On the Effects of Tangential Air Inlets Distribution Configurations to the Combustion Characteristics of a Direct Injection Liquid Fueled Swirl Flameless Combustor (SFC).

Adam. K
High Speed Reacting Flow Lab (HiREF), School of Mechanical Engineering, Universiti Teknologi Malaysia

M. A. Wahid
High Speed Reacting Flow Lab (HiREF), School of Mechanical Engineering, Universiti Teknologi Malaysia

https://doi.org/10.5109/4372267

出版情報：Evergreen. 8 (1), pp.117-122, 2021-03. Transdisciplinary Research and Education Center for Green Technologies, Kyushu University
バージョン：

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Adam. K [1], M. A. Wahid [2*]

[1,2] High Speed Reacting Flow Lab (HiREF), School of Mechanical Engineering, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia

* Author to whom correspondence should be addressed:
E-mail: mazlan@mail.fkm.utm.my

(Received November 27, 2020; Revised January 30, 2021; accepted March 23, 2021).

Abstract: Liquid fueled flameless combustion is a new niche in the energy-engineering department. The current trend on flameless combustion is mostly focused on gas fuel application due to the ease of achieving and maintaining flameless mode in the combustion process. The main purpose of this paper is to discuss the effects of evenly distributing tangential air inlets along the length of the combustion chamber of a Direct Injection Liquid Fueled Swirl Flameless Combustor (SFC) to the combustion characteristics in flameless mode. Ethyl alcohol or ethanol was used throughout the whole experiment. Only four tangential air inlets were used in this experiment for each configuration, whereas ethanol was directly injected axially. All 9 configurations were strategically divided into three categories; a) single inlet location, b) dual inlet locations, and c) triple inlet locations. The experiments were conducted at close to stoichiometry condition. The results showed that, although flameless mode was successfully achieved and stabilized at every configuration, it was also found that tangential air inlet configuration has a significant effect in the optimization and behavior of liquid fueled flameless combustion. The highest peak temperature was recorded by Configuration (G) at 800.45 ºC, bur interestingly managed to produce the lowest value for the emission of CO and NO_x gases, which were at 134 ppm and 0 ppm respectively. Thus, it was concluded that the best tangential air inlet configuration in this work was Configuration (G).

Keywords: Ethanol; Liquid fuel; Flameless Combustion; Swirl.

1. Introduction and background

Flameless combustion comes in many names depending on the approach and mechanism used to achieve flameless condition. The idea originated from Excess Enthalpy Combustion concept[1)]. Some of them called it as Mild Combustion, especially in Italy, whereas in Japan, it is called High Temperature Air Combustion (HiTAC)[2)]. A similar kind of technology is called Flameless Oxidation (FLOX)[3)] in Germany, and Low NO_x Injection (LNI)[4)] in the United States of America.

It is important to understand that flameless combustion possessed several traits that differentiate it from conventional combustion, as shown in Table 1. The traits of flameless mode was explained clearly by Derudi in his paper[5)] . In other words, Table 1 can be used as a benchmark on the identification of flameless mode in any combustion process. Furthermore, due to the flexibility of this technology, it is believed to be highly compatible with all existing fuel, regardless if its gas fuel, liquid fuel, or even solid fuel[6)]. This made it feasible to implement this combustion concept to the current combustion machines or power generators currently used in the industry with minimal cost for modifications[7)]. Incidentally, due to the low operating temperature, and the uniformity of temperature profile produced during the combustion process inside the combustion chamber, it is also believed that the life time of the equipment will significantly improve, thus reducing the maintenance cost significantly [3)].

The demand of green technology for power generation has been rising exponentially due to the energy crisis the world has been facing for the past several years [8)]. Global electricity usage has been increasing regardless of the condition and the level of development stage of any country[9)]. The combustion of fossil fuel for energy generation has been one of the main contributors of greenhouse effect that causes climate change and global warming[10)]. Thus the race to find renewable and alternative energy source has been increasing[11)]. Researchers has also been focusing on new energy conversion systems as a counter measure for global warming[12]. But very little focus was given to flameless combustion technology[13]. Ironically, in recent years, it is evident that this technology possesses the highest compatibility with the current power generation technologies and the most practical method to pursue in having green power generation technology[14].

Table 1. Conventional vs. Flameless combustion

	Conventional Combustion	**Flameless Combustion**
Flame	Observable flame front	Invisible flame front
Peak Temperature	Usually above the thermal NO_x formation temperature. >1200°C	<1200°C
Reaction products	High concentration of harmful emission; ie. CO, SO_x, NO_x.	Extremely low level of pollutant. CO < 50 ppm, NO_x, < 30 ppm ,
Temperature fluctuation	High flame temperature fluctuation	Due to the non-existent of flame front , temperature fluctuation is minimized, thus producing a uniformly distributed temperature profile throughout the combustion chamber

Previous flameless combustion researches are mainly focused on the use of gaseous fuel as the reactant for the combustion process[15]. This is due to the fact that gaseous fuel mix homogenously with air or oxidant to produce a combustible mixture[16]. Unfortunately, the same cannot be said to liquid fuel and solid fuel, where a mixture of either solid fuel with oxidant, or liquid fuel with oxidant will only produce heterogeneous mixture that is difficult to combust[16]. Thus making them the least favorite topic for research, resulting into scarce literatures available on the flameless combustion using liquid and solid fuel[17].

Nevertheless, several attempts have been made by researchers recently in trying to understand the flameless combustion using liquid fuel[18].

Mahendra proposed an inverse conical shaped flameless combustor. The top end was tapered to maximize the recirculation and entrainment of reactant mixture for improved fuel evaporation[19]. Kerosene was injected with a clockwise swirl direction while on the hand, air was injected with a counter-clockwise swirl direction to maximize mixing process. This setup successfully achieved flameless mode in low thermal input of 21.5 kW, but failed to maintain it at higher thermal input[20].

He then proposed a dual chamber burner to counteract the problem with high thermal input and high intensity application faced by the previous design. The second design uses the 2nd chamber to maximize the swirl effect, thus increasing the recirculation and the entrainment of reactant mixture even further compared to the single chamber design[19]. The result showed that the dual chamber burner successfully achieved flameless mode at 20 kW, 30kW, 40kW, and 60kW[21].

Derudi in his work also utilized the dual chamber design but with a different approach. A Dual-Nozzle configuration was developed to avoid pyrolysis and to counteract the difficulties in igniting liquid fuel[19]. The first nozzle was used to preheat the combustion chamber using gas fuel up to above the auto ignition temperature. Once that is achieved and flameless mode was established, liquid fuel was injected perpendicularly to the gas fuel injector, together with the secondary air supply. It was found out that this Dual-Nozzle configuration is highly recommended to burn a wide range of liquid fuel in flameless mode. It was also recorded that it was possible to maintain a flameless mode under low recirculation ratios ($K_v < 3$)[5].

One of the latest work in liquid fueled flameless combustor is performed by J. Ye. where he used various types of liquid fuel in his experiment. His experiments were performed under high pressure application by pre-heating the liquid fuel into its vapor state prior to injection into the combustion chamber. This step was a crucial step to produce a homogeneous mixture of fuel and oxidant for combustion process. The burner utilized a reverse flow approach where the exhaust channel sits at the same panel of the inlet flank. This maximizes entrainment of reactant mixture and recirculation of flue gas. The burner also had a hemispherical shaped top to assist in recirculation and reactant mixture entrainment[22]. It was concluded in his experiment that alcohol based liquid fuel has the most stability in flameless combustion under high pressure application compared to alkane and ketone liquid fuels.

In another work performed by Luhmann, using the similar concept of reverse flow configuration, he injected fuel and air at room temperature, without pre-vaporization of liquid fuel. But he made that preheating the combustion chamber up to above the auto ignition temperature as a requirement. It is also important to note that a twin liquid fuel atomizer configuration was used as the fuel injector. This was done to maximize atomization of liquid fuel to produce a relatively homogenous reactant mixture for combustion process. The results of the experiment relayed that flameless mode using light fuel was successfully maintained at air ratios 1.1 and 1.2[23].

Swirl Number, (S) is a dimensionless number that represents the strength of a swirl flow. It is defined as the ratio of the axial flux of angular momentum to the axial flux of axial momentum. It is well known that it is nearly impossible to measure and calculate S in any combustion application process accurately[3]. Nevertheless, researchers have been successful in calculating the swirl number using Geometric Swirl Number, (S_g) equation as shown in Equation 1[24].

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

where,

m_t = total mass flow rate through injector
m_T = total mass flow rate in the chamber
D = diameter of chamber
d = diameter of injector
Θ = injection angle
n = number of injector

The objective of this work is to investigate the effects of tangential air inlet configurations to the combustion characteristics of a Swirl Flameless Combustor (SFC) which will be directly injected with ethanol fuel. To emphasize the effects of tangential air inlet configuration to the flameless combustion characteristics, it is worth to note that throughout the experiment, the S_g will remain constant by maintaining several operating conditions as follows; a) constant number of activated tangential air inlets in every configuration, b) constant flow rate of air supply, and c) constant flow rate of liquid fuel.

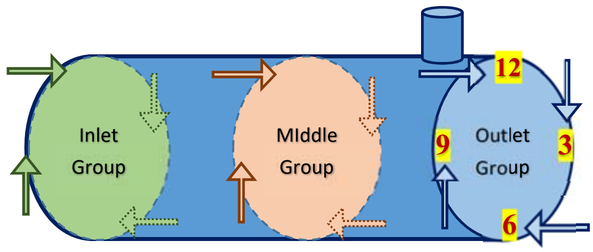


Fig. 1 : Tangential inlet position.

2. Methodology and experimental setup

The experiment is divided into two stages; a) pre-heating stage, and b) flameless mode stage. During the first stage, the combustion chamber will be pre-heated with LPG gas up to above the auto-ignition temperature of ethanol fuel. This step is a crucial step in preparing the combustion chamber into an optimized condition for "flameless mode"[25]. After the combustion chamber is pre-heated into the desired temperature, ethanol fuel will be introduced gradually while simultaneously, the LPG fuel will be gradually being reduced until only 100% ethanol is being used in the combustion process. Ethanol was selected to be used as the fuel for flameless mode due to its ability to have better combustion in high pressure condition and lowering the emission of CO emission[26]. It is important to note that during this stage, all 12 tangential air inlets were used during pre-heating stage.

The burner consists of one axial liquid fuel injector at the center of the inlet flank surrounded by an array of (6 x 3) axial gas fuel injectors, and 12 tangential air inlets strategically positioned throughout the body of the combustion chamber.

All 12 air inlets are divided into three groups of four tangential inlets, which are for group (Inlet), located near the inlet flank, whereas for group (Middle) is located at the middle of the length of the combustion chamber, while for group (Outlet), near the exhaust channel at the other end of the chamber. Each group has four tangential inlets which are evenly distributed along the circumference of the chamber at the position of 12 o'clock, 3 o'clock, 6 o'clock, and 9 o'clock respectively. The positions of the air tangential air inlets are represented in Fig. 1.

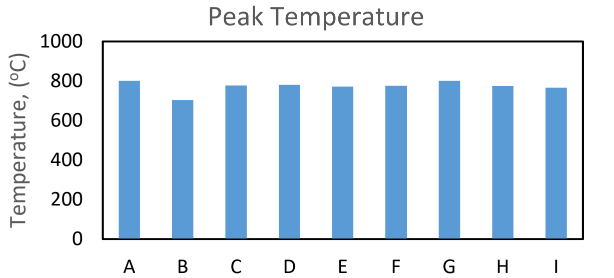


Fig. 2.: Peak Temperature of each configuration

In this particular work, it is essential to note that only four out of all 12 air inlets were activated in any configuration. All activated air inlets were strategically arranged to highlight the differences between a focused swirl injection to an evenly distributed swirl injection. All 9 configurations were divided into three categories depending on the number of inlet groups activated during the experiment; a) one group, b) two groups, and c) all three groups activated. The arrangement and number of activated air inlets in every configuration are represented in Table 2.

Table 2. Amount of activated tangential air inlets in every Configuration from A~I.

Single group	Dual groups	Triple groups
0 0 4 (A)	0 2 2 (D)	1 1 2 (G)
0 4 0 (B)	2 0 2 (E)	1 2 1 (H)
4 0 0 (C)	2 2 0 (F)	2 1 1 (I)

During flameless mode, all nine configurations were tested under the same condition. Ethanol fuel was injected at 4.48 x 10^{-4} kg/s, while air was injected tangentially through the activated inlets at a constant flowrate of 3.85 x 10^{-3} kg/s to produce a mixture of relatively at stoichiometric condition.

3. Results and Discussion

In order to understand the effects of tangential air inlet configurations to the flameless combustion characteristics, four aspects were studied to represent the characteristics of a flameless combustion as follows; a) the peak temperature, b) temperature profile, c) CO emission, and d) NO_x emission.

From the result, it is clearly shown in Fig. 2 that regardless of the tangential air inlet configurations, the peak temperature was maintained under 850 ºC for every configuration. This result agrees with one of the traits of flameless combustion as explained in the earlier paragraph and is a very desirable result. This is supported by the fact that flameless mode was observed to be well maintained regardless of the configuration tested in this experiment./

Since the peak temperature are well below the thermal NO_x formation temperature, NO_x production was reduced significantly as shown in Fig. 4. The highest peak temperature was recorded by Configuration (G) at 800.4 ºC, while the lowest recorded peak temperature was shown by Configuration (B) at 703 ºC.

Meanwhile, as illustrated in Fig. 3, the temperature profile indicated that the temperature fluctuation inside the furnace has been reduced significantly. It can be observed that for every configuration, there are no steep temperature gradient due to the absence of flame front inside the furnace.

Fig. 3 also proves that even though there are no flame inside the combustion chamber, the combustion reaction still took place inside the combustion chamber by producing heat energy as a product of the combustion reaction process. Furthermore, it can be assumed from the trends shown in the temperature profile that the combustion reaction zone occupied the whole volume of the combustion chamber, as opposed to the conventional combustion where the reaction zone is only at the flame front.

Investigating further into Fig. 3, the result showed that there were temperature drops at both ends of the combustion chamber. This is due to the dilution effect caused by the injection of fresh cold reactants at the inlet flank. It is worth to note that, the reactants were injected at room temperature. On the other hand, at the other end of the chamber, the temperature drop is believed to be caused by the exhaust channel located on the top of the combustion chamber. Exhaust gas was released through the exhaust channel releasing heat into the environment.

Coincidentally, it can be seen that the lowest range of temperature profile were recorded by Configuration (B) while the highest range of temperature profile was again recorded by Configuration (G).

As explained earlier, one of the main advantages of flameless combustion is the low-level emission of pollutant, namely CO and NO_x gas. By investigating Fig. 4 (a), even though all configuration successfully maintained flameless mode, one can see that CO emission can be very high, even went up to 1767 ppm recorded by Configuration (A), whilst the lowest recorded CO emission was taken at 133 ppm by Configuration (G). Moreover, Fig. 4 (b) showed a similar trend with the emission of NO_x gas. The highest NO_x emission was recorded by Configuration (A) at 140 ppm, where on the other hand, surprisingly Configuration (G) managed to nullify the emission of NO_x altogether. There was no emission of NO_x recorded by Configuration G.

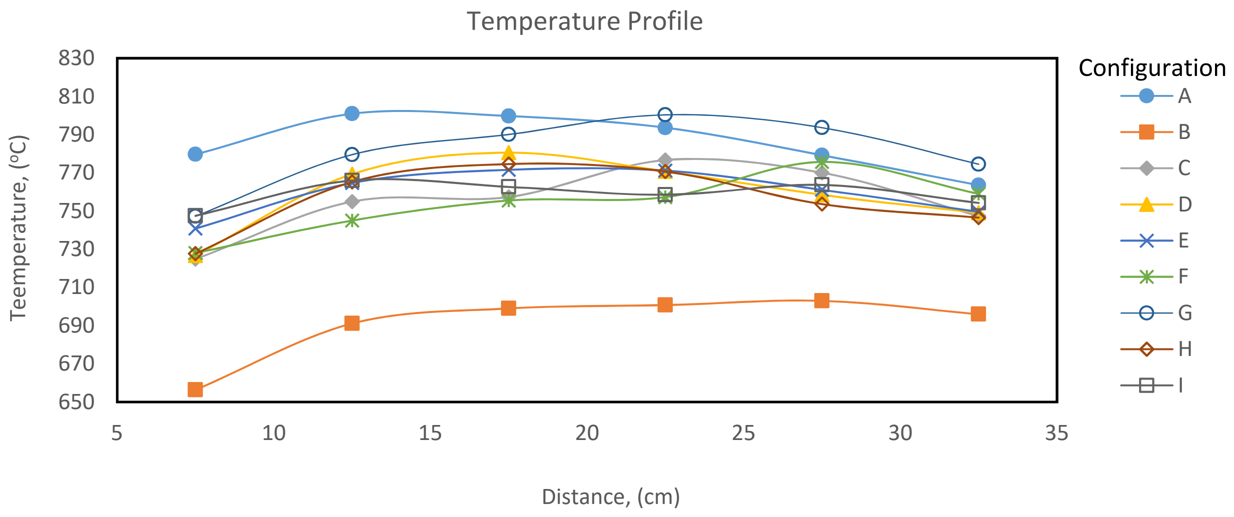
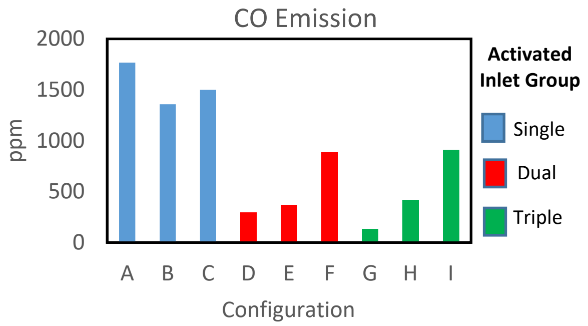


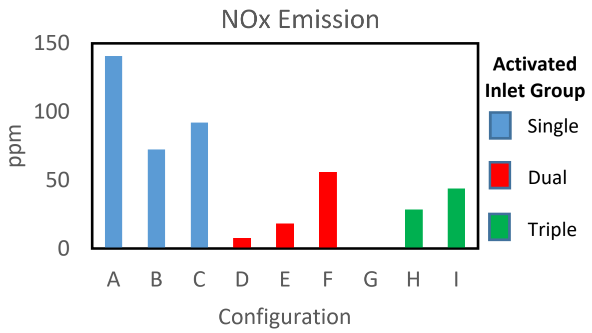
Fig. 3 : Temperature profile for each configuration.

By investigating further, Fig. 4 clearly showed that the configuration of tangential air inlets places a significant role in reducing the emission of CO and NO_x gas. By increasing the number of groups of tangential inlets used in the combustion process, the swirl injection points were dispersed, thus covering a larger area inside the furnace.

Even though the S_g were kept constant by keeping the number of activated tangential air inlet constant, it can be seen clearly that rearranging the position of air inlets by distributing them evenly throughout the length and the circumferential of the combustion chamber, reduces the emission of CO and NO_x gas significantly. This is believed to be caused by better mixing and better entrainment of reactant mixture inside the furnace, resulting into improved rate of combustion reaction.



(a)



(b)

Fig. 4 : (a) CO gas emission, and (b) NO_x gas emission

4. Conclusions

A Direct Injection liquid fueled Swirl Flameless Combustor (SFC) was used in an experiment to study the effects of tangential air inlet configurations to the characteristics of flameless combustion. Nine inlet configurations were tested in this experiment ranging from Configuration (A) ~ Configuration (I). The configurations were divided into three categories, as such depending on the number of inlet groups activated during the experiment; a) Single, b) Dual, and c) Triple. It is important to know that S_g was kept constant by restricting the number of inlet injector to 4 inlets for every configuration. This is to emphasize that any changes in the flameless combustion characteristics is due to the tangential air inlet configurations, not due to the changes in strength of the swirl flow.

From the results, in can be concluded that tangential air inlet that also acted as swirl generator inside the combustion chamber played a major role in optimization of flameless combustion. The way the inlets were being rearranged and repositioned during combustion process gave significant changes to the characteristics of flameless combustion. By dispersing and evenly distributing the points of swirl generating injectors throughout the surface of the furnace, the mixing and the entrainment of reactant mixture were improved tremendously, all without the need of increasing the strength of the swirl flow. This resulted into improved temperature uniformity inside the combustion chamber, and most importantly significant reduction of CO and NO_x emission.

Furthermore, it can also be concluded that the best tangential air inlet configuration is Configuration (G), where all inlet groups were activated. The sole reason of Configuration (G) was superior compared to Configuration (H) and Configuration (I) from the same group was due to the geometric reasons, where we can see in Table 2, Configuration (G) has the advantage of having 2 swirl injectors activated near the exhaust channel. The centrifugal force produced from the swirl injectors became a type of restriction the flow of exhaust gas into the environment. This resulted into improved entrainment of reactant mixture compared to other configurations in the same group.

Finally, to conclude, Configuration (G) was recorded to have the highest peak temperature at 800.4°C, and produced the lowest CO and NO_x emission, at 133 ppm and 0 ppm respectively.

Acknowledgements

This study was sponsored by Universiti Teknologi Malaysia under UTM High Impact Research with vote number 09G05.

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