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Experimental Analysis of Tangential-Vane Swirl Atomizer Spray Angle

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ABSTRACT

A swirl atomizer is a widely applied spray-generating device. The swirling motion of a swirl atomizer is induced either by a tangential inlet or a swirl-generating vane. The swirling effect produces a spray with a wide angle which is important in various applications such as gas cooling, diesel engine combustion, and automatic hand sanitizer. An intense swirling mechanism was reported to significantly affect the spray angle. An attempt was made by combining tangential inlet and swirl-generating vane in a single embodiment to create a more intense swirling effect. The experiment was conducted with pipe flow in transition and turbulence regimes. The shadowgraph technique was applied to acquire the spray images. The images were processed using image processing software. It was found that the combined swirling mechanism produces a wider spray angle compared to the individual tangential inlet swirl atomizer. It was also found that the swirling intensity has a bigger effect on the spray angle than the Reynolds number.

1. Introduction

A swirl atomizer has a wide range of applications, including gas cooling, diesel engine combustion, and automatic hand sanitizer. This type of atomizer generates spray by applying swirling effects to the liquid via tangential inlets or a swirl-generating vane. This atomizer is very synonym to the spray profile with a wide spray angle. A wide spray dispersion of a swirl atomizer paired with a slower velocity field will allow for a more uniform mixing of the intake gases than an impinging jet atomizer in gas cooling applications [1]. In typical direct injection diesel engines, spray angle is an essential parameter that controls fuel evaporation, combustion, and emissions [2]. A larger spray angle is required in automatic hand sanitizer [3] for a wider sanitizing coverage. The spray angle is defined as the angle between the two tangents of the spray field boundary discharged from the orifice [4].

Atomizer geometrical effects on the spray angle were previously reported by researchers. Gad *et al.,* [2] and Chen *et al.,* [5] investigated the effect of discharge orifice length-to-diameter ratio (l_o/d_o) of the spray angle emanating from a swirl atomizer and observed a decrease of spray angle with the increase of l_o/d_o. Jedelsky and Jicha [6] varied the intensity of the swirl-generating vane and

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discovered that a more intense swirl-generating vane produces a larger spray angle. Ghaffar *et al.,* [7] observed the combined effect of swirl-generating vane intensity and discharge orifice diameter resulting in a wide spray angle discharging from a swirl effervescent atomizer. Ghaffar *et al.,* [8] encountered the dependency of spray angle to the injection pressure alongside the atomizer geometrical parameters. Najafi *et al.,* [9] and Dafsari *et al.,* [10] found that an increase in Reynolds number (Re) widens the spray angle discharge from a swirl atomizer.

The optical method is one way for spray measurement and can be divided into imaging and non-imaging. This method is non-intrusive in nature, which accounts for the preferability and popularity of flow visualization [11]. The imaging method is more advantageous, and it is important to visualize primary spray formation; a region where the transformation of the bulk liquid into droplets occurs. Shadowgraph imaging stands out as a usually inexpensive but powerful technique [12]. Asgarian *et al.,* [13] make use of shadowgraph to acquire the droplet size distribution of an atomizer discharging a flat liquid sheet. Najafi *et al.,* [9] applied the shadowgraph imaging technique to investigate the spray angle, breakup length, and droplet size of a swirl atomizer.

A vast area of research was conducted to investigate the spray characteristics of either tangential inlet swirl atomizers or swirl-generating vane swirl atomizers. To the best of the author's knowledge, an attempt to investigate the combined effect of both swirling mechanisms is very rare. The purpose of this study was to determine whether a combined hybrid atomization would be advantageous to each atomization technique. This study will make use of image analysis for the determination of the spray characteristics. Spray angle was selected as the spray characteristic because it is believed that the whirling mechanisms will significantly alter the spray angle.

2. Methodology

2.1 Atomizer Construction

This new atomizer design allows the configuration of the two swirling elements, i.e., tangential inlets and swirl-generating vane, present in a single embodiment. The fluids enter the atomizer via tangential inlets. The schematic of the new design is shown in Figure 1.

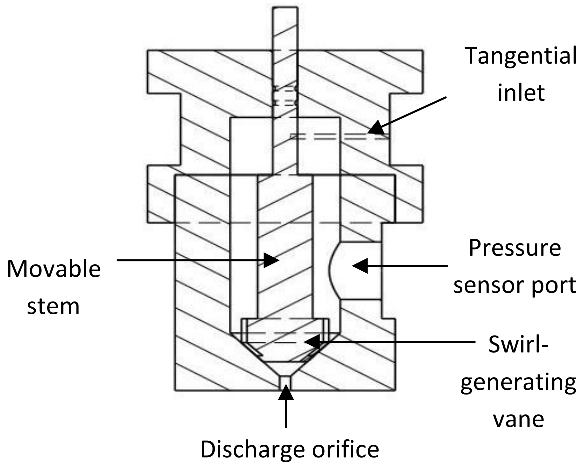


Fig. 1. Schematic of the new swirl effervescent atomizer

Further downstream, the fluids pass through a swirl-generating vane, resulting in the fluids experiencing the swirling effect from tangential inlets and the swirl-generating vane. Before discharging the atomizer via a discharge orifice, the fluids will enter a conical section. The swirl-generating vane is attached to a movable stem placed at the centre of the atomizer body. Moving the stem upward will elongate the length of the swirling chamber and diminish the effect of the swirl-generating vane.

2.2 Experiment

An experimental test rig was manufactured as a platform for the atomizer performance test. Water was used as the working fluid considering its availability and ease of handling. A centrifugal self-priming pump was utilized for delivering water from the water supply tank to the atomizer through the waterline. The amount of water flowing out of the pump was controlled by a ball valve installed at the outlet. Measurement of water flow rates in the system was obtained from the water flow meter. The flow of water was controlled by a water flow control valve. A water strainer was installed prior to the water flow meter inlet to prevent unwanted debris from passing through the meter which led to a malfunction [14]. The water injection pressure was measured by a digital pressure gauge. The atomizer was fixed in a vertically downward position and produced water sprays into a water collection tank. The schematic of the test rig is shown in Figure 2.

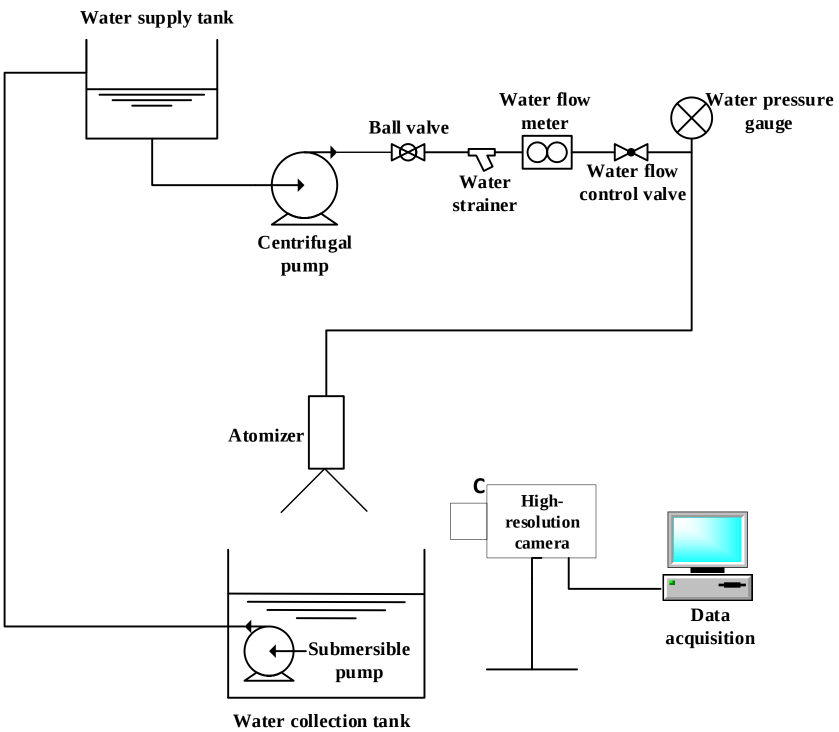


Fig. 2. Schematic of the experimental test rig

The investigation of the spray angle produced by a tangential-vane swirl atomizer involved the effect of the Reynolds number. The range of the Reynolds number is chosen to be more than 2300 considering this is the boundary where a pipe flow reaches a transition regime [15]. Details of the value of the Reynolds number used in this experiment are shown in Table 1. The Reynolds number in this experiment is defined in Eq. (1).

Table 1
Range of experiment

Experiment no.	Reynolds number	Flow regime
1	3528	Transition
2	5292	Turbulence
3	7056	Turbulence

$$Re = \frac{\rho_L U_L d_o}{\mu_L} \quad (1)$$

where ρ_L is the liquid density, U_L is the liquid velocity, d_o is the discharge orifice diameter, and μ_L is the liquid viscosity. Since there is no change in liquid and discharge orifice diameter, the change in Reynolds number depends on liquid velocity.

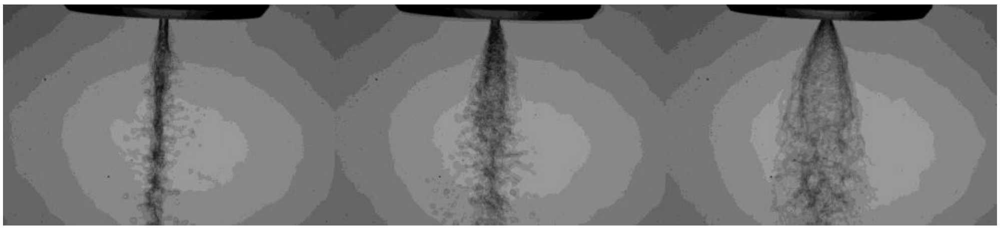
2.3 Image Analysis

The photographic system is comprised of a still camera with speedlight backlighting as a setup for shadowgraph technique. A light diffuser was installed at the speedlight to allow the evenness of lighting. A Nikon digital single-lens reflex (DSLR) camera was used with an adjustable focal length. For scientific imaging especially for schlieren and shadowgraph, there is a strong case in favor of the digital imaging over film [16]. A short focal length was not practicable because the producing sprays would drench the camera. The photograph was obtained with an aperture setting of f/18 and an ISO = 100. A remote controller was used to trigger the camera to minimize vibration.

Acquired images were processed using ImageJ. Each set comprises of 10 images. These images were stacked and converted to an 8-bit format for further processing. The stacked images were then projected using Z-Projection (average). Subtraction of background was conducted for the projected images. Then, the acquired image is converted to binary form by adjusting the image threshold. A binary form is more favorable for the measurement of spray angle since the black spray profile boundary is visualized against the white background.

3. Results

The resultant spray angle for both pure tangential and combined tangential with swirl-generating vane was presented. The disintegration regimes of the pure tangential and combined tangential with swirl-generating vane are illustrated in Figure 3 and Figure 4.



(a) (b) (c)

Fig. 3. Z-projected images of the resultant spray emanating from the pure tangential inlet setting at Re (a) 3528, (b) 5292, and (c) 7056

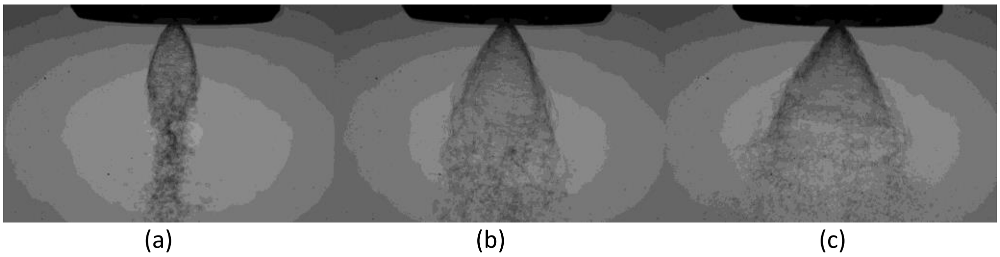


Fig. 4. Z-projected images of the resultant spray emanating from the combined tangential inlet with swirl-generating vane setting at Re (a) 3528, (b) 5292, and (c) 7056

The disintegration regime of a swirl atomizer consists of five stages as described by Lefebvre and McDonell [17] and shown in Figure 5. The stages can be described as follows

i. Dribble stage: liquid dribbles from the orifice.
ii. Distorted pencil: liquid leaves as a thin distorted pencil.
iii. Onion stage: a cone forms at the orifice but is contracted by surface tension forces into a closed bubble.
iv. Tulip stage: the bubble opens into a hollow tulip shape terminating in a ragged edge, where the liquid disintegrates into large drops.
v. Fully developed spray: the curved surface straightens to form a conical sheet. As the sheet expands, its thickness diminishes, and it soon becomes unstable and disintegrates into ligaments and then drops in the form of a well-defined hollow-cone spray.

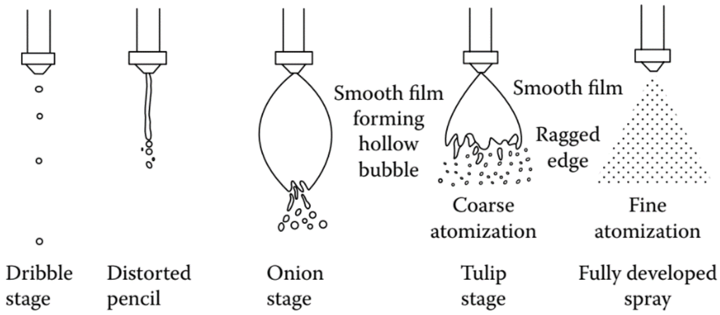


Fig. 5. Stages of liquid disintegration in swirl atomization [17]

The spray angle measurement was only performed as the disintegration regime reached the onion stage. Figure 2(a) was excluded from the measurement since the stage is the distorted pencil. The resultant spray angle for both settings is shown in Figure 6.

It was discovered that as the Reynolds number increases, so does the spray angle. This was also observed by Najafi *et al.,* [9] and Dafsari *et al.,* [10]. This is attributed to the turbulence levels in the jet discharging the atomizer directly influencing the spray angle. Higher turbulence levels increase the ratio of radial to axial velocity in the spray leading to a wider spray angle [17].

Another observation that significantly affects the spray angle is the geometrical parameters. Figure 5 shows that the combined tangential inlet with swirl-generating vane setting has a larger spray angle compared to the pure tangential inlet setting. The reason for this phenomenon might be the number of tangential inlets. According to Hamid *et al.,* [18] and Yule and Widger [19], increasing the tangential inlet number or decreasing the tangential inlet diameter results in a wider spray cone angle. The intensity of the swirl-generating vane might be another reason why the combined tangential inlet with swirl-generating vane setting has a larger spray angle. This was also reported by Jedelsky and Jicha [6].

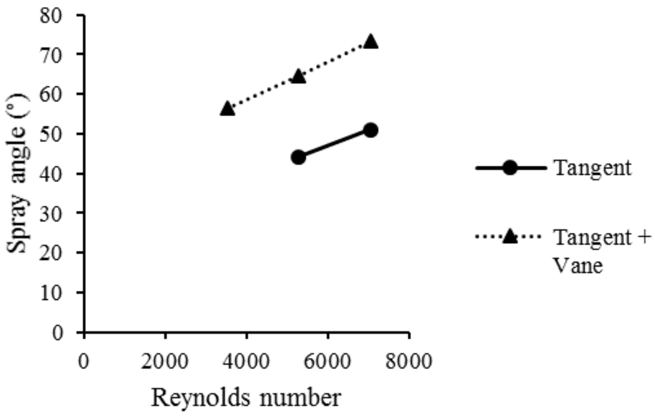


Fig. 6. Spray angle results from both settings

It is also interesting to note that the spray angle of the combined tangential inlet with swirl-generating vane setting is larger than the pure tangential inlet setting even at a smaller Reynolds number. The spray angle of pure tangential at Re = 5292 is smaller than the spray angle of the combined tangential inlet with swirl-generating vane at Re = 3528. The spray angle of pure tangential at Re = 7056 is smaller than the spray angle of the combined tangential inlet with swirl-generating vane at Re = 5292. This visualizes the dominance of swirl intensity over Reynolds number in controlling the spray angle. Friction might be a source that could lessen a swirl intensity in an atomizer. This is the significance of designing an atomizer with circular geometry over rectangular geometry as a rectangular shape chamber induces a higher friction force [20].

4. Conclusions

A spray characteristic, specifically the spray angle of a hybrid swirl atomizer was investigated. This atomizer consists of both a tangential inlet and a swirl-generating vane. Shadowgraph imaging was utilized for image acquisition. ImageJ was used for the post-processing and spray angle measurement. The analysis revealed that the spray angle increases with Reynolds number and swirl intensity. It is also observed that swirl intensity has a more dominant effect on the spray angle compared to the Reynolds number.

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