

GAS CORE CHARACTERISTICS OF SWIRL EFFERVESCENT ATOMIZER

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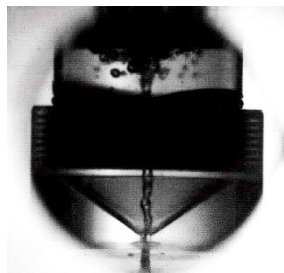
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Graphical abstract



Abstract

Swirl effervescent atomizer consists of two atomization mechanisms, effervescent and swirl. For a swirl-related atomizer, the air/gas core diameter was reported to be one of the factors affecting the widening of spray angle. A wider spray angle is important to provide a better spray distribution. The characteristic of gas core in an inside-out swirl effervescent atomizer was investigated as part of the study in understanding the mechanism of this type of atomization. The interaction effects between three independent parameters (i.e. swirl-generating vane angle, gas flowrate and discharge orifice diameter) on the size and characteristics of the gas core were investigated. Water and nitrogen gas were used respectively as the working fluid and atomization gas. The high-speed shadowgraph technique was utilized to record the videos of the gas core structures. The video recordings were converted to image sequences and analyzed using an image processing software. It was concluded that a larger gas core was produced with an increasing vane angle or gas flowrate. The increasing gas flowrate tends to increase the gas core size for all cases of the vane angle. Increasing the orifice diameter tends to increase the gas core size for all cases of the gas flowrate. The interaction between the orifice diameter and swirl-generating vane angle on the size of the gas core was inconclusive.

Keywords: Swirl effervescent atomizer, gas core, shadowgraph

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1.0 INTRODUCTION

Swirl effervescent atomizer is one of the most recent existing atomizers which could be classified as a pneumatic atomizer. It consists of two atomization mechanisms, effervescent and swirl. The mechanism of swirl atomizer is that the liquid flows through a tangential inlet/swirl insert to create a swirling motion which consists of high angular velocity, thereby creating an air-cored vortex. The air core is an important internal flow structure of a swirl-related atomizer since it characterizes the stability of the spray [1]. Datta and Som [2] have theoretically found that an increase in orifice diameter increases the air core diameter which was also experimentally observed by Rashid *et al.* [3]. The relation of air core formation to tangential inlet port diameter was numerically investigated by Datta and Som [2] and experimentally

by Hamid *et al.* [4]. In both studies, they found that the air core diameter was inversely proportional to tangential inlet port diameter. Hamid *et al.* [4] have also investigated the relation between tangential inlet port diameter and spray angle and found that both parameters are inversely related. This phenomenon was also reported by Hussein *et al.* [5].

The development of the internal flow (air/gas core) of effervescent atomizer is governed by the formation and evolution of air/gas bubbles inside the atomizer. According to Sovani *et al.* [6], the evolution of bubble in effervescent atomizer is influenced by the gas injection geometry (outside-in/inside-out), the geometries of the mixing chamber, the contraction contour upstream of the discharge orifice, injection pressure, gas to liquid ratio (GLR) and liquid physical properties.

The development of internal flow structure is a very rapid process which requires high-speed video recordings. Yao and Fang [7] and Kenny *et al.* [8] utilized high-speed video camera in observing liquid film thickness inside pressure swirl atomizers. They also made use of backlight illumination technique during the recordings. The internal flow structures of effervescent atomizer was visualized using high-speed video camera as performed by Huang *et al.* [9] and Sen *et al.* [10]. This technique was applied in our previous work [11] for measuring the spray angle of the swirl effervescent atomizer.

In this paper, a 3 factors 3 levels Box-Behnken design of experiment was used to evaluate the interaction effects of three independent parameters; swirl-generating vane angle, gas flowrate, and discharge orifice diameter on the gas core of swirl effervescent atomization. Design of experiment (DOE) is an experimental strategy in which factors are varied simultaneously instead of one at a time. DOE is more advantageous than the conventional one-factor-at-a-time method because the one-factor-at-a-time method fails to consider any possible interaction between the factors [12]. The Box-Behnken design (BBD) is one of the more advantageous because it has the ability to avoid the extreme conditions of an experiment [13].

Literature surveys reveal that (to our knowledge) there are limited studies on the gas core of swirl effervescent atomization in recent years. Due to the fact that air/gas core is an important features in a swirl-based atomizer as it characterizes a stability of a spray hence, this study is very important.

2.0 EXPERIMENTAL METHODS

2.1 Atomizer Geometries and Operating Principles

The swirl effervescent atomizer deployed has an inside-out gas injection configuration that enables gas bubbles coming out from the aeration tube to mix with the bulk liquid in the mixing chamber. The schematic of the swirl effervescent atomizer is shown in Figure 1.

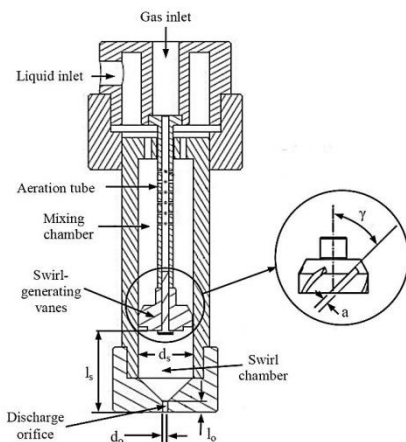


Figure 1 Schematic of a newly designed atomizer with the nomenclature of atomizer geometries

The atomizer has two inlets in which liquid enters the mixing chamber through the side inlet and gas enters through the central inlet. The gas-liquid mixture passes through the swirl-generating vanes which create swirling effects on the mixture before exiting the injector through the discharge orifice. The atomizer main body is made up of Perspex to facilitate internal flow visualization.

2.2 Experimental Test Rig

An experimental test rig was constructed to perform the atomizer performance test. Water was used as the working fluid and nitrogen as the atomizing gas. A centrifugal pump delivers water from the water supply tank to the atomizer through the water-line. The amount of water flowing out of the pump controlled by the all valve. Pressure regulator controls the amount of gas flow from the nitrogen gas. Measurement of water and gas flow rate in the system is obtained through water and gas flow meter respectively. The flow of both water and gas are controlled by globe valves. Water strainer is installed at the inlet of water flow meter to prevent unwanted debris passing through the meter which could cause malfunctioned. Water and gas injection pressures are measured by digital pressure gauges. Water flow and gas check valve installed at the inlet of the atomizer to allow only one-direction flow. The atomizer fixed in vertical downward position produce water sprays into a water collection tank. A submersible pump delivers the water back into the water supply tank to complete the cycle. The water flowrate was held at a constant value. The video recordings of the resultant sprays produced were captured by a high-speed video camera with 800x600 resolutions at 1000 frames per second. The shutter speed was set to maximum value of 5 μ s. Shadowgraph technique was applied in acquiring the resultant sprays video recordings. A line diagram of the test-rig is shown in Figure 2.

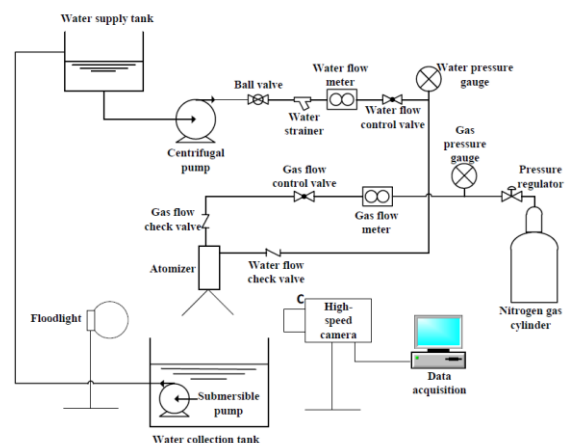


Figure 2 Line diagram of test rig

2.3 Experimental Design

The gas core diameter was determined using a 3 factors 3 levels Box-Behnken design. The independent parameters used are swirl-generating vane angle, gas flowrate, and discharge orifice diameter. The levels of each parameters are shown in Table 1 and the matrix

of experiments are shown in Table 2. The amount of gas flowrates selected in this study allows a bubbly flow regime exists inside the mixing chamber of the atomizer. The bubbly flow regime is the main features of an effervescent-related atomizer. The reason is the rapidly expanding air bubbles shatter the liquid phase and thereby enhancing the atomization quality [14].

Table 1 Range of factors and levels of atomizer performance test

Factors	Low (-1)	Middle (0)	High (+1)
Swirl-generating vane angle, γ (°)	30	45	60
Gas flowrates, Q (l/min)	0.2	0.4	0.6
Discharge orifice diameter, d_o (mm)	1.5	2.0	2.5

Table 2 Design matrix for atomizer performance test

Run no.	Swirl-generating vane angle	GLR	Discharge orifice diameter
1	0	-1	+1
2	+1	0	+1
3	0	+1	-1
4	0	-1	-1
5	-1	0	-1
6	0	+1	+1
7	-1	0	+1
8	+1	+1	0
9	0	0	0
10	-1	+1	0
11	+1	0	-1
12	-1	-1	0
13	0	0	0
14	0	0	0
15	+1	-1	0

2.4 Gas Core Diameter Measurement

Acquired videos were converted to sequence of images using video capture software. These sequences of images were processed via image

processing software for further analysis. A horizontal straight line vane (marked in red in Figure 3), downstream of the swirl-generating was drawn on the captured image to measure the gas core diameter. Based on the straight line, a grayscale profile was

plotted to visualize the changes of gray values along the line as shown in Figure 4. The captured images were converted to 8-bit images for further analysis. In the 8-bit image format, the range of the grayscale is between 0 for total absence (i.e. black) to 255 for total presence (i.e. white). Gas core diameter was obtained by taking the distance between two points at the lowest gray value as indicated in Figure 4. Due to the dynamic nature of the flow, the gas core shapes and size were changing over time. Hence, an average value was taken by considering several images at different time instants. The exact values corresponding to the grayscale profile are shown in Figure 5.

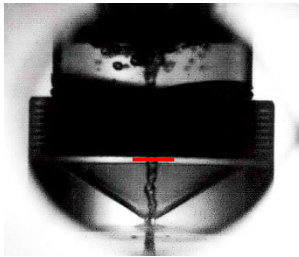


Figure 3 Measurement of gas core diameter using straight line tool

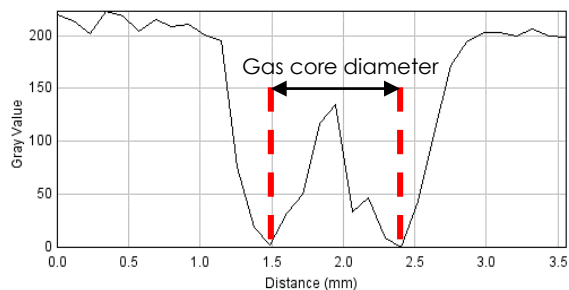


Figure 4 Gray values profile plot from ImageJ for one measurement

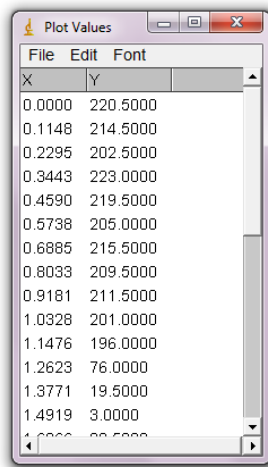


Figure 5 Part of the plot exact values correspond to Figure 4

3.0 RESULTS AND DISCUSSION

The results of the gas core diameter obtained are shown in Figure 6 to Figure 8. Figure 6 illustrates the interaction effect between swirl-generating vane angles and gas flowrate on the gas core diameter. It can be clearly observed in Figure 6 that swirl-generating vane angle and gas flowrate did not display an antagonistic interaction with each other which could moderate the effect of each parameter on the gas core diameter. This can be observed as there is no intersection between the line graphs. The gas core diameter increases with the increase of gas flowrate at every angle of swirl-generating vane. This was believed due to the characteristics of gas bubbles developed as the gas flowrate increased. This needs further investigations and to be discussed in another paper. Specifically in Figure 6, in the case of 0.2l/min gas flowrate, the size of the gas core is between 0.342 to 0.367mm. For the case of 0.4l/min gas flowrate, the size of the gas core varied between 0.704 to 0.999mm. In the case of 0.6l/min gas flowrate, the range of the gas core size is between 0.831 to 1.308mm. The gas core diameter is observed to increase with the swirl-generating vane angle at gas flowrates of 0.4l/min and 0.6l/min. This is likely caused by the swirl intensity of the flowing liquid. As reported by Ghaffar *et al.* [11], increasing the swirl-generating vane angle has produced an increase in the swirl intensity of the internal flow. However, at 0.2l/min, gas core diameter was unaffected by the changes in the swirl-generating vane angle. The gas core diameter at this condition remained at certain value regardless of the change in the swirl-generating vane angle. This may suggest that the swirl intensity at this condition is very weak.

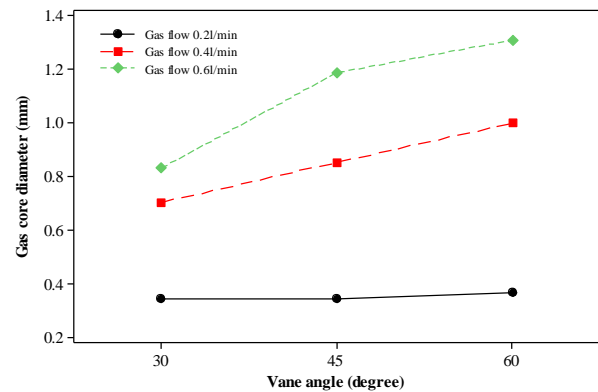


Figure 6 Interaction plots between swirl-generating vane angle with gas flowrate on gas core diameter

The plots of gas core diameter due to the interaction effect of gas flowrate and discharge orifice diameter is presented in Figure 7. Figure 7 shows that at all orifice diameter, the gas core diameter enlarged with the increase of gas flowrates. It is also can be deduced that at every gas flowrate, an

increase in orifice diameter lead to an increase of gas core diameter. This suggests that larger exit orifice allows larger gas core diameter to be formed inside the swirl chamber.

Figure 8 visualizes the effect of interaction between discharge orifice diameters with swirl-generating vane angle on the gas core diameter. It shows that at 30° and 60° swirl-generating vane angle, gas core diameter shows a decrement as discharge orifice diameter en-larges from 1.5mm to 2mm. Further enlargement of discharge orifice diameter resulting enlargement of gas core diameter. This trend however is different at 45° swirl-generating vane angle. At this condition, changes of discharge orifice diameter from 1.5mm to 2.5mm only shows enlargement of gas core diameter.

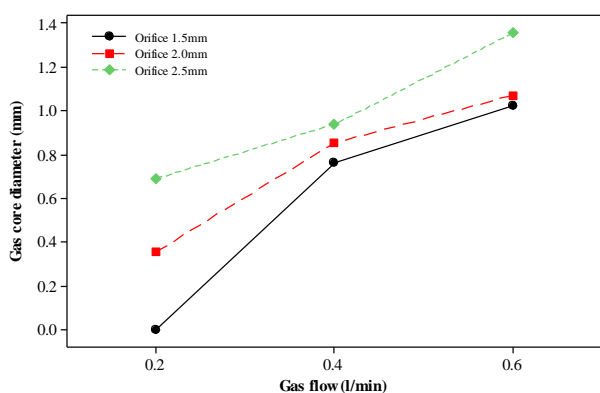


Figure 7 Interaction plots between gas flowrate with discharge orifice diameter on gas core diameter

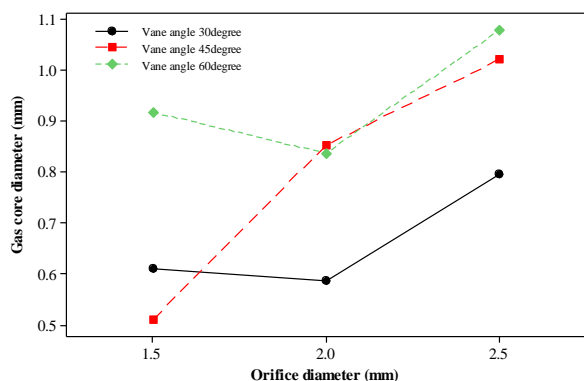


Figure 8 Interaction plots between discharge orifice diameter with swirl-generating vane angle on gas core diameter

Particularly in Figure 8, the gas core size for the case of 30° swirl-generating vane angle is ranging between 0.587 to 0.796mm. For the case of 45° swirl-generating vane angle, the size is between 0.511 to 1.022mm. For the case of 60° swirl-generating vane angle, the size is between 0.838 to 1.079mm. Based on the result, the combined effect of orifice diameter and vane angle is more complex compared to earlier cases described in Figure 6 and Figure 7. This suggests that the

interaction of these two parameters is inconclusive and requires further investigations.

4.0 CONCLUSIONS

This study is aimed primarily to understand the interactions between the gas flowrates with swirl-generating vane angle and discharge orifice diameter to the size of gas core formed inside a swirl effervescent atomizer. Based on the results obtained, the following can be concluded:

- i. Larger gas core was produced with increasing swirl-generating vane angle. The increasing gas flowrate tends to increase the size of the gas core for all cases of vane angle. In the case of 0.6l/min gas flowrate, the size of the gas core is between 0.831 mm and 1.308 mm.
- ii. Increasing gas flowrate produced larger gas core. The increasing discharge orifice diameter tends to increase the size of the gas core for all cases of gas flowrate. In the case of 1.5 mm orifice diameter, the size of the gas core is between 0 and 1.021 mm.
- iii. The combined effects of discharge orifice diameter and swirl-generating vane angle on the size of the gas core was inconclusive. In the case of 45° vane angle, the size of the gas core is between 0.511 mm and 1.022 mm

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