Combustion and Flame 162 (2015) 1234–1248

Contents lists available at ScienceDirect

Combustion and Flame

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

Structure of hydrogen-rich transverse jets in a vitiated turbulent flow

Sgouria Lyra [a,*], Benjamin Wilde [b], Hemanth Kolla [a], Jerry M. Seitzman [c], Timothy C. Lieuwen [c], Jacqueline H. Chen [a]

[a] Reacting Flow Research Department, Combustion Research Facility, Sandia National Laboratories, Livermore, CA 94551, USA
[b] School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
[c] School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

ARTICLE INFO

Article history:
Received 23 July 2014
Received in revised form 23 October 2014
Accepted 24 October 2014
Available online 24 November 2014

Keywords:
DNS
Experiment
Transverse jet
Vitiated crossflow

ABSTRACT

This paper reports the results of a joint experimental and numerical study of the flow characteristics and flame structure of a hydrogen rich jet injected normal to a turbulent, vitiated crossflow of lean methane combustion products. Simultaneous high-speed stereoscopic PIV and OH PLIF measurements were obtained and analyzed alongside three-dimensional direct numerical simulations of inert and reacting JICF with detailed H_2/CO chemistry. Both the experiment and the simulation reveal that, contrary to most previous studies of reacting JICF stabilized in low-to-moderate temperature air crossflow, the present conditions lead to a burner-attached flame that initiates uniformly around the burner edge. Significant asymmetry is observed, however, between the reaction zones located on the windward and leeward sides of the jet, due to the substantially different scalar dissipation rates. The windward reaction zone is much thinner in the near field, while also exhibiting significantly higher local and global heat release than the much broader reaction zone found on the leeward side of the jet. The unsteady dynamics of the windward shear layer, which largely control the important jet/crossflow mixing processes in that region, are explored in order to elucidate the important flow stability implications arising in the inert and reacting JICF. The paper concludes with an analysis of the ignition, flame characteristics, and global structure of the burner-attached flame. Chemical explosive mode analysis (CEMA) shows that the entire windward shear layer, and a large region on the leeward side of the jet, are highly explosive prior to ignition and are dominated by non-premixed flame structures after ignition. The predominantly mixing limited nature of the flow after ignition is examined by computing the Takeno flame index, which shows that ~70% of the heat release occurs in non-premixed regions.

1. Introduction

The jet in crossflow (JICF) is a canonical configuration employed in many industrial and transportation combustion systems. It facilitates rapid mixing between two streams, driven primarily by a complex three-dimensional flow field [1]. Considering combustion applications specifically, the JICF is widely encountered in aircraft and electric power generating gas turbine combustors. For lean, premixed systems, JICF technology is used in both the fuel/air mixers/nozzles and the combustor itself. For instance the lean-premixed-prevaporized (LPP) concept of aircraft engine combustor relies on a JICF type fuel injector to quickly mix the vaporizing liquid fuel with gaseous air. Likewise, industrial gas turbine combustors operating with gaseous fuels employ a JICF based fuel premixer. In both of these applications, the JICF provides rapid mixing to enable the primary combustion zone to operate in a lean premixed mode.

The JICF is also used in staged combustors, such as RQL (rich, quick-quench lean) systems, in both aircraft and stationary gas turbines where either an air jet mixes with a rich, vitiated crossflow, or a secondary fuel jet issues into lean combustion products from a primary combustion zone. Fuel staging is an attractive design strategy as it can facilitate fuel flexibility and enable load variations while satisfying stringent emissions regulations. However, for fuel premixing the JICF near field flame stabilization is important to flameholding safety (*i.e.*, to ensure that a flame cannot stabilize in the JICF wake if it were to flashback [2]), while for staged combustion, the design concern is primarily that of temperature uniformity into the turbine, NO_x emissions from the secondary zone, and JICF thermoacoustics.

The fundamental momentum and scalar transport in non-reacting JICF has been studied extensively both experimentally and numerically. Comprehensive recent reviews are given by Karagozian [3] and Mahesh [4]. Previous work has focused primarily on the influence of momentum flux ratio, density ratio, nozzle geometry,

* Corresponding author.

http://dx.doi.org/10.1016/j.combustflame.2014.10.014
0010-2180/

Reynolds number, and boundary layer thickness in inert JICF configurations [1,5–10]. Much less is known, however, about the behavior of reacting JICF, particularly at crossflow temperatures relevant in practical devices. Flames can be stabilized by both flame propagation and autoignition processes, depending upon crossflow temperature and fuel composition. Near field flame stabilization in moderate temperature crossflow was studied experimentally [11] and using direct numerical simulations [12,13]. Flame blowout limits in JICFs have been reported by a number of studies which correlate the lift-off hight with the laminar burning velocity, the jet diameter and the jet and crossflow velocities, [14–17]. Higher temperature crossflows were recently studied experimentally [18–20], which emphasized the role of autoignition in flame stabilization at high temperature.

The near field flame structure is also of interest and, in particular, the effect of the spatial heat release distribution on the instantaneous flow field and the shear layer dynamics. As the fuel jet discharges into the crossflow, the shear layer between the windward side of the jet and the crossflow rolls up into concentrated regions of vorticity (the shear layer vortices, SLV) near the exit of the jet injector and amalgamate with downstream distance. The elevated temperature of the vitiated crossflow can make autoignition phenomena very important in the jet near field and lead to a burner-attached flame stabilized in the stagnation region upstream of the windward shear layer. Recent experimental and numerical findings suggest that the character of the windward shear layer, and thus the spatio-temporal dynamics of the SLV, is sensitive to changes in the jet-to-crossflow momentum flux ratio, J, and the jet-to-crossflow density ratio, S.

Megerian et al. [21] performed hot-wire measurements in the windward shear layer of JICF with different J. They observed a dramatic shift in the velocity spectra and a significant concentration of spectral power into a dominant fundamental mode and its harmonics when J was reduced below $J \sim 10$. They interpreted this spectral shift as a transition from convective instability, where the shear layer acts as a noise amplifier, to global instability, where the flow behaves as a self-excited oscillator. Subsequent DNS and global linear stability analysis of non-reacting $J = 9$ JICF performed by Bagheri et al. [22] and Schlatter et al. [23] identified two global modes, including a high-frequency mode associated with the windward shear layer and a lower-frequency mode found in the leeward side of the jet. Getsinger et al. [24] extended the earlier hot-wire measurements by Megerian et al. [21] to consider variable density ratio, S, transverse jets and found that the JICF exhibited evidence of global instability for $S < 0.45$, which is lower than the critical S found for axial jets [25]. The study of Getsinger et al. [24] also reported that the J value at which the convective to global mode transition occurred was independent of density ratio, whereas axial jet studies suggest that the convective-global stability transition is a function of S.

In this study, results are presented from a joint experimental–numerical investigation of a hydrogen-rich jet in a vitiated crossflow comprised of products of methane combustion, using complementary information from experiments and direct numerical simulations (DNS). While the experimental and DNS conditions are not identical, significant effort was put forth to match important fluid mechanic and chemical kinetic parameters, in order to enable mutually useful comparisons of the results.

Despite the fact that JICFs have been widely studied, the configuration has not been examined in its entirety, especially for turbulent vitiated crossflows which lead to nozzle attached flames. To the authors' knowledge this is the first joint experimental and numerical study of vitiated JICFs specifically designed to lie in the same turbulence and thermochemical parameter space aiming to provide complementary insights and to enable understanding of the coupled role of flow, kinetics, and hydrodynamic stability. Since this is the first presentation on this effort particular emphasis has been placed on a thorough description of the experimental facility and diagnostics, the details of the simulation as well as on the analysis of the flame structure and the distinct characteristics of the present complex, reacting JICF. The motivation behind the joint DNS/experimental study is to provide complementary information and establish that the statistical trends describing the flow and flame structure are qualitatively similar. The DNS is then used to glean fine scale information regarding the reacting shear layer dynamics and the mode of combustion in vitiated conditions. Measurements and DNS data from this arrangement can also serve as validation data for a posteriori testing and assessment of LES and RANS combustion models as has been done for low-temperature JICFs [26].

Hence, the main focus of the present work is to investigate the characteristics of a complex reacting jet in crossflow as revealed by high speed laser diagnostics and DNS. The mean flame and flow structure is examined using mutual insights gained from the experimental and DNS data. For example, while jet flames are nominally axisymmetric in the absence of crossflow, there are significant distinctions between windward and leeward flame structures in the JICF which are emphasized – their respective characteristics are reported and compared. Time-resolved DNS data are used to investigate the unsteady dynamics of the shear layer of the reacting jet in comparison with its non-reacting counterpart. Chemical explosive mode analysis is used to quantify the propensity of the mixture to proceed to thermal runaway in isolation prior to ignition. Finally, the degree of premixedness of the heat release zones are investigated using the Takeno flame index. The remainder of the paper is structured as follows. Section 2 describes the experimental facility and the diagnostics used in the experiment. Section 3 describes the DNS code and the physical and numerical parameters of the configuration. The experimental data and the DNS results are presented and compared in Section 4. Finally, the main findings and conclusions drawn from the analysis are summarized in Section 5.

2. Experimental facility and diagnostics

Two experimental test conditions are considered in the present work, one where the JICF is non-reacting and one where it is reacting. The crossflow is comprised of cold air for the non-reacting condition and is vitiated for the reacting condition. The motivation for this choice will be discussed in more detail in Section 3. The experimental facility utilized for both conditions is comprised of three sections: (i) a vitiator, (ii) a flow conditioning section, and (iii) an optically accessible test section. A schematic of the facility is shown in Fig. 1. The vitiator section consists of a natural gas burner coupled to a cylindrical, refractory-lined combustion chamber. In the reacting case, the vitiator is operated at an overall equivalence ratio of $\Phi = 0.46$.

Hot product gases from the vitiator flow into the rectangular flow conditioning section and opposed air inlets inject a metered quantity of room-temperature dilution air to reduce the temperature of the vitiated products to $T = 1{,}200$ K. A series of settling chambers and flow straighteners condition the crossflow prior to the test section, where the jet is injected flush with the lower wall. The crossflow enters at $T_\infty = 300$ K and $T_\infty = 1{,}200$ K in the non-reacting and the reacting cases, respectively. The Reynolds number of the crossflow in the test section based on mean velocity, U_∞, and the hydraulic diameter of channel at the inlet to the test section for the reacting and non-reacting conditions is Re_∞ = 10,270 and Re_∞ = 40,090, respectively.

The test section dimensions are 127 mm × 76.2 mm and optical access is provided by quartz windows at the top and sides of the