Unsteadiness in Effervescent Sprays: Influence of Operational Conditions and Atomizer Design

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Abstract

Effervescent atomizers become more frequent in industrial applications as they produce fine and controllable spray even at low input pressure. However their spray is inherently unsteady; this feature is generally improper and it is necessary to minimize spray unsteadiness e.g. in case of combustion applications. In this study we focus on a single-hole effervescent atomizer spraying light heating oil with air as atomizing medium in the "outside-in" gas injection configuration. The spray is measured using Phase Doppler anemometer and the Edwards and Marx's spray unsteadiness evaluation method is applied. Variation of spray unsteadiness with droplet size, spatial location in the spray and influence of atomizer operation conditions on spray unsteadiness is evaluated on exemplary atomizer. Several atomizer internal dimensions are modified for study of influence of atomizer design on spray steadiness: size and number of aeration holes, their location and diameter of the mixing chamber. Results show that spray unsteadiness is spatially dependent; the unsteadiness is low in the spray centerline and increases with radial distance. Spray unsteadiness moderately increases with axial distance. Influence of operation conditions, air gauge pressure and gas to liquid ratio, is weak. The spray unsteadiness can be reduced by a proper dimensioning of atomizer internal geometry; short mixing chamber with high number of small aeration holes provides spray with low level of unsteadiness.

Introduction

Effervescent atomization technique, developed in the late 1980s, become more frequent in industrial applications as this kind of twin-fluid atomizers with internal mixing produce fine and controllable spray even at low input pressure. One of their main drawbacks is spray unsteadiness. Luong and Sojka found the effervescent sprays are inherently unsteady [1]; this feature is generally improper and it is necessary to minimize it e.g. in combustion applications. Spray unsteadiness in effervescent sprays is believed to be strongly connected with atomizer internal two-phase flow in contrast with e.g. pressure atomizers where droplet clustering is induced by interaction of droplets and surrounding atmosphere. Jedelsky and Jicha [2] describe the connection between atomizer internal two-phase flow and resulting spray unsteadiness: "If the mixing chamber is occupied by large volumes of separated phases then also the resulting mixture flowing through the exit orifice is inhomogeneous. Varying instant gas to liquid ratio (GLR) or even existence of liquid bridges at the exit cross section leads to varying amount of energy of the compressed atomizing air with respect to the amount of the atomized liquid. Then the discharged mixture consists of larger liquid ligaments followed by discharge of the air with low concentration of smaller droplets. As a result also velocity of the mixture at the exit cross section varies. This finally implicates an unsteady spray and forms a droplet clusters."

Effervescent spray unsteadiness varies with spatial location in the spray cone; it is low near spray centerline and increases with radial distance from the spray centerline reaching maximum value near the spray edge [1, 3]. Level of spray unsteadiness also increases with axial distance from the atomizer exit orifice [1]. Papers [1, 2, 4] show influence of operation conditions on the spray unsteadiness. Higher values of spray unsteadiness were documented when nozzle operated in slug flow regime, lower unsteadiness were found in case of uniform bubbly or annular internal two-phase flow. There is a lack of information in the literature on relation between spray unsteadiness and atomizer internal geometry. As it was shown in work of Chin and Lefebvre [5], dimensions of mixing chamber together with atomizer operation conditions determine internal two-phase flow regime. Otahal and Jicha [6] and Maldonado et al. [7] indicate that size of the mixing chamber influence the two-phase flow stability and hence also resulting spray unsteadiness. Injection of gas into liquid in the mixing chamber and resulting two-phase flow structure is controlled by a size of aeration holes, their number and position.

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Presented paper documents spray unsteadiness in droplets of different size, variation of spray unsteadiness with spatial location in the spray and influence of operation conditions on spray unsteadiness. Main part of the paper is focused on influence of atomizer internal design on spray unsteadiness. Concluding remarks give a recommendation for atomizer design with reduced spray unsteadiness. This work is a follow-up of two our previous publications. We studied influence of atomizer operation conditions and atomizer internal geometry on droplet size in the spray in paper [8] and likewise we evaluated influence of these factors on spray structure and spray cone angle in [9].

Experimental Facility

Experimental equipment includes effervescent atomizer, cold test bench with fluid supply system and Phase/Doppler Particle Analyzer. Description of our experimental facility and Dantec 1D P/DPA used for droplet arrival time measurement can be found in [2].

Single-hole, plain orifice atomizer (Fig. 1) is powered with light heating oil (LHO) and uses air as an atomizing medium in the "outside-in" gas injection configuration. It consists of a cylindrical body in which an aerator tube is inserted. The aerator is connected with an exit nozzle. The LHO enters the central orifice of the aerator from left side, while the air is injected into the liquid, through a set of small holes in the aerator envelope. Both fluids form a two-phase mixture, flow downstream and exit the atomizer through a discharge orifice to the ambient atmosphere in the form of a spray.

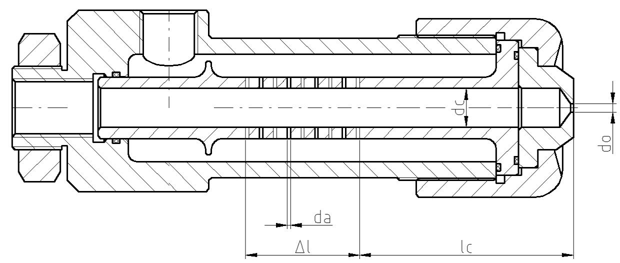

Figure 1. Schematic layout of the atomizer.

A volume of a mixing chamber formed inside the aerator tube is given by the length downstream of the last row of air holes, l_c, and the internal diameter of the aerator tube, d_c. The length l_c, diameter d_c together with span length Δl, diameter d_a and number of aeration holes, N, are varied in this study. Several atomizers were manufactured for testing; their dimensions can be seen in Table 1 bellow. Exit orifice has always diameter d_o of 2.5 mm and length of 0.7 mm. There is a conical junction with the apical angle of 120° in front of the orifice.

The atomizer was continuously operated and studied in the vertical downward position of the main axis. The air and oil supplies are controlled separately. Operational conditions of the twin-fluid atomizer with given geometry and fluids with defined physical properties can be basically described by any two independent parameters. We choose the air gauge pressure and GLR. Thus other parameters, liquid pressure, liquid and air flow rates, are dependent upon them. Experiments were performed for several air gauge pressures and GLR values. Gauge pressures and volumetric flow rates of LHO and atomizing air were measured, GLR was calculated. Temperatures of both fluids were kept at 20 +/- 3 °C. Physical properties of used LHO were: dynamic viscosity 0.0185 kg/m s, surface tension 0.0297 kg/s^2 and density 874 kg/m^3.

Spray Unsteadiness Measurement Method

Edwards and Marx [10] developed a theoretical framework for analysis of the time-based multipoint statistics of sprays. Based on this work it is possible to distinguish between steady and unsteady sprays. Steady sprays according to [10] are defined as those whose interparticle arrival time distribution obeys inhomogeneous Poisson statistics. Unsteady sprays are those whose interparticle arrival time distribution does not obey inhomogeneous Poisson statistics. The formalism of determining if a spray is steady can be summarized as follows: assumption that the spray is steady and calculation of the interparticle arrival time distribution function, measurement of the interparticle arrival times for the spray in question and forming of the corresponding distribution function, comparison of the two functions. Short description of the evaluation is made hereinafter, for a comprehensive description of the entire calculation procedure see [1, 10]. The experimental interparticle time distribution $h_{exp}(\tau_j)$ is in our case determined from single P/DPA realization. Edwards and Marx [10] show that:

$$h_{\exp}\left(\tau_j\right) = \frac{H\left(\tau_j\right)}{N \cdot \Delta\tau_j}\,. \qquad (1)$$

Where τ_j is the interparticle time gap j, $H(\tau_j)$ is the number of events that fall within the jth interparticle time gap, N is the total number of interparticle events, and $\Delta\tau_j$ is the width of the jth interparticle time gap and is determined by the difference between τ_j and τ_{j-1}. τ_j corresponds to a particular time gap between two particles which is calculated by taking the difference between two particles' arrival time at the probe volume. $H(\tau_j)$ is found by keeping track of the number of times when an interparticle time gap event falls between τ_j and τ_{j-1}. For calculating the experimental distribution the interparticle time has to be divided into bins with a certain width. The binning which is done in a dynamic way was derived by Luong and Sojka [1]. Fritsching and Heinlein [3] found several sources of errors influencing the number of droplets measured using P/DPA. To reduce this influence the final binning was arranged into bins with a constant width according to [3]: $\Delta\tau = \tau_{j=Q}/Q$. Number of interparticle bins, Q, was always set to 20. The ideal spray is modeled, according to Edwards and Marx [10], as a marked, inhomogeneous Poisson process. The finite theoretical interparticle time distribution is then:

$$h_{th}(\tau) = \frac{\zeta^2 (t_T - \tau)\cdot \exp(-\zeta\tau)}{\zeta t_T - 1 + \exp(-\zeta\tau)} . \qquad (2)$$

where $\zeta = N/t_T$. If the theoretical and the experimental interparticle time distributions are found, their comparison can be made. As a measure of closeness of the observed values to the corresponding expected values the random variable χ^2 is calculated:

$$\chi^2 = \sum_{j=1}^{Q} \frac{\left(H(\tau_j) - N\cdot h(\tau_j)\right)^2}{N\cdot h(\tau_j)} . \qquad (3)$$

Once χ^2 is known, the hypothetical model can be accepted or rejected depending on desired significance level; we used significance level 0.01 for all data evaluation. Here we introduce new value, δ:

$$\delta = \sum_{j=1}^{Q} \frac{\left(H(\tau_j) - N\cdot h(\tau_j)\right)^2}{N\cdot h(\tau_j)^2} . \qquad (4)$$

It express deviation between expected (ideal Poisson process) distribution (2) and measured distribution (1). Value δ is used as a scale of the spray unsteadiness. The smaller δ value, the better is the agreement between the known data and the proposed model. By other words the δ value represents the spray unsteadiness level.

Results and Discussion

Variation of spray unsteadiness with spatial location in the spray for different size classes is demonstrated on data of atomizer E34 (see Table 1 bellow) at atomizing pressure 0.3 MPa and 5 % GLR in position 150 mm downstream the exit orifice. Fig. 2, left shows χ^2 value of different size classes for different radial distances from the spray centerline. Expected deviation for given evaluation setup is also marked in the plot. Width of the size classes was set to 10 µm. The size width was extended until statistical criteria were not fulfilled if there were not enough data for correct evaluation. No distinct tendency in behaviour of droplets of different size is seen. All data except the

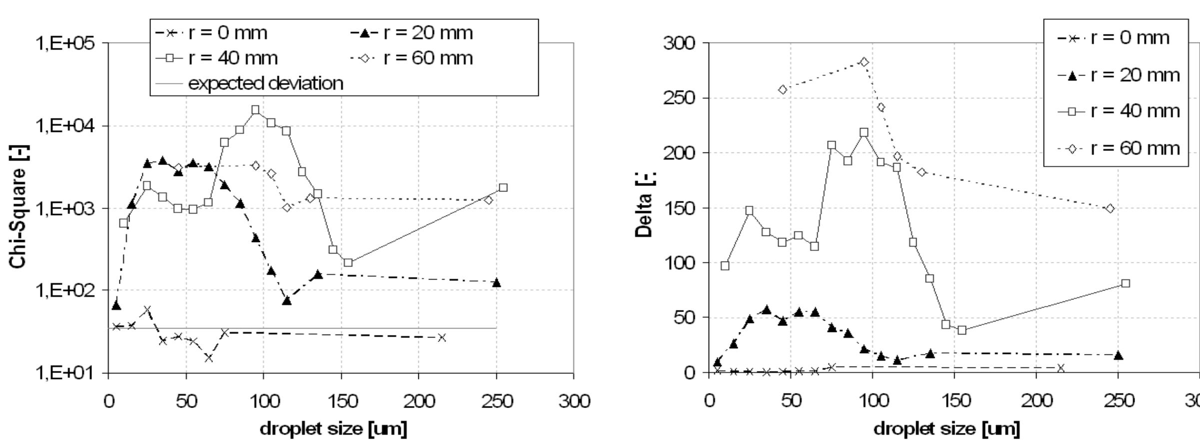

Figure 2. Variation of χ^2 (left) and δ (right) with droplet size at several radial distances, atomizer E34.

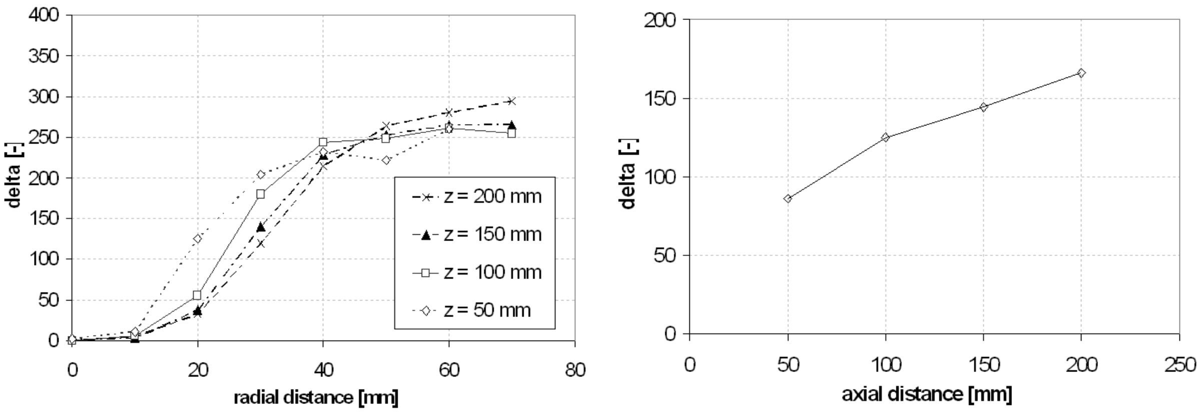

Figure 3. Variation of δ with radial distance (left), variation of integral δ with axial distance (right).

droplets in the spray centerline show higher χ^2 values than is the expected deviation. It means that from statistical point of view the spray is unsteady, except centerline positions. Spray unsteadiness level, represented by δ value, is for the same data documented in Fig. 2, right. There is no significant dependency between δ and droplet size. Droplets in larger radial distances from the spray centerline give higher δ. This behaviour with both large and small droplets unsteady is in contrast with pressure atomizer sprays. It indirectly confirms the assumption that effervescent spray unsteadiness results from internal two-phase flow and that spray unsteadiness is inherent to this atomization type. For deeper analysis and description see paper of Luong and Sojka [1].

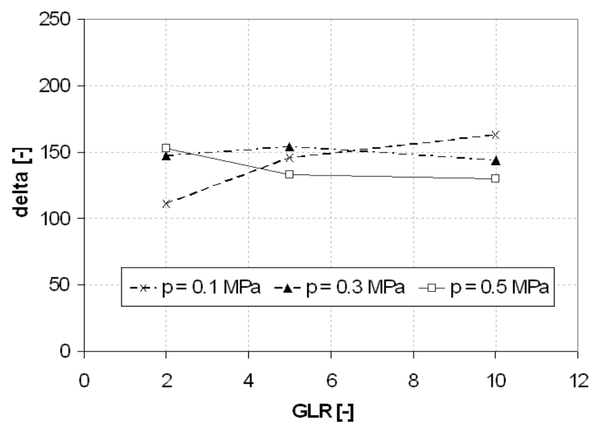

Figure 4. Influence of inlet pressure and GLR on δ.

To reduce data and simplify comparison between different spray positions we do not distinguish between different droplet size classes in given spray position and evaluate all droplets together in further analysis. Variation of δ with radial distance from the spray centerline for several axial distances from exit orifice is shown in Fig. 3 left. The δ shows similar profiles for all axial positions; low value near the spray axis, steep increase with radial distance and maximum near the spray border. This behaviour probably results from phase distribution through the mixing tube and exit orifice cross-section. For most two-phase flow regimes gas fraction is high near the cross-section centre and decreases to the wall. This tendency is more distinct namely in regimes with higher pressure and at higher GLR [6]. Low atomization energy in the spray borders leads to formation of larger ligaments of atomized liquid and finally to droplet clusters. Jet unsteadiness could be another reason for this variation of δ with radial position.

We perform another reduction of data introducing overall δ value:

$$\overline{\delta} = \frac{\sum_{i=1}^{n} \delta_i f_i \pi \left[(r_i + \Delta r/2)^2 - (r_i - \Delta r/2)^2 \right]}{\sum_{i=1}^{n} f_i \pi \left[(r_i + \Delta r/2)^2 - (r_i - \Delta r/2)^2 \right]} \cong \frac{\sum_{i=1}^{n} \delta_i f_i r_i}{\sum_{i=1}^{n} f_i r_i} . \quad (5)$$

where r_i is radial distance, Δr is distance between measurement positions and f_i is droplet data rate in position i. This calculation uses droplet data rate and cross-section area as weighting factors. Results of this calculation show that δ increases with axial distance from exit orifice, see Fig. 3, right. This result is in accordance with findings of Luong and Sojka [1]. One particular reason is probably development of spray and interaction of droplets with discharged gas. Influence of operation pressure and GLR on overall δ value, documented in Fig. 4, is very weak, no systematic tendency was found. This is in contrast with findings in other works [1, 2].

Atomizer Internal Geometry

Based on our previous works [8, 9] we have defined four geometrical parameters to study in this work: total area and diameter of aeration holes, diameter of the mixing chamber and location of the aerator holes relative to the final discharge orifice (see Fig. 1 above). All the parameters are related to some characteristic atomizer dimension to make further analysis simple. Dimensions of all atomizers together with the dimensionless parameters are given in Table 1. Measurements of spray unsteadiness were carried out using P/DPA at radial profiles 150 mm downstream of the final discharge orifice at air gauge pressure 0.1 MPa and 2 % GLR.

Table 1. Atomizers tested and overall δ for air gauge pressure 0.1 MPa and GLR 2 %.

Atomizer	l_c (mm)	Δl (mm)	d_c (mm)	d_a (mm)	n (-)	r_a (-)	$10.r_n$ (-)	r_{dc} (-)	r_{lc} (-)	δ (-)
E21	90	30	5.5	0.7	60	4.70	0.17	2.2	16.4	116.8
E22	85	30	5.5	1.0	30	4.80	0.33	2.2	15.5	117.6
E23	85	25	5.5	1.3	18	4.87	0.56	2.2	15.5	135.6
E24	90	25	5.5	1.5	13	4.68	0.77	2.2	16.4	150.4
E25	85	30	5.5	1.0	30	4.80	0.33	2.2	15.5	117.6
E26	85	30	8.0	1.0	30	4.80	0.33	3.2	10.6	147.6
E27	85	25	11.0	1.0	30	4.80	0.33	4.4	7.7	155.2
E28	85	40	14.0	1.0	30	4.80	0.33	5.6	6.1	127.3
E29	75	0	14.0	1.0	8	1.28	1.25	5.6	5.4	163.2
E30	55	0	14.0	1.0	8	1.28	1.25	5.6	3.9	134.7
E31	35	0	14.0	1.0	8	1.28	1.25	5.6	2.5	95.9
E32	65	10	14.0	1.0	24	3.84	0.42	5.6	4.6	140.9
E33	50	10	14.0	1.0	24	3.84	0.42	5.6	3.6	91.2
E34	35	10	14.0	1.0	24	3.84	0.42	5.6	2.5	110.7
E35	65	20	14.0	1.0	40	6.40	0.25	5.6	4.6	122.2
E36	45	20	14.0	1.0	40	6.40	0.25	5.6	3.2	103.9
E37	35	20	14.0	1.0	40	6.40	0.25	5.6	2.5	109.5
E38	35	40	14.0	1.0	80	12.8	0.13	5.6	2.5	101.5

Atomizers E25-E28 were used to study the impact of the mixing chamber diameter, d_c, on spray unsteadiness. The mixing chamber diameter, d_c, is related to the exit orifice diameter, d_o, giving relative mixing chamber diameter $r_{dc} = d_c / d_o$. The diameter of air injection holes d_a, was varied on atomizers E21-E24. The number of the aerator holes, N, was also varied to keep the total aeration cross-section area constant. Influence of relative area of single aeration hole on spray is described by $r_n = A_a / NA_a = \left(\pi d_a^2/4\right)/\left(N\pi d_a^2/4\right) = 1/N$. Atomizers E30, E33, E36 and E38 were used to investigate the influence of the aeration cross-section area; aeration hole number was modified while their diameter maintained constant. Ratio of aeration area to the discharge orifice area is $r_a = NA_a / A_o = N\left(d_a/d_o\right)^2$. Distance between last set of aeration holes and the final discharge orifice, l_c, defines the relative mixing distance $r_{lc} = l_c / d_c = r_{dc} d_c / d_o$. The parameter r_{lc} was studied with atomizers E29-E31 having one line of aeration holes (each line with 8 holes), with atomizers E32-E34 having three lines of aeration holes and with atomizers E35-E37 having five lines of aeration holes.

Level of spray unsteadiness, δ, decreases with reduction in the diameter of air injection holes. Smaller aeration holes probably produces smaller bubbles and therefore more homogeneous two-phase flow. Influence of aeration cross-section area is not monotonic but mostly larger cross section area gives lower δ. A reason could be the same as in previous case. Influence of mixing chamber diameter is indistinctive. Relative mixing distance, r_{lc} significantly influences spray unsteadiness in case of one line of aeration holes; δ increases with r_{lc}. Influence of r_{lc} for three and five lines of aeration holes is not significant.

Conclusions

Effervescent spray unsteadiness varies significantly with the spatial location in the spray. Spray is relatively steady near the spray centerline, spray unsteadiness increases with radial distance. Spray unsteadiness also reasonably increases with axial distance from exit orifice. Operation conditions were found to have little effect on the spray unsteadiness in pressure range 0.1 – 0.3 MPa and GLR 2 – 10 %. Study of internal geometry show that spray unsteadiness can be reduced using atomizer with large number of small aeration holes and with short mixing chamber.

Acknowledgement

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Nomenclature

A	area, m^2, mm^2
d	diameter, mm, µm
f	droplet frequency, Hz
GLR	gas-to-liquid ratio by mass, %
$H(\tau j)$	number of events that fall within the *j*th interparticle time gap, 1/s
h_{exp}	experimental interparticle time distribution, 1/s
h_{th}	theoretical interparticle time distribution, 1/s
l	length, mm
N	total number of interparticle events
n	number of aeration holes
p	pressure, Pa
Q	number of interparticle bins
r	radial distance, mm
t	time, s
t_T	total measurement time, s
z	axial distance, mm
$\Delta\tau_j$	width of the *j*th interparticle time, s
δ	scale of spray unsteadiness
ζ	intensity function, 1/s
τ	interparticle arrival time, s
χ^2	Chi-square value

Subscripts

i, *j*	index number
c	mixing chamber
a	aeration hole

References

1. Luong, J.T.K., and Sojka, P.E. *Atomization and Sprays* 9:87-109 (1999).
2. Jedelsky, J., and Jicha, M., *Atomization and Sprays* 1:49-83 (2008).
3. Fritsching, U., and Heinlein, J., *3rd Int. Symp. on Two-Phase Flow Modelling and Exp.*, Pisa, Italy, 2004.
4. Jedelsky, J., and Jicha, M., *10th International Conference on Liquid Atomization and Spray Systems*, Kjoto, Japan, August 2006, pp. 1-8.
5. Chin, J.S., and Lefebvre, A.H., *Atomization and Sprays* 3:463-475 (1993).
6. Otahal, J., and Jicha, M., *22nd International Conference on Liquid Atomization and Spray Systems*, Como Lake, Italy, September 2008, pp. 1-4.
7. Maldonado, S., Fleck, B., Heidrick, T., Amirfazli, A., Chan, E.W., and Knapper, B., *Atomization and Sprays* 8:699-722 (2008).
8. Jedelsky, J., Otahal, J., and Jicha, M., *19th International Symposium on Transport Phenomena*, Reykjavik, Iceland, August 2008, pp. 1-8.
9. Jedelsky, J., Landsmann, M., Otahal, J., and Jicha, M., *22nd International Conference on Liquid Atomization and Spray Systems*, Como Lake, Italy, September 2008, pp. 1-8.
10. Edwards, C.F., and Marx, K.D., *Atomization and Sprays* 5:475-506 (1995).