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Numerical study of the effect of gas-to-liquid ratio on the internal and external flows of the effervescent atomizers

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Draft

Abstract

In an effort to capture the complex evolving interface of internal and external flow in an effervescent atomizer, a compressible Eulerian method along with Volume of Fluid coupled with the Large Eddy Simulation model are employed in a two-phase flow system. The water is injected into the atomizer with the constant mass flow rate of 0.0133 kg/s (i.e. 800 *mL/min*). The mass flow rate of air is adjusted to provide the variation of GLR from 0.55 to 2.6%. It is observed that the increase in the gas-to-liquid ratio (GLR) is accompanied with an evolution of the internal flow from a complex bubbly flow to an annular flow, which consequently reduces the liquid film thickness at the discharge orifice. Further studies on the internal pressure illustrate the critical condition, which leads to the choked flow and pressure oscillations at the discharge orifice. The examination of increasing the GLR and evolution of internal flow result in the alternation of primary atomization parameters such as shortening the breakup length and widening the spray cone angle. The numerical predictions are in good agreement with the experimental results under the same operating conditions.

Keywords: Effervescent atomization, Internal and external flow, VOF method, Large Eddy Simulation, Multiphase flow

1. Introduction

Effervescent nozzle is a distinct type of atomizer falling into the internal-mixing twin-fluid category of atomizers. However, the principal technique contrarily differs from other types of atomizers in this category. At the outset, this technique was introduced by Lefebvre et al. (Lefebvre et al. 1988; Lefebvre 1988; Wang et al. 1989) and Roesler (Roesler & Lefebvre 1989) as “aerated liquid atomization” in the early 1990s. The term “effervescent atomization” was primarily used by Buckner et al. (Buckner et al. 1990; Buckner et al. 1990). Since then, effervescent atomization has been used in a wide range of applications such as internal combustion engines, gas turbine engines, chemical processing, agriculture, spray drying, thermal spray coatings, etc.

During the past two decades, researchers revealed the advantages of the effervescent atomizer in comparison to the conventional, twin-fluid and rotary atomizers. Previously illustrated experimental results show that the pressure required for desirable atomization is much lower than what is needed for other types of atomizers (Lefebvre 1988; Wang et al. 1989; Buckner et al. 1990). In such context, the drop sizes for each specific pressure are smaller than what is obtained by other conventional methods (Lefebvre 1988; Roesler & Lefebvre 1989; Buckner et al. 1990). Moreover, due to the lower inject pressure; the gas flow rate is much lower than other kinds of twin-fluid atomizers. Consequently, less energy is required to inject atomizing gas (Lefebvre 1988; Roesler & Lefebvre 1989; Buckner et al. 1990). Furthermore, the diameter of the discharge orifice is greater than conventional atomizers' exit diameters; accordingly, they have a higher flow rate and lower probability of clogging (Roesler & Lefebvre 1989; Marek & Cooper 1980). In addition to other benefits of using an effervescent atomizer, it is particularly beneficial in combustion applications. This is due to its ability to reduce the pollutant emissions because of the existence of air in the spray core (Lefebvre 1988). The effect of viscosity of liquid on the mean drop size is relatively low, which shows the capability of the

effervescent atomizer to handle different liquids (Buckner & Sojka 1991; Buckner et al. 1989). It should be added that due to the lower exit velocity of the fluid, than those for conventional atomizers, erosion is decreased for injecting suspension by an effervescent atomizer (Chawla 1985).

The independent parameters affecting the spray characteristics of effervescent atomizer are categorized by Sovani et al. (2001) which includes injection pressure drop, gas to liquid ratio (GLR), physical properties of the liquid and internal geometry of the atomizer. J. Jedelsky and M. Jicha (2015) experimentally investigated and optimized multi-hole effervescent nozzles. They concluded that the spray cone angle was reduced by reduction of the pressure and the GLR for the narrow-angle exit orifice. In contrast, the cone angle was constant for wide exit orifice atomizers. Furthermore, they indicated that these atomizers tend to be unsteady at lower pressures and GLRs. The effect of physical properties of the liquid and air, such as viscosity and surface tension has been investigated by different researchers. Few researchers including Buckner and Sojka (Buckner & Sojka 1991; Buckner et al. 1989) reported that the viscosity of liquid has no effect on the droplet mean diameter. Nevertheless, Lund et al. (1993) and Sutherland et al. (1995; 1997) indicated a small dependency of the droplet mean diameter on the viscosity. Lund et al. (1993) illustrated that a four times increase in viscosity results in only 15% increase in droplet mean diameter. In contrast to these results, which were obtained at rather lower injection pressure in the range of 0.2-2.0 MPa, Satapathy et al. (1998) demonstrated a strong dependency of mean droplet size on viscosity in the relatively higher pressure range of 11-33 MPa. In addition, Stähle et al. (2015) indicated that a slug flow formed at the low GLRs for the liquids with high viscosity (i.e 308 mPa.s). This resulted in very large and deformed droplets and consequently concluded that the effervescent atomizer is not suitable for drying of the food. Other researchers such as Kleinhans et al. (2016) confirmed the unsteadiness of the spray at low GLRs; however, they found out that the GLR threshold for the spray unsteadiness was dependent on the geometry of their nozzles.

In terms of surface tension effects, Lund et al. (1993) and Sutherland et al. (1995; 1997) reported contrary results. Lund et al. (1993) reported an increase in Sauter Mean Diameter (SMD) by increasing surface tension while Sutherland et al. (1995; 1997) results indicated that SMD remains constant by varying the surface tension. Liu et al. (2011) experimentally studied the effect of fluid physical properties on unsteadiness of effervescent atomization for water and mixture of water/glycerol. They realized that the increase in GLR for water case results in a more unsteady spray while the outcomes for mixture case indicated that spray is more unsteady by reducing GLR.

In comparison to the large number of studies that carried out experimentally on effervescent atomization, only a few researchers have numerically studied this process. Initially, Buckner and Sojka (1993) based on the mass flow rate of the liquid, gas phase, and fluid properties proposed a model to calculate the mean droplet size after a primary breakup. This approach was improved by Lund et al. (1993) by adding the effect of atomizer exit geometry. The aerodynamic effect of gas was incorporated by Sutherland et al. (1997) to include the influence of relative velocity between gas and liquid phases. Later on, by introducing a secondary atomization model using a Lagrangian approach, Xiong et al. (2009) predicted the droplet mean size. Despite the complexity of the phenomena occurring inside, which affects the flow outside of the atomizer, a few researchers tried to simulate the internal flow. Esfarjani and Dolatabadi (2009) numerically studied the structure of two-phase flow inside the effervescent atomizer using an incompressible Eulerian-Eulerian approach. They resulted that the fluid properties do not have a significant effect on the thickness of liquid in the discharge passage of orifice in different GLRs. Since they employed an Eulerian-Eulerian approach, they were forced to use an averaging approximation in order to calculate the film thickness. During their analysis, they did not employ any surface tracking method to capture the interface between the two phases. Thus, several fundamental phenomena such as the evolution of the interface, disturbances on the interface that are the source of atomization in primary atomization, surface

tension effect, and external flow are missing in their study. Pougatch et al. (2014) simulated the effect of mixture non-uniformity using an in-house code based on the Eulerian-Eulerian method. They concluded that the radial non-uniformity of the inlet volume fraction has a minor effect on the average droplet size. In contrast, the vertical non-uniformity had a significant effect on the droplet mass distribution and increased the average droplet diameter.

In the current work, a compressible two-phase volume of fluid method along with a large eddy simulation turbulence model is employed to study the internal and external flow of an effervescent atomizer. These models are able to capture surface evolution and disturbances as well as pressure jump and choking phenomena. Furthermore, as most of the experimental setups are only able to study qualitatively the far field spray, there is lack of near-field study. Therefore, in addition to the internal flow, near-field external flow is investigated to provide a better understanding of the dense spray at the nozzle exit. The range of GLR for numerical studies is selected between 0.55 and 2.6% in order to compare with the available in-house experimental results.

2. Geometry and boundary conditions

As depicted in Fig. 1, the water is injected into the atomizer through the upper inlet with the constant mass flow rate of 0.0133 kg/s (i.e. 800 mL/min). The air phase is introduced to the mixing chamber with constant mass flow rate as well from a smaller circular area with the diameter of 0.7 mm at the end of the tube in the middle of the atomizer. The mass flow rate of air is adjusted to provide the variation of GLR from 0.55 to 2.6%, as tabulated in table 1. Diameter of discharge orifice is 2 mm with length-to-diameter ratio of two. The computational domain is $50 \times 50 \times 25$ mm. The atomizer walls are set to have no-slip velocity and zero-gradient pressure conditions. The top surface is set to be a wall according to the experimental setup. In

addition, the side and the bottom surfaces are set to be as total pressure while velocity is calculated based on the pressure field.

A combined structured hexahedral and polyhedral mesh, as shown in Fig.2, is generated along with local refinement in order to have efficient computations. The mesh size in the refined part is in the range of 20 to 30 μm . The numerical schemes are chosen in a way to ensure the second order accuracy of the simulation.

The k values of turbulence flow for inlets are obtained using.

$$k = \frac{3}{2}(UI)^2 \quad (1)$$

where “ I ” and U refer to the turbulence intensity and initial velocity magnitude, respectively. The value of turbulence intensity for liquid inlet assumed to be at the low level of 2% as the velocity and Reynolds number are low. This value for air inlet is considered to be relatively higher (i.e. 10%) due to the high velocity of air phase.

3. Governing Equations

The governing equations of the computational model for the compressible phenomena occurring in effervescent atomizer are continuity, momentum, and energy equations. The continuity and momentum equations are,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{U}) = 0 \quad (2)$$

$$\frac{\partial (\rho \vec{U})}{\partial t} + \nabla \cdot (\rho \vec{U} \vec{U}) = -\nabla p + \nabla \cdot (\mu \nabla \vec{U}) + (\nabla \vec{U}) \cdot \nabla \mu - \rho g - g \cdot \vec{x} \nabla \rho + \sigma \kappa \nabla \alpha \quad (3)$$

where $\vec{U}$ is the velocity vector, p , x , ρ , σ , a , k are pressure, position vector, density, surface tension, body force (gravity) acceleration and the curvature of the interface, respectively. To capture the interface evolutions, a compressible volume of fluid method is employed in which the distribution of the mixture density and the viscosity are calculated using α known as the volume fraction of the main phase,

$$\rho = \alpha\rho_l + (1 - \alpha)\rho_g \quad (4)$$

$$\mu = \alpha\mu_l + (1 - \alpha)\mu_g \quad (5)$$

where g and l are the subscripts indicating liquid and gas phases, respectively. In order to designate the interface, the scalar indicator, α , is employed. The values of α based on the Heaviside function is unity in the liquid phase, zero in the gas phase and a distribution between zero and unity for the interface between both. The function of this scalar indicator is as follows,

$$\alpha = \begin{cases} 1 & \text{in liquid} \\ 0 < \alpha < 1 & \text{at the interface} \\ 0 & \text{in gas} \end{cases} \quad (6)$$

For compressible flow according to equation (7), the discontinuity will spread into the computational domain, as:

$$\frac{\partial \alpha}{\partial t} + (\vec{U} \cdot \nabla) \alpha = (\alpha_l(1 - \alpha_l)) \left(\frac{\psi_g}{\rho_g} - \frac{\psi_l}{\rho_l} \right) \frac{DP}{Dt} \quad (7)$$

where ψ_l and ψ_g are compressibility factor of the two phases.

Rusche (Rusche, 2002) proposed a bounded compression term, which leads to a sharper interface between the different phases. The modified equation of volume fraction with the extra artificial compressive term is as follows,

$$\frac{\partial \alpha}{\partial t} + (\vec{U} \cdot \nabla) \alpha + \nabla \cdot (\vec{U}_r \alpha (1 - \alpha)) = (\alpha_l(1 - \alpha_l)) \left(\frac{g}{\rho_g} - \frac{\psi_l}{\rho_l} \right) \frac{DP}{Dt} \quad (8)$$

The artificial compressive term is equal to zero outside the interface. Due to the term of $\alpha(1 - \alpha)$. U_r is the relative normal velocity of the interface and is equal to,

$$U_r = k_c n \max \frac{|\vec{n} \cdot \vec{U}|}{|S|^2} \quad (9)$$

$$\vec{n} = \frac{\nabla \alpha}{|\nabla \alpha| + \delta} \quad (10)$$

where $\vec{n}$, the interface unit normal vector, calculated by obtaining the gradient of α at the cell faces, δ is a small amount to avoid singularity where $\nabla \alpha = 0$, S is the surface area vector, and k_c is an adjustable coefficient to define the amount of compression in equation 9, chosen to be $k_c = 1.5$. The artificial compression term helps to achieve a sharper interface without affecting the solution outside the region due to $\alpha(1 - \alpha)$ term, which automatically diminishes the effect of the compressive term outside of the interface. The surface tension term affects only interfacial cells and is modeled as a body force using the Continuum Surface Force method (Rusche, 2002),

$$F_b = \sigma k \nabla \alpha \quad (11)$$

where the curvature of the free surface, k , is

$$k = -\nabla \cdot \left(\frac{\nabla \alpha}{|\nabla \alpha|} \right) \quad (12)$$

The energy equation is as follows,

$$\frac{\partial(\rho e)}{\partial t} + \nabla \cdot (\rho \vec{U} e) - \nabla \cdot q + p \nabla \cdot \vec{U} = 0 \quad (13)$$

where q represents the summation of the molecular and turbulent heat flux and e is the average of internal energy based on volume fraction as,

$$q = q_{ml} + q_{Turb} \quad (14)$$

$$e = \frac{c_{v,l} \alpha_l \rho_l T + c_{v,g} (1 - \alpha_l) \rho_g T}{\rho} \quad (15)$$

The closure of the chosen system of equations in compressible flow will be the ideal gas equation of state and a linear model for liquid phase (Eq. 17),

$$P = \rho RT \quad (16)$$

$$\rho = \rho_0 + \psi_l(P - P_0) \quad (17)$$

In Large Eddy Simulation (LES) approach using one equation for finding Subgrid Scale (SGS) kinetic energy, smooth filtering coefficient of Δ is considered one with maximum Δ ratio of 1.1. Eddy viscosity and SGS kinematic viscosity are employed to approximate the SGS stress tensor where they both have a transport equation proposed by Yoshizawa and Horiuti (Yoshizawa & Horiuti, 1985) described by,

$$\tau_{SGS} = \overline{UU} - \overline{U}\overline{U} \quad (18)$$

$$\tau_{SGS} = \frac{2}{3} k_{SGS} l = -\frac{\mu_{SGS}}{\rho} [\nabla \overline{U} + (\nabla \overline{U})^T] \quad (19)$$

$$\frac{\partial k_{SGS}}{\partial t} + \nabla \cdot (k_{SGS} \overline{U}) = \nabla \cdot [(\vartheta + \vartheta_{SGS}) \nabla k_{SGS}] - \varepsilon - \vartheta_{SGS} S^2 \quad (20)$$

where ε , ϑ_{SGS} and S are calculated through following equations:

$$\varepsilon = \Delta C_\varepsilon (k_{SGS})^{3/2} \quad (21)$$

$$\vartheta_{SGS} = \Delta C_k (k_{SGS})^{1/2} \quad (22)$$

$$\bar{S} = \frac{1}{2} [\nabla \overline{U} + (\nabla \overline{U})^T] \quad (23)$$

where $C_\varepsilon = 1.05$ and $C_k = 0.07$. It should be noted that the SGS filtering is used to perform the modeling; however, the filters are not treated at the interfaces. Consequently, the SGS filtering is not treated at the interface.

It should be mentioned that all the simulation are carried out using Open Source Field Operation and Manipulation (OpenFOAM) C++ libraries. It is an open source CFD toolbox developed by OpenCFD Ltd (Anon., n.d.) and uses the finite volume scheme to discretize the governing equations.

4. Results and discussion

4.1. Internal flow pattern

Characteristics of the external flow in effervescent atomization such as breakup length, primary-secondary atomization, cone angle, and velocity are governed by the flow structure

inside the atomizer. Different parameters such as the atomizer geometry (i.e. mixing chamber size, aerator holes numbers, size, and location), GLR, and fluid properties have a significant influence on the internal flow. Considering the complexity and required computation time for capturing pure bubbly flow, the effect of bubbly flow (close to plug/transient flow) at the discharge orifice and outside is captured. The bubble detachment in the passage of the discharge orifice and bubble stretching are shown in Fig. 3. In the beginning, bubbles start growing in the mixing chamber and then stretching towards the orifice passage (Fig. 3-a). As the velocity increases at the beginning of the discharge orifice, the detachment of bubbles initiates (Fig 3-b). Due to the lower pressure in the discharge passage, the detached bubble expands gradually which result in pressure variations (Fig 3-c). In continuation, the bubbles suddenly expand upon exiting the discharge orifice, which results in bubbles bursting downstream the atomizer (Fig 3-d). In figure 3 also, in pictures, a, b and c, one cycle of the process is shown and in picture d, 4 cycles after are shown. In picture d, one bubble is burst outside and three bubbles are following with almost the same periodical condition. The mechanism of breakup is in good agreement with the visual studies of Roesler and Lefebvre (1988) for bubbly flow regime.

The initial regime in the atomizer is bubbly flow, where the small bubbles grow upon passing the discharge orifice and their consequent sudden burst results in liquid fragmentation, i.e., atomization. The effect of GLR on internal flow pattern is compared to Tabrizi's experiments (Tabrizi 2013) in Figs. 4 and 5. In these figures, the iso-surface of the volume fraction of 0.5 represents the interface between two phases for the numerical results.

The comparison shows that at low GLRs, for example, $GLR = 0.55\%$, the bubbles are stretching in the mixing chamber due to the high pressure and low velocity which leads to the bubble bursting in the orifice discharge. This regime is categorized as the bubbly flow (Fig. 4). By further increase in GLR, for example, $1.1\text{--}2.6\%$, the flow is altering to the annular flow where a core of gas flow is surrounded by a thin layer of the liquid sheet (Fig. 5). The results are in a

good agreement with Tabrizi's (Tabrizi 2013), and Roesler and Lefebvre's experiments (Roesler & Lefebvre 1989) in the sense of the type of the flow in the orifice.

4.1.1. Liquid film thickness

In this section, the thickness of the liquid film in the discharged passage is numerically studied. One of the main effective parameters on liquid thickness is the level of GLR and this effect is more significant in relatively lower GLRs. After reaching to a certain level, any further increase in GLR leads to the slight reduction in the thickness. Lin et al. (2001) have experimentally investigated the effect of various GLR levels and the liquid flow rate on the liquid film thickness in a square cross-section effervescent atomizer. They proposed an empirical equation base on the gas flow rate. The current numerical results will be compared with their correlation for a specific range. The liquid film thickness is calculated by averaging data through the time with the following formula.

$$t = \frac{1}{2}(D_o - D_g) \quad (27)$$

where t is the liquid thickness, D_o is the diameter of discharge orifice and D_g is the diameter of the gas core. It should be noted that the value of D_g is calculated by averaging the area, where the gas core has occupied at the discharge orifice and calculating the equivalent diameter. For example, the liquid film thickness for GLR=2.6% at the exit plane of the discharge orifice is shown in Fig. 6, where α is volume fraction with the range of unity for liquid phase and zero for the gas phase. For higher GLRs, the measurement of gas core diameter is easier since there are fewer oscillations in the diameter by time. The determined liquid film thickness compared with the proposed correlation based on gas flow rate by Lin et al. (2001) is presented in Fig. 7. As shown, the measured simulation data have the same trend as the experimental results and both are in good agreement with each other.

It should be noted that Lin et al. (2001) used a square cross-section atomizer for better shadowgraphy purposes. However, for calculation of film thickness, they considered the hydraulic diameter to relate it to more practical cylindrical discharge orifices. Both results demonstrate the immense effect of aerating gas flow rate on liquid film thickness. As shown in Fig. 7, variations in the lower range of GLRs lead to rapid variations in film thickness, whereas the further increase in the higher range of GLRs results in a slight change in liquid film thickness. The advantage of a thinner liquid film is earlier break-up of the liquid sheet and consequently smaller droplets with higher velocity. Having small droplets is beneficial in different applications such as drying, combustion, and suspension thermal spray. In suspension thermal spray where the suspension is a method to inject sub-micron to nano-size particles through liquid into a plasma plume, having smaller droplets is beneficial as they contain a smaller amount of particles. The smaller amount of particles leads to the smaller size particle agglomerations after rapid evaporation of liquid phase. The smaller the droplets, the smaller produced agglomerated particles, which results in better particle distributions and higher coating quality.

4.1.2. Internal flow

One of the challenging issues of understanding the principal of effervescent sprays is to understand the internal flow properties such as pressure gradients, velocity change, temperature, and critical conditions of flow. Prediction of flow condition based on the liquid volume fraction has a significant influence on the external flow characteristics. Chawla (1985) has reported that however the speed of sound in single-phase flow for water and air is respectively 1300 m/s and 300 m/s, the speed of sound has a sudden decrease in two-phase flow mixture where it reaches the value as low as 20 to 30 m/s. The consequence of this critical condition is the pressure jump occurring at the orifice exit. This relatively higher-pressure difference at discharge orifice exit results in a sudden expansion of the gas phase and breakup of the liquid even at lower velocities.

The numerical results show that the effervescent atomizer is too unsteady and frequently works in the critical condition. At the beginning of the process, the pressure of the atomizer increases to a maximum value depending on the GLR value (i.e. gas injection pressure). The internal pressure of the atomizer gradually decreases upon exiting of the air phase.

Within the few starting steps, when the gas reaches the discharge orifice, the pressure in the atomizer is at the maximum point. Nevertheless, through further additional time steps, the internal pressure of the atomizer decreases to reach a stable pressure. It is observed that by reaching the critical condition, few oscillations inside the nozzle occur which creates the unsteadiness behavior of the effervescent atomizer.

The pressure variations inside the atomizer are accompanied by the temperature variations of gas, particularly in the orifice passage where the pressure changes are significant. The same phenomenon happens at the discharge orifice where a pressure jump occurs due to the choked flow. Because of high expansion rate and high velocity of the gas phase at the discharge orifice, the gas temperature drops suddenly. In addition, both temperature and pressure show an oscillatory behavior inside the orifice exit. The oscillatory behavior of the internal pressure at the discharged orifice of the atomizer is captured by extracting data through time. Figure 8 shows the location of the data extraction.

The sample oscillatory behavior resulting from the effect of choked flow at the discharged orifice is shown in Fig.9. The instabilities of the pressure at the discharge orifice as well as pressure differences between the discharge orifice and ambient are due to choked flow occurring at the atomizer exit. The mixture reaches a sonic condition even in much lower velocities (Chawla 1985). Those oscillations transmit to liquid and gas interface that result in waves on the interface and consequently breakup of the liquid sheets upon exiting from the discharge orifice.

The frequent variations of the pressure at the discharge orifice in the simulation probably can be used for calculating the frequency of the choked flow occurring at the atomizer exit,

though, it requires further studies to relate this frequency to the working condition frequency of the effervescent atomizer. The effect of different GLRs is shown in the following figures as a sample where two other GLRs of 1.1% and 1.6% are studied.

For GLR values of 1.1 and 1.6%, the amplitude of the pressure oscillations and the average values show a decrease in comparison to higher GLRs. The lower amplitude of oscillations results in lower rate of expansion of the gas phase upon exiting from the discharged orifice and consequently a smaller cone angle. By further reduction in the flow rate of the injected gas, the mixing chamber and the overall atomizer pressure are decreased and the frequency of instabilities decreases for lower GLRs as depicted in Fig. 9, which results in the more unsteady spray. The increase in unsteadiness of the spray is also concluded by Liu et al. (2011) where they indicated that the unsteadiness of the spray is rapidly reduced close to the $GLR = 3\%$.

For GLRs less than 0.55% where the flow is nearly bubbly (Fig. 10), the trend of decreasing the magnitude of oscillations by reducing the GLR is evident. However, once a large bubble leaves the orifice discharge, the pressure has few peaks, which are due to the flow choking. The trend of pressure variations demonstrates that the GLR has a significant effect on frequency and magnitude of the pressure variations of the effervescent atomizer. This unsteadiness is beneficial in suspension injection where the steady injectors struggle with clogging problem while the unsteadiness in terms of pressure change in the effervescent atomizer serves as a self-cleaning mechanism.

4.2. External flow

This section presents the results of the numerical study of the effect of various GLRs on the primary atomization parameters i.e. breakup length and cone angle. Furthermore, the relationship between the internal flow and these parameters is comprehensively discussed. Finally, the velocity of liquid and air are investigated in the near field for various GLRs.

4.2.1. Liquid Breakup length and cone angle

The first set of images in Figs. 11 and 12, demonstrate the variation of breakup length according to GLRs. For lower GLRs (i.e. $\text{GLR} = 0.55\%$) the bubble gradually expands upon exiting from the discharge orifice due to the pressure jump. This gradual expansion results in longer breakup length whereas, by a further increase in GLR, the internal flow pattern changes. The transition from the bubbly flow with random breakups to the annular flow by a further increase in GLRs leads to a steadier and shorter breakup length.

It should be noted that the mechanism of breakup from low GLR to higher GLR alters from breakups due to bubble expansion to breakup due to high interface disturbances in higher GLRs. These mechanisms of breakups are in agreement with the experimental results of Buckner & Sojka (1991) and Santangelo & Sojka (1995). Moreover, the visual comparison of results is in good agreement with experimental results of Tabrizi (2013) in Fig.13, where the breakup lengths are averaged through the time. Fig. 13 shows that the breakup length has the highest value of 8.7 mm for the lowest GLR of 0.55%. By increasing the amount of aeration i.e. increasing GLR to 1.1%, 1.6%, and 2.6%, the breakup length reduces to the lower values of 5.9, 4.6, and 1.1 mm, respectively. The trend of results is in good agreement with those obtained by Tabrizi's (Tabrizi 2013) experiments as shown in Fig. 13. For Maximum GLR where the atomization occurs near the atomizer exit, experimental method of measurement has more error due to the usage of shadowgraphy. However, numerical results show a shorter breakup length for higher GLRs, where shadowgraphy is not able to give accurate results.

The next critical parameter that narrows the application of each atomizer is the cone angle of the spray plume. Fig. 14 demonstrates the effect of alternation in GLR on the spray cone angle. These results are obtained by averaging the cone angle through time. As shown in Fig. 14, the cone angle increases suddenly from 9 to 13° due to the transition from the bubbly flow ($\text{GLR}=0.55\%$) to the annular flow ($\text{GLR}=1.1\%$). By further increase in GLR to 2.6%, the cone angle gradually increases to its maximum value of 16 degrees. At the bubbly flow regime, the

expansion of the bubbles helps to overcome surface forces. However, in the annular regime, the resultant breakups are due to overcoming aerodynamic forces on the liquid sheet surface tension. The trend of growth of the cone angle is in good agreement with the experimental results of Tabrizi (2013).

4.2.2. Flow analysis at the nozzle exit

Another determinant parameter of the atomization is the velocity of liquid and air that defines the downstream characteristics of the droplets. Due to the existence of the liquid trunk in the near-field of the nozzle exit, spray characterization techniques such as Phase Doppler Particle Analyzer (PDPA) and Particle Image Velocimetry (PIV) cannot be used efficiently. However, this important parameter can be studied by extracting the results from the numerical simulation of the flow at the near-field of the nozzle exit.

The effect of different GLRs on liquid and air phases velocity is shown in Figs. 15 to 17. At the lowest GLR (0.55%), the velocity of air is at its lowest value with a maximum value of 50 m/s near the atomizer exit and lowest value of 10 m/s at the end of the domain. The velocity of liquid for this case is in the range of 3-7 m/s. Since the pattern of the atomization in the lower GLR is undesirable for our application, a further increase in GLR is required to reach to the applicable range. The results illustrate that by increasing GLR from 0.55 to 1.1%, the velocity of both phases increases to the higher value of 100 m/s for air and 23 m/s for the liquid phase. The average velocity of the liquid for a GLR of 1.1% is around 13 m/s. An additional increase in GLR up to 2.6% leads to significantly higher and wider velocity profile for air phase and consequently the liquid phase. It should be noted that higher velocity in the liquid phase for higher GLRs is due to the higher gas velocity and the thinner liquid film thickness discussed in the previous section. In the internal flow, an increase in the gas flow rate squeezes the liquid film thickness, thus the liquid exits the discharge orifice with a higher velocity.

The significant difference between the velocity of the liquid and the gas phases illustrated in these figures shows the effect of aerodynamic forces on the primary breakup of the liquid trunk.

As depicted in Fig. 18, the average velocity of the gas phase at the discharge orifice is at its higher value and reduces by an increase in axial distance from the discharge orifice. The high value of the relative velocity between two phases dominates the aerodynamic forces and produces a high shear stress rate at the atomizer exit. The shear stresses along with surface disturbances initiate the primary breakup of the liquid trunk to ligaments and large droplets. This effect is more obvious for the maximum GLR value, where the generated droplets are smaller and there is no liquid trunk in the downstream region. The high relative velocity close to the discharge orifice has been reported by Qian et al. (2011) as well.

Figs. 19 and 20 show the penetration rate of the gas phase and the liquid phase for the largest GLR value of 2.6%. The transfer of momentum energy of the gas phase to the liquid phase helps a better penetration rate for the droplets. Close to the atomizer exit, the gas phase velocity is at its maximum and, with distance down the jet, the gas phase energy dissipates. High air momentum transferring to the liquid at the center of profile enhances the velocity of liquid droplets and, consequently, a velocity profile with the higher velocity at the center is obtained.

5. Conclusion

With immense applications of effervescent atomizers in combustion and suspension thermal spraying, a better understanding of the internal and external flow structure will allow us to improve the associated processes. For achieving this goal, in this study, a three-dimensional analysis of the two-phase flow inside and outside of an effervescent atomizer was carried out. A compressible, Eulerian two-phase model along with VOF surface capturing and LES turbulent model was employed to simulate the internal and the external flow. The influence of flow parameters such as gas to liquid ratio and the relative velocity between phases on spray

characteristics such as the cone angle and the breakup length was investigated. The results were compared with the experimental studies of Tabrizi (2013).

The results of this study show that by increasing the GLR values from 0.55 to 2.6% the cone angle and instabilities on the surfaces of the ligaments are enhanced. Consequently, a uniform spray and a shorter breakup length were obtained. The external flow characteristics were the direct consequences of the change of the internal flow structure from bubbly to annular by increasing in GLR. The external flow also was directly affected by the increase of pressure oscillations and consequently enhanced interface disturbances due to higher interactions of the gas/liquid phases as well as a decrease in liquid film thickness. Furthermore, the pulsating behavior of the flow in the discharge orifice demonstrates the anti-clogging characteristic of effervescent nozzles, which makes them suitable for wide range of applications specifically for suspension atomization. This work serves as a pioneering work toward further numerical studies on capturing the complex structure of internal and external flow in effervescent atomizers.

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Table 1 Mass flow rate of injected gas

GLR (%)	Gas mass flow rate $\left(\frac{kg}{s}\right)$
0.55	7.315e-5
1.1	14.63e-5
1.6	21.28e-5
2.6	34.58e-5

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Figure 1. Computational domain and relevant boundary conditions

Figure 2. Mid-plane of computational domain showing local refinement

Figure 3. Sequences of bubble formations to bubble bursting for GLR=0.55%, a) bubble stretching, b) bubble formation, c) bubble detachment, and d) bubble expansion.

Figure 4. Comparison of the pattern of the bubbly flow for a) numerical b) experimental (Tabrizi, 2013) results

Figure 5. Comparison of the pattern of the annular flow for a) numerical b) experimental (Tabrizi, 2013) results

Figure 6. Liquid volume fraction at GLR=2.6%

Figure 7. Comparison of numerical prediction with the experimental results of Lin et al. (Lin, et al., 2001)

Figure 8. Position of investigation point

Figure 9. Pressure variations at the discharge orifice for a) GLR=1.1 b) GLR=1.6%

Figure 10. Pressure variations at the exit orifice for GLR=0.55%

Figure 11. Primary Breakup for various GLRs of a) 0.55 b) 1.1 c) 1.6 and d) 2.6%

Figure 12. Experimental study of breakup for various GLRs of a) 0.55 b) 1.1 c) 1.6 and d) 2.6% (Tabrizi, 2013)

Figure 13. Liquid breakup length for different GLRs

Figure 14. Variations of the cone angle for different GLRs

Figure 15. Velocity contours of a) air and b) liquid in GLR=0.55%

Figure 16. Velocity contours of a) air and b) liquid for GLR=1.1%

Figure 17. Velocity contours of a) air and b) liquid for GLR=2.6%

Figure 18. The average velocity of air in different GLRs and axial distances from nozzle exit.

Figure 19. The velocity of air in mixture at different cross sectional distances of nozzle exit

Figure 20. The velocity and the pattern of the liquid ligaments/droplets near the nozzle exit for GLR=2.6%

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