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Development of a Backlight Imaging System to Investigate Liquid Breakup in Near-Field Swirl Atomizer

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Abstract. A shadowgraph technique developed in this work aims to investigate the influence of swirl in air-blast atomizer such as the ones adopted in gas turbine engines. In this our initial effort, the system includes a light source, a high-speed camera, a swirl atomizer, a compressed air system, gas and liquid regulators. The light source here is a 700 W continuous LED lamb. A suitable camera is 5 to 10 kHz with a spatial resolution of 10 µm. The preliminary outcome shows that the flow rate significantly affects the spray structure and spray angle. This needs to be investigated further to understand in detailed about micro information of liquid fragments deriving from the liquid jet in atomizing zone when accounting for swirl and/or turbulent conditions and this will be done and reported in our future work.

Keywords: Swirl atomization · Backlight imaging · Spray structure · Liquid fragments

1 Introduction

Prior to combustion process in heat engines, different from gases, liquid fuels involve a number of physical processes such as atomization, droplet-droplet collision, vaporization, and mixing. These physical processes add a significant complication into the liquid fuel combustion process [1]. In the atomization process, for example, liquid fuels encompass a number of phenomena including fuel jet primary atomization [2, 3], secondary breakup [4–6] and droplet-droplet interaction [7, 8]. Primary atomization initiates the process where the bulk liquid breaks up to form droplets near the liquid surface [3, 9], followed by secondary atomization where the droplets move at a relative velocity to the surrounding environment and the aerodynamic forces cause the droplets to deform and breakup into smaller droplets and other fragments [6, 9, 10]. Correlations between internal injector information (pressure, swirl, turbulent), exit plane parameters (velocity, Weber number-We, Reynold number - Re, and Ohnesorge number - Oh), characteristics of near-field fragments and downstream parameters (drop size, velocity, and distribution) need to be investigated. Swirl is normally adopted to enhance the

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liquid breakup at the near-field of atomizers where primary and secondary breakup occurred but this makes the atomization process much more complicated. This technique aims to capture liquid fragments derived in the near-field and this will provide a good database for studying atomization mechanism in the future.

Break-up is generally achieved by liquid-air interfacial aerodynamic forces which can be enhanced by surrounding gas phase turbulence. One of the most important objectives of atomization studies overall is to determine the appropriate operating conditions leading to a particular desired droplet size which can ultimately optimize evaporation and mixing quality. Studies of fuel atomization have been performed using: (i) practical systems such as IC engines [11], (ii) constant volume systems or open environment systems using practical injectors [12–15], or (iii) cross flow air streams, drop towers, laboratory injectors setup also in open air environment [9]. Approach (i) and (ii) can normally help to observe only the macroscopic information of the sprays in practical systems such as spray angle and penetration. In the first two approaches, the spray is too dense and the process is too fast so that the current diagnostic capabilities are challenged. The last method of flow in a cross stream of air is a fundamental approach which is capable of quantifying microscopic parameters such as breakup length and time, breakup mechanism, and shapes and size of liquid blobs, fragments, their population and/or velocity.

Non-dimensional parameters of relevance, as mentioned briefly above, including the gas Reynolds number (Re), the liquid Ohnesorge number (Oh) and the Weber number (We), are commonly adopted to atomization studies and provided in Eqs. 1 to 3, respectively.

$$Re = \frac{\rho_g.U_g D}{\mu_g} \tag{1}$$

$$Oh = \frac{\mu_l}{\sqrt{\rho_l.\sigma_l.D}} \tag{2}$$

$$We = \frac{\rho_g.(U_g - U_l)^2 D}{\sigma_l} \tag{3}$$

where ρ_l is the liquid density; ρ_g is the gas density; U_g is the gas velocity; U_l is the liquid jet velocity; D is the liquid jet diameter; μ_g is the gas dynamic viscosity; μ_l is the liquid dynamic viscosity; and σ_l is the liquid surface tension.

Measurement techniques in non-dilute sprays remain limited with shadowgraph or backlight methods still being the most commonly used, second to Laser Doppler Anemometry/Particle Doppler Anemometry (LDA/PDA) which is limited to spherical droplets (e.g. a size range from 2–120 μm in the LDA/PDA system used in [16]). Backlight imaging has been used to observe a number of phenomena including observation of breakup morphology [17], the deformation rate of drops [18] and the qualitative evolution of ligaments [18]. The technique is also employed to observe and estimate the Rayleigh-Taylor and Kelvin-Helmholtz instability wave lengths [2, 5, 19]. To distinguish between different types of fluid elements including filaments, a number of shape quantifying parameters has been reviewed extensively in [16] in which the two most common parameters are the ratio of area over the square of perimeter of the object and the aspect ratio, respectively. Despite these advances, the characterization of fluid elements that arise from atomizing zone, especially when accounting for swirl and turbulent conditions, remains very loose and this work attempts to provide a methodical approach to this characterization, which in turn allows for a better physical understanding of the atomization process.

2 Experimental Issues

2.1 Injection and Fuel Supply System

The main components of a common fuel supply system include fuel tank, fuel pump, fuel control, filter and injector. These are not shown here but the injector's technical drawing is shown in Fig. 1. The functions of this system are to store and supply fuel to the fuel injector under a predetermined pressure and flow rate. Firstly, fuel pump supplies fuel to the fuel control unit, in which fuel flow rate is adjusted to provide required value. The fuel, under pressure, passes through filters, injector and finally exits the nozzle where atomization occurs.

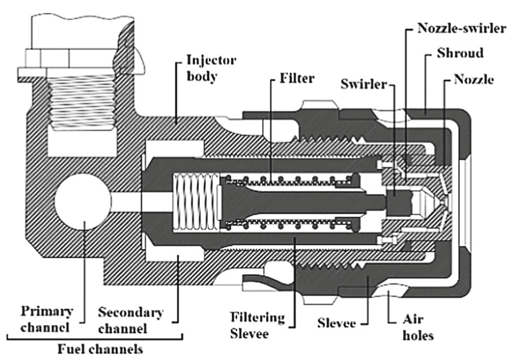

Fig. 1. Schematic of the swirl atomizer

Figure 1 shows the injector structure. For this type, the injector consists of two fuel channels (primary and secondary, respectively), swiller, nozzle and shroud. The two channels are designed so that the injector is capable to deliver a wide range of fuel flow rates. When using the primary channel, a small fuel amount can be supplied to the injector while high flow rate conditions are operated using both channels. The nozzle-swirler is located just right before the nozzle and as such it works as a nozzle for primary channel but a swirler for secondary channel. Besides, a swirler that located in the nozzle-swirler is used for the primary channel. These swirlers create a swirling motion to the fuel stream to generate a wide spray angle. It is important to note here that the nozzle-swirler and the swirler could be able to be disassembled and as such the atomization characteristics could be studied with or without the swirler. This type of injector creates a conical hollow sheet near discharge orifice. This is an airblast atomizer in which a liquid jet or sheet is exposed to air flowing at high velocity. Thus, around the face of shroud, a number of slant holes is used to supply high-velocity airstream to break up the liquid jet.

3 Camera and Back-Light Setup

Figure 2 schematically shows the experiment setup in this study. Fuel is supplied to the injector using a hydraulic system consisting of pneumatic source, fuel tank, hydraulic valves and filters (regulator). The spray structure is recorded using shadowgraph technique [16], in which cameras are used to capture the shadow of liquid fragments passing through a backlight source. The macro information of spray like spray angle will be measured using a CCD camera while micro parameters including dynamic characteristics of fuel fragments derived from near-field zone of nozzle exit require a high-speed camera (about 5000 to 20000 fps). In addition, the optical lenses are capable of adjusting magnification (from 10–20x) and are located at a distance varying between 100–300 mm from the injector centerline to avoid blurred image by fuel mist.

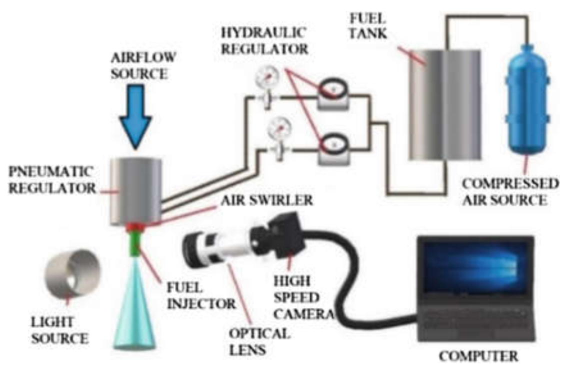

Fig. 2. Experiment setup

4 Preliminary Outcome

The main purpose of the fuel injection process is to break down fuel jet to fine droplets, which mixes with oxidants (air) to create burning mixture. This process includes the presence of a liquid core or a liquid sheet, primary breakup, secondary breakup, mixing with air and evaporation. This study shows our initial efforts to develop the system and the preliminary result reported here only limit to spray angle. It is also noted here that the airblast is not included at this stage.

Figure 3 shows an example of a spray angle. Initially, the obtained images allow to measure the spray angle under different fuel injection conditions. A Matlab code has also been developed using binary approach to measure the spray angle automatically. The reader is directed to refs [16] for further details of this technique.

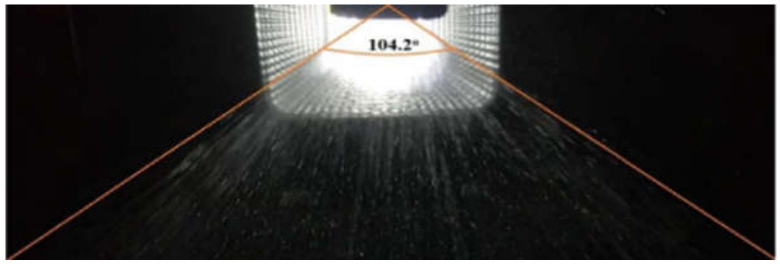

Fig. 3. Example of spray structure estimation (injection pressure = 5 bar, only primary channel used, no air-blast in this stage)

Figure 4 is the diagram of the relationship between fuel flow rate and spray angle. As the flow increases, the spray angle is enlarged significantly. This also implies that it is very important to study microstructure of this spray to understand the influence of swirl and/or turbulent conditions on the atomization characteristics. The potential output could be fuel fragment morphologies, axial and radial velocity, volume and mass flux and this is under investigation and will report in the future.

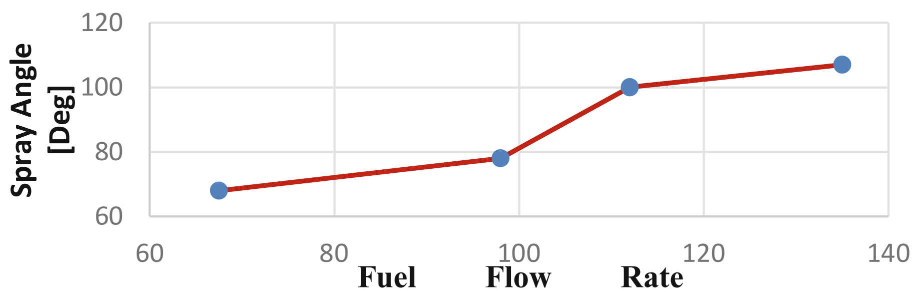

Fig. 4. Spray angle vs. fuel flow rate (primary fuel supply channel only)

5 Conclusion

A shadowgraph imaging system has been developed successfully in this study which aims to study the influence of swirl and turbulent on fuel atomization characteristics. An initial effort has also been paid to output the spray angle. The output implies that the spray angle is significantly affected by fuel flow rate and it is suggested here to study micro structure of this spray to understand the influence of swirl and/or turbulent conditions on the atomization characteristics including fuel fragment morphologies, axial and radial velocity, volume and mass flux.

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