COMBUSTION CHARACTERISTICS OF A SWIRL COMBUSTOR OPERATING ON KEROSENE VEGETABLE COOKING OIL (VCO) FUEL BLENDS.

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DECLARATION

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

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

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LIST OF ABBREVIATIONS

PIM	Porous Inert Media
NO_X	Nitrogen Oxide
CO	Carbon Monoxide
VCO	Vegetable Cooking Oil
KVCO	Kerosene and Vegetable Cooking Oil
AFR	Air-Fuel Ratio
$\dot{m}$	Mass Flow Rate
ø	Equivalence Ratio
LPM	Liter per minute
AFR	Air-Fuel Ratio

CIRI-CIRI PEMBAKARAN BERPUSARAN YANG BEROPERASI MENGGUNAKAN CAMPURAN MINYAK MASAK SAYURAN DAN MINYAK TANAH.

ABSTRAK

Kajian ini adalah untuk mengkaji ciri-ciri pembakaran berpusaran yang beroperasi menggunakan campuran minyak masak sayuran dan kerosin. Tujuan eksperimen ini adalah untuk mengkaji prestasi pembakaran untuk sebuah pembakar berpusaran dengan menggunakan campuran minyak masak sayuran dan kerosin berbantukan media berliang dalam proses pembakaran. Pembakaran berpusar terhasil daripada dua sisi punca udara berlawanan arah untuk mengelakkan haba keluar dari pembakar. Ciri-ciri pembakaran bahan api dianalisis berdasarkan daripada prestasi dan suhu yang terhasil bersama dengan bentuk api di dalam pembakar semasa proses pembakaran. Eksperimen dijalankan dengan dua keadaan iaitu menggunakan satu kemasukkan bekalan udara dan dua kemasukkan bekalan udara. Punca udara tersebut diubah dengan memanipulasikan kadar alir udara daripada 2 hingga 10 liter per minit. Bekalan bahan api pula dimalarkan sepanjang eksperimen iaitu 0.001LPM dan menggunakan pelbagai campuran bahan api iaitu 100% kerosin, 90/10% KVCO, 75/25% KVCO and 50/50% KVCO. Hasil daripada pemerhatian kedua kaedah menunjukkan yang suhu tertinggi direkodkan pada bahan api 100% kerosin menggunakan dua punca udara iaitu 815.3 K dan nisbah persamaan berdekatan dengan keadaan stoikiometri. Nisbah persamaan adalah berkadar songsang dengan suhu. Tambahan pula, campuran bahan api tidak membantu untuk meningkatkan process pembakaran oleh kerana kandungan bahan api minyak masak.

COMBUSTION CHARACTERISTICS OF A SWIRL COMBUSTOR OPERATING ON KEROSENE VEGETABLE COOKING OIL (VCO) FUEL BLENDS.

ABSTRACT

This research explores the combustion characteristics of a swirl combustor operating on KVCO fuel blends.The aim of this experiment is to study the performance and combustion characteristics of porous medium combustion using kerosene and vegetable cooking oil (VCO) as fuel blends. The swirl combustion is formed from the tangential air inlet that prevents heat loss in the chamber. The characteristics of the fuel were analyzed in terms of the performance and the temperature generated as well as the flow of the flame inside the combustor during the combustion. The experiment consists of two parts; using single air inlet ports and dual air inlet ports. The air flow rate was varied from 2 to 10 LPM and the fuel flow rate was fixed 0.01LPM during the experiment. Four fuel blends have experimented; 100% kerosene, 90/10% KVCO, 75/25% KVCO and 50/50% KVCO. Results show that both findings depicted the highest temperature recorded with 100 kerosene using two air inlet ports which is 815.3K and the equivalence ratio is close to stoichiometry. It shows that the swirling air helped in reducing the heat loss in the combustion process. The equivalence ratio is inversely proportional to the temperature. In addition, the mixture of fuel blends did not improve the combustion process due to the content of the vegetable cooking oil.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The research on the combustion of a swirl flow combustor has been carried out for many years. This research is to utilize the combustion for power generation in meso-scale combustor system. The swirl combustion for this research uses the mixture of kerosene and VCO. This search is to substitute the current energy consumption which is fossil fuel. To ensure sustainability on the ecosystem of the fossil fuel, new types of fuel must be used to generate power. Vegetables cooking oil are a renewable source that is produced by the plant. They are not harmful and they are easy to harvest. The recent interest in personal power systems further underscores the need for compact, efficient, human compatible, lightweight power sources (Dunn-Rankin, Leal, & Walther, 2005). This is one of the reasons that makes research on combustor of vegetable cooking oil and kerosene for power generator as a promising solution to meet the need for power source and energy.

The global demand for energy is expected to increase dramatically. It shows the significance and the scale of this study to understand the combustion process so that one can improve and build a clean and efficient combustion system. Also, the characteristics of the fuel are strongly influenced by the combustion process. The chemical reactions cause incomplete combustion or quenching of the reactions in the wall region. There might be some chemical reactions that takes place when the mixture of KVCO. The world needs another industrial revolution in which our sources of energy are affordable, accessible and sustainable. Energy efficiency and conservation, as well as decarbonizing our energy sources, are essential to this revolution. Reducing carbon emissions on the timescale needed to mitigate the worst risks of climate change (Chu & Majumdar, 2012). The power lost on the large surface-to-volume ratio of small scale combustor effect in reducing the temperature hence reducing the efficiency.

Meso scale combustion is a concept of utilizing a flow-blurring injector to produce fine fuel droplets of fuel. By introducing the secondary air inlets make air to swirl in the combustor. This effect will be explored in this research from the experiment and the simulation. The combustion will be analyzed from the surface temperature.

The use of porous inert media(PIM) also will give a big influenced. Although it is a new approach, it is an effective method to increase the contact surface area and conduction heat transfer for liquid fuel vaporization and flame stabilization (Li, Chao, & Dunn-Rankin, 2008). The porous burner also has the potential to produce lower emissions in combustion using liquid fuels. It gives rise to high radiant output, low emission of NOx and CO, high flame speed, high power density and modulation and also the conduction and radiation modes of heat transfer is significant. The porous burner has the ability to replace the conventional spray combustion due to its compact size, yielding a satisfactorily wide stable combustion region, fuel flexible owing to enhanced evaporation and low in cost (Jugjai & Pongsai, 2007). The porous burner is made by alumina, Al_2O_3. It has thermal conductivity about 38.5 W/mK, which is good for the combustion compared to stainless steel which has lower thermal conductivity. Besides, alumina resists strong acid and alkali attack at elevated temperatures and have high strength and stiffness. (Fuse, Kobayashi, & Hasatani, 2005) state that vaporizing combustion was sustained with recovering a part of its thermal radiation heat through the porous burner and they achieve complete combustion under the equivalence ratio ranged from 0.63 to 0.80.

Figure 1 Alumina porous inert media

The mix fuel blends of kerosene and vegetable cooking oil (VCO) were used in this experiment. Kerosene which is also known as paraffin is a clear liquid that has low viscosity that is formed from the fractional distillation of petroleum. It contains carbon atoms between 10 and 16 per molecule and it has a density of around 0.78–0.81 g/cm^3. The flash point of kerosene is between 37 and 65 °C and the heat of combustion of kerosene is similar to that of diesel fuel; its lower heating value is 43.1 MJ/kg and its higher heating value is 46.2 MJ/kg(Shehatta, M. ElKotb, & Salem, 2014). For vegetable cooking oil, it is fats extract from seeds, or less often, from other parts of fruits. The chemical properties depend on the constituent of the plant that was extracted. Nowadays, vegetable oils are also used to make biodiesel, which can be easily used similar to conventional diesel. The use of vegetable oils as alternative energy is growing and the availability of biodiesel around the world is increasing.(Suhartono, Suharto, & Eka Ahyati, 2018)

1.2 Research Background

Combustion characteristics of a swirl combustor operating on kerosene− vegetable cooking oil (VCO) fuel blends cover both experimental and simulation research. This research uses the meso-scale combustor as its apparatus. The meso-scale combustor is a low-cost meso-scale or also called a miniature heat engine that can provide high thermal conductivity and long lasting application. Kerosene and vegetable cooking oil fuel blends were used in this research. This fuel was blended together and act as the fuel for the combustor. The kerosene is used to help the combustion process.

The primary purpose of this work is to study the combustion characteristics and the performance of the kerosene vegetable cooking oil blend as fuel. The combustion performance will be evaluated from the temperature and the heat flow.

The design of the meso-scale combustor has been studied from the aspect of dimension and material for the combustor. The meso-scale combustor was designed using Computer Aided Design (CAD) and SolidWorks. This CAD design was used to simulate the combustion process of the fuel. ANSYS Fluent was utilized for the simulation process. From the simulation, we can determine the characteristics of the heat flow and the performance produced by the combustion process of the fuel. Then, the experiment was carried out on the meso-scale combustor by using kerosene and vegetable cooking oil blend as fuel. The temperature will be recorded in the combustor using thermal imager. The results were then compared with the simulation. This is important to ensure the sustainability of fossil fuel and produce clean energy for the ecosystem.

1.3 Problem Statement

Among the topics that have been discussed, the main objective for the project is to study the characteristics of swirl combustion, performance and efficiency by using kerosene and vegetable cooking oil as fuel. But, the main problem for the meso-scale combustor is high surface heat loss due to the large surface area-to-volume ratio, uniformity of fuel and flame flow and the emission of the carbon monoxide (CO) and Nitrogen Oxide (NOx). Threrefore, a small size meso-scale combustor is used to reduce heat loss in the combustion process.

1.4 Objectives

1. To study the characteristics of the swirl combustion using kerosene and vegetable cooking oil as fuel blends.

1. To study the fuel of mixture KVCO and the flow of combustion.
2. To study the effect of introducing two air supply inlets in the combustion

1.5 Scope of Work

To achieve the objective of this research, below is the scope of work that needs to be done;

1. Study the design including the dimension and materials of the meso-scale combustor.
2. Simulation of the heat flow of the combustor
3. Experimenting on the fuel of kerosene and vegetable cooking oil and study its characteristics, performance and heat flow of the combustion.

CHAPTER 2

LITERATURE REVIEW

2.1 Combustion Using Liquid Fuel

Research on liquid fuel combustion has widely been investigated for many years and a lot of methods had been used. (Luhmann, Maldonado, Spörl, & Scheffknecht, 2017) investigated the flameless combustion of light fuel which was adopted in a reverse- flow cooled combustion chamber fired with cold air by using five different twin fluid atomizers with varying the spray angle. Fuel and combustion air are intensively mixed with recirculated flue-gas to form a hot diluted mixture avoiding temperature peaks and provide fuel lean combustion conditions. The result shows that a flameless combustion mode can be achieved at air equivalent ration at 1.1 by using 0^o and 40^o nozzles angle. On the other hand, (Rydén et al., 2013) use a different approaches by using chemical looping liquid fuel for the combustion while (Xu et al., 2019) use fuel with rich and lean combustion burner with mild combustion to reduce the NO_x emissions. Both researches uses liquid fuel but they use a different approach to achieve their objective. (Xu et al., 2019) state that the horizontal fuel-rich/lean combustion burner is able to reduce the NO_x emissions.

(Giorgi, Sciolti, Capilongo, & Ficarella, 2016) study the behaviour of flame by different air-fuel mixing strategies using single and multiple air fuel injections on the performance of a lean liquid fuel swirled combustor. This experiment using the Green Engine burner with particular of the injection holes with a fixed air flow rate $85x10^{-3}$kg/s. From the data, if the fuel/air ratio is decreased, the OH* chemilumienescence intensity decrease. The reduction of the fuel/air ratio allows the decrease of the NOx emissions with 25% and 34% respectively for the non-premixed and partially premixed mode.

Figure 2 The experimental setup of the Green Engine burner with a particular injection hole

2.2 Design of The Combustor

Besides the liquid fuel, a lot of research also have been done by using different design and setup of the combustor to study the combustion process. One of it is (Li et al., 2008), they study on the flame structure by using a meso-scale combustor in Figure 2. They also use a different types of porous media. The schematic diagram of the meso-scale combustor is shown in Figure 2 below. The combustion yields different flame structure and the corresponding stabilization mechanism due to their different thermal properties. The location of the tricbrachial flame dictates the characteristic stabilization mechanism of the porous combustor with porous materials. On the other hand, (Shantanu, Mahendra Reddy, & Karmakar, 2018) use a mini meso-scale combustor to study the heat recirculated high intensity for mini gas turbine applications. In this experiment, an annular heat exchanger is used and placed around the combustion chamber to preheat the air by varied the thermal inputs (0.2–1.0 kW) and the equivalent ratio ($\phi = 0.25$–1.4). From the results, it shows that stable combustion is achieved with high thermal intensity and ultra-low emissions.

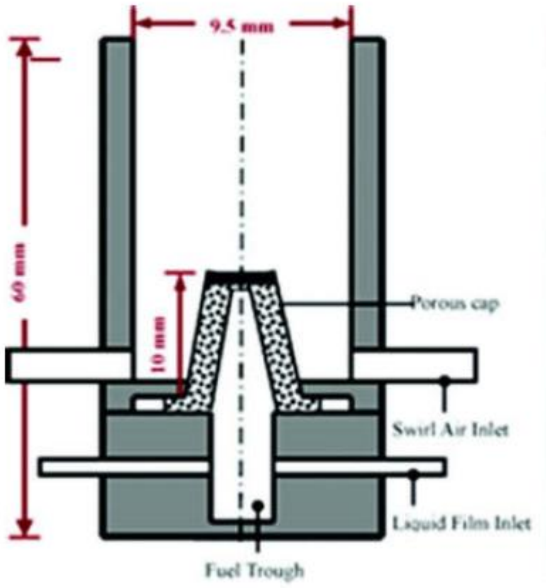


Figure 3 Schematic diagram of the meso-scale combustor of the (Li et al., 2008)

Another study that uses meso-scale combustor is (Wierzbicki, Lee, & Gupta, 2014), its purpose is to study the combustion of propane in a meso-scale heat recirculating combustor. They also use two different catalysts, rhodium and platinum in the combustion. The role of the rhodium and platinum catalyse are analyzed in terms of extinction, conversion, selectivity and activation energy. This experiment shows that both catalysts were able to sustain very lean combustion down to an equivalence ratio of $\phi = 0.593$ for the Rhodium catalyst and $\phi = 0.322$ for Platinum. The calculated activation energies for each catalyst (74.7 kJ/mol for Rhodium and 13.8 kJ/mol for Platinum) suggested that the combustion reactions on Rh were largely controlled by chemical reaction kinetics and on the Platinum by diffusion limitations.

2.3 Combustion using Porous Inert Media

Another method doing research of combustion is using porous media, many research have been done using porous media as the medium to absorb the fuel for the combustion. (Kaplan & Hall, 1995) has been researching on the combustion of liquid fuel within the highly porous inert medium. Highly porous material were used to recirculate the enthalpy from the products. It shows that the porous ceramics serve as an enthalpy feedback medium that allow the post-flame enthalpy to be transported to the pre-flame region. Some of the researchers proposed inserting a porous solid of high conductivity into the flame to conduct the post-flame enthalpy to aid in preheating the fresh mixture by (Takeno & Sato, 1979). It is done by choosing the porosity. of the solid to control the heat transfer coefficient between the solid and the gas.

Apart from that, (Zhang, Li, Zheng, Chen, & Qin, 2017) also use porous media in their research to study the characteristic of porous media burner under various back pressure. They observed the combustion condition of premixed air inside or on the surface of a porous media burner, investigated the flame stability range and figured out the distribution laws of combustion gas flow and resistance loss, so as to achieve an optimized design and efficient operation of the device.(Devi, Sahoo, & Muthukumar, 2019) focus on the low emission combustion using the porous radiant burner in biogas combustion. Their result shows that by using porous radiant burner the emission reduces 95% and 85% in pollutant emissions of CO and NOx, respectively.

CHAPTER 3

METHODOLOGY

3.1 Experimental Setup

The experiment consists of two different set-ups; the first one is for a single flow air inlet and the second one is for two flow air inlets. The schematic diagram is shown in Figure 4 and Figure 5 below. The combustor has two air inlet ports and one fuel inlet at the base of the combustor chamber. In the combustor, there is a holder that contains a porous media. The material for the porous media is alumina. The holder connects the fuel inlet to the KVCO fuel blends that will be absorbed by the porous alumina in the combustor. The air inlet was controlled by the volumetric flow meter and supplied by the air compressor. The fuel was injected 0.01LPM using a syringe that was connected to the pipe into the porous alumina inside the combustor. The temperature will be recorded using Fluke Thermal Imager Ti27.

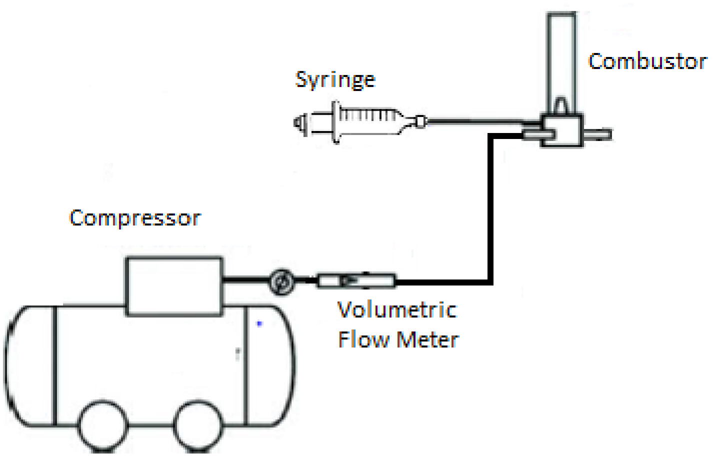


Figure 4 Schematic diagram for one air flow inlet experiment set-up

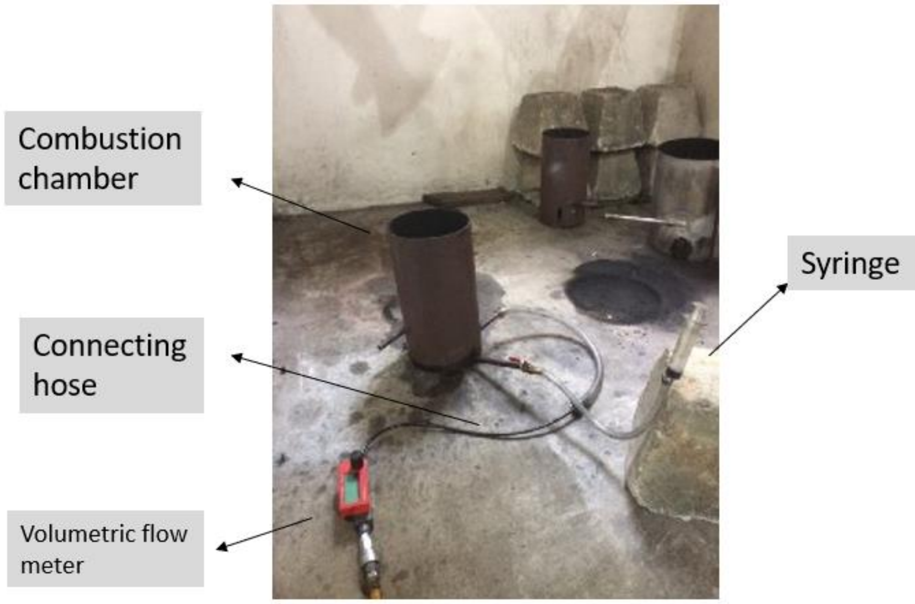


Figure 5 Experimental Set-up for one air flow inlet

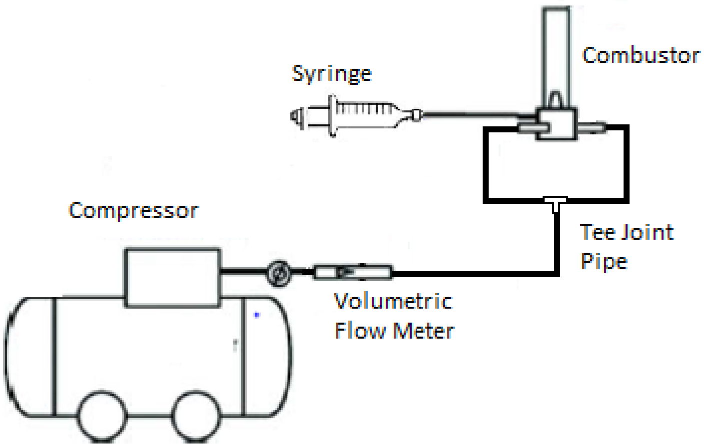


Figure 6 Schematic diagram for two air flow inlet experiment set-up

Figure 7 Experimental set-up for two air flow inlet

Before the experiment was started, four types of fuel were prepared by mixing the KVCO. The fuel blends were prepared using two different mass of the fuel and mix it together. Mass balance was used to determine both the fuel masses and a stirrer was used to stir the mixing fuel. The fuel was ensured to be completely mixed thoroughly. The fuel was categorized as 100% kerosene, 90/10 KVCO, 75/25 KVCO and 50/50 KVCO.

Both experiments have the same experimental set-up but the only difference is the air flow inlet. For one air flow inlet, the air supply air connected directly from the volumetric flow meter and connect to one of the air inlet ports. While for the two flows air inlet, the tee joint was used to separate the air flow and connect both of the air inlet ports. The tangential of two air inlet will help to produce swirl combustion and reduce the heat loss in the combustion.

Before starts the combustion, gasoline was used to start the combustion because the flashpoint for kerosene is high. Therefore, gasoline help to start combustion. Let the combustor occur for a few minutes to ensure that all gasoline is used in the combustion. The fuel was injected with a constant flow rate while we adjust the air flow using a volumetric flow meter. After the temperature remains steady, the thermal imager is used to record the temperature and the flame profile in the combustor.

The experiment was carried out by using the different air flow rates that supplies into the combustor which is 10, 8, 6, 4 and 2 L/min. For the fuel, we injected the fuel for 5ml/min every 5 min for all the mix fuel blends which is 100% kerosene, 90/10 KVCO, 75/25 KVCO and 50/50 KVCO.

3.2 Simulation Set-up

Before starts the simulation, the geometry was design using SolidWorks software for both a single inlet and two inlet combustors. Then, the geometry was imported into the DesignModeler in ANSYS Fluent software. The geometry was mesh in the ANSYS Fluent software for both designs. For a single air inlet, it consists of 25 376 nodes while the dual air inlets consist of 22 307 nodes. We defined the important parts that affect the experiment which is air inlet as the air supply in the combustor, fuel inlet as the fuel supply in the combustor and the outlet is the output of the experiment.

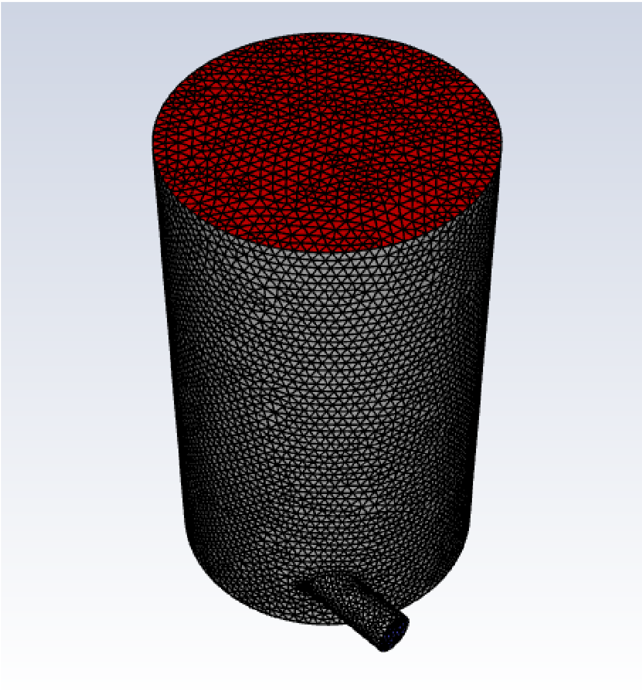


Figure 8 Combustor with one air flow ports model

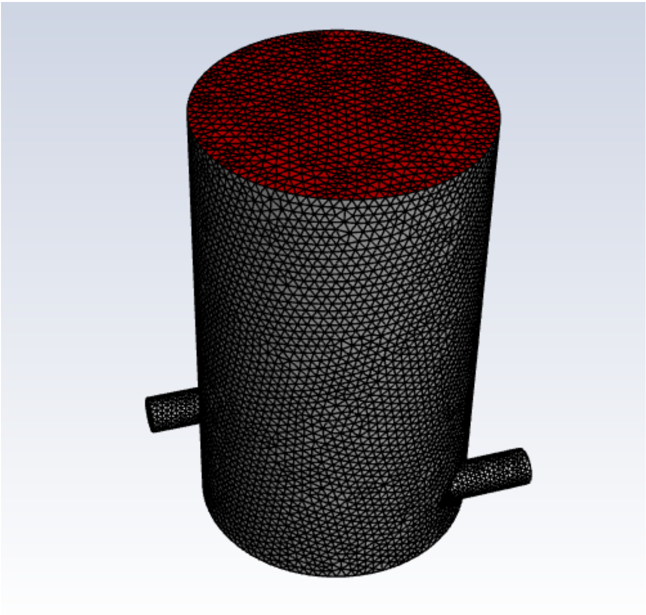


Figure 9 Combustor with two air flow ports model

The simulation starts after setting the model for the combustion mode. Kerosene and air were selected as the material of the combustion. The boundary condition was set up for air inlet and fuel inlet by using the value of the flow rate of the experimental value. The simulation start after we initialize the combustion from the fuel inlet. After the simulation is run completely, the data is recorded and saved.

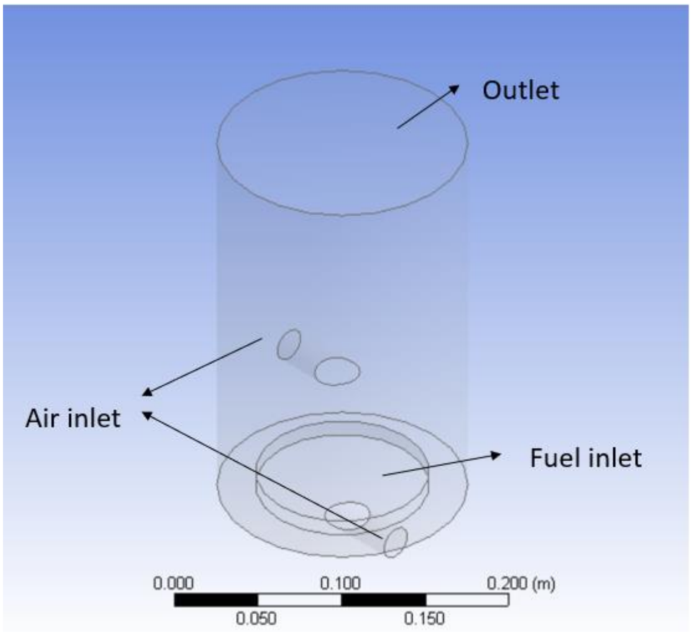


Figure 10 Setting the primary boundary condition

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

In this chapter, the result of the combustion process is discussed. The developed simulation result is compared with the experimental result. The calculation involved in this experiment is to determine the mass flow rate of air and fuel.

To calculate the air-fuel ratio, the mass flow rate in kg/s of air is divided by the mass flow rate of fuel. The equation is as follow:

$$AFR_{actual} = \frac{\dot{m}_{air}}{\dot{m}_{fuel}}$$

While, from the calculated AFR_{actual}, the equivalence ratio, ø, can be found by dividing $AFR_{stoichiometry}$ with AFR_{actual}.

$$ø = \frac{AFR_{stoichiometry}}{AFR_{actual}}$$

4.2 One Inlet Air Flow

4.2.1 100% Kerosene

The effect of equivalence ratio on the temperature of 100% kerosene on the one inlet air flow rate by using porous media is shown in Figure 11. The temperature was obtained in the combustion chamber at the central surface of the porous media by using Fluke Thermal Imager. We analyze the temperature by using various equivalent ratios. The peak value of the temperature from the experiment is 806.8K at ø = 1.076. The trend shows that whenever we increase the equivalent means more fuel in the combustion the temperature will decrease. This is because the air that is supplied is not enough to complete the combustion in the chamber. The simulation result shows that the same trends as the experiment result as the temperature decrease when equivalent ratio increase.

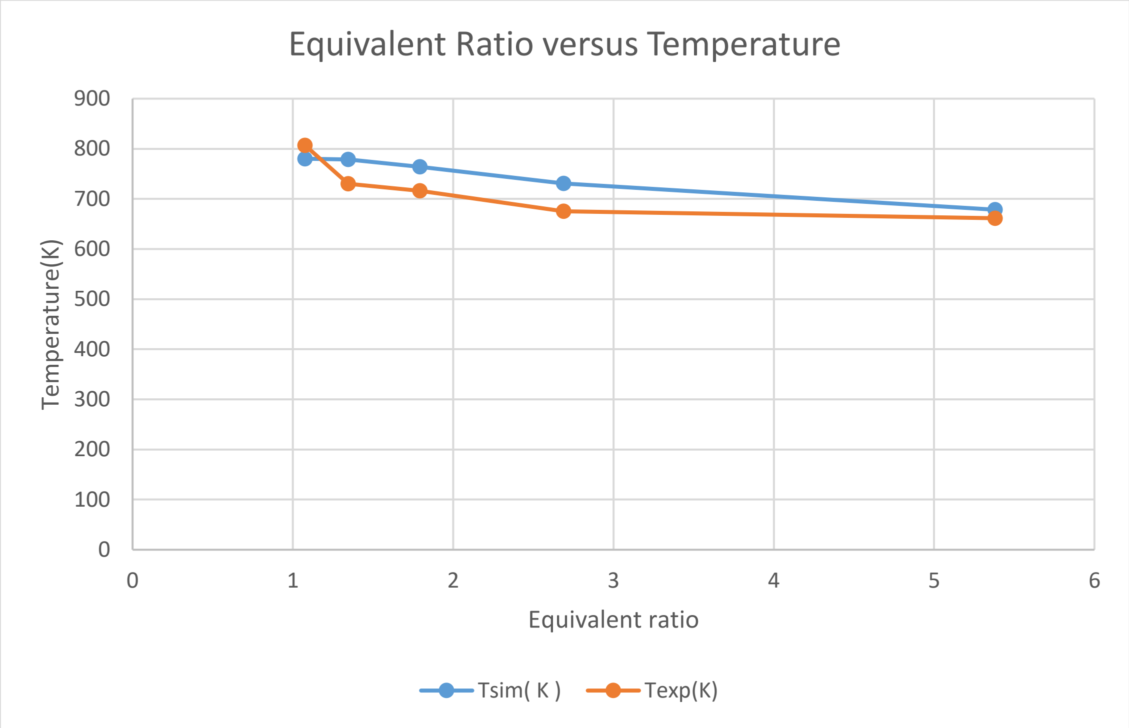


Figure 11 Statistical data from the experiment of 100% kerosene fuel one inlet air flow

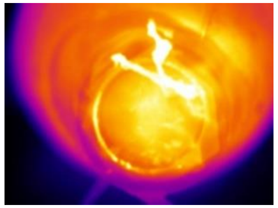
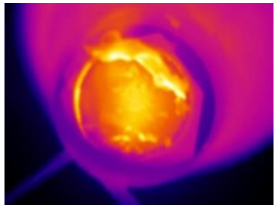
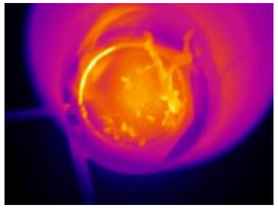
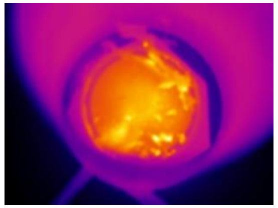
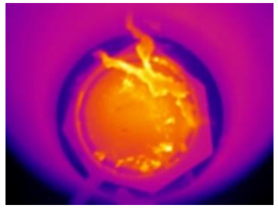
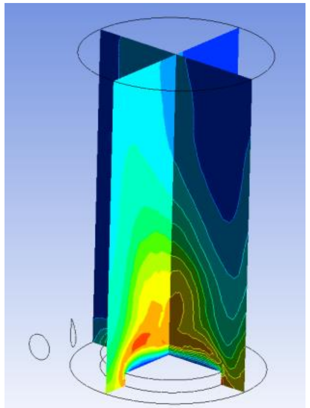
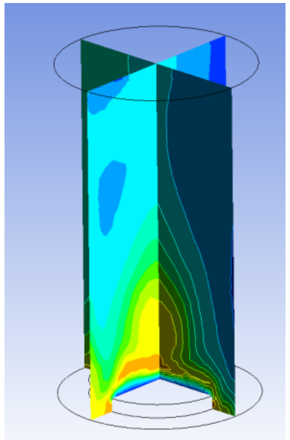
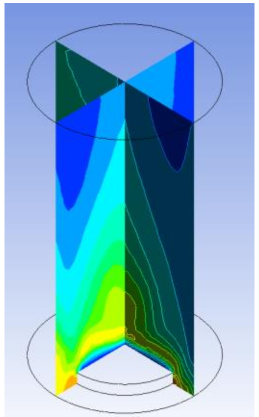
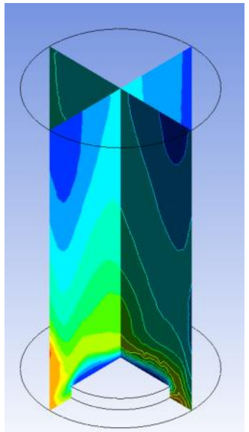
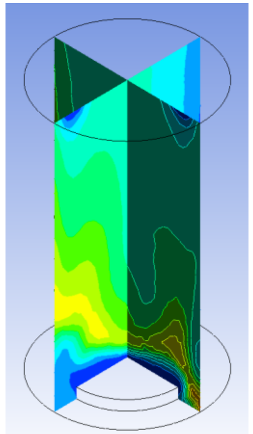
Air flow rate, $\dot{m}_{air}$ (LPM)	10	8	6	4	2
Experiment					
Simulation					

Table 1 Flame structure of one air inlets flow using 100% kerosene

4.2.2 90% Kerosene 10% Vegetable Cooking Oil(VCO)

The show the temperature profile of the combustion using 90/10 KVCO as the mix fuel blends. The temperature decreases in the experimental value from 740.5 Kelvin to667.84 Kelvin. The peak temperature also reduces compare to the 100% kerosene where the value is 740.5Kelvin which lower than 840.5 Kelvin. This shows that the mix blends fuel will effects the product of the temperature profile since the 10% vegetable cooking oil has higher viscosity and density. VCO penetrate longer in the combustion chamber than kerosene.(Capuano, Costa, Di Fraia, Massarotti, & Vanoli, 2017)

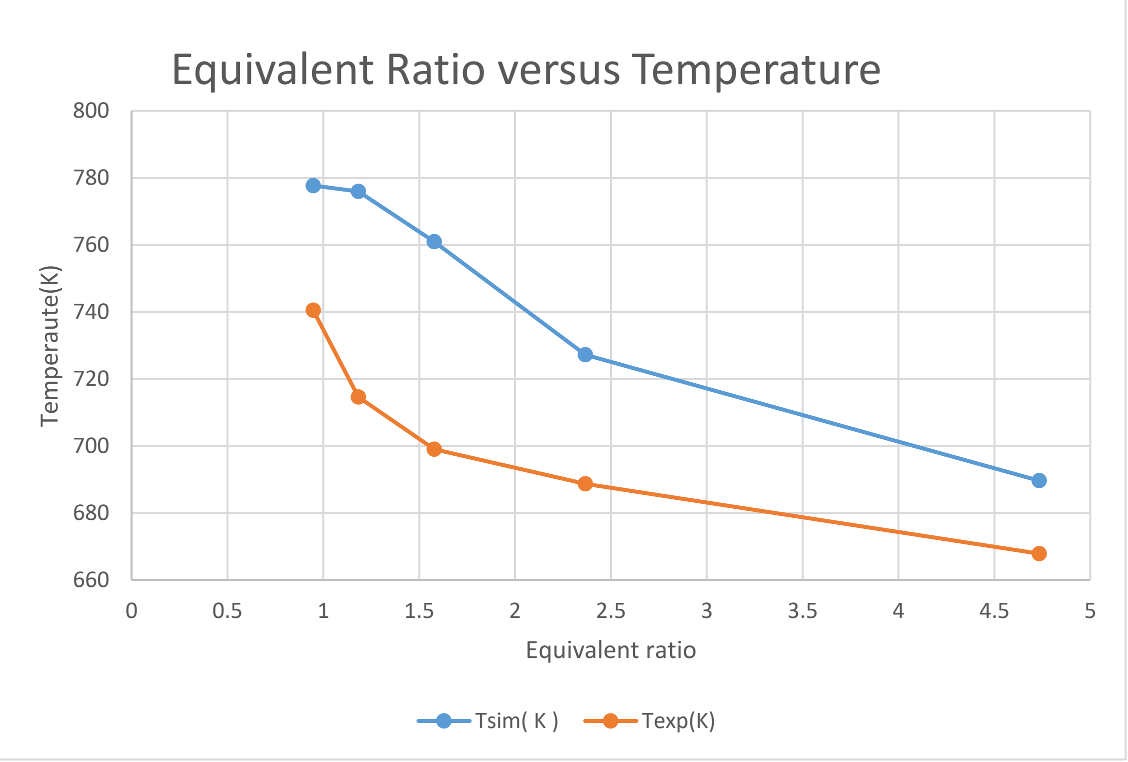


Figure 12 Statistical data from the experiment of 90/10 KVCO fuel one inlet air flow

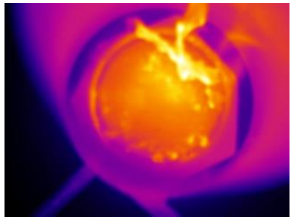
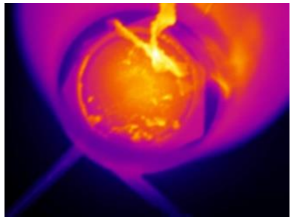
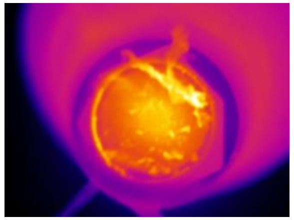
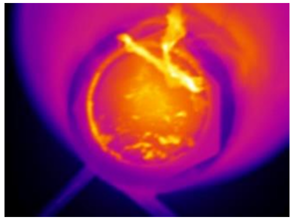
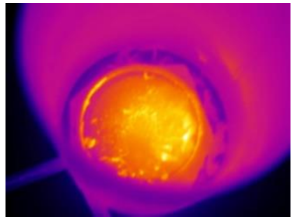
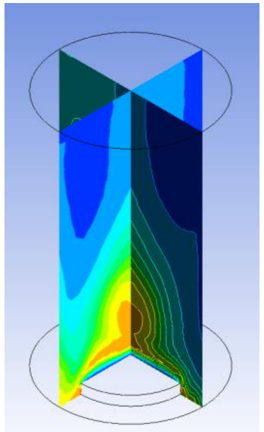
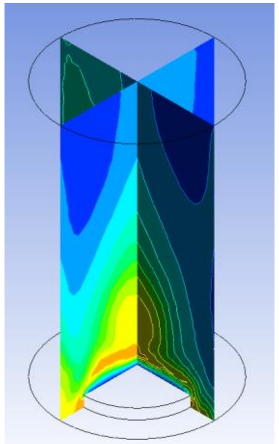
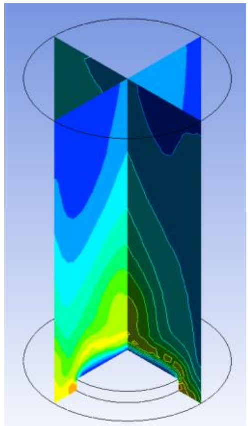
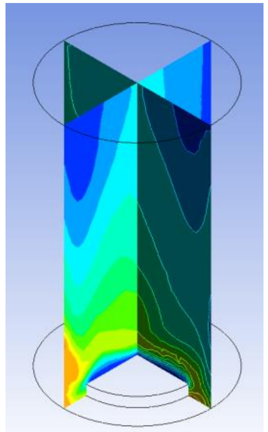
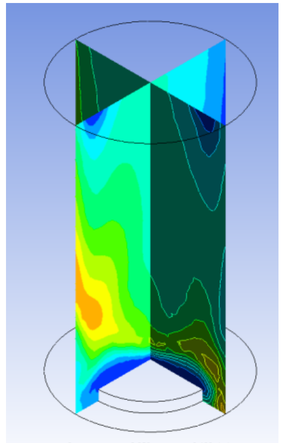
Air flow rate, $\dot{m}_{air}$ (LPM)	10	8	6	4	2
Experiment					
Simulation					

Table 2 Flame structure of one air inlets flow using 90/10 KVCO

4.2.3 75% Kerosene 25% Vegetable Cooking Oil(VCO)

As for the 75/25 KVCO result, it seems that the higher temperature recorded in 10LPM which is 774.45 Kelvin higher than 740.5 Kelvin from 90/10 KVCO. The trends from the experimental data show different from the simulation. It drastically decreases from the 10LPM to 4LPM. This flaw might be the effect from the unstable air supply by the compressor that supplies more air in the experiment. The combustion only stable at ø > 2.607 where there is an only slightest change of the temperature profile.

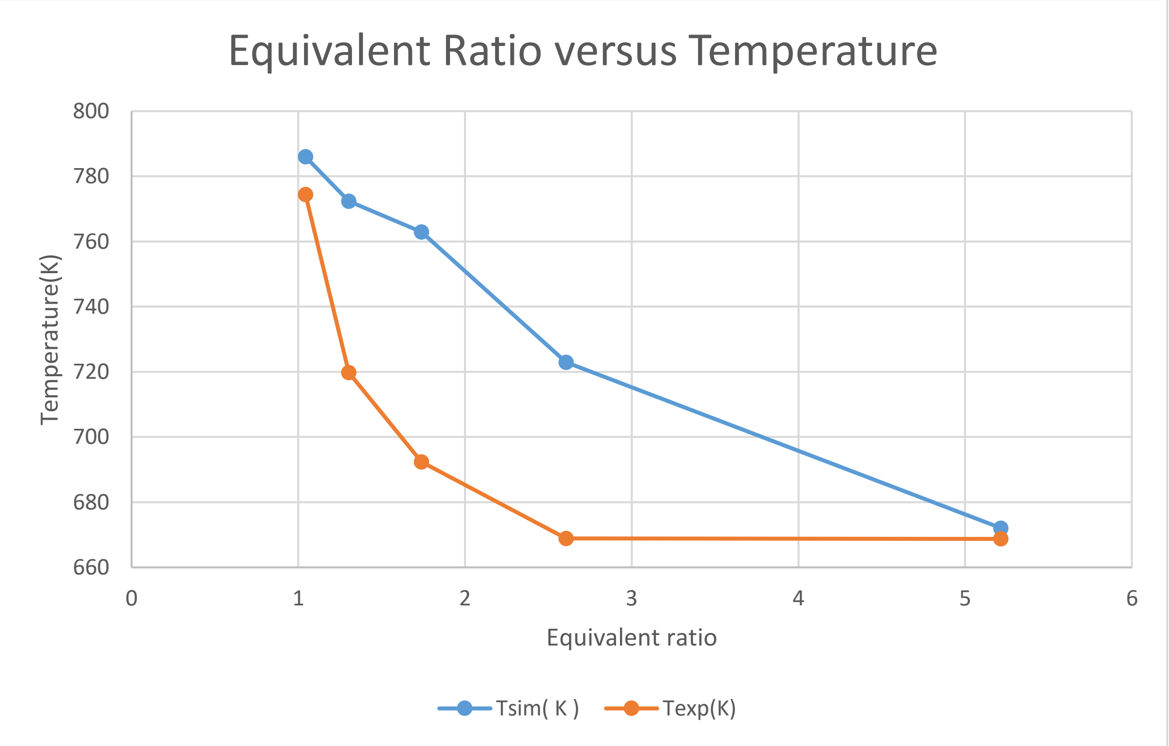


Figure 13 Statistical data from the experiment of 75/25 KVCO fuel one inlet air flow

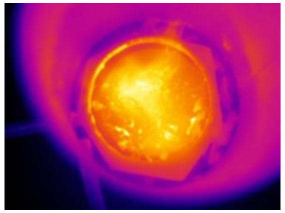
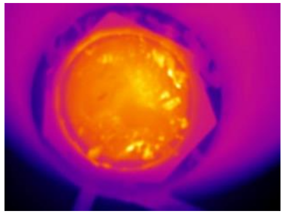
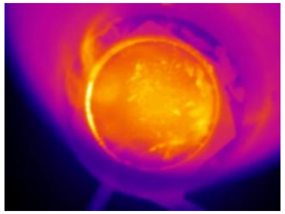
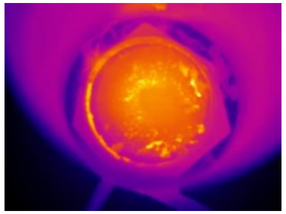
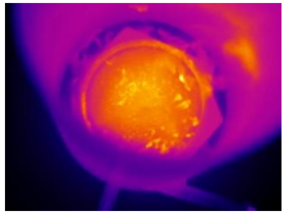
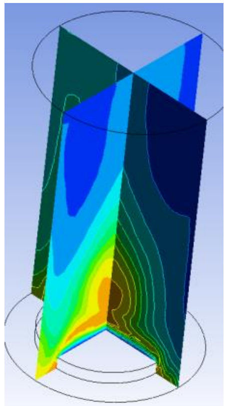
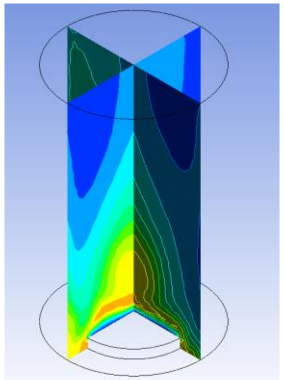
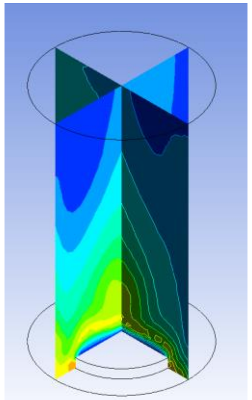
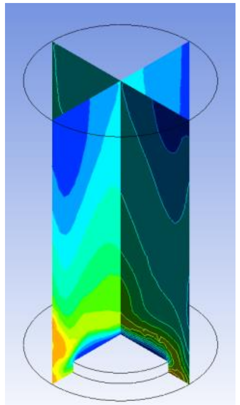
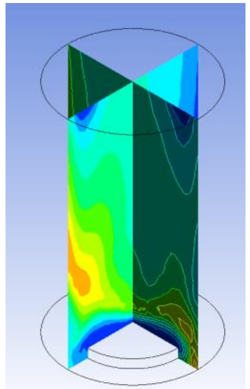
Air flow rate, $\dot{m}_{air}$ (LPM)	10	8	6	4	2
Experiment					
Simulation					

Table 3 Flame structure of one air inlets flow using 75/25 KVCO

4.2.4 50% Kerosene 50% Vegetable Cooking Oil(VCO)

From the 50/50 KVCO, we can see that the combustion has been stable because the different of the temperature from 0.9645< ø < 4.8228 only a little. The fuel properties have influenced the combustion process this causes the temperature decrease. It shows that the vegetable cooking oil was not improved the combustion process as the percentage of vegetable cooking oil increase the temperature also decreases.

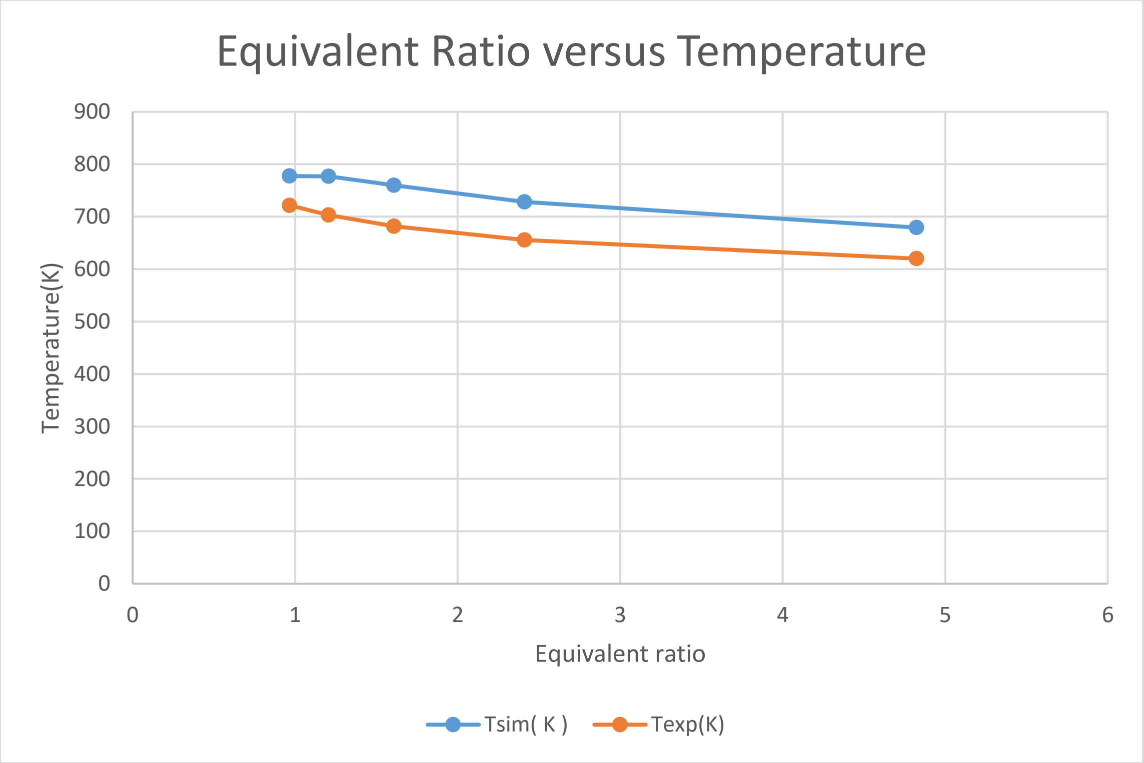


Figure 14 Statistical data from the experiment of 50/50 KVCO fuel one inlet air flow

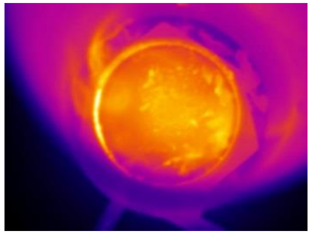
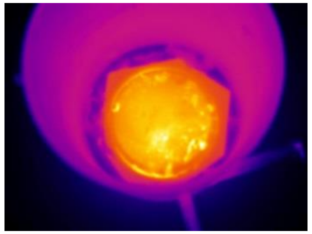
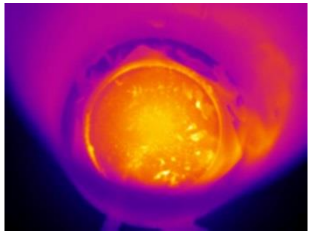
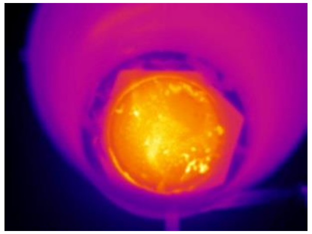
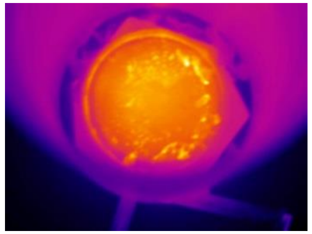
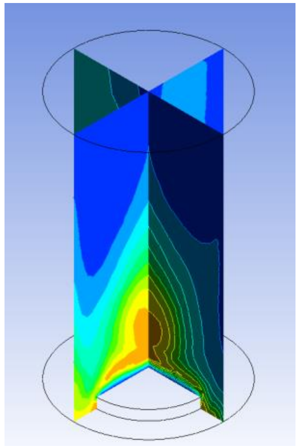
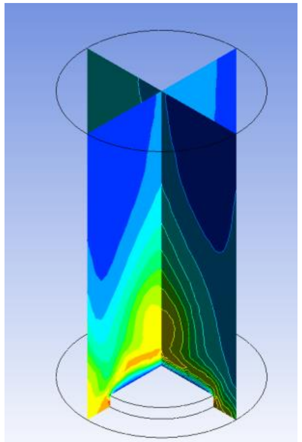
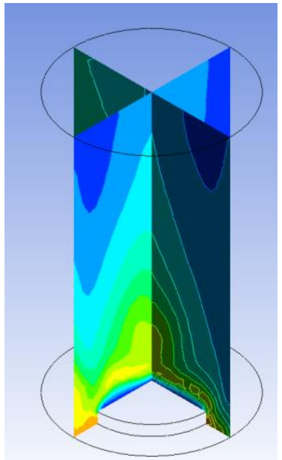
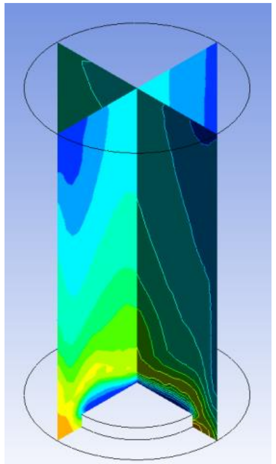
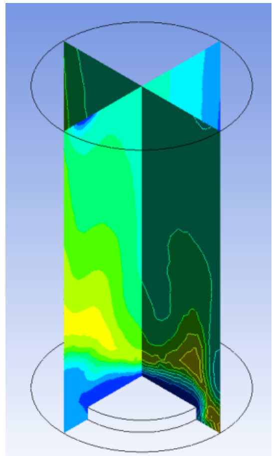
Air flow rate, $\dot{m}_{air}$ (LPM)	10	8	6	4	2
Experiment					
Simulation					

Table 4 Flame structure of one air inlets flow using 50/50 KVCO