Combustion and Flame 176 (2017) 511–520

Contents lists available at ScienceDirect

Combustion and Flame

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

Turbulent spray flames of intermediate density: Stability and near-field structure

Albyn Lowe[a], Agisilaos Kourmatzis[b], Assaad R. Masri[a,*]

[a] School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, NSW 2006 Australia
[b] Department of Engineering, Macquarie University, Sydney, NSW 2109, Australia

ARTICLE INFO

Article history:
Received 1 September 2016
Revised 20 October 2016
Accepted 28 October 2016
Available online 9 December 2016

Keywords:
Spray jets
Spray flames
Turbulent combustion
Atomization
Droplet dynamics

ABSTRACT

This paper presents an experimental study of turbulent spray jets and flames where the liquid loading is intermediate between the two extremes of dense and dilute; a region of significant importance in practical applications. A new piloted burner is introduced for this purpose featuring air-blast atomization, with liquid injection from a needle that can be translated within a co-flowing air stream. The stability characteristics are presented for three recess lengths using acetone as fuel. High-speed shadowgraph imaging is performed in the atomization region of jets and flames having different liquid loading and recess distances. Three types of fluid fragments are used to map the evolution of these sprays: droplets, ligaments and 'irregular' shapes. Statistics for each class of these fluid shapes are presented to map the boundary conditions at the jet exit plane and to track their evolution with downstream distance along the jet. These show clearly how ligaments and irregular shapes break down to supply more droplets further downstream. Measurements of liquid surface area show a peak in the mean area and its rms of fluctuations around two jet diameters from the point of injection marking the region of maximum atomization. It is also evident that the process of primary and secondary atomization is completed by about seven jet diameters from the liquid injection point. This burner provides a versatile platform for studying these flows and the resulting information is already proving to be extremely useful in the development and validation of related models for turbulent spray jets and flames.

1. Introduction

Efforts to improve modelling capabilities of turbulent spray flows have focused either on simple dilute flows or on the more complex extreme of dense sprays at engine-like conditions. In dilute sprays, simple configurations such as jet flames [1–5] or auto-ignition in hot vitiated co-flows [4,6,7] are measured and parallel efforts to compute flame structure are mainly co-ordinated by the series of International Workshops on the Turbulent Combustion of Sprays (TCS) (http://www.tcs-workshop.org/). On the other extreme, the Engine Combustion Network Workshops (ECN) (http://www.sandia.gov/ecn/ECNworkshop.php) use realistic operating conditions reproduced in optical engines or constant volume chambers [8–12] with either gasoline or diesel fuels. Modelling efforts there are mainly concerned with penetration depth, ignition delays and lift-off length of the transient spray pulses [13–19]. The data sets made available for both the ECN and TCS workshops cover reacting and non-reacting flows.

This paper investigates the intermediate zone between the dense core and the dilute tip of spray jets. This region which encapsulates secondary atomization regimes and possibly the tail-end of primary atomization [20], has received little attention from combustion modellers as well as experimentalists despite its importance in practical combustors. The current study is motivated by two main issues: (i) to develop an improved understanding of the evolution of fluid structures as they shed from the liquid core and transition to form droplets. This is provided through high-speed imaging in well-controlled flows, (ii) to establish a database for spray jets and flames of intermediate density using a burner that is amenable to modelling and that serves as a platform for the development of predictive tools. It is noted at the outset that high-pressure and super-critical effects on spray atomization [21,22], while important, are considered to be outside the scope of the present study.

Moderately dense flows are defined here as regions of the spray where (i) droplet-droplet interactions may occur (unlike dilute sprays) and (ii) the optical depth is intermediate between that of dense and dilute sprays such that conventional backlit illumination techniques may be applied. In an earlier study of the auto-ignition characteristics of such sprays [23], three types of liquid

* Corresponding author.
E-mail addresses: agi.kourmatzis@mq.edu.au (A. Kourmatzis), assaad.masri@sydney.edu.au (A.R. Masri).

http://dx.doi.org/10.1016/j.combustflame.2016.10.024

fragments were identified as representative features of primary atomization: ligaments, droplets, and irregular shapes. This classification, which is extended here to turbulent piloted flames, may be potentially established as a more realistic approach for representing dense sprays. It will form a more realistic extension of the current 'blob method' [14–16,18,19] which simply assumes that the liquid is injected as large spherical droplets that will fragment and decrease in size further downstream.

The first section of the paper introduces the design and stability features of a new burner, referred to as the Sydney Needle Spray Burner (SYNSBURN^{TM}), for the study of turbulent combustion in sprays of intermediate density. This is followed by a detailed experimental study of the flow-field of selected spray cases using LDV/PDA as well as shadowgraph imaging and analysis of the near-field structure. Results are reported for acetone fuel only while data for other liquid fuels such as ethanol and selected biodiesels may be made available on-line. This section presents statistics for the boundary conditions, the evolution of the fluid fragments, and the variation in surface area of the fluid with downstream distance.

2. The Burner

The burner, shown schematically in Fig. 1, uses air-blast to atomize liquid issuing from a needle with a diameter $D_l = 686\,\mu m$, centred in a fast co-flowing stream of air in a jet diameter, $D = 10$ mm. A key feature of the burner is that the needle can be recessed by up to 80mm upstream of the jet exit plane. This is similar, in principle, to the gaseous piloted burner that has been used earlier to investigate the effects of inlet compositional inhomogeneity on flame structure [24–26]. The air-blasting jet is surrounded by a pilot with an outer annulus diameter, $D_p = 25$ mm, where premixed hydrogen, acetylene and air issue under stoichiometric conditions with an unburnt velocity $U_{bu} = 1.5$ m/s. The pilot composition is such that its C/H ratio is the same as that of the main fuel, which is acetone, and provides a heat release of 3.25 kW albeit with a peak adiabatic flame temperature of 2512 K. This is higher than that of acetone that peaks at 2281 K and $\varphi = 1.05$. The entire burner assembly is mounted in a wind tunnel providing a co-flowing air stream with a mean axial velocity of 5 m/s.

The parameters controlling flame stability include the recess length, Lr, the liquid mass flowrate, Q (g/min), the air-blast velocity, U_j, and the contribution of heat release from the pilot. The pilot effects are known from earlier studies of dilute spray flames [1–3] and are not studied here. The relevant effects of the first three parameters on flame stability are examined here and more quantitative results are presented in later sections. Global flame instability is qualitatively defined as the 'blow-off' velocity, U_{bo} at which the main flame becomes visibly intermittent and periodically detached from the pilot flame. This generally involves 'necking' of the flame slightly downstream of the pilot and the detection of lighter blue colours as well as a characteristic rumbling sound. Three other methods to quantify blow-off are also examined: (i) thermocouples were placed at $x/D = 50$ to identity abrupt drops in temperature, (ii) high-speed silicon photodiodes with blue-enhanced spectral response were used to monitor fluctuations in emissivity around $x/D = 5$–10, and (iii) a sound level meter was applied to delineate oscillations in noise level. It is found that the results obtained from these methods are comparable and lie within a band of ∼4% from the qualitative visual/audible approach; hence stability limits obtained from the qualitative method only are presented here for convenience.

Flame stability limits for acetone flames are shown in Fig. 2a vs. liquid mass loading for different recess lengths of Lr = 0 mm,

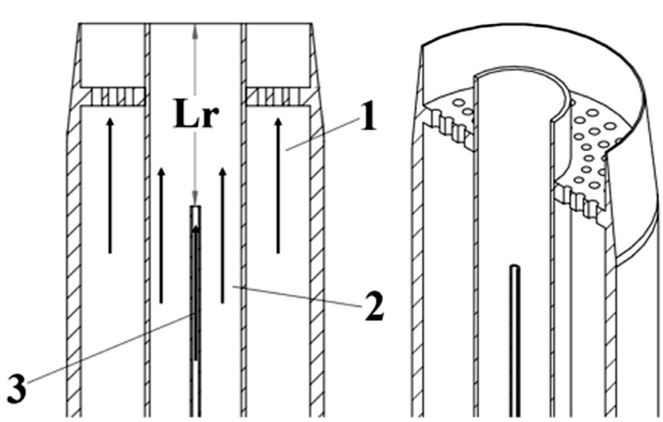

Fig. 1. Cross-section schematic of atomizer and burner assembly showing the pilot stream (1), main air jet stream (2) and liquid fuel stream (3).

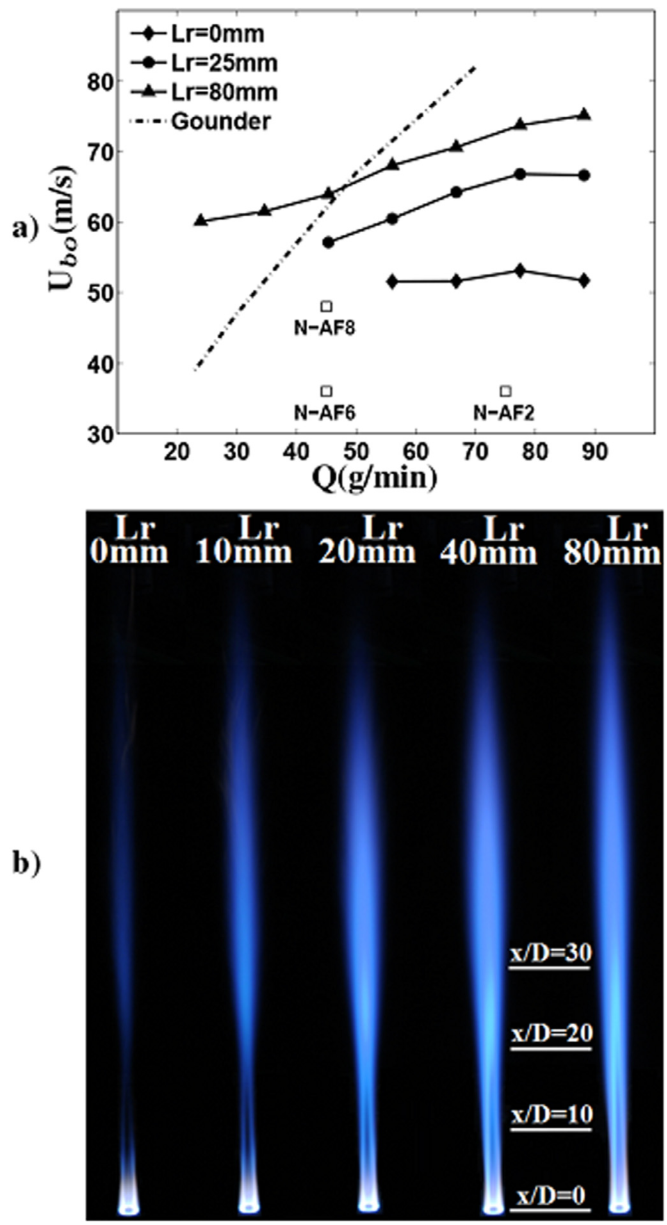

Fig. 2. (a) Blow-off air-blast jet velocity (U_{bo}) plotted vs. liquid acetone mass loading (Q) as a function of recess length (Lr). Dashed line corresponds to equivalent dilute sprays from Gounder et al. [1–5] and boxes specify selected cases defined in Table 1. (b) Sample long exposure (1s) images of the acetone flames for a mass loading of $Q = 75$ g/min and $U_j = 60$ m/s at various recess lengths.