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EFFERVESCENT ATOMIZATION MECHANICS

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Abstract. *This work consists of determining the mean axial velocities of the liquid and gas in the exit orifice of the effervescent atomizer, dimensionless interface diameter, axial reaction of the effervescent atomizer and Reynolds number of the liquid by applying the control volume method. Ten effervescent atomizers operating under different atomization conditions were selected. The developed method allows obtaining some variables in the exit orifice of the atomizer. From these variables it was determined that the interval for the liquid exit velocity, gas exit velocity, dimensionless interface diameter, axial reaction and Reynolds number of the liquid was [16.053, 66.173 m/s], [0.492, 10.172 m/s], [0.550, 0.957], [-3.449, -88.502 N] and [126.949, 426.598], respectively. From the results obtained, it was concluded that the estimates of the variables of interest are consistent with the experimental observations, thus validating the method developed for future studies in the effervescent atomization of other liquids.*

Keywords: *Effervescent atomization, Navier-Stokes equations, control volume method.*

1. INTRODUCTION

Effervescent atomization is a phenomenon that depends about a large number of variables that can be classified into three types: operational, geometric and fluid-dynamic variables. Currently, in many experimental studies they mention certain trends in the behavior of some of the parameters of the spray obtained, such as, for example, the mean diameter of the spray droplets (usually Sauter's mean diameter) as a function of some variable, without presenting any analytical relationship between the variables, showing a lack of physical understanding of the phenomenon of effervescent atomization.

Fluid mechanics can be understood as a great analysis, which can be divided into three types, which are: integral fluid dynamic analysis, fluid dynamic differential and dimensionless. The integral fluid-dynamic analysis consists of using the Reynolds Transport Theorem applied to a control volume. Fluid dynamic differential analysis is based on the use of Navier-Stokes equations so that through convenient boundary conditions it is possible to study the kinetics of a fluid. Finally, the dimensional analysis is based on the use of Vaschy-Buckingham's theorem to determine the maximum number of independent dimensionless groups using a certain number of physical variables, to later establish a dimensionless model for the estimation of a dependent dimensionless group using experimental results.

With respect to effervescent atomization, there are many advances in the studies of fluid dynamic differential analysis (Panchagnula et al., 1996) through the dispersion relationships obtained. On the other hand, there are still few studies developed in integral fluid dynamics analysis (Buckner and Sojka, 1993) and dimensionless analysis (Mandato et al., 2012) in effervescent atomization.

In the present research, an integral fluid-dynamic analysis of the effervescent atomization is developed using the equations of conservation of mass, moment and energy. This analysis was developed to determine three variables which are the average axial velocity of the liquid and gas, the interface diameter of the gas in the outlet of the atomizer and the axial reaction of the atomizer to the two-phase flow inside the aerator.

2. MATERIALS AND METHODS

2.1 Application of the control volume method

The application of the control volume method is based on the selection of a continuous system and the use of the Reynolds Transport Theorem. Figure 1 presents the control volume selected for the application of the Reynolds Transport Theorem. An annular flow was assumed in the exit orifice for the two-phase flow. The control volume selected was studied with respect to an inertial reference system.

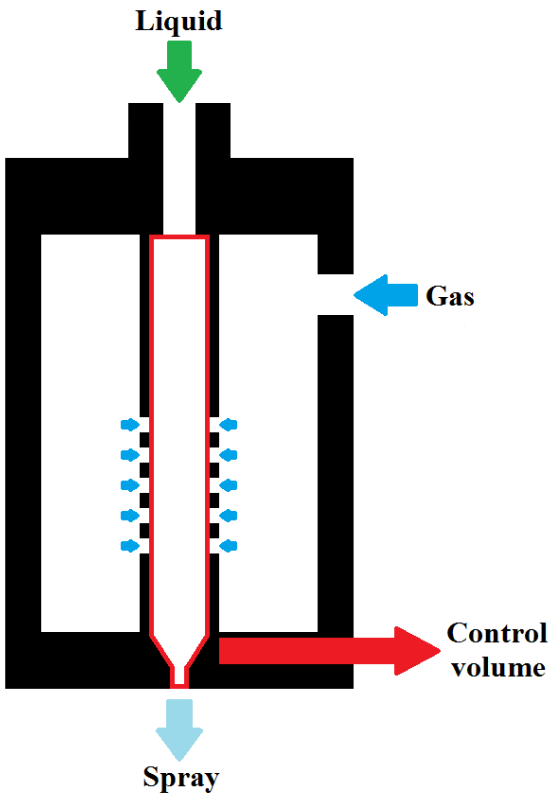

Figure 1. Simplified scheme of an effervescent atomizer of "outside-in" type

The Reynolds Transport Theorem is expressed in Eq. (1). A cinematic condition for all velocity fields of the flows is established in Eq. (2).

$$\iint_{CS} \eta\left(\rho\vec{V}\cdot\vec{n}\right)\,dA + \frac{\partial}{\partial t}\iiint_{CV} \eta\rho\,d\forall = \frac{DN}{Dt} \qquad (1)$$

$$\vec{V}\times\vec{n} = 0 \qquad (2)$$

In the following sections, the applications of the control volume method using Eq. (1) for the conservation laws of mass, energy and moment will be presented.

In the next equations the physico-chemical, geometric and operational variables used in the effervescent atomization will be used for the applications of the conservation laws. The physico-chemical variables ρ_G, ρ_L, γ and

μ_L represent the density of the gas, density of the liquid, surface tension of the liquid and viscosity of the liquid, respectively. The geometric variables d_o, d_I and $A_{L,ent}$ represent the diameter of the atomizer exit orifice, interface diameter of the annular biphasic flow in the atomizer exit orifice and area of the liquid entry surface, respectively. The operating variables GLR, $\dot{m}_L$, $P_{Gau,L,ent}$, $P_{Abs,L,ent}$ and $P_{Abs,G,ent}$ represent the ratio of the gas and liquid mass flows, liquid mass flow, liquid entry gauge pressure, liquid entry absolute pressure and gas entry absolute pressure, respectively.

2.2 Application of the law of mass conservation

The Eq. (3) presents the application of the mass conservation equation ($\eta = 1$) in the control volume presented in Fig. 1. In Eq. (4), the interface diameter of the annular biphasic flow at the exit orifice of the atomizer is presented by means of a quadratic equation. In Eq. (5) the thickness of the liquid flow in the exit orifice of the atomizer (e_{Thi}) is determined. In addition to the aforementioned variables, other variables were presented such as $\overline{V}_{L,exi}$ and $\overline{V}_{G,exi}$ which are the mean velocity of the liquid and the mean velocity of the gas in the exit orifice of the atomizer, respectively.

$$\iint_{CS} \rho \vec{V} \cdot \vec{n} \, dA + \frac{\partial}{\partial t} \iiint_{CV} \rho \, d\forall = 0 \tag{3}$$

$$\left(\rho_L \overline{V}_{L,exi} - \rho_G \overline{V}_{G,exi}\right) d_I^2 - \rho_L \overline{V}_{L,exi} d_o^2 + \frac{4(1+GLR)\dot{m}_L}{\pi} = 0 \tag{4}$$

$$e_{Thi} := \frac{d_o - d_I}{2} = 0.5 d_o \left[1 - \sqrt{\frac{\rho_L \overline{V}_{L,exi} - \dfrac{4(1+GLR)\dot{m}_L}{\pi d_o^2}}{\rho_L \overline{V}_{L,exi} - \rho_G \overline{V}_{G,exi}}} \right] \tag{5}$$

2.3 Application of the law of conservation of energy

The Eq. (6) presents the application of the energy conservation equation ($\eta = u + P_{Abs}/\rho + V^2/2$) in the control volume presented in Fig. 1. In Eq. (7) an expression is presented using a quadratic equation that uses the squares of the exit velocities of the liquid and gas flows.

In addition to the aforementioned variables, other variables were presented such as P_{Abs}, P_{Atm}, $P_{Gau,L,ent}$, $P_{Abs,L,ent}$, $P_{Abs,G,ent}$, $\alpha_{L,E}$, $\alpha_{G,E}$, $\beta_{L,E}$, $\beta_{G,E}$, $u_{L,ent}$, $u_{G,ent}$, $u_{L,exi}$ and $u_{G,exi}$ which are the absolute pressure, atmospheric pressure, gauge liquid entry pressure, absolute liquid entry pressure, absolute gas entry pressure, liquid entry energy kinetic coefficient, gas entry energy kinetic coefficient, liquid exit energy kinetic coefficient, gas exit energy kinetic coefficient, liquid entry internal energy, gas entry internal energy, liquid exit internal energy and gas exit internal energy, respectively. In this study there are two very important dimensionless variables that are π_D and π_P, these variables are defined as dimensionless diameter of interface in the exit orifice and ratio of the exit gauge pressure and entry of the liquid flow, respectively.

$$\iint_{SC} \left(u + \frac{P_{Abs}}{\rho} + \frac{V^2}{2} \right) \left(\rho \vec{V} \cdot \vec{n} \right) dA + \frac{\partial}{\partial t} \iiint_{VC} \left(u + \frac{P_{Abs}}{\rho} + \frac{V^2}{2} \right) \rho \, d\forall = \frac{DE}{Dt} \tag{6}$$

$$\overline{V}_{L,exi}^{2}+\left(\frac{GLR\beta_{G,E}}{\beta_{L,E}}\right)\overline{V}_{G,exi}^{2}+\left(\frac{2P_{Gau,L,ent}}{\beta_{L,E}}\right)\left(\frac{1}{\rho_L}+\frac{GLR}{\rho_G}\right)\pi_P+\frac{4GLR\gamma}{\beta_{L,E}\rho_G d_I}+$$
$$\left(\frac{2P_{Atm}}{\beta_{L,E}}\right)\left(\frac{1}{\rho_L}+\frac{GLR}{\rho_G}\right)-\frac{2P_{Abs,L,ent}}{\beta_{L,E}\rho_L}-\frac{\alpha_{L,E}\overline{V}_{L,ent}^{2}}{\beta_{L,E}}-\frac{2GLRP_{Abs,G,ent}}{\beta_{L,E}\rho_G}- \tag{7}$$
$$\frac{GLR\alpha_{G,E}\overline{V}_{G,ent}^{2}}{\beta_{L,E}}+\frac{2\left(u_{L,exi}+GLRu_{G,exi}-u_{L,ent}-GLRu_{G,ent}\right)}{\beta_{L,E}}=0$$

2.4 Kinetic model for biphasic annular flows in steady state

Initially it was necessary to simplify the mass and energy conservation equations through some final assumptions about:

1) The values of kinetic coefficients for liquid and gas in the entry orifices of the control volume.
2) The values of kinetic coefficients for the turbulent flow in the exit orifices of the control volume.
3) The reference specific internal energy for the liquid and gas in the entry and exit orifices of the control volume.

The assumptions made were presented in Eqs. (8) – (10).

$$\alpha_{L,E}=1.05 \;\wedge\; \alpha_{G,E}=1.05 \tag{8}$$

$$\beta_{L,E}=1.05 \;\wedge\; \beta_{G,E}=1.05 \tag{9}$$

$$u_{L,ent}=0 \;,\; u_{L,exi}=0 \;,\; u_{G,ent}=0 \;\wedge\; u_{G,exi}=0 \tag{10}$$

After using the previous assumptions to simplify the mass and energy conservation equations presented in Eqs. (4) and (7), Eqs. (11) and (12) were obtained, respectively.

$$\overline{V}_{G,exi}=\frac{\rho_L}{\rho_G}\left[1-\left(\frac{d_o}{d_I}\right)^2\right]\overline{V}_{L,exi}+\frac{4\left(1+GLR\right)\dot{m}_L}{\pi\rho_G d_I^2} \tag{11}$$

$$\overline{V}_{L,exi}^{2}+\left(\frac{GLR\beta_{G,E}}{\beta_{L,E}}\right)\overline{V}_{G,exi}^{2}+\left(\frac{2P_{Gau,L,ent}}{\beta_{L,E}}\right)\left(\frac{1}{\rho_L}+\frac{GLR}{\rho_G}\right)\pi_P+\frac{4GLR\gamma}{\beta_{L,E}\rho_G d_I}+$$
$$\left(\frac{2P_{Atm}}{\beta_{L,E}}\right)\left(\frac{1}{\rho_L}+\frac{GLR}{\rho_G}\right)-\frac{2P_{Abs,L,ent}}{\beta_{L,E}\rho_L}-\frac{\alpha_{L,E}\overline{V}_{L,ent}^{2}}{\beta_{L,E}}-\frac{2GLRP_{Abs,G,ent}}{\beta_{L,E}\rho_G}-\frac{GLR\alpha_{G,E}\overline{V}_{G,ent}^{2}}{\beta_{L,E}}=0 \tag{12}$$

Subsequently, Eq. (11) in Eq. (12) was substituted to obtain the kinetic model presented in Eq. (13).

$$\left[\left(k_1+1\right)\pi_D^4-2k_1\pi_D^2+k_1\right]\overline{V}_{L,exi}^{2}+k_2\left(\pi_D^2-1\right)\overline{V}_{L,exi}+\left(k_3\pi_P\pi_D^4+k_4\pi_D^4+k_5\pi_D^3+k_6\right)=0 \tag{13}$$

where:

$$k_1=\left(\frac{GLR\beta_{G,E}}{\beta_{L,E}}\right)\left(\frac{\rho_L}{\rho_G}\right)^2 \tag{14}$$

$$k_2=\left(\frac{8GLR\beta_{G,E}}{\beta_{L,E}}\right)\left(\frac{\rho_L}{\rho_G}\right)\left[\frac{\left(1+GLR\right)\dot{m}_L}{\pi e\rho_G d_o^2}\right] \tag{15}$$

$$k_3 = \left(\frac{2P_{Gau,L,ent}}{\beta_{L,E}}\right)\left(\frac{1}{\rho_L} + \frac{GLR}{\rho_G}\right) \tag{16}$$

$$k_4 = \left(\frac{2P_{Atm}}{\beta_{L,E}}\right)\left(\frac{1}{\rho_L} + \frac{GLR}{\rho_G}\right) - \left(\frac{2P_{Abs,L,ent}}{\beta_{L,E}\rho_L} + \frac{\alpha_{L,E}\overline{V}^2_{L,ent}}{\beta_{L,E}} + \frac{2GLRP_{Abs,G,ent}}{\beta_{L,E}\rho_G} + \frac{GLR\alpha_{G,E}\overline{V}^2_{G,ent}}{\beta_{L,E}}\right) \tag{17}$$

$$k_5 = \frac{4GLR\gamma}{\beta_{L,E}\rho_G d_o} \tag{18}$$

$$k_6 = \left(\frac{16GLR\beta_{G,E}}{\beta_{L,E}}\right)\left[\frac{(1+GLR)\dot{m}_L}{\pi\rho_G d_o^2}\right]^2 \tag{19}$$

In fluid mechanics, one dimensionless parameter of great importance is the Reynolds number, because this number expresses the ratio of inertia force and viscous force (Brennen, 2005). In the context of atomization, it was defined in Eq. (20) the number of Reynolds of the annular liquid flow in the exit orifice of an atomizer.

$$Re_L = \frac{\rho_L \overline{V}_{L,exi}\ e_{Thi}}{\mu_L} \tag{20}$$

2.5 Application of the momentum conservation equation for the effervescent atomizer of outside-in type

The Eq. (21) presents the application of the momentum conservation equation ($\eta = \vec{V}$) in the control volume selected in Fig. 1. In Eq. (22) the calculation for the axial reaction at the selected control volume was presented. In addition to the aforementioned variables, other variables were presented in this section such as $\beta_{L,Q}$ and $\beta_{G,Q}$ which are the liquid entry moment kinetic coefficient and the gas entry moment kinetic coefficient, respectively.

$$\iint_{CS} \vec{V}\left(\rho\vec{V}\cdot\vec{n}\right)\, dA + \frac{\partial}{\partial t}\iiint_{CV} \vec{V}\rho\, d\forall = \frac{D\vec{Q}}{Dt} \tag{21}$$

$$R_z = \beta_{L,Q}\dot{m}_L\overline{V}_{L,exi} + GLR\beta_{G,Q}\dot{m}_L\overline{V}_{G,exi} + \frac{\pi\gamma d_I}{2} - \alpha_{L,Q}\dot{m}_L\overline{V}_{L,ent} - P_{Abs,L,ent}A_{L,ent} + \left(P_{Atm} + P_{Gau,L,ent}\pi_P\right)\left(\frac{\pi d_o^2}{4}\right) \tag{22}$$

2.6 Cinematic condition of characterization for effervescent atomization

Since there were not many experimental researches with respect to velocities $\overline{V}_{L,exi}$ and $\overline{V}_{G,exi}$, this research proposed a cinematic condition that particularizes both velocities. The cinematic condition consists about minimization of the sum of squares for both velocities. The minimization of the sum of squares for both velocities was considered due to the fact that sound velocity is very small in a biphasic mixture water-air, with minimum velocity at approximately 20 to 30 m/s, at temperature and standard pressure (Brennen, 2005). In order to establish the cinematic condition, the objective function was defined in Eq. (23).

$$F_{Obj}(\pi_D, \pi_P) = \overline{V}^2_{L,exi} + \overline{V}^2_{G,exi} \tag{23}$$

3. RESULTS AND DISCUSSIONS

This section presents the results obtained from the kinetic model using 10 experimental data obtained from 10 effervescent atomizers of outside-in type with an exit orifice in the atomizers (Jedelsky et al. 2009). The mean diameter of the spray drops was the integral Sauter mean diameter ID_{32}. Experimental data of the diameter ID_{32} employed in the researches of Jedelsky et al. (2009) were presented in Tab. 1. The effervescent atomizers used had different geometric designs and were operated under different operating conditions for the atomization of light heating oil.

Table 1. Results of the mean axial velocity of liquid and gas, and the reaction of the atomizer.

Atomizer	$P_{Gau,L,ent}$ $[MPa]$	GLR	π_D	$\bar{V}_{L,exit}$ $[m/s]$	$\bar{V}_{G,exit}$ $[m/s]$	R_z $[N]$	Re_L	ID_{32} $[\mu m]$
E23	0.1	0.05	0.888	19.251	2.013	-3.477	127.327	94.6
E24	0.1	0.05	0.897	20.871	2.415	-3.449	126.949	94.2
E25	0.3	0.02	0.639	18.474	0.899	-6.797	393.838	87.9
E26	0.3	0.02	0.550	16.053	0.492	-17.479	426.598	85.8
E27	0.3	0.05	0.746	17.493	0.619	-35.612	262.390	80.6
E28	0.3	0.05	0.761	18.867	0.733	-59.189	266.287	83.2
E29	0.3	0.10	0.957	66.173	10.172	-58.318	168.035	79.9
E30	0.3	0.10	0.957	64.278	9.769	-58.388	163.223	80.9
E31	0.5	0.05	0.889	51.988	5.542	-87.251	340.781	88.9
E32	0.5	0.05	0.725	23.803	0.742	-88.502	386.558	76.6

For analysis of the results of variables π_D , $\bar{V}_{L,exi}$, $\bar{V}_{G,exi}$, R_z and Re_L, operating variables such as $P_{Gau,L,ent}$ and GLR were fundamental. Substituting the 10 experimental data selected in the objective function to be minimized, the value $\pi_P = 1$ was always obtained, which has physical sense because the atomizer length is relatively small whereby the pressure loss in the liquid flow can be considered zero. Because there isn't a change in temperature and in the liquid pressure between the entry and exit orifices of the control volume, it was concluded that the solutions obtained were for a case of an isentropic transformation of the liquid flow.

Additionally, the kinetic model allows determination of the Reynolds number of the annular liquid flow Re_L, which will be established as a fundamental parameter in the design and selection of effervescent atomizers for certain operation conditions and fluid dynamic characteristics of employed fluids. Thus, determination of all the variables mentioned previously helped to develop the method for design the effervescent atomizers. The Reynolds number Re_L was one parameter which served very well to explain the integral Sauter mean diameter ID_{32}. From results in Tab. 1, it was observed that for effervescent atomizers E25, E26 and E32 which were those with high Re_L, the smaller integral Sauter mean diameters ID_{32} were obtained. This demonstrates that there is a relationship between Re_L and ID_{32}, which means that a high Re_L produces a low ID_{32}, or some other low representative diameter of spray drops. Atomization is a transient phenomenon, but with estimations done of the Reynolds number of the annular liquid flow, a coherent explanation can be achieved of the atomization phenomenon for a steady state.

4. CONCLUSIONS

The method developed in the present research satisfactorily calculates the mean axial velocities of the liquid and gas, the diameter of the dimensionless interface and the axial reaction of the atomizer. The calculated results of the variables of interest in this research are consistent with the trends observed in the experimental research developed in the effervescent atomization, demonstrating the validity of the application of the method developed for future estimations of the variables $\bar{V}_{L,exi}$, $\bar{V}_{G,exi}$ and Re_L in effervescent atomization.

The method developed also allows a better physical understanding of atomization in function of all variables of influence, such as geometric variables, fluid dynamic variables and operational variables. The method allows the establishment of a direct relation between the representative diameter of the spray drops and the Reynolds number of the liquid annular flow for effervescent atomization. This quality is very important for future designs of effervescent atomizers.

5. ACKNOWLEDGEMENTS

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