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Turbulent Combustion of the Diesel Fuel in a Cylindrical Combustion Chamber

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Abstract – An experimental work was carried out to investigate the effect of the double swirl on the combustion performance of a Diesel fuel spray in a confined chamber. Eight combinations of double swirl arrangements were examined. The flame thermal and chemical structures were studied on the comparative basis. The combustion efficiency was calculated based on the exhaust gas species concentrations. The results indicated that the optimum flame performance as achieved with the co-swirl mode when the inner air stream is swirled at 60o while the outer air stream is swirled at 45o. This is attributed to providing a significant swirl strength around the fuel injector and a simultaneous flow shearing effect via the swirl angle difference between the two streams. In most of the counter-swirl flow combination, the excessive flow strain produced by the high relative swirl angles was found to produce local flame extinction and deterioration in the combustion efficiency.

Keywords: Swirl Flow, Diesel Spray, Combustion, Flow Recirculation, Hydrocarbon Oxidation

1. Introduction

The fuel-air mixing and the transport processes within the flame are greatly linked in the combustion systems (Jeon et al., 2024). The flame stability limits strongly depend on the rates of the physical and chemical processes across the flame. In order to enhance the flame stability limits and the combustion efficiency, a highly turbulent flow should prevail (which is typical achieved when a flow recirculation zone is provided). The flow recirculation zone provides a well-mixed zone between the reactants and the hot combustion products (Amin, 1991). This acts as a continuous source of ignition since it provides heat and chemically active species (Hemaiza and Abdelhalim, 2022).

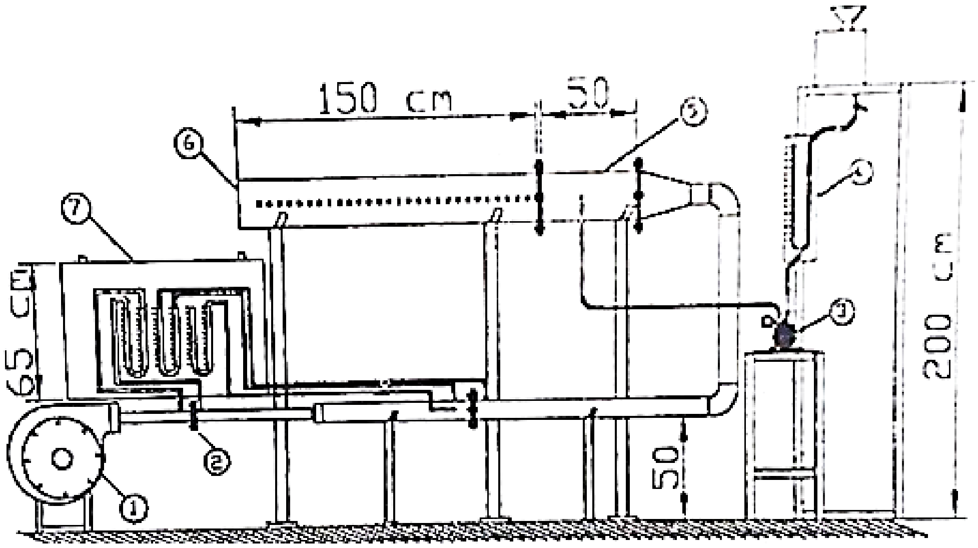
Swirlers are often used to generate the internal recirculation zone via establishing high levels of vorticity which is associated with an adverse pressure gradient along the combustor axis, thus driving the flow reversal. Swirlers provide tangential momentum which enhance the flow shearing (Chen et al., 2021). It is well-known that the double concentric swirlers play an ever-increasing role in the design of combustors (Kang et al., 2022). This is because the double swirl allows the adjustment of the radial distribution of the tangential momentum. The physical and chemical processes are thus accelerated by the swirl whose intensity depends on the swirl mode, the relative swirl angle and the diameter ratio of the inner swirler and the outer swirler in addition to the shape of the swirler vanes and the individual swirl angles (Gupta et al., 1998). The combustor/swirler confinement ratio additionally affect the flow aerodynamic field as it creates corner recirculaion zones (Ghanem, 1996).

The aim of the present work is to study the effect of the double swirl action on the flame characteristics with respect to the swirl mode (the co- versus the counter-swirl), the overall swirl number, the individual swirl strength and the relative swirl angle between the two streams. Inasmuch as the spray flames require a highly turbulent flow to aid in getting fast fuel evaporation, rapid fuel-air mixing and promoted fuel-oxidation kinetics, the relevant parameters such as the fuel injection pressure, the fuel injector protruding distance and the confinement ratio are tuned. This is achieved during the preliminary stage of investigation.

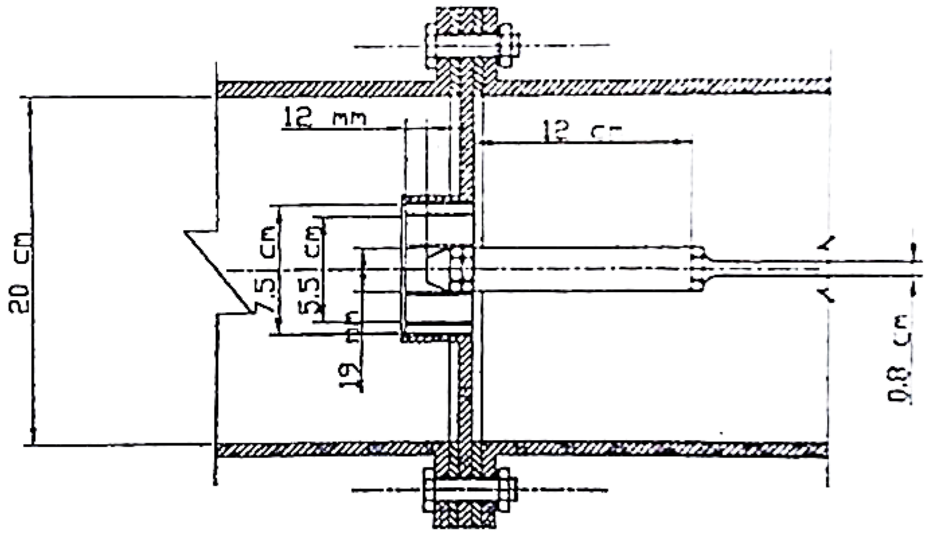
2. Description of the Test Rig

As shown in Fig. 1a, the flame tube is a horizontal, uncooled seamless steel tube that is 20 cm diameter and 1.5 m long. It is machined with 28 equally spaced tapings for the purpose of providing the access for the measuring probes.

As shown in Fig. 1b, the double swirl burner has two concentric annuli with independent swirl angles, while the fuel is concentrically introduced inside the swirler hub. Each swirler has 8 straight vanes for both the inner and outer annuli. Table 1 shows the dimensions of the double swirlers where the swirl angles are measured from the swirler axis.



(a)



(b)

Fig. 1.

Table 1: Swirler Dimensions

Swirler	**Outer Ring**		**Intermediate Ring**		**Inner Ring**		**Inner Angle (°)**	**Outer Angle (°)**	**Mode**
	D_o (cm)	**D_i (cm)**	**D_o (cm)**	**D_i (cm)**	**D_o (cm)**	**D_i (cm)**			
1	7.5	7	6	5.5	2.3	1.9	45	45	Co-
2	7.5	7	6	5.5	2.3	1.9	60	60	Co-
3	7.5	7	6	5.5	2.3	1.9	45	60	Co-
4	7.5	7	6	5.5	2.3	1.9	60	45	Co-
5	7.5	7	6	5.5	2.3	1.9	45	45	Counter-
6	7.5	7	6	5.5	2.3	1.9	60	60	Counter-
7	7.5	7	6	5.5	2.3	1.9	45	60	Counter-
8	7.5	7	6	5.5	2.3	1.9	60	45	Counter-

The air supply system includes a 1.5 HP, 2800 rpm electrically-driven blower, two sharp-edged orifices, a ball valve and delivery connections. The fuel supply system includes a gear pump which is directly connected to a 0.09 kW, 670 rpm electric motor. The liquid fuel is delivered to the fuel gun through a steel pipe. The fuel gun is fitted to the swirler hub and the fuel is atomized with a 60° spray cone angle. The air flow rate is measured by an orifice-meter and a U-tube manometer. The fuel flow rate is measured by recording the time that is elapsed when a certain fuel volume is withdrawn from the tank. A Pt-10%Pt Rh thermocouple is utilized to measure the local values of the flame temperature after getting corrected for the radiation and convection heat transfer among the flame, the thermocouple bead and the combustor wall. The combustor wall temperatures are measured by a K-type thermocouple upon getting embedded into the tapings. An electrochemical gas analyzer is utilized to measure the CO and HC exhaust gas concentrations. A fuel flow rate of 2 kg/hr, a fuel injection pressure of 12 bar and an overall excess air of 24% are maintained during the whole investigation.

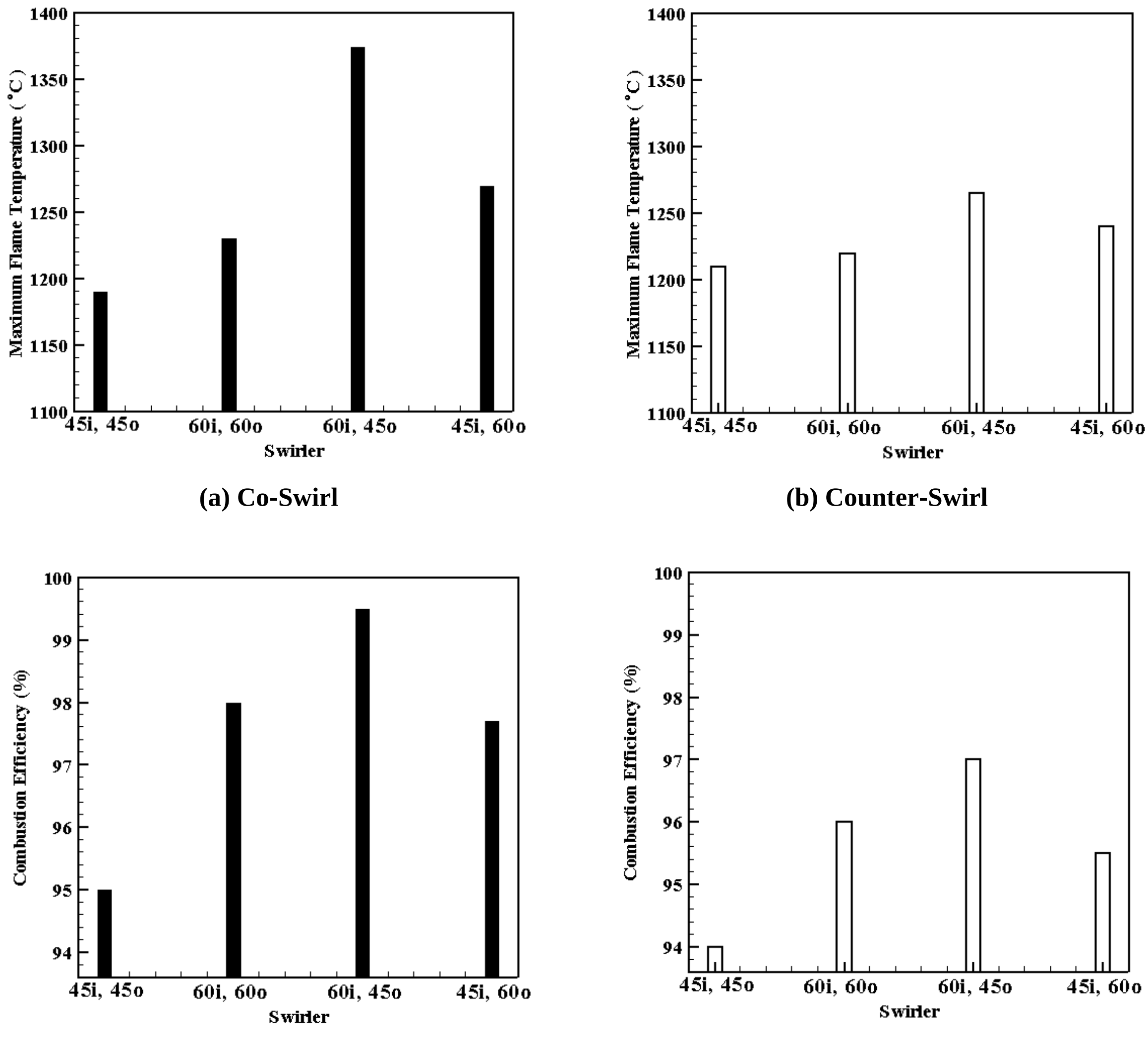
The swirl number [S] is calculated according to Vu and Goulden (1982) as follows:

$$S = \frac{2}{3}\frac{\tan\theta_i(r_i^3 - r_{ii}^3) + \tan\theta_o(r_\infty^3 - r_i^3)}{(r_\infty^2 - r_{ii}^2)r_\infty}$$

Where the subscripts ii, i, ∞ respectively refer to the inner, the intermediate and the outer radii of the swirler.

3. Results and Discussion

It can be noticed from Fig. 2 that the peak flame temperature and the peak combustion efficiency coincide. This is because enhancing the fuel-air mixing and accelerating the combustion kinetics lead to larger heat release rates which are associated with higher peak flame temperatures and greater rates of fuel oxidation (thus causing greater combustion efficiencies). This holds true for co-swirl (Fig. 2a and Fig. 2b) as well as for counter-swirl (Fig. 2c and Fig. 2d).



(a) Co-Swirl

(b) Counter-Swirl

(c) Co-Swirl

(d) Counter-Swirl

Fig.2.

It is noticed that upon employing co-swirl, the flame spectrum is reddish and sooty with the swirler of 45° inner swirl angle and 45° outer swirl angle (Fig. 3a). This is a result of having a small swirl angle in addition to the absence of a relative swirl angle between the inner and outer streams (Zhang et al., 2023). As the inner swirl angle remains at 45° while the outer swirl angle increases to 60°, the flow shearing effects at the outer stream develop across a large surface area. This causes the reaction zone temperatures to increase such that the flame spectrum turns into yellow (Fig. 3b). On the other hand, if the inner swirl angle becomes 60° and the outer swirl angle becomes 45°, the most intensive flame spectrum is obtained (Fig. 3c). This testifies to the importance of the inner swirl in establishing a strong adverse pressure gradient for getting intense flow recirculation such that the combustion efficiency gets its maximum magnitude. This is in agreement with the results of Zhang et al. (1991) and Liao et al. (2000).

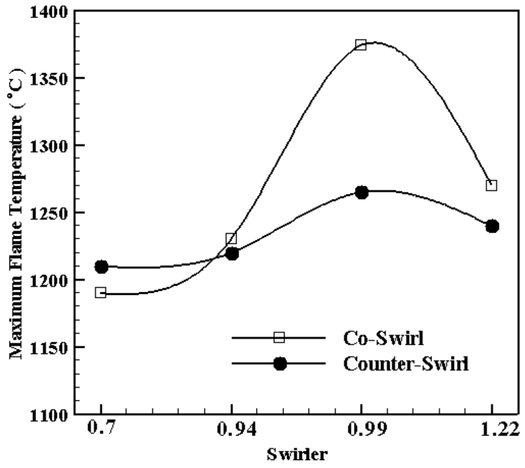
(a)

(b)

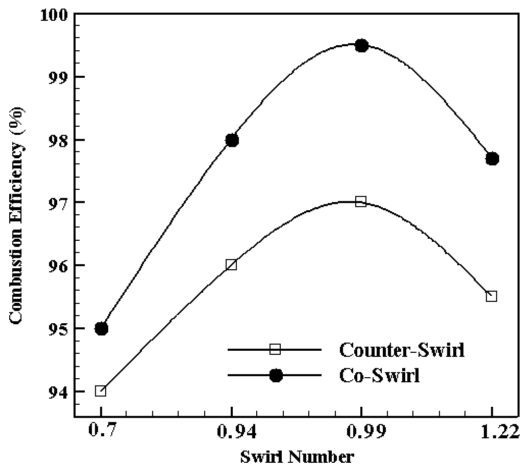
(c)

Fig 3.

In terms of the swirl number, the maximum flame temperature occurs at a swirl number of 0.99 (Fig. 4a), while the peak combustion efficiency is reached at the same swirl number of 0.99 (Fig. 4b). This indicates that the excessive swirl number is not the proper condition for the optimum combustion performance (Papafilippou et al., 2024). In this regard, the consequent excessive shearing stresses causes local flame extinction and deterioration (Alkadi, 1995). Therefore, when the swirl number is sufficiently close to 1.0, the enhancement in fuel-air mixing and reaction rates are optimally obtained.



(a)



(b)

Fig 4.

At the swirl number of 0.7, the enhanced heat transfer from the co-swirl flame causes the peak flame temperature to become slightly below the peak flame temperature for the counter-swirl flame (Fig. 4a). This can be supported by the findings of Desoky et al. (1989) and Wu et al. (1991), who found that the swirl flow enhances the rates of heat transfer across the flame.

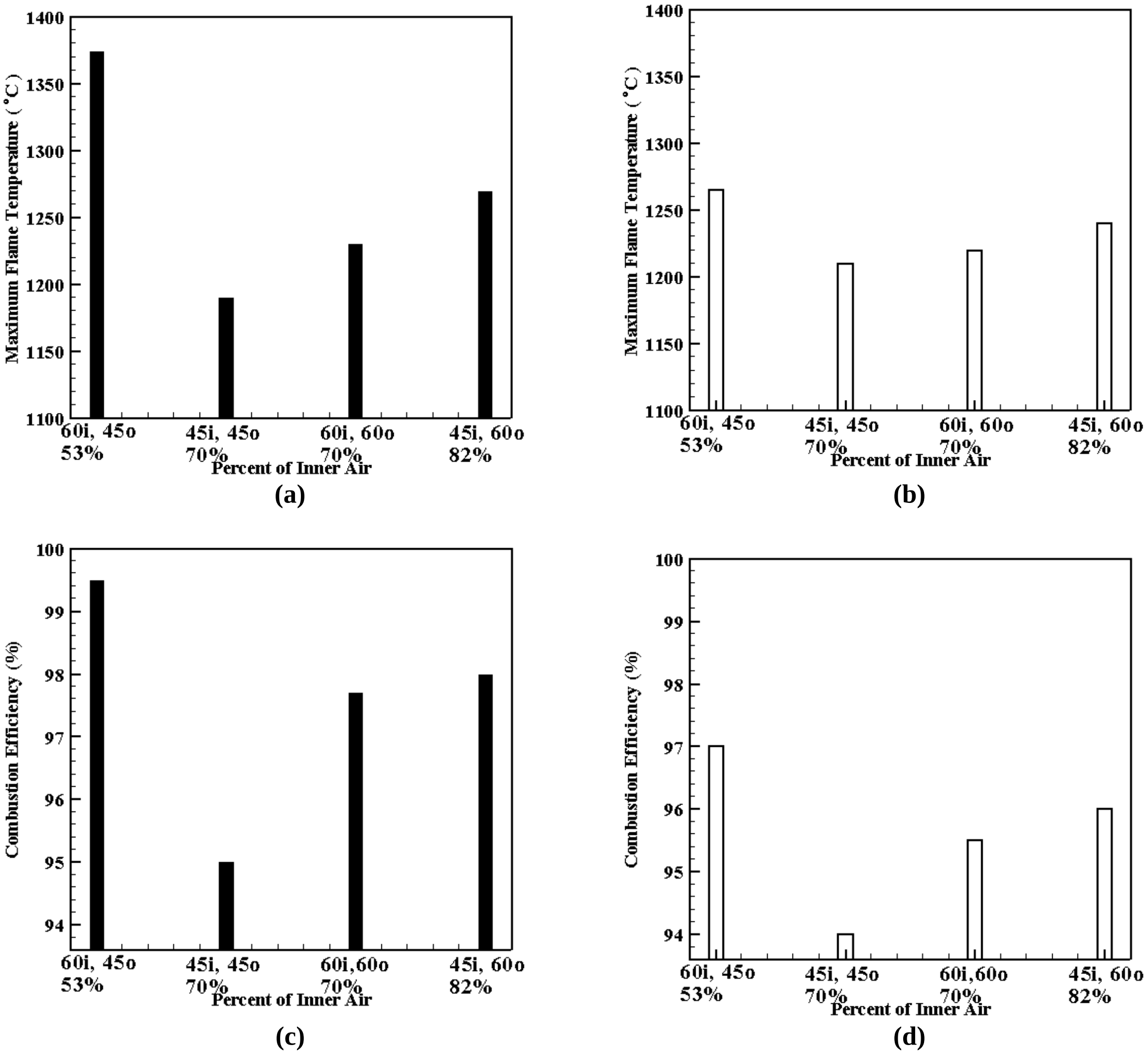


Fig.5.

It is interesting to note from Fig. 5 that the percent of the inner air from the total combustion air is dictated by the available cross-section area for each swirler partition as well as the comparative pressure drop experienced across the two swirler flow partition areas. Therefore, for both the co- and the counter-swirl flow; increasing the inner swirl angle contributes to increasing the percent of the inner air (Beltagui, 1988). In this regard, when the inner and the outer swirler angles are equal, the same 70% of the total combustion air flows through the inner swirler. On the other hand, when the inner swirl angle is 60 and the outer swirl angle is 45, much of the total combustion air flows through the outer swirl area as it experiences less pressure drop such that 53% of the total combustion air flows through the inner annulus. The reverse is true when the inner swirl angle is 45 and the outer swirl angle is 60 (such that the maximum percent of the inner air takes place with 82%).

Durbin and Ballal (1994) stated that the co-swirling flow has wider flame stability limits. In the counter-swirl flames, the flame local extinction takes place when the rate of heat transport cannot keep pace with the transport of mass upon getting excessive shear stresses (Elghoroury, 1991).

It is worthy to report the results which correspond to the flame stabilization and to what extent the flame stability limits are extended upon applying the swirl effects. Under normal operating conditions, it was possible to increase the combustor firing capacity up to 138 kW for all the swirling flame combinations of the double swirl. In comparison, under no swirling conditions, the flame blowout limit was recorded at 23 kW. Such significant extension in the flame stability limit due to swirl is attributed to the favorable effect of the flow recirculation zones (Jeon et al., 2024). In this regard, the recirculation of heat and active species in the upstream direction provides an effective source of sustaining much increase in the firing capacity (Zhang et al., 2023).

A further insight into the effect of the swirl on the kinetics of combustion for the gaseous and liquid fuels in addition to the biomass fuels is provided herein. It is well-known that methane (CH_4) is the simplest hydrocarbons. When methane is combusted, CH_4 forms CH_3 after H abstraction. Then there are three dominant reaction pathways of CH_3: (1) CH_3 recombination to form C_2H_6 and other C_2 species (C_2H_5 and C_2H_4); (2) CH_3 oxidation pathways (CH_3OH, CH_3O, CH_2OH and CH_2O); and (3) further H abstraction to form CH_2, CH2(s) or CH_2*. The reaction pathways depend exponentially on the temperature which is greatly enhanced in the flame stabilization region due to swirl before becoming highly uniform in the post-flame zone. While the oxidation of the liquid fuels with their heavier hydrocarbon molecules are more complex, the swirl favorably accelerates the combustion kinetics. With much more complexity in the combustion of biomass, the swirl enhances the rates of drying, devolatilization, combustion of volatiles and combustion of char inside the swirling biomass combustors (Papafilippou et al., 2024).

It has to be additionally highlighted that there are contradicting requirements of high temperature to get fast combustion and reduced peak temperature to minimize the NOx emissions. The role of swirl is thus to let the average flame temperature sufficiently high for oxidation. Simultaneously, the peak temperature is reduced due to the correspondingly high rates of flow strain which result in flattening the temperature profiles. For nitrogen-free fuels, the NOx is formed according to the thermal mechanism which is affected by the peak temperature within the flame. On the other hand, with fuels which contain nitrogen, a significant portion of the NOx emissions arise from the fuel NOx due to the attack of oxygen on the nitrogen atoms in the fuel. A third mechanism is attributed to the reaction which takes place between the atmospheric air nitrogen and the hydrocarbon fragments and this is denoted by the prompt NOx. Conversely, NOx can be converted to molecular nitrogen in the oxygen- deficient regions. In this regard, when a NOx reducing environment prevails, reburn reactions of NOx into N_2 take place.

Conclusions

The co-swirl mode with the inner 60° and the outer 45° swirl angles pronounced the optimum performance for Diesel fuel combustion in terms of the highest peak flame temperature and the least CO and HC exhaust species concentrations. Under such conditions, the portion of the air which flows through the swirler inner annulus is sufficient for providing an aerodynamically controlled oxidizing atmosphere for the fuel vapor as long as the high swirl strength for the inner air supply is supported by a relative swirl angle with the outer swirl. The fuel injector protruding distance from the swirler hub should be negative such that the fuel vapor is introduced prior to the swirler face and subsequently is subjected to all the recirculatory flow shearing impact within the recirculation zone. The inner swirl strength is more important than the outer swirl strength while a relative difference should be maintained in the co-swirl mode for improving the flow shearing effect. The counter-swirl was found to cause local flame extinction when the relative swirl angle becomes sufficiently large in the case of 60° inner and 60° outer swirl angles.

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