International Journal of Heat and Fluid Flow 72 (2018) 200–213

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Experimental and numerical investigation of turbulent isothermal and reacting flows in a non-premixed swirl burner

Zakaria Mansouri[a,*], Toufik Boushaki[a,b]

[a] Institut de Combustion, Aérothermique, Réactivité et Environnement (ICARE), CNRS-INSIS, 1C Avenue de la Recherche Scientifique, 45071 Orléans Cedex 2, France
[b] Université d'Orléans, IUT, GTE, 16 Rue Issoudun, 45067 Orléans cedex 2, France

ARTICLE INFO

Keywords:
Delayed Detached Eddy Simulation
Non-premixed combustion
RANS
Stereo-PIV
Swirling instability

ABSTRACT

This paper focuses on the experimental and numerical investigation of CH_4/air non-premixed flame stabilized over a swirler burner with radial fuel injectors. The flame operates under a global equivalence ratio $\Phi = 0.8$, a high swirl number $S_n = 1.4$ and at atmospheric pressure. Reynolds averaged Navier-Stokes (RANS) calculations, Delayed-Detached Eddy Simulation (DDES) and experimental measurements are performed for both cases, non-reacting and reacting swirling flows. Numerical flow fields are compared with detailed Stereoscopic Particle Image Velocimetry (Stereo-PIV) fields under non-reactive and reactive conditions. Temperature measurements are also performed and compared to the computed ones in the reacting flow. The analysis of averaged results reveals the presence of a central recirculation zone (CRZ), a swirling jet region (SJ) and shear layers (SL) for both flows. The instantaneous turbulent structures at the burner exit, visualized by the Q-criterion, display different instability modes. The main instabilities are the vortex rings due to the Kelvin–Helmholtz instability, and finger structures generated by the swirling instability. The presence of the flame leads to increase the jet angle compared to the non-reacting flow. The main flame front is found highly wrinkled and rolled up around the vortex ring structures. A small flame ring is present near the fuel injector; it is formed due to the presence of a recirculation bubble (RB) at this region.

1. Introduction

The combustion systems used in the energy sector can generally be divided into three categories: (1) gas turbines for electricity production and industrial purposes, (2) internal combustion engines and aeronautical engines for transport, and (3) industrial burners and furnaces. The sustainable development and enhancement of all of these combustion systems are the key parameter to mitigate climate change. In the present investigation, attention will be focused to the third category of industrial burners and furnaces. Recent designs of these burners have introduced swirl vanes referred to as a swirler, which is used to aerodynamically stabilize the flame. To categorize a swirling flow, the dimensionless swirl number (S_n) is used. It is defined as the axial flux of angular momentum divided by the axial flux of axial momentum and the burner diameter (Beer and Chigier, 1972). The advantages of using swirlers are numerous such as: stable and very short flames, high heat flux rates, low CO emissions and uniform species concentrations (Villasenor and Escalera, 1998; Zhou et al., 2015). Thus, the swirling flow promotes recirculation zones composed of burnt gases, which enhance the flame stabilization and insure a permanent ignition. The flow dynamic in burners equipped with a swirler is very complex, (Gupta et al., 1984; Stone and Menon, 2001), different phenomena (vortex breakdown, instabilities, unsteady structures…), Sarpkaya, 1995; Panda and McLaughlin 1994), and different flame shapes (V flames, M flames…), Stöhr et al., 2012; Mansouri et al., 2016b), can be found over a wide range of operating conditions.

In the following, we present a review of studies concerning the current understanding of the swirling flames. Foremost, the swirling flow within a combustor consists of several features: (1) a central recirculation zone (CRZ) caused by vortex breakdown phenomenon, (2) an outer recirculation zone (ORZ) caused by the sudden expansion of the burner nozzle in to the combustion chamber, (3) an inner shear layer (ISL) between the CRZ and the swirling jet (SJ), (4) an outer shear layer (OSL) between the SJ and the ORZ. The behavior of the flames associated to swirling flows depends on several variables, such as: swirler geometry, swirl number, burner geometry, fuel type, equivalence ratio, Reynolds number. For instance, Durbin et al., (1996) observed different flame shapes in a double swirler combustor depending on the swirled air intensity. Strong intensity of outer swirl and zero of inner swirl produced a flame attached to the burner lip. The opposite

* Corresponding author.
E-mail addresses: zakaria.mansouri@cnrs-orleans.fr (Z. Mansouri), toufik.boushaki@cnrs-orleans.fr (T. Boushaki).

https://doi.org/10.1016/j.ijheatfluidflow.2018.06.007
Received 20 October 2017; Received in revised form 7 June 2018; Accepted 11 June 2018

case produced lifted flame with a premixing of air and fuel at the base of the flame. Thumuluru and Lieuwen (2009) investigated the factors influencing flame position and stabilization location in an annular swirled burner. They observed three basic flame holding locations, which are the CRZ, the ISL and the OSL. For example, by changing the equivalence ratio or the flow velocity, the flame can be spatially distributed in the CRZ or the ISL. Stöhr et al., (2012) studied the effect of varying thermal powers (from 10 kW to 35 kW) of a gas turbine combustor on swirling flame response. They detected a coherent vortex structure called precessing vortex core (PVC) in the ISL and a co-rotating helical vortex in the OSL. Their results showed that the flames are mainly stabilized in the inner shear layer (ISL), where the PVC is also located. Huang and Yang (2005) investigated the effect of swirl on combustion dynamics in a swirl-stabilized combustor. They reported that the unsteady swirling flame behavior is possibly due to two dominant instability mechanisms. The first is the low frequency oscillations of the PVC and the vortex shedding due to Kelvin–Helmholtz (K-H) instability. The second is that the swirl may alter the flame topology which causes oscillatory heat release, which could be coupled with velocity fluctuations and dynamic pressure.

We next review the most important features of the swirling flows, which are the coherent structures. Several investigations on turbulent high swirl flows have been carried out to identify them (Freitag et al., 2006; García-Villalba and Fröhlich 2006 and Bulat et al., 2015). These 3D structures evolve due to the K-H instabilities that occur in shear layers, Syred (2006). They could alter the flame surface and cause heat release fluctuations in a combustion chamber, which can lead to combustion instabilities; Boxx et al., (2012). The physical features of turbulent isothermal and reacting swirling flows including the coherent structures and flame surface are treated in this work. The investigation of 3D coherent structures under isothermal and reacting conditions is important to characterize the swirling flame dynamics. Experimental and numerical approaches are being used to study practical and fundamental characteristics of swirling flames by researchers worldwide. Boushaki et al., (2017a) studied the 3D isothermal flow in a complex coaxial non-premixed swirled burner. The experimental technique consists of the Volumetric 3-component Velocimetry V3V® for 3D velocity measurements. They measured the flow field at the burner exit in a volume of $50 \times 50 \times 22\ mm^3$. The results were compared to previous Stereoscopic Particle Image Velocimetry (Stereo-PIV) measurements performed by the authors. They found a very good agreement between V3V and Stereo-PIV results. Also, they visualized the swirling behavior of the flow and the recirculation zone using 3D streamlines and 3D fields of velocities. (Widenhorn et al., 2008, 2009a, 2009b), at the German Aerospace Center (DLR), employed experimental and numerical works to investigate isothermal and reacting flows in a gas turbine model combustor. They used Laser Doppler Anemometry (LDA) technique for velocity measurements and Raman technique for temperature and mixture fraction measurements. They adopted the hybrid turbulence models, Detached Eddy Simulation (DES) and the Scale Adaptive Simulation (SAS) for the simulations. The averaged results showed that the flow field contains a CRZ, shear layers as well as an ORZ. The flame was lifted and stabilized by the CRZ. The instantaneous results showed that the flame front is strongly wrinkled due to the strong unsteady vortices located in the inner and outer shear layers. Also, it was demonstrated that the DES shows a remarkable predictive capacity of 3D coherent structures evolved from flow instabilities.

Besides Widenhorn et al. mentioned studies, our previous investigation of a vortex model burner using DES showed the presence of dominant strong vortices in the shear layers (Mansouri et al., 2016a). The 3D flow structure was completely asymmetric, helical and it contains different eddies with different sizes and forms. The flame front was affected strongly by these vortices, it was highly curved, wrinkled, and rolled up. Although such numerical study is of both practical and fundamental interests, it is not sufficient to investigate the coherent structures/swirling flame interaction. Indeed, none of the aforementioned studies characterized the instabilities and the coherent structures that could appear or disappear from isothermal to reacting condition in swirling flows. In addition, there is insufficient knowledge on the coherent structure and shear layer behaviors under the effects of the combustion heat release. In order to further increase the knowledge on the swirling combustion, this paper deals the averaged and temporal characteristics of turbulent swirling isothermal and reacting flows with a transverse jet of fuel, using both RANS and DES calculations as well as experimental measurements. A novel burner configuration is used. It has a coaxial configuration, high intensity swirler, a radial injection of the fuel through small holes and the presence of a confinement. It operates under turbulent regime and generates a high unsteady non-premixed flame. It is a complex configuration, but very helpful to reveal the practical and fundamental aspects this type of installations.

The present paper aims three objectives. The first is to experimentally investigate the flow behavior and the combustion in this type of rather complex burner. The second is to examine the predicting capacity of RANS and DES in reproducing the experimental results. The third is to further complete by DES calculations the understanding of unsteady phenomena (coherent structures, precessing vortices, unsteady heat release…) that are difficult to study experimentally in such configuration. The obtained results include the validation of computations/measurements, the flow fields in reactive and non-reactive cases, temperature fields, combustion species and the heat of reactions.

2. Experimental setup and measurements

The test-rig presented in Fig. 1 was used for the experimental study of the isothermal swirling flow field by Boushaki et al. (2017a) and for the impact of oxygen enrichment on non-premixed swirling flames by Merlo et al. (2013). The burner is coaxial; it is fed by air in the annular part and by methane in the central tube. This later ends with eight radial holes (of 3 mm of diameter) with 1 mm before the burner exit. The swirler, located in the annular part at 60 mm from the exit burner, ensures the rotation of air. The inner diameter of the central tube is $D_{tube} = 15$ mm and the outer diameter of the co-axial tube is $D = 38$ mm. The burner is placed in a combustion chamber of 25 kW power and 48x48x100 cm^3 dimensions. The walls of the combustion chamber are water cooled on the outside and refractory-lined inside. Six windows are arranged in each face of the chamber allowing optical access to the entire length of flow and flame. A detailed description of the burner and the combustion chamber are reported in Boushaki et al. (2017a); Merlo et al. (2013) and Merlo et al. (2014).

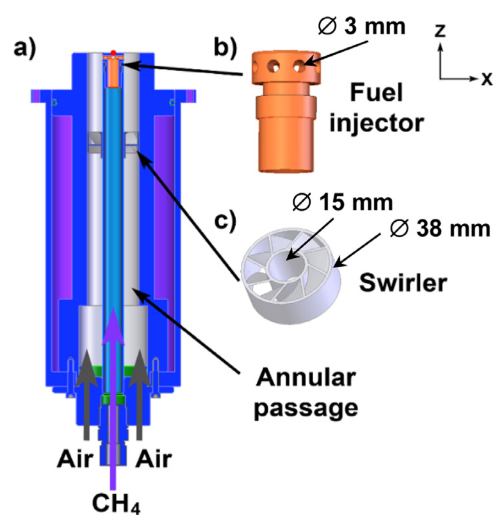

Fig. 1. A schematic view of the burner (a), the radial fuel injector (b) and the axial swirler (c). The red dot at the tip of the injector indicates the origin of the design frame ($x = y = z = 0$).