International Journal of Heat and Fluid Flow xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Effects of coflow temperature and composition on ethanol spray flames in hot-diluted coflow

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Spray flames
Mild combustion
Hot-diluted coflow
Phase Doppler anemometry
Coherent anti-Stokes Raman scattering
Ethanol fuel

ABSTRACT

Ethanol pressure-swirl sprays issuing in a hot-diluted oxidizer coflow with different temperature and composition were studied. The bulk coflow temperature was varied together with the oxygen volume fraction. The bulk coflow temperature was changed from 1480 K to 1225 K and the oxygen volume fraction from 7.1% to 10.1%. The liquid mass flow rates were chosen to yield spray flames with nearly identical Weber number. Laser Doppler anemometry, phase Doppler anemometry and coherent anti-Stokes Raman scattering were applied in the spray region and the coflow inlet. The current measurements provide a thorough description of the spray structure, droplet dispersion and gas temperature fields as well as a comprehensive database useful for validation of numerical models. Visual observations of the flame luminescence reveal that the lift-off height depends on the liquid mass flow rates as well as the coflow conditions. The lift-off height is shown to increase for lower coflow temperatures and higher liquid mass flow rates. It is found that lift-off behavior depends on the droplet convective, vaporization and chemical time scales prior to ignition. Phase Doppler anemometry results indicate that the droplet mean size and velocity distribution close to the atomizer are not influenced by the coflow conditions. A flame-front develops at the outer region of the spray where a low density of large droplets are present. A significant number of peak temperatures samples above 2000 K is observed at this location. Decrease of the coflow temperature leads to a reduction of the local peak temperatures. Closer to the center axis, the local mixture composition becomes increasingly rich and the heat-release is lower than in the outer region.

1. Introduction

Moderate or Intense Low-Oxygen Dilution (MILD) combustion has prompted great interest as a new clean combustion concept. The operation principle is based on the dilution of fuel with preheated air and high temperature combustion gas recirculation yielding an overall small temperature increase due to the heat capacity augmentation and, consequently, low NO_x emissions (Wünning and Wünning, 1997; Cavalieri and de Joannon, 2004). This unique combustion mode has completely different characteristics from a conventional operating method concerning flammability limits, combustion stability, combustion noise, and ignition process and has been studied both in industrial furnaces and laboratory scale setups for various gaseous fuels. Issues of interest for the studies included flame chemistry (Medwell and Dally, 2012; Medwell et al., 2007; Ihme and See, 2011), flow dynamics (Oldenhof et al., 2011, 2013; Dally et al., 2002), stabilization mechanisms (Oldenhof et al., 2010), emissions formation and quantification of the thermal field uniformity under various operational conditions (Coelho and Peters, 2001; Veríssimo et al., 2011, 2013).

A review of earlier research show that MILD combustion for liquids fuels has received little attention (Tsuji et al., 2002; Weber et al., 2005; Wu et al., 2007; Derudi and Rota, 2011). Studies have been performed mainly in industrial and semi-industrial scale furnaces and focused on the sustainability of MILD regime for heavy fuel oils as well as the factors resulting in furnace performance deterioration. Tsuji et al. (2002) investigated the applicability of heavy fuel oils in industrial furnaces operating in MILD conditions. The oxygen content and the pre-heated air temperature were varied systematically (Y_{O_2} = 3–15% and T = 573–1553 K) to investigate the changing state of the flame form and the resulting pollutant emission. A strong dependence of the flame stability and chemiluminescence with the preheated air and oxygen dilution was observed as well as a substantial increase of NO_x production for heavy fuel oils. Other studies (Weber et al., 2005; Wu et al., 2007) in industrial scale test furnaces operating in MILD conditions

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2014.10.006
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showed a homogenized temperature field in furnaces. However, only for certain nozzle configurations and fuel oil grades a high-temperature process without the penalty of increased NO_x emissions was achievable. Derudi and Rota (2011) carried out an experimental study on a dual-nozzle laboratory scale burner arranged in a crossflow configuration. Pure liquid *n*-octane and other mixtures involving hydrocarbons commonly found in practical fuels were used. The experiments were designed to map the dependence of the MILD combustion region with two main operating parameters: average combustion chamber temperature and dilution ratio. Results on NO_x and CO emissions showed that MILD conditions of liquid hydrocarbons was attainable for lower combustion gas recirculation ratio as compared to the LPG fuel counterparts. Additionally, increase of the oxygen dilution was witnessed to have a slight positive effect on pollutant emissions for lower average combustion chamber temperature.

The aforementioned studies clearly show the practical importance of the technology, however, many aspects in the near-injector region are not investigated. In the spray region, the fuel stream first has to be shattered into an ensemble of droplets with a desirable distribution of sizes and velocities in order to achieve the required rate of vaporization, chemical heat-release, levels of conversion and pollutant emissions. Instabilities at the liquid–gas interface in the near-atomizer region lead to primary and secondary break-up. The liquid fragments in surrounding gas form a dispersed multiphase flow, where droplets are evaporating and subject to turbulent dispersion. The dispersed droplets modify the gas-phase turbulence and the released fuel vapor depending on the relative speed of evaporation, mixing and combustion, burns in diffusion flames around individual droplets or clusters of droplets, or in partially premixed gaseous flames (Jenny et al., 2012). The temperature and composition of the oxidizer influence the time scales of phase change and reaction, making a spray flame in conventional combustion different from that of a hot-diluted combustion regime.

The present work concerns a fundamental experimental study. The objective is to reach understanding of the spray region by using a laboratory scale burner developed to study spray combustion in MILD conditions. The burner design retains the relevant physical processes of practical combustion systems. However, the composition of the gases entrained into the spray are controlled by a secondary burner rather than the furnace aerodynamics. The spray flame is unconfined and specifically designed to allow for easy access of state-of-the-art laser diagnostics (Barlow, 2007).

Goix et al. (1994), Cessou and Stepowski (1996), and Stepowski et al. (1994) investigated stabilization of flame structures above an airblast injector fed with liquid methanol. The qualitative structure of the reacting spray and its reaction zone were investigated by Mie scattering imaging and OH^* Planar LIF. Phase Doppler anemometry was used to measure droplet size statistics. The results show two outer reaction zones where strong OH signals are present. It is observed that flame stabilization occurs in the large scale mixing structures at the edge of the jet where the small droplets have sufficient time to vaporize, mix with entrained air, and burn. A discussion was presented concerning the lift-off position, motivated by a mixture-fraction formulation. In an effort to establish general features of combusting sprays in hot-diluted coflow without the influence of the near-injector dense region, O'Loughlin and Masri (2011) used a nebuliser instead of a pressure atomizer. Simultaneous high-speed OH–CH^* Planar LIF and droplet Mie scattering show that ignition OH kernels formation and growth is the mechanism of spray flame stabilization in hot-diluted conditions. The oxygen mole fraction in the coflow (12% by volume) of O'Loughlin and Masri (2011) is, however, rather high compared to other studies of combustion systems operating in MILD conditions (Derudi and Rota, 2011; Tsuji et al., 2002).

The present study is an extension of earlier work by the authors on the structure of pressure-swirl spray flames in conventional and hot-diluted combustion regime (Correia Rodrigues et al., 2014). The burner facility, atomizer type and the liquid fuel used in this study were identical. A commercial pressure-swirl atomizer was used for generating the spray. In this way the liquid atomization and gas flow in the combustion chamber are very strongly coupled and experiments remain close to the most common configuration used in industrial practice. All measurements are made up to locations as close to the atomizer as possible to unveil features of the near-injector region. Ethanol was used as fuel because of the well-defined physical properties and well-documented chemical mechanism (Marinov, 1999; Röhl and Peters, 2009).

In the authors' previous study (Correia Rodrigues et al., 2014), measurements of profiles of droplet size and velocity and gas-phase temperature were performed in an axisymmetric spray issuing in air and in hot-diluted coflow. The results show that in a reacting spray in air coflow, an inner and an outer flame-front are present. In hot-diluted coflow, weakening of the inner flame-front occurs due to the local gaseous mixture richness. At the location of the outer flame-front temperature samples above 2000 K persist. In this study, three spray issuing in hot-diluted coflows with different temperature and composition were studied. The present study complements our previous work (Correia Rodrigues et al., 2014) and contributes to the current literature by: (a) describing changes in the flame structure and identifying the driving parameter for peak temperature reduction in the outer flame-front region, (b) providing a comprehensive set of measurements that extend the initial database for model validation of poly-dispersed sprays, and (c) provide insight into the physical mechanisms controlling the spray flame lift-off height in hot-diluted conditions.

This paper is structured as follows: Section 2 briefly describes the burner facility and measurement techniques used in the present study. Section 3 presents the input parameters as well as the coflow boundary conditions for three test cases. Section 4 presents the results on spray flames visual appearance, lift-off behavior, droplet distribution and spray flame structure. A summary of the spray phenomenology and a discussion of the spray flame stabilization mechanisms is also given. In Section 5, conclusions are presented.

2. Experimental method

2.1. Burner facility

Experiments are carried out in a burner facility (Fig. 1) at Delft University of Technology. It consists of an ethanol spray (C_2H_5OH) issuing in a coflow of hot combustion products. The hot combustion products are generated by a secondary burner. It consists of a hexagonal packing arrangement of identical 5 mm diameter vertical pipes with each end welded to perforated plates. At half-height of each individual vertical pipe, four 0.5 mm holes were drilled in a cross-configuration (see section A-A in Fig. 1). The incoming air flows through the vertical pipes and mixes with Dutch Natural Gas (DNG) forced through the 0.5 mm holes. The mixture then forms a matrix of small flames stabilized on the perforated plate. A vertical pipe with 270 mm length and 160 mm inner diameter prevents the coflow of hot combustion products from mixing with the surrounding air. As the hot combustion products flow through the vertical pipe their temperature is decreasing due to the heat loss to the surroundings by radiation from the vertical pipe. Hereafter, the coflow of hot combustion products will be refer as 'hot-diluted coflow'.

Please cite this article in press as: Correia Rodrigues, H., et al. Effects of coflow temperature and composition on ethanol spray flames in hot-diluted coflow. Int. J. Heat Fluid Flow (2014), http://dx.doi.org/10.1016/j.ijheatfluidflow.2014.10.006