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Local extinction mechanisms analysis of spray jet flame using high speed diagnostics

Antoine Verdier, Javier Marrero Santiago, Alexis Vandel, Gilles Godard, Gilles Cabot, Bruno Renou*

INSA Rouen, UNIROUEN, CNRS, CORIA, Normandie Universite, Rouen 76000, France

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ABSTRACT

This paper reports an experimental study where flame structure, flow topology and local extinction mechanisms of *n*-heptane spray flames are investigated. The burner consists of an annular non-swirling co-flow of air that surrounds a central hollow-cone spray injector, leading to a lifted spray flame. The experiments include measurements of droplet size and velocity by Phase Doppler Anemometry (PDA), flame structure by High-Speed Planar Laser Induced Fluorescence of OH radical (HS-OH-PLIF) simultaneously recorded with the velocity fields of the reactive flow obtained by High-Speed Particle Image Velocimetry (HS-PIV). The poly-disperse spray distribution yields small droplets along the centerline axis while the majority of the mass is located as large droplets along the spray borders. These large droplets associated with high velocities have ballistic trajectories and strongly interact with the inner wrinkled partially premixed flame front and the outer diffusion flame front. Simultaneous HS-OH-PLIF and HS-PIV images characterize the dynamics of extinction events in the spray jet flame. In the inner reaction zone, local flame extinctions are mainly controlled by the shear layer induced by the co-flow and the fuel–air heterogeneities due to the evaporation of small droplets in the vicinity of the flame front. The large scales of turbulence in the shear layer play a significant role in the dynamics of these extinctions. It is also found that the large inertial droplets penetrate the lower part of the inner front reaching the burned gases, where they evaporate rapidly. They also disturb the outer reaction zone due to the low droplets temperature and the rich mixture in the wake of droplet. These new results on local extinction of spray flames and droplet–flame interactions will also strengthen the CORIA Rouen Spray Burner (CRSB) database for the improvement of evaporation and combustion models for reacting sprays.

1. Introduction

New burner designs must move onto configurations with lower pollutant emissions and higher efficiency. This requires a fundamental understanding of the processes involved in two-phase and lean combustion. Two-phase combustion carries coupled multi-physical and chemical phenomena which generally take place simultaneously within the combustion chambers. To overcome the difficulties resulting from real geometries, the jet spray flame configuration is taken as a reference for many experimental investigations. This canonical configuration includes a central pressure or air-blast fuel injector, surrounded by a co-flow that may present different thermophysical properties (composition, temperature, etc.). The flame is stabilized downstream of the injection and presents several kinds of flame structures. Past pioneering works [1–3] investigated the flame structures in the stabilization zones of a two-phase jet flame above a coaxial air-blast injector. From quantitative OH Planar Laser Induced Fluorescence (OH-PLIF) measurements, authors suggested that the flame presented a structure of two diverging and opposed diffusion-like fronts. In their Jet Spray Flame burner, operating with a pressurized fuel injector and a large bluff-body, Friedmann et al. [4] showed that the spray flame also may have a dual reaction zone structure consisting of an outer diffusion flame and an inner partially-premixed flame. However, changing either the co-flow rate [5,6] or the co-flow composition [7] affects the flame topology, and local extinctions within the inner reaction zone may occur intermittently. These results highlighted the variety of flame structures in the Jet Spray Flame configuration, associated to the burner geometry and the fuel droplet generation. To enhance the understanding of the droplets–turbulence–flame interactions and to improve modeling capabilities of turbulent spray reacting flows, novel experimental facilities were designed by several research groups to

* Corresponding author.
E-mail address: renou@coria.fr (B. Renou).

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perform extensive measurements on the dispersed and carrier phases.

The Sydney Spray Burner, developed by Masri and co-workers [8–10], consists of a piloted spray burner where fuel is injected in the carrier air co-flow by a nebulizer located upstream inside the spray nozzle. The two-phase flame is stabilized by an annular pilot flame. Authors provided an extensive database on the phenomena of interest in dilute sprays: droplet dispersion, droplet evaporation, turbulence–droplets interactions and droplet–flame interactions. The Delft Spray burner was designed by Roekaerts et al. [11,12] to study spray combustion in Moderate or Intense Low-oxygen Dilution (MILD) conditions. It consists of a pressure-swirl atomizer that produces a spray of ethanol droplets issuing in a co-flow of either air or hot combustion products. Dispersed and carrier phase properties were measured by Phase Doppler Anemometry (PDA), and a Coherent Anti-Stokes Raman Spectroscopy (CARS) system was used to evaluate the gas-phase temperature statistics. The Cambridge Spray Burner was updated from the gaseous bluff-body swirl burner by changing the injection system [13,14]. *N*-heptane is injected through a pressure swirl hollow cone injector located within the bluff-body surrounded by a swirled air co-flow. The burner operated close to blow-off limits and specific optical diagnostics (high-speed OH-PLIF and joint PLIF measurements of CH_2O and OH) were applied successfully both to investigate the local flame structure, the reaction zones, and local extinction holes along the flame sheet. More recently, the Rouen Spray Burner was proposed as a new configuration to evaluate the droplet–flame interactions by using original optical diagnostics [15]. The experimental set-up is composed of an annular non-swirled air co-flow that surrounds a central hollow-cone spray injector, leading to a flame stabilized downstream. Both PDA, OH-PLIF and Global Rainbow Technique (GRT) were applied to quantify the evolutions of fuel droplet properties (size, velocity and temperature) across the flame front, leading to a complete database for validating LES codes.

The previous databases appear to be fundamental tools to validate or to improve LES codes, which are sensitive to the selected chemical mechanisms (global or detailed chemistry for instance) and combustion models, and which are able to predict several types of local flame structure encountered in spray flame. Ma and Roekaerts [16] performed a 3D LES with Flamelet Generated Manifolds (FGM) of two configurations in the Delft Spray dataset. They demonstrated that the flame structures are directly impacted by any changes in the magnitude of different characteristic time scales of the flow: fuel droplet evaporation, convection and reaction. The swirling ethanol spray flame near blow-off conditions (Cambridge burner) was investigated by Guisti et al. [17,18] using the LES/CMC approach with a simple and detailed chemical mechanisms. They demonstrated that a detailed kinetic scheme was more appropriate and able to capture the flame structure and its dynamics, such as local extinctions and the lift-off height. The recent comparison between LES and the experimental results of the CORIA Rouen Spray Burner (CRSB) database [15] was done by Shum-Kivan et al. [19]. The authors demonstrated the ability of LES (AVBP) to accurately predict the spray jet flame structure. However, although the global shape is well predicted by the simulation, the position of the leading edge is underestimated compared to the measurements deduced from OH-PLIF. This demonstrates that the simulation of such geometries is a complex task, since it requires at least an accurate forecast of the fuel vapor and thermal budget between the droplet and its gaseous surrounding through the evaporation model. A detailed description of the combustion reactions able to predict the different modes of combustion is also necessary [20].

Due to the complexity of the multi-physical phenomena, it is essential to develop and validate numerical models with accurate experimental data for numerous practical combustion applications.

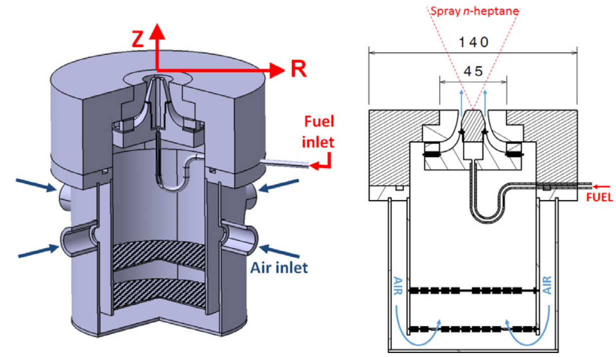

Fig. 1. Detail of the injection system. Dimensions in (mm).

With the improvement of the high repetition rates, high-speed diagnostics can resolve in time the scalars in turbulent flows. These efforts have yielded a greater understanding of the turbulent flame dynamics by tracking the evolution in time of transient phenomena such as local extinction, auto-ignition and turbulence–chemistry interactions [21–24]. However, an insight on the mechanisms that control the flame dynamics and the transient phenomena such as extinction or re-ignition in two-phase flows is still in progress due to the measurement complexities in spray combustion. Despite the recent works on the application of high speed diagnostics in spray combustion [13,25], obtaining accurate experimental data on transient phenomena such as local extinction mechanisms in real and representative two-phase flow configurations are still challenging.

In the current study, the CRSB database is completed with temporal and spatial measurements of the flame front and its associated velocity field. Additional PDA results are also considered and presented. The objective of this work is to extend understanding of turbulence–flame interactions in the spray jet flame and droplet–flame interactions by combining two high-speed optical diagnostics. This paper is organized as follows. Section 2 describes the burner and the optical diagnostics. The global shape of the flame and the associated aerodynamics in terms of dispersed and carrier phase are presented in the first part of Section 3. Moreover, the local extinction mechanisms which occur in the reaction zone will be discussed. A summary of the flame dynamics with transient phenomena mechanisms is provided in Section 4.

2. Experimental setup

This section is dedicated to the description of the burner, the operating conditions and the optical diagnostics applied during the experiments.

2.1. Burner and operating conditions

Figure 1 illustrates the CORIA Rouen Spray Burner (CRSB), which is based on the geometry of the gaseous KIAI burner [26]. The atmospheric unconfined burner is composed of an external annular non-swirling air co-flow and a pressurized liquid fuel injector (Danfoss, $1.35\,kg\,h^{-1}$, hollow cone with a angle of 80°). The air duct is equipped with 18 radial vanes (non-swirling) that break any large flow structures remaining in the plenum. The air-flow is then guided by a convergent into the chamber surrounding the fuel injector and forming a turbulent air co-flow. An electronic Coriolis flow controller (Bronkhorst, CORI-FLOW, $[0–2]\,g\,s^{-1}$) regulated the *n*-heptane mass flow rate and a thermal flow controller (Bronkhorst, EL-FLOW, $[0–15]\,g\,s^{-1}$) was used to control the air mass flow rate. The inlet conditions were $6\,g\,s^{-1}$ ($T = 298 \pm 2\,K$) and $0.28\,g\,s^{-1}$ ($T = 298 \pm 2\,K$) for the air and fuel, respectively.