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Research Paper

Spray characteristics of pressure-swirl nozzles at different nozzle diameters

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ABSTRACT

The spray characteristics from a pressure-swirl nozzle, a widely used device in agriculture, combustion and aerospace, have been investigated in this study experimentally with focus on the effects of nozzle hole size and injection pressure on spray morphology, velocity distribution, and spray angle. Particle image velocimetry (PIV) is used to measure the velocity distribution of the fuel (jet-fuel No. 3) sprays generated by the nozzles with orifice diameter of 0.3 mm, 0.5 mm, and 0.8 mm at a fixed orifice length of 1.0 mm, under injection pressure ranging from 0.1 MPa to 2.0 MPa. It is found from this study that there exists a critical injection pressure of 1.5 MPa beyond which the spray angle becomes independent of pressure, meanwhile; the sprays from nozzle with an orifice length/diameter ratio of 2 have larger spray angles associated with higher velocities. From the data obtained by this study and Buckingham π theorem, a correlation of the spray angle (θ) and Reynolds number (Re) has been developed, as $Re = 1.4Re^{0.39}$, where is defined by orifice diameter and exit velocity estimated by fuel mass flow rate and orifice area.

1. Introduction

Due to its good spray performances and geometrical simplicity, the pressure-swirl atomizing nozzle is widely used in many fields, such as agriculture, combustion, and aerospace. In this device, liquid fuel is forced to follow a helical path emerging from the nozzle and breaks up into a cluster of thin sheets. The liquid sheets disintegrate into ligaments and then small droplets under the effect of external mechanical stress (see Fig. 1a). Finally, the small droplets are exposed to the oxidizing environment, and burn in the gas turbines. Smaller liquid droplets with larger surface areas are preferred because they help increase evaporation rates and reduce combustion-generated polluting gasses [1]. The performances of the nozzles are characterized in the above fuel fragmentation process.

This process consists of first and second atomizations [2]. Although the first atomization plays no direct role in fuel combustion, it can affect fuel vaporization and the mixing of fuel/air antioxidant. The spray angle is an important parameter to evaluate this atomization process. The spray angle should be neither small nor large. A small spray angle leads to a small region between the fuel and the antioxidant, and a significant overlapping field is observed for the wide spray angle [3]. These extreme conditions can cause instability in the output power of the gas turbine. Therefore, a reasonable spray angle is necessary. Additionally, spray velocity and morphology are important factors affecting combustion stability. Thinner liquid sheets, smaller droplets, and lower fuel concentrations result from a wider velocity distribution, which also tends to increase the instability of output power.

In the previous researches on spray angle, Taylor [4] derived that the dependence of the spray angle on the ratio of the inlet ports area to the swirl chamber diameter and orifice diameter according to inviscid theory, then he modified the relationship on the basis of experimental data by considering viscous effects. However, the theoretical predictions are lower than the experiment values. Rizk and Lefebvre [5] predicted that the spray angle formulation was only related to the ratio of air core-to-orifice area. Their estimated spray angle value was slightly larger than experimental data because fluid properties were ignored. Moreover, Chen et al. [6] developed an empirical formula to describe the relationship between the spray angle, nozzle diameter, liquid density, working pressure, and viscosity. Later, Rizk and Lefebvre [7] conducted a series of experiments and found out that the spray angle increases with working pressure and summarized an exponential relationship between spay angle (θ) and Reynolds number as

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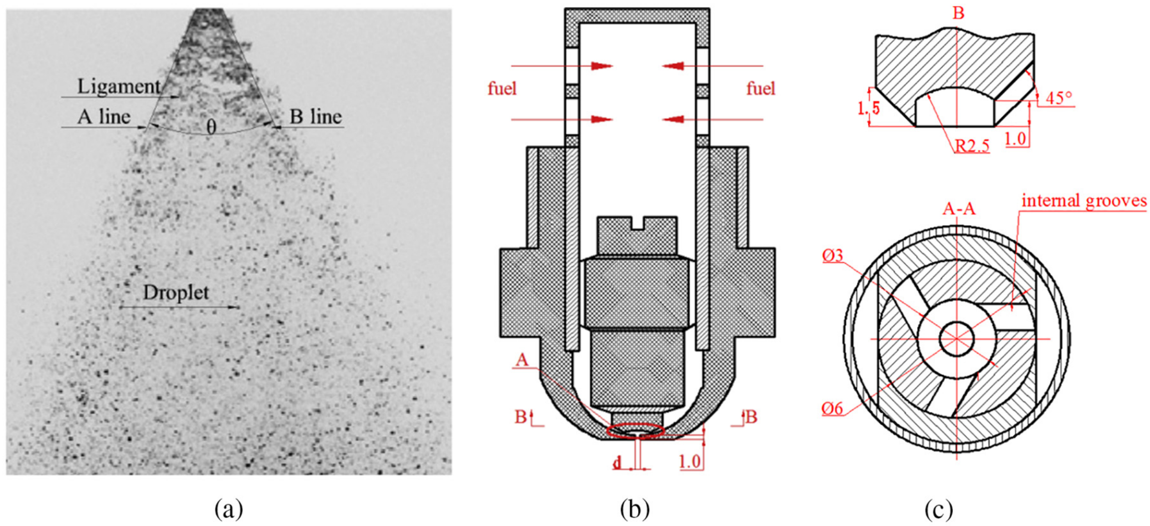

Fig. 1. (a) The spray characteristics outside of the pressure-swirl nozzle. (b) Schematic diagram of a typical pressure-swirl nozzle. (c) Geometry of the swirl chamber. All dimensions are in millimetres.

$\theta \sim Re^{0.22}$, while Ballester and Dopazo [8] obtained the expression as $\theta \sim Re^{0.\,9}$. This diversity of spray angle trend suggested that the effect of Reynolds number is not always the same. Furthermore, Rashid [9] found that the variation of spray cone angle with respect to injection pressure shows an almost linear trend for all atomizers at an injection pressure below 6 bar. In addition, Lan et al. [10] observed that the spray cone angles are mainly located in the range of $80 \sim 105°$, the angle changes slightly with the pressure. These previous correlations are not suitable for some pressure-swirl nozzle since spray angle depends on the exact geometry or dimensions of the nozzle [11]. Therefore, it is necessary to clarify the variation of the spray angle with pressure and nozzle diameter as these parameters have a profound impact on gas-turbine combustion performance [6]. Owing to the quick development of new optical measurement methods, more and more non-intrusive optical technologies, including laser-induced incandescence (LII), particle imaging velocimetry (PIV), laser imaging, and laser-induced fluorescence (LIF), are used to study instantaneous flow field and spray morphology experimentally. Among these approaches, PIV can be used to characterize turbulence properties and analyze spatial flow structures; it is a well-established technology for measuring fuel spray velocity fields. Lukas et al. [12] studied the differences of spray morphology and velocity magnitudes between the simplex and spill-return nozzles. In these experiments, PIV technology was used to measure flow field, spray structure, and spray angle.

The velocity field is another remarkable parameter that estimates spray quality for the pressure-swirl nozzle. Regarding spray morphology, increases in tangential velocity or swirl strength can cause the fluid mass to be shifted from the spray axis to the spray periphery. During the spray process, velocity magnitude is related to the thickness of the liquid sheet and the size of droplets [12]. A higher tangential velocity is prone to form thinner liquid sheet, a wider spray angle, and smaller droplets, which are beneficial to the combustion in the gas turbine. On the other hand, velocity is closely related to spray dispersion. More dispersion will result in a more uniform circumferential distribution of liquid in the spray [13–15]. There is available research on the spray angle, droplet size, and liquid sheets of the pressure-swirl nozzle. However, because velocity varies due to the high-velocity gradients and large velocity differences within an image [16], the effect of nozzle diameter on the spray velocity field of pressure-swirl nozzle requires further investigation. The influence of nozzle geometry on spray characteristics has become a hot research topic for improving the gas engine efficiency. A series of experiments have been carried out to design different swirl chambers that adapt to different environments in gas turbines [17–20]. In general, the swirl chamber and nozzle orifice are two independent primary structures affecting the spray characteristics for the pressure-swirl nozzle. The orifice, where fuel microscopic and macroscopic characteristics change, is one of the most important parts. An early atomization study on the effect of the nozzle orifice length/diameter ratio on spray characteristics was described by Chen and Lefebvre [14]. They found that circumferential liquid distribution is most uniform and that the nozzle appears to be more ideal for gas turbines when this length/diameter ratio equals 2. The nozzle orifice shape is also an important parameter. Broniarz-Press et al. [21] noted that among three orifice shapes (cylindrical, conical, and double profile), a nozzle with a profiled orifice is best. The swirl chamber is another aspect directly affecting internal flow characteristics and fuel atomization. The relationships between spray characteristics (discharge coefficient, liquid sheet, air core and spray angle, etc.) and swirl chamber geometry are abundant, but the relationships vary among chamber geometries. For example, Datta and Som [22] believed that spray angle increased with pressure, while there was little difference between maximum and minimum spray angles as tested by Lee [11]. In addition, Fu and Yang [23] noted that a minimum spray angle occurred for a nozzle with a diameter of 1.0 mm. In this experiment, the purpose was to test spray characteristics for the pressure-swirl nozzle with a new swirl chamber. Details on the structure size are described in Fig. 1(b) and (c).

Although many studies have been performed on the spray characteristics of the pressure-swirl nozzle, most of them focus on horizontally designed grooves [21,22,24–28]. The advantage of the horizontal design is that it keeps fuel charged from the nozzle hole at the maximum tangential speed, which can produce the widened spray angle. Broniar et al. experimented on the effect of orifice shape on the atomization process under the horizontally designed grooves [21]. Additionally, from numerical computations, theoretical predictions of air core diameter, the coefficient of discharge and spray cone angle have been made for pressure-swirl nozzles with four horizontally designed swirl slots [22]. However, spray characteristics dramatically change when there is a downward