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Research Paper

Optimization of stepped conical swirler with multiple jets for pre-mixed turbulent swirl flames

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HIGHLIGHTS

- A new swirler for pre-mixed turbulent swirl flame is presented.
- Swirl stepped conical plate with multiple jets is designed and optimized.
- Three dimensional numerical simulation and experimental studies are conducted.
- Jet angle 10° and 15° give uniform temperature and lowest pressure drop.

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ABSTRACT

In the following numerical simulations and experimental work had been used to optimize a new stepped conical swirler that used in lean pre-mixed combustion process. Three dimensional computational models were built-up to solve the swirling reacting flow and experimental setup was used to validate this model. Several jet swirl angles were studied so that the developed flow structure varied as a consequence of changing the swirler geometry. New swirl flow structures were identified and analyzed. The velocity and temperature distribution after the swirl plate were presented for jet angles changed from 0° to 25° with step equal to 5°. The numerical model results give good agreement with the experimental results. Well defined large swirl structures were shown by results and it is highly depend on the jet swirl angle. The conclusion is that the jet swirl angles have a big effect not only on the temperature distribution but also on the pressure drop across the swirler. The Swirl plat with jet angle from 10° to 15° gives the most uniform temperature distribution and also the minimum pressure drop across the swirler.

1. Introduction

Swirl flame stability and combustion characteristic are a topic of major interest for many practical devices such as domestic boilers and gas turbine combustors. In many systems, the flame is anchored by hot gases which in some cases form the core of a swirl flow that generated by an aerodynamic injector. In other cases the flame is anchored using hot products which are recirculated in the wake of a bluff body. The stable flame takes an inverted conical shape, and the flame-front is subjected to wrinkling and straining by large scale eddies. The tip of flame moves freely in the flow field and it is therefore more susceptible to perturbations. Extensive studies have been conducted on combustors with swirling flows [1,2] with high concentration on their three-dimensional characteristics and methodology for flame holding [3–5]. Radhakrishnan et al. [6] performed an experimental analysis on a constant cross-sectional area tubular combustor. It was reported that the length of the recirculation zone downstream of a flame holder is a more appropriate length scale for defining the flame stability characteristics than its geometric size, although the latter is a more easily measurable quantity. An experimental study was offered by El-Mahalawy et al. [7] to investigate the stability characteristics of free diffusion flames produced by the injection of gaseous fuel into center of a reverse flow zone formed by a bluff body which is placed in the air stream at a burner mouth. The results showed the diminished effect of cone angle of bluff body on the extinction values. This result leaves the area blocked to be solely dominant geometrical factor affecting stability performance.

Schefer [8] studied a method for detecting and preventing lean blowout in a pre-mixed swirl stabilized combustor was stated by Prakash et al. [9]. They also stated that splitting the total fuel

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Nomenclature

Φ	equivalence ratio
Q_f	fuel volume flow rate
h_a	difference between height of total and static pressure in manometer
V_a	air velocity
Sc_t	turbulent Schmidt number,
μ_t	turbulent viscosity
D_t	turbulent diffusivity
Y_P	mass fraction of any product species
Y_R	mass fraction of a particular reactant
A	empirical constant equal to 4.0
B	empirical constant equal to 0.5

Abbreviations

CFD	computational fluid dynamic
C.C	combustion chamber

between swirling, pre-mixed and an annulus central pre-mixed pilot could improve safety margin by shifting Φ lean blow out to leaner values. Mixture fraction and reaction zone behavior have been measured to investigate the stability characteristics of partially premixed turbulent lifted methane flames [10]. The data showed that the mixture fraction field on approaching the stabilization region was uniquely characterized by a certain level of mean and Root Mean Square (RMS) fluctuations. This suggests that the stabilization mechanism was likely to be controlled by premixed flame propagation at the stabilization region. Triple flame structure was detected in the flames, which was likely to be the appropriate model at the stabilization point. For reacting swirling flows, the recirculation region disappeared and only a small negative axial velocity region was formed near the fuel injection ports. The flame was stabilized inside the combustor because of the flame base was anchored near the negative axial velocity region close to fuel injection ports. This is a result of experimentally and numerically study of Choi et al. [11]. The soot characteristics of the center body burner could be altered dramatically via simple changes in the operating conditions. One of interesting operating regimes in which a flame lifts off and forms a column of soot was identified when oxygen in the annulus air jet was reduced sufficiently. Soot that was transported into the recirculation zoon (RZs) was found to have a significant effect on the flame lift-off height. Katta et al. [12] they also found numerically that the radiation from the soot decreases the temperature, slows the auto ignition process, and increases the lift-off height. This also is the same contribution if the soot oxidation through O and OH radicals is considered.

The flame stabilization mechanism and the conditions leading to blow off of a laminar pre-mixed flame were studied downstream of a heat-conducting perforated-plate/multi-hole burner. Also a two dimensional simulation with detailed chemical kinetics and species transport for methane-air combustion were performed by Kushal S. Kedia et al. [13]. The results showed a bell-shaped flame stabilized above the burner plate hole, with a U-shaped section anchored between neighboring holes. A comprehensive survey of flame pattern behavior was presented by Vanoverberghe et al. [14]. They identified five different flame states among which four of them are suitable in various domestic and industrial applications. The study has proved that proper settings of swirl and premixing degree can be retained as predominant factors in the setup and transition between different flame states. Ruggles et al. [15] studied the behavior of three very different flame and flow structures within an atmospheric swirl-stabilized dump combustor. The interaction between the flame and the internal recirculation zone of the vortex breakdown was determined to be responsible for differences observed in behavior at the three forcing frequencies. Vorticity within the shear layers was found to be the source of harmonic frequency generation of the imposed perturbation frequencies. The data is presented in detail to facilitate CFD model comparisons, particularly LES. A lean partially premixed swirling combustor was studied numerically by Li et al. [16]; the swirl flow by vanes is resolved with large-eddy simulation (LES). The flow and combustion dynamics for non-reacting and reacting situations was analyzed, where the intrinsic effects of swirl vanes and counter flows on the vortex formation, vorticity distribution for non-reacting cases were examined.

Day et al. [17] presented simulations of laboratory-scale Low Swirl Burner (LSB) flames in order to develop a characterization of the interaction of thermal/diffusive unstable flames with turbulence at the correct scales of laboratory experiments. An integrated measure of consumption along the path lines was shown to serve as a generalized analog of the Eulerian-computed consumption-based burning speed. The diffusive fuel flux divergence along the path lines was shown to correlate directly with integrated consumption rate. Insights gained through the Lagrangian diagnostic analysis served as the underpinning of a new procedure to interpret OH-PLIF images from the LSB experiment. Bourgouin et al. [18] investigated the sensitivity of the mean flow field and unsteady structures to small changes in the swirler design. Numerical simulation based on Large Eddy Simulations and experimental work is used to study two different radial swirlers. The mean velocity is changed as a result of the geometrical difference especially at the injection area. The structure of the recirculation zones is modified and its effect on the precessing vortex core is then explored with the numerical results. Eldrainy et al. [19] presented a variable blade swirler configuration for gas turbine combustors and industrial burners. The flow dynamics downstream the swirler was explored using Large Eddy Simulation (LES). Two Reynolds-averaged Navier Stokes (RANS) simulation cases utilizing the standard and realizable k–ε turbulence models were also conducted for two objectives. The results show that the counter-rotating configuration produces higher turbulence kinetic energy and more compact recirculation zone compared to the co-rotating configuration.

Fan et al. [20] developed a micro-combustor with a bluff body; the dimension effect of the bluff body on the blow-off limit was investigated with a detailed H_2/O_2 reaction mechanism. Wan et al. [21] investigated numerically hydrogen combustion characteristics in a micro-combustor with wall cavities. Operating and geometrical parameters of the cavities are studied. The flame-splitting limit is calculated at different velocities and length/depth ratio of the cavity. Micro-combustor with a triangular bluff body was developed by Fan et al. [22]. The effect of bluff body shape on the blow-off limit was investigated. The results show that the blow-off limits for the triangular and semicircular bluff bodies are 36 and 43 m/s respectively. The triangular bluff body has a smaller blow-off limit because of the stronger flame stretching as compared with the semicircular case. Wan et al. [23] investigated experimentally the behavior of premixed CH_4/air flame in mesoscale channels with and without cavities. Numerical simulation