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Investigation of the effects of quarl and initial conditions on swirling non-premixed methane flames: Flow field, temperature, and species distributions

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HIGHLIGHTS

- We examined the effect of the quarl geometry on the flame structure of swirling non-premixed flame.
- Measurements of the turbulent flow field, gas concentration and temperature field are presented.
- Stereoscopic planar image velocimetry was applied to obtain instantaneous velocity components.

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ABSTRACT

Detailed measurements are presented of the turbulent flow field, gas species concentrations and temperature field in a non-premixed methane swirl flame. Attention is given to the effect of the quarl geometry on the flame structure and emission characteristics due to its importance in gas turbine and industrial burner applications. Two different quarls were fitted to the burner exit, one a straight quarl and the other a diverging quarl of 15° half cone angle. Stereoscopic Particle Image Velocimetry (SPIV) was applied to obtain the three components of the instantaneous velocity on a vertical plane immediately downstream of the quarl exit. Temperature and gaseous species measurements were made both inside and downstream of the quarls, using a fine wire thermocouple and sampling probe, respectively. This work provides experimental verification by complementary techniques. The results showed that although the main flame structures were governed by the swirl motion imparted to the air stream, the quarl geometry, fuel loading and air loading also had a significant effect on the flow pattern, turbulence intensity, mixture formation, temperature distribution, emissions and flame stabilization. Particularly, in the case of the straight quarl flame, the flow pattern leads to strong, rapid mixing and reduces the residence time for NO formation within the internal recirculation zone (IRZ). However, for the diverging quarl flames, the recirculation zone is shifted radially outward, and the turbulent interaction between the central fuel jet and the internal recirculation zone IRZ induces another small vortex between these two flow features. Less mixing near the diverging quarl exit is observed, with a higher concentration of NO and CO in the post-combustion zone. The instantaneous flow field for both flames showed the existence of small scale vortical structure near the shear layers which were not apparent in the time averaged flow field. These structures, along with high levels of turbulence present in the shear layer, result in the enhancement of the mixing, especially with straight quarl. This article outlines results that yield deeper insight into the combustion of swirling flames stabilized within the quarl and to establish an experimental data base for modelers.

1. Introduction

Swirl flows have been widely investigated because of their extensive use in a wide range of practical combustion systems, including gas turbine combustion, industrial burners, and furnaces [1,2]. Although a quarl is commonly used in gas turbine and indus-

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trial burners with swirling flames, there have been few studies on the effects of the quarl geometry on the combustion characteristics. Many free or confined swirl diffusion flame studies have been performed using burners with a straight exit burner (*i.e.,* no quarl). Experimental results have established the general characteristics of swirl flows and revealed important effects of swirl on promoting flame stability and increasing combustion efficiency [3–7].

Measurements of the concentrations of gas species, temperature and emissions of pollutants in non-premixed swirling flames are presented in [8–10]. Two typical flame configurations arise according to the primary air ratio in non-premixed propane swirling flames. In the first type of flame, the fuel burns at near stoichiometric conditions to form a ring flame around the recirculation zone. In the second type, the fuel layer is diluted by mixing with surrounding air. The second flame type showed a lower NO_x emission relative to the first one but with a higher concentration of unburned hydrocarbons [8]. The effect of fuel–air mixing on the flame structure and NO_x emissions in swirling methane jet flames was experimentally studied [9]. Two modes of combustion effected the emissions: type 1 was fuel jet dominated combustion and type 2 was strongly recirculating combustion. In strongly recirculating flames, a uniform mixture is formed in the recirculation zone that helps to reduce the NO_x emissions relative to the fuel jet dominated combustion mode. The NO_x emission level can further be reduced by using an annular fuel injector with a significant decrease in CO concentration due to the enhanced mixing. In-flame measurements of flow field, temperature, and gas concentration were conducted to clarify the mechanism of NO formation [10] in these two types of combustion.

The effects of the swirling flow on the spray characteristics with straight exit burner has been examined by Presser et al. [11]. Under non-burning and burning conditions, the fuel–air interaction in a kerosene spray swirling flames was examined, and provided qualitative details and quantitative measurements of the induced spray. The effects of the physical properties of four different fuels on the swirl spray flames was addressed by these researchers in [12]. They concluded that the fuel viscosity effected the mean droplet size and spray velocity distribution, with a negligible effect of the surface tension. The flame structures were seen to be influenced by the fuel volatility and with increasing carbon to hydrogen fuel ratio, the flame luminosity was observed to increase. Straight exit, double swirl burners have been proposed as a method to develop air staging to reduce NO_x burner [13,14]. They showed that the radial distribution of species and temperature differs significantly in the air staged flames, for which some interpretations have been suggested. The most important parameter was the air distribution, which can lead to air staging along the flame length and reductions of NO_x to one third of that the flames without staging [13]. The details of the swirl effects on the combustion characteristics of premixed swirling flames issued from a double concentric swirl burner was examined by Gupta et al. [15] and Marshall and Gupta [16]. The temperature (mean and fluctuations) fields of two co-swirl and counter-swirl flames has been investigated. The symmetry of the flame and NO_x emissions were found to be greatly influenced by the swirl direction. Most of these studies investigated swirling flames with a straight exit into a free environment [8,9,11–17] and/or in a gas turbine model combustor [18–23].

In recent years a variety of laser-based studies in swirling flames have been reported. The main advantages of these techniques is their ability to acquire 2D fields of velocities and scalars with a high spatial and temporal resolution. These techniques were employed to measure the flow field, structure, temperature, and species distributions of a swirl flame in a laboratory-scale gas turbine [18]. Three flames with thermal powers between 7.6 and 34.9 KW were investigated. These flames were observed to behave differently with respect to combustion instabilities. In addition, the near-field flow structure of isothermal swirling flows and reacting non-premixed swirling flames was measured in a straight exit laboratory burner without quarl by [17]. Two fuel injection geometries, co-axial and radial, leading to different mixing mechanisms were investigated and characterized. Their study indicated that, although the main flame structure and mixing process are governed by the swirl motion, the fuel injectors play an important role in flame stabilization. The simultaneous measurements of particle image velocimetry (PIV) and planar laser induced fluorescence (PLIF) of OH or CH radicals facilitated the investigation of the flame-flow interaction in different swirling geometry. For example, the effects of turbulence chemistry interactions in gas turbine model combustor have been investigated in [19], the effects of precessing vortex core (PVC) on the flame structure and vortex flame interaction have been investigated, see [20–22], and they concluded that the PVC causes considerable aerodynamic stretch of the reaction zone and locally may yield to flame disruption, quenching or extinction [22]. Recently, Stohr et al. [23] investigated the transient effects of fuel–air mixing induced by PVC in partially premixed swirling flame using simultaneous measurements of PIV and PLIF imaging of both OH and acetone (used as a fuel tracer). They [23] showed that the PVC could induced periodic changes from a well-mixed zone to a pure air in the composition of the unburned gases near the flame root.

Relevant swirling flame work with a quarl, includes a study of the stability maps of a swirl-stabilized, nonpremixed natural gas burner with three quarls and three fuel nozzle arrangements by Milosavljevic et al. [24]. The quarl half-angles were 20° and 25°, the ratios of length to quarl exit diameter were $L/D = 1$ and 1.9, and the maximum swirl number was 1.8. They concluded that the leanest flames were found in the 20°, $L/D = 1$ quarl, and the poorest stability was provided by the 25°, $L/D = 1.9$ quarl. In a different study, the flow field and flame structure of a turbulent non-premixed swirl flame with a straight exit burner (no quarl) was measured by Shen et al. [25] and results were compared with existing data on a diverging quarl flame in [26] to provide further insight into the effect of the burner geometry on the flame structure. The flow field of their study was determined using the isothermal equivalent to the swirling flames via a laser Doppler velocimeter.

It is clear that the effects of a quarl on the flow field and combustion of reacting swirling flames have not been adequately investigated. In addition, no measurements of gaseous concentration, temperature, and velocity inside the quarl are available, although such measurements are important for establishing real boundary conditions. Here, the influence of the initial conditions (both fuel and air loading) on the structure of a free turbulent swirl diffusion flame with either a straight or diverging quarl is experimentally investigated. Comprehensive measurements of turbulent near flow field and just above the quarl exit using stereoscopic PIV and in-flame measurements of temperature and chemical species concentration inside of and downstream from the quarl are reported.

2. Experimental setup and measurement techniques

A schematic of the swirl-stabilized flame apparatus is shown in Fig. 1a. The burner consisted of two concentric tubes with an annulus that supplied swirled air and a central pipe delivering the fuel (methane). The swirl was generated via four tangential air inlets that mixed the tangential air with axial air upstream of the burner. The swirling coaxial airflow surrounded the central fuel tube with an inner diameter, d_f, of 4.4 mm and outer diameter, d_{fo}, of 6.3 mm. The air tube diameter, d_A, at the throat ($Z = 0$ mm) indicated in Fig. 1a, was 27 mm. The flame was established in a quarl down-