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Spray and atomization of a common rail fuel injector with non-circular orifices

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HIGHLIGHTS

- High pressure diesel sprays using non-circular orifices were tested for common rail injectors.
- Spray width clearly demonstrates axis-switching for all non-circular orifices.
- Sprays from non-circular orifices exhibit large width and cone angle with better air entrainment.
- Droplet size depends on locations and injection conditions for different orifice geometry.

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ABSTRACT

This paper presents an experimental study on diesel sprays from non-circular orifices in ambient air. The non-circular geometry includes rectangular, square, and triangular shapes. The obtained spray characteristics were compared with those of a circular orifice. The injection pressures were varied from 300 bar (30 MPa) to 1000 bar (100 MPa). Macroscopic spray characteristics like spray cone angle and spray width were measured using a high speed camera. A laser diffraction technique was used to measure the droplet size, i.e. Sauter mean diameter, of the sprays at different axial locations. Spray behavior was measured from different orientations of the non-circular geometric shapes, including edges and corners. Spray widths measured along the spray length clearly demonstrated the presence of axis-switching phenomenon in high pressure diesel sprays obtained from non-circular orifices even at injection pressures as high as 1000 bar. They also exhibited larger widths and hence, larger surface areas, greater cone angles than sprays from a circular orifice. Thus, sprays from non-circular geometric shapes are expected to achieve better air entrainment and hence, mixing than the circular orifices. Droplet size obtained depended on the location of measurement and injection pressure and different behaviors were observed at different locations. It was noticed that non-circular orifices could induce greater instabilities in the diesel sprays thereby leading to faster atomization. As a result, an improvement in the spray characteristics can be achieved using non-circular geometries. Axis-switching phenomenon is expected to play an important role in improving the spray characteristics and the non-circular geometry may provide a cost effective approach for passively controlling the spray characteristics.

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1. Introduction

This paper is a continuation of our previous work where the effect of non-circular orifice geometry on the breakup phenomenon of low pressure water jets was studied [1]. In this work, a high pressure common rail diesel injection setup was employed to discharge diesel fuel from a single-hole nozzle at pressures ranging from 300 to 1000 bar (30–100 MPa). Nozzles used had non-circular geometries (rectangular, square, and triangular) and the results were compared with a circular orifice. Spray was discharged into quiescent ambient air at room temperature and pressure conditions.

2. Literature review

To date, the majority of the research work on diesel sprays has been carried out on the jets issued from circular orifices [2–5]. Few studies have considered the non-circular orifice geometries. Although some work has been carried out, liquid sprays from

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non-circular orifices like rectangular, square, and triangular geometries have not received much attention. Spray characteristics like spray tip velocity, penetration, width, angle intermittency and heat release rate of elliptic nozzles at injection pressures varying from 300 to 1300 bar were studied by Jacobsson et al. [6] and were compared with the results obtained from circular and step orifices. They observed substantial differences in the spray characteristics. Xi et al. [7] studied the liquid jet atomization from elliptical nozzles by varying the aspect ratios and observed the phenomenon of axis-switching, i.e. the spray width was larger in the minor axis plane, then further downstream it became circular and eventually reversed its configuration along the jet axis. Crighton [8] also reported that elongated jets tend to exhibit lateral flapping motion along their minor axes.

Even in case of air and gas jets, laboratory studies using elliptic nozzles [9–11] and nozzles with corners, e.g. rectangular, triangular, star-shaped [12–14] have shown that as the jets move downstream, their cross-sections change similarly to the shape of the orifice geometry but with axes successively rotating at the angle characteristic of the orifice geometry. This phenomenon is a result of self-induced Biot–Savart deformation of vortex rings with non-uniform azimuthal curvature and interaction between azimuthal and stream-wise vorticity [15]. As a consequence, elliptical and rectangular jets have been reported to have greater entrainment rate than their equivalent circular jets [9,16–17]. The rectangular orifice presents a special case. It incorporates the features of aspect ratio, similar to an elliptical orifice and the effects of corners, similar to square and triangular orifices. Hertzberg and Ho [18] found that the cross over location is directly proportional to the aspect ratio of the orifice. Similar to the Rayleigh's analysis for a cylindrical jet [3], Drazin and Reid conducted stability analysis for planar jets [19]. They found that a finite planar jet is always unstable to the surface tension instabilities and the basic tendency is towards contraction, which occurs with considerable inertial overshoot, leading to axis-switching phenomenon. Moreover, according to Soderberg and Alfredson [20], the jet is also subjected to the process of velocity profile relaxation as it is issued from the nozzle. The interaction of the relaxation of the boundary layer or turbulent eddies with the free surface tension and acceleration due to gravity generates potentially unstable waves which grow in amplitude downstream and contribute to the jet breakup. Konkachbaev et al. [21] observed axis-switching phenomenon in slab jets and explained it as a result of surface tension and corner vortices.

Kawamura et al. [22] studied the spray characteristics of a slit nozzle for direct injection gasoline engines. The slit nozzle formed a thin fan shaped spray. They determined some empirical relations for spray penetration and Sauter mean diameter of droplets based on their experimental observations. In order to achieve homogeneous air–fuel mixture for diesel combustion, a slit orifice nozzle was used by Yamamoto and Niimura [23]. They observed the spray from different directions, parallel to and perpendicular to the nozzle hole slit. However, they did not observe any improvement in air entrainment by changing the orifice geometry from circular to rectangular because of the large surface area of the jet in the latter case. Chen and Brenner [24] have theoretically optimized the orifice geometry required to generate minimum droplet size and determined it to be a non-circular orifice in the shape of stretched triangles. Using numerical surface minimization techniques, McGuinness et al. [25] have shown that further improvement can be achieved by making the boundaries of the triangular orifice three-dimensional or non-planar.

Based upon the brief reviews, it can be concluded that in case of non-circular geometric jets, the breakup phenomenon is different from circular jets. Non-circular orifices can induce enhanced instabilities in the spray. It is expected that non-circular orifices can give better atomization as compared to circular orifices. Despite of such major changes over circular orifices, it is very difficult to find works which have extensively studied other non-circular shapes like square and triangles and even rectangle and ellipse for liquid jet pressures varying up to 1000 bar. This work investigates spray characteristics of non-circular orifices over an injection pressure range of 300–1000 bar. Spray has been analyzed from different orientations and for a number of macroscopic and microscopic spray properties. Results obtained have been compared to those obtained from the circular orifices.

3. Experimental set up and procedure

3.1. Common rail high pressure injection system

The fuel injection system is illustrated schematically in Fig. 1(a) and a picture of the actual setup is shown in Fig. 1(b). A common rail fuel system was used to control the fuel at a given injection pressure (up to 1350 bar) by a custom PID Labview program. The injection process is controlled by a pulse/delay generator (Stanford Research Systems, Inc.), by which we were able to control the start and the length of injection signal (injection duration). Further details of the fuel injection system can be found in a previous publication [26]. Specially fabricated nozzles with circular and non-circular orifices were used in this work. The injector nozzle has only one orifice along its axis. Details of the nozzle dimensions are given in Table 1 and Fig. 2. Fig. 2 contains schematics of orifice dimensions requested to be drilled as well as magnified images of the actual orifices. Magnified images of the orifices were captured using an Olympus ST-6 measure microscope (Shinjuku, Tokyo, Japan). The orifices were drilled by an electric discharge machining (EDM) process. Due to the limitation of the EDM process, the final nozzle area of the triangular orifice has a relatively large difference from other shapes because of the corners. Table 1 also includes details about the orifice length or depth (L) to hydraulic diameter (D_h) ratio for each shape. The hydraulic diameter of an orifice is $4A/P$, where A is the orifice cross-sectional area and P is the wetted perimeter of the orifice. The L/D ratio signifies the velocity relaxation effect (changes in liquid flow profile or velocity profile due to cessation of a solid boundary) seen in each orifice. L/D ratios are nearly the same for all of the orifice shapes indicating minimal variation between the flows due to velocity relaxation. No. 2 ultra-low sulfur diesel fuel was used in the experiments. Sprays were injected into the ambient atmosphere at room temperature and atmospheric pressure (1 atm).

3.2. Spray image acquisition system

A high-speed camera (Phantom 4.3) with a Nikon® UV 105-mm $f/(32–4.5)$ lens was used to capture the images of the fuel spray (Fig. 1b). The high speed camera captured the Mie-scattering signal from the spray. The image intensity depends on both the droplet size and the droplet number density assuming constant light source intensity. The camera was operated a frame rate of 7312 frames per second at a pixel resolution of 112×600 (physical dimension is $22.4\ \text{mm} \times 120\ \text{mm}$) with the exposure time of $11\ \mu\text{s}$ in this study. A light source was used to illuminate the spray for the image acquisition. The camera trigger was also synchronous with the injector trigger. The triggers were activated using a pulse of duration of 2 ms. After an averaged injection delay of 0.5 ms, spray images were acquired up to a duration of 6 ms which was also the duration during which the spray was visible before diffusing in the atmosphere. For each test condition, five runs were made with each comprising of 50 frames. Based on these 250 frames, spray properties like spray width and cone angle were calculated and then an average value was obtained. Properties were evaluated

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