Experimental investigations on pressure swirl atomized lifted flames in a co-flow field

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Abstract:

In the present work, the effect of coflow velocity and fuel injection pressure on flame lift-off height, flame stabilization, flame fluctuations in liquid spray flames has been experimentally investigated for two different coflow cases (a) cold flow and (b) cold flow with nitrogen dilution. Lift-off height is proportional to the coflow velocity and inversely proportional to the injection pressure. Dependence of flame lift-off height on the fuel mass flow rate has been investigated using different fuel injectors with identical spray cone angle and mean droplet diameter. It has been observed that contrary to gaseous diffusion flames, the flame lift-off height decreases with an increase in the fuel mass flow rate. Mean droplet diameter has a dominating effect on flame stability. The fluctuations in the stabilization point of lifted flame are proportional to the coflow velocity. For N_2 dilution case, the flame blows-off at lower coflow velocities due to lower concentration of O_2 in the coflow.

Introduction:

The pollutant emissions from the combustion of the fossil fuels for power generation and propulsion systems negatively affect the environment. Researchers are attempting to reduce the emissions and maximize the combustion efficiency of these systems. In recent years, it has become a challenge to reduce the emissions of oxides of nitrogen (NOx), carbon monoxide (CO) and unburned hydrocarbons (UHC). Since NOx actively participates in ozone depletion, formation of photochemical smog and acid rains [1], it is extremely important to reduce the formation of NOx during the combustion process itself. This has led to the development of many low NOx emission techniques. The process of exhaust gas recirculation in the combustion zone finds better application for the reduction of thermal NOx and CO emissions. Suppression of formation of NOx through thermal route has been suggested as a better solution for overall NOx control [3]. It has been reported that internal recirculation of combustion products results in the dilution and preheating of fresh reactants that helps in suppressing thermal NOx and CO emissions [2, 4]. The above process is also known as flameless combustion or mild combustion in which the reaction zone is almost invisible within the volume of the combustor [5].

Flameless combustion technique has caught the attention of researchers' for reducing the pollutant emissions from combustion systems [2, 4-6]. During last two decades, many researchers achieved flameless combustion with different gaseous fuels and combustor configurations [4, 7]. The exhaust gas recirculation in flameless combustion leads to distributed combustion reaction throughout the combustor volume and uniform, well distributed temperature field [8, 9]. To obtain flameless combustion in a system, the combustion products should be re-circulated in large quantities to ensure that flame is blown off from primary combustion zone [6, 7, and 10]. Therefore, it becomes extremely important to understand the characteristics of lifted flames and their blow off characteristics under different conditions of co-flow velocity, fuel type, flow rate, co-flow temperature and dilution of co-flowing air [6]. However, very little work has been reported in the application of liquid fuels in flameless combustors [18]. Since the flame lift-off and blow out are important parameters for achieving flameless combustion [6, 7].

Early studies on lifted spray flames suggested a structure similar to that of a corresponding gas diffusion flame, because most of the droplets evaporate very close to the fuel nozzle and only a single reaction zone is present, [11]. However, recent investigations have reported that the flame can exhibit a double structure, originating at the leading edge and diverges in downstream location [12-14]. Further, it has been reported by Chiu et al. [15] that flame stabilization in reacting sprays occurs where small droplets are available (to readily provide a mixable fuel vapor) and large-scale structures exist (which mixes the fuel vapor with entrained air). The study of the flame with and without co-flow states that without co-flow, the flame exhibits a single flame structure similar to that observed in lifted gaseous jet diffusion flames [14]. The addition of low-speed co-flow lifts the flame and permits increased entrainment of air into the lifted flame front.

In the present study detailed investigations have been carried out for two different conditions of co-flow and a range of co-flow velocities (a) Cold flow (air supplied at ambient temperature) (b) Cold air with nitrogen dilution. Pressure swirl injectors (Nozzle1; N1 and Nozzle2; N2) of various mass flow rates with injection pressure variation of 5 bar - 9 bar (SMD range of 30 μm to 65 μm) are selected (Myers and Lefebvre, 1986).

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Experimental setup details

The experiments have been carried out for two different conditions, (a) Co-flow: air supplied at atmospheric temperature in a co-flow chamber with velocity range of 0.1 to 0.67 m/s. (b) Co- flow with dilution: in this case, co-flow is diluted with Nitrogen (99.999% pure) to understand the effect of co-flow dilution on lifted spray flames. This study helps in analyzing the droplet evaporation characteristics based on lift-off height for both the cases.

Figure 1 shows the schematic of the present experimental setup for the lifted jet flames. Co flowing air is supplied through a centrifugal blower with an air blowing capacity of 0 - 4.3 m^3/s. Air is blown from the bottom of the conical chamber. Multiple wire screens have been placed inside the conical and cylindrical portion of the co-flow delivery system to ensure uniform velocity profile at various angular and radial positions and maintain very low velocity fluctuations, less than $\pm$ 0.05 m/s. Co-flow velocity across the chamber at different locations is measured by VELOCICALC is an Air Velocity Meter of Model 9555 Series. The resolution with a telescopic probe (Hot wire type) is 0.01 m/s over the range of 0 to 50 m/s with an accuracy of $\pm$ 3%. Kerosene is used as fuel and its typical properties are density = 780 - 810 kg/m^3, Flash point = 334 K, Auto ignition temperature = 493 K and Lower heating value = 43.1 MJ/kg. The fuel (kerosene) line is passed through a pipe located at the centre of the chamber. A fuel tank of 2 liter capacity is pressurized with a high pressure air. The tank pressure is maintained constant through a pneumatic pressure regulator from 5.0 bar to 9.0 bar, depending upon the duration of the experiment. The fuel is injected through a Donfoss [16] make solid cone spray swirl injector with a spray cone angle of 45^o. For the case of co-flow with dilution, co-flow air is diluted by Nitrogen gas (99.99% pure) and different oxygen levels were maintained between 17 to 21% (molar). N_2 gas is supplied from a high pressure cylinder at the inlet port (eye) of the centrifugal blower. Suction of the air blower ensured proper mixing of Nitrogen with the incoming air. The mole fraction of oxygen is measured along different locations of the chamber with a Quintox KM-9106 gas analyzer.

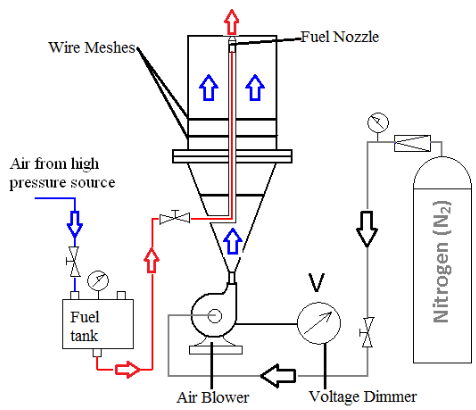

Figure 1 Schematic block diagram of experimental setup.

Results and discussion

In this present work, the effect of parameters such as co-flow velocity, injection pressure and dilution rate on flame lift-off height and its fluctuations has been experimentally investigated. The discharge coefficient (C_d) is defined as the ratio of actual to the theoretical discharge of the fluid from an orifice, [17]. C_d for both the nozzle in the current experiment is in the range of 0.28 - 0.3. The spray cone angle for both the injectors is 45^o, and their SMD at 9bar pressure (design pressure) is in the range of 38 - 42 microns (measured with a Malvern mastersizer).

Variation of lift-off height with normal co-flow conditions:

In the present work, the variation of the flame lift-off height, its fluctuation with the co-flow velocity and injector pressure has been experimentally measured. It is clear from Fig. 2 that flame lift-off height increases with an increase in the co-flow velocity. Figure 2 also shows the effect of variation of the injection pressure on the flame lift-off height for nozzle N1. It can be clearly seen that as the injection pressure increases, the flame lift-off height decreases. An increase in the injection pressure leads to a decrease in the mean droplet size (SMD) as confirmed from our measurements of SMD using laser diffraction based measurement of particle size.

As the injection pressure is increased from 5.0 to 9.0 bars, the mean droplet size (SMD) decreased from 65 micron to 38 microns. Larger droplets take longer time to evaporate and generate a combustible mixture. Droplet life time has been reported as a function of co-flow temperature and sauter mean diameter (SMD) $t_e = f(T_g, SMD^2)$ and SMD as a function of mass flow rate and injection pressure $SMD \propto \sigma^a \nu^b m^c \Delta P^{-d}$. For instance, at an ambient temperature of 573 K and droplet temperature 293 K, time take to evaporate a 40 microns size droplet will be 18.8 ms and a 65 micron droplet would take 49.6 ms. The evaporation time increases by 164% [17]. Due to larger size of the droplets, the flame lift-off height increases from 141 mm to 186 mm at a co-flow velocity of 0.37 m/s, when the injection pressure is reduced from 9 to 5 bar. The flame blows off at a much lower co-flow velocity for 5 bar injection pressure as bigger droplets are formed. However, the flame stabilization position is enhanced from 234 mm at 9 bar injection pressure to 306 mm at 5 bar injection pressure. The fluctuations in the flame position near the flame stabilization point increase with a decrease in the injection pressure because the larger droplets create uneven mixture and it leads to increased flame fluctuations.

Figure 3 shows the variation of the flame lift-off height with respect to variation of the co-flow velocity for different nozzles (N1=1.72 kg/h and N2=2.76 kg/h) at 9.0 bar injection pressure. It indicates that as the mass flow rate of the nozzle increases, the flame lift-off height decreases. It is to be noted that the mean droplet diameter and spray cone angle remain same for both the nozzles at an injection pressure of 9 bar. The lift-off height decreases due to an increase in the mass flow rate as it creates a denser fuel cloud (increase the droplet number density). In case of higher fuel mass flow rate, the droplet motion rate towards the downstream position will be less as compared to lower fuel mass flow rate at a same co-flow velocity. For instance, due to this effect, the flame lift-off height increases from 210 mm to 235 mm for a co-flow velocity of 0.57 m/s for Nozzle N1. The fluctuations in the flame lift-off height increase with an increase in the fuel mass flow rate and co-flow velocity.

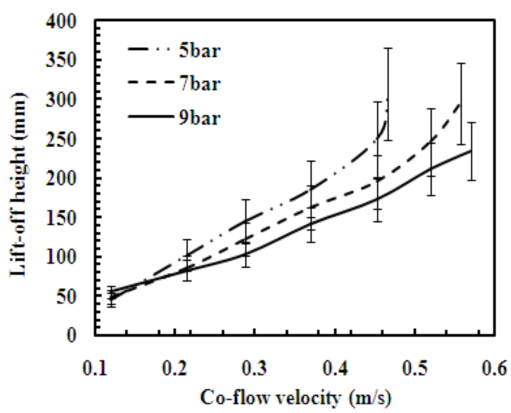

Figure 2 Lift-off height variation with co-flow velocity of nozzle 1 (N1) at different injection pressures of 5 bar, 7 bar and 9 bar.

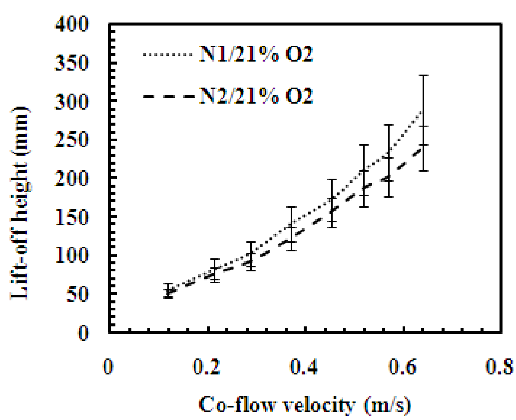

Figure 3 Lift-off height variation with co-flow velocity of nozzle 1 (N1) and nozzle 2 (N2) at injection pressures of 9 bar.

Effect of co-flow dilution on flame lift-off height:

A comparison of flame lift-off height and its fluctuations for different dilution conditions (by varying the O_2 concentration in the co-flow for nozzle 2 (N2) at 9 bar injection pressure) is shown in Fig. 4. The O_2 content in the co flowing stream is reduced from 21% to 17% with 1% step variation. It can be clearly seen that as O_2 concentration is reduced from 21% to 17%, the flame lift-off height increases from 92 mm to 276 mm at a co-flow velocity of 0.29 m/s. Due to non-availability of sufficient oxygen in the co-flowing air, the flame moves to the downstream location. The curves obtained from experimental results show dual behavior with co-flow velocity as indicated by Zone I and Zone II. Lift-off height variation in zone-I and zone-II follows a linear behaviour. However, the slopes of these curves are different. The increase in co-flow velocity increases the availability of O_2 eventhough O_2 mole fraction is maintained constant. In the zone-II (above the line A-B), lift-off height increases rapidly with a different slope. This rapid variation of slope is perhaps due to the competetion between the availability of oxygen and higher velocities in the co-flow leading to flame stabilization at a particular location in the downstream. For all the conditions (21% O_2 to 17% O_2), blow-off limits follow an alomost linear trend, as shown by curve a-b (Fig. 4). As injection pressure is increased from 7.0 to 9.0 bars for the same co-flow velocity, the flame lift-off height decreases due to a decrease in the mean droplet diameter, the same phenomenon has shown in Fig. 5. The fluctuations in the flame stabilization point increase with the dilution. Since the entrained air mixes with the additional fuel and forms combustible mixture at a downstream position, the flame has been observed to be stable even at a much downstream position. The effect of change in the mass flow rate on flame lift-off height at 17 % O_2 concentration is shown in Fig. 6. The increase in the fuel mass flow rate enhances the flame stabilization near the blow-off and flame stabilization point shifts from 225 to 280 mm position for same injection pressure of 9 bar at 17% O_2.

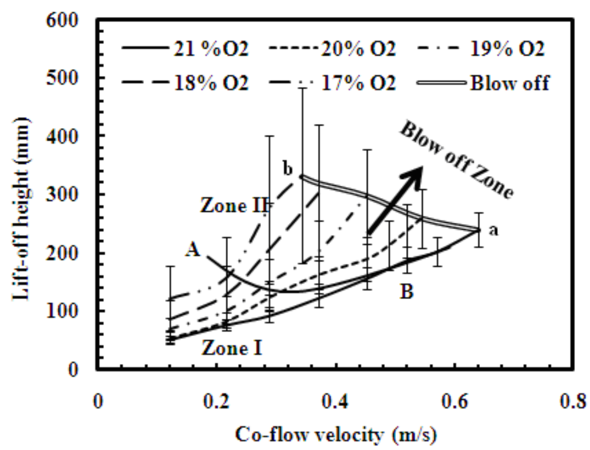

Figure 4 Comparisons of lift-off height and fluctuations of flame at different dilution conditions (17% O_2 to 21%O_2) by varying the co-flow velocity for nozzle 2 (N2) at 9bar injection pressure

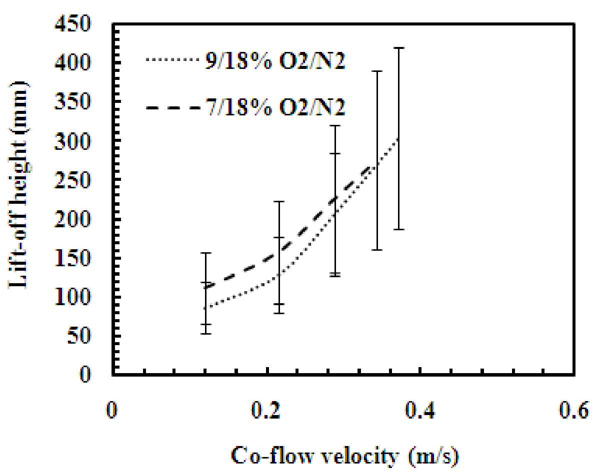

Figure 5 Comparisons of lift-off height 18% dilution conditions by varying the co-flow velocity for nozzle 1 (N1) at 7 bar and 9 bar injection pressure

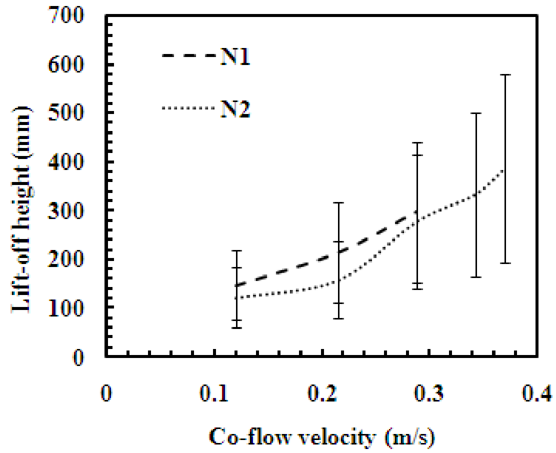

Figure 6 Comparisons of lift-off height and fluctuations of flame at 17% O_2 dilution conditions by varying the co-flow velocity at 9 bar injection pressure for nozzle 1 and nozzle 2

Study of controlling parameters

It has been observed that the flame lift-off height is controlled by the SMD (Sauter mean diameter) of the droplets, co-flow velocity (V_c), spray ejection velocity (U), mass flow rate of the fuel ($\dot{m}$), injection pressure (ΔP), spray cone angle, co-flow temperature (T_g) and O_2 mass fraction.

$$SMD \propto \sigma^a \nu^b \dot{m}^c \Delta P^{-d}$$

$$H \propto f(SMD, \Delta P, V_\alpha, Y_{ox}^n, T_g, t_e)$$

$$t_e = f(T_g, SMD^2)$$

Lift-off height is inversely proportional toY_{OX}^n. Droplet life time is inverse proportional with co-flow temperature. The fuel droplet ejection velocity is controlled through injection pressure. As the injection pressure is increased, the droplet ejection velocity also increases. Hence, the study of the lift-off height of the flame can be effectively done by defining two non-dimensional parameters i.e. H/SMD (H- lift-off height) and V_α/U (V_α- co-flow velocity, U- injection velocity). Figure 7 shows the variation of H/SMD with respect to V_α/U. The data collapses into a very thin zone on the plot. This indicates a strong dependence of flame lift-off height on these parameters for all operating conditions considered in the present experiments. It clearly shows a linear relation between both the non-dimensional parameters for all the operating conditions.

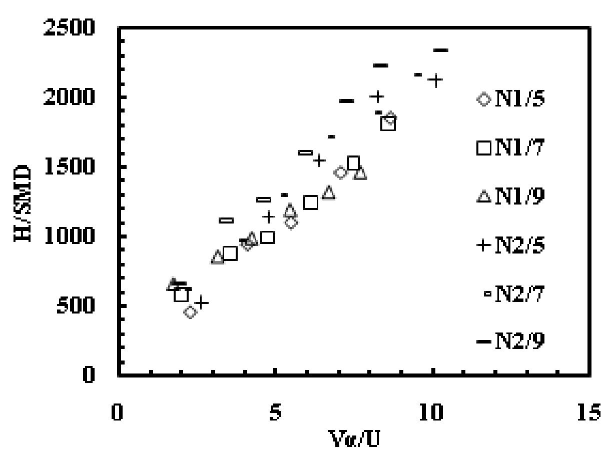

Figure 7 Non-Dimensional variation of flame lift-off

Conclusions

In the present work, the effect of co-flow velocity on the flame lift-off height of liquid fuel spray obtained from pressure swirl injectors has been experimentally investigated. It has been observed that flame lift-off height varies linearly with co-flow velocity in non-dilution case. Dual behavior has been observed for dilution case. The flame lift-off also depends on the change in the mass flow rate of the fuel injector. The results indicate that as the mass flow increases, the blow-off limits are enhanced for a range of co-flow velocities. At very low co-flow velocities flame is attached to nozzle. Blow off height is increased enormously for diluted co-flow case at moderate co-flow velocities. The data plotted with non-dimensional parameters shows that the flame lift-off height indicates that the flame stabilization for sprays can be related to the mean drop size of spray which is governed by the variation of the fuel injection pressure. All the curves at different operating conditions are following same non dimensional characteristics. Data collapses into a very thin zone on the plot. The dilution also increases the flame fluctuations at higher lift-off heights due to non-availability of O_2 and the inability of spray to form a proper combustible mixture for sustaining a stable flame.

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