Effect of Asymmetric Fuel Injection on the Combustion Characteristics of Liquid Fuel Fired Flameless Combustor

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Abstract

In the present work, effect of asymmetric location of fuel injection nozzle on the different combustion characteristics has been investigated. A single solid cone type pressure swirl nozzle, N1 has been considered with different high injection pressures (14, 30, and 48 bar) to achieve different fuel flow rates of 2.5 kg/hr (30 kW), 3.12 kg/hr (37.27 kW), and 4.46 kg/hr (53.23 kW). Effect of air preheating has been investigated for the kerosene fuel at a fixed temperature of 800K. Combustor exhibited more stability in the flameless regime with asymmetrical fuel injection up to equivalence ratios, ϕ=0.4. That helps reducing the NO_x emissions. The measured CO and NO_x emissions were in the range of 28-161 ppm and 2-32 ppm for all heat inputs and equivalence ratio (ϕ = 0.4 to 0.92), respectively. Measured sound levels were in the range of 93-99 dB and 98-103 dB for the flameless and transition mode respectively.

Introduction

Higher pollutant emissions from combustion systems cause harmful effects like acid rains, smog and haze resulting in global warming. Therefore, it is extremely important to explore and develop newer combustion techniques with lower pollutant emissions. Mild combustion has been reported to have several promising features of low CO and NOx emissions along with uniformity in temperature distribution leading to increase in thermal efficiency. In mild/flameless combustion, hot combustion products are recirculated into fresh incoming mixture. This dilution reduces the reaction rate and results in the distributed reaction zone inside the combustor [1-3].

The characteristics of flameless combustion have been extensively studied and investigated with gaseous fuels by various researchers [1-13]. Peters and coworkers [4, 5] have studied the effect of recirculation of hot combustion products and highly preheated air to achieve flameless combustion mode in a reverse flow furnace configuration. Yetter et al. [6] have investigated the effect of asymmetrical fuel port location on the NOx emissions and interestingly found out that combustion shows unusual stability with asymmetric fuel port location. Kumar et al. [7, 8] proposed a forward flow configuration to achieve flameless combustion using frustum of a cone to increase the recirculation inside the combustor and achieved higher

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heat release densities up to 10 MW/m^3. Dally et al. [9] investigated the effect of dilution by adding CO_2 and N_2 to reduce the NO_x formation in flameless combustion mode. Verissimo et al. [10, 11] have reported the effect of thermal input and air injection velocity on the combustion parameters by changing the air injector diameters [9, 10]. Kurse et al. [12] and Ye et al. [13] have proposed newer combustor configurations for possible application in gas turbine applications at higher pressure (2-5 bar). Overall, significant contributions have been made to gain understanding on various physical and chemical aspects involved in flameless combustion with gaseous fuels, very little efforts have been reported in literature on flameless/mild combustion with liquid fuels.

Many challenges are involved in achieving the flameless combustion with liquid fuels, such as spray formation, evaporation and mixing along with the preheating and dilution of fresh reactants through recirculation of hot combustion products from post combustion zone [17]. Due to higher density of liquid fuels ($\rho_{liquid}/\rho_{gas} \approx 800$), it becomes difficult to entrain large quantities of hot combustion products into primary zone to achieve the desired dilution ratios [17]. Therefore, it is difficult to achieve higher recirculation ratios of hot combustion products into the spray of liquid fuels.

Derudi et al. [14] have studied the mild combustion of liquid fuels in a tubular furnace using preheated air at high temperatures. To achieve improved mixing, the fuel and air injection ports were arranged perpendicular to each other [14]. Reddy et al. [17-19] proposed various single and double-stage combustors configurations and operated with liquid fuels to achieve flameless combustion mode. Conical combustor geometries and high-pressure swirl nozzles were used to enhance recirculation of hot combustion products and better mixing with higher heat release rates (~20 MW/m^3). However, there was no efforts made to understand the effect of fuel injection nozzle location on the combustion characteristics. Location of input fuel nozzle has significant effect on the dilution and mixing of the fresh mixture thereby affecting the combustion characteristics of the swirl-stabilized flameless combustor with tangential air-injection. Therefore, it is extremely necessary to study the effect of inlet fuel nozzle location on the different combustion characteristics of the combustor operating in flameless mode.

In this paper, effect of fuel injection nozzle location on the temperature, emissions, heat-flux, and acoustic emissions has been investigated followed by a brief summary of the contributions for the present work. Fuel was injected at higher pressures to achieve finer spray particles resulting in enhanced mixing and dilution.

Experimental set up

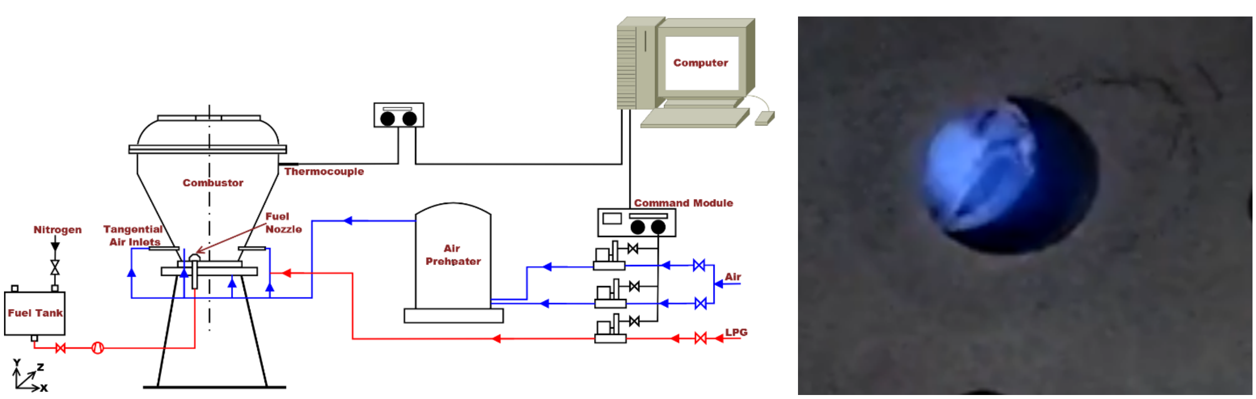

Figure 1. (a) Schematic diagram of experimental setup (b) Visual observation of flameless combustion

Figure. 1 (a) shows the schematic diagram of the experimental setup. The combustor was placed vertically on a test stand. Kerosene fuel was stored in a tank, pressurized by nitrogen gas and was supplied at different injection pressures from a solid cone type pressure swirl nozzle located at 23 mm from the center of combustor. The air was injected tangentially through four peripheral ports at the bottom of the combustor. Air was supplied using Aalborg make electric mass flow controllers (range 0-500 LPM; accuracy: ±1.5 % of full scale). For the startup process, the combustor was ignited with LPG-air mixture. Initially, it was run for 2-3 minutes to sufficiently increase the temperature of combustor walls. After that, the kerosene was injected at 5 bar and LPG supply was then gradually reduced to zero. Kerosene supply pressure was then increased to 14, 30, and 48 bar respectively according to the fuel flow requirements of 2.5 kg/hr (30 kW), 3.12 kg/hr (37.27 kW), and 4.46 kg/hr (53.23 kW). Combustor was set to run for 5-10 minutes at the stoichiometric conditions for these fuel flow rates. In this period the kerosene and air was combusted at stoichiometric conditions to ensure flame stabilization. Afterword, a chamfered plate was placed on the top of the combustor for reducing the exit diameter from 80 mm to 25 mm. It led to the increased recirculation of hot combustion products and combustion mode was shifted to the flameless mode [17] (Fig. 1 (b)).

Temperature was measured using OMEGA made R-type ($d_{junction}$=0.25 mm) thermocouple. All the temperature measurements were corrected for convective and radiative heat losses from the thermocouple junction. Emission was measured using a Quintox KM 9106 flue gas analyzer. This analyzer has an O_2 sensor (0-25 % range, 0.1% accuracy), CO sensor (0-10,000 ppm, ±5 ppm accuracy), NO sensor (0-5000 ppm, ±1 ppm accuracy), and CO_2 sensor. Acoustic emissions were measured using a Lautron SL-4001 sound level meter with its range varying from 35 to 130 dB and a resolution of 0.1 dB with a response time of 200 ms.

Results

Figure 2 shows the temperature distribution inside the combustor at an axial distance of 120 mm for ϕ= 0.92 operating condition in the radial direction for three different thermal inputs. Measurements were taken for kerosene fuel and air was preheated at a temperature of 800K. The measured temperatures have been corrected for convection and radiation losses from the thermocouple junction. Difference between measured and corrected temperature was ~8 % of measured value. Temperature was measured using OMEGA made R-type thermocouple of 0.25 mm wire diameter. Thermocouple response time is ~0.3 sec, which is very large as compared to turbulent time scale (~3ms) hence temperature readings were taken over a period of ~15 sec and average of that reading is presented in Fig. 2.

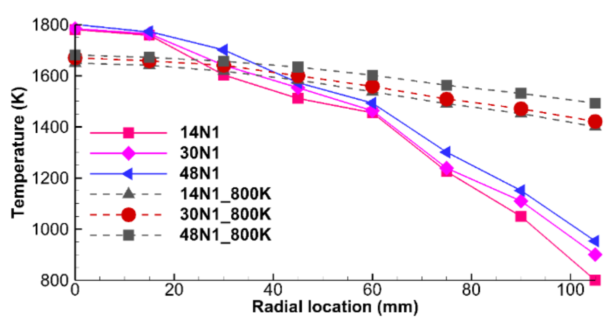

Figure 2. Temperature distribution across the combustor at ϕ=0.92 for kerosene fuel.

It is clear from the Fig. 2, that temperature distribution becomes more uniform with increasing thermal input from 30 to 53.23 kW. Maximum temperature was observed at the center and decreased towards the wall. Wall temperatures were measured as 800K, 900K, and 953K for the cases of 14N1, 30N1, and 48N1 respectively. Temperature profiles were observed to become more flat after using preheated air instead of room temperature air. Maximum temperature at the center decreased with air preheating and higher wall temperatures were measured as compared to non-preheating case. 1401K, 1421, and 1492K were measured for the three different thermal inputs at the wall with the preheating temperature of 800K. It clearly shows the advantage of preheated air as the maximum temperature difference between center and wall was measured as 980K for non-preheating case and 249K for the preheating case. This difference is vital and shows a positive scope towards the MILD combustion of liquid fuels.

Figure 3a shows the variation of CO emissions for three different thermal inputs discussed above for kerosene fuel. All the emissions are corrected to 15 % O_2 level. Results are presented for the preheated as well as non-preheated cases and compared for the operating condition, 14N1 of Symmetrical fuel injection.

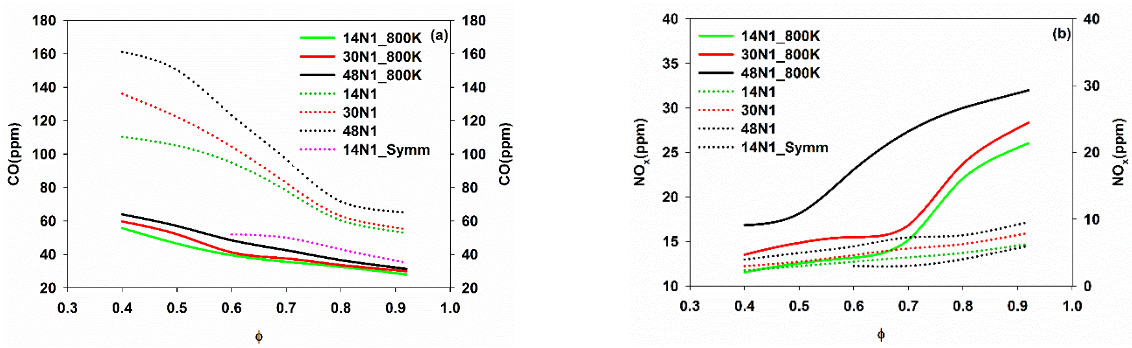

Figure 3. Distribution of (a) CO emissions with and without the air preheating, Solid lines- With preheating (Left Y Axis) and (b) NO_x emissions with and without the air preheating, Solid lines- With preheating (Left Y Axis)

It is clear from the Fig. 3a that preheating reduces the CO emissions drastically due to high temperature involved in the reactions. CO emissions varied from 52-161 ppm and 28-64 ppm for no-preheated and preheated cases respectively, as the equivalence ratio, ϕ varied from 0.92 to 0.4. Results clearly show the advantage of high pressure fuel injection, as even with very high thermal input CO emissions did not increase too much.

For the case of asymmetric fuel injection, flameless combustion was achieved even at very low equivalence ratios. Measurements were taken from equivalence ratio, ϕ=0.92 to 0.4. For the symmetric fuel injection, flameless combustion was stable up to ϕ=0.6. Asymmetrical fuel injection showed unusual stability for the flameless combustion condition as the combustion was stable up to ϕ=0.4. Yetter et al [6] also reported the stability of low NO_x emission combustion up to very lean equivalence ratio, while using asymmetric fuel injection. Since thermal NO_x was drastically reduced for the lean mixtures, asymmetric fuel injection is proved to be the suitable choice for gas turbine applications.

Figure 3b shows the variation of NO_x emissions for kerosene fuel for all the operating conditions. Results are presented for asymmetric fuel injection and compared with case of 14N1 of symmetric fuel injection. It is clear from the Fig. 3b that preheating results in comparatively higher NO_x emissions as compared to the non-preheating case. It happens due to the presence of higher temperature of air inside the combustor.

Since asymmetric fuel injection results in an unusual stability for very lean fuel-air mixtures, lesser NO_x as compared to symmetrical fuel injection was observed as shown in Fig. 3b.

NO_x emissions varied from 10-2 ppm for the different operating conditions as the equivalence ratio ϕ, varies from 0.92 to 0.4. For the air preheating of 800K NO_x was found to vary between 32-11 as ϕ changes from 0.92 to 0.4. Results for the asymmetrical fuel injection shows that due to lean operating range lesser emissions are measured as compared to symmetrical fuel injection at equivalence ratio, $\phi<0.6$.

Figure 4 shows the instantaneous variation of sound level for all the operating conditions and various modes of combustion. The measurements were taken over a specific period of time and values are presented in Fig. 4. Initially, the base level emissions for cold flow condition were observed to vary in a range of 90-93 dB except some instantaneous peaks.

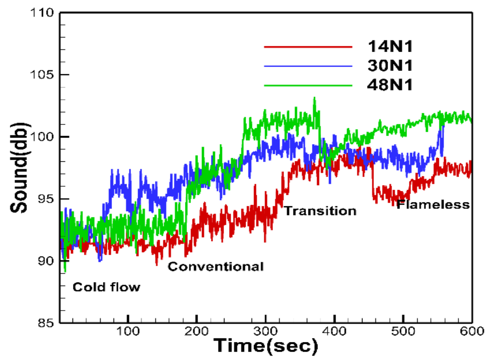

Figure 4. Variation of acoustic emissions for case I and case II during various combustion modes.

During the initial start-up, the combustor was run in conventional mode with exhaust diameter of 80 mm. After an initial start-up time of 5-10 minutes, a chamfered plate was placed at the top to reduce the combustor exit diameter from 80 mm to 25 mm. This led to an increase in the acoustic emissions as the combustor operation shifted to a transition mode. After some time, a steep reduction in the acoustic emissions was observed due to the transition into the flameless mode. Sound level of less than 102 dB was observed for all the thermal inputs in flameless mode. For the case of 30N1, measured noise was less than 97 dB in flameless mode.

Summary

Flameless combustion showed the unusual stability with asymmetrical fuel injection. Effect of asymmetric fuel injection was investigated on the combustion characteristics like CO, NO_x, temperature, acoustic emissions etc. Preheating resulted in less CO emissions and slightly higher NO_x emissions as compared to non-preheating case for kerosene. Acoustic emissions were also found to be relatively much lower in flameless mode, which shows the potential of flameless combustion for gas turbine and industrial applications.

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