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Spray flame structure in conventional and hot-diluted combustion regime

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ABSTRACT

A laboratory scale experimental setup was built to study ethanol pressure-swirl spray flames in a coflow of either air or hot-diluted oxidant. The latter case resembles conditions similar to those found in practical combustion systems of liquid fuels operating in MILD conditions.

First, experiments have been performed to investigate the phenomena associated with the atomization process. High-speed visualizations show that in the presence of a hot-diluted coflow, an almost immediate disruption of the liquid jet takes place, indicating significant changes in the atomization mechanism, compared to the case with air coflow. Secondly, a comprehensive set of measurements was obtained by complementary single-point measurement techniques to reveal the gas and droplets flow fields as well as temperature fields. Measurements of droplet size and velocity components in the spray region were obtained by phase Doppler anemometry. Gas temperature was measured using coherent anti-Stokes Raman spectroscopy even in regions with droplet density as high as 10^5 cm^{-3}. It has been observed that in a reacting spray in air coflow, an inner and an outer flame-front are present. For a reacting spray with similar injection pressure in hot-diluted coflow, weakening of the inner flame-front is attributed to the fact that the gaseous mixture becomes increasingly rich towards the center region. Consequently, a significant reduction of occurrence of temperature samples above 2000 K is observed throughout most of the spray region.

1. Introduction

The technology of Moderate and Intense Low oxygen Dilution combustion, or 'flameless combustion' relies on the dilution of fresh reactants with cooled recirculated combustion products prior to the main combustion zone thereby lowering flame adiabatic temperature and, consequently, reducing significantly nitric oxides (NO_x) emissions [1]. For this process to be effective, a combination of sufficiently large recycle ratio of combustion products and a mixture temperature exceeding the auto-ignition temperature of the fuel is required [2–4].

The most notable and comprehensive experimental studies on MILD conditions were performed in laboratory scale non-premixed gaseous flames. Those studies consist of symmetric jet flames issuing into a stable hot and diluted coflow. Dally et al. [5] developed a jet-in-hot-coflow (JHC) burner able to operate at a wide range of coflow temperatures and O_2 levels. In the reported experiments the oxygen mass percentage in the oxidizer coflow ranged from 3% to 9%. Measurements of reactive scalars in a CH_4/H_2 flame were performed only at one side of the flame. Modeling studies of these flames revealed that the accurate representation of the initial coflow radial profiles of velocity statistics and scalar statistics are of utmost importance [6]. Oldenhof et al. [7,8] constructed a similar JHC burner, but modified the secondary burner to allow optical measurement techniques for flow velocity based on tracer particles. Mean velocity and temperature fields were measured in non-premixed Dutch natural gas flames in a hot coflow with oxygen mass percentage ranging from 7.6% to 10.9% [7]. A small temperature increase was found in the shear region and, velocity and turbulent stresses profiles in the reaction zones were not significantly affected by the chemical reactions [7]. High-speed recordings of the luminescence at the flame base, showed that the stabilization mechanism is based on auto-ignition kernels that grow into large pockets [8].

Compared to turbulent gaseous flames, in turbulent spray flames additional phenomena come into play. Mixing of a disintegrating liquid jet with its surroundings differs from that of a gaseous jet. To create the spray flame, the fuel stream first has to be disintegrated 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

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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 [9]. Also the temperature and composition of the oxidizer influences the time scales of phase change and reaction, making a spray flame in hot-diluted combustion regime different from that of a conventional spray flame in air.

The viability of combustion of liquid fuel in a diluted oxidizer at industrial and semi-industrial scale has been investigated in the literature. Tsuji et al. [10] reported experiments in a kerosene spray flame oxidized by preheated air diluted with combustion products with an oxygen percentage ranging from 3% to 10%. Weber et al. [11] performed experiments on MILD combustion of light fuel oil in a furnace at a power of 0.58 MW. Recently, Reddy et al. [12,13] reported experimental and numerical studies of a two-stage labscale combustor where MILD conditions were reached using intense swirl. These investigations provide encouraging results on the applicability of MILD combustion to liquid fuels. However, the configurations studied did not allow for detailed laser diagnostic measurements needed to obtain insights on the fundamental aspects of this combustion technique.

The present work concerns an experimental study. The objective is to reach understanding, in an analogous way as done for gaseous fuels, by using a special burner design allowing for detailed observations. A laboratory scale burner was developed to study spray combustion under 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. Moreover, the spray flame is unconfined, allowing good optical access for complementary laser diagnostic techniques. Ethanol was used as fuel because of the well-defined properties. Fuel atomization is done using a commercial pressure-swirl atomizer. To clearly identify the characteristics of MILD combustion in comparison to conventional combustion two cases are considered. In the first case the fuel jet is injected in a coflow of ambient air and in the second case in a hot-diluted coflow with 9.2% oxygen by volume. This study contributes to the current literature in three ways: (a) by advancing the use of laser diagnostic techniques in turbulent spray flames. This is done by reporting, to the authors' knowledge, for the first time gas-phase temperature statistics in the spray region by means of coherent anti-Stokes Raman spectroscopy technique; (b) by providing a comprehensive set of measurements that can be further used as valuable database for model validation of polydispersed sprays [9]; and (c) by providing understanding of the qualitative features of the transition of a liquid jet into a mixture of vapor and stable droplets in a hot surrounding environment.

It is known that the liquid atomization process and the near-atomizer region plays a keyrole in the entire spray flame characteristics and dynamics also further downstream [14,15]. Advanced diagnostic techniques in two-phase flows have been introduced at a slower pace than the gaseous counterparts and it has been difficult to obtain sufficiently accurate experimental data in near field of spray flames. To circumvent this problem, fundamental studies of turbulent spray flames have been made using a nebuliser instead of a pressure atomizer. In this configuration, the complexity induced by the near-atomizer effects in the dense-region of a pressure atomizer can be avoided and dilute spray flames with simple and well-defined boundary conditions studied. Karpetis and Gomez [16] reported on a series of experiments using methanol fuel. O'Loughlin and Masri [17] extended the burner design of Karpetis and Gomez to study the effect of a hot-diluted coflow on a dilute spray. 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. It may be argued though that the oxygen mole fraction in the coflow (12% by volume) is rather high compared to other studies of combustion systems operating in MILD conditions [10,18].

In the present study a commercial atomizer was used for generating the spray instead of a nebulizer, because we considered it important to remain close to the most common configuration used in industrial practice. The results provide a valuable dataset for model validation of sprays in MILD conditions and complements other datasets already available in the literature [9]. The model validation studies conducted on other experimental databases [19–22], have used a variety of RANS based approaches, as reviewed by Jenny et al. [9]. It is observed that the selection of more advanced submodels for turbulence-chemistry interaction yield better predictions, e.g. progressing from flamelet model to spray flamelet model, or from assumed PDF to transported PDF. Sensitivity to inlet boundary conditions and difficulty to predict correct spreading of the spray and mean temperature have been reported in several of the modeling studies. The literature review also shows successful modeling studies using Large Eddy Simulation (LES) for several types of spray flames burning outside the MILD combustion regime. For example, a swirl stabilized kerosene flame was studied using LES-PDF with stochastic field method by Jones et al. [23]. A pilot-stabilized ethanol flame was studied using LES-PDF with stochastic particle method by Heyes et al. [24] and using LES-CMC by Ukai et al. [25]. The studies show that in LES sufficient precision in the representation of the turbulence-chemistry interaction on the subgrid scale is necessary.

In view of this, complementary pointwise laser-based measurement techniques were employed separately in the coflow inlet conditions and spray region to obtain a detailed and accurate dataset for model validation. The presented dataset is sufficiently complete to eliminate or at least constrain possibilities to get good model predictions by merely tuning of model constants. All measurements are made up to locations as close to the atomizer as possible. Additionally, high-speed visualizations were carried out to unveil the atomization mechanisms of the different spray flames. The use of new experimental techniques such as ballistic imaging [26] and X-ray absorption methods [27], would enable further progress towards a more complete measurements. Also detailed numerical studies [28] have the potential to provide understanding and detailed description of the atomization process. These advanced experimental and numerical techniques could be used to complement the observations using high speed camera reported here.

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 for three test-cases: non-reacting evaporating spray, reacting spray in air coflow and reacting spray in hot-diluted coflow. Section 4 presents results on: (1) Comprehensive description of the coflow inlet turbulent characteristics; (2) high-speed visualization and analysis of liquid jet breakup and, last, (3) a discussion of the most notable features of spray flames structure in air and hot-diluted coflow. In Section 6, conclusions are presented.

2. Experimental method

2.1. Burner facility

Figure 1 shows a schematic of the burner facility. It consists of a pressure-swirl atomizer that produces a spray of fine fuel droplets issuing in a coflow of either air or hot combustion products.