Effect of CO_2 dilution on combustion characteristics of a liquid fuel-fired flameless combustor

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1 Abstract

Effects of CO_2 dilution on combustion characteristics such as temperature distribution and gaseous emissions are studied experimentally. The combustor operates in the flameless mode for the range of operating conditions studied here. Kerosene is used as fuel for the present study. Thermal input is varied between 30 kW-53.23 kW and the air preheat temperature is kept as 800 K. The dilution level is maintained at 9% by volume of the total air. CO_2 dilution results in reduced temperatures at all locations in the combustor. CO_2 dilution has a negligible effect on the CO emissions in flameless mode, however, NO_x emissions are observed to affect significantly.

2 Introduction

Gas turbines are vital for energy production and transportation in the field of aviation. Both land based and aviation gas turbines emit harmful pollutants such as CO, NO_x, HC, and particulate matter (PM). These emissions affect the environment in near earth atmosphere and in the upper troposphere. Also, the emission norms are going to be more and stricter in the near future as it is targeted to reduce NO_x by 90 % and noise from flying aircraft by 65% compared to the basic design of 2001[1].

Some novel combustion techniques like flameless/MILD combustion appears to be a suitable choice due to its well-known characteristics like distributed combustion, low pollutant emissions, low acoustic oscillations, and enhanced stability [2]. Flameless combustion is a mixing controlled, unstable combustion process, which can be achieved by simultaneously recirculating the exhaust gases and preheating the combustible mixture [2]. Flameless combustion has been studied for the application in industrial furnaces and burners [3-16]. Plessing and co-workers [3-4] studied the reverse flow industrial furnace operating in MILD combustion. They argued that the high momentum fuel jet significantly affects the reaction zone and its location was found in the far downstream inside the furnace in MILD combustion mode. Dally et al. [5] investigated the same furnace but rather working on the dilution of the fuel by inert species to

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achieve the conditions similar to that of MILD combustion. Dally et al. [6] studied the famous jet in hot coflow (JHC) burner by varying the oxygen concentration in the hot co-flow. They found that the CO and the maximum temperature reduce when the O_2 concentration is reduced from 9% to 3%. Kumar et al. [7-8] studied a MILD combustion burner at high heat density (~2 - 10 MW/m^3) and thermal power (3 - 150 kW). The preheating and internal recirculation of the exhaust gases were achieved through geometric modifications. Effect of jet velocity on the emissions from a FLOX combustor was studied by Verissimo et al. [9]. The high velocity of oxidizer at low equivalence ratio resulted in increased mixing and therefore low NO_x emissions.

In a first, the MILD combustion at elevated pressures was studied by Kruse et al. [10] in a reverse flow configuration. They reported a decrease in NO_x emissions at high pressures. But the opposite trend was reported while operating with prevaporized liquid fuels at high pressures by Ye et al. [11]. They suggested the use of N_2 as the carrier gas to counter that increase in NO_x emissions.

Colorless distributed combustion for liquid fuels was reported by Khalil et al. [12] by diluting the air by CO_2 to simulate the product gases. It was concluded that the level of oxidizer at which the transition to distributed combustion occurs is independent of the fuel type. Flameless combustion with liquid fuels was studied in detail by Reddy et al. [13-14] in a swirl-stabilized combustor with high recirculation conditions. They used a tangential air injection scheme to generate the high-intensity swirl and a geometric obstruction at the exit of the combustor to enhance the recirculation [14]. Sharma et al. [15] investigated the effect of spray size on different combustion characteristics. They concluded the extension of the stability limit by the offset of the atomizer position from the center [16]. The use of CO_2 as a diluent to fuel was reported to have a significant change on the flame structure in the JHC burner [5]. It was argued that the high momentum of fuel jet is not the necessary condition to achieve the desired conditions for MILD combustion. The effect of CO_2 as a carrier gas with the oxidizer is expected to be significant; however, it has not been discovered in details with liquid fuel flameless combustion. The present paper deals with the effect of CO_2 dilution in the oxidizer on different combustion characteristics in a flameless combustor. Initially, different spray parameters are presented for the present set of operating conditions. After that, experimental investigations are performed to study the effect of CO_2 dilution on gaseous emissions and temperature.

3 Experiments

3.1 Spray studies

A single solid cone type pressure swirl atomizer is used for the present study. The atomizer is calibrated at three different injection pressures of 14, 30, and 48 bar to achieve the fuel flow rates of 2.5kg/hr (30 kW), 3.12 kg/hr (37.27 kW), and 4.46 kg/hr (53.23 kW) for kerosene. The nozzle diameter is 0.187 mm and it results in the cone angles of 56°, 59°, and 64° for the operating conditions of 14N1(14 bar fuel injection pressure for nozzle N1), 30N1, and 48N1 respectively. The detailed cold flow shadowgraphy study is performed to calculate the spray parameters such as Sauter Mean Diameter (SMD), droplet number density (DND) and cone angle. SMD varies from 34 to 19 µm as the injection pressure is increased from 14 to 48 bar. Higher injection pressures lead to finer spray which is beneficial in flameless combustion regime [15]. The detailed description of spray parameters is given somewhere else [16].

3.2 Experimental set up

Figure 1 shows the schematic of the experimental setup. It consists of a swirl-stabilized combustor, placed over a vertical stand. The liquid fuel is supplied from the bottom and air is injected from four tangential inlet ports. The tangential air injection is aimed at increasing the residence time by creating the central vortex inside the combustor. Tangential air injection results in high centrifugal forces which increase the residence time of hot gases in the recirculation zone.

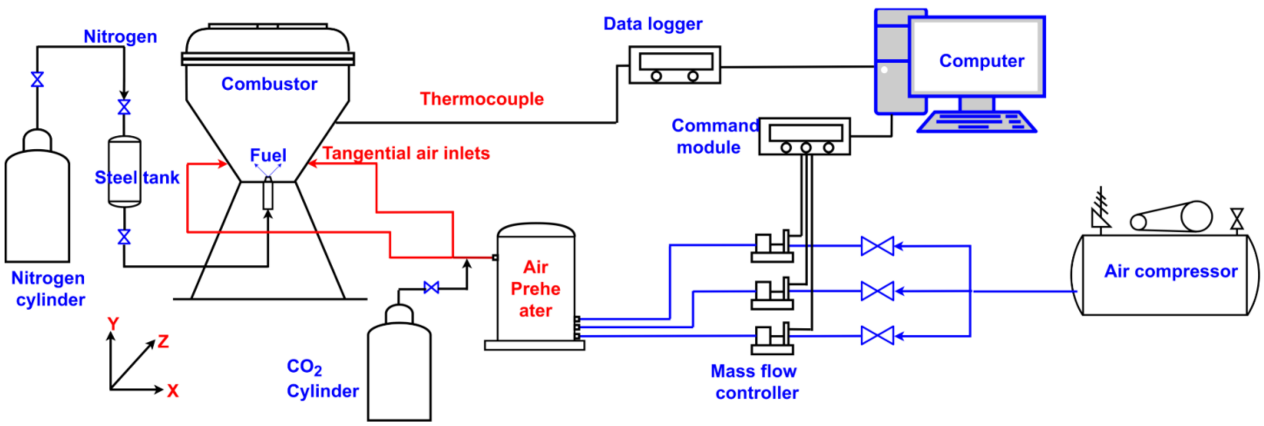

Figure 1. Schematic diagram of experimental setup

Air is preheated to a temperature of 800 K for all the operating conditions of thermal inputs. An air preheater of 36 kW capacity is used to preheat the air. CO_2 is added to the air stream after preheating and before entering into the combustor. After premixing with hot air, the mixture of air and CO_2 enters into the combustor. Kerosene is stored in a stainless steel tank and pressurized with nitrogen. Initially, the kerosene is supplied at 10 bar injection pressure and the combustor is ignited using a pilot. After that, the injection pressure is increased to the pre-set values of 14, 30, and 48 bar. It is then allowed to run for 5-7 minutes at the stoichiometric condition in conventional mode. A chamfered plate is then placed at the exit to i) decrease the exit diameter from 80 mm to 37 mm and ii) enhance the recirculation of the combustion products. Details about the complete mechanism are given somewhere else [16] as it is beyond the space restriction for this paper. The combustion switches to the flameless mode and the exit diameters are further varied according to the thermal input requirements. The air flow rate is controlled with three Aalborg make electric mass flow controllers with an accuracy of ±1.5 % of full scale. Air is heated to a temperature of 800 K for all the operating conditions using a 36 kW electric heater. The temperature inside the combustor is measured using OMEGA made R-type thermocouples of 2.5 mm wire diameter along with a data logging system. Exhaust gases concentration is measured using a TESTO 350 flue gas analyzer (O_2 sensor: 0–25% range and 0.1% accurate, CO sensor: 0–10,000 ppm range and ±5% accurate, NO sensor: 0–5000 ppm and ±5 ppm accurate, and C_xH_y sensor: 0–50,000 ppm).

Amount of the CO_2 added is 9% by volume of air. Details about the CO_2 dilution and operating conditions are given in Table 1.

Table 1: Operating conditions of ϕ, air flow rate (liter per minute-LPM), CO_2 flow rate and O_2 concentration (%)

Operating Condition	ϕ	Air (LPM)	CO_2 (LPM)	O_2 (%)
14N1	0.8	686.23	61.76	19.27
30N1	0.8	856.42	77.08	19.27
48N1	0.8	1224.24	110.18	19.27

3.3 Temperature distribution

Figure 2 shows the measured temperature distribution for the cases of 14N1, 30N1, and 48N1 at an axial distance of 120 mm from the bottom of the combustor. Thermocouple response time is less (~0.3 s) compared to the turbulent time scale (~ 3 ms) hence the measurements are taken over a period of ~30 sec with average reading presented here. Convective and radiative heat loss corrections are applied for the measurements and the corrected temperatures deviate by ~ 8 % from the measured value [16].

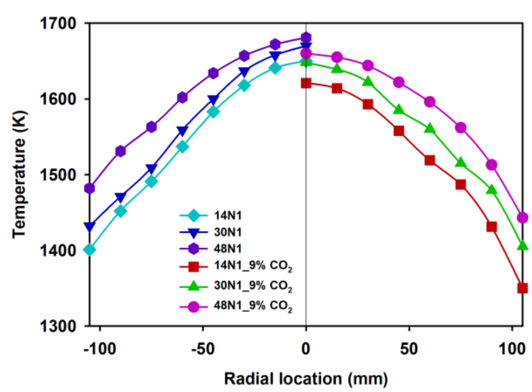

Figure 2. Temperature distribution, Left: without the CO_2 dilution; right: with CO_2 dilution

It is clear from Figure 2 that dilution by CO_2 helps to lower the maximum temperature along the centreline of the combustor. It can be attributed to the reduced oxygen concentration, which is 19.27% compared to the pure air (21%). Also, the assistance from the recirculation and dilution by geometric means leads to low and flat temperature profiles. Wall temperatures drop slightly with the dilution of CO_2 and they are recorded as 1350 K, 1405 K, and 1443 K compared to 1401 K, 1432 K, and 1482 K (0%dilution) for 14N1, 30N1, and 48N1 respectively. Difference between the centreline and wall temperature for 14N1, 30N1, and 48N1 are recorded as 271 K, 243 K, and 217 K respectively. This reduced temperature field is expected to have a significant effect on NO_x emissions.

3.4 Emission characteristics

CO and NO_x emissions are measured at different equivalence ratios for all the thermal inputs. Measurements shown here are corrected to 15% O_2 level as a standard gas turbine practice. Recorded emissions are compared with the earlier work with 0% dilution for the same operating condition. Figure 3 shows the variation of CO and NO_x emissions for different thermal inputs.

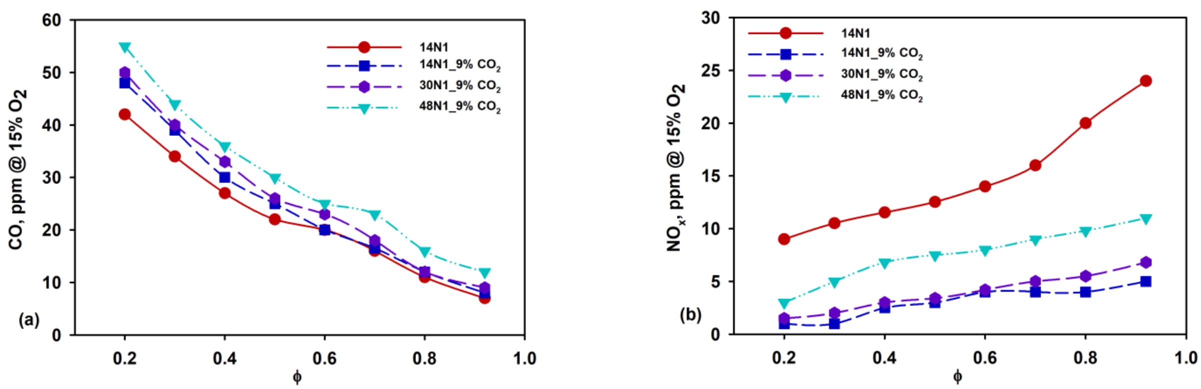

Figure 3. Variation of (a) CO emissions and (b) NO_x emissions for different thermal inputs

It is clear from Figure 3 that the dilution of CO_2 has no significant effect on the CO emissions except slight low emissions at ultra-lean mixtures. For the ϕ range, 0.2-0.5, the CO increases slightly with a decrease in the oxygen concentration for 14N1. A maximum value of 55 ppm is measured for the 48N1 at ϕ=0.2. CO is observed to increase with increasing thermal input. Though the increased temperature for higher thermal input results in higher temperature, the reduced residence time might lead to an increased level of CO formation. It is interesting to note from Figure 3 that NO_x decreases sharply as the oxygen concentration is reduced in the air. The NO_x is reduced by about 80% with the CO_2 dilution. Reduced temperatures with CO_2 dilution result in ultra-low NO_x emissions. Measured NO_x is as low as 1 ppm for the 14N1 operating condition and the maximum value measured is 9 ppm for the extreme condition of 48N1 and ϕ=0.92. It can be concluded that the dilution by CO2 gas in the air stream has a significant effect on NO_x emissions in the conditions typical of MILD combustion.

4. Summary

CO_2 dilution in the MILD combustion environment has a significant effect on the NO_x emissions; however, CO emissions are more or less remains unaffected by the dilution. The temperature in the combustor is reduced as the effect of the CO_2 dilution, which can be attributed to the low concentration of oxygen in the air stream.

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