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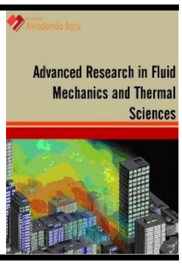

The Effects of Multiple Swirl Generator Inlets Circumferential Distribution to a Liquid Fuelled Ultra-High Swirl Flameless Combustion Characteristics

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ABSTRACT

This paper presents the experimental results of a simple cylindrical shaped, liquid fuelled flameless combustor which utilizes ultra-high swirl flow in the combustion process. 4 different swirl generator inlet configurations were tested in this work. Ethanol fuel were used during flameless mode. The experiments were conducted at equivalence ratio (Φ=1), with the flow rate of fuel set at 30 ml/min, and flow rate of air at 400 scfh. The results revealed that by using all 12 tangential air inlets (swirl generator injectors), the swirl strength was reduced through evenly distributing the position of the injectors circumferentially. As a result, the combustor successfully suppressed the emission of NO_x and CO to zero ppm for both gasses. It was also reported that flameless mode was established in all configurations, regardless of the swirl strength.

1. Introduction

In the last few decades, the world's energy usage has been causing pollution and global warming at an alarming rate [1,2]. The depletion of fossil fuels are also causing energy crisis worldwide. Over 90% of world's energy consumption is supplied by the combustion of fossil fuels [3] and 20% came from transportation [4]. Thus, the race of searching for alternative fuels [5], improving the efficiency of combustion process and clean energy generating system resulted into the discovery of various new technologies and combustion techniques as a counter measure for global warming. One of the most promising findings is called flameless combustion. Flameless combustion or Flameless Oxidation (FLOX®) is a unique combustion technology that was first discovered in the late eighties [6]. It can be defined as a complete combustion process without the presence of visible flame [7].

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One of the requirements of establishing flameless mode is to increase the temperature of the reaction zone to be above the auto ignition temperature of the fuel mixture. Aided by strong recirculation of hot flue gas inside the combustion chamber, a conventional flame can be transformed into flameless combustion [8,9].

It was developed for the purpose of NO_x abatement in the combustion process [10]. Flameless combustion is proven to produce extremely low level of NOx and CO gas [11]. This is due to the nature of flameless combustion where the front flame is absent throughout the whole reaction zone of the combustion reaction. Without the presence of flame front, the temperature inside the reaction zone was suppressed below the temperature of the thermal NO_x formation, which is the main contributor of NO_x emission for most combustion processes [12,13]. This also contributed into lower combustion operating temperature and peak temperature inside the combustion chamber. As a result, the cost of maintenance can be significantly reduced due to the increased machine lifetime in long term application [14].

Another advantage and unique characteristics of flameless combustion is the condition where almost non-existence of temperature fluctuation inside the combustion chamber. This is due to the dilution effect that comes with strong recirculation of hot flue gas. This as a matter of fact, made it looked like the temperature field or temperature profile inside the combustion chamber to be uniform and homogenous throughout the whole volume of the combustion chamber. Yang *et al.,* defined the temperature uniformity ratio (R_u) as shown in Eq. (1) [15]

$$R_u = \left[\sum\left(\frac{T-\bar{T}}{\bar{T}}\right)^2\right]^{\frac{1}{2}} \tag{1}$$

where
R_u=*ratio of temperature uniformity*
T =*measured temperature at any point in Kelvin*
$\bar{T}$ =average temperature

As R_u approaches zero, the fluctuation of temperature also becomes smaller. In other words, the temperature profile inside the combustion chamber is more uniformed as the value of R_u decreases and approaches zero [16]. Previous studies have reported uniform temperature distributions for flameless combustion [16–19].

Previous studies concerning flameless combustion were mainly focused on the use of gaseous fuel [20]. This is due to the homogeneous mixture produced from the mixing process of gaseous fuel and air. A homogeneous reactant mixture was found to be exceptionally advantageous in establishing flameless mode [21,22]. Contrary to gaseous fuel, by mixing liquid fuel with air, a heterogeneous reactant mixture is produced. This causes extra energy is required in changing the phase of the fuel from liquid to gas, thus increasing the reaction time. As a result, this will allow the liquid fuel to silt at the bottom of the rig, thus reducing the efficiency of the process, and obstructing the production of flameless mode. Thus, a much more complex mixing method that involves atomization and vaporization of liquid fuel through jet spray is needed to produce a relatively homogenous mixture for combustion process [20,23,24].

In this particular work, swirl flow was introduced into the combustion process to improve the rate of reactants mixing, increase the entrainment of fuel mixture, and to improve the efficiency of the rate of combustion inside the combustion chamber [21]. Swirl flow is a type of flow that contains both axial and tangential components (vortex flow) in the velocity vector [25]. One of the approaches for calculating geometric swirl number was introduced by Guo *et al.,* and was also adapted in another study by Guo *et al.,* as shown in Eq. (2). The similarity of the geometrical design concept between the previously mentioned researches to the test section in this research consists of the use of multiple tangential inlets to introduce swirl flow into a laminar axial flow. Eq. (2) not only took into account the mass flow rate ratio of the tangential injections and the axial injections, but also the number of tangential injectors and the degree of tangential inlet being injected into the main test section [26,27]. Thus, the geometrical swirl in this work is calculated using Eq. (2) as shown below.

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

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

2. Methodology

A new type of flameless combustor was developed in the High-Speed Reacting Flow (HiREF) research laboratory here in Universiti Teknologi Malaysia. The liquid-fueled ultra-high swirl 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 that most of the designs in previous works had complex geometries and were also quite miniscule compared to industrial scale [14]. Thus, a semi-industrial scale liquid fueled flameless combustor was designed using simple cylindrical geometry to minimize manufacturing cost and to prove that geometric structure has minimal effect on the success rate of achieving flameless mode.

The combustor was installed with 12 tangential air inlets that acted as swirl generators. All 12 air inlets are divided into three groups of four tangential inlets as follows. For the group (SG1), the injectors are located near the exhaust channel, whereas for the group (SG2) is located at the middle of the length of the combustion chamber, while for the group (SG3), located near the inlet flank. 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 tangential air inlets are represented in Figure 1.

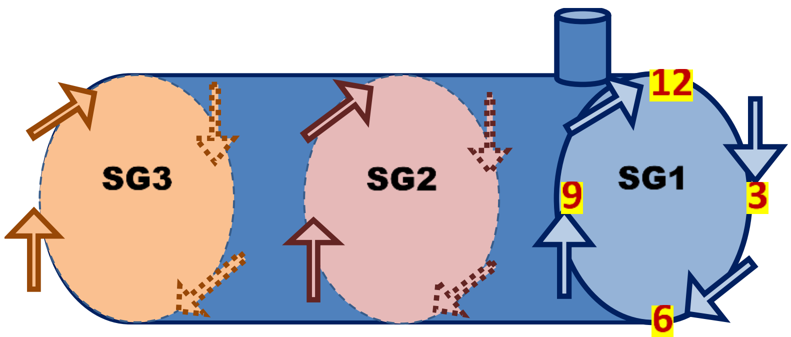
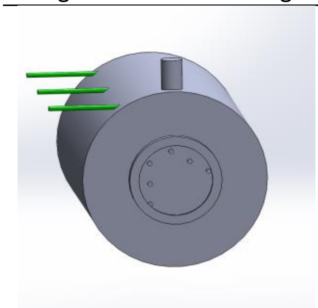
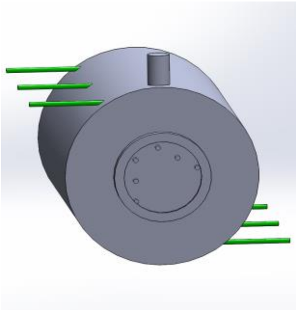
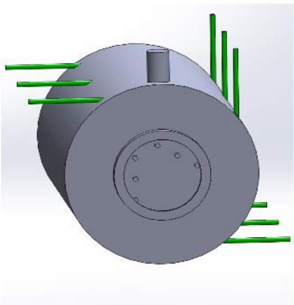
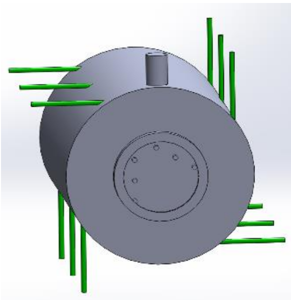


Fig. 1. Tangential inlet position

In this work, the number of activated tangential injectors were selected by activating only one injector from each injector groups. This is followed by increasing the number of activated injectors by one from every group. This process is repeated until all 12 tangential air injectors were activated. To summarize this step, the activated tangential injectors are listed as in Table 1.

Table 1
Positions of activated tangential air inlet injectors for study case case (A~D) at equivalence ratio (Φ): 1

Tangential air inlet configuration	Number of swirl injectors, (n)	Geometrical Swirl number, (S_g)
 A	3	≈600
 B	6	≈300
 C	9	≈200
 D	12	≈150

The objective of this experiment is to investigate the effects of changes in swirl strength or geometrical swirl number (S_g) due to the changes in the numbers of activated tangential inlets to the combustion characteristics of flameless combustion. It is also important to note that, the changes in the amount of activated tangential air inlets also represents the changes in the arrangement of the swirl generator injectors (tangential air inlet) distribution, as shown in Table 1. In this experiment, the equivalence ratio was at (Φ=1) where the flow rate of both combustion air and the liquid fuel were kept constant at 30 ml/min and 400 scfh, respectively. This step is to ensure the isolation of swirl changes due to changes in the reactant mixture.

3. Results and Discussion

According to Eq. (2), the number of injectors is inversely proportional to the geometric swirl number (S_g) that represents the strength of the swirl flow inside the combustion chamber. This translates into, as the number of injectors increases, the swirl number decreases, as shown in Table 1. It is known that swirl flow improves the mixing of reactants, longer entrainment of flue gas, increases the recirculation of flue gas inside the combustion chamber, and improves the combustion reaction rate [28–30]. Thus, it is a perfectly logical hypothesis to assume that as the swirl increases, the production of NO_x and CO gas decreases. But for ultra-high swirl application, it may not be true. This is shown in the result below. From the literature study, a study focused specifically on ultra-high swirl flameless combustion was not found in any literature. Most of the swirl flow study involving combustion was performed in a relatively low (S_g< 10) compared to this work that involves S_g> 100.

From the results, it can clearly be seen that as the number of injectors increase, the emission of CO gas decreased reassuringly until the production of CO was completely abated (emission of CO at 0 ppm), as shown in Figure 2. On the other hand, Figure 3 showed that the level of emission of NO_x gas were very close for $n \leq 9$. But interestingly as soon as n = 12, the emission of NO_x gas was completely abated (emission of NO_x at 0 ppm). These results are in line with previous studies [10].

From further investigation, Figure 4 and Figure 5 revealed that as the swirl number increased, the emission of CO and NO_x gas increased significantly. This is opposite to the initial assumption where it was shown in previous works, as the swirl increased, the emission of NO_x and CO gas will be reduced [21]. It was obvious that CO emission increased significantly with the increase of swirl number. Whereas for the emission level of NO_x gas, a sudden increase was observed at ($S_g \leq 200$), and emission level maintained in between 45 ~55 ppm as the swirl number increases.

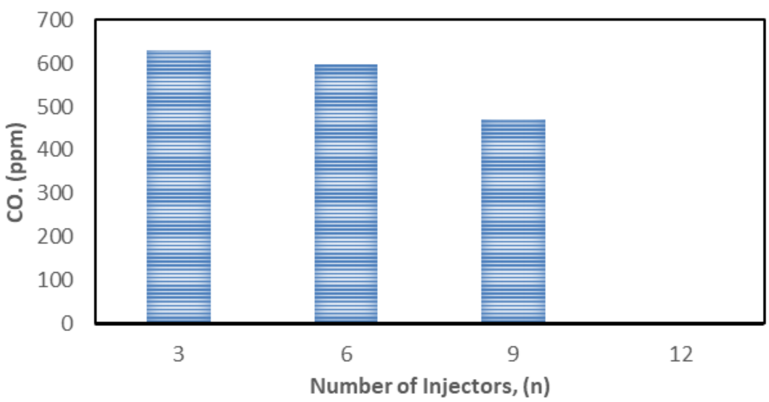


Fig. 2. Emission level of CO gas for different numbers of activated tangential injectors

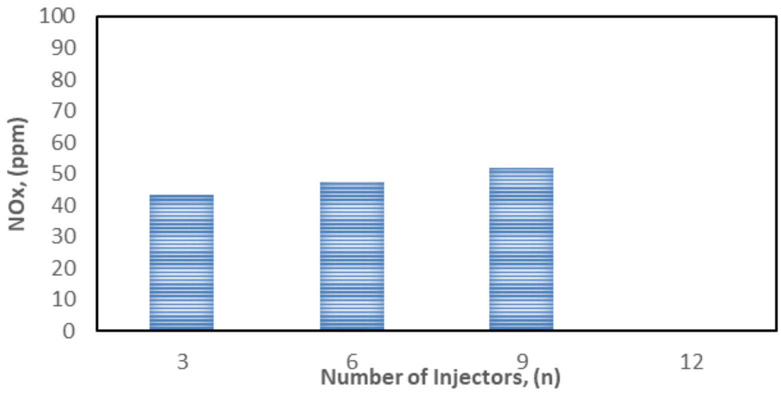


Fig. 3. Emission level of NO_x gas for different numbers of activated tangential injectors

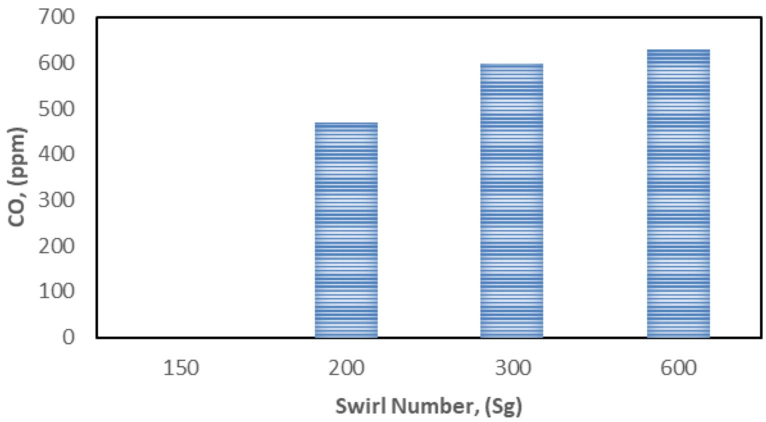


Fig. 4. Emission level of CO gas for different Swirl Numbers (S_g)

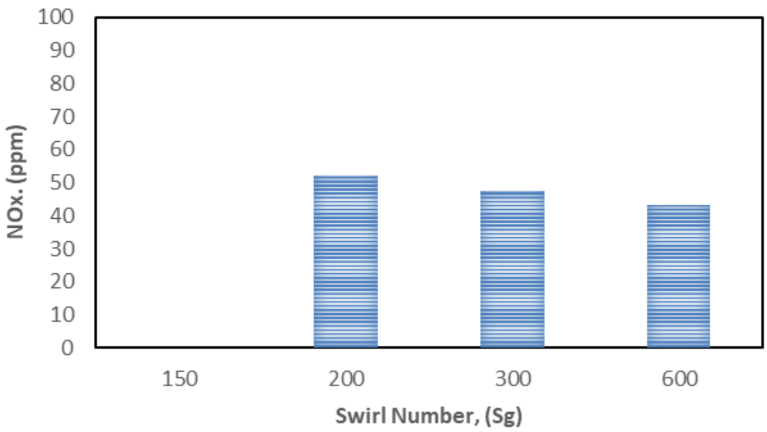


Fig. 5. Emission level of NOx gas for different Swirl Number (Sg)

It is worthy to note that although the emission level differs from each study case, all study case was recorded to successfully maintain flameless mode throughout the experiments. This can be supported by the fact that the temperature fluctuation inside the combustion chamber was relatively non-existent, as revealed by Figure 6 and Figure 7. From further inspection, the results also showed that the peak temperature remained relatively the same, with a difference of less than 50^oC regardless of the swirl number. These two characteristics suit well into the behaviour of flameless combustion [31].

To further support this claim, Table 2. lists the temperature uniformity (R_u) inside the combustion chamber for all study case. As previously mentioned, as R_u approaches zero, the temperature fluctuation inside the combustion chamber also reduces. Thus, the smaller the values of R_u becomes, the more uniform the temperature profile inside the combustion chamber is. From Table 2, regardless of the number of the activated tangential inlets, or the swirl number, all the values of R_u for every studied case are very small, which is a unique trait of flameless combustion. This indicates that a flameless environment was most likely maintained inside the combustion chamber.

Table 2
Temperature Uniformity for the various number of injectors

No. of Injectors	S_g	Temperature uniformity, (R_u)
3	600	0.053
6	300	0.035
9	200	0.042
12	150	0.030

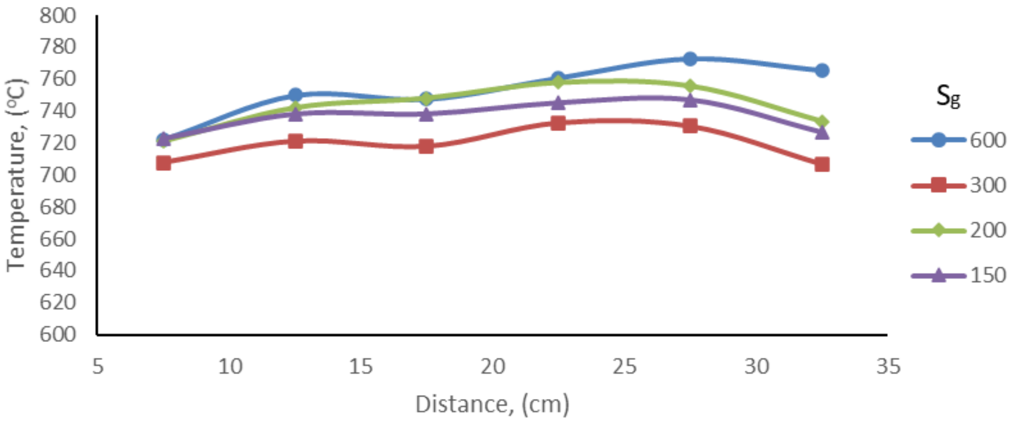


Fig. 6. Temperature profile for different geometrical swirl number (Sg)

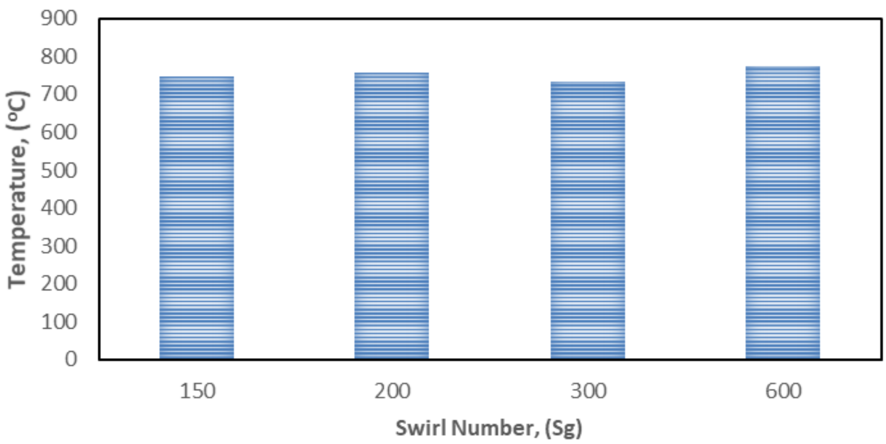


Fig. 7. Peak temperature at different geometrical swirl number (S_g)

Therefore, from the results shown above, it can be observed that too high of a level of swirl intensity with poor positioning of swirl generator reduces the efficiency of the combustion process, and produces an extremely high level of harmful gas emission, despite the fact that flameless mode was successfully maintained throughout the combustion process. It is worthy to note that flameless mode is known to reduce emission of NOx and CO gasses [32]. This rather contradictory result is most probably due to poor heat transfer in the combustion process. It is also believed that uneven mixing between the reactant mixture and flue gas inside the combustion chamber was also causing the emission level to increase despite the fact that high swirl flow exists inside the combustion chamber.

By adding the number of tangential injectors and evenly dividing the swirl strength through the extra swirl generator circumferentially, the mixing of recirculated flue gas and unburned fuel mixture was optimized, improving the rate of combustion and thus, rapidly reducing the production of CO and NO_x gas substantially [33,34].

4. Conclusions

This work has managed to experimentally proven a liquid fuelled combustion technique and concept, that has the capability of generating power with zero emission of both CO and NO_x gases on a simple cylindrical shaped flameless combustor by utilising ultra-high swirl flow. This was made possible mainly due to two factors. The first factor is the fact that the peak temperature inside the combustion chamber was significantly lower compared to conventional combustion. This prevented thermal NO_x formation to take place during the combustion process, and at the same time, prevents dissociation of CO_2 gas into CO gas caused by high temperature [35,36]. This is evident as flameless mode was established regardless of swirl number, and tangential air inlet (swirl generator injectors) configuration.

The second factor is the reinforcement of swirl flow from the reintroduction of swirl injector further downstream axially and also circumferentially. By doing so, it is believed to counter the effect of swirl decay throughout the whole volume of the combustion chamber and as a result, maximizes the entrainment of flue gas. This allowed for significant improvement in the mixing of unburned fuel in the flue gas with the fresh reactant's mixture for complete combustion. Thus, as a conclusion, for the sole purpose of optimization and reducing the emission of CO and NO_x gases of liquid fuelled flameless combustion, the number of injectors, and the location of swirl generator (tangential injection type) has a much more significant effect compared to the strength of the swirl.

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