EFFECTS OF AIR INLET ANGLE ON THE COMBUSTION AND EMISSION CHARACTERISTICS OF A CYLINDRICAL CHAMBER FUELED WITH WASTE COOKING OIL BLENDS

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DECLARATION

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LIST OF ABBREVIATIONS

BA	Blade Angle
BSFC	Brake Specific Fuel Consumption
B100	100% Pure Biodiesel
CD	Combustion Duration
DI	Direct Injection
DS	Double Swirl
GVD	Guide Vanes Design
ICE	Internal Combustion Engine
IDF	Inverse Diffusion Flames
LS	Lateral Swirl
SN	Swirl Number
SR	Swirl Ratio
SS	Separated Swirl
WCO	Waste Cooking Oil
WFGCS	Wall Flow Guided Combustion System

ABSTRAK

Keterbatasan bahan api fosil telah mendorong pencarian menyeluruh untuk sumber boleh diperbaharui alternatif. Bahan api diesel yang diperbuat daripada petroleum boleh digantikan dengan biodiesel, sumber tenaga alternatif. Konstituen utama dalam bahan api biodiesel ialah ester yang diperbuat daripada lemak sayuran atau haiwan. Ia dianggap sebagai alternatif tenaga yang berkesan, sihat dan semula jadi untuk bahan api fosil. Walau bagaimanapun, minyak sayuran atau sisa minyak masak kurang mudah terbakar dan lebih likat daripada diesel tulen. Titisan yang lebih besar dihasilkan kerana kualiti pengabusan yang lemah. Titisan ini akan terbakar secara perlahan kerana kelewatan pencucuhan yang lebih singkat. Di samping itu, ciri pengatoman yang lemah bagi sisa minyak masak akan membawa kepada pencampuran bahan api udara yang lemah. Percampuran udara-bahan api yang lemah akan mengakibatkan prestasi pembakaran dan pelepasan yang buruk. Oleh itu, gerakan pusingan diperkenalkan untuk menambah baik pencampuran udara-bahan api dengan mewujudkan zon peredaran semula gelora yang sengit. Sudut masuk akan menjejaskan pergerakan udara di dalam kebuk pembakaran. Sebuah kebuk pembakaran silinder dengan dua salur udara tangen telah dicipta. Kesan udara berpusar dengan sudut masuk udara tangen 0°, 10°, 20°, 30° dan 45° telah disiasat. Kadar aliran jisim udara dan bahan api adalah sama untuk semua model untuk mempunyai perbandingan yang lebih baik bagi kesan gerakan pusingan. Profil suhu dan halaju dan pecahan jisim O_2, CO_2 dan pencemar NO dinilai secara kritikal. Sepanjang julat sudut masuk udara tangen yang diperiksa, sudut optimum didapati ialah 45°. Kebuk pembakaran dengan sudut tangen 45° mengeluarkan bahan pencemar paling sedikit NO. Selain itu, didapati minyak tanah lebih baik sedikit daripada sisa bahan bakar minyak masak dari segi ciri-ciri pembakaran dan pelepasan. Kelikatan dan nombor setana minyak tanah adalah lebih rendah daripada sisa bahan bakar minyak masak supaya ia agak lemah dalam ciri pengatoman dan pengewapan. Ini akan mengakibatkan pelepasan CO_2 dan pencemar NO yang lebih rendah. Walau bagaimanapun, sisa bahan bakar minyak masakboleh menjadi sumber tenaga alternatif kerana ia boleh diperbaharui dan terbiodegradasi. Ia juga mempunyai prestasi pembakaran yang serupa dengan bahan api konvensional.

ABSTRACT

The scarcity of fossil fuels had greatly prompted a thorough search for alternative renewable resources. Diesel fuel made of petroleum could be replaced with biodiesel, an alternative energy source. One of the main constituents in biodiesel fuels is esters which are made of vegetable or animal fats. They are regarded as effective, healthy, and natural energy alternatives for fossil fuels. However, vegetable oil or waste cooking oil (WCO) is less combustible and possess higher viscosity compared with pure diesel. Larger droplets are generally produced due to the poor atomization quality. These droplets will burn slowly because of the shorter ignition delay. In addition, poor atomization characteristics of WCO will lead to poor air-fuel mixing. The poor air-fuel mixing results in bad performance of combustion and emission. Therefore, swirl motion is introduced to improve air-fuel mixing by creating an intense turbulent recirculation zone. The inlet angle affects the air motion inside the combustion chamber. A cylindrical combustion chamber with two tangential air inlets were created. The effects of air swirling with tangential air inlet angles of 0°, 10°, 20°, 30° and 45° were investigated using Ansys Fluent with a model of species transport. The mass flow rate of air and fuel are the same for all models to compare the effects of swirl motion better. The temperature and velocity profiles as well as the mass fraction of O_2, CO_2 and pollutant NO are comprehensively evaluated. Over the range of tangential air inlet angles examined, the optimal angle was discovered to be 45°. The combustion chamber with tangential angle of 45° emitted the least pollutants of NO. Furthermore, it was also found that kerosene is slightly better than WCO fuel in terms of combustion and emissions characteristics. The viscosity and cetane number of kerosene is lower than that of WCO fuel so that it is comparatively poor in atomization and vaporization characteristics. This phenomenon has resulted in lower emissions of CO_2 and pollutant NO. However, WCO fuel can be an alternative resource of energy as it is renewable and biodegradable. It also has similar combustion performance with the conventional fuel.

CHAPTER 1 INTRODUCTION

1.1 Overview of Project

The research on alternative fuels and clean combustion techniques has been necessitated by dwindling fossil fuel resources, rising energy demand, and widespread environmental pollution caused by fossil fuel combustion. Biodiesel is being extensively researched to find a solution to the issue of fossil fuel depletion. Biodiesel usage is fast becoming a worldwide trend due to its renewable nature, recycling potential from waste sources, and manufacturing flexibility when compared to traditional diesel.

Biodiesel fuels are mostly made from esters generated from waste cooking oils or animal fats. They are classified as an alternative form of energy to petroleum because they are clean, efficient, and natural. Waste cooking oils and diesel are miscible, and their blends are stable regardless of the mixing ratio or their storage time. Because of a wide range of waste vegetable oils and biodiesel fuel components from various resources, full compliance with biodiesel regulations may not always be attainable. Furthermore, biodiesel fuels have higher boiling point and viscosity and these properties may adversely impact the combustion process, resulting in slower burning and longer combustion duration (CD). Research on biodiesel fuel should focus on long-term renewable sources and their implications on engine combustion, performance, and emissions. As a result, researchers have conducted several investigations on WCO biodiesel and its blends with regular diesel fuel. They mixed kerosene and gasoline with WCO biodiesel and the volumetric ratio of the kerosene and gasoline added to WCO biodiesel were (5% kerosene, 95 % biodiesel for K5), (10 % kerosene, 90 % biodiesel for K10), (5% gasoline, 95 % biodiesel for G5) and (10 % kerosene, 90 % biodiesel for G10), respectively. They found that WCO biodiesel decreases CO, unburned hydrocarbon and smoke emissions but increases NOx emissions compared to conventional diesel (Gad and Ismail, 2021).

Modern internal combustion engines (ICE) are designed to generate gas vorticity (swirl) to create higher turbulence in the combustion chamber. Air motion in the chamber is an effective method in ICE to optimize the air-fuel mixing process and subsequently achieve faster burning rates. Swirl creates an intense turbulent recirculation zone, which stabilizes the flame and enhances fuel and air mixing, resulting in greater and faster homogeneous mixture. The unfavourable axial pressure gradient caused by air swirling during combustion generates an internal recirculation region through the furnace axis while simultaneously eliminating the exterior recirculation region near the walls. It is known to be highly effective if the regulating inlet angle is varied, instead of controlling the stoichiometric ratio in the primary combustion zone.

Some burners have high combustion temperatures and the fuel-air ratio far exceeds the stoichiometric air-to-fuel ratios, leading to the production of carbon monoxide, nitrogen oxides, and unburned hydrocarbons. Therefore, the introduction of new strategies, such as air swirling and the use of waste cooking oil fuels, on pollutant emissions in burners must be fully addressed.

1.2 Problem Statement

In recent years, many researchers have investigated the widespread consumption of fossil fuels as the main energy source for ICE, leading to the search for alternative energy sources. Waste cooking oil (WCO) can be converted into biodiesel, which is a renewable energy source. However, viscosity of WCO biodiesel is higher than conventional fuel. This results in poor atomization which leads to poor air-fuel mixing. The poor air-fuel mixing will affect the performance of combustion and emission. Furthermore, swirl motion is suitable for the mixing of air and fuel because it can stabilize the flame and reduce pollutant. Swirl motion can be added into the combustion chamber to enhance turbulence. As a result, the improvement of air-fuel mixing of WCO biodiesel leads to an increase in combustion efficiency. The main factor that affects the swirl motion is the angle of tangential air inlet. When the tangential air inlet angle is varied from 0˚ to certain angle, the air particles show a swirling motion after the air inlet port. This is because the larger tangential air inlet angle will make the trajectory of air particles more disordered. Thus, the main objective of this project is to aim for a better understanding on the influences of swirl motion on the combustion and emission characteristics of biodiesel produced from waste cooking oil.

1.3 Objectives

(i) To study the influence of swirl motion on combustion and emission characteristics of a cylindrical combustion chamber with WCO fuel using Ansys Fluent.

(ii) To investigate the difference in combustion and emission performance of a cylindrical combustion chamber between WCO fuel and conventional fuel using Ansys Fluent.

1.4 Scope of Project

In this project, the influence of swirl motion on combustion and emission characteristics of waste cooking oil fuel will be investigated. Firstly, the concept of swirl combustion is proposed, designed and analyzed. A cylindrical combustion chamber which consists of two tangential air inlets to provide swirling motion to the combustion. The model was used in this project to vary the angles of the tangential air inlets, from 0º to 45º. SOLIDWORKS software will be used for 3D CAD modelling and the designs were then verified using ANSYS software in terms of temperature, velocity, species and pollutants.

There are several limitations on the project. Firstly, the chemical properties of WCO biodiesel used for simulation were obtained from relevant journal articles. The information obtained from these journal articles might not be exactly similar with the fuel used for the simulation. The accuracy of the generated results could be affected due to inaccurate input data.

Furthermore, the dimensions of the solid models were also determined by referring to several journal articles. A good design of combustion chamber can make use of turbulent motion of air to improve the air-fuel mixing. The dimensions of combustion chamber found from several related articles might be inappropriate to apply to the simulation model of the project. Thus, the results generated from the simulation model could be affected in terms of the accuracy due to the inappropriate dimensions.

CHAPTER 2 LITERATURE REVIEW

Several relevant reviews of the previous studies are provided in this chapter. These studies include the combustion of liquid fuel, swirl combustion, and the influence of swirl motion on the combustion of liquid fuel.

2.1 Combustion of Liquid Fuel

Combustion is defined as a chemical reaction in which a fuel is heated and reacted with oxidizing agent to produce energy, and it is usually accompanied by the production of heat and flame. The combustion can be divided into five main types which are complete combustion, incomplete combustion, rapid combustion, spontaneous combustion, and explosive combustion (Akanksha, 2021).

Complete combustion of liquid fuel produces water vapor and carbon dioxide in the presence of sufficient oxygen (Sadati et al., 2015; Kanniche et al., 2010). The chemical equation for complete combustion of a hydrocarbon with oxygen as the oxidizing agent can be written as:

$$2C_8H_{18} + 25O_2 \text{ -----> } 18CO_2 + 16H_2O$$

A blue flame generally signifies a complete combustion. The emission of smoke is negligible because all of the reactants are completely burned. This means that the complete combustion is environmentally friendly compared to an incomplete combustion (Osborn, 2018).

Incomplete combustion occurs because of improper mixture of air-fuel, deficient residence time, inadequate temperature, and insufficient total excess air (Caillat and Vakkilainen, 2013). The products of incomplete combustion are water, carbon monoxide and carbon. The chemical reaction for incomplete combustion of hydrocarbon with oxygen as the oxidizing agent can be written as:

$$4CH_4 + 5O_2 \text{ -----> } 2CO + 8H_2O + 2C$$

A yellow or orange coloured flame is occasionally produced to show incomplete combustion. The fuel will not be combusted completely and the combustion process generates pollutant and smoke emission. Furthermore, lower amount of energy is produced from incomplete combustion compared to complete combustion (Osborn, 2018).

2.1.1 Waste Cooking Oil (WCO)

Waste cooking oil (WCO) is a vegetable oil that has been used in the preparation of the food but it is not appropriate for re-use (Kataria, Mohapatra and Kundu, 2019). When compared to other edible and non-edible oil sources, WCO is the most economical option (Attia and Hassaneen, 2016). Furthermore, much of the WCO is dumped into rivers and open areas, polluting the environment. WCO can be effectively disposed of by replacing it and using it as fuel in internal combustion engines (Senthil and Jaikumar, 2014). Waste cooking oil is desirable as a diesel engine fuel because it is readily available and it shares similar properties with that of diesel fuel (Muralidharan and Vasudevan, 2011). The heating value of waste cooking-oil biodiesel is around 15% lower than that of diesel fuel (Tushar, Prashant and Vishwanath, 2013). Table 2.1 shows some of the salient properties of WCO in comparison to conventional diesel. Generally, waste cooking oils have high viscosity, low volatility, and high molecular weight, which prevents them from being used directly in combustion systems (Karmakar and Mukherjee, 2010). Direct use of waste cooking oils in diesel engines present several drawbacks, including injector stickiness, poor atomization, and carbon deposits. Various methods, such as transesterification, combining with diesel fuel or alcohols, and preheating, were used to reduce the viscosity of waste cooking oils (Sanli, 2018).

Table 2.1: Comparison between properties of WCO and diesel (Senthil and Jaikumar, 2014)

Properties	**Diesel**	**Waste Cooking Oil (WCO)**
Density (kg/m3)	840	880
Low heating value (kJ/kg)	42,490	39,600
Viscosity (CST) @ 30°C	4.59	45
Flash point (°C)	52 – 96	273
Cetane number	45	37
Auto ignition temperature (°C)	260	300

WCO that has been discarded can be used to produce biodiesel. It outperforms other alternative fuels in terms of environmental and economic benefits. Because the price of raw edible oils is expensive, the price of biodiesel produced from raw edible oils will be higher compared to biodiesel produced from WCO. The price of raw edible oil is approximately 75–90 percent of the price of the biodiesel fuel. Meanwhile, the use of raw edible oils (food-grade feedstocks) in biodiesel fuel production could raise food-chain costs. As a result, the use of low-cost waste feedstocks may be successful in the industrialization and commercialization of biodiesel fuels, lowering the cost dramatically (Talebian – Kiakalaieh, Amin and Mazaheri, 2013). As a result, using waste cooking oils in biodiesel manufacturing would be a more cost-effective and long-term option (Nurfitri, Maniam, Hindryawati, Yusoff and Ganesan, S., 2013).

The most popular method for producing biodiesel is transesterification, which involves converting single/triglyceride molecules of vegetable oils into smaller, straight-chain molecules, as shown schematically in Figure 2.1. The efficiency in which oil is converted into biodiesel is determined by the catalyst type and concentration, the kind and molar ratio of alcohol, as well as other reaction factors such as duration, temperature, and mixing rate (Aboelazayem, El-Gendy, Abdel-Rehim, Ashour and Sadek, 2018). Aboelazayem et al. (2018) indicated that the best results were obtained at a reaction temperature of 60 °C, a 1 percent w/w potassium hydroxide (KOH) catalyst, and a molar ratio of methanol to oil of 6:1, with a product yield of roughly 96 percent (Attia and Hassaneen, 2016).

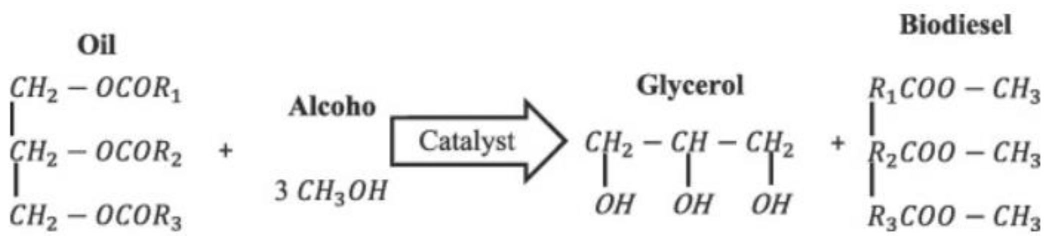


Figure 2.1: Stoichiometric Transesterification reaction (Aboelazayem, El-Gendy, Abdel-Rehim, Ashour and Sadek, 2018)

Alternatively, WCO can be blended with conventional light and heavy diesel oils, allowing for more cost-effective use while also improving environmental and health conditions through waste management (Asri and Sari, 2015).

2.1.2 Combustion Characteristics and Gas Emissions of Waste Cooking Oil Biodiesel Blends

Over the years, most of the research were carried out using various types of engines with biodiesel made of different oils. In addition, they have focused on the influence of various factors on the performance of an engine with combustion and emission characteristics of biodiesel. Numerous scientists have studied the effects of methyl esters fuel mixtures on the performance and emissions of compression ignition engines (Suresh, Jawahar and Richard, 2018). Biodiesel produced by the transesterification process was the subject of practically all the reported literature research. Engine testing with higher blend ratios of biodiesel, up to 100% pure biodiesel, are likewise scarce. Nonetheless, these experiments found that biodiesel may be used in standard diesel engines with little or no modification up to a volume proportion of 20%. (Madheshiya and Vedrtnam, 2014). With regards to this, biodiesel was tested in a laboratory-scale diesel engine at blend levels up to 100%. (B100). To determine the best blend, researchers compared the engine performance, emissions, and combustion properties of biodiesel blends to crude diesel (Gad, Abu-Elyazeed, Mohamed and Hashim, 2021). Figure 2.2 illustrates the brake specific fuel consumption (BSFC) of several blends against engine load. Because the pyrolysis WCO has a lower viscosity than gas oil, increasing the blending ratio with diesel oil from 0 to 100% caused an increased in the specific fuel consumption. Due to the lower viscosities of the WCO biodiesel blends, the injected fuel had a smaller droplet size, less fuel penetration, inappropriate fuel-air mixing, and reduced combustion efficiency (Hirkude and Padalkar, 2012).

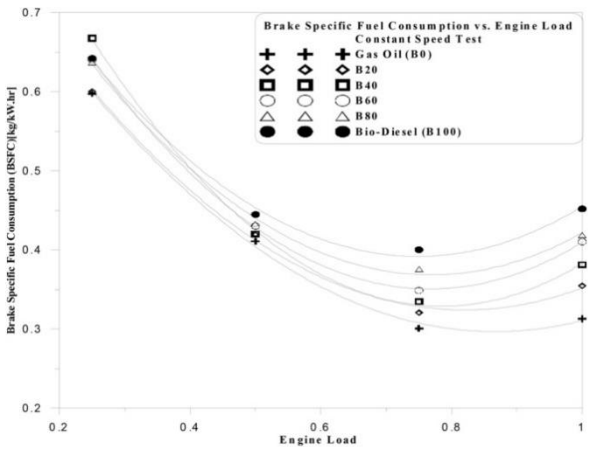


Figure 2.2: Influence of WCO biodiesel blend ratio at different loads on BSFC (Hirkude and Padalkar, 2012)

The nitrogen oxide concentrations of the WCO biodiesel blends were shown in Figure 2.3 against the variation in the engine load. An increased in the NOx emissions is attributed to a higher engine load because of the greater fuel usage. Because the pyrolysis WCO has lower cetane number, it has poor ignition capabilities and emits less NOx than crude diesel. Lower cetane number of the pyrolysis WCO also leads to a longer ignition delay, an increased in blend ratio was found to suppress the NOx generation at higher engine loads. This scenario provides the fuel additional time to be prepared, mixed, and burned (Tesfa, Mishra, Zhang, Gu and Ball, 2013).

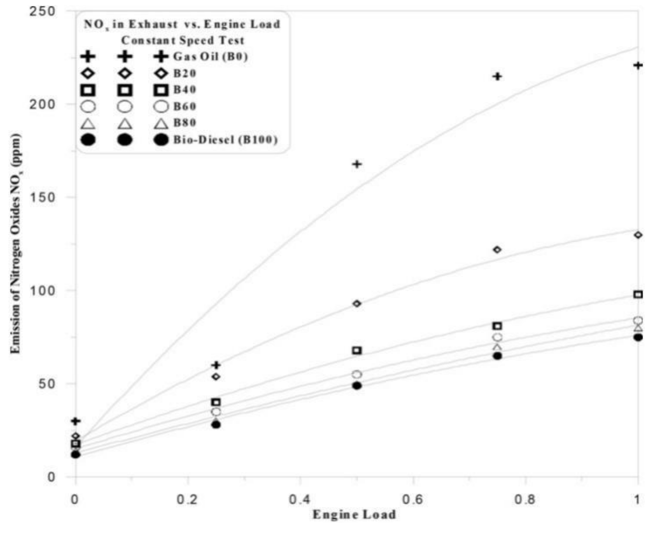


Figure 2.3: Influence of WCO biodiesel blend ratio with engine load on NOx emissions (Tesfa, Mishra, Zhang, Gu and Ball, 2013)

Figure 2.4 depicts the smoke emissions of the WCO biodiesel blends when the engine load was varied. An increased in the smoke emissions is linked to the increased engine load, which was the result of the increased fuel consumption. The lower combustion efficiency of WCO biodiesel blends was caused by the lower viscosity of pyrolysis WCO, which resulted in increased smoke emissions. The pyrolysis WCO produced more smoke due to its lower viscosity, lower fuel penetration and droplet size, and inappropriate fuel-air mixing (Das, Sarkar, Datta and Santra, 2018).

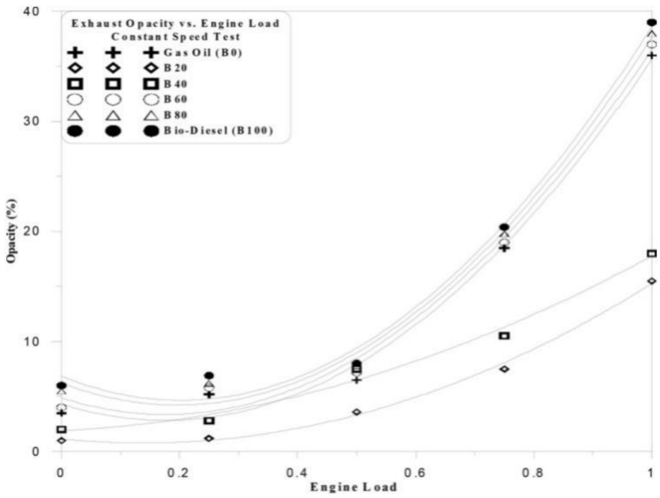


Figure 2.4: Influence of WCO biodiesel blends with the engine load on smoke emissions (Das, Sarkar, Datta and Santra, 2018)

2.2 Swirl Combustion

Using biofuel directly in diesel engine is generally restricted because it can create a variety of engine problems, including poor atomization, reduction in combustion efficiency and altered ignition delay (Hamid, Idroas, Basha, Sa'Ad, Che Mat, Abdullah and Zainal Alauddin, 2016). To alleviate these problems, in-cylinder airflow characteristics must be improved. Theoretically, evaporation and diffusion are improved with faster in-cylinder air flow. The combustion will be improved (Shahir, Masjuki, Kalam, Imran and Ashraful, 2016). Researchers have proposed numerous strategies, including altering the intake system, redesigning the piston crown, and utilizing guide vanes to direct the appropriate air flow characteristics (Che Mat, Idroas, Hamid and Zainal, 2018). To produce optimum in-cylinder air flow characteristics, the guide vanes design (GVD), such as vane height, vane number, vane angle and vane length has attracted a lot of attention (Bari and Saad, 2015). The angle of the swirler vane has a substantial impact on temperature, combustion efficiency, and NO and CO emissions. At small and large swirl angles, combustion efficiency is higher. Nevertheless, soot, CO and NOx emissions are at the lowest levels at the optimum vane angle (Pourhoseini and Asadi, 2016). The effects of air swirling with swirl air vane angles of 15°, 25°, 35°, 45°, 60°, and 90° were investigated. Over the range of vane angles examined, the optimal vane angle was discovered to be 45°. In the test conducted by Navid and Alireza (2018), a sample of an air swirler with a vane angle is shown in Figure 2.5.

Figure 2.5: A sample vane air swirler of the research tests (Navid and Alireza, 2018)

Using computational fluid dynamic modelling, the influence of swirling blade angle and equivalence ratio on the combustion parameters of a methanol swirling burner was examined numerically. The geometric structure of the methanol combustor equipped with a methanol swirl burner is shown in Figure 2.6. The results reveal that the optimal swirling blade angle (BA) arrangement of (First BA of 45° + Second BA of 60°) and the burner design is developed for an effective equivalence ratio range of (1.0 - 1.25), resulting in the best methanol swirling burner combustion performance (Jing, Zhao, Wang, Li, Du, Zhu and Zayed, 2021).

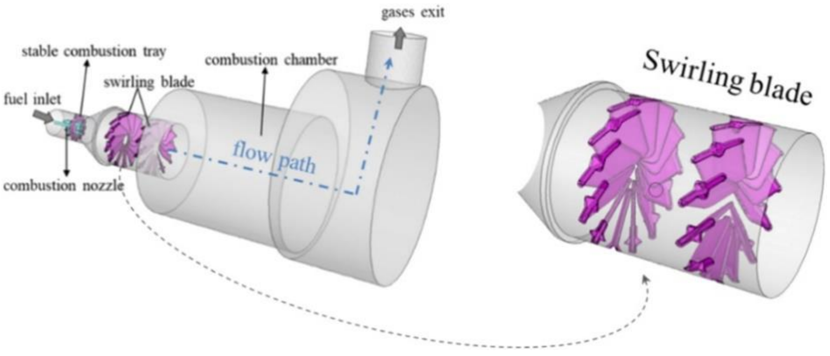


Figure 2.6: Methanol combustor equipped with a methanol swirl burner (Jing, Zhao, Wang, Li, Du, Zhu and Zayed, 2021)

The angular momentum of the combustion air is measured by the swirl intensity. It is identified by the swirl number, SN, which is defined as the ratio of axial angular momentum flow to axial momentum flux. Flame length, flame stability, and combustion intensity are influenced by the SN (Chong and Hochgreb, 2015). The use of a lean premixed concept with low swirl combustion ($0.4 < SN < 0.55$) is one of the easiest and most effective ways to reduce NOx emissions. A divergent turbulent flow field, rather than a recirculation zone, is used to stabilize the flame in this condition (Therkelsen, Littlejohn and Cheng, 2012).

The angular velocity of swirling flow is approximately proportional to the engine speed. The swirl ratio (SR) is defined as the angular velocity normalized by the engine speed. The SR is a term that is frequently used to indicate the strength of the in-cylinder flow motion (Yi, 2010). When SR increases, the heat transfer coefficient of the in-cylinder air increases, and greater amount of energy is transferred to the cylinder head and cylinder. This will result in an increased in the heat dissipating capacity of cooling water (Benajes, Olmeda, Martin, Blanco-Cavero and Warey, 2017). An experiment was conducted to see the SR influences on the swirl chamber combustion system and emission characteristics, and the simulation results revealed that the combustion system produced the lowest NOX emissions and soot at SRs of 0.2 and 0.8, respectively (Wei, Wang, Leng, Liu and Ji, 2013).

A wall flow guided combustion system (WFGCS) optimizes fuel-air mixing by guiding the fuel distribution using a geometrical design of a specific structure on the chamber wall (Su, Li and He, 2015). Both a double swirl (DS) and a lateral swirl (LS) combustion system are known as WFGCS (Li, Zhou and Zhao, 2016). The design of a DS combustion system chamber incorporates a circular ridge on the chamber wall, as shown in Figure 2.7. When the fuel contacts with the circular ridge, two swirls form in the inner and outer chambers, thus reducing fuel deposit on the wall and increasing air utilization in the middle area of the chamber. The DS combustion system effectively reduces fuel usage and soot emission, according to experimental and simulation data (Su, Li and He, 2015). The separated swirl (SS) combustion system chamber shown in Figure 2.8 is divided into three sections which are an outer chamber, an inner chamber, and a separated chamber with two circular ridges (the first circular ridge and the second circular ridge). There are two types of holes in the injector utilized in the SS combustion system, such as upper and lower holes. The swirl forms when the spray contacts the circular ridges, improving air utilization in the SS combustion system chamber and speeding up the fuel/air mixture, as seen in Figure 2.9. The study shows that SS combustion system chamber is a suitable design to reduce soot emissions (Li, Zhou and

Zhao, 2016). Unique split-flow innovations were built in the sidewall of the LS combustion system, and the number is twice the number of nozzle holes, based on the typical combustion chamber. The LS combustion system designed by Beijing Institute of Technology is shown in Figure 2.10 (Chen, Li, Li, Zhao and Liu, 2019). Through interferential and wall-flow-guided interactions, the LS combustion system enhances circumferential air usage of in-cylinder fuel-air mixing and combustion chamber. When a spray jet contacts the convex edge, two strong lateral swirls develop in nearby split arcs. After flowing out of the split arc outlet, the interferential interaction between surrounding wall jets occurs, facilitating further fuel-air mixing and fuel diffusion. Experiments have shown that the LS combustion system greatly reduces fuel consumption and soot emissions while providing excellent combustion performance at a low surplus air coefficient of 1.3 (Chen, Li, Li, Zhao and Liu, 2019).

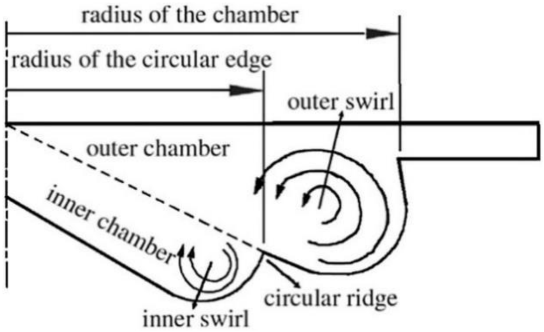


Figure 2.7: Double swirl combustion system (Su, Li and He, 2015)

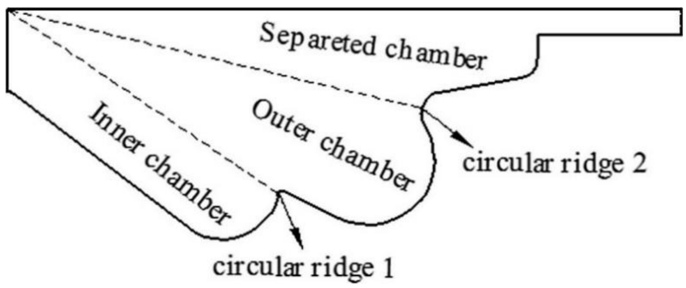


Figure 2.8: New separated swirl combustion system (Li, Zhou and Zhao, 2016)

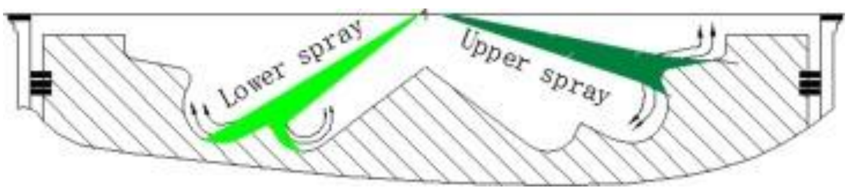


Figure 2.9: The design principle of the SSCS (Li, Zhou and Zhao, 2016)

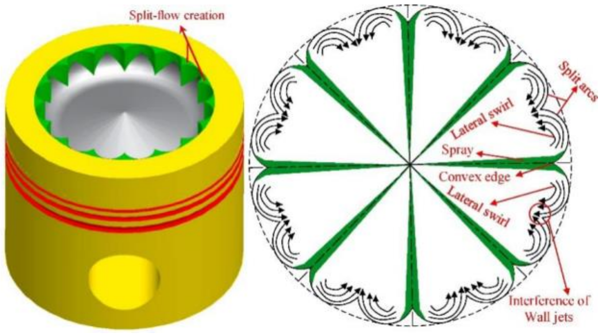


Figure 2.10: Design principle of the LSCS (Chen, Li, Li, Zhao and Liu, 2019)

2.3 Influence of Swirl Motion on the Combustion of Liquid Fuel

The swirl motion can stabilize the flame and improve mixing performance in high-speed flow (Gobbato, Masi and Cappelletti, 2017). In swirler burners/combustors and swirling atomization, flow fields, transport, mixing properties of swirling flow, pollutant of soot emissions in swirl flames, have all been intensively researched. A swirling flow is well known for promoting flow mixing and mass transfer, heat transfer, combustion temperature, combustion efficiency, and reducing pollution formation (Wang, Bauer and Gulder, 2019).

The primary challenges in the effective use of biofuel in industrial applications is its high volatility, uncontrolled explosion, and the difficult task in the equipment design (Benedetto, Sanchirico and Sarli, 2018). Consequently, the combustion and emissions performance would be affected. A possible way to overcome the drawbacks of biofuels is to utilize the aerodynamic processes in the combustor. In gas turbine combustion, air swirlers are commonly used to provide central recirculating flows that help in stabilizing the flame. Central recirculating flows recycle a portion of the hot combustion product and mix it with incoming new reactant and air, thus speeding up the rate of reaction and increasing combustion intensity, ensuring flame stability (Lefebvre and Ballal, 2010).

In comparison to an open flame, an impinging swirling flame significantly lowers the CO and NOx emissions. The ambient air was involved in a whirlpool generated by a high-speed spinning gas, which enhanced flame surface areas and improved combustion efficiency. In terms of the flame structure, combustion stability, and emission qualities, the swirling inverse diffusion flames (IDF) were compared. The results showed that in the co-swirl burners, the flame was shorter and more stable. In terms of pollutant emission qualities, the co-swirling IDF had fewer CO emissions and the counter swirling flame had lower NOx emissions (Ashraf and Saad, 2016).

For combustion in direct injection (DI) diesel engines, an intake swirl plays a vital role in determining the in-cylinder motion. The fuel/air mixing, combustion process and in-cylinder spray are all affected by the intake swirl, which has resulted in numerous research works (Praveen and Kiragi, 2014). The intake swirl causes the fuel to be widely disseminated in the combustion chamber, improving in-cylinder fuel-air mixing, and the appropriate intake swirl intensity causes the fuel to be widely distributed in the combustion chamber (Sun, Sun, Lu, Wang and Jia, 2017). Several researchers have investigated the combustion and fuel-air mixing parameters under strong intake swirl in a diesel engine with a large diameter of cylinder. The results revealed that under low loads, the fuel-air mixing zones are primarily at the center of combustion chamber, whereas under high loads, the fuel-air mixing zone is confined in the spray front and the outer ring of the combustion chamber (Wang, Yu, Li, Su, Yang and Wu, 2019). Intake swirl is generated in proper way to enhance the fuel-air mixing and combustion (Benajes, Olmeda, Martin, Blanco-Cavero and Warey, 2017).

2.4 Summary

This section covers related information to the topic of this project. Firstly, combustion of liquid fuel was discussed. Toxic emissions from various combustion devices are major sources of concern because of their potentially lethal influence on human life and pollution of the environment. Aside from the environmental concerns, there are issues of excessive consumption and the availability of traditional depleted fossil fuel reserves. Biodiesel is a viable alternative fuel to reduce hazardous emissions from combustion and it can completely or partially replace fossil fuels. The biodiesel derived from waste cooking oil is a cost-effective and environmentally friendly solution to dispose of waste and convert to energy. However, waste cooking oils have high viscosity, poor volatility, and high molecular weight, which prevents them from being used directly in combustion systems. It is critical to transform waste cooking oil into biodiesel by pyrolysis, emulsification, or transesterification in this regard. WCO biodiesel reduces the NOx and CO emissions. Nevertheless, the combustion performance of WCO biodiesel is poor compared to conventional fuel.

Apart from that, swirl flow is affected by the vane angle of swirler. Despite the fact that swirling airflow is beneficial for flame stabilization, an excessive increase in vane angle was discovered to negatively affected the flame instability. A lower vane angle will generally increase NOx emissions in an unfavourable way due to the poor fuel-air mixing. In general, the combustion efficiency is higher at small and large vane angles, whereas the lowest CO, NOx and soot emissions will be happened at the optimum vane angle.

Lastly, the major impacts of swirl are to increase flame stability by forming toroidal recirculation zones and to shorten combustion times by producing high rates of ambient fluid entrainment and quick mixing, especially near the recirculation zone boundaries. For instance, in engineering applications such as industrial furnaces and gas turbines, swirling burners have been frequently used. The swirling flow formed by the whirling burners improves the mixing of air and fuel, resulting in a well-blended mixture. It can also provide a high recirculation flow near the burner outlet, which helps to stabilize the flame and decrease pollutant emissions.

CHAPTER 3 METHODOLOGY

3.1 Introduction

The focus of this project is to simulate various angles of tangential air inlets into the cylindrical combustion chamber. The primary purpose of the simulation is to analyze the influence of swirl motion on combustion and emission characteristics of biodiesel produced from WCO. The software used for the simulation was Ansys Fluent. Prior to carrying out the simulation, the solid models were drawn in SOLIDWORKS. The chamber power scale in kW thermal is calculated using Equation (1).

$$\eta_{ith} = \frac{ip}{\dot{m}_f \times Q_{net}} \quad (1)$$

where $\eta_{ith}$is the indicated thermal efficiency, ip is the indicated thermal power (kW), $\dot{m}_f$ is the mass flow rate of fuel (kg/s), and Q_{net} is the lower calorific value of fuel (kJ/kg).

Assume η_{ith} is 90% and the values of $\dot{m}_f$ and Q_{net} are obtained from Appendix C,

$$\eta_{ith} = \frac{ip}{\dot{m}_f \times Q_{net}}$$

$$0.90 = \frac{ip}{0.02283 \times 37500}$$

$$i_p = 770.51kW$$

The target application for the cylindrical combustion chamber is the boiler of gas turbine. The combustion chamber of boiler is where the fuel is burned to heat the water. The combustion chamber consists of the burner that is intended to offer a very safe environment for the high-temperature burning of volatile fuel.

3.2 Simulation Models

A cylindrical combustion chamber was used as a solid model, and it was incorporated with two tangential air inlets. The hollow combustion chamber was simulated with variable angles of two tangential air inlets, θ. The angles, θ were 0º, 10º, 20º, 30º and 45º and these angles were measured from the central axis of air tube. The fuel was fed to the combustion chamber through a gravity-fed system. The gravity-fed system consists of a tank and a valve. The tank was fully filled with the fuel. The fuel inlet was positioned at the bottom of the combustion chamber. When the valve was opened, the fuel will be transferred to the combustion chamber. The multi hole nozzle was used to spray the fuel into the combustion chamber and the fuel was atomized. This is a significant function because it is the first phase in getting appropriate mixing of fuel and air in combustion chamber. The diameter of fuel droplet is small and it will completely and instantly vaporize before the combustion process starts (Kiang, 2018). In addition, the smaller size of fuel droplet will increase the efficiency of mixing and combustion. Figure 3.1 illustrates the process of transferring the fuel to combustion chamber. The schematic diagram of the simulation model is shown in Figure 3.2.

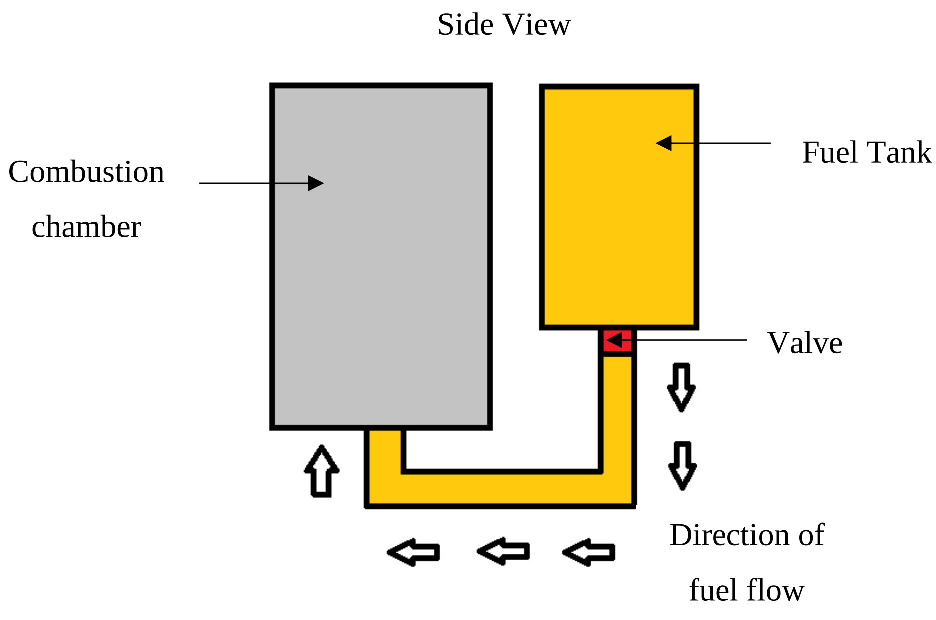


Figure 3.1: Illustration diagram of process of gravity-fed system

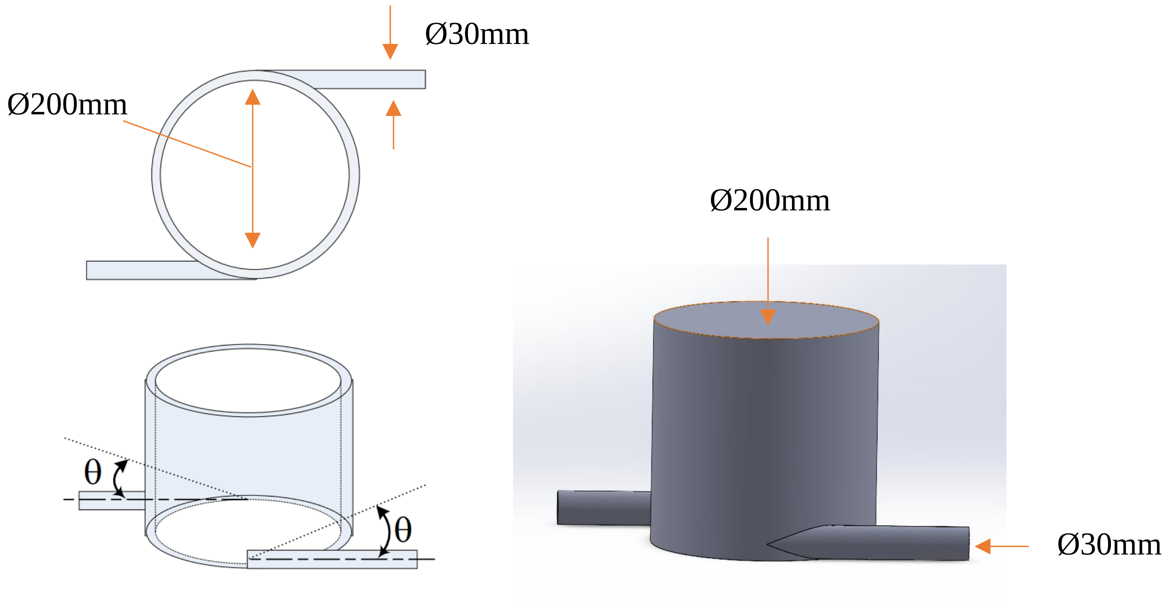


Figure 3.2: Schematic diagram of simulation model

SOLIDWORKS software was used for 3-D modelling. For the simulation model, the gravity-fed system was initially excluded because the preliminary aim was to focus on the reaction of combustion inside the chamber. Therefore, the method of transferring the fuel was deemed insignificant, initially. The fuel inlet is shown in Figure 3.2.

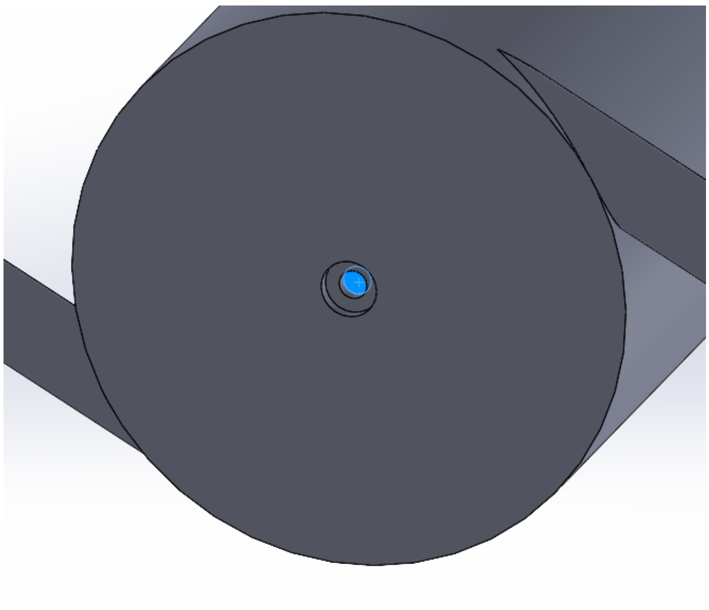


Figure 3.3: Location of fuel inlet for simulation model

The method of trigonometry of right-angled triangle is applied to draw the simulation models with different angles of tangential air inlets, θ. The dimension of tube of air inlet is 180mm. By referring to Figure 3.3, when it is altered to a particular angle, the tube will become hypotenuse of a right-angled triangle. Therefore, adjacent and opposite can be determined by applying the angle, θ.

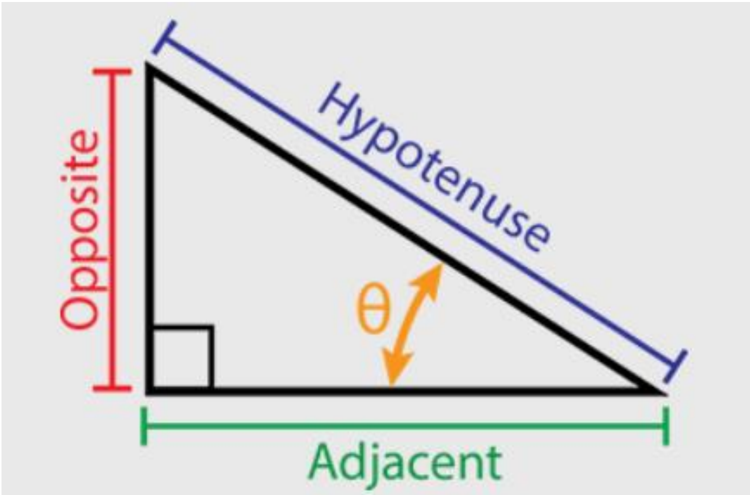


Figure 3.4: Trigonometry of right-angled triangle

The viscosity model used in simulation is k-epsilon. The species model applied in simulation is species transport and the setting is shown in Figure 3.5. Species transport will show how multi-species are reacting. This model is suitable to be applied when different types of fuel are used.

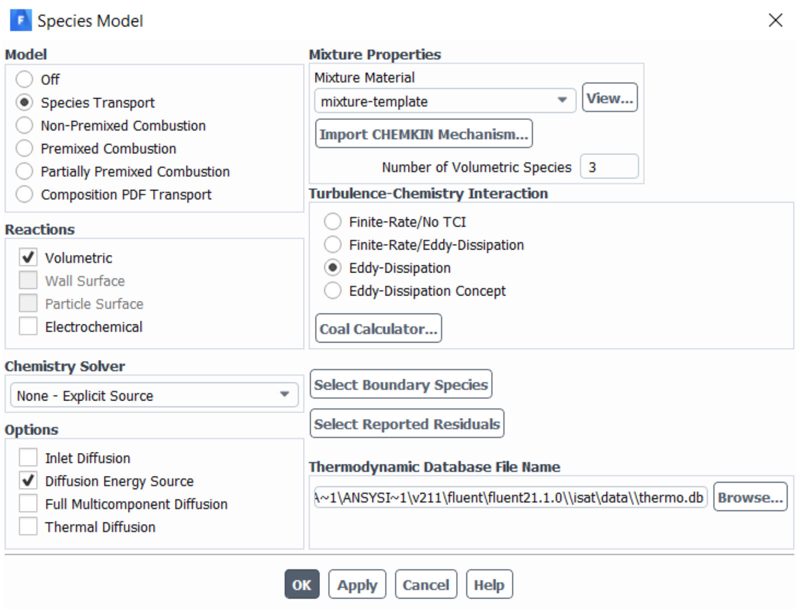


Figure 3.5: The setting of species transport

3.3 Simulation

3.3.1 Input Data of Simulation

Ansys Fluent requires several input data to perform the simulation. Thus, this section covers the calculation part to identify the input data. An experimental dataset was provided by the project supervisor to determine the chemical formula of biofuel derived from WCO as shown in Table 3.1. The detailed calculation for determining the chemical formula of WCO fuel can be found from Appendix C. The chemical formula of the fuel used for the simulation is $C_{19}H_{38}O_2$. This fuel is known as pure biodiesel derived from WCO. The chemical properties of $C_{19}H_{38}O_2$ are listed in Table 3.2 (Geng, Mao, Zhang, Wei, You, Ju and Chen, 2017).

Table 3.1: Results obtained from an experimental dataset

Fuel	100 WCO
Molar Mass of Diesel, M_D (kg/kmol)	170
Molar Mass of WCO, M_{WCO} (kg/kmol)	298
Mass of Diesel, m_D (g)	0
Mass of WCO, m_{WCO} (g)	1200
Number of Mole of Diesel, N_D	0
Number of Mole of WCO, N_{WCO}	4.026845638
Total mole, N_T	4.026845638
Fraction of Diesel, X_D	0
Fraction of WCO, X_{WCO}	1
No. of C atoms	19
No. of H atoms	38
No. of O atoms	2
A/F	12.6943
% C (by mass)	0.765101
% H (by mass)	0.127516779

Table 3.2: Chemical properties of waste cooking oil biodiesel (B100) (Geng, Mao, Zhang, Wei, You, Ju and Chen, 2017)

Fuel	Waste Cooking Oil Biodiesel (B100)
Density $(\boldsymbol{kg/m^3})$	873.8
Viscosity $(\boldsymbol{mm^2/s})$	4.395
Cetane Number	55.3
Sulfur content (mg/kg)	<10
Heat of Evaporation (kJ/kg)	300
Lower Heating Value (MJ/kg)	37.5
Flash Point (˚C)	182.5
Carbon Content (wt%)	77.1

3.3.2 Flow Chart of the Simulation

The simulation parameters were varied and these parameters include different angles of tangential air inlets of the cylindrical combustion chamber. The system used for the simulation is Fluid Flow (Fluent). There are five main categories, and these were geometry, mesh, setup, solution and results. The geometry was imported from the models drawn using SOLIDWORKS. The boundary conditions of the model were air inlets, fuel inlet, outer wall and outlet of combustion chamber. Before generating the mesh, the boundary conditions needed to be specified. Then, the input data were inserted into the setup. The solution was obtained with 3000 iterations. The results of the temperature distribution, velocity distribution, mass fraction of species and pollutants were then generated. Graphs of mass fraction of species and pollutants against y-z plane were also plotted. These steps were repeated by importing the geometry with different angles of the tangential air inlets.

Upon completing the simulation for all models, the optimal angle of tangential air inlets was determined. Then, the fuel was changed to kerosene to compare the combustion and emission characteristics with the biodiesel produced from WCO. The flow chart of the simulation process is shown in Figure 3.4.

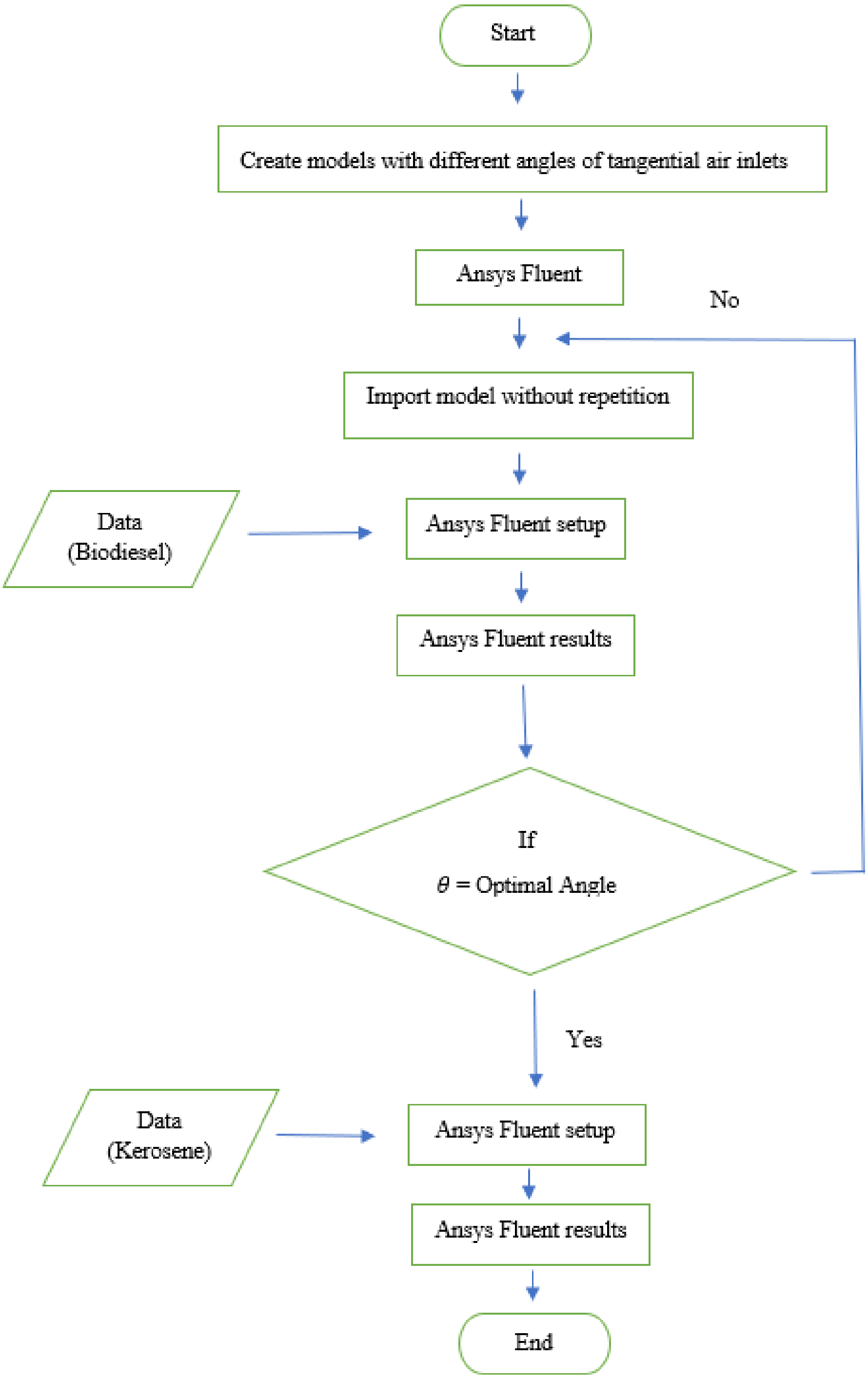


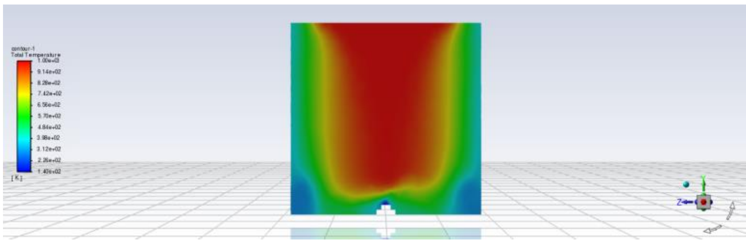
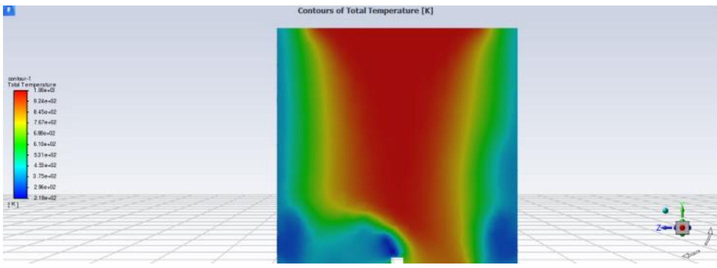
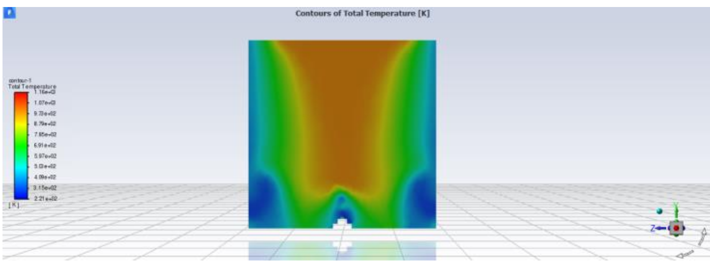
Figure 3.6: Flow chart of simulation

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Results

Five different angles of tangential air inlets, θ (0º, 10º, 20º, 30º and 45º) were varied in a cylindrical combustion chamber with WCO biodiesel to determine the influence of swirl motion on the combustion and emission characteristics. Kerosene was used to compare with WCO biodiesel at an optimum angle of the tangential air inlet. The results generated were temperature distribution, velocity distribution, mass fraction of the reactants, and products, and pollutants.

4.1.1 Effect of Tangential Air Inlets Angles on Combustion and Emission Characteristics of Cylindrical Combustion Chamber with WCO Biodiesel

Angle, θ (º)	**Temperature Distribution**
0	
10	
20	

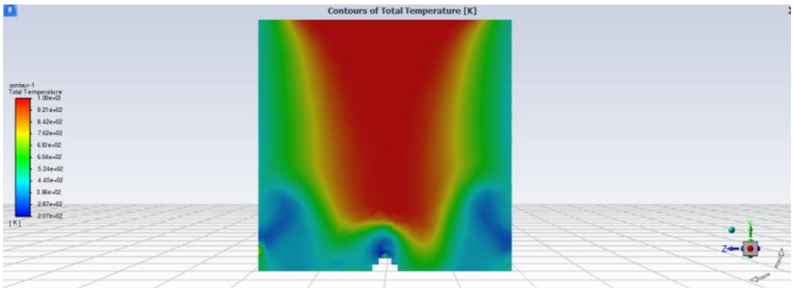
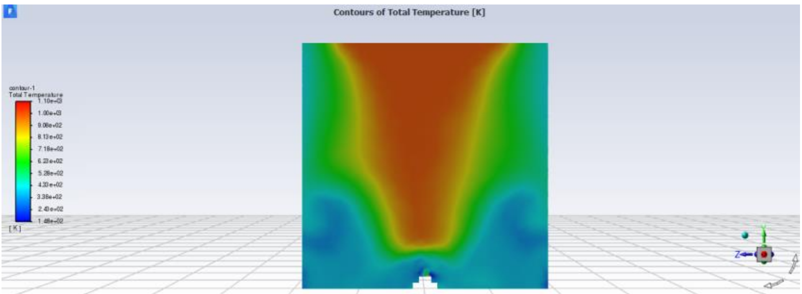
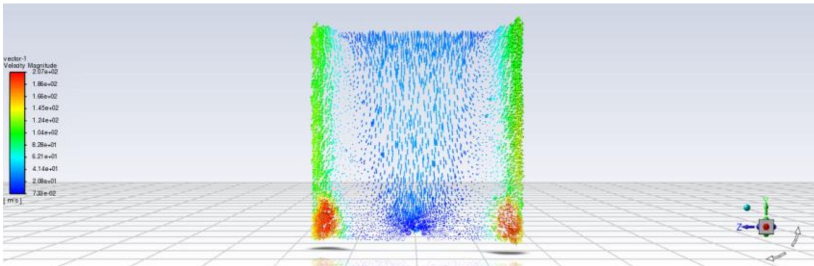
30	
45	

Figure 4.1: Temperature distribution for different angles of tangential air inlets

Angle, θ (º)	**Velocity Distribution**
0	
10