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Experimental investigation of the effect of fuel nozzle geometry on the stability of a swirling non-premixed methane flame

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ABSTRACT

An experimental investigation on the stability of a swirling non-premixed methane flame is reported in this paper. Methane gas is supplied through a central nozzle, and combustion (co-flow) air is supplied through an annulus surrounding the nozzle. Two main parameters were varied independently, which are the nozzle geometry and swirl strength; however the exit velocity of the central (fuel nozzle) jet and co-airflow were also varied to provide a wide range of test conditions. Two nozzles were tested: a contracted circular (referred to hereafter as CCN) and a rectangular (referred to hereafter as RN), which have similar equivalent diameter, D_e (defined as the diameter of a round slot having the same exit area as the nozzle geometry). The contracted circular nozzle has a diameter of 4.82 mm, and the rectangular nozzle has a diameter of 4.71 with an aspect ratio of 2:1. The swirl strength of the co-flow was varied by changing the vanes' angle. The main results obtained from this study show that the rectangular nozzle exhibits higher entrainment and jet spreading rates compared with its CCN counterpart. In addition, the results revealed that increasing the swirl strength creates a flow recirculation zone which is larger with the RN compared with that of the corresponding CCN. These flow features associated with the RN lead to an enhanced mixing which consequently promotes better flame stability compared with its CCN counterpart.

1. Introduction

Stability of jet (diffusion) flames without co-flow is better understood than jet flames with co-flow, as evidenced by the large amount of published work which has resulted in, for example, several correlations intended to describe some of the jet flame stability aspects such as liftoff height, flame length, and blowout velocity (e.g., [1–3] to cite only a few). Introducing co-airflow to a jet flame would change the whole dynamics of the flowfield and thereby makes the control of the resulting flow more complicated. The effect of co-flow and in particular swirling co-flow on the stability of a diffusion flame has also been studied quite extensively but it is still relatively less understood due to the additional complexity caused by the presence of swirl. The extensive research carried out on swirling flames is mainly driven by their practical application in several engineering power systems such as gas turbine combustors and industrial furnaces.

Most published studies of swirling flames agree that swirl enhances flame stability by generating a recirculating vortex, which then controls the size and shape of the flame, and enhances combustion intensity (e.g., [4–12]). For instance, several studies in the literature reported that there is a strong correlation between swirling flame stability and mixing. For example, Sheen et al. [7] noted that swirl increases the rate of fluid entrainment and mixing. This is a confirmation of the results of Panda and McLaughlin [13] who found that spreading and mass entrainment rates increase for swirling jets compared with non-swirling jets. Syred and Beer [4] and Wu and Fricker [6] reported that swirl strength influences the growth rate of the size and strength of the recirculation zone. Recently, Garcia-Villalba et al. [14] examined swirl-generated coherent structures and their growth in the near-field of an annular swirling jet using Large Eddy Simulation (LES).

Moreover, published results (e.g., [15–18]) showed that the presence of a swirl results in a rapid rate of mixing between the fuel and oxidant which significantly reduces the flame temperature well below that of the adiabatic equilibrium at the upstream end of the recirculation zone, and hence lowers NO_x formation, as well causes an increase in the flame stability limits. Olivani et al. [19] also reported that pollutant emission, including NO_x, can be reduced through mixing induced by swirl-generating vortices.

It has also been established that swirl affects both the longitudinal and azimuthal instability modes leading to a modification of the combustion dynamics (Paschereit et al. [20]). As a result of the knowledge of the importance of large scale structures as

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drivers of combustion instabilities, several published studies examined both passive and active means to control the vortical motion (e.g., Coats [5], Cala et al. [21], Schadow and Gutmark [22]). The active means of controlling vortical motion used in the literatures are largely acoustic excitation while passive means are, for example, the use of tabs or the use of asymmetric nozzles (e.g., Schadow and Gutmark [22]). Note that depending on the initial velocity profile of a jet, coherent structures may be produced. For example, it is well understood that a fully developed pipe flow may be unstable to a narrow range of low-frequency Kelvin–Helmholz instability modes and may not produce coherent structures while other geometries that are only unstable to a broader spectrum of much higher-frequency modes almost always produce coherent structures (e.g., Coats [5]).

In a recent investigation, Iyogun and Birouk [23] used passive means of generating coherent structures to assess its impact on the stability of a swirling turbulent non-premixed methane flame. The study ([23]) examined flame length, liftoff velocity, liftoff height, and blowout velocity as a function of swirl strength, S; co-flow exit velocity, U_a; jet exit velocity, U_j; and more importantly fuel nozzle geometry. It was found that the rectangular nozzle (RN) generates a significantly more stable flame than its contracted circular nozzle (CCN) counterpart. That is, the blowout velocity of the RN swirling methane diffusion flame is higher than that of the CCN for identical test conditions, and all the liftoff velocity, liftoff height, and flame length are lower (though not to the same extent) than those of the corresponding contracted circular nozzle flame. These observations clearly indicate that asymmetric fuel nozzle has an impact on the stability of swirling non-premixed flame. More importantly, the blowout velocity of the RN flame seemed to increase as the co-flow swirl strength increases.

The present study is an extension of the authors' previous work [23] to shed more light on how non-symmetric fuel nozzle impacts the resulting swirling non-premixed flame. To do so, additional new experimental data were presented here to help explain the impact of nozzle geometry on swirling flame stability.

2. Experimental set-up and test conditions

Fig. 1a depicts a schematic diagram of the burner. The complete experimental test rig consists mainly of a burner (shown in Fig. 1a), and a flow control panel and a seeding system (not shown here). The burner consists of a central fuel nozzle surrounded by an annulus (called also here co-flow) of air which passes through the swirl generator vanes before exiting the burner. A schematic diagram of a swirl generator is presented in Figs. 1b and 1c.

The central jet was either methane gas (99% purity) supplied from a compressed methane cylinder (for examining reacting flow) or air (for examining non-reacting flow) supplied from a laboratory compressed air line. The desired flowrates of the methane gas and air were measured via flowmeters in which the flowrate measured was based on the flow delivery pressure and the flowmeter's reading. The delivery pressure was 40 PSIG and 30 PSIG for the central jet and co-airflow, respectively. Matheson rotameter for the central nozzle jet (methane or air) was calibrated at atmospheric pressure, while Brooks Instrument flowmeter and Cole–Parmer Flowmeter used for the co-airflow were calibrated at 30 PSIG and atmospheric pressure, respectively. Consequently, a correction factor was used when running at higher pressures, which is given as $Q_{act} = Q_{read}\sqrt{P_{act}/P_{atm}}$, where Q_{act} is the actual flow rate, Q_{read} is the flowrate read from the flowmeter, P_{act} is the pressure at the inlet of the flowmeter and P_{atm} the room atmospheric pressure. The exit velocities quoted in the present paper were based on readings from flowmeters and the exit cross-sectional areas. Matheson rotameter used for the central nozzle (methane or air), has a full-scale accuracy of ±5%.

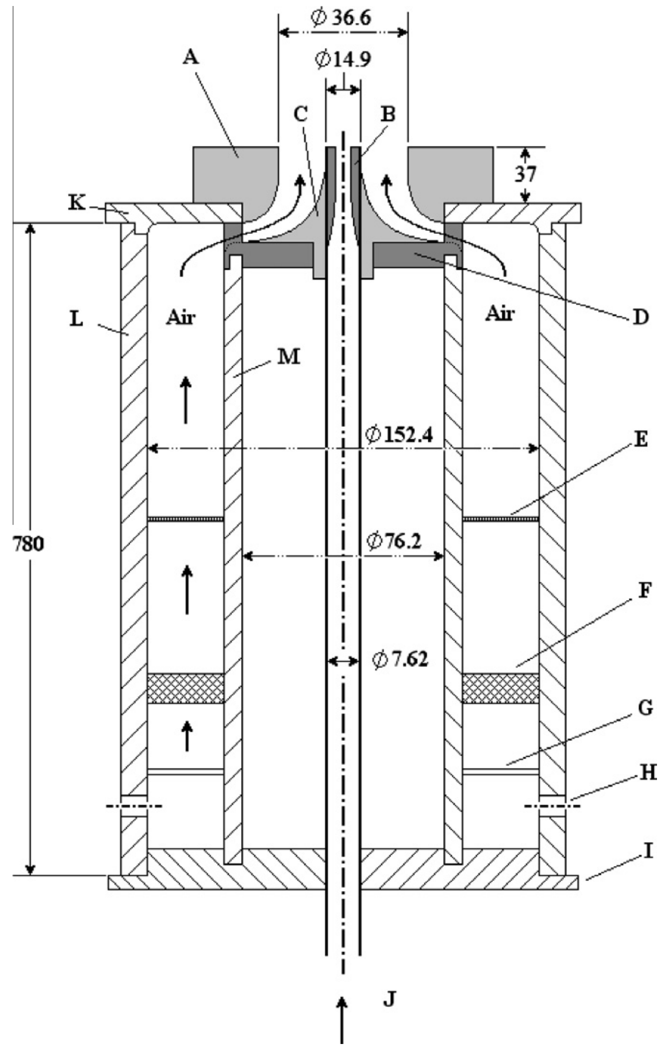

Fig. 1a. Schematic diagram of burner set-up (all dimensions are in mm). A – swirl pipe, B – nozzle, C – nozzle holder, D – vane swirl generator, E – fine screen, F – honeycomb, G – coarse screen, H – four equally-spaced tangential air ports, I – bottom plate, J – methane (or air for non-reacting experiments), K – top plate, L – outer chamber, and M – inner chamber.

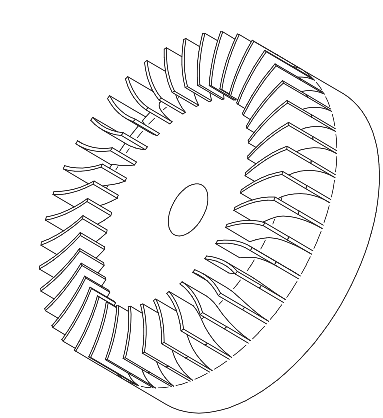

Fig. 1b. Schematic diagram of a typical swirl generator.

For the reacting flow experiment, methane gas supplied from a compressed cylinder flows through a settling chamber (not shown in Fig. 1), where it mixes with seeding particles of titanium oxide having an average diameter of 0.2 μm. It is then conveyed through