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On the Effects of Fuel Inlet Configurations and Equivalence Ratio to the Pre-Heating Stage of A Liquid Fuelled Flameless Swirl Combustor

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Abstract. Flameless combustion has once again managed to attract the attention of various researchers in trying to find an alternative solution in the energy crisis that we are facing today. Thus, to join in into the parade, a lab-scale liquid fuelled Flameless Swirl Combustor (FSC) was fabricated in the High Speed Reacting Flow Lab (HiREF) to study the flameless combustion using liquid fuel. The combustion process in this combustor has two stages: preheating stage (using gas fuel) and flameless mode (using liquid fuel). This paper will be focusing on the pre-heating stage of the overall flameless combustion process using Liquefied Petroleum Gas (LPG). Gas fuel is injected axially while air at room temperature is injected tangentially from 12 inlet ports. 18 gas fuel inlets were arranged in a hexagon shaped array on the inlet flank. 6 inlet configurations with different equivalence ratios ranged from 0.3 to 1.2 were tested to preheat the combustion chamber. The results shows that regardless of different inlet configurations, flameless mode was successfully achieved using gas fuel at equivalence ratios around 0.6 and the peak temperature inside the chamber never exceeds 900ºC which is well below the temperature of thermal NO_x formation. It can also be observed that for equivalence ratios lower than 0.65, the temperature profile inside the chamber has less fluctuation compared to the higher ends of the equivalence ratios. The results also showed that the maximum peak temperature (T_{max}) was almost always achieved just above the equivalence ratio of 0.7 and Swirl Number (S_g) of 350.

Keywords: Flameless Combustion; Swirl; Inlet configurations.

INTRODUCTION

The demand on safe and green energy generation technology has been increasing exponentially throughout the recent years [8, 9]. Rigorous studies were focused on other potential solutions to the world's energy crisis such as hybrid technology, solar energy, fuel cell technology, etc. But very little focus was given to a particular technology called flameless combustion. Whereas, it is this particular technology that can actually realistically be considered to be the most practical and closest answer to the energy crisis that we are facing now [2, 3] This can be supported by the fact that this technology is applicable to almost all of the existing fuel, whether they are in solid phase, liquid phase, or gaseous phase, thus making it feasible to be used in the nearest future [2].

Due to this fact, it is believed that less modification is needed to apply this technology to current technology used in industries. Another huge advantage of using flameless combustion is that the emission of dangerous and harmful gases such as NO_x, SO_x and CO can be minimized to almost none [2-7]. The produced CO_2 is almost pure, therefore making it possible to extract it for other beneficial industrial uses. Flameless combustion operating temperature, the peak temperature, and the fluctuation of the flame temperature is generally significantly lower than conventional combustion process [10-12]. As a result, longer lifetime and less maintenance needed for the operation of the combustion chamber and other related parts equipped together with the energy generator, thus lowering the cost of operation in long term application.

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Swirl Number (S) is used to gauge the strength of a swirl flow, and is defined as the ratio of the axial flux of angular momentum to the axial flux of axial momentum. The application of tangential injected air supply in this particular work utilizes the swirl flow to maximize the internal recirculation of exhaust gas (EGR). It was found that EGR is an effective method of NOx suppression [13]. Nevertheless, often it is very difficult to obtain the swirl number experimentally, due to the difficulty in measuring the angular flux momentum and the axial flux momentum inside a combustion chamber [1]. Therefore, most researchers opted to do simulations to obtain the values of swirl number. On the other hand, there are many researchers successfully obtained the swirl number by deriving geometric swirl number (S_g) equations. In this particular work, **Equation 1** was used to calculate the values of swirl number [1].

Another main aspect being studied was the effects of air to fuel (AFR) equivalence ratio (λ) on the combustion characteristics. Equivalence ratio is defined as the ratio of actual AFR ratio to the stoichiometric AFR for a given mixture. For a mixture to have a value of $\lambda=1.0$, it means that the mixture is at stoichiometric, while a value of $\lambda<1.0$, the mixture is said to be rich, and if a mixture has a value of $\lambda>1.0$, the mixture is said to be a lean mixture [1]. The formula of AFR, and λ are given in **Equation 2** and **Equation 3** respectively.

$$S_g = \left(\frac{m_t}{m_T}\right)^2 \left(\frac{D}{d}\right)^2 \frac{\sin\theta}{n} \qquad \textbf{Eqn. 1}$$

$$AFR = \frac{\dot{m}_{air}}{\dot{m}_{fuel}} \qquad \textbf{Eqn. 2}$$

$$\lambda = \frac{AFR_{actual}}{AFR_{stoic}} \qquad \textbf{Eqn. 3}$$

where,

m_t = *total mass flow rate through injector*
m_T = *total mass flow rate in the chamber*
$\dot{m}_{air}$ = *massflow rate of air*
$\dot{m}_{fuel}$ = *mass flow rate of fuel*
D = diameter of chamber
d = diameter of injector
Θ = injection angle
n = number of injector

Types of Flameless Combustion Technologies

Flameless combustion has different other names depending on the mechanism, or approach used in achieving flameless condition. The idea originated from Excess Enthalpy Combustion concept. Some of them called it as Mild Combustion, especially in Italy, whereas in Japan, it is called High Temperature Air Combustion (HiTAC). A similar kind of technology is called Flameless Oxidation (FLOX) in Germany, Low NO_x Injection (LNI) in the United States of America, and Fuel Direct Injection (FDI) developed by Tokyo Gas Company [8].

EXPERIMENTAL SETUP

A lab-scaled, horizontal Liquid Fueled Normal Temperature Air Flameless Combustor (NTAFC) was developed in Hiref lab to study the characteristics of a liquid fueled flameless combustor. The combustor was purposely built with a cylindrical shape to investigate the effects of simple geometry of a combustor to the feasibility of liquid fueled flameless combustion, and to imitate the shape of common combustors currently used in the industry. The combustion chamber was constructed with a two layer design with the sole purpose of retaining heat inside the chamber.

The inner wall of the combustion chamber has a diameter of 300 mm and was made with a refractory cement material with a thickness of 75 mm. The outer layer of the combustion chamber was made with stainless steel with a thickness of 1 cm. Both the front (outlet flank) and the back (inlet flank) of the combustion chamber were closed with stainless steel plates of the same thickness as the outer wall of the combustion chamber. An observation window made from a 1 cm thick quartz was installed at the outlet flank of the chamber. While on the other hand, the inlet flank was installed with a specifically designed reactants supply channels that will be explained below. An exhaust channel for flue gas was prepared at the top of the combustion chamber near the outlet flank. The exhaust channel has an outer diameter of 40 mm and a thickness of 2 mm. While the reactants supply system used in the experiments was made from stainless steel tubes with an outer diameter of 9 mm and a thickness of 1 mm.

The combustor has 2 types of air supplies to inject air into the chamber; axially and also tangentially. A total of 19 channels were used to supply either gas fuel, liquid fuel, exhaust gas recirculation, or axial air supply at the inlet flank. A liquid fuel injector was installed at the center of a hexagon shaped array of 18 inlet channels that can be manipulated to either supply air, gas fuel, or recirculated exhaust gas. This design was used to study the effects of reactants configurations effect on the combustion characteristics during experiments. On the other hand, a separate set of 12 air inlets specifically positioned tangentially near the inlet, the middle, and the outlet of the chamber, were located at the top, bottom, and both sides of the chamber to introduce anti-clockwise swirl effects inside the chamber. Two separate air compressors were used to supply axial air and tangential air respectively. The configurations used in the experiments are shown in **Figure 2**.

Instrumentation for data gathering purposes consists of several types of sensors and equipment as follows. 6 thermocouples type-K were inserted from the top and along the length of the burner to measure the temperature profile inside the chamber. The thermocouples were connected to a TC-08 PICO logger and a computer for recording the temperature profile of the inside of the combustion chamber. To control the flow rates of the reactants, Rotameters were used at 4 different reactants supply lines as follows; liquid fuel, gas fuel, axial air supply, and tangential air supply.

A pressurized liquid fuel tank was used in the experiment to supply alcohol as liquid fuel. The liquid fuel tank was pressurized using N_2 gas, before being injected into the combustion chamber. Furthermore, an exhaust gas recirculation system were installed at the exhaust channel. The recirculated exhaust gas is transferred by a suction blade to the inlet flanks to investigate the effects of EGR to the combustion characteristics.

The experimental setup explained above is shown in Figure 1.

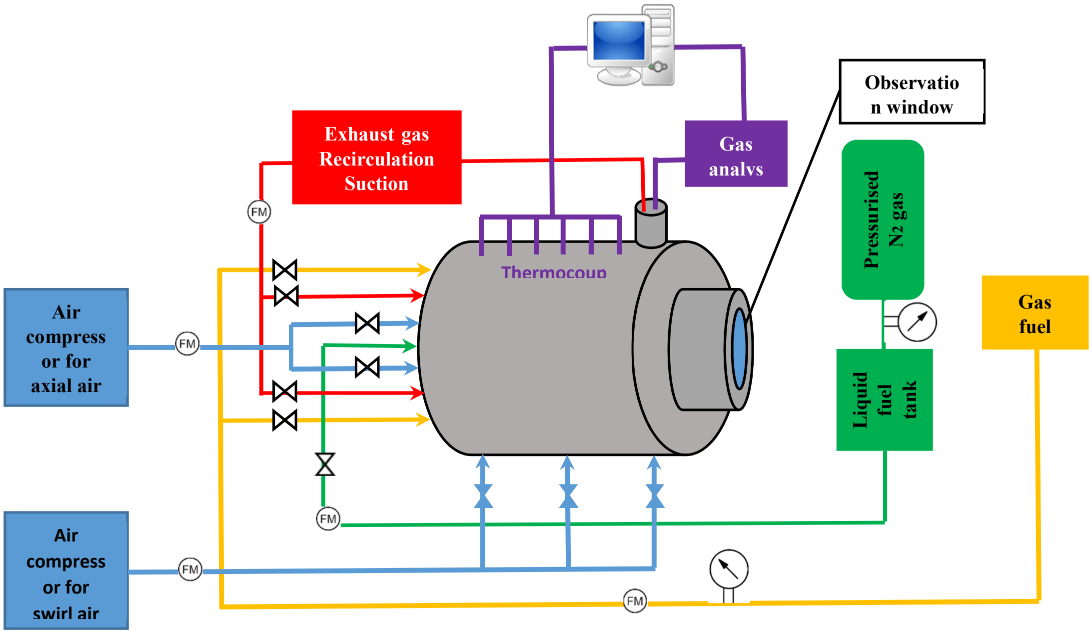


Figure 1 Experimental setup

Methodology

The main experiment procedure is divided into two parts. First part is the preheating stage of the combustor using LPG as fuel. Both swirl air and axial air injection were activated to maximize mixing of the reactants. The chamber will be heated up until the temperature increased to above the auto-ignition temperature of the liquid fuel that will be used in the second part of the combustion process. This stage is essential in achieving flameless mode using liquid fuel. After the temperature of the combustion chamber were increased to the required temperature, liquid fuel will gradually be introduced into the combustion chamber while simultaneously decreasing the supply of gas fuel until flameless mode is achieved.

Incidentally, this paper focuses on the effects of swirl air to the pre-heating stage of the burner. At this stage, the main objective is to preheat the combustion chamber to above the auto-ignition temperature of the liquid fuel that will be used in the second stage of the experiment as mentioned earlier. From the literature, it was also found out to be more beneficial to establish flameless mode using liquid fuel if the preheating stage had also successfully achieved flameless mode. Thus, in this paper, the effects of reactants inlet configurations were also investigated.

From the hexagon shaped inlet array, LPG can be injected into the chamber with 3 different distances from the center of the chamber; 9 cm, 11cm, and 13 cm respectively. For every distance, 6 of the inlet channels with the same distance to the center of the chamber will be used to inject gas, and different equivalence ratios of reactants were tested to investigate the effects of gas injection distance to the stability of flameless mode. Both the inlet configurations and the tested equivalent ratios during this experiment are shown in **Figure 2** and **Table 1** respectively.

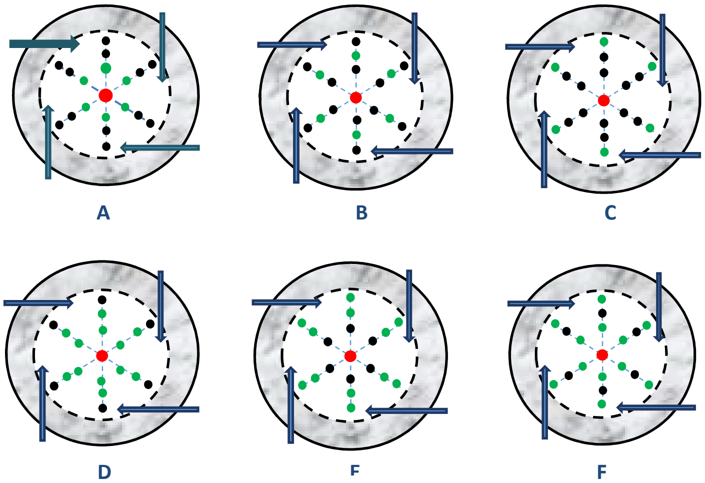


Figure 2 Inlet flank ports arrangements;

🔴 Liquid fuel injector
🟢 Gas fuel
🔵 Tangential air supply
● Closed channel
■ Ceramic wall

No.	Tangential air flow rate (scfh)	Gas flow rate (scfh)	Equivalence Ratio, λ
1	200	30	0.39
2	250	30	0.49
3	300	30	0.60
4	350	30	0.71
5	400	30	0.82
6	450	30	0.92
7	550	30	1.14

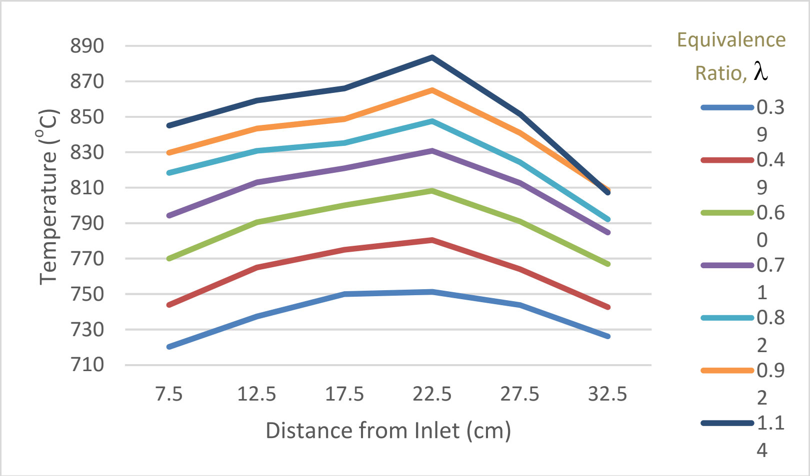
Table 1 Experimented equivalence ratio values

RESULTS AND DISCUSSION

The main concern of this work is to investigate the flameless burner performances and characteristics during pre-heating stage. Thus, a parametric study was carried out by varying inlet configurations, and equivalence ratio. It is also worth mentioning that only tangential air supply was used during the study. This in result also means that higher equivalence ratios will produce higher swirl number.

By changing the flow rate of tangential air supply, the equivalence ratio and swirl number changes accordingly. A total of 7 equivalence ratios were tested in this experiment as shown in Table 1 while maintaining the flow rate of fuel constant. On the other hand, the effects of 6 change in the configuration of gas fuel inlet was also studied. A total of 6 inlet configurations were tested in this experiment. 3 of the configurations used only 6 inlet channels, while in the other 3 configurations, the number of air inlet were doubled to 12 inlet channels without changing the flow rate. This is to study the effects of number of inlet channels to the combustion process.

<table>
<tr><th>Inlet Configuration</th><th>Temperature Profile</th></tr>
<tr><td>A-Inner Inlet</td><td>



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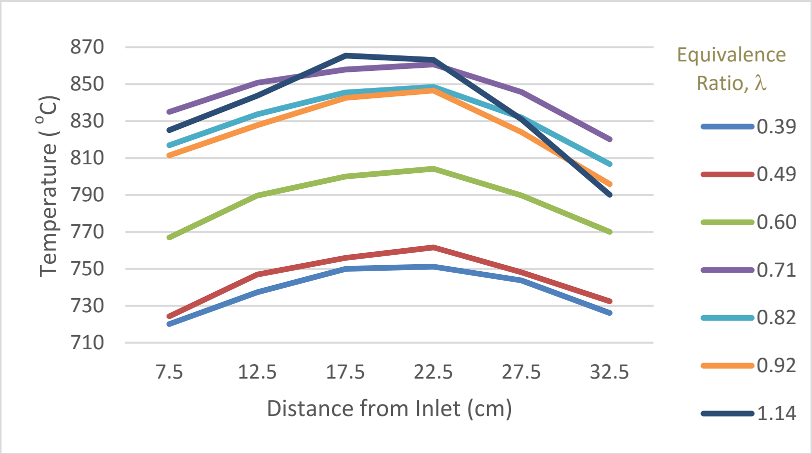
<tr><td>B-Middle Inlet</td><td>



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<tr><td>C-Outer Inlet</td><td></td></tr>
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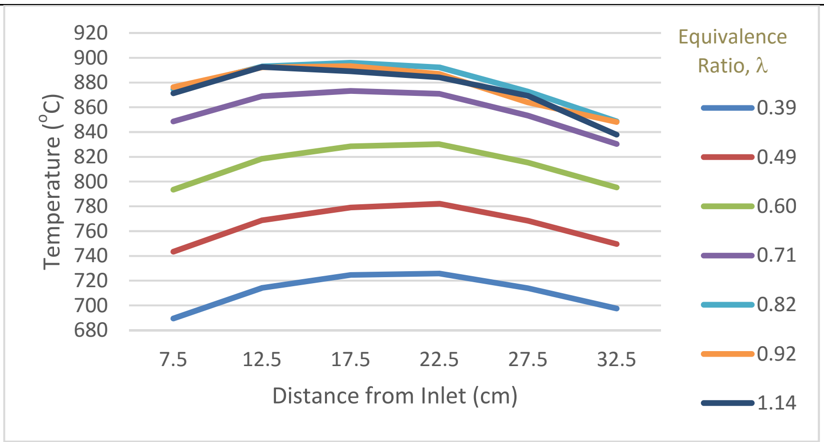
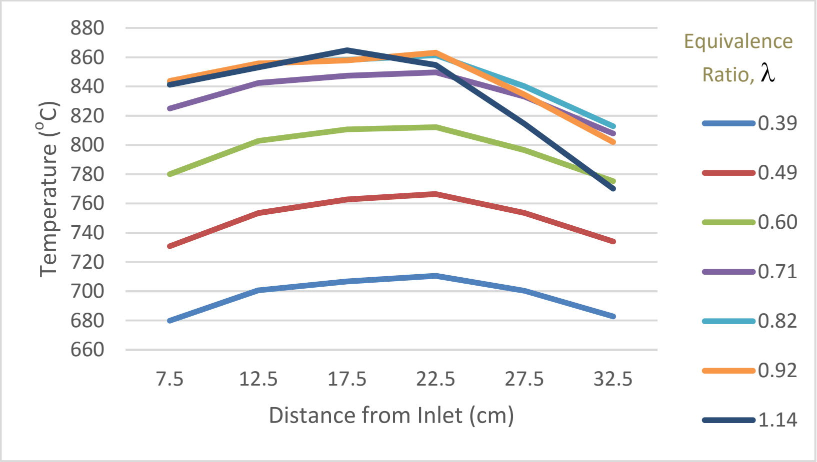
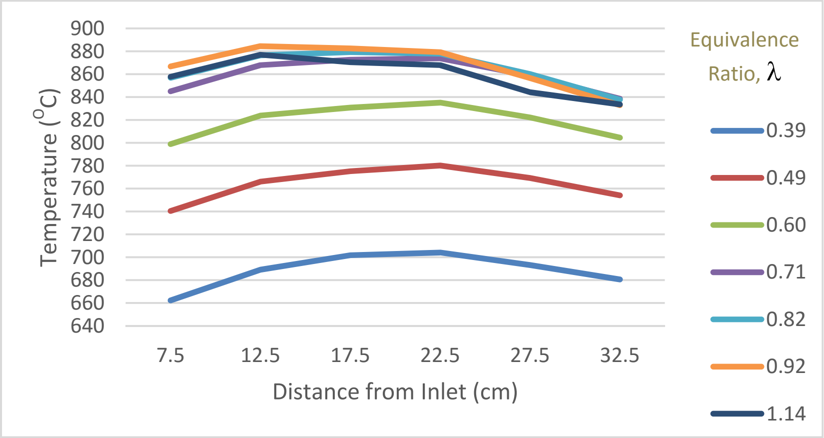
	
D-Dual Inner Inlet	
E-Dual Outer inlet	

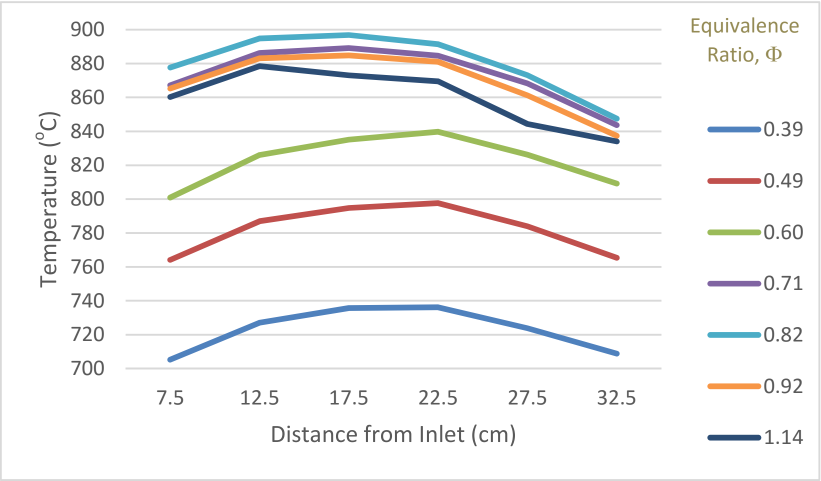
F=Outer + Inner Inlet	

Figure 3 Temperature Profile

As graphically represented in Figure 3, the temperature profiles inside the combustion chamber had similar trend throughout the whole configurations and for all equivalence ratios. The temperatures near the inlet and outlet flanks were lower compared to the center of the combustion chamber as the peak temperatures were often measured close to the center of the combustion chamber. The lower temperatures at the inlet flank is believed to be caused by the effect of dilution due to the injection of fresh fuel which was injected at room temperature. Furthermore, the low temperatures at the outlet flank was believed to be caused by heat lost from exhaust gas exiting the combustion chamber and through the observation window. The temperature fluctuations are almost non-existent in the combustion chamber, except for when the equivalence ratio reaches 1.14. Another valuable observation from the experiment is that the peak temperature never exceeded 900ºC line. This is well below the temperature of thermal NO_x formation, which is at 1200ºC [2]. This should resulted into significant reduction of NO_x formation during the experiment. From **Figure 3**, there were no significant changes observed due to doubling the number of fuel injectors.

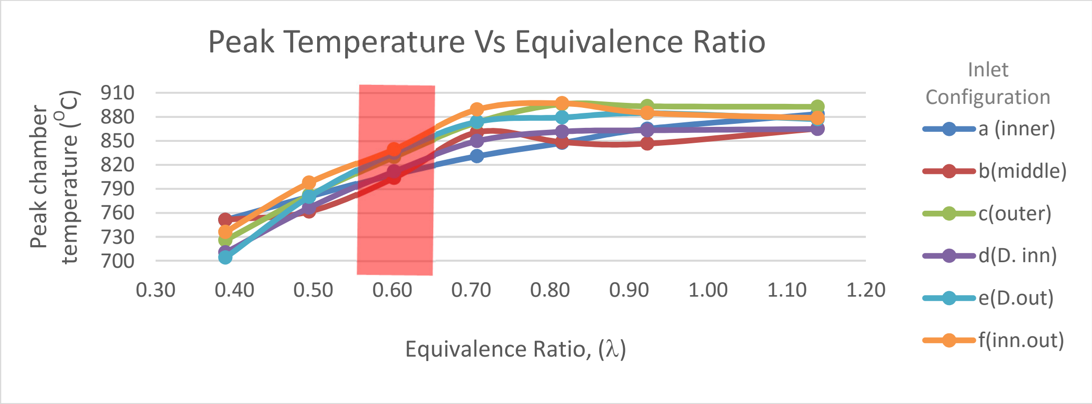


Figure 4 Peak Temperature VS Equivalence Ratio

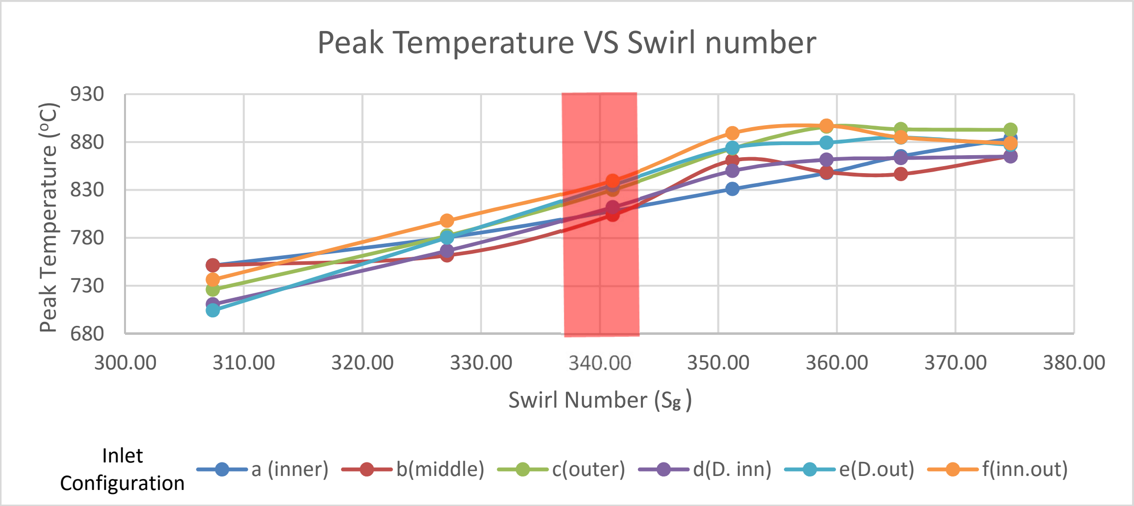


Figure 5 Peak Temperature VS Swirl Number

Before studying **Figure 5**, it is worth mentioning that in **Figure 3**, the temperature profile graphs showed that the temperature profile ranges are very similar starting from equivalence ratio 0.71 to 1.14. While on the other hand, the overall temperature profile inside the combustion chamber were significantly lower for equivalence ratio from 0.39 to 0.60. It is believed that this is due to the insufficient swirl flow produced from the air inlet which were injected tangentially. As mentioned previously in this particular experiment, as equivalence ratio increased, the swirl number also increases. This is strongly supported by **Figure 4** and **Figure 5**, where it is clearly shown that the values of peak temperatures started to stabilize at $\lambda > 0.71$ and $S_g > 350$. In addition, the red shaded area in both **Figure 4** and **Figure 5** indicate the values where flameless mode was successfully sustained. Specifically, regardless of inlet configurations, flameless mode was achieved at equivalence ratio of around 0.59 and swirl number 341.

CONCLUSION

A liquid fuelled Flameless Swirl Combustor (FSC) was developed in Hiref to investigate the feasibility of liquid fuelled flameless combustor. This paper is focused on the preheating stage using LPG gas. Only tangential air inlets were used to supply air to the combustion process. The effects of 6 different inlet configurations with a variety of equivalence ratios ranging from 0.39 to 1.14 were studied in this experiment. Due to the air inlet injected tangentially, the increase in equivalence ratio also increases the swirl number inside the combustion chamber. The changes in inlet configurations and doubling the number of gas fuel inlets were found out to have insignificant effects to the stability of flameless mode. It is also known that regardless of the fuel inlet configuration and equivalence ratio, the trend of the temperature profile inside the combustion chamber remained similar, where the peak temperatures were measured around the middle of the chamber and a temperature reduction at both the ends of the chamber. Incidentally, the peak temperatures measured throughout the experiment never exceeded 900^{o}C, which is well below the thermal NO$_x$ temperature which is at 1200^{o}C. It was observed that with $S_g < 350$, the overall temperature profile decreased due to the low equivalence ratio and low swirl effect. But by increasing the $S_g > 350$, the range of temperature profile for all inlet configurations were maintained in between 800^{o}C to 900^{o}C and the values of the peak temperature became stable. Finally, flameless mode were sustained during the preheating stage at around equivalence ratio of 0.59 and swirl number 341 regardless of inlet configurations. To conclude, it was determined that the optimal condition for pre-heating the chamber was by using configuration C(outer inlet) at equivalence ratio of around 0.59 and swirl number 341.

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