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Preliminary Analysis of Swirl Effervescent Atomization Droplet Diameter Distribution

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Abstract—**A swirl effervescent atomizer capable of producing fine droplets with relatively low injection pressures. A critical aspect of atomization is the resultant droplet diameter distribution, which portrays the efficiency of the atomization process. Dimensional analysis was conducted to identify the most significant parameters influencing the droplet diameter distribution. Three dimensionless numbers were selected considering their importance, which are the liquid Reynolds number, Re, the gas Reynolds number, and the swirl chamber length to discharge orifice diameter ratio. A test rig was fabricated to test the atomizer. Water acts as the working fluid, and air acts as the atomization assistance. The resultant spray images were captured using the shadowgraph technique. The images were analysed for droplet diameter measurement. The liquid Reynolds number and gas Reynolds number were found to have a significant impact on the droplet diameter distribution, particularly with an increase in the percentage of fine droplets. However, the dependence of the droplet diameter distribution on the geometrical ratio is less significant. This result is important for a preliminary understanding of the swirl effervescent atomization mechanics.**

Keywords—*Swirl effervescent atomization, Droplet diameter distribution, Reynolds number, Image analysis.*

I. INTRODUCTION

Swirl effervescent atomization is an advanced liquid atomzation technique that combines the principles of swirl and effervescent atomization. This method involves injecting gas into a liquid flow upstream of the discharge orifice, creating a two-phase mixture. As this mixture exits the atomizer, it undergoes rapid expansion, resulting in the formation of fine droplets. The addition of swirl to this process enhances atomization by imparting centrifugal force to the liquid, further promoting breakup and dispersion.

This atomization technique finds applications across various industries, including gas turbine combustion [1] and boilers [2]. Its ability to produce fine droplets with relatively low injection pressures makes it particularly attractive for these applications. The droplet diameter is the most important parameter in investigating a spray discharge from an atomizer. It is an indication of the completion of bulk liquid disintegration into a spray. At any given working condition, practical atomizers do not create sprays of uniform drop diameter; instead, the spray can be thought of as a spectrum of drop diameters dispersed around some arbitrarily chosen mean value [3]. A graphical representation of droplet diameters may be obtained by plotting a histogram of droplet diameter frequency distribution.

To simplify the complex interplay of variables in atomization, this study applies dimensional analysis using the Buckingham-Π theorem, which is a formal extension of Rayleigh's method. Rayleigh's approach involves identifying how physical quantities relate based on their dimensions (e.g., length, time, mass), while Buckingham's theorem provides a systematic way to group these variables into dimensionless numbers. These groups, called Π terms, help reveal the underlying physics by reducing the number of variables and highlighting dominant effects such as fluid properties, flow conditions, and geometry [4]. This framework is especially useful in atomization studies, where multiple interacting factors influence droplet formation.

Chinn [5] made use of dimensional analysis to investigate the inviscid flow of the swirl atomizer. Lachin *et al.* [6] use dimensional analysis to allow the prediction of the injection pressure as a function of the relevant fluid properties, process operating conditions, and atomizer geometric parameters for jet swirl

atomizer. Shafaee *et al.* [7] use dimensional analysis for the investigation of spray angle and droplet size distribution from a twin-fluid atomizer. Gödeke *et al.* [8] use dimensional analysis to characterize the ligament and droplet formation of a high-speed bell atomization. Conahan [9] performed dimensional analysis for jet impingement research. Hormozinezhad *et al.* [10] made use of dimensional analysis for the study of non-Newtonian droplet generation.

Apart from the importance of the dimensionless numbers in characterizing the droplet diameter distribution, the study of these parameters on the swirl effervescent atomizer is scarce, based on the author's knowledge. Hence, the present study aims of reporting the effect of the various dimensionless numbers on the droplet diameter distribution of the swirl effervescent atomizer for a better understanding on the swirl effervescent atomization mechanics.

II.   METHODOLOGY

A. Dimensional Analysis

The objective of this study is to present the droplet diameter distribution. However, for dimensional analysis, a representative diameter is required. This representative value is typically expressed as a mean droplet diameter, among which the Sauter mean diameter (D_{32}) is a commonly used metric. In this study, D_{32} was selected because it is particularly relevant to mass transfer processes as stated by Mugele and Evans [11].

D_{32} is hypothesized to be a function of several variables and can be written as:

$$D_{32} = f\left(d_o, d_s, d_p, l_o, l_s, \mu_L, \sigma_L, \dot{m}_L, \dot{m}_G, \Delta P_L\right) \quad (1)$$
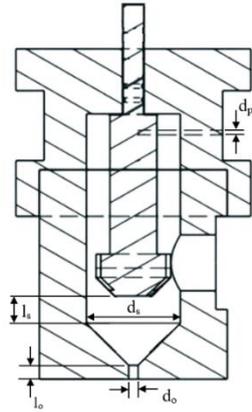

Fig. 1. Schematic of an atomizer design with labelled geometrical parameters. Adapted from Ghaffar *et al.* [12].

The hypothesis regarding the listed variables is derived from a summary of the review presented in [13], which examines the parameters influencing the droplet mean diameter. These parameters include the discharge orifice diameter, d_o, swirl chamber diameter, d_s, inlet port diameter, d_p, discharge orifice length, l_o, swirl chamber length, l_s, liquid viscosity, μ_L, liquid surface tension, σ_L, liquid mass flowrate, $\dot{m}_L$, gas mass

flowrate, $\dot{m}_G$, and liquid injection pressure differential, ΔP_L. Figure 1 illustrates the schematic of an atomizer, highlighting the aforementioned geometrical parameters.

According to the Buckingham theorem, for a system with N variables and D independent physical dimensions (such as length, mass, and time), the number of dimensionless groups is given by G = N − D. Since there are 11 variables as in Eq. (1), there are 8 dimensionless groups.

Accordingly, eight Π terms were formulated to analyze the relationship between droplet mean diameter and the identified parameters. The selection of repeating variables must include primary quantities representative of geometric, kinematics, and dynamics characteristics. The discharge orifice diameter, d_o was chosen to represent geometry, as it has been reported in the literature to exert a more significant influence on droplet mean diameter compared to other geometric parameters. The liquid mass flowrate, $\dot{m}_L$, was selected as the kinematics quantity, given its direct dependence on velocity. Although the gas mass flow rate, $\dot{m}_G$, is also available, $\dot{m}_L$ was preferred due to its stronger reported impact on droplet mean diameter. The liquid injection pressure differential, ΔP_L was chosen to represent dynamic effects, as it reflects force and acceleration within the system. Moreover, liquid injection pressure differential, ΔP_L is widely recognized in the literature as a key parameter in characterizing droplet formation. The listed three quantities; d_o, $\dot{m}_L$, ΔP_L were also selected as repeating variables because they cannot be combined among themselves to form any dimensionless product, thereby satisfying the requirements of the Buckingham-Π theorem.

The eight Π terms are:

$$\Pi_1 = \frac{D_{32}}{d_o} \quad (2)$$

$$\Pi_2 = \frac{d_s}{d_o} \quad (3)$$

$$\Pi_3 = \frac{d_p}{d_o} \quad (4)$$

$$\Pi_4 = \frac{l_o}{d_o} \quad (5)$$

$$\Pi_5 = \frac{l_s}{d_o} \quad (6)$$

$$\Pi_6 = \frac{d_o \cdot \mu}{\dot{m}_L} \quad (7)$$

$$\Pi_7 = \frac{\sigma_L}{d_o \cdot \Delta P_L} \quad (8)$$

$$\Pi_8 = \frac{\dot{m}_G}{\dot{m}_L} \qquad (9)$$

Π_2 can be re-written in the form of dimensionless number orifice-to-swirl chamber diameter ratio, N,

$$N = \frac{d_o}{d_s} = \frac{1}{\Pi_2} \qquad (10)$$

Since,

$$Re_L = \frac{\rho_L V_L d_o}{\mu_L} \qquad (11)$$

It can be re-written as a function of $\dot{m}_L$ with $V = \frac{\dot{m}_L}{\rho A}$ and $A = \frac{\pi d_o{}^2}{4}$ and yields,

$$Re_L = \frac{4\dot{m}_L}{\pi \mu d_o} \qquad (12)$$

Rearranging Π_6 yields

$$Re_L = \frac{4\dot{m}_L}{\pi \mu d_o} = \frac{4}{\pi} \cdot \frac{1}{\Pi_6} \qquad (13)$$

Π_8 is the dimensionless number gas-to-liquid ratio, GLR

$$GLR = \frac{\dot{m}_G}{\dot{m}_L} = \Pi_8 \qquad (14)$$

$\Pi_2 = N$ was not selected, as the investigated atomizer geometry involves variations in swirl chamber length, rendering N less representative of the system's geometric influence. Instead, $\Pi_5 = \frac{l_s}{d_o}$, the ratio of swirl chamber length to discharge orifice diameter, was chosen to better capture the geometric variation relevant to droplet formation. Similarly, $\Pi_8 = GLR$ was substituted with gas Reynolds number, Re_G considering this parameter will be used for a regime map construction later. Notably, gas-to-liquid ratio, GLR is generally proportional to gas Reynolds number, Re_G since both equations share the gas mass flowrate, $\dot{m}_G$ in the numerator, reinforcing the validity of this substitution.

B. Atomizer and Experimental Setup

A new swirl-effervescent atomizer design was fabricated, as illustrated in Fig. 2. This configuration integrates tangential inlets and swirl-generating vanes within a single embodiment. Fluids enter the atomizer through tangential inlets and subsequently pass through the swirl-generating vane, which enhances rotational motion. Downstream, the swirling flow enters a conical section before exiting through the discharge orifice. The swirl-generating vane is connected to a movable stem located at the centre of the atomizer. Adjusting the stem position alters the length of the swirl chamber. Raising the stem increases

the swirl chamber length and diminishes the swirl-generating vane's influence on the swirling flow.
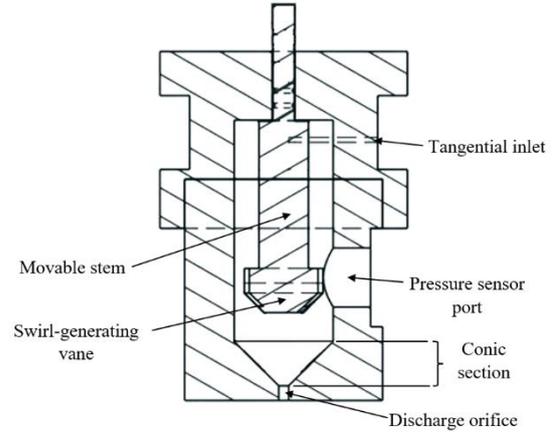

Fig. 2. Schematic of the new swirl effervescent atomizer design. Adapted from Ghaffar et al. [12].

A dedicated test rig was constructed to evaluate the performance of the atomizer. Water served as the working fluid, while compressed air provided atomization assistance. Spray visualization was conducted using a shadowgraph optical imaging technique, enabling high-contrast capture of droplet structures. Subsequent image processing methods were applied to extract quantitative data from the acquired images. The procedures for droplet diameter quantification were described in detail in [14].

C. Experimental Design

Droplet diameter distributions were investigated across a range of liquid Reynolds numbers, $847 < Re_L < 2540$, and gas Reynolds number, $0 < Re_G < 1514$. These operating conditions correspond to the initial stages of the liquid disintegration regime map proposed by Lorcher et al. [15], which served as the basis for selecting the Reynolds number ranges. Although the full regime map will be presented in a separate publication, the present study focuses on flow conditions characterized by single bubbles and homogeneous bubbly flow within the atomizer. The objective is to evaluate the swirl-effervescent atomizer's capability to disintegrate bulk liquid efficiently under low-energy input conditions.

The ratio of swirl chamber length to discharge orifice diameter was varied within the range $1.5 < l_s/d_o < 9.0$. With the discharge orifice diameter fixed at 2 mm, variations in the ratio were solely attributed to changes in the swirl chamber length, l_s. The maximum ratio of swirl chamber length to discharge orifice diameter, l_s/d_o of 9.0 corresponds to a swirl chamber length of 18 mm, which was selected based on the design guidelines proposed by Yang et al. [16]. Their methodology recommends a swirl chamber length twice the radial location of the tangential inlet centre in which the value is 9 mm in the present design. Modifying the swirl chamber length can influence internal flow stability, as reported by Kim et al. [17] and affect droplet transport dynamics, as demonstrated

by Fong *et al.* [18]. Therefore, tests were conducted with swirl chamber lengths shorter than 9.0 mm to investigate their impact on droplet diameter in the swirl effervescent atomizer. Experimental parameters are summarized in Table I. The study employed a Box–Behnken Design (BBD) approach to systematically explore the effects of key variables. Within this framework, one parameter was held constant at its mid-range value, as detailed in [14]. Details of the experimental design parameters are shown in Table I.

Table I. Range of experimental design parameters.

Parameter	Range		
	Low	*Medium*	*High*
Liquid Reynolds number	847	1270	2540
Gas Reynolds number	0	728	1514
Swirl chamber length to discharge orifice diameter ratio	1.5	4.5	9.0

III.   RESULTS AND DISCUSSIONS

The droplet diameter distribution of the investigated swirl-effervescent atomizer is presented using histogram plots, which visualize the effects of key operating parameters: liquid Reynolds number, gas Reynolds number, and the swirl chamber length to discharge orifice diameter ratio. Figure 3 illustrates the distribution corresponding to variations in liquid Reynolds number.

All histograms in Figs. 3, 4, and 5 were constructed using a bin width of 400 µm, selected based on the reported maximum droplet diameter for typical effervescent atomizers [19]. An additional threshold, discussed in the following paragraph, is the 2000 µm borderline which representing the upper limit of droplet size measurable by laser diffraction instruments. Droplets exceeding this threshold are classified as coarse droplets.

At a liquid Reynolds number of 847, droplets with diameters ≤400 µm were observed to be the most frequently discharged from the atomizer, as shown in Fig. 3(a). These fine droplets accounted for 32.33% of the total distribution. Additionally, 66.92% of all droplets exhibited diameters below 2000 µm, which aligns with the upper measurement limit of standard laser diffraction instruments. Notably, over half of the droplets did not exceed 33.33% of the maximum available droplet diameter (6000 µm).

Figure 3(b) presents the droplet diameter distribution at a liquid Reynolds number of 1270. Similar to the case in Fig. 3(a), droplets with diameters of 400 µm exhibited the highest frequency; however, the proportion increased to 46.65%. A notable reduction in larger droplets was observed compared to the distribution at liquid Reynolds number 847 with 92.8% of droplets falling below the 2000 µm threshold. An abrupt shift in the distribution toward finer droplets is evident in Fig. 3(c), corresponding to liquid Reynolds number of 2540. Here, 70.83% of droplets measured 400 µm or less, and 99.19% were

below 2000 µm. This leftward shift in the droplet diameter distribution across increasing liquid Reynolds numbers highlights the significant influence of liquid Reynolds numbers on atomization behaviour. The observed trend may be attributed to changes in internal flow regimes. Laminar flow typically occurs at liquid Reynolds numbers < 2100, while transitional flow is expected at liquid Reynolds numbers between 2100 and 4000, and turbulent flow dominates beyond liquid Reynolds numbers > 4000 [20]. Since all tested conditions fall within the laminar and transitional regimes, the finer droplets at liquid Reynolds number 2540 suggest enhanced liquid disintegration under transitional flow, compared to the relatively coarser distributions observed under laminar conditions at liquid Reynolds numbers 847 and 1270.
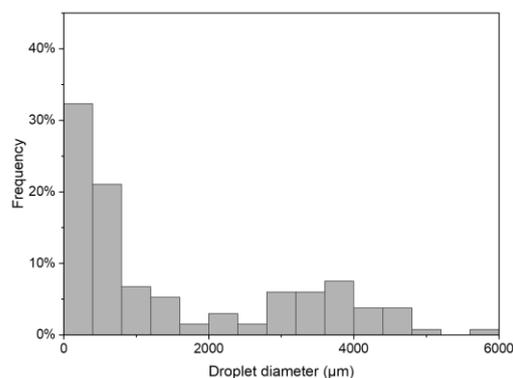

(a)
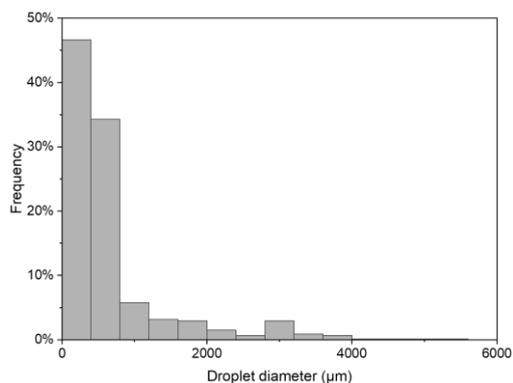
(b)
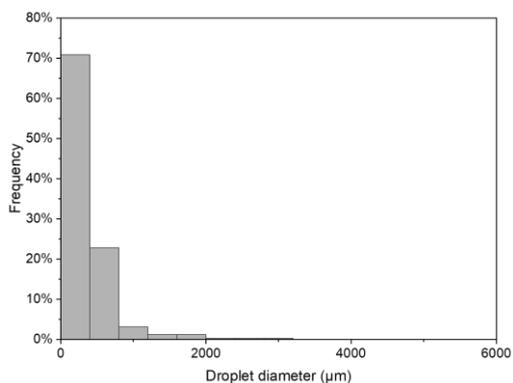
(c)

Fig. 3. Droplet diameter distribution plot of liquid Reynolds number (a) 847, (b) 1270 and (c) 2540 (Constant: $Re_G = 728$ and $l_s/d_o = 4.5$).
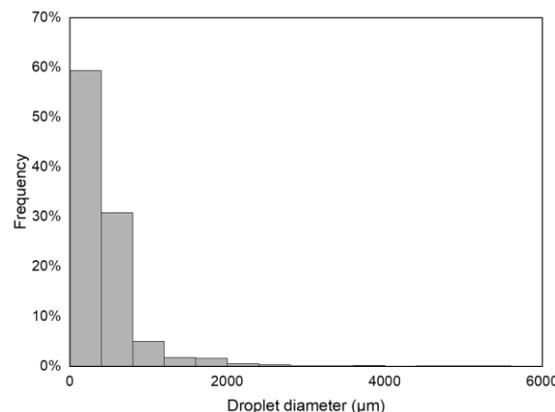
Figure 4 presents the droplet diameter distributions under varying gas Reynolds numbers. At gas Reynolds numbers, $Re_G = 0$, shown in Fig. 4(a), the influence of gas flow on atomization is absent. Under this condition, 24.83% of droplets exhibit diameters $\leq 400\,\mu m$, while 63.76% fall below the $2000\,\mu m$ threshold. This distribution closely resembles the trend observed in Fig. 3(a), where atomization is primarily driven by liquid flow alone. The similarity suggests that in the absence of gas assistance, the droplet breakup mechanism remains dominated by liquid-phase dynamics.
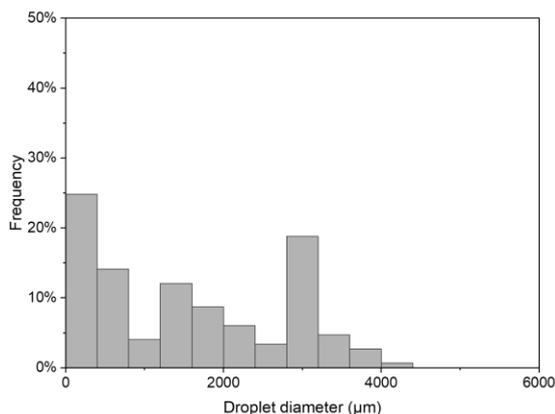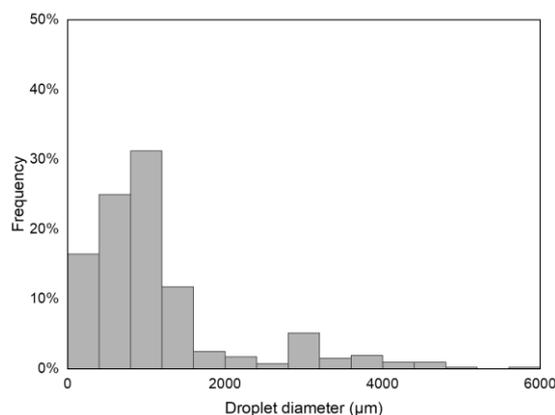
As the gas Reynolds number increases from 0 to 728, the droplet diameter distribution undergoes a notable shift. In Fig. 4(b), droplets within the $800\,\mu m$ to $1200\,\mu m$ range become the most prevalent, comprising 31.25% of the total population. Additionally, the proportion of droplets with diameters $\leq 2000\,\mu m$ rises significantly to 86.93%, compared to 63.76% in Fig. 4(a). Upon further increase of gas Reynolds numbers, Re_G to 1514, as illustrated in Fig. 4(c), the distribution shifts leftward, indicating finer atomization. This pattern closely mirrors the distribution observed in Fig. 3. Specifically, 51.83% of droplets fall within the $400\,\mu m$ range, and 97.97% remain below $2000\,\mu m$. These findings underscore the critical role of gas flow as the primary energy source in pneumatic or twin-fluid atomization, directly influencing spray characteristics such as droplet size and uniformity.

The histograms of the droplet diameter distribution under the influence of swirl chamber length to discharge orifice diameter ratio are presented in Fig. 5. It is visualized in Fig. 5(a), with swirl chamber length to discharge orifice diameter ratio, l_s/d_o at 1.5, 31.07% of droplets exhibit diameters $\leq 400\ \mu m$, while 90.86% remain within the $2000\ \mu m$ threshold. When the swirl chamber length to discharge orifice diameter ratio, l_s/d_o is increased to 4.5, as shown in Fig. 5(b), the proportion of fine droplets ($\leq 400\ \mu m$) rises markedly to 64.95%, with 95.14% of droplets falling below $2000\ \mu m$. At swirl chamber length to discharge orifice diameter ratio, l_s/d_o of 9.0, depicted in Fig. 5(c), 43.88% of droplets are $\leq 400\ \mu m$, and 93.73% do not exceed $2000\ \mu m$. These results suggest that while some variation in droplet size occurs with changes in swirl chamber length to discharge orifice diameter ratio, l_s/d_o, the overall distribution remains relatively consistent. This limited sensitivity may be attributed to the dominant role of gas-phase energy in twin-fluid atomization, where the atomizing air or gas governs droplet breakup more significantly than geometric parameters. Consequently, the influence of swirl chamber geometry is secondary to the momentum and flow characteristics of the injected gas.
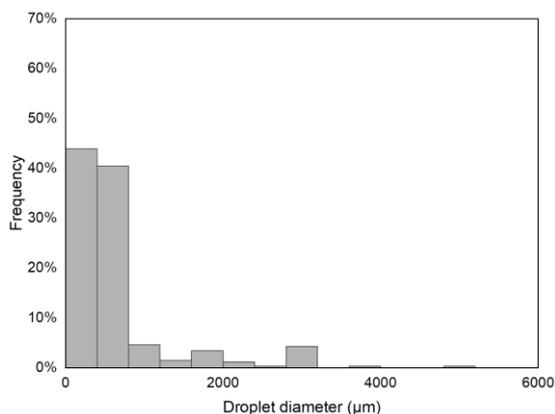

(a)

(b)

(c)
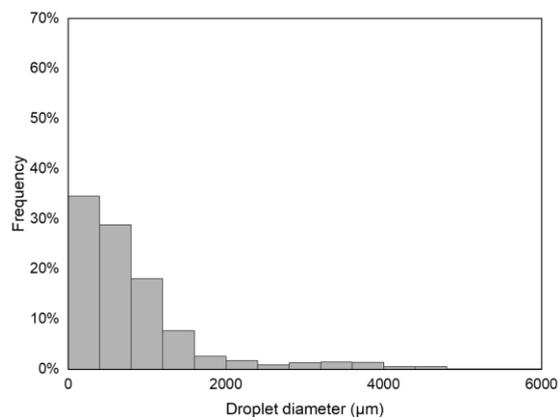
Fig. 4. Droplet diameter distribution plot of gas Reynolds number (a) 0, (b) 728, and (c) 1514 (Constant: $Re_L = 1270$ and $l_s/d_o = 4.5$).

(a)
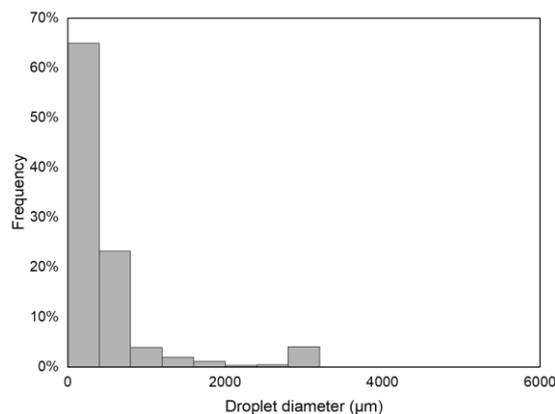
(b)

(c)

Fig. 5. Droplet diameter distribution plot of swirl chamber length to discharge orifice diameter ratio (a) 1.5, (b) 4.5, and (c) 9 (Constant: $Re_L = 1270$ and $Re_G = 728$).

IV. CONCLUSION

The preliminary analysis of the droplet diameter distribution of swirl effervescent atomizer is presented. It was found that the droplet diameter distribution is largely affected by the liquid Reynolds numbers and gas Reynolds number with the increase of fine droplets percentage. The geometrical dependent was observed to have less significant effects. The pronounced sensitivity of droplet diameter distribution to liquid and gas Reynolds numbers suggests that optimizing flow conditions rather than relying heavily on geometric modifications can be a more effective strategy for achieving finer sprays. This is particularly relevant for low-pressure systems where energy efficiency is critical, such as in agricultural spraying, fuel injection, or medical nebulization. Designers may prioritize adjustable flow control mechanisms or integrate feedback systems to modulate Reynolds numbers dynamically. Furthermore, the diminished influence of the swirl chamber length to discharge orifice diameter ratio implies that compact designs with simplified geometries may still yield effective atomization, opening avenues for miniaturized or portable atomizer systems.

AUTHOR CONTRIBUTIONS

Zulkifli Abdul Ghaffar: Conceptualization, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing –Original Draft Preparation; Salmiah Kasolang: Conceptualization, Validation, Project Administration, Resources, Supervision, Writing –Review & Editing; Ahmad Hussein Abdul Hamid: Conceptualization, Validation, Project Administration, Resources, Supervision, Writing – Review & Editing.

CONFLICT OF INTERESTS

No conflict of interests was disclosed.

ETHICS STATEMENTS

Our publication ethics follow The Committee of Publication Ethics (COPE) guideline. https://publicationethics.org/

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