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A comparative study of the port geometrical effects on sharp corners' jet triple flames

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ABSTRACT

The performance of sharp corners' jet triple flames was modulated by compromising the increase in both the number of sharp corners between 3 and 16 and the overall perimeter up to 218% with the reduction in vertex angle to 30°. While the turbulent kinetic energy peak value correlated with the vertex angle and its average value depended on the number of corners, the entrainment rate gain was pronounced in accordance with the perimeter. By having each port stabilizing the inner flame wing such that the sharp corners lay on the diffusion flame envelope at its base, the flow strain due to corners increased the triple flame stability limit to a maximum of 9.2 m/s and minimized the NO_x emissions to 14 ppm. Upon incorporating the swirl impact, the highest firing rate was reached at a jet velocity of 26.3 m/s at which excessive entrainment of reactants into corners provided a compact flame with a firing intensity of 50.3 MJ/m^3. While the flame length was related to the extent of jet deformation from the circular shape, a flame shortening by 67% was verified by an enhancement of 192% over the circular port entrainment rate. Improved combustion efficiencies with respective decrease in CO and HC emissions to 61 ppm and 0.04% were reported by maximizing the effect of sharp edged appendices. The swirl introduced a favorable advection transport, whereby the turbulence peaks at corners merged to provide a relative increase of 11.8 times in the average turbulence energy. By effectively combining the active and passive control techniques via providing swirl and modulating the port geometry, the lean operation limit extended by 19% from that of the circular port whereby NO_x emissions for triple flames case II had a minimum of 4 ppm.

1. Introduction

Extensive research has been commissioned to employ non-traditional combustor designs with unconventional firing techniques involving turbulence modulation to be the prime key factor for the optimum performance. A dramatic gain in the combustion efficiency is subsequently acquired in combination with reduced NO_x emissions, both at extensive flame stability limits. Regarding such challenging compromise, there are still favorable impacts that can be additionally stimulated by various passive and active combustion control techniques which further enrich the turbulence/combustion interaction scenarios. In this sense, sharp corner ports have recently been testified to be attractive burner configurations by their favorable turbulent flow features pronounced at each corner boundary layer interface (where turbulence evolves via augmenting the shearing stresses). Reactive flow modulation in relevance to such port flow fields thus provides stabilized/efficient combustion.

Earlier studies of square and triangular jets showed that they significantly increase the small scale turbulence intensity at the corners whereas large scale vortices are sustained at the flat sides [1]. The small scale turbulence is a consequence of small vortices formed inside the nozzle corners due to the jet shearing around the corner across a limited zone, while there is a more space at the flat sides to pronounce larger vortices. The subsequent strain across the shear layers is thus manifested by both large scale coherence and finer scale velocity fluctuations [2]. For a diffusion flame jet, combustion at the flat segments becomes confined in those periodic large scale structures while reactions at the corners occur in randomly disturbed small flamelets [3]. The co-existence of such different scale structures is advantageous; since enhanced fine scale mixing at a corner makes it the best location for ignition (where less cool air is entrained), while large scale mixing on flat sides provides the air necessary to sustain combustion.

The evolution of square and triangular jets is characterized by differential shear-layer growth rates at the flat and vertex sections (as different momentum thicknesses exist), where the different spreading rates lead to axis switching [4]. In this case, as the jet develops downstream the differential growth rates pass through possible cross-over points at which the jet dimensions on the two axes are equal. Its cross-section thus regularly evolves through similar shapes with the axes successively rotated at angles characteristic of the jet geometry. Quinn [5] stated that the cross-over

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location varied from 3 to 7 times the jet equivalent diameter. The differences in the nozzle profile (having been either an orifice- or a contoured-nozzle) yield a different distribution of the initial shear layer thickness. The highest mixing rate and fluctuation in velocities occur in the orifice plate jet (where the stream-wise velocity profile is saddle-backed), as the jet width at the major axis plane is initially reduced for the orifice jet due to the vena contracta effect [6]. The momentum transport across the jet is considerably enhanced by hairpin vortices aligned with the corners [7].

There is a consequent enhancement in the mass entrainment due to such axis switching mechanism as reported by Vandsburger and Ding [8], where the triangular cross sections were found to have superior emission performance due to the small scale turbulence enhancement [9]. This can be explained by the results of Gutmark et al. [10], who stated that the differential thickness of the shear layer initially emanating from the flat sides increase with reducing their corner angle (from a thickness ratio of 1.5 for the 90°Corner to 2.9 for the 30°Corner). In the work of Phillips and Birouk [11], the triangular port had the best flame stability (with the highest air blow-out velocities); where the flame lift-off height decreases as the jet entrainment increases [12]. The isosceles triangular jets were concluded by Miller et al. [13] and Mi et al. [14] to have the best mixing enhancement characteristics as flow structures with counter-rotating vortex pairs were seen initially aligned with the corners, thus testifying to faster mixing [15].

Through more recent studies, the fluid dynamics/mixing characteristics of sharp corners were highlighted by Quinn [16], who stated that coherent structures exist in the near field mixing of both isosceles and equilateral triangles thus enlarging the velocity decay rate relative to round jets. The turbulence develops in the shear layers emanating from the flat sides and gets transported by diffusion to the jet centerline while it moves downstream by convection.

Parallel to those documented works, Baird and Gollahalli [17] stated that stretching the burner port cross-section (as a passive control technique) increases efficiency and reduces emissions as the focusing of active species is modulated by the flame curvature. Since this target was first devoted to diffusion flames, little work has been done to reveal the effects of the various sharp corner geometries on premixed flames (even at partial levels of premixing). Among few studies that coupled partially premixed flames with sharp corners, Gollahalli and Subba [9] showed that triangular ports increase air entrainment by 30%, decrease NO_x emissions by 15% and increase CO emissions by 20%. More works should examine the elimination of such CO concentrations found in their work by providing more intensive combustion as well as more homogenous temperatures to prevent CO_2 dissociation and further reduce NO_x emissions. In addition, few studies were carried out on co-axial sharp corners' ports whose enhanced mixing features were reported for co-axial square jets [18,19]; where they had an experimental evidence of axis-switching for both the inner and outer jets. In this regard, straining the flow that concentrically surrounds the sharp corners' jet becomes a favorable feature to enrich researches on both premixed and non-premixed flames.

There is also still further work to be done on other multiple sharp corner shapes that have more corners to reveal their increasing role as turbulence centers for intensifying entrainment into axisymmetric shapes. Strengthening the disturbance propagation is currently proposed by optimizing the geometrical parameters of the single port sharp corner jets (including the number of vertices, the vertex angle and the perimeter). The turbulence thus develops faster and is amplified by the flat sides where large scale structures prevail. Furthermore, more favorable turbulence effects may be acquired by intensifying the velocity gradients via a swirling-flow arrangement around the sharp corners' port. In this case, high shearing stresses develop at corners and become augmented by the flow strain due to swirl. The swirl intensifies the turbulent kinetic energy originally developing at corners and the extent of intensification depends on how close the turbulence centers circumferentially exist relative to each other. The strain peak value is still a function of the vertex angle.

Regarding the relevant aerodynamic aspects, previous researches were conducted on cross-flow circular jets onto co-flow streams to promote the flame stability, where the flow recirculation into the wake region induces shear layer vortices [20]. At such conditions, intense shear is produced by large scale mixing and strong entrainment of reactants exists for more efficient combustion [21]. The couple between cross flow (as a tool for active control) and sharp corners was recognized very recently [22]. Such couple is currently recalled by the transport of turbulent kinetic energy between sharp corners via the action of swirl.

Seeking for innovative firing configurations, triple flames (which combine premixed and non-premixed flames) have recently been addressed as industrial flames that exhibit the stability characteristics revealed when they were tested as a model for lifted flames. In this sense, Chung and Lee [23] revealed the features of mixing rich and lean fuel/air pockets in lifted flames to involve a triple flame structure that combines two premixed flame wings and a non-premixed flame zone. Later, Elgamal et al. [24] addressed the features of swirling triple flames as a target for industrial furnaces. It follows that the triple flames can acquire the features of maximizing the reaction rates by sharp corners (for premixed flames) in addition to enhancing the entrainment/shearing effects by sharp corners and swirl (for non-premixed flame).

Accordingly, there is still a room for investigating turbulence/combustion interaction by employing a swirling-flow as an active control technique in conjunction with the geometry passive control. Both premixed and non-premixed flames are thought to reveal more favorable features with sharp corners in the triple flame fashion. In this case, combining the sharp corners with the swirling flow contributes to straining the premixed flame reaction zone and eliminating the HC emissions of the non-premixed flame envelope. Furthermore, as shorter residence times prevail across the premixed flame sheet at higher sustainable firing rates (in addition to the locally reduced temperature peaks by turbulence in the non-premixed flame zone); the NO_x emissions are reduced [25].

The active/passive control couple thus provides the flame performance modulation. Inasmuch as the ignition kinetics will be sensitive to such scenario dictated by the turbulence intensification and the flame stretch at corners, the flame stability limits are extended further. The higher combustion intensities across the sustained reaction zones will provide a potential merit for acquiring higher combustion efficiencies and minimized NO_x/unburned constituent emissions. The current work objective is thus to control the maximum and average turbulence intensities pertaining to different port geometries.

2. Experimental test rig and layout

The test rig layout is shown in Fig. 1a (mainly comprising the fuel cylinder (1), the air blower (2), the set of flow measuring orifices such as the one denoted by (7) as well as the combustor section (12)). The air issues from the blower exit pipe and a portion that is regulated by the valve (5) goes directly through the pipe (8) to the combustor where it is tangentially introduced through the elbow (10). The other portion is split by the T-fitting (19) into separately controlled air quantities that provide the oxidizing streams for the triple flame wings at the swirl burner (11). The fuel streams for the two mixtures flowing through the pipes (9) and (14) are provided by the common line (3) before it is divided by the connection (20) to reach the premixing tubes (15) and (16).