incorporate a good package for simulate the combustion phenomena.

ANSYS-FLUENT setup will perform several CFD calculation and mathematical processes which are governed by fluid flow governing equations. The governing equations are series of balances and fluid properties which are continuity equation (Eq. 1), momentum balance (Eq. 2), energy balance (Eq. 3 or 4) and partial mass balances (Eq. 5). These governing equations were discretised by ANSYS-FLUENT for every point of the system. Different models were resorted by ANSYS-FLUENT to estimate various parameters such as chemical reactions and viscous behaviour. The selection of the models based on the problem or the requirements. The details of the model's selection will be discussed in next section. For setup, the initial step is turning on energy equation. The governing Equation 1-5 are shown below:

$$\frac{\delta\rho U}{\delta t} + \nabla.\rho U = 0 \qquad (1)$$

$$\frac{\delta\rho U}{\delta t} + (\nabla.\rho UU) = -\nabla p + \nabla.\tau + \rho g \qquad (2)$$

$$\frac{\delta\rho h}{\delta t} + \nabla.\rho U = \nabla.\lambda_e\nabla T - \nabla.q_r + \nabla.\textstyle\sum_l \rho\, h_l(T) D_e \nabla m_l \qquad (3)$$

$$\rho C_p \frac{DT}{Dt} = \nabla.\lambda_e\nabla T - \nabla.\textstyle\sum_l \rho\, h_l(T) D_e\nabla m_l - \rho \sum_l \frac{Dm_l}{Dt} h_l(T) \qquad (4)$$

$$\frac{\delta\rho m_l}{\delta t} + \nabla.\rho U m_l = \nabla.D_e\rho\nabla m_l - R_1 \qquad (5)$$

#### 3.3.2.1 Viscous Model

Since there will be a fluid flowing through the combustion chamber, the viscous model had activated as shown as Figure 3-9. K-epsilon model was chosen to estimate the turbulent-flow behaviour of the combustion systems. Viscous model is practical for many flows and its convergence is simple. The model is made up by two equations which are turbulent kinetic energy ($k$) (Eq. 6) and the turbulent dissipation rate ($\epsilon$) (Eq. 7).

$$\frac{\delta(\rho k)}{\delta t} + \frac{\delta(\rho k u_i)}{\delta x_i} = \frac{\delta}{\delta x_j}\left[(\mu + \frac{\mu_t}{\sigma_k})\frac{\delta k}{\delta x_j}\right] + P_k + P_b + \rho\epsilon - Y_M + S_k \qquad (6)$$

$$\frac{\delta(\rho\in)}{\delta t} + \frac{\delta(\rho\in u_i)}{\delta x_i} = \frac{\delta}{\delta x_j}\left[(\mu + \frac{\mu_t}{\sigma_\in})\frac{\delta\in}{\delta x_j}\right] + C_{1\in}\frac{\in}{k}(P_k + C_{3\in}P_b) - \rho C_{2\in}\frac{\in^2}{k} + S_\in \qquad (7)$$

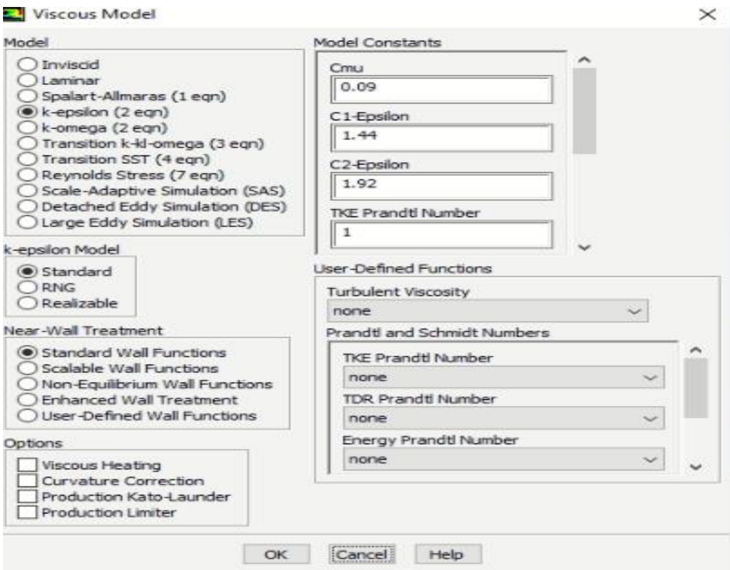


Figure 3-9: Viscous Model

#### 3.3.2.2 Species Transport Model

There are several species models are available in ANSYS-FLUENT which are Species transport, non-premixed combustion and non-premixed with radiation. Species transport model was activated since its lower computing demand compared to other species model. Generally, species transport model can be used to determine the geometry that will produce combustion. Therefore, this model is significant since it can provide the initial estimation of the minimum size in which the combustion process will start occurring. Besides, Eddy-Dissipation equations were activated in the volumetric combustion model as shown as Figure 3-10.

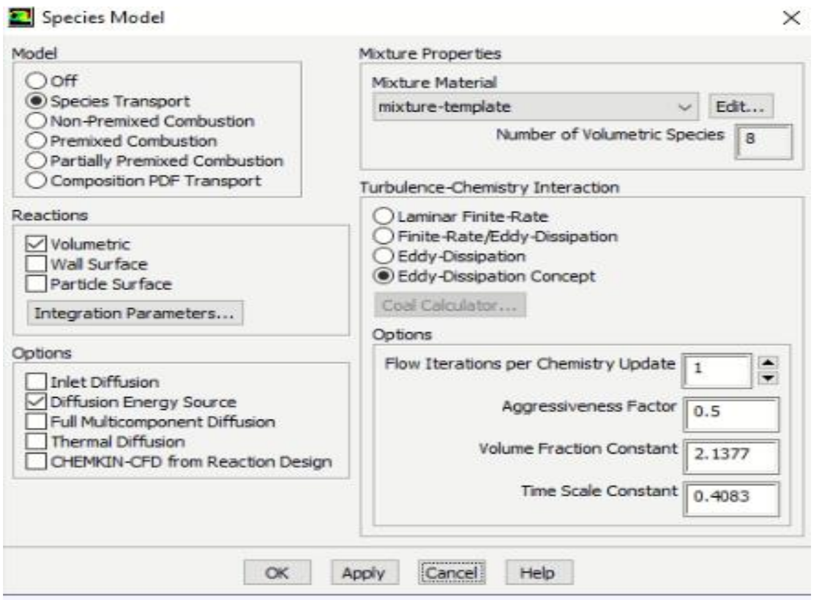

Figure 3-10: Species Model

#### 3.3.2.3 Material

As mentioned before, the biofuel that was used in single stage MGT application was palm oil or vegetable oil. A chemical formula of palm oil was given by project supervisor which is $C_{55}H_{90.8}O_{1.33}$. The combustion balanced equation was calculated to determine the mole number of reactants and products (Eq. 8). The details calculation can be referred as **Appendixes B**. The properties of palm oil are shown as Table 3-1. Besides palm oil, other formula of materials such as carbon dioxide, carbon monoxide, methane and nitrogen were selected. After creating the materials, four reactions under mixture-template were created. These four reactions were balanced (Eq. 9 – Eq.12). Based on chemical kinetic theory, activation energy will be created from collisions between molecules which have an initial energy greater than or equal to an energy. Therefore, the activation energy can be given by Arrhenius equation (Eq. 13) which relates to rate exponent and pre-exponential factor. The details of Arrhenius Equation can refer to **Appendixes B**. The properties of four reactions are tabulated in Table 3-2 and Table 3-3.

Combustion Balanced Equation:

$$C_{55}H_{90.8}O_{1.33} + 77.035O_2 + 289.6516N_2 \rightarrow 55CO_2 + 45.4H_2O + 289.6516N_2 \tag{8}$$

Reaction 1:

$$C_{55}H_{90.8}O_{1.33} + 25.4O_2 \rightarrow 52.25CO_2 + 39.9H_2 + 2.75CH_4 \tag{9}$$

Reaction 2:

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \tag{10}$$

Reaction 3:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{11}$$

Reaction 4:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{12}$$

Arrhenius Equation:

$$k = Ae^{-\frac{E_A}{RT}} \tag{13}$$

Table 3-1: Properties of Palm Oil

| **Parameters** | **Value** |
|---|---|
| Chemical Formula | $C_{55}H_{90.8}O_{1.33}$ |
| Specific Heat, Cp (J/kg.K) | 1875 |
| Molecular Weight (kg/kmol) | 772.13 |
| Standard State Enthalpy (J/kg.mol) | -2.497$\times 10^8$ |
| Standard State Entropy (J/kg.mol.K) | 540531 |
| Temperature (K) | 298.15 |

Table 3-2: Properties of Reactions 1 and 2

<table>
<tr><th>Reaction</th><th colspan="4">1</th><th colspan="2">2</th></tr>
<tr><td>Number of Reaction</td><td colspan="4">2</td><td colspan="2">2</td></tr>
<tr><td>Species</td><td colspan="2">$C_{55}H_{90.8}O_{1.33}$</td><td colspan="2">$O_2$</td><td>CO</td><td>$O_2$</td></tr>
<tr><td>Static Coefficient</td><td colspan="2">1</td><td colspan="2">25.4</td><td>1</td><td>0.5</td></tr>
<tr><td>Rate Exponent</td><td colspan="2">0</td><td colspan="2">1</td><td>1</td><td>1</td></tr>
<tr><td>Number of Products</td><td colspan="4">3</td><td colspan="2">1</td></tr>
<tr><td>Species</td><td>CO</td><td colspan="2">$H_2$</td><td>$CH_4$</td><td colspan="2">$CO_2$</td></tr>
<tr><td>Static Coefficient</td><td>52.25</td><td colspan="2">39.9</td><td>2.75</td><td colspan="2">1</td></tr>
<tr><td>Rate Exponent</td><td>0</td><td colspan="2">0</td><td>0</td><td colspan="2">0</td></tr>
<tr><td>Pre-Exponential Factor</td><td colspan="4">$2.587 \times 10^9$</td><td colspan="2">$2.239 \times 10^{12}$</td></tr>
<tr><td>Activation Energy J/kg.mol</td><td colspan="4">$1.256 \times 10^8$</td><td colspan="2">$1.70 \times 10^8$</td></tr>
</table>

Table 3-3: Properties of Reactions 3 and 4

| **Reaction** | **3** | | **4** | |
|---|---|---|---|---|
| Number of Reaction | 2 | | 2 | |
| Species | $H_2$ | $O_2$ | $CH_4$ | $O_2$ |
| Static Coefficient | 1 | 0.5 | 1 | 2 |
| Rate Exponent | 1 | 1 | 1 | 1 |
| Number of Products | 1 | | 2 | |
| Species | $H_2O$ | | $CO_2$ | $H_2O$ |
| Static Coefficient | 1 | | 1 | 2 |
| Rate Exponent | 0 | | 0 | 0 |
| Pre-Exponential Factor | $9.87 \times 10^8$ | | $2.119 \times 10^{11}$ | |
| Activation Energy (J/kg.mol) | $3.10 \times 10^7$ | | $2.027 \times 10^8$ | |

### 3.3.2.4 Discrete Phase Model (DPM)

Discrete Phase Model (DPM) was activated by selecting interaction with continuous phase and unsteady particle tracking. DPM is specialized in simulating liquid spray and suspended particle trajectory. Discrete particles in liquid form have introduced to integral continuous (gas) phase to simulate diesel spray formation. The particle time set up size was set to 0.001s for 1000 maximum number of steps as shown as Figure 3-11. For physical model, temperature dependent latent heat was selected. The injection type of DPM model is swirl pressurized atomizer and the particle type is in droplet since the liquid form of particles become droplet after exit of the chamber. The number of particles stream were set to 100 as shown as Figure 3-12. The other properties of injection such as position and flow rate were tabulated in Table 3-4.

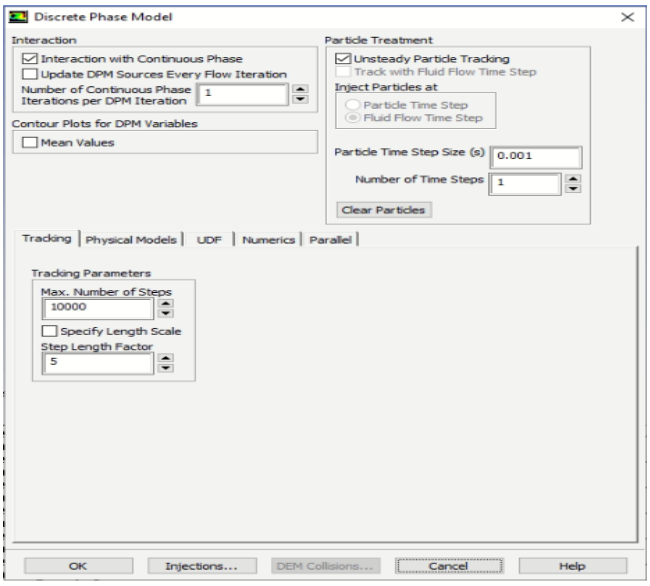

Figure 3-11: Discrete Phase Model (DPM)

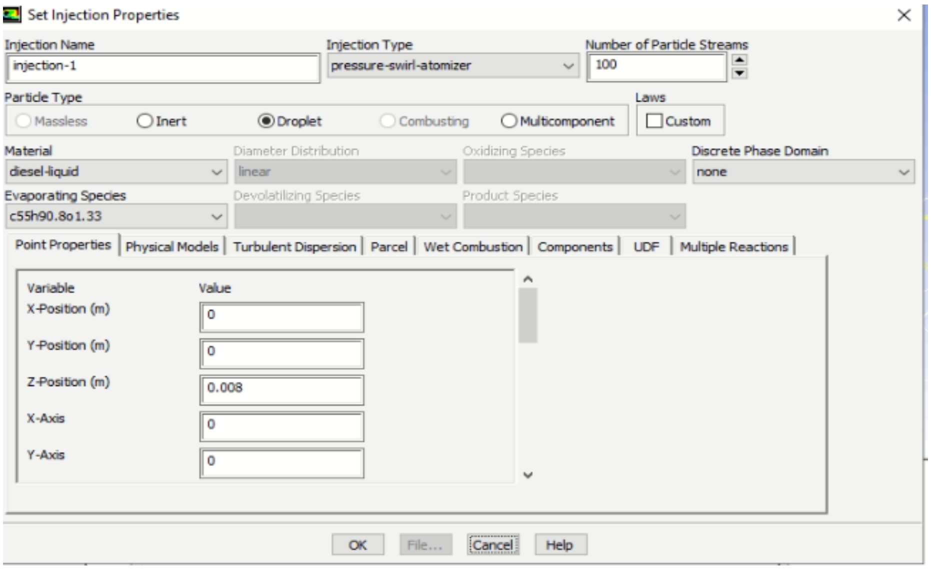

Figure 3-12: Set Injection Properties

Table 3-4: Properties of Set Injection

| | |
|---|---|
| Injection Type | Pressure-Swirl-Atomizer |
| Particle Type | Droplet |
| Number of Particle Streams | 100 |
| Material | Diesel Liquid |
| Evaporating Species | $C_{55}H_{90.8}O_{1.33}$ |
| Position (m) | X: 0 Y: 0 Z: 0.008 |
| Axis | X: 0 Y: 0 Z: 1 |
| Temperature (K) | 300 |
| Flow Rate (kg/s) | 0.002623333 |
| Start Time (s) | 0 |
| Stop Time (s) | 20 |
| Injector Inner Diameter (m) | 0.001 |
| Spray Half Angle (deg) | 15 |
| Upstream Pressure (atm) | 16 |
| Sheet Constant | 12 |
| Ligament Constant | 0.5 |
| Atomizer Dispersion Angle | 6 |

#### 3.3.2.5 NOx Model

Under Species Transport section, NOx model can be activated by selecting three distinct chemical kinetic processes which are thermal NOx, prompt NOx and fuel NOx formation as shown as Figure 3-13. These three pathways are significant to be chosen since thermal NOx is produced by the oxidation of atmospheric nitrogen present in the combustion air. For Prompt NOx, it is using global kinetic parameters and formed by high-speed reactions at the flame front while fuel NOx is formed by oxidation of nitrogen contained in the fuel. Equation 14 and 15 show the principal reactions governing the formation of thermal NOx from molecular nitrogen while equation 16 shows formation of thermal NOx:

$$O + N_2 \rightleftharpoons N + NO \quad (14)$$

$$N + O_2 \rightleftharpoons O + NO \quad (15)$$

$$N + OH \rightleftharpoons H + NO \quad (16)$$

The concentration of O atoms and free radical OH will be required to evaluate the NOx formation. Therefore, an equilibrium was set for O atoms and none for free radical OH. The fuel species was selected on $C_{55}H_{90.8}O_{1.33}$. For prompt NOx, the fuel carbon atom is 55 while equivalent ratio is 0.43. In fuel NOx, the fuel type was set in gas form as shown as Figure 3-14.

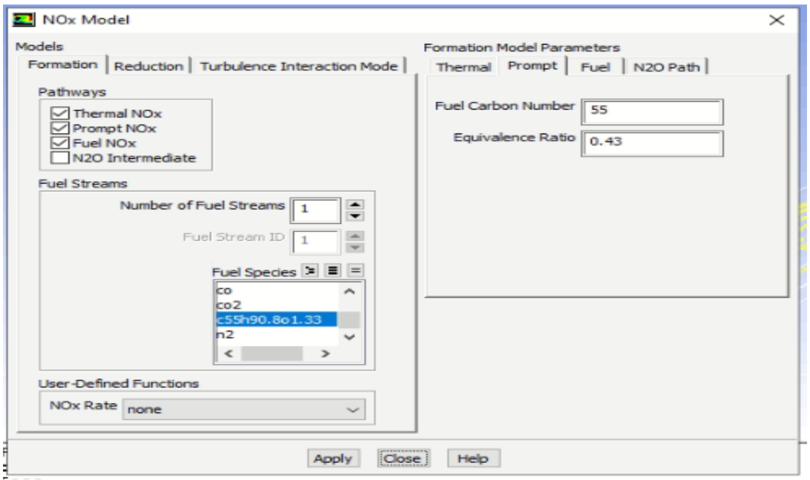


Figure 3-13: Prompt NOx in NOx Model

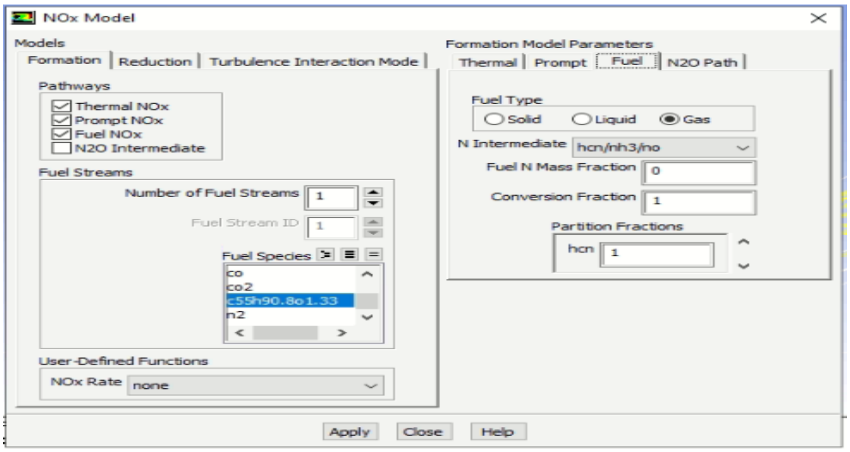

Figure 3-14: Fuel NOx in NOx Model

### 3.3.2.6 Acoustic Model

Acoustic Model can be activated by selecting Broadband Noise Sources as shown as Figure 3-15. Combustion process will cause a lot of noises or sound from the chamber. With the aid of acoustic simulation, it can help to optimize the sound produced from the combustion chamber. Therefore, a high prediction of acoustic effects of combustion chamber can be achieved and maximize the acoustic benefits.

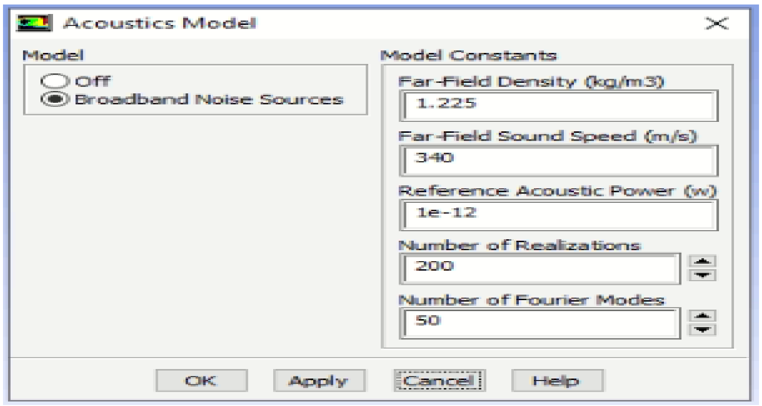

Figure 3-15: Acoustic Model

### 3.3.2.7 Boundary Conditions

In ANSYS-FLUENT, Boundary Conditions are a necessary component of a mathematical model since they will direct the flow motion which contribute to a unique solution. There are three boundary conditions in this model which are Inlet, Outlet and Wall. The type of Inlet was changed to Mass-Flow-Inlet instead of Pressure-Inlet as shown as Figure 3-16 while Outlet and wall remains same setting.