Journal of Propulsion and Power
Vol. 27, No. 4, July–August 2011

Technical Notes

Effect of Air Injection Configuration on Characteristics of Effervescent Sprays

Hrishikesh P. Gadgil* and B. N. Raghunandan†
Indian Institute of Science, Bangalore 560 012, India

DOI: 10.2514/1.B34052

I. Introduction

EFFERVESCENT atomization is an internal-mixing-type twin fluid atomization in which a small amount of gas called atomizing gas is introduced into the bulk of the liquid to form a two-phase bubbly mixture, which is then exited through the final discharge orifice. Effervescent atomization is becoming a good option for gas turbine engines [1], diesel engines [2], and scramjet engines [3] for producing fine drop sizes of liquid fuels. Considerable experimentation has been carried out for studying the characteristics of effervescent atomizers over the last two decades. Lefebvre et al. [4] and Roesler and Lefebvre [5] measured drop sizes at the lowest reported injection pressure (34.5 kPa), while Satapathy et al. [6] did experiments at pressures as high as 33 MPa. However, the effect of injection pressure was found to be more pronounced at lower injection pressures. An exception to this was observed by Buckner and Sojka [7] for high-viscosity liquids where the Sauter mean diameter (SMD) was independent of the injection pressure. Similar results were confirmed by Buckner and Sojka [8] and Geckler and Sojka [9] for high-viscosity liquids.

The gas-to-liquid ratio (GLR) by mass is an important governing parameter in effervescent atomizers. Past studies showed that the mean drop size is a nonlinear function of GLR, with SMD decreasing with increasing GLR. Several investigators reported that the mean drop size is largely independent of the final discharge orifice diameter [2,4,5,8,10,11]. Chen and Lefebvre [12] noted that the effervescent sprays have wider cone angles compared with the sprays produced by plain-orifice atomizers. This is a consequence of the rapid expansion of the gas phase in the core of the spray. Wade et al. [2] and Sovani et al. [13] observed an increase in spray cone angle with an increase in GLR due to the higher expansion of the atomizing gas. However, the cone angle of sprays produced by plain-orifice effervescent atomizers is always less than 23 deg.

These studies show that considerable efforts have been made for investigating the effects of various parameters on spray characteristics. However, some of the sample studies quoted in Table 1 indicate large variations in SMD ranges for different configurations at similar GLR. A more detailed comparison is presented by Lorcher et al. [17]. These large variations in mean drop size are possibly due to flow variations caused by different injector configurations. From this point of view, a comparative study of two different designs of an effervescent atomizer is presented in this Note.

Received 22 June 2010; revision received 22 December 2010; accepted for publication 1 March 2011.

*Graduate Student, Department of Aerospace Engineering, Karnataka; ghrishi@aero.iisc.ernet.in (Corresponding Author).

†Professor, Department of Aerospace Engineering, Karnataka. Member AIAA.

II. Experimental Setup

The schematics of the two injector configurations used in this study are shown in Fig. 1. The two configurations differ in terms of the location of air injection. In configuration A, air is injected and mixed with water inside the mixing chamber and well upstream of the final orifice. In configuration B, the air is injected directly inside the final orifice.

The experimental facility includes a water tank pressurized with the compressed air taken from a compressor, which can deliver the air up to 1.47 MPa pressure. The water line is connected to the side port of injector A or to the top port of injector B through the control valve and pressure gauge. The top port of injector A and the side port of injector B are supplied with high-pressure air from a compressor through the control valve, pressure gauge, and flowmeter. The flowmeter is calibrated to an accuracy of 2%. Mean drop size (SMD) of the spray is measured with an accuracy of 2% by using a Malvern MastersizerX instrument, which works on the principle of laser diffraction by liquid drops. The flow visualization experiments are carried out with a stroboscope (1538-A STROBOTAC) for illuminating the spray and a Sony Handycam (DCR-DVD710E) in backlighting mode. The spray characteristics, like spray cone angle, are measured from around 50 spray images, and averaged values are used for analysis.

III. Results and Discussions

The variation of SMD with GLR for injector configuration A is shown in Fig. 2a. The measurements are done at four different pressure drops and at 120 mm downstream of the orifice. As the plot shows, the SMD values are mainly governed by GLR and are not influenced by pressure drop, which is consistent with past results in the literature. The SMD falls sharply at very low GLRs. As GLR is increased, this variation becomes moderate. At relatively high values of GLR (greater than 4%), the variation in SMD is very small. The SMD reaches an asymptotic value and is then almost independent of GLR. This smallest SMD value largely depends on the orifice diameter.

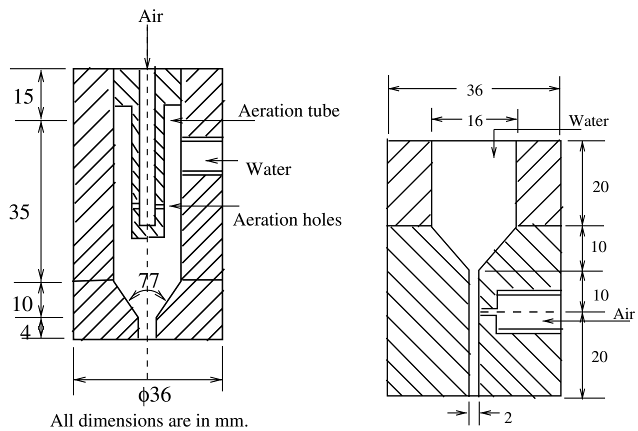
The variation of SMD with GLR for injector configuration B is shown in Fig. 2b. The falling trend of SMD with GLR is almost similar to that of injector A. However, SMD in the case of injector B decreases smoothly with GLR. The rate of fall of SMD also decreases with GLR, and SMD finally attains a value that is almost independent of GLR.

Although the variation of SMD with GLR is qualitatively similar for both injector configurations, there are many marked differences. SMD at low GLR values falls more sharply in the case of injector A compared with injector B. It may be deduced from Fig. 2 that lower SMD can be achieved at a given GLR value with configuration A compared with configuration B. For example, at a 0.196 MPa

Table 1 Studies showing different ranges of drop sizes for different injector geometries and GLR ranges

Reference	Configuration	GLR, %	SMD, μm
Lefebvre et al. [4]	Inside out[a]	2–22	20–300
Panchagnula and Sojka [14]	Outside in[b]	2–10	60–90
Roesler and Lefebvre [5]	Outside in	0.1–5	30–120
Lund et al. [15]	Inside out	1–7	40–60
Bush and Sojka [16]	Inside out	1–10	30–70
Whitlow and Lefebvre [10]	Outside in	0–60	20–70

[a]In the inside-out configuration, gas flows inside the perforated tube and bubbles outward into the surrounding liquid.
[b]In the outside-in configuration, liquid flows inside a perforated tube, and the atomizing gas is injected into it through holes in the tube wall.



a) Injector configuration A **b) Injector configuration B**

Fig. 1 Geometry of injector configurations.

pressure drop and around a 1% GLR, injector A gives 297 μm SMD while injector B gives 629 μm SMD. This suggests that injecting atomizing gas inside the mixing chamber before the final orifice is an efficient way for getting fine drop size at lower GLRs. This marked difference in SMD for a given GLR is limited up to 4–5% GLR. Beyond that, SMD is almost same for both the configurations at a given airflow rate. Thus, the asymptotic value of SMD that can be attained is the same for both injector configurations. This may be an indication of a similar spray breakup mechanism at higher GLRs.

Since there is a considerable difference in SMD values at low GLR, altogether different spray breakup mechanisms may exist in this range of GLR for the two configurations. To verify this, the near-orifice spray structures of both injectors are compared. It is well described in the literature that the rapidly expanding gas bubbles shatter the liquid film around them, causing the spray breakup at low GLR in a typical effervescent atomizer, like A. The near-orifice spray structures at low GLR for both the configurations are shown in Fig. 3. In Fig. 3a, the shattering effect of trapped air bubbles or slugs may be seen. The bursting of trapped bubbles produces a splash, creating fine drops from the liquid film surrounding the bubble. However, no such significant splashing resulting from bubble bursting is seen for same GLR in Fig. 3b. This implies that the spray breakup does not take place because of exploding gas bubbles in the case of injector B. In fact, since the air is introduced into the orifice where there is a very small cross-sectional area available for flow (and hence, liquid velocities are comparatively higher), the process of bubble formation gets suppressed. Instead, the water and air flow as two separate streams, unlike injector A. This leads to the fact that the available area for the liquid to flow through the orifice gets reduced, because the coflowing airstream occupies a major volume fraction. A consequent increase in liquid velocity leads to a higher, effective pressure drop across the orifice. Also, there is a shearing effect on the liquid jet from the coflowing airstream that helps in atomization. Thus, the atomization in injector B is a combined effect of the increase in the resultant pressure drop and the shearing effect of the airstream. The disintegration of drops from the edges of the liquid jet in Fig. 3b indicates the presence of the shearing effect. Thus, the spray breakup mechanism in injector B significantly differs from that in injector A, at least at lower GLRs.

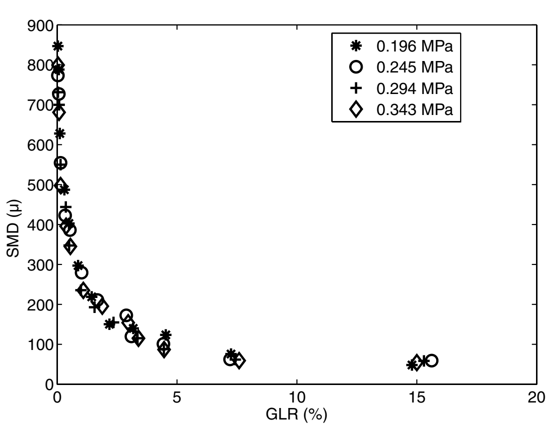
Since the bubbly flow regime is bypassed in injector B, it has to depend on the shearing between coflowing streams and the orifice blockage for spray breakup. A low airflow rate results in lower air velocities, and hence less effective shearing action. It also results in a smaller amount of orifice blockage. Thus, an annular type of flow at low airflow rates in injector B proves less effective in terms of breakup, and hence produces coarse drop sizes. In contrast with this, the injector configuration A under similar conditions of GLR is assisted by the bursting of air bubbles. The air bubbles reduce the thickness of the surrounding liquid jet to a very small value before bursting, and thereby enhance atomization quality at lower airflow rates. This is how configuration A performs better than B in terms of the mean drop size at low GLRs.

At higher airflow rates, however, injector A shifts to an annular flow regime, wherein the core air jet is surrounded by annular liquid film and the two phases flow as two separate streams. This flow structure is very similar to what exists in injector configuration B. So, after a particular value of GLR (around 3–4%) when injector A is in annular flow regime, the atomization mechanism in both injectors is the shear between the liquid stream and the coflowing high-speed airstream. At higher airflow rates, the air velocities are high enough to produce shearing of liquid film effectively. Hence, the SMD generated by both the injectors is almost the same at higher GLRs.

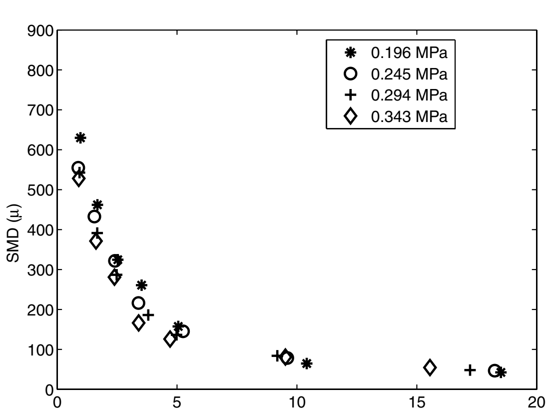
In effervescent atomization, where carrying the atomizing gas might be a stringent constraint, injector A proves better, as it can produce finer drop sizes, consuming a smaller amount of atomizing gas. Higher GLR drastically reduces the liquid (fuel) flow rate. Whenever the demand for a higher fuel flow rate arises during the operation, lowering GLR becomes inevitable and, consequently, injector A turns out to be the better option.

The spray cone angle is one of the important external spray characteristics. Figure 4 compares the cone angle variation in the two configurations. In the case of injector configuration A, the spray cone angle initially increases monotonically with GLR and then becomes steady. However, the spray cone angle is almost same with GLR in the case of injector B. It varies in between 10 to 12 deg. Also, it may be seen that the spray cone angle is much more in the case of configuration A than injector B at a given GLR. Thus, injector A seems superior to injector B in terms of the spray cone angle.

In the case of injector A, air is injected inside the mixing chamber where pressure is considerably higher than the ambient; thus, formation of the two-phase mixture takes place at high pressure. As the two-phase flow chokes at very low pressure drops [18], the underexpanded two-phase jet expands as it comes out of the orifice.

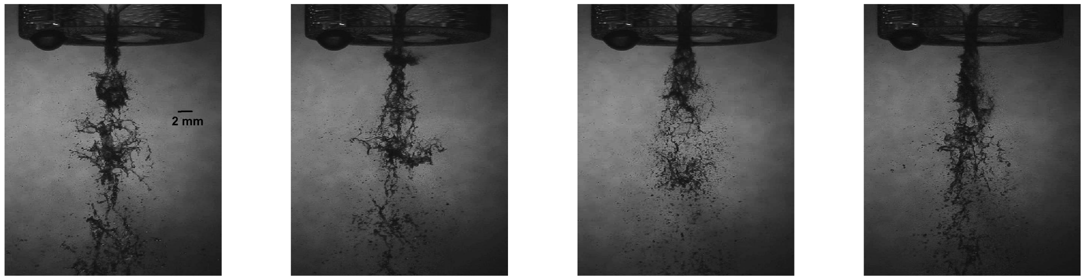


a) Injector configuration A

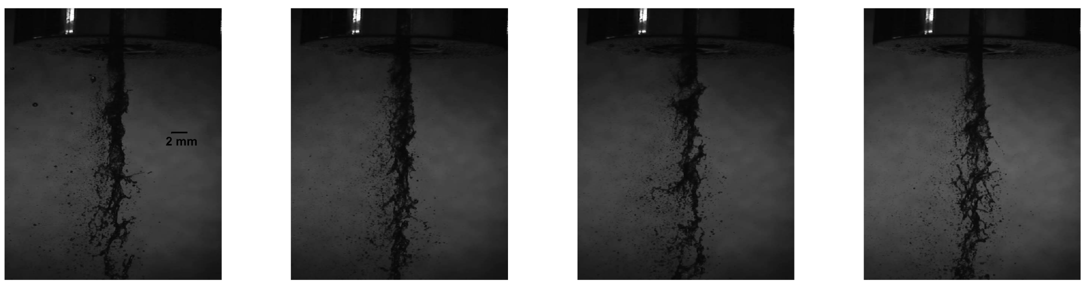


b) Injector configuration B

Fig. 2 Variation of SMD with GLR at different pressure drops for configurations A and B ($D_0 = 2$ mm).



a) Injector configuration A



b) Injector configuration B

Fig. 3 Comparative near-orifice spray structures for both configurations. The representative images are instantaneous pictures ($\Delta P = 0.196$ MPa, GLR $\approx 1\%$, $D_0 = 2$ mm).

Increase in GLR results in increasing the degree of underexpansion; hence, greater energy is available for expansion of the atomizing gas. This leads to higher cone angles as GLR is increased. In the case of injector B, the air is injected inside the orifice where pressure is lower compared with the mixing chamber. Although the two-phase mixture in underexpanded in both the cases, the degree of underexpansion is more in the case of injector A. This causes the two-phase mixture in injector A to form a wider spray cone for allowing the complete expansion to the ambient value.

Unsteadiness is a characteristic feature of conventional effervescent atomizers, which is highly undesirable. Spray unsteadiness here refers to the unsteadiness associated with the spray breakup. This is due to the fact that the primary breakup mechanism is the randomly exploding gas bubbles. The degree of unsteadiness depends largely on GLR. Difference in the near-orifice spray structures in four consecutive frames may be easily observed in Fig. 3a. The splashing resulting from the bubble explosion, as well as a typical annular type of conical spray, is seen at different time instants, indicating unsteadiness in the spray breakup phenomenon. These fluctuations in breakup phenomenon tend to increase as the GLR is decreased. However, the spray structures of injector B (Fig. 3b) are almost similar qualitatively. This is due to prevention of the bubble formation process in injector B. In this case, the two-phase mixture is of the form of two coflowing streams that make the operation of the injector smooth and steady. Injection of air inside the orifice (configuration B) always maintains the injector operation in single mode without internal and external flow transitions. Hence, configuration B is better in terms of steady operation compared with configuration A.

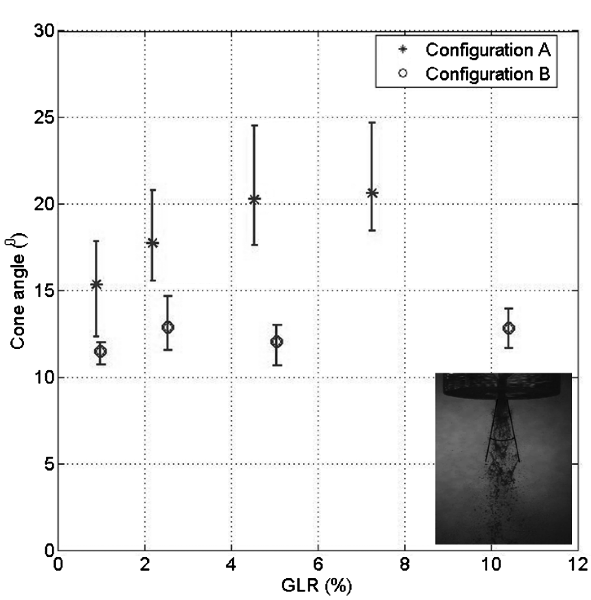


Fig. 4 Comparison of cone angles at different GLRs for both configurations ($\Delta P = 0.196$ MPa, $D_0 = 2$ mm). The method of cone angle measurement is shown as an inset.

IV. Conclusions

The comparative study of two configurations of an effervescent atomizer shows that the bubbly flow regime is suppressed in configuration B, even at low GLR. It is observed that the mean drop size produced by configuration A is much smaller than that produced by configuration B for the same GLR, indicating the superiority of the bubble-bursting phenomenon in producing finer spray at lower GLRs. Also, the cone angles are seen to be higher in the case of injector A for various GLR values due to injection of air at higher pressures. However, configuration A is found to be highly unsteady compared with configuration B due to intermittent bubble bursting, which is undesirable.

References

[1] Lefebvre, A. H., Wang, X. F., and Martin, C. A., "A Novel Method of Atomization with Potential Gas Turbine Application," *Indian Defence Science Journal*, Vol. 38, 1988, pp. 353–362.

[2] Wade, R. A., Weerts, J. M., Sojka, P. E., Gore, J. P., and Eckerle, W. A., "Effervescent Atomization at Injection Pressures in the MPa Range," *Atomization and Sprays*, Vol. 9, No. 6, 1999, pp. 651–667.

[3] Mathur, T., Lin, K. C., Kennedy, P., Gruber, M., Donbar, J., Jackson, T., and Billig, F., "Liquid JP-7 Combustion in a SCRAMJET Combustor," 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, AL, AIAA Paper 2000-3581, July 2000.

[4] Lefebvre, A. H., Wang, X. F., and Martin, C. A., "Spray Characteristics of Aerated-Liquid Pressure Atomizers," *Journal of Propulsion and Power*, Vol. 4, No. 4, 1988, pp. 293–298. doi:10.2514/3.23066

[5] Roesler, T. C., and Lefebvre, A. H., "Studies on Aerated-Liquid Atomization," *International Journal of Turbo and Jet Engines*, Vol. 6,

Nos. 3–4, 1989, pp. 221–229.

[6] Satapathy, M. R., Sovani, S. D., Sojka, P. E., Gore, J. P., Eckerle, W. A., and Crofts, J. D., "The Effect of Ambient Density on the Performance of an Effervescent Atomizer operating in the MPa Injection Pressure Range," *Proceedings of the Technical Meeting of the Central States Section of the Combustion Institute*, Combustion Inst., Pittsburgh, PA, 1998, pp. 76–80.

[7] Buckner, H. E., and Sojka, P. E., "Effervescent Atomization of High Viscosity Fluids. Part 1: Newtonian Liquids," *Atomization and Sprays*, Vol. 1, No. 3, 1991, pp. 239–252.

[8] Buckner, H. N., Sojka, P. E., and Lefebvre, A. H., "Effervescent Atomization of Coal-Water Slurries," American Soc. of Mechanical Engineers Publication PD-30, Fairfield, NJ, 1990, pp. 105–108.

[9] Geckler, S. C., and Sojka, P. E., "High Mass Flow Rate Effervescent Atomization of Viscoelastic Fluids," *Fluid Mechanics and Heat Transfer in Sprays*, edited by J. W. Hoyt, American Soc. of Mechanical Engineers , Vols. Fed-178/HTD-270, Fairfield, NJ, 1993, pp. 109–115.

[10] Whitlow, J. D., and Lefebvre, A. H., "Effervescent Atomizer Operation and Spray Characteristics," *Atomization and Sprays*, Vol. 3, No. 2, 1993, pp. 137–155.

[11] Li, J., Lefebvre, A. H., and Rollbuhler, J. R., "Effervescent Atomizers for Small Gas Turbines," American Soc. of Mechanical Engineers Publication PD-30, Fairfield, NJ, 1994, pp. 1–6.

[12] Chen, S. K., and Lefebvre, A. H., "Spray Cone Angles of Effervescent Atomizers," *Atomization and Sprays*, Vol. 4, No. 3, 1994, pp. 291–301.

[13] Sovani, S. D., Chou, E., Sojka, P. E., Gore, J. P., Eckerle, W. A., and Crofts, J. D., "High Pressure Effervescent Atomization: Effect of Ambient Pressure on Spray Cone Angles," *Fuel*, Vol. 80, No. 3, 2001, pp. 427–435.
doi:10.1016/S0016-2361(00)00105-8

[14] Panchagnula, M. V., and Sojka, P. E., "Spatial Droplet Velocity and Size Profiles in Effervescent Atomizer-Produced Sprays," *Fuel*, Vol. 78, No. 6, 1999, pp. 729–741.
doi:10.1016/S0016-2361(98)00192-6

[15] Lund, M. T., Sojka, P. E., Lefebvre, A. H., and Gosselin, P. G., "Effervescent Atomization at Low Mass Flow Rates, Part 1: The Influence of Surface Tension," *Atomization and Sprays*, Vol. 3, No. 1, 1993, pp. 77–89.

[16] Bush, S. G., and Sojka, P. E., "Entrainment of Effervescent Sprays at Low Mass Flowrates," *Proceedings of the Sixth International Conference on Liquid Atomization and Spray Systems*, Rouen, France, Inst. of Liquid Atomization and Spray System, 1994.

[17] Lorcher, M., Schmidt, F., and Mewes, D., "Effervescent Atomization of Liquids," *Atomization and Sprays*, Vol. 15, No. 2, 2005, pp. 145–168.
doi:10.1615/AtomizSpr.v15.i2.30

[18] Chawla, J. B., "Atomization of Liquids Employing the Low Sonic Velocity in Liquid/Gas Mixtures," *Proceedings of the Third International Conference on Liquid Atomization and Spray Systems*, Inst. of Liquid Atomization and Spray System Paper LP/1A/5/1985, 1985, pp. 1–7.

A. Gupta
Associate Editor