Combustion and Flame 162 (2015) 978–996

Contents lists available at ScienceDirect

Combustion and Flame

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

Characterization of atomization and combustion in moderately dense turbulent spray flames

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ARTICLE INFO

Article history:
Received 13 May 2014
Received in revised form 9 September 2014
Accepted 24 September 2014
Available online 13 October 2014

Keywords:
Atomization
Spray combustion
Turbulence
Image processing

ABSTRACT

This paper presents a study of spray jets and flames where the liquid fuel loading in the carrier air is such that there are substantial liquid–liquid interactions close to the exit plane. The burner consists of an air-blast atomizer located within a wide hot co-flow used to stabilize turbulent auto-igniting spray flames. Laser/phase Doppler anemometry, microscopic backlit imaging coupled with advanced image processing, broadband chemiluminescence and OH-PLIF imaging are utilized. A key focus here is on a novel characterization of the spray boundary condition in terms of non-spherical shapes of fluid fragments. Three different classes of shapes, namely: ligaments, droplets, and large, generally irregular objects are examined. Statistics for each of these fragments are computed in a range of sprays and it is found that their size and probability of occurence depends on the initial Weber number and fuel/air mass ratio (F/A). The change in chemiluminescence emission that is measured as a function of the F/A ratio trends in the same manner as the change in the size of the largest non-spherical objects in the spray. In addition, it is found that changes in the growth of reaction zone width occur as estimated from OH images of laser induced fluorescence, and this is also controlled by the F/A ratio. Therefore, the spray structure at the exit plane may partly dictate the downstream flame characteristics; and this could be largely due to the presence of non-spherical fragments and hence the different rates of atomization and vapourization amongst the different sprays. The burner, as well as the classification of the spray introduced here, while complex, can form a platform for the improvement of models for moderately dense reacting sprays.

1. Introduction

Spray flows are nominally classified as dilute or dense depending on the relative amount of liquid per unit gaseous volume. Dilute sprays can be characterised as flows having an assembly of spherical droplets with pre-specified distributions for size and number density and with minimal or no droplet–droplet interaction [1–5]. The other extreme of dense sprays involves complex processes associated with primary atomization of liquid cores such that optical depths are very high and hence new and sophisticated techniques are necessary to probe such flows. Linne [6] provides an excellent review of recent advances in the diagnostics of dense sprays; a field that remains only vaguely understood and beyond the scope of this paper. Current understanding of dilute sprays is significantly more advanced [7–15]. This is due to the relative ease of diagnostics and the existence of a database of dilute spray burners [9,16,17,12,7] which has facilitated modelling capabilities. This has been done through international efforts such as the workshop series on the turbulent combustion of sprays (TCS) and the reader is directed to Jenny et al. [18] for a thorough overview of advances in dilute spray modelling.

This paper addresses an intermediate class of sprays, referred to here as 'moderately dense'. They are defined loosely as flows where (i) droplet–droplet interactions (atomization, coalescence and collisions) may occur, and (ii) the optical depth is intermediate between that of dense and dilute sprays such that conventional backlit illumination techniques may be applied. Moderately dense sprays are highly relevant as they are likely to dominate the regions of practical combustors between the dense liquid core and the reaction zones. In these sprays, conventional techniques such as laser/phase Doppler anemometry are limited because they reject a large portion of the liquid mass flux due to the presence of non-sphericity in the liquid fragments, a situation that is common in canonical atomization problems [19,20].

The characterization of moderately dense spray jets remains quite difficult since the liquid core fragments into arrays of complex shapes which undergo subsequent processes of secondary atomization before the final formation of spherical and well dispersed droplets [19,20]. Quantitative data describing the topology

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http://dx.doi.org/10.1016/j.combustflame.2014.09.021
0010-2180/

and statistics of fragments at the spray boundary is severely lacking. Such information is a necessity if robust break-up models and/or numerical methods for direct calculation of break-up processes are to be further developed where significant progress in these areas has been achieved recently [21–29]. Of particular relevance would be an experimental platform where these models could be tested for use in combusting problems and ultimately incorporate the full spray generation, dispersion and combustion processes.

Flows of moderate spray density will be characterised here in terms of a range of liquid shape categories. Analysis of these liquid fragments would constitute a step-change from the classical approach of representing non-dilute sprays as an assembly of large 'spherical blobs' that further breakdown into smaller spheres. Accounting for non-spherical droplets is further relevant for a number of reasons: Firstly, for a fixed volume of liquid, objects of irregular shapes will have different surface area and hence varying rates of vapourization. Secondly, non-spherical droplets will atomize at different rates that depend on their characteristic Weber numbers, orientations to the main flow, and mass flux ratios between the liquid and air [30,31]. The classification of non-spherical 'ligament' structures is not new in the context of atomization problems [19] and image processing techniques have been developed elsewhere to characterize objects of different shape [32–35] but detailed quantitative measurements, particularly upstream of a spray flame, are scarce in the literature. Introducing and measuring such phenomena in reacting flows will allow for a better understanding of the role of atomization in the region upstream of a flame base.

The burner introduced here to stabilise turbulent spray flames of moderate density is a modified version of the wide hot vitiated co-flow burner that has been used extensively to investigate auto-ignition of gaseous fuels [36–39] and dilute sprays [40,41]. For a more thorough review of ignition the reader is directed to the paper of Mastorakos [42]. The key difference between the current burner and that of OLoughlin and Masri [40] is the air-blast atomizer located in the centre of the co-flow. This configuration enables a detailed understanding of the relationship between complex atomization characteristics of the spray field at the boundary and downstream processes such as auto-ignition and subsequent heat release zones. Conventional laser/phase Doppler anemometry is used where applicable in order to characterize the velocity by sub-ranging over small droplets only. Mass flux and overall SMD measurements from PDA are only possible for the spherical droplet portion of these sprays. For that reason, tools for advanced image processing are developed to analyse images in terms of the selected classes of liquid fragments. These fragments are analysed in order to provide quantities such as size distributions conditioned on shape, two dimensional area fractions, and an equivalent measure of object concentration. Imaging of broadband chemiluminescence as well laser induced fluorescence of OH (PLIF-OH) is applied to visualize the structure of the reaction zones.

2. Experimental methodology

A schematic of the burner is shown in Fig. 1. It consists of a centrally located air blast atomizer which issues an ethanol spray into a vitiated co-flow provided by the combustion products of lean premixed hydrogen-air flames. The hot co-flow is set to a temperature of T_{co} = 1307 K as measured by a Pt-0%Rh-Pt-10%Rh thermocouple and the burnt velocity is estimated to be 3.5 m/s. The co-flow shrouds the spray from laboratory air for about 20 jet diameters downstream of the exit plane and this region is referred to as the 'valid-region', within which measurements are made. The intact liquid (ethanol) jet of diameter $D_l = 500\ \mu\text{m}$ is located only a couple of air jet diameters upstream of the air-blast nozzle exit (D = 10 mm) such that only a slightly atomized liquid jet/air 'mixture' is ejected from the nozzle as shown in Fig. 1. By controlling the air jet velocity and the mass ratio of liquid fuel over carrier air (F/A), the level of atomization at the exit plane is therefore controlled. This is in contrast to the traditional Sydney Spray burner [12] where a dilute spray is always ejected from the nozzle.

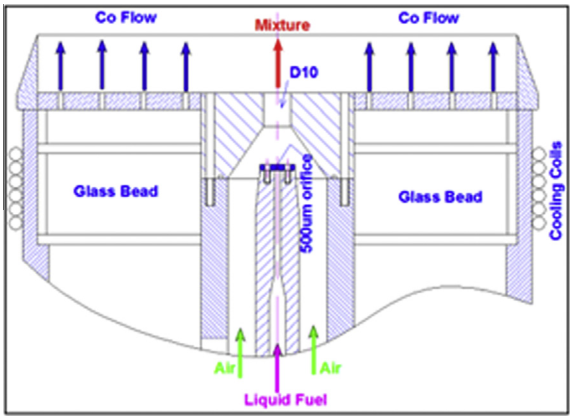

Fig. 1. Schematic of the burner.

2.1. Techniques and experimental uncertainties

Microscopic backlit imaging is conducted at a repetition rate of 10 kHz using the second harmonic from a Edgewave Nd-YAG laser diffused through a series of opal glass optics as a source of illumination of the break-up zone. A high speed CMOS camera and long distance microscope (QM-100) are used providing a field of view of 2.8 × 2.8 mm with a 768 × 768 pixel resolution where 2000 images are collected per position. Images are binarized in order to extract quantitative information where an incorrect choice of pixel threshold can result in errors in size estimation of liquid objects in excess of 100% [43,44] due to the method being a line of sight technique. A two-stage calibration study has therefore been undertaken to determine a suitable threshold and this is described in substantial detail in the Appendix. Testing the calibrated threshold against a series of air-blast sprays of varying Weber number, and comparing with PDA results, has resulted in deviations in the SMD from 2% to 12% when employing the same rejection conditions in terms of size and sphericity. Size is calibrated based on the average of the major and minor axis of an object, rather than the object areas, and this done in order to intrinsically check the accuracy of aspect ratio estimation from the images. The Appendix also examines the systematic error due to defocusing effects and a conservative estimate of error would suggest between 15% and 20%, which is similar to that reported for volume flux measurements with a PDA instrument [12]. The LDA/PDA system used here is a commercial TSI two component measurement device which has been extensively described in previous work along with its associated uncertainties [12].

The high speed OH-PLIF system uses the second harmonic from a 10 kHz Edgewave Nd-YAG to pump a Sirah Allegro dye laser which is tuned to the $Q_1(6)$ line of the $A^2\Sigma < -X^2\Pi(1,0)$ system of OH at 283.01 nm providing approximately 2 W at 10 kHz. The detection system consists of a LaVision High-Speed-Star 6 (HSS6) CMOS camera with a lens-coupled, UV sensitive, two-stage intensifier (High-Speed IRO: Intensified Relay Optics, LaVision). The repetition rate of the camera is 10 kHz with an array of 768 × 768 pixels. The signal is collected through a UG-11 glass filter and a Semrock long-pass filter with a cut at 300 nm. Further details on the PLIF system can be obtained from Juddoo and Masri [45].