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Air assisted atomization and spray density characterization of ethanol and a range of biodiesels

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HIGHLIGHTS

- ▶ PDA and microscopic imaging have been used to assess the atomization characteristics of different biodiesels and ethanol.
- ▶ Two image processing techniques are suggested to characterize sprays with a large proportion of deformed droplets.
- ▶ The biodiesels are more difficult to atomize, however, the majority of break-up for all liquids occurs by $x/D = 5$.
- ▶ An increase in Weber number results in a reduction in the probability of long and short ligaments appearing.

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ABSTRACT

Phase Doppler/laser Doppler anemometry (PDA/LDA) and microscopic high speed imaging have been applied to an air assisted spray using three different biodiesels (fatty acid methyl esters of short, medium and long chain length) and ethanol. The momentum decay and droplet size characteristics of the four fuels have been compared as a function of Reynolds number, mass loading, and radial position for a number of downstream locations. The PDA/LDA results suggest that the spray characteristics are very similar past $x/D = 5$ showing that the majority of break-up occurs in the near exit plane region, with minimal secondary atomization occurring further downstream. Microscopic high speed imaging has revealed qualitative information on the breakup structure as a function of physical properties and downstream locations showing significantly different atomization behaviour at the exit plane. An automated image processing technique has been applied to calculate the liquid blockage area as a measure of the spray density and degree of atomization. The technique has revealed the dependence of liquid blockage area on the fuel physical properties, showing that the long chain length biodiesel has more unbroken liquid at the exit plane. Furthermore, a manual processing method has been used to provide detailed statistical information on the probability of occurence of shapes such as long ligaments, short ligaments, unbroken liquid volumes, and deformed droplets appearing in the spray. The probability of a long ligament appearing in the long chain biodiesel is much higher while ethanol and the short chain biodiesel have yielded very similar results. In addition to revealing information on the atomization characteristics of these biodiesels, the two image processing techniques suggest a simple and alternative way of characterizing atomizing sprays.

1. Introduction

Spray formation is a process of crucial importance in improving internal combustion engines, gas turbines and other combustion systems used in power plants and transport applications. Small droplets are crucial in order to increase surface area and therefore the mass transfer rates from the liquid to the gas phase. Generating a spray broadly involves a series of atomization processes which for a simple cylindrical liquid jet injected into air involves primary atomization [1–6] and secondary atomization [7,2,8,3]. Primary atomization is the break-up of a liquid jet into ligaments or fragments [2,3], and secondary atomization involves the break-up of droplets into smaller droplets [7]. The primary stage is affected by a number of parameters which are fully described elsewhere [2,1]. In twin fluid atomization, which is of particular relevance in gas turbine applications and applications which require a high degree of air entrainment, the fluid flow properties of both the liquid jet and atomizing fluid become very important [9].

In a coaxial type air-blast atomizer, which is the focus of this contribution, primary atomization is mainly dictated by the air and liquid physical properties, the blast air velocity, the liquid jet velocity, along with certain geometric parameters which are extensively reviewed in the literature [9,1,3]. Non-dimensional parame-

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ters of relevance include the liquid and air jet Reynolds numbers (Re_l and Re_j), the liquid jet Ohnesorge number (Oh_l) and the exit Weber number (We_l), provided in Eqs. (1)–(4). Other non-dimensional parameters which are important in describing the operation of an air-blast atomizer are detailed elsewhere [10].

$$Re_l = \frac{\rho_l U_l D_l}{\mu_l} \tag{1}$$

$$Re_j = \frac{\rho U_j D}{\mu} \tag{2}$$

$$Oh_l = \frac{\mu_l}{\sqrt{\rho_l \sigma_l D}} \tag{3}$$

$$We_l = \frac{\rho_g (U_g - U_l)^2 D}{\sigma_l} \tag{4}$$

The last decades have emphasized the requirement for alternative energy sources particularly in the transport sector, where combustible fuels will remain to be the prime source of energy for the foreseeable future. With the gradual advent of biofuels and the increasing use of blends with a wide variation in physical properties, it is vital to re-examine conventional atomization systems operating with these alternative fuels. Combustible biofuels which originate from feedstocks such as soy, coconut, canola, palm oils and other variants are gradually being considered [11–14].

Variations in fuel properties of biodiesels and organic fuels made from different feedstocks are expected to affect the atomization and combustion characteristics. Research has been conducted to understand the physical properties of these fuels [11,13,15] as well as their spray and atomization characteristics in a wide variety of spray experiments [16–20] including constant volume chambers [12] and common-rail injectors [21]. More fundamental studies have involved the study of secondary atomization of a monodisperse droplet stream [17].

While work has clearly been conducted in improving our understanding of biodiesel atomization, there is generally a lack of information on the atomization characteristics of the constituent fatty acid methyl esters (FAMEs) of many of the biofuels investigated in the past. Here, we investigate the spray characteristics of three FAMEs, namely C810 (saturated short chain length), C1214 (saturated medium chain length), and esterol 116 (methyl oleate, partially unsaturated long chain length), while we also compare with ethanol. Ethanol, as with the biodiesels, is an oxygenated fuel, but has a lower viscosity and surface tension than FAMEs.

Fatty acid esters made by alcohol transesterification have been recognized as diesel-like fuels for compression ignition (CI) engines and kerosene-like fuels for gas turbine engines [14]. CI engines have operated successfully with pure biodiesels and blends of biodiesels [22]. Ethanol, considered a renewable fuel, can be blended with gasoline (gasohol) in spark ignition (SI) engines [23] and with diesel (diesehol) [24] to operate CI engines and homogeneous-charge-compression-ignition (HCCI) engines [25]. Additionally, ethanol can also be a solvent for biodiesel production [26], and therefore could be a sub-component in biodiesels which may have certain effects on biodiesel combustion and spray characteristics.

Investigating FAMEs and ethanol fuels will allow for an isolated understanding of the atomization and combustion characteristics of the consituent components of biodiesel. The resulting knowledge will be useful for the development of improved computational tools and for comparing with the performance of such fuels in real engines. In terms of combustion, it is necessary to examine in simple yet representative experimental setups, how issues such as the heat release and flame structures vary in a variety of biodiesel driven flames, where similar analysis must be conducted as done previously for conventional fuel spray flames [27–30].

In this contribution, we concentrate on the atomization characteristics of non-reacting sprays. A well characterized multiple stage atomizer in an air-blast mode is used in order to qualitatively and quantitatively investigate the atomization characteristics of these fuels. Measurements are made using phase Doppler/laser Doppler anemometry in conjunction with a long distance microscope coupled to a high speed camera with a significantly diffused high speed laser as the source of illumination. The imaging layout has allowed for visualization of the break-up region. While primary and secondary atomization has been examined in the past, there is still a lack of quantitative information regarding the primary atomization region or what is also referred to as the 'dense spray' region. Even though phase Doppler anemometry is commonly used in the primary atomization region, the measured result can be quite misleading due to the high data rejection rates present [31,32]. In this contribution, we extract quantitative information from microscopic images that complements the PDA results such as blockage area, and statistical quantities such as the probability of appearance of a particularly shaped liquid fragment.

The paper is structured as follows. Firstly, the atomizer utilized for the experiments is presented and described along with the experimental methodology and associated uncertainties. Secondly, the test conditions are presented along with the physical properties of the liquids used throughout the experiments. Droplet velocities and sizes conditioned on the smallest droplets, which are taken to be representative of the gas phase while also unconditioned results are shown as a function of radial position and downstream location for all fuels. A brief description of the turbulent characteristics of the spray are then provided for all fuels. A selection of representative break-up images is provided followed by the description of the quantitative image processing procedure which is used to give a measure of the density of the spray or liquid blockage area. Finally, the classification procedure which has been used to statistically describe the various atomized liquid shapes is presented with results for all fuels.

2. Experimental setup and procedure

Fig. 1 shows three dimensional views of the multiple stage atomizer utilized in these experiments. The atomizer consists of an effervescent stage (zone 1) and an air assisted stage containing airblast ports (port 2) and swirl ports (port 3). The effervescent atomization mode offers a considerable reduction in droplet size at the expense of a complex atomization process that involves interphase mixing upstream of the liquid nozzle (part 1) [33,34]. This adds a level of complication which for the purpose of studying biodiesel atomization is not desirable. In these experiments only the coaxially flowing airblast air of ports 2 is utilized as the air assisted mechanism. The liquid nozzle diameter D_l fixed to part 1 is kept at a constant 0.5 mm for all experiments and the airblast nozzle diameter D of part 2 is fixed at 10 mm. The reader should note that this airblast geometry is somewhat different from a conventional coaxial air assisted atomizer where the liquid injection nozzle is located on the same horizontal plane as the air nozzle [9]. In this atomizer, the liquid injection nozzle (part 1) is located upstream of the air nozzle for a number of design reasons discussed elsewhere [35].

Fig. 2 shows the diagnostic tools used to characterize the spray. A commercial laser Doppler/phase Doppler anemometry system (TSI Model FSA 3500/4000) was used for droplet velocity and size characterization. The receiver was positioned in a 50 degree forward scattering configuration. An Argon-ion laser feeds the two-channel fibre optics assembly. This assembly transmits two pairs of beams with wavelengths 514.5 nm and 488 nm which are used for measuring the axial and radial components of velocity respectively. A Bragg cell shifts one beam from each pair by 40 MHz to allow measurement of velocity in the negative direction. Built-in probe volume correction (PVC) in the software (FlowSizer) has