

A NEW DOUBLE-SLIT CURVED WALL-JET (CWJ) BURNER FOR STABILIZING TURBULENT PREMIXED AND NON-PREMIXED FLAMES

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ABSTRACT

A novel double-slit curved wall-jet (CWJ) burner was proposed and employed, which utilizes the Coanda effect by supplying fuel and air as annular-inward jets over a curved surface. We investigated the stabilization characteristics and structure of methane/air, and propane/air turbulent premixed and non-premixed flames with varying global equivalence ratio, ϕ , and Reynolds number, Re. Simultaneous time-resolved measurements of particle image velocimetry and planar laser-induced fluorescence of OH radicals were conducted. The burner showed potential for stable operation for methane flames with relatively large fuel loading and overall rich conditions. These have a non-sooting nature. However, propane flames exhibit stable mode for a wider range of equivalence ratio and Re.

Mixing characteristics in the cold flow of nonpremixed cases were first examined using acetone fluorescence technique, indicating substantial transport between the fuel and air by exhibiting appreciable premixing conditions. PIV measurements revealed that velocity gradients in the shear layers at the boundaries of the annular jets generate the turbulence, enhanced with the collisions in the interaction jet, IJ, region. Turbulent mean and rms velocities were influenced significantly by Re and high rms turbulent velocities are generated within the recirculation zone improving the flame stabilization in this burner. Premixed and non-premixed flames with high equivalence ratio were found to be more resistant to local extinction and exhibited a more corrugated and folded nature, particularly at high Re. For flames with low equivalence ratio, the processes of local quenching at IJ region and of re-ignition within merged jet region maintained these flames further downstream particularly for non-premixed methane flame, revealing a strong intermittency.

INTRODUCTION

For high Reynolds number (Re) flow in particular, stabilization of turbulent premixed and non-premixed flames is essential for the operation of high-intensity combustion systems, in such application as to gas turbines and industrial burners. The combustion characteristics of these flames have been studied extensively with regard to a stable operation of practical combustion systems and in order to improve understanding of turbulent flame structures. Simple jet flames with hydrogen and hydrocarbon fuels (Barlow et al., 2000) have been widely investigated as a canonical flow configuration; however, they are subjected to flame stabilization issues including liftoff and blowout at high Reynolds numbers (Choi & Chung, 2013; Chaudhuri et al., 2010). Flame structures and characteristics of piloted jet flames (Barlow et al., 2005), bluff body flames (Dally et al., 1998), and swirl flames (Masri et al., 2004) have been studied with improved flame stabilization to high fuel loading.

A new type of burner, 'curved wall-jet (CWJ) burner', has been proposed and tested for premixed flames exhibiting satisfactory flame stabilization characteristics (Gil et al., 1998). The burner utilized the Coanda effect (Gregory-Smith & Hawkins, 1991), as schematically shown in Fig. 1a. In the turbulent premixed flame study (Gil et al., 1998), a mixture of fuel/air was injected over a curved wall as a form of annular-inward jet. Due to the curvature of streamlines, a low-pressure region is generated, resulting in a wall-attachment of flow to the curved surface. As the static pressure recovers, the walljet separates to form a recirculation zone (RZ). The annular-inward jet collides over RZ in an interaction jet region, generating a high level of turbulence by the collision and ambient air entrainment, and subsequently develops as a merged jet in the downstream. Such burner resulted in improved flame stabilization and a short flame length. Kim et al. (2009) further improved flame stabilization by modifying the burner tip, introducing a concave cavity on the tip.

In the present study, the burner design was further modified to accommodate not only premixed but also a non-premixed fuel/air supply, the latter can suppress flashback for safe operation, while potentially maintaining the advantages of burning reactants under partially premixed conditions, short flame length, and the improved stabilization. For this, a double-slit configuration was adopted to supply fuel and air separately or their mixture for non-premixed and premixed combustion, respectively (see Fig. 1b). The fuel and air can mix along the curved wall before the non-premixed flame is stabilized in a recirculation zone. Rapid mixing between fuel/air layers could result in low sooting characteristics similar to premixed combustion situation. Simultaneous particle image velocimetry (PIV) and OH planar laser-induced fluorescence (PLIF) techniques were applied (Kohse-Höinghaus, 2002). Such techniques have been applied previously (Boxx et al., 2010; Han & Mungal, 2003) for better understanding of flame structure and turbulenceflame interaction. Acetone PLIF measurements were conducted to clarify the characteristics of qualitative fuel/air mixing under non-reactive flow conditions. Dynamic features of flame fronts are reported, including turbulence statistics, localized flame extinction and reignition, and flame-turbulence interaction, which can provide database for turbulent combustion modelling.



Figure 1. Schematic of flow field in CWJ burner (a) configuration of the douple slit CWJ burner (b).

EXPERIMENT AND DIAGNOSTICS Burner and Flames

The burner has a center body (cylinder with a diameter of 50 mm with a hemi-spherical tip) and two cylinders with curved-converging sections (see Fig. 1b). A concave spherical cavity with R56 mm was created on top of the hemi-sphere (3.37 mm in depth and 24 mm in width at the tip); such dimensions gave better flame stabilization compared with that in (Kim et al., 2009). The inner surfaces of the curved sections have an exit of 43 mm diameter, forming slits for the reactants, fuel, and air supplies as shown in Fig. 1b. For premixed flames, the reactants (R) mix together then are supplied to the burner through the inner slit while, for non-premixed flames, fuel (F) and air (A) are supplied separately through the inner and outer slits respectively as shown in Fig. 1b. The converging sections of the two cylinders guided reactants, fuel, and air tangentially to the curved wall of the center body toward the axis to form annular-inward jets.

Propane (>99.5%), methane (>99.995%) and air were supplied to the burner. Experiments were conducted by varying the flow rates as well as ϕ . Representative conditions are listed in Table 1, where V_0 is the exit velocity, \dot{m} is the mass flow rate, ϕ is the global equivalence ratio, and the subscripts in and out indicate inner and outer slits, respectively while a and f designate air and fuel respectively. PP1 represents propane turbulent premixed flame while MN1 indicates methane turbulent **n**on-premixed flame. The exit areas (A_0) of the slits are calculated from the normal projections from the tip of the inner cylinder to the center body and to the inner surface of the outer cylinder, these being 81 and 85 mm² for the inner and outer slits, respectively. Characteristic Reynolds number $Re=DeV_0/v$, is represented for reactants and air of premixed and non-premixed flames respectively, based on the effective diameter, $D_e = \sqrt{4A_0/\pi}$, and the kinematic viscosity v. Values of V_0 are based on the areas associated with the inner and outer slits for premixed and nonpremixed flames respectively as well as their flow rates. Near stoichiometric (flames MN1, MP1, PN1 and PP1) and rich (flames MN2, MP2, PN2 and PP2) mixtures were tested as previous studies (Gil et al., 1998; Kim et al., 2009) demonstrated that the premixed CWJ burner was more effective in flame stabilization with rich mixtures. This is because fuel/air mixtures are slightly diluted due to ambient air entrainment in the wall-jet region, before reaching a flame stabilization zone.

Table 1 Experimental	conditions
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Flame	<i>V</i> _{0,<i>in</i>} [m/s]	<i>V_{0,out}</i> [m/s]	Re	\dot{m}_a/\dot{m}_f	ϕ
MN1	1.46	12.35	8300	14.96	1.15
MN2	3.09	24.69	16600	10.75	1.60
MP1	13.90	0	9600	14.96	1.15
MP2	27.28	0	19730	10.75	1.60
PN1	0.75	13.17	8900	13.48	1.15
PN2	2.06	26.05	17520	9.69	1.60
PP1	13.90	0	9650	13.48	1.15
PP2	27.28	0	19320	9.69	1.60

Combustion Diagnostics

The PIV system consisted of a high-repetition rate (up to 10 kHz) twin-cavity diode-pumped Nd:YLF laser (Litron, LDY304-PIV; 527 nm, 28 mJ/pulse, 5 ns pulse duration) and a CMOS camera (LaVision, Imager Pro HS 4M; 2016×2016 pixels) coupled with a controller. Double-pulses with a time separation of 20-40 µs were repeated at 1 kHz. The laser output formed a sheet approximately 1 mm in thickness and 70 mm in height by a series of lenses.

Seed particles were titanium dioxide (TiO₂, nominal diameter 0.18 μ m) and the seed levels were adjusted for

spurious vectors to be less than 5% in the image processing. A perspective distortion from the camera system was calibrated by imaging a 3-D dot target (LaVision type 11). Velocity fields were determined through multi-pass vector computation software (Davis 8.1) with an interrogation size ranging from 128×128 to 32×32 pixels and 50% overlap, yielding a 0.76×0.76 mm² spatial resolution.

The high-speed PLIF system consisted of a diodepumped Nd:YAG laser (Edgewave, IS16II-E; 532 nm) and a dye laser (Sirah, Credo-Dye), whose output was frequency-doubled to 283.57 nm to excite $Q_1(8)$ line of A-X (1,0) OH transition with about 0.3 mJ/pulse at 10 kHz repetition rate. OH signals were detected at 295-345 nm with an intensified CMOS camera (LaVision, HSS8 and IRO; 1024×1024 pixels). Elastic scattering noise from the laser sheet and background noise were reduced by using a band-pass filter (>80% at 320 nm) and also by minimizing the intensifier gate time (200 ns). The spatial resolution was around 100 μ m/pixel.

An acetone PLIF technique was used to elucidate qualitative fuel/air mixing characteristics under nonreactive flow conditions (Kang et al., 2009). Acetone was seeded in the fuel slit by supplying air through a seeder at the same flow rate of fuel as in the reactive flow conditions. The seeder produces a mixture of air and acetone vapor with approximately 25% by volume based on the saturation temperature of the acetone (20°C) (Bryant et al., 2000). Acetone was excited with the same laser for OH-PLIF (Edgewave, IS16II-E and a dye laser) and a band-pass filter (>75% at 410 nm) was used to detect the acetone signal at 380-480 nm with the same intensified CMOS camera. The acetone PLIF signals were measured near the fuel slit region toward the downstream. The intensity of acetone PLIF signal at the fuel slit exit was used as a reference in determining 2D mixture fraction distribution.

RESULTS AND DISCUSSION Flow Field Characteristics

Flow field was measured with the PIV setup. A cylindrical coordinate system is adopted in representing data with (r,z) in the radial and axial coordinates, respectively, with z=0 at the tip of the cavity (see Fig. 1b). Data collected from 1500 images were analyzed and the mean velocities (V_r, V_z) and rms velocities (V_r', V_z') were determined in the radial and axial coordinates, respectively. The spatial distributions of (V_r, V_z) are shown in Fig. 2, together with color-coded magnitudes of the mean velocity (V) for flames PP2 (lift) and PN2 (right).

The flow field consists of a recirculation zone (RZ), an interaction jet (IJ) region with the collision of the annular-inward jets near z=10 mm, and a downstream merged jet (MJ) region. Inner and outer shear layers (ISL and OSL), surrounding the annular-inward jets (AJ) can also be identified. As can be seen in Fig. 2, values of V exhibit higher values in premixed flames (PP2) but nonpremixed flames reveal slight lower values. This is attributed partially to the heat release effect and the impact of the annular-jet toward the curved wall. The latter is less dominant in premixed flames as the inner surface of the jet contacts the wall directly. Also, the annular jet of the non-premixed flames (PN2) extends more radially than the corresponding premixed flames (PP2) as clearly shown in Fig. 2.

The axial (at r=0) profiles of the mean velocities are plotted in Fig. 3 for (a) premixed and (b) non-premixed flames listed in Table 1. The recirculation zone (RZ) is clearly exhibited by V_z , having negative values for 0<z<6 mm, which approaches -12 m/s (case PP2). In the interaction jet region (IJ), V_z increases rapidly and then maintains near uniform values to z=60 mm in the merged jet region (MJ). Values of V_z increase with Re and they exhibit higher values in premixed flames compared with the corresponding non-premixed flames. Propane turbulent premixed flame (PP2) shows higher values of V_z than the methane premixed flame (MP2). This is attributed to the intermittent propagation of methane flame fronts that is confirmed by OH images. Also, propane flames have higher heat release rate than methane flames. This is not the case for non-premixed flames as these flames reveal comparable values of V_z .



Figure 2. Spatial distribution of mean velocity fields with color-coded magnitude V for flames PP2 (lift) and PN2 (right).

The axial profiles of rms turbulent velocities, $u' = \sqrt{(V_r'^2 + V_z'^2)}$, are shown in Fig. 4 for (a) premixed and (b) non-premixed flames listed in Table 1. Values of u' have large values in RZ peaking in the interaction jet region, and maintains reasonably uniform low values in the merged jet region for the investigated premixed and non-premixed flames. The higher the Re, the higher the level of turbulence particularly within the RZ and IJ region, resulting from the formed shear layers due to a significant velocity gradient. Also, these results indicate that the collision of annular-inward jet near the boundaries of RZ influences relatively the generated turbulence.

These rms velocities are significantly expected to be influenced by the heat release when reacting and nonreacting flows are compared (Hartung et al., 2008).



Figure 3. Axial profiles of axial mean velocities (V_z) for premixed (a) and nonpremixed (b) flames.



Figure 4. Axial profiles of rms turbulent velocity (\boldsymbol{u}') for premixed (a) and nonpremixed (b) flames.

Mixing characteristics in non-reacting flow

An appreciable mixing between fuel and air streams along the curved wall is expected for the present nonpremixed CWJ-burner although they have a relatively short curved distance to mix before entering the cavity zone. In this regard, acetone PLIF measurements were conducted to elucidate such mixing characteristics along the curved wall and recirculation zone. Due to limitations of acetone decomposition at high temperature, cold flow conditions of the cases N2 and P2 were tested for nonpremixed and premixed flames respectively. Figure 5 shows the spatial distribution of instantaneous acetone signals (a,b) and the radial profiles of the mass fraction at three different axial position namely A, B, and C (c) for the conditions that simulate flames N2 (a) and P2 (b).

The images show the hydrodynamic characteristics of the Coanda effect. They clearly exhibit that the acetone (fuel) and air streams are wall-attached to the hemispherical curved-wall surface. Between the fuel and air streams, intense mixing and shear layers are formed due to concentration and velocity gradients. The flow separation occurs near the cavity region. The instantaneous images demonstrate large-scale structures in the mixing layers, enhancing turbulent transport.

The radial distributions of the mass fraction (Fig. 5c) show comparable trends for the premixed (dashed curve) and non-premixed (solid curve) cases. Similar profiles along the curved wall were measured for premixed and

non-premixed cases; however, the premixed case reveals slight higher values downstream. Non-premixed case shows high dispersion of mixtures as the mass fraction is highly fluctuated.

The results indicate that the proposed double-slit configuration enhances the fuel/air mixing appreciably before reaching the recirculation zone for flame stabilization and the downstream interaction jet region, implying that the fuel/air can be burnt under partially premixed conditions despite they are supplied separately to the burner. The mixing characteristics could be influenced with flame through thermal expansion and buoyancy induced flow entrainment. The rapid mixing behaviour of the fuel and air in the present double-slit CWJ burner support the non-sooting flame behaviour.



Figure 5. Typical instantaneous images of acetone PLIF for non-reacting flows in typical conditions of flames N2 (a) and P2 (b) respectively and thier radial profiles (c) at three different axial positions, A, B and C.

Flame Front Structure

The fast, 10 kHz, OH-PLIF system was employed to give insights on various dynamics of turbulent premixed and non-premixed flames as well as to investigate the temporal behaviour of these flames. Typical instantaneous images of OH are shown in Figs. 6 and 7 for premixed and non-premixed flames respectively revealing the existence of a recirculation zone upstream at the concave cavity followed by, for premixed flames, thin neck at the interaction jet region and then the highest OH signal zone further downstream. By inspecting these figures, we can derive the following features: (1) the recirculation zone is somewhat clear and confined within the burner tip for propane flames (PP2, MP2, and PN2) however, flame MN2 reveals no clear RZ destabilizing such flame; (2) the production of OH radical in the interaction jet region is

appreciably influenced in methane non-premixed flames (MN1 and MN2) where OH intensity is low while a broadening zone of relatively higher OH intensity is observed in propane non-premixed flames (PN1 and PN2); (3) the reaction sheets distribute predominantly downstream in the merged jet region in low Re flames, however, in high Re premixed and non-premixed flames, the reactions take place further downstream within many isolated pockets associated with high OH signals; Such trend is more pronounced in methane flames (MP2 and MN2); (4) the influence of ambient air entrainment is apparent in flames (PN2 and PP2) (high Re) as the high OH intensity extends spatially in the r direction. Such trend is not observed for low Re flames (e.g. MP1, PP1); (5) these images imply that the downstream part of the flame front is maintained by small flame elements detached from RZ, and its wrinkleness depends on the nature of the flame seeds, emerging from the RZ.



Figure 6. Snap shots of OH-PLIF images for premixed flames showing the flame structure.

Flame Extinction and reignition

Flame quenching/re-ignition behaviour, as one of the flame dynamic features, can be further elucidated from the high-speed OH-PLIF images that are shown in Figs. 8 and 9 for flames PP2 and PN2 respectively. Frequent events of local flame extinction are observed at the interaction jet region which is confirmed by conducting horizontal laser sheet measurements (not shown). Some flame kernels that initiated in the recirculation zone are detached at the interaction jet region and convected downstream toward the merged-jet region. As they encounter a favourable combustion environment, these kernels induce a reignition process further downstream as shown in Fig. 6 for flame MP2 with white circle. OH images of flames PP2 and PN2 exhibit more disconnected and patchy OH distributions (island structures) downstream as its Re is high and consequently more energetic eddies are exist. This results in existence of zones without OH as shown in flame MN2. It is also observed the sudden appearance and disappearance of OH pockets downstream marked by red circles in flames PP2 and PN2 as an indicative of whether out-of-plane advection or auto-ignition of hot unburned gases conveted towards these locations. For non-premixed methane flames of high Re, quenching and re-ignition are likely to exhibit a high level of intermittency. Such flame intermittent occurred significantly at IJ is manifested by the high values of u' that strengthens the strain rate.



Figure 7. Snap shots of OH-PLIF images for nonpremixed flames showing the flame structure.

Flame fronts in flames PP2 and PN2 exhibit higher wrinkling degree and corrugation due to the energetic eddies (high Re) and low Markstien number (high ϕ) (Tseng et al., 1993). Accordingly long protruding flamelets contract and burn out as marked by white dashed circles in Figs. 6 and 7. These flamelets might merge reducing the wrinkled flame front area and consequently burning rate (Bradley et al., 2011).



Figure 8. Time sequence of instantaneous OH-PLIF images measured in flame PP2, $\Delta T=0.2$ ms.

For high Re flames, the instantaneous flame structure is very different and also changes significantly over time as shown in Figs. 8 and 9 for flames PP2 and PN2 respectively. The reaction zone is highly contorted, with significant changes in the instantaneous flame structure; this is associated with the fragmentation of the reaction zone. The temporal evolution of the convective flame seeds in the RZ and MJ region are shown with red and white lines respectively in Fig. 8. It is unlikely to keep a propagated flame front within the IJ region as these flame seeds are exposed to high strain rate.



Figure 9. Time sequence of instantaneous OH-PLIF images measured in flame PN2, ΔT =0.2 ms.

CONCLUSION

A double-slit curved-wall jet burner was employed to investigate the stabilization characteristics and structure of methane/air, and propane/air turbulent premixed and nonpremixed flames with varying equivalence ratio and Reynolds number. High speed OH-PLIF delineated reaction zone contours and simultaneously PIV quantified the flow field features. Such burner showed reasonable (significant) stable operation for methane (propane) flames with relatively large fuel loading, depicting overall rich conditions. The fuel/air mixing field was investigated using acetone PLIF technique, exhibiting appreciable mixing between the reactants along the curved-wall surface and further downstream in RZ, IJ and MJ regions. PIV measurements revealed that the flow field consisted of a wall-jet region leading to a recirculation zone through flow separation, an interaction jet region, followed by a merged-jet region. Velocity gradients in the shear layers at the boundaries of the annular jets generate the turbulence that is enhanced with jet collisions near IJ region. Turbulent mean and rms velocities were influenced significantly by Re and premixed flames exhibit higher values than non-premixed flames. OH images showed that propane flame fronts were found to be more resistant to local extinction and exhibited a less wrinkling degree for low Re. However, local quenching and re-ignition processes were likely for methane non-premixed and all high Re flames, revealing a strong intermittency, which increases with Re. These flames, at these extreme conditions, exhibited a more corrugated and folded nature.

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