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Development of Liquid Fueled Flameless Combustor

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Abstract Flameless combustion has become one of the newest focus in the search for cleaner, greener, and safer energy generation technology. Different designs of combustion chambers were used for different types of fuels. Since most of the previous studies were focused on gaseous fuel application, this paper will discuss on the configuration of the combustion chamber, the geometric factor and the approach used in designing the combustion chamber for liquid fuels to achieve flameless combustion conditions. Several configuration such as single stage chambers, two stage chambers, and reverse-flow configured chamber are explained in this paper. Therefore, the purpose of this paper is to review the progress and latest achievement in flameless combustion using liquid fuel. Necessary comparison between the performances and the characteristics of the combustion process was done especially in the products of the combustion process. At the end of this paper, a newly developed liquid fueled flameless combustor will be proposed and discussed.

Keywords: Flameless combustion; Mild combustion; Liquid fuels; Flue gas recirculation; clean energy.

INTRODUCTION

Most of the flameless combustion researches so far were focused on gaseous fuel. But ironically, liquid fuel is considered to be the most widely used type of fuel currently, but very little study were carried out in this aspect [9].Moderate or Intense Low oxygen Dilution (MILD) combustion, Flameless Oxidation (FLOX), and High temperature Air Combustion (HiTAC), are other names used to address Flameless combustion.

The increasing demand on safe and green energy generation technology throughout the recent years resulted in rigorous studies in potential fields such as hybrid technology, solar energy and fuel cell technology [1]. However, little attention has been given to a particular technology called flameless combustion. In flameless combustion, it is possible to apply the existing fuel in the combustion process regardless of whether they are in gaseous phase, liquid phase or even solid phase. This makes flameless combustion feasible to be used in the nearest future [2]. It is also believed that, due to high familiarity and compatibility to the existing fuel, less modification is needed to apply this technology to the industry. In flameless mode, combustion operating temperature, peak temperature, and the fluctuation of the flame temperature are significantly lower then conventional combustion process [3]. As a result,

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longer lifetime and less maintainance will be 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.

Another huge advantage by using flameless combustion is the emissions of dangerous and harmful gases such as NO_x, SO_x, and CO can be minimized to a very minimal amount [1,4,5,12]. CO_2 gas that is being produced is almost pure, making it possible to be extracted for other beneficial industrial uses.

The objective of this paper is to study on the design and development of a novel direct injection liquid fueled Normal Temperature Air Flameless Combustor (NTAFC). One of the main characteristics of this burner is that it utilizes the use of swirl flow to maximize internal recirculation ratio of ehaust gas (EGR), which was found to be n effective method in suppressing thermal NO_x formation [13].

PREVIOUS WORKS

Single Chamber Flameless Combustor

As can be seen in **Table 1**, the combustor is placed vertically on a test stand with the fuel injector was located at the center of the combustor. While the kerosene was stored in a pressurized stainless-steel tank at a pressure of 9 bar. Since the fuel injector is moving in clockwise rotation to spray fuel, therefore, air injection in counter clockwise manner was selected to provide more shear force to the flow. The purpose of this selection is to enhance the mixing and evaporation of the droplets. Electric mass flow controllers was used to regulate the air supply to the combustor.

The basis used for these set up is to overcome the three parameters that affect the stabilization of the flameless combustion which is Sauter Mean Diameter (SMD), characteristics of the combustion process such as droplets distribution, evaporation, mixture formation and dilution of reactants, and reaction rate in the reaction zone.

In order to overcome these three parameters, the author has suggested by increasing the residence times and recirculation. It leads to the usage of the pressure swirl fuel injector to inject the kerosene because high swirl enhances the hot air trapped within the swirling flow and the high recirculation allows good mixing of the of products and reactants.

In this study, the flameless combustion was stabilized when the thermal input is 21.5 kW and the maximum ratio of reactant dilution is 3.2 with low emissions using the combustor. However, when the same combustor was tested at higher thermal inputs, the flameless combustion was not stabilized and inside the combustor, large quantities of unburned fuel accumulates. Also, the usage of chamfer at the top of the combustor to enhance the droplets residence time and recirculation rate has been proved in this study. The combustor used shows an outstanding performance and having the potential to be used in industries and gas turbine applications.

Dual Chamber Flameless Combustor

The following design was also suggested later by Mahendra et al. [6], and the setup is nearly similar to the single stage combustor. The major difference is the two stage combustor having two separate chambers in order to maximize the recirculation and the reactant dilution ratio. During this study, three types of fuels which is kerosene, diesel and gasoline were used. Shape of cone is being implemented at the top parts of the primary and secondary chamber purposely to maximize the swirl effect inside the chambers. As shown in the Figure 2 above, four air inlets is positioned tangentially at the bottom of both chambers to enhance the swirl effect that required to produce flameless combustion.

In this study, author has successfully presented experimental and numerical results of flameless combustion with different thermal input of 20, 30, 40 and 60 kW using two stage combustor. Also, with the decrement in the port diameter of the primary chamber, the ratio of the reactants dilution increase.

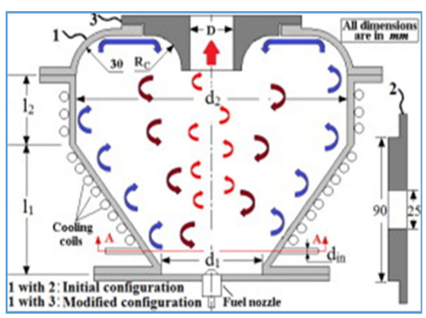
Another extensive work in investigating the feasibility of using liquid fuel in flameless mode was done by Derudi in 2011. His burner has a Dual-Nozzle configuration. The two sectioned combustion chamber was made from quartz and has an internal diameter of 50 mm and a height of 350 mm. The first section, which was located at the lower part of the combustion chamber was filled with quartz pellets to improve heat exchange rate during preheating stage of the combustion air. The primary nozzle was used for gaseous fuel and air for Single-Nozzle configuration of the combustion process. After flameless mode was successfully sustained in the Single-Nozzle configuration, liquid fuel and secondary air were injected into the combustion chamber perpendicular to the gas fuel nozzle. This dual stage combustion process was carried out to avoid pyrolysis and also the difficulties in firing up liquid fuel. The experiments showed that a Dual-Nozzle configuration combustor is highly recommended to burn various liquid fuels in the flameless mode, and the sustainability of flameless mode depends more on the type of states of the fuel (gas or liquid) compared to the composition of the fuel. It was also found out that it is possible to maintain flameless mode under low dilution ratios (K_v<3).

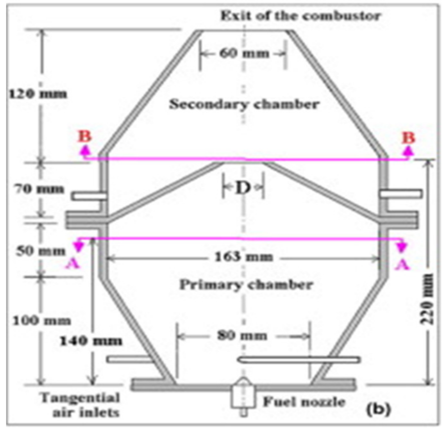
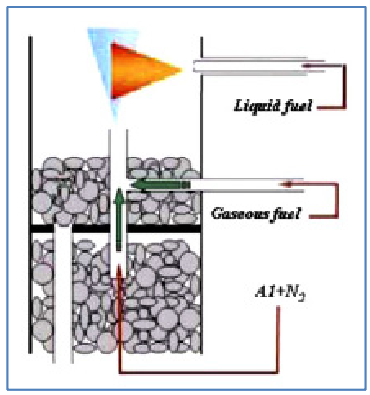
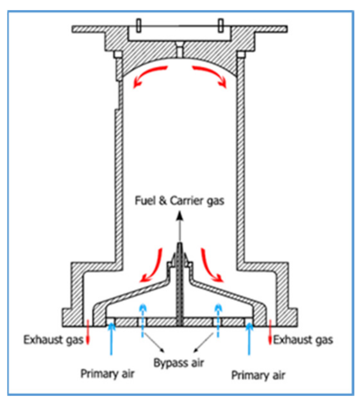
Reverse Flow Configured Flameless Combustor

One of the latest works concerning liquid fueled flameless combustor used a reverse-flow configuration, which previously succeeded in achieving flameless mode using gaseous fuel. J. Ye et. al. studied using different types of liquid fuels consists from alcohol, ketone, and alkane fuels. Most of current studies on liquid fuels flameless combustion were done under atmospheric pressure. Thus, J. Ye performed a study for liquid fueled flameless combustion under high pressure with various types of liquid fuels. Liquid fuels were vaporized prior being injected into the combustor, thus producing a homogenous mixture of fuel and air, ready to be combusted inside the chamber. The main purpose of this distinctive step that differs from previous study was to avoid the complexity of heterogeneous mixture produced from mixing gas and liquid, allowing them to focus more on the effect of pressure, fuel type, and carrier gas to the flameless mode.

The pre-vaporized liquid fuel was injected into the chamber using air or nitrogen gas as the carrier gas. From the design of the combustor, there are two significant key points that plays a major role in establishing flameless combustion. The first is the reverse-flow configuration applied in the combustion system, helps by increasing the rate of internal recirculation of exhaust gases, while in the same time dilutes the reactants mixture. The second key point is the semi hemispherical top which helps in guiding the re-circulated exhaust gases close to the reactant nozzles where constant and steady entrainment ratio of exhaust gases are achieved.

As studied by Luhmann, a cooled reverse-flow flameless combustor using light fuel was tested in 2017 with cold air. Usually in previous studies, combustion air was often preheated due to improving the rate of successfully achieving flameless mode using any type of fuel. Even though the main combustion process uses cold air combustion, preheating of the combustion chamber was required to above auto ignition temperature. The burner consists of a twin liquid fuel atomizer configuration. Several parameters were studied such as spray angle, bore diameter of the twin fluid atomizers, atomizing air pressures, air ratios, and thermal input. The results of the experiment relayed that flameless mode using light fuel was successfully maintained at air ratios 1.1 1nd 1.2 depending on the bore diameters. But it was observed that NO_x and CO emission was lower for bigger bore diameters compared to smaller bore diameters. This was due to bigger bore diameters produced smaller droplets, thus better fuel evaporation and better reactants mixture.

No.	Type	Graphic	Researcher
1	Single Chamber		Mahendra

2	Dual Chamber		Mahendra
3	Dual chamber		M. Derudi
4	Reverse-flow configured flameless combustor		Jingjing Ye

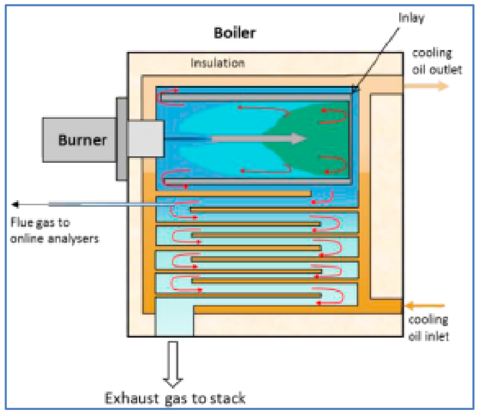
5	Reverse-flow configured flameless combustor		H. Luhmann

Table 1 Previous liquid fuel flameless combustor

DESIGN AND GEOMETRY OF THE DIRECT INJECTION LIQUID FUELED NORMAL AIR TEMPERATURE FLAMELESS COMBUSTOR (NTAFC)

A new type of flameless combustor was developed in the High Speed Reacting Flow (HiREF) research laboratory here in University Teknologi Malaysia. The flameless combustor was designed with the objective of simplifying the structural geometry of a liquid fueled flameless combustor and the overall combustion process to achieve flameless mode. It can be seen from several previous designs as shown in Table 1, most of the designs had quite complex geometries and were also quite miniscule compared to industrial scale. Thus, a semi-industrial scale liquid fueled flameless combustor was designed using a simple cylindrical geometry to minimize manufacturing cost, and to prove that geometric structure have minimal effect on the successful rate of achieving flameless mode.

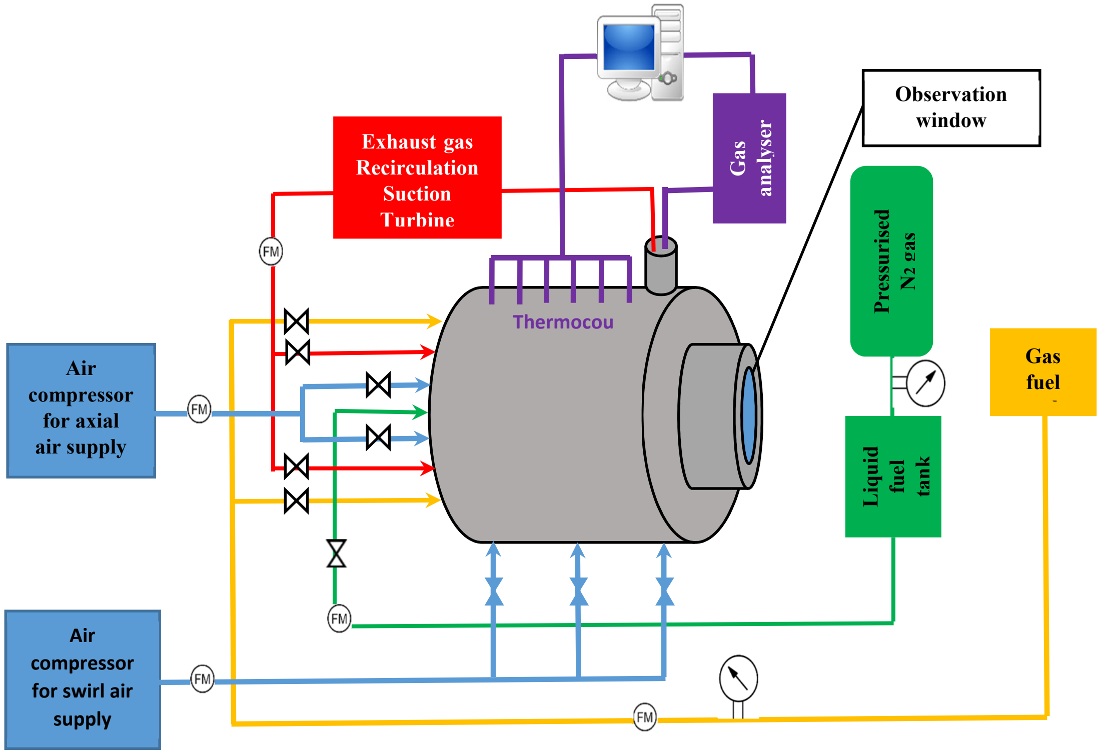


Figure 1 Experimental setup

The newly designed combustor has two layers of materials used in the construction. The inner wall of the combustor is made of high temperature industrial refractory cement, covered by a thick layer of stainless steel wall. The inner diameter of the combustor is 300mm, while the thickness of the refractory layer is 65 mm, followed by the stainless steel outer wall at 10 mm thickness. 12 air inlets were specifically installed tangentially to introduce swirl flow into the combustion chamber. On the other hand, 18 inlet ports were stationed at the inlet flank in a hexagon shaped array. These ports are interchangeable between air inlets, gas fuel inlets, or exhaust gas recirculation (EGR) inlets. At the center of the hexagon array sits a liquid fuel atomizer. Meanwhile, the exhaust channel is located on top of the combustion chamber at the other end, opposite the inlet flank. An observation window made from quartz allows for visualization inspection.

In the first stage of the research, experiments were done using gaseous fuel to produce flameless mode. LPG fuel was successfully used to achieve flameless mode using the configuration as shown in **Figure 2**. Initially, LPG was used to heat up the chamber to above the auto-ignition temperature of LPG which is from 410°C~580°C. This is a crucial step in producing flameless mode in a large chamber. During this stage, only tangential air inlet was used for preheating the chamber, the advantage of using swirl flow is the increase of internal recirculation of the reactants, thus better mixing of the reactants and unburned fuel.

Flameless mode was maintained at around 700°C to 900°C as shown in **Figure 3**. Channel 1 showed the temperatures closest to the inlet surface of the chamber while Channel 6 showed the temperatures at the other end of the chamber. It is worth mentioning that since the exhaust channel was adjacent to the thermocouple for Channel 6, explaining the decrease of the temperature at Channel 6 during flameless mode.

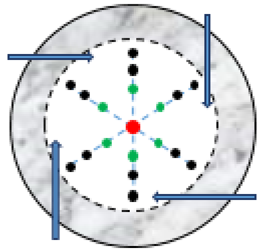


Figure 2 Inlet flank ports arrangements;

- Liquid fuel injector
- Gas fuel
- Tangential air supply
- Closed channel
- Ceramic wall

PRELIMINARY EXPERIMENTAL RESULTS

Preliminary experiments were done to get some early understandings of the performances of the flameless burner. LPG was used with different equivalence ratios (λ) to investigate the effects of different equivalence ratios to the temperatures inside the combustion chamber. This is an essential step for preheating the combustion chamber. As mentioned earlier, 6 thermocouples type-K were used and stationed on the top side, along the combustion chamber. The point of measurements were taken at the center of the combustion chamber. From the results, it is clearly shown that the temperature profile inside the combustion chamber were similar despite different equivalence ratios were applied during the experiment. But from another aspect, the result from **Figure 4** showed that the peak temperature was nearly directly proportional to the values of equivalence ratio. It is also worth mentioning that the peak temperature never exceeded 900^{o}C, which is well below the thermal NO_x formation temperature which is at 1200^{o}C. Flameless was successfully sustained as shown in **Figure 5** at equivalence ratio around 0.59.

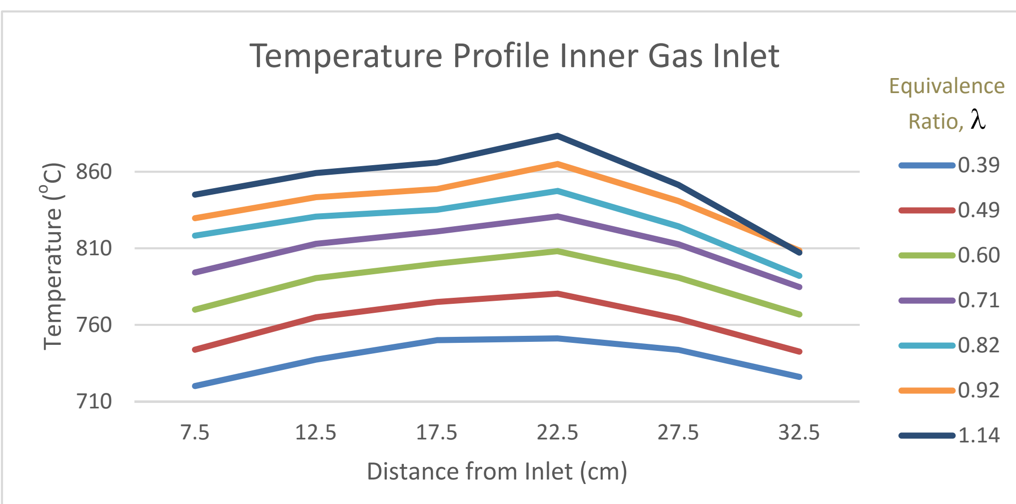


Figure 3 Temperature Profile

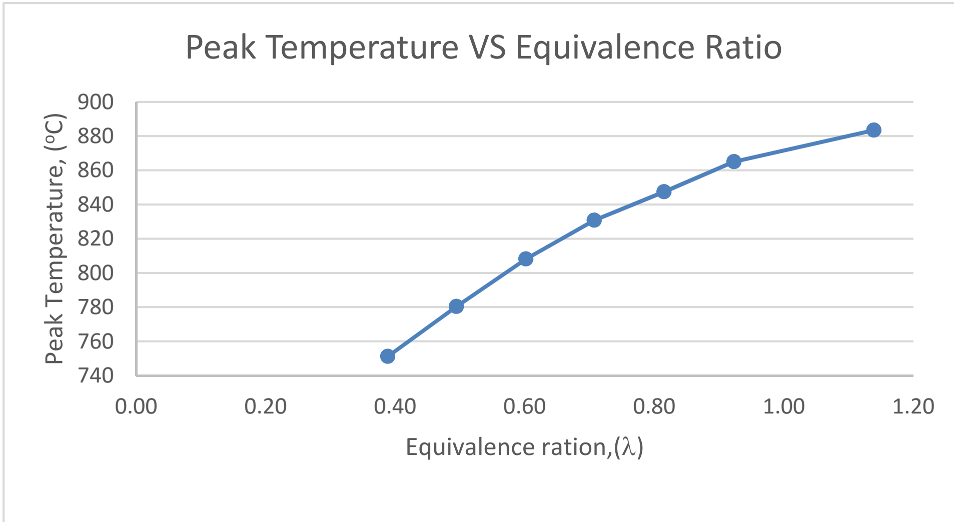


Figure 4 Peak TemperatureVS Equivalence Ratio

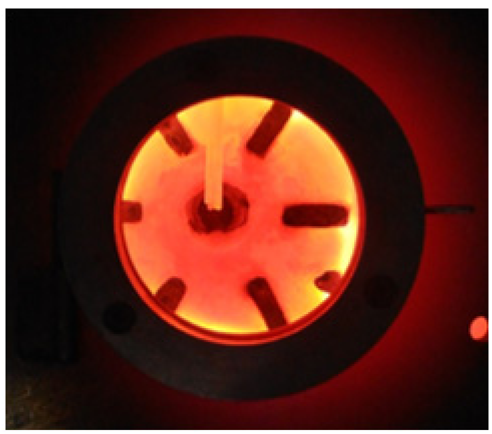


Figure 5 Flameless mode using LPG

CONCLUSION

Four different design approaches was discussed in this paper for flameless combustion chamber designs in particular for liquid fuels. The single stage combustion chamber managed to produce flameless combustion using liquid fuels at low intensity but failed to stabilize flameless combustion mode in higher intensity conditions. Thus a two stage design was proposed. This in result made it successful in maintaining flameless combustion mode in high intensity conditions for gasoline, diesel, and kerosene as fuels. A recent study of pre-vaporized liquid fuel flameless combustion using reverse flow configuration managed to realized flameless mode in high pressure condition using alcohol, ketone, and alkane as fuels. It was found out that alcohol has the most stabilized flameless mode out of the three types of liquid fuels. Last but not least, a new cylindrical single chamber flameless combustion reactor with a much larger volume was proposed that specializes in burning liquid fuel. It utilizes maximum swirling effect by multiple air injection to increase fuel residence time and mixing time to ensure flameless mode in all condition. The chamber had successfully achieved flameless mode using LPG as fuel. The results showed that the temperature profile inside the combustion chamber was similar despite having different equivalence ratios, and the peak temperature was almost directly proportional to the equivalence ratio. It was also observed that despite different equivalence ratios, the peak temperature never exceeded 900ºC. Last but not least, flameless mode was successfully achieved at around equivalence ratio of around 0.59. In the future, various types of liquid fuels will be used and compared to study the feasibility of liquid fuel in flameless mode in a large combustion chamber.

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