# Effervescent atomizer: influence of the internal geometry on atomization performance

J. Jedelsky, J. Otahal* and M. Jicha
Faculty of Mechanical Engineering, Brno University of Technology
Brno, Czech Republic

**Abstract**
Our work is being conducted with the aim to develop an effervescent atomizer for industrial burners that will generate a fine and stable spray in large turn-down ratio. The single-hole, plain orifice atomizer is powered with light heating oil and uses air as an atomizing medium in the "outside-in" gas injection configuration. Published design concepts of the effervescent atomizer are described. Based on the published results several design parameters are modified: size and number of aerator holes, their location and diameter of the mixing chamber. Influence of these parameters on spray performance is studied at atomizing pressures 0.1, 0.3 and 0.5 MPa and gas-to-liquid-ratio (GLR) of 2, 5 and 10%.

## Introduction

A method of atomization commonly referred to as „effervescent atomization" was developed in the late 1980s by Lefebvre and co-workers [1]. Also some earlier works [2, 3] mention similar concepts. Effervescent atomizers can be categorized as twin-fluid atomizers with internal mixing. In the simplest form of the effervescent atomizer, a gas is injected directly at low velocity into a flowing liquid at some point upstream of the atomizer exit orifice in such a way to create a bubbly two-phase flow. As the liquid flows through the discharge orifice it is transformed by the gas bubbles into thin shreds and ligaments. When the gas bubbles emerge from the nozzle at sufficient pressure drop, they expand so rapidly that the surrounding liquid is shattered into droplets.

Effervescent atomizers are becoming more and more commonplace in numerous engineering applications in which a liquid must be fragmented into droplets. Major advantage of effervescent atomizers is their relative insensitivity to fuel physical properties and ability to provide good atomization over a wide range of operating conditions even for less refined fuels. A possibility to vary both the operating pressure and also the ratio of flow rates of gas and liquid, GLR, leads to large atomizer turn-down ratios. As the atomizing gas is utilized by effervescent atomizer in relatively efficient manner, a good atomization can be achieved using very small flow rates of the gas. Another attractive feature is good atomization even when operating at low injection pressures. Furthermore the E-atomizers can have larger orifice than conventional atomizers which alleviates clogging problems and facilitates atomizer fabrication. It also predestinates this type of pneumatic atomizers for atomization of suspensions and slurries [4-8].

Despite of its inherent simplicity the effervescent atomizer gives possibility for wide variety of design configurations. Large amount of literature can be found to describe an influence of geometry of the liquid-air mixing system on performance of effervescent atomizers. It is shown that optimization of the atomizer design can improve the spray characteristics. Surprising diversity of design modifications can be seen in different papers. However it is not fully possible to generalize these results made for different effervescent atomizer concepts and for liquids of different physical properties (typically water). Moreover currently only SMD is often evaluated and other important spray parameters (spray cone angle, velocity profiles, entrainment number and mass flux) are neglected. The SMD varies with spray position and this feature is often neglected. In this study we bring an overview of design concepts investigated by different researchers together with specification and description of important geometric parameters. Our work is being conducted with the aim to develop an effervescent atomizer for industrial burners that will generate fine and stable spray in large turn-down ratio. The single-hole, plain orifice atomizer is powered with light heating oil and uses air as an atomizing medium in the "outside-in" gas injection configuration. Several design parameters are modified: size and number of aerator holes, their location and diameter of the mixing chamber. Influence of these parameters on the spray performance is studied at atomizing pressures 0.1, 0.3 and 0.5 MPa and GLR of 2, 5 and 10%. A near nozzle spray visualization by digital camera illustrates the atomization process at different operation modes.

## Effervescent Atomizer Configurations

Already in some early papers [9] a lot of different designs of effervescent atomizer appeared. We will attempt to make their basic classification here. To simplify our task we focus only on single-hole plain-orifice atomizers. Design described in different works can thus be divided into three basic groups, see Fig. 1.

Type A: In this configuration the liquid flows through a central tube. Gas is introduced into the liquid

* Corresponding author: otahal@fme.vutbr.cz
Proceedings of the 21th ILASS - Europe Meeting 2007

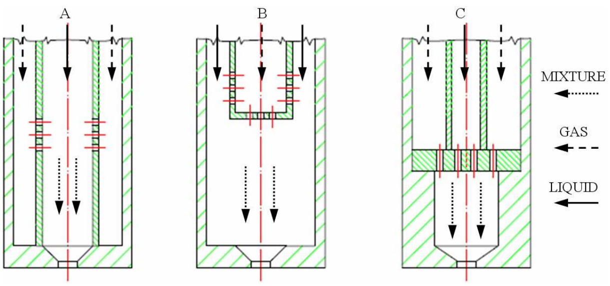


Fig. 1. Simplified schemes of design configurations of the effervescent atomizer.

by a set of small holes. This “outside-in” gas injection configuration enables large liquid flow area which prevents from clogging and thus it is also feasible for atomization of slurries. This probably the most frequent configuration has been studied in [3, 4, 7, 8, 10-21] and other papers. An option with switched inputs of the gas and liquid, an “inside-out” gas injection modification of the A-type is less frequent, it is described e.g. in [9].

Type B: Liquid flows through an annular port formed by atomizer body and aerator tube. Gas is introduced into the liquid by a set of small holes from the aerator side and/or from the aerator bottom. This “outside-in” modification is mentioned in works [9, 22-27]. An “inside-out” gas injection modification of the B-type has not been found in the literature.

Type C: Both the fluids enter separately into the mixing chamber. This configuration enables an independent control of the gas and liquid input velocity, direction and distribution. This version has been studied in [28, 29].

Usage of different inserts inside the mixing chamber can modify and improve mixing and internal two-phase flow [19, 27]. Input of the gas can be modified by changing the position of aeration holes, their size and directions. Disintegration of pure liquids may be enhanced using perforated plates in front of the discharge orifice. Application of the so called ligament-control inserts can be found in works [24, 26]. Note that atomizers with annular discharge orifice [9, 30, 31] or multi-hole atomizers [11, 12, 19, 32] can have slightly different design and probably also other more complicated and sophisticated configurations could appear in the future.

In our research we decided to use the A-type effervescent atomizer with “outside-in” gas injection configuration which seems to be the most promising for atomization of light heating oil and possible utilization for waste fuels in the future.

## Important Geometrical Parameters

Internal geometry of the effervescent atomizer is described by dimensions of its mixing chamber and by size and shape of discharge orifice. Main parameters of the mixing chamber studied in the past are:

- Size and number of aerator holes; investigated by [27, 33]. These values define a total area *A* through which gas penetrates into the liquid. Sometimes also a ratio of the final discharge orifice area to the total area of the aerator holes is used as an evaluated parameter [34, 35].
- Location of the aerator holes relative to the final discharge orifice [20, 27]. This parameter determines a development length of the two-phase mixture inside the atomizer.
- Cross section area (given by its diameter in case of cylindrical shape) of mixing chamber modifies velocity and hence a character of the two-phase flow [36]; this parameter was studied in [27]. Mixing chamber with rectangular shape was described in [37]. The cross section area of the mixing chamber together with the distance of the last set of aerator holes relative to the exit orifice defines the volume of the mixing chamber.
- Direction of aeration holes [27, 29, 33, 36]; it modifies the direction of input of the gas into the liquid. Tangentional direction leads to swirl motion of the mixture and it can improve mixing process; an inclination angle between liquid flow (aerator axis) and the aeration holes can also modify two-phase flow.

Difference between the “inside-out” and “outside-in” gas injection configuration has been studied in [27]. Discharge orifice geometry is determined by:

- Orifice diameter [1, 4, 11, 20, 27, 28, 38].
- Convergence angle at the inlet of the discharge orifice [9].
- Length to diameter ratio [9].

Based on the analysis of the above mentioned research works, we have defined four important geometrical parameters to study in the present work: diameter and number of aerator holes, location of the aerator holes relative to the final discharge orifice and diameter of the mixing chamber.

## Experimental Facility

Experimental equipment includes effervescent atomizer, cold test bench with fluid supply system and Phase/Doppler Particle Analyzer. Our single-hole, plain orifice atomizer of A type (Fig. 1) is powered with light heating oil and uses air as an atomizing medium in the “outside-in” gas injection configuration, see Fig. 2. It consists of a cylindrical body in which an aerator tube is inserted. The aerator is connected with an exit nozzle. The liquid (oil) enters the central orifice of the aerator from a 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.

The volume of the mixing chamber formed inside the aerator tube is given by a length downstream of the last row of air holes $L_1$ and internal diameter of the aerator tube, $D_2$. The exit orifice has a diameter $D_1$ of 2.5 mm and a length of 0.7 mm. There is a conical junction with the apical angle of 120° in front of the orifice. The length $L_1$, internal diameter $D_2$ together with the span length $\Delta L = L_2 - L_1$, diameter $D_3$ and number of aeration holes *n* are varied in this study.

The air and oil supplies are controlled separately. Operational conditions of the twin-fluid atomizer with

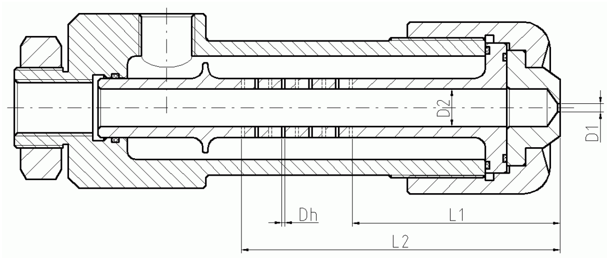


Fig. 2. Schematic layout of the research atomizer.

given geometry can be basically described by any two independent parameters. The air gauge pressure and GLR were chosen in our case. Experiments were performed for several air gauge pressures and GLR values. Temperature, gauge pressure and volumetric flow rates of both fluids were measured. The atomizer was studied in the vertical position of the main axis. Physical properties of the atomized liquid – light heating oil are documented in [36]. Description of our experimental facility and Dantec 1D Phase/Doppler Particle Analyser (P/DPA) used for drop size and velocity measurement can be found in [39].

**Spray Structure**

As it has been shown in number of publications, droplet size and velocity significantly depend on the input pressure drop and on GLR [11, 17, 19, 33, 37, 39]. Results for atomizing pressure of 0.2MPa are documented in Fig. 3, top. Radial profiles of Sauter Mean Diameter $D_{32}$ at the lowest GLR are almost flat with indistinctive local maximum in the atomizer axis. This shape of $D_{32}$ profiles is also documented in [12, 40], profiles with more distinct maximum in the atomizer axis were seen in [28].

An increase of GLR leads to a decrease of $D_{32}$ in the entire radial profile but mainly in the atomizer axis. For GLR higher then 0.6% the profiles tend to be inversely bell-shaped with a minimum in the spray axis. This change of $D_{32}$ profiles with GLR can be related to a character of internal two-phase flow which is bubbly in case of small GLR, changing to slug, annular and finally to dispersed with an increase of GLR. For more information see [36]. To characterize atomization quality by a single parameter we introduce a term of Integral Sauter Mean Diameter $ID_{32}$, which represents a whole spray at certain cross section perpendicular to the axis of the nozzle exit orifice. Simplified equation for calculation of $ID_{32}$ as derived in [6] reads:

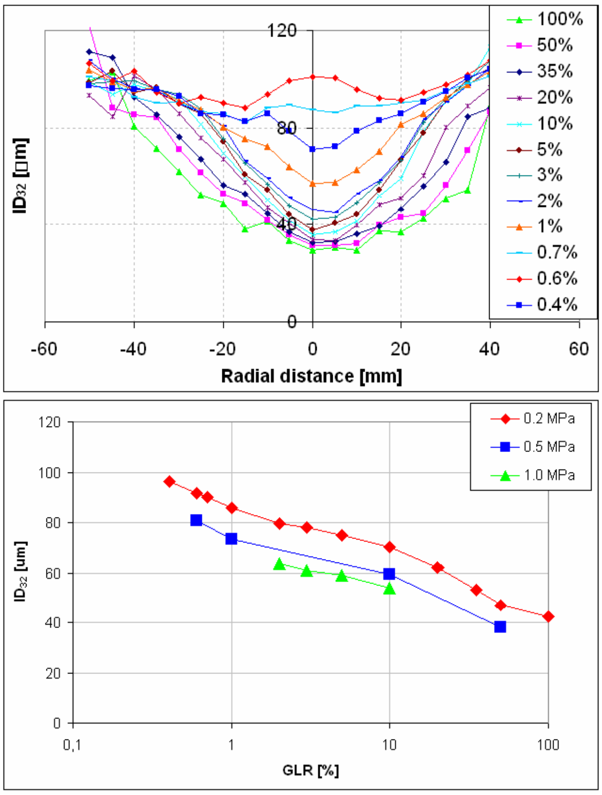


Fig. 3. Radial profiles of $D_{32}$ at p=0.2MPa and different GLR (top) and influence of pressure and GLR on $ID_{32}$ (bottom).

$$ID_{32} = \sum_{i=2}^{n} \left( r_i \cdot D_{30\_i}^3 \cdot f_i \right) \Big/ \sum_{i=2}^{n} \left( r_i \cdot D_{20\_i}^2 \cdot f_i \right) \quad (1)$$

where $D_{30\_i}$ and $D_{20\_i}$ are volumetric and surface diameters of droplets measured in position $r_i$. An ensemble of $n$ droplets is measured using P/DPA with droplet frequency $f_i$.

Resulting $ID_{32}$ calculated from data measured in radial profiles of $D_{32}$ 150mm downstream the exit orifice are shown in Fig. 3, bottom. The $ID_{32}$ decreases from 95µm at GLR 0.4% to 42µm at GLR 100% for pressure 0.2MPa. An increase of input gas pressure also leads to a finer spray. This dependence of atomization

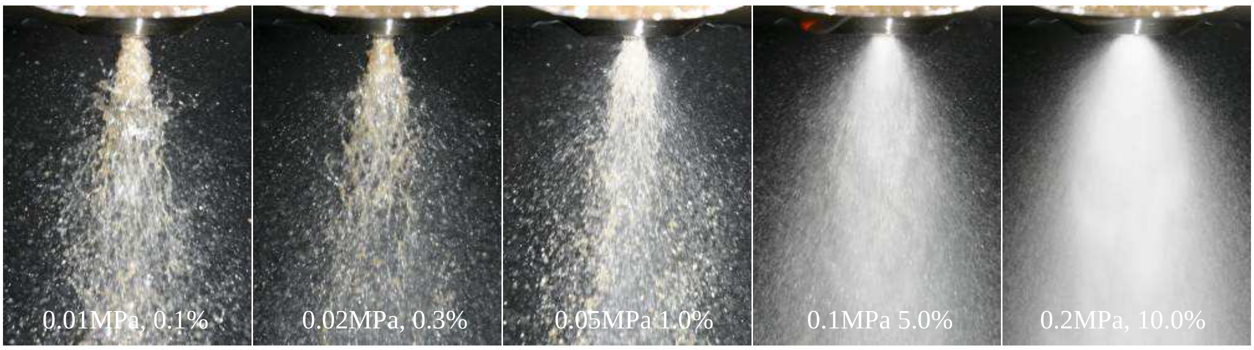


Fig. 4. Spray structure of effervescent atomizer at varying air gauge pressure and GLR.

performance on atomizer operation conditions is in general agreement with our earlier findings [17, 19] as well as with results of other investigators [1, 22, 33].

Near nozzle spray structure was visualized by a digital camera CANON EOS 300D using telephoto zoom lens CANON EF 100mm. Several different operation regimes at operation pressure and GLR varying are documented in Fig. 4.

At very low GLR, about 0.1%, and low pressure 0.01MPa the liquid forms continual film and ligaments at the nozzle exit, gas flows mainly through the central part of the exit orifice with higher velocity deforming the liquid surfaces and tearing the liquid into smaller fractions and finally into droplets. The liquid is additionally fragmented due to stretching of the ligaments and internal turbulent motion. Also shear stress due to still ambient air contributes to the disintegration. Atomization process proceeds through a relatively large distance from the nozzle exit.

Increase of GLR enables easier and faster disintegration of liquid volumes and shortens the atomization distance. The gas overcomes forces of liquid surface tension by shear stress due to slip velocity between the gas and liquid phase and also by expansion of the pressurized gas volumes enveloped by liquid phase. At GLR of about 2% and higher there is no compact liquid volume observed; the spray already in close distance from the exit orifice contains a number of small particles. We assume that also at higher GLR a liquid core exists at the nozzle exit but it is not clearly visible due to the presence of a cloud of the small droplets surrounding this continuous liquid bulk.

**Influence of Atomizer Geometrical Parameters on Spray Performance**

Based on published results we have defined four geometrical parameters to study in this work: the diameter $D_3$ and number of aerator holes $n$, location of the aerator holes relative to the final discharge orifice $L_1$ and diameter of the mixing chamber $D_2$. Several atomizers were designed for this study; their dimensions can be seen in Table 1. Atomization properties of the atomizers were measured at air gauge pressures 0.1, 0.3 and 0.5MPa at GLR 2, 5 and 10%. Only some results are processed in Table 2 due to the paper limitation.

Atomizers E25-E28 were used to study the influence of the diameter of the mixing chamber $D_2$. Mixing chamber diameter at given operation conditions (flow rates of the gas and liquid) influences a velocity of the internal flow of the two-phase mixture. The velocity increases with a decrease of the cross-section area of the chamber. At lower pressure and lower GLR the two-phase mixture is bubbly or slug and moves with a lower velocity [36]. At higher pressure the mixture changes to annular. Data in Table 2 shows a higher influence of the mixing chamber diameter at lower pressure, where the smallest $ID_{32}$ can be found for diameters between 8 and 11mm. For higher pressure and GLR the dependence of $ID_{32}$ on the chamber diameter almost disappears. We can conclude that the optimum diameter of the mixing chamber for our range of operation conditions is about 10mm for the orifice diameter 2.5mm.

Table 1. Atomizers under test.

| Atomizer | $L_1$ (mm) | $\Delta L$ (mm) | $D_2$ (mm) | $D_3$ (mm) | $n$ (-) |
|---|---|---|---|---|---|
| E21 | 90 | 30 | 5,5 | 0,7 | 60 |
| E22 | 85 | 30 | 5,5 | 1,0 | 30 |
| E23 | 85 | 25 | 5,5 | 1,3 | 18 |
| E24 | 90 | 25 | 5,5 | 1,5 | 13 |
| E25 | 85 | 30 | 5,5 | 1,0 | 30 |
| E26 | 85 | 30 | 8,0 | 1,0 | 30 |
| E27 | 85 | 25 | 11,0 | 1,0 | 30 |
| E28 | 85 | 40 | 14,0 | 1,0 | 30 |
| E29 | 75 | 0 | 14,0 | 1,0 | 8 |
| E30 | 55 | 0 | 14,0 | 1,0 | 8 |
| E31 | 35 | 0 | 14,0 | 1,0 | 8 |
| E32 | 65 | 10 | 14,0 | 1,0 | 24 |
| E33 | 50 | 10 | 14,0 | 1,0 | 24 |
| E34 | 35 | 10 | 14,0 | 1,0 | 24 |
| E35 | 65 | 20 | 14,0 | 1,0 | 40 |
| E36 | 45 | 20 | 14,0 | 1,0 | 40 |
| E37 | 35 | 20 | 14,0 | 1,0 | 40 |
| E38 | 35 | 40 | 14,0 | 1,0 | 80 |

Table 2. Integral Sauter mean diameter [μm] in spray at different operation pressure and GLR.

| $p$ (MPa) | | | 0,1 | 0,3 | 0,3 | 0,3 | 0,5 |
|---|---|---|---|---|---|---|---|
| GLR (%) | | | 5 | 2 | 5 | 10 | 5 |
| E25 | $D_2$ (mm) | 5,5 | 95,4 | 87,9 | 83,5 | 75,6 | 78,3 |
| E26 | | 8 | 87,8 | 85,8 | 81,5 | 76,6 | 78,2 |
| E27 | | 11 | 88,9 | 84,6 | 80,6 | 75,2 | 77,6 |
| E28 | | 14 | 92,6 | 88,2 | 83,2 | 77,0 | 78,2 |
| E21 | $D_3$ (mm) | 0,7 | 96,9 | 88,2 | 82,8 | 75,0 | 76,8 |
| E22 | | 1,0 | 95,8 | 88,4 | 83,9 | 76,1 | 78,8 |
| E23 | | 1,3 | 94,6 | 87,4 | 83,8 | 77,4 | 79,2 |
| E24 | | 1,5 | 94,2 | 91,2 | 86,8 | 77,0 | 78,7 |
| E30 | $n$ (-) | 8 | 96,0 | 93,7 | 87,3 | 80,9 | 82,6 |
| E33 | | 24 | 94,6 | 91,4 | 85,9 | 81,5 | 83,6 |
| E36 | | 40 | 89,1 | 86,0 | 84,5 | 76,5 | 80,0 |
| E38 | | 80 | 90,5 | 85,0 | 83,8 | 77,0 | 77,6 |
| E31 | $L_1$ (mm) | 35 | 100,1 | 92,0 | 89,3 | 84,9 | 88,9 |
| E30 | | 55 | 96,0 | 93,7 | 88,3 | 81,8 | 83,5 |
| E29 | | 75 | 91,5 | 88,5 | 86,0 | 79,9 | 81,9 |
| E34 | $L_1$ (mm) | 35 | 96,8 | 90,7 | 87,9 | 81,9 | 83,0 |
| E33 | | 50 | 94,6 | 91,4 | 87,2 | 82,8 | 84,9 |
| E32 | | 65 | 91,7 | 90,1 | 85,6 | 80,6 | 76,6 |
| E37 | $L_1$ (mm) | 35 | 89,8 | 91,6 | 84,6 | 79,8 | 77,9 |
| E36 | | 45 | 88,3 | 85,0 | 83,6 | 75,6 | 79,1 |
| E35 | | 65 | 93,3 | 85,6 | 83,5 | 77,7 | 79,4 |

The diameter of aerator holes $D_3$ was varied using atomizers E21-E24. The number of the aerator holes was also varied to keep the total aeration cross-section area constant. Table 2 documents that at pressure

0.1MPa and GLR 5%, the $ID_{32}$ decreases with the enlargement of the diameter of aerator holes. Similar behaviour was seen also at regimes p=0.1MPa-GLR 2% and p=0.1MPa-GLR 10% (not documented here). At higher pressures 0.3 and 0.5MPa the $ID_{32}$ shows opposite behaviour. Optimum design of the diameter of aerator holes hence depends on an assumed range of operation pressures. Generally, the influence of aerator holes diameter on the atomization performance is relatively small, compared to other factors. We recommend designing the aerator chamber with rather smaller diameter of aerator holes to acquire good results in larger range of operation conditions.

Atomizers E30, E33, E36 and E38 were used to investigate the influence of the aeration cross-section area on the atomization process. The cross section area was modified by changing the number of aerator holes $n$. Table 2 shows that increase of aeration area leads to improvement of the $ID_{32}$. This effect can be associated with a more homogeneous mixture in case of larger number of aeration holes.

Location of aeration holes relative to the exit orifice is described by the length $L_1$. This parameter was studied in atomizers E29-E31 with one line of aeration holes (each line with 8 holes), atomizers E32-E34 with three lines of aeration holes and atomizers E35-E37 with five lines of aeration holes. Relatively strong dependence of the location of aeration holes on $ID_{32}$ is seen in case of a single row of the aeration holes. The influence of location of aeration holes on the $ID_{32}$ is reduced in case of 3 lines of aeration holes and almost disappears in case of 5 lines of aeration holes. In case of low number of aeration holes used and mainly in case of lower pressure and lower GLR an unsteady spray was observed. This phenomenon was more distinctive for larger distances $L_1$. The effervescent spray unsteadiness is described in more detail in [41]. It would be useful to make a deeper study to evaluate also the influence of operation conditions on the spray unsteadiness. Comparison of results for all the atomizers E29-E37 leads to conclusions that the best results are acquired with higher number of aeration holes.

## Conclusions

Presented results document variation of droplet size characterized by Sauter mean diameter with position in the spray. It leads us to a definition of integral value of Sauter mean diameter for the description of the atomization performance by a single parameter. Evaluation of this parameter on a set of nozzles with modified design parameters results in several conclusions: influence of atomizer design on its performance is moderate. Optimum results can be acquired with mixing chamber diameter about 4-times exit orifice diameter, larger number of aeration holes and their smaller diameter leads to decrease of droplet size. Operation pressure and GLR significantly influence the droplet size.

## Acknowledgement

The authors gratefully acknowledge a financial support from the project GA 101/06/0750 funded by the Czech grant agency.

## References

1. A. H. Lefebvre, X. F. Wang, and C. A. Martin, Spray characteristics of aerated-liquid pressure atomizers. /AIAA J Prop Power/, 4(4), pp. 293–298, 1988.
2. J. M. Chawla, Atomization of Liquids Employing the Low Sonic Velocity in Liquid/Gas Mixtures; Proceedings of the Third ICLASS-85, LP/1A/5/1-7, 1985.
3. E. Sher and D. Elata, Spray formation from pressure cans by flashing. /Ind Eng Chem Process Des Dev/, 16, pp. 237–242, 1977.
4. H. N. Buckner, P. E. Sojka, and A. H. Lefebvre, Effervescent atomization of coal-water slurries. /ASME Publ/, PD-30, pp. 105–108, 1990.
5. B. Mulhem, U. Fritsching, G. Schulte, and K. Bauckhage, Characterisation of Twin-Fluid Atomisation for Suspensions, ICLASS, 2003.
6. J. Jedelsky, M. Jicha, and J. Otahal, Atomization of Waste Liquids. 9th FLUCOME. (In print), 2007.
7. F. Schmidt, M. Lörcher, and D. Mewes, Measured Velocity Profile inside a Twin-Fluid Atomizer Generating a Suspension Spray, 10th ICLASS, 2006.
8. D. Loebker and H. J. Empie, Effervescent Spraying: A New Approach to Spraying High Solids Black Liquor, IPST Tech. Pap. Ser. No. 724, 11p., 1998.
9. J. S. Chin and A. H. Lefebvre, A design procedure for effervescent atomizers. /ASME J Engng Gas Turbines Power/, 117, pp. 226–271, 1995.
10. S. K. Chen, A. H. Lefebvre, and J. R. Rollbuhler, Influence of ambient air pressure on effervescent atomization. /J Propulsion Power/, 9(1), pp. 10–15, 1993.
11. J. D. Whitlow and A. H. Lefebvre, Effervescent atomizer operation and spray characteristics. Atomization and Sprays, 3, pp. 137–155, 1993.
12. J. Li, A. H. Lefebvre, and J. R. Rollbuhler, Effervescent atomizers for small gas turbines. American Society of Mechanical Engineers, 94-GT-495, 1–6, 1994.
13. P. J. Santangelo and P. E. Sojka, A holographic investigation of the near nozzle structure of an effervescent atomizer produced spray. Atomization and Sprays Vol. 5, pp. 137–155, 1995.
14. M. R. Satapathy, S. D. Sovani, P. E. Sojka, J. P. Gore, W. A. Eckerle, and J. D. Crofts, The Effect of Ambient Density on the Performance of an Effervescent Atomizer Operating in the MPa Injection Pressure Range, Proc. of 1998 Techn. Meeting of the Central States Section of Comb. Inst., pp. 76-80, 1998.
15. J. Karnawat and A. Kushari, Controlled atomization using a twin-fluid swirl atomizer, Experiments in Fluids, Vol. 41, No. 4, 2006.

16. M. E. Ferreira, J. C. F. Teixeira, C. J. Bates, and P. J. Bowen, Detailed Investigation of the Influence of Fluid Viscosity on the Performance Characteristics of Plain-Orifice Effervescent Atomizers, Atomization & Sprays, Vol. 11, No 2, 2001.
17. M. Jicha, J. Jedelsky, J. Otahal, and J. Slama, Influence of some geometrical parameters on the characteristics of effervescent atomization, Int. Conf. ILASS Europe, pp.345-350, 2002.
18. M. V. Panchagnula, T. J. Kuta, P. E. Sojka, and M. W. Plesniak, Modifying entrainment in ligament-controlled effervescent atomizer-produced sprays. 10th ILASS, Ottawa, ON, p. 35–39, 1997.
19. J. Jedelsky, M. Jicha, and J. Slama, Characteristics and behaviour of multi-hole effervescent atomizers. 19th ILASS Europe, pp. 521-526, 2004.
20. R. A. Wade, J. M. Weerts, P. E. Sojka, J. P. Gore, and W. A. Eckerle, Effervescent atomization at injection pressures in MPa range. Atomization and Sprays, 9(6), pp. 651–667, 1999.
21. Y. Funawatashi, S. Kawashima, E. Kozuka, Y. Sakamura, and T. Suzuki, The Influence of Nozzle Flow Patterns on Spray Particle Size of Internal Mixing Twin-Fluid Atomizers, No.40(20030301) pp. 53-54 , The Japan Society of Mechanical Engineers, 2003.
22. S. G. Bush and P. E. Sojka, Entrainment by effervescent sprays at low mass flowrates. Fluid Mechanics and Heat Mass Transfer in Sprays, ASME. pp. 117–121, 1993.
23. M. T. Lund and P. E. Sojka, Effervescent atomization at low mass flow-rates. Part 2: the structure of the spray. 5th Annual Conf. on Liquid Atomization and Spray Systems, San Ramon, CA, pp. 233–237, 1992.
24. J. J. Sutherland, P. E. Sojka, and M. W. Plesniak, Ligament controlled effervescent atomization. /Atomization Sprays/, 7 (4), pp. 383–406, 1997.
25. P. Dutta, J. P. Gore, Y. R. Sivathanu, and P. E. Sojka, Global properties of high liquid loading turbulent crude oil+methane/air spray flames. /Combustion Flame/, 97, pp. 251–260, 1994.
26. T. J. Kuta, M. W. Plesniak, and P. E. Sojka, Entrainment Control for Ligament Controlled Effervescent Atomizer Sprays, Atomization and Sprays 13(5&6), 561-577, 2003.
27. A. Mostafa, M. Fouad, M. Enayet, and S. Osman, Measurements of Spray Characteristics Produced by Effervescent Atomizers, AIAA-2004-3378, 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Fort Lauderdale, Florida, July 11-14, 2004.
28. S. G. Lee, B. C. Joo, K. C. Kim, and B. J. Rho, Influence of ALR on Disintegration Characteristics in Pneumatic Spray, International Journal of Automotive Technology, Vol. 1, No. 2, pp. 95−100, 2000.
29. N. Tamaki, M. Shimizu and H. Hiroyasu, Atomization of High-viscous Liquid Jet by Internal Mixing Twin-Fluid Atomizer, Proc. of 19th ILASS-Europe, pp. 412-417, 2004.
30. S. V. Sankar, D. M. Robart, and W. D. Bachalo, Swirl effervescent atomizer for spray combustion. /ASME HTD/, 317–312, pp. 175–182, 1995.
31. R. O. Colantonio, The applicability of jet-shear-layer mixing and effervescent atomization for low-NOx combustors, J. eng. gas turbine power, vol. 120, no 1, pp. 17-23, 1998.
32. F. Morelli, S. Ligasacchi, and M. Bizzarri, Development of Effervescent atomizers for Oil-Fired Power Stations. 9th ICLASS, 2003.
33. E. Sher, M. Koren, D. Katoshewski and V. Kholmer, Energy consideration and experimental study of effervescent atomizers, Paper II.7, Proceedings of ILASS-Europe, 2000.
34. T. C. Roesler and A. H. Lefebvre, Studies on aerated-liquid atomization. Int. J. Turbo Jet Engines; 6, pp. 221-30, 1989.
35. J. S. Chin and A. H. Lefebvre, Flow regimes in effervescent atomization. Atomization and Sprays; vol. 3, pp. 463-75, 1993.
36. J. Jedelsky and M. Jicha, Characteristics of a Two-phase Flow Inside the Mixing Chamber of an Effervescent Atomizer, 3rd Int. Symp. on Two-Phase Flow Modelling and Experimentation, 2004.
37. S. D. Sovani, P. E. Sojka, and A. H. Lefebvre, Effervescent Atomization, Progress in Energy and Combustion Science 27, pp.483-521, 2001.
38. T. C. Roesler and A. H. Lefebvre, Studies on aerated-liquid atomization. ASME Winter Annual Meeting, Boston, Massachusetts, Paper 87-WA/HT-17, 1987.
39. J. Jedelsky, M. Jicha, and J. Slama, Characterization of spray generated by multihole effervescent atomizer and comparison with standard Y-jet atomizer, Proc. of 9th ICLASS, pp. 0311, 2003.
40. A. Kufferath, B. Wende, and W. Leuckel, Influence of liquid flow conditions on spray characteristics of internal-mixing twin-fluid atomizers. Int. J. of Heat and Fluid Flow. Vol.20, Issue 5, pp.513-519, 1999.
41. J. Jedelsky and M. Jicha, Unsteadiness in Effervescent sprays – a new evaluation method and the influence of operational conditions. Atomization and Sprays, (In print), 2007.