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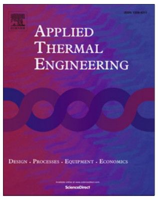

Effect of mixture flow stratification on premixed flame structure and emissions under counter-rotating swirl burner configuration

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HIGHLIGHTS

- Flame structure of counter swirl flame depends on mixture and flow stratification.
- High swirl flow in the inner annulus generates elongated and enlarged flame reaction zone.
- Mixture and flow stratification affect local emissions.
- Rich stratification of inner channel results in higher NO_x and CO emissions.
- Enrichment of outer annulus shows comparable emission levels to homogenous premixed flames.

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ABSTRACT

An investigation of the flame structure and emission performance of stratified swirl methane/air flames was performed by using a double-annulus counter-rotating premixed swirl burner. Stratification of the flow and mixtures were established by varying the bulk air flow rates and mixture equivalence ratios between the inner and outer annuli. Two distinct flame fronts were stabilised at the burner outlet, separated by a shear layer due to velocity differences. Higher swirl flow in the inner annulus generates an elongated and enlarged area of flame reaction zone due to increased flame intensity, as the flame shape is strongly dependent on the velocity magnitude exiting the annulus. Mixture and flow stratification affect local emissions. A richer mixture stratification within the inner channel at 70:30 flow split results in 91% and 49% higher emission rates of NO and CO respectively compared to premixed arrangement, in spite generally aiding flame stability. Enrichment of the outer annulus at 70:30 split flow shows only slightly higher levels of NO and CO emissions by 3% and 9% respectively compared to a homogenous mixture.

1. Introduction

Lean premixed swirl-stabilised flame technology is widely employed in many applications such as gas turbines [1], internal combustion engines [2], industrial furnaces [3] and boilers [4] for effective flame and emissions control. Swirl imparts good mixing and stability to flames via the formation of a central recirculation zone which promotes good mixing between incoming reactants and products [5]. Lean premixed flames offer good emissions characteristics, but can become unstable as the temperatures become lower [6]. Additional stability can be obtained at higher equivalence ratios, but at the price of high NO_x emissions. This compromise is often met by using a higher temperature pilot flame. Study of the complexities of swirl within combustors is usually confined to a single annulus swirl configuration [7], while investigation of multiple swirl flames containing a pilot stream is relatively scarce. The establishment of multi-swirl piloted flames results in an equivalence ratio stratification which affects flow field, flame stability, mixing and emissions, which have not been thoroughly characterised.

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A few multiple swirl flames established from gaseous and liquid fuels have been studied by Gupta et al. [8] and Durbin and Ballal [9]. Gupta et al. [8] have performed extensive studies on the effect of swirl on flames to show that a double annulus swirl flame burner enables the control of radial distribution of flow and the degree of swirl to achieve stable flames over a wide range of operating conditions. In a related study, Gupta et al. [10] compared the spatial temperature distribution of unconfined double concentric premixed swirl flames under co- and counter-swirl arrangements, showing that the arrangement of the swirl direction, co- or counter-swirl, has great influence on the flame symmetry and stability. In that study, counter-swirl flames were reported to show non-symmetrical temperature fluctuations caused by the thin and intense reaction zone in the flame, which may influence NO_x formation and emissions. Durbin and Ballal [9] concurred with Gupta et al., and observed improved flame stability for flame established from counter-swirl configuration by utilising a double swirl step combustor. The flame length was decreased when the outer vane angle increased and inner air velocity decreased. Lean blowout was improved when the outer swirl flow intensity was increased. These investigations focused mainly on overall flame structure and stability, but the effect of flow stratification on emissions was not investigated nor quantified.

Liquid fuel injection under multi-swirl configuration has been investigated by some groups. Merkle et al. [11] compared the differences between co- and counter-swirl on the turbulent flow and mixture field of a liquid fuel airblast atomizer. The counter-swirl arrangement was reported to exhibit increased strength of internal recirculation zone as evident by the increased mass flow recirculated but with a reduction of length in axial direction. This is attributed to the faster decay of tangential velocity for counter-rotating air flow, induced by partial compensation of inversely oriented angular momentum fluxes. However, analysis of turbulence quantities show considerable attenuation of the turbulent exchange of momentum perpendicular to the main flow direction for counter-rotating airflows compared to co-rotating flow. This is in contrast to the report by Ateshkadi et al. [12], where counter-swirl configuration increased the radial dispersion of flow for liquid fuel airblast atomizer. The latter further showed that flame stability limits was improved with lower lean blow off limit due to increased strength of recirculation zone, which assists in the transport of fuel droplets.

The performance of emissions using a multiple annulus swirl burner was investigated by Toqan et al. [13]. A radially stratified flame was created via a combination of swirling flow and strong radial density gradient, by injecting fuel through the central nozzle enveloped by rotating air, separating the fuel rich cone from the lean outer region in staged combustion. Low NO_x emissions were achieved through the increased residence time of the mixture under fuel-rich conditions and the use of burned gas recirculation through the burner. Terasaki and Hayashi [14] compared the NO_x emission performance of a double-swirler combustor with the single-swirler of non-premixed, direct central fuel injection burner. The double annulus co-rotating swirl burner was reported to emit low level of NO_x under lean conditions, which was attributed to the rapid mixing process, compared to the conventional swirl burner. To date, there have been no studies on the emissions under counter-swirl double flame configuration.

The present work examines the effect of mixture stratification on the flame structure and emission performance of premixed gaseous flames using a double concentric counter-rotating swirl burner. Quantification of the emissions data and examination of the flame structure provides the insight of the flame shape and stability of a counter-rotating flame burner. The data obtained from the well-defined geometry can also be used as flame modelling validation target.

2. Experimental

2.1. Burner setup and flow delivery system

The schematic of the counter-swirl flame burner and flow delivery system used in the present experiment is shown in Fig. 1a. The swirl flame burner made from stainless steel consists of two annuli with two swirlers placed at the burner outlet. The internal swirler in the inner annulus has eight straight vanes fixed at 45° to the centreline axial axis. The outer swirler comprises of ten straight vanes attached to the swirler hub at 50°. The vane thickness for all vanes (inner and outer swirlers) is 1.5 mm. The internal swirl vanes are arranged in clockwise whereas the outer swirler vanes are arranged in counter-clockwise direction, forming a counter-rotating swirl flow motion at the burner outlet. The pair of swirlers, arranged in concentric at the burner outlet is shown in Fig. 1b. The calculated swirl numbers based on the swirler geometry are $S_N = 0.77$ and 1.04 for the internal and external swirlers respectively, based on the geometric expression

$$S_N = \frac{2}{3}\left[\frac{1-(D_h/D_s)^3}{1-(D_h/D_s)^2}\right]\tan\theta \qquad (1)$$

where D_h and D_s represent the swirler hub diameter and the swirler diameter respectively, and θ is the angle of the swirl blade from the centreline [15]. The relatively high swirl number ($S_N > 0.6$) for both swirlers allows the generation of strong swirl with sufficient intensity to stabilise the flame [16]. A circular quartz tube with diameter 100 mm and 150 mm length forms the combustor wall at the burner outlet, allowing optical access for flame visualisation. Table 1 shows the geometry of the double annulus counter-rotating swirl flame burner. For the flow delivery system, four mass flow controllers (Alicat: MCR series, ±1% accuracy full scale) were utilised to supply gaseous fuel (methane) and air to the burner. Methane (99.7% purity, LHV: 50 MJ/kg) was used as the source of hydrocarbon fuel. For each annulus, the air and methane supplies were regulated by mass flow controllers. Premixing of fuel/air for each channel occurs independently at the burner plenum prior to delivery to the burner outlet. The mixtures were ignited at the combustor outlet using a flame torch after both annulus flows were established.

2.2. Operating conditions

The counter-rotating flames were established at different combinations of fuel/air ratios and bulk air flow rates to enable examination of the flame structures and emission performance, as shown in different test series and cases denoted alphanumerically in Table 2. The operating conditions for the investigation of the flame structure via imaging are shown in test series IM, whereas the emissions test operating conditions are shown in the test series of A, B (identical to IM), T, U and V.

These cases are organized as follows: the total air flow rate is always maintained constant, and split between inner and outer annulus, denoted by the air flow split ratio. In case A (baseline), the flame is fully premixed, and the flow rates evenly split, whilst the equivalence ratio is varied. In fully premixed case B (identical to IM), the base flame is kept evenly split at $\phi_{i,o} = 0.7$, while the swirl air split is varied. For case T, the air split ratio and global equivalence ratio are maintained at 50:50 and $\phi_g = 0.8$ respectively, while the equivalence ratio of the annuli are varied from inner to outer enrichment. In case U, the equivalence ratio for the inner and outer annulus are fixed, while the air flow ratio is varied. Finally, for case V, the stratification of the annuli flows is kept fixed, while the air flow split ratio is varied.

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