CHARACTERISTICS AND BEHAVIOUR OF MULTI-HOLE EFFERVESCENT ATOMIZERS

J. Jedelsky[1], M. Jicha[1], J. Slama[2]

[1]Brno University of Technology, Faculty of Mechanical Engineering, Technicka 2, 61669 Brno, Czech Republic, jicha@eu.fme.vutbr.cz
[2]Prvni brnenska strojirna, Prumyslova ctvrt, 674 86 Trebic, Czech Republic

Abstract

The paper shows results of continuos research of multi-hole effervescent atomizers for industrial burners. The atomizer is powered with light heating oil and uses air as an atomizing medium. Here we focus on several new versions of multi-hole effervescent atomizers developed on the basis of previous research. Detailed description of spray quality is presented. 3-D graphs show spatial distribution of Sauter Mean Diameter and mean velocity. Influence of design and operational conditions on spray quality is analyzed. Size-velocity correlation and size and velocity distribution is described. The results are compared with results of other authors. Two-phase flow inside the atomizers is described by Baker's map for horizontal flow. Our previous results with two-phase flow visualization invoked a possibility of liquid-gas gravitational separation. Results of spray heterogeneity measurements show that differences between fuel flow rate of individual holes can be of the order of tens %. Effervescent atomizer sprays tend to be unsteady under some operating conditions. Spray unsteadiness at lower pressure and GLR were observed and measured.

1. Introduction

Effervescent atomizers are becoming more and more commonplace in numerous engineering applications in which a liquid must be fragmented into droplets. Effervescent atomizers in combustion applications lead to lower pollutant emissions due to presence of air in the spray core. Major advantage of effervescent atomizers is their relative insensitivity to fuel physical properties and ability to perform over a wide range of liquid flow rates and can provide good atomization over a wide range of operating conditions even for less refined fuels. Furthermore the E-atomizers can have larger orifice than conventional atomizers which alleviates clogging problems and facilitates atomizer fabrication.

The study of effervescent atomizers 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 atomizer is powered with light heating oil and uses air as an atomizing medium. This research is a follow up of a research done previously with single-hole effervescent atomizers with various geometrical features of both, the aerator and the body of the atomizer [1]. Based on results of this study a multi-hole effervescent atomizer was designed in several geometrical modifications. Flow rates of both fluids and discharge coefficient as function of pressure and GLR (Gas-to-Liquid Ratio) for predetermined turn-down ratio have been studied [3]. Other paper deals with detailed measurement of spray quality (D_{32}, velocity profiles, mass fluxes) and the parameters of effervescent atomizer are compared with the ones of standard Y-jet atomizer [2]. Simplified transparent atomizer was designed to observe internal two-phase flow of oil and air using high speed video camera [4].

2. Atomizer description and operation

Based on previous research [1-3], four atomizers E8, E9, E10 and E12 were designed which are studied here. Atomizers E8 and E10 have concept shown schematically in Fig.1. Fuel enters the aerator from left side. Atomising gas (air in our case) enters the aerator through a set of holes and mixes with fuel.

The mixing chamber has the inner diameter of 16mm. There is a conical shaft placed inside the chamber so the gap gradually enlarges from 1mm at the position of the first row of aerator holes. There are 168 holes of the diameter of 1.2mm in 21 rows, 8 holes in one row always turned through 45°. The last row of the holes ends up at the position of the tip of the conical shaft. The tip of nozzle has 6 orifices of the diameter of 2.2mm. Axes of the orifices form a full angle of 60° for atomizer E8 and 90° for atomizer E9. Atomizer E10 and E12 has no shaft inside the aerator and only the first row of 6 aerator holes and/or the last row of 4 aerator holes, resp. The inside aerator diameter is 10mm. Aerator holes of atomizer E10 have tangential direction with angle 45°. Axes of the orifices form a full angle of 60° for both atomizers.

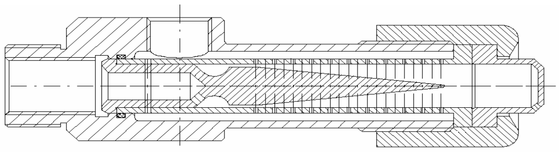

Fig.1: Schematic layout of effervescent atomizer.

Tab.1: Atomizer operational conditions and parameters.

atomizer		E8-E9		E8	E10-E12		E10	E12
p_g	GLR	d_p	M_l	p_{RMS}	d_p	M_l	p_{RMS}	p_{RMS}
[MPa]	[%]	kPa	$ml.s^{-1}$	kPa	kPa	$ml.s^{-1}$	kPa	kPa
0.2	3	-25	144	2.35	17	118	2.49	1.13
0.2	5	-13	110	2.23	41	84	1.57	1.61
0.2	10	-4	71	2.21	74	49	1.50	2.21
0.6	3	-78	299	1.40	-7	274	0.76	0.86
0.6	5	-48	236	1.31	36	204	0.87	0.89
0.6	10	-16	156	0.83	113	128	0.98	1.11
1.0	3	-151	438	0.57	-33	395	0.73	0.88
1.0	5	-91	340	0.71	32	301	0.95	0.56
1.0	10	-45	232	0.68	157	189	0.57	0.90

Atomizers for burners have to ensure good spray in all range from minimum to maximum fuel flow rate M_l. Actual turndown ratio is 1:5. Typical air over-pressure to obtain the maximum flow rate is p_g=1.0MPa with GLR 3%. For minimum flow rate p_g=0.2MPa, GLR 10%. Detailed experiments were performed for all combinations of pressure 0.2, 0.6, 1.0MPa and GLR 3, 5, 10 %. Operational conditions of atomizers E8 and E10 are presented in Tab.1. Also difference between input air and fuel pressure $d_p = p_g - p_l$ is included. Atomizer E9 was operated under the same operational conditiosn as the atomizer E8 and atomizer E12 as the atomizer E10. Value p_{RMS} relates to spray unsteadiness and it is described later.

3. Spray quality

Spray quality of single-hole effervescent atomizers and some results for multi-hole atomizers compared with Y-jet atomizer were presented in our previous papers [1,2]. Here we describe results obtained for atomizers E8, E9, E10 and E12. More attention is paid only to atomizer E10 that was chosen as representative.

The droplet diameter and velocity were evaluated with Phase Doppler analyser. The PDA setup and the configuration of test bench were described in [2]. A collector and deflector of spray were installed to ensure measurement of spray from only a single nozzle. Atomizer was installed with the orifice axis in vertical position. The co-ordinate system is shown in Fig.2.

The measurement was made in several planes with grid point separation 5x5mm. Planes configuration was: XY for Z=100, 150, 200mm, XZ for Y=0mm, YZ for X=0mm. Number of samples in each point was limited by 20000 or by measurement time 30s, what occurred first. Points with less than 1000 samples were rejected.

Results of D_{32} and mean axial velocity are seen in Fig.3 and 4. The structure of the spray is very similar to the single-hole atomizer. The spray is axially symmetrical. Lowest values of D_{32} about 30μm are seen near the nozzle axis. Downstream D_{32} slightly increases. This could result from drop interactions and coalescence as effervescent atomizer sprays are highly turbulent [10]. Maximum velocity, 40m.s^{-1}, is seen near the nozzle axis.

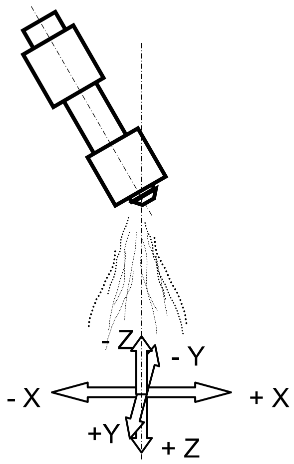

Fig.2: Schematic view of meaurement coordinates.

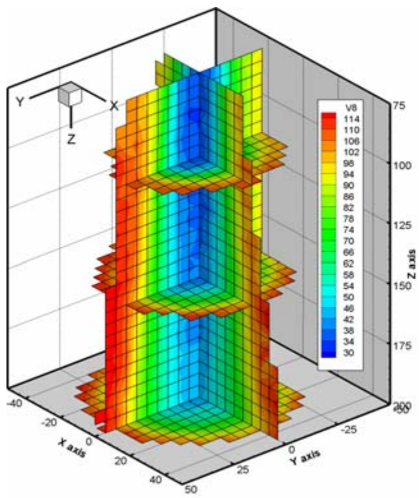

Fig.3: D_{32} of one orifice of multi-hole atomizer E10: p_a=0.6MPa, GLR=0.05.

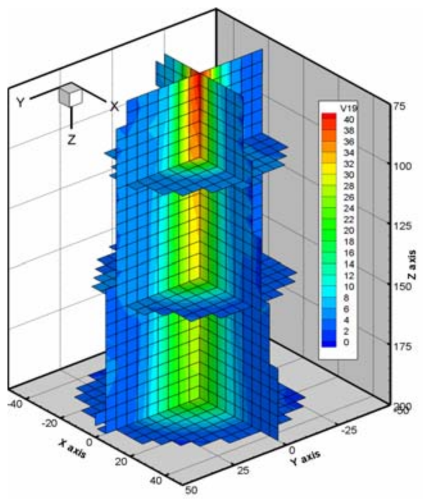

Fig.4: Axial component of mean velocity of one orifice of multi-hole atomizer E10: p_a=0.6MPa, GLR=0.05.

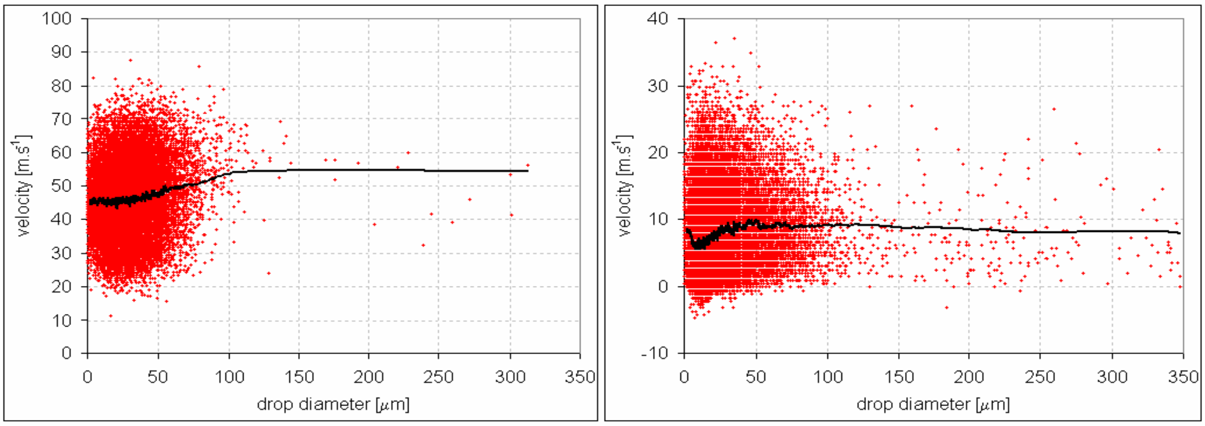

Fig.5: Diameter-axial velocity correlation, atomizer E10: p_a=0.6MPa, GLR=0.05; left: position (0, 0, 152), right: position (30, 0, 152).

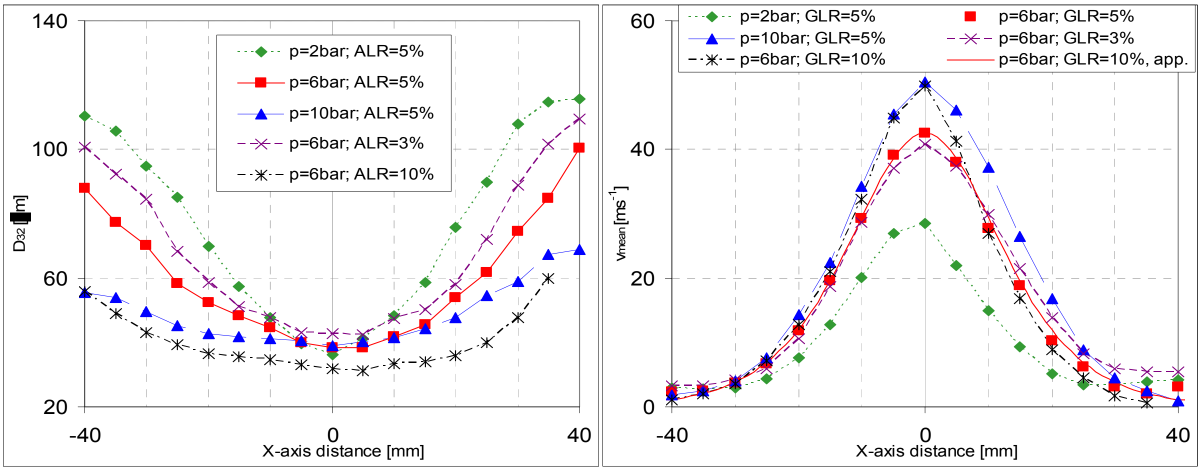

Fig.6: Dependance of D_{32} (left) and mean axial velocity (right) on air pressure p_g and GLR for atomizer E10, position Y=0mm, Z=152mm.

The diameter-axial velocity correlation is presented in Fig.5. The solid line represents an average size per 256 drops. Spray at nozzle axis contains mainly droplets smaller than 100μm, which results in D_{32} of 38.3μm. Spray in position 30mm from the nozzle axis has wider size spectrum, some droplets are even larger than 350μm, which is the maximum value measured by PDA. This corresponds with [11]. D_{32} is in this case 74.4μm. From Fig.5 it follows that the size-velocity correlation is negligible, regardless of radial position. This latter and further results [9], showing that the size-velocity correlation is insignificant regardless of pressure, GLR or axial location, are in good agreement with [10].

An influence of GLR and fluid pressure on drop sizes and velocity is seen in Fig.6. The spray is characterised by smallest droplets at the centre of the spray, where typical values of D_{32} range from 30 to 40μm and by larger droplets at the edges of the spray. Fig.6 shows that with the increasing distance from the exit orifice the profiles are more flat. Radial profiles correspond with our previous results for single-hole effervescent atomizers [1]. This might be a result of lower energy of expanding gas on the periphery of the spray, which leads to worse atomization. Higher air pressure and/or higher GLR lead to more flat size profile. Similar results were also presented in [12]. These results are not in agreement with [10 and13], where a negligible dependence of D_{32} on distance from the nozzle axis was found and with [12], where also inverse profiles are presented. One possible explanation of the differences might be a different internal configuration of atomizers.

Average velocity shows a bell-shaped profile. Formula for velocity profile from [10]:

$$v = V_{\max} \operatorname{sech}^2\left(\sigma \frac{r}{x}\right) \tag{1}$$

shows a good correlation with our results for spray half-angle less than 11° (radial distance 30mm at the distance 152mm from the exit orifice) as it is seen on Fig.6 for pressure 0.6MPa and GLR 5%. Value of σ=4.1e-4.

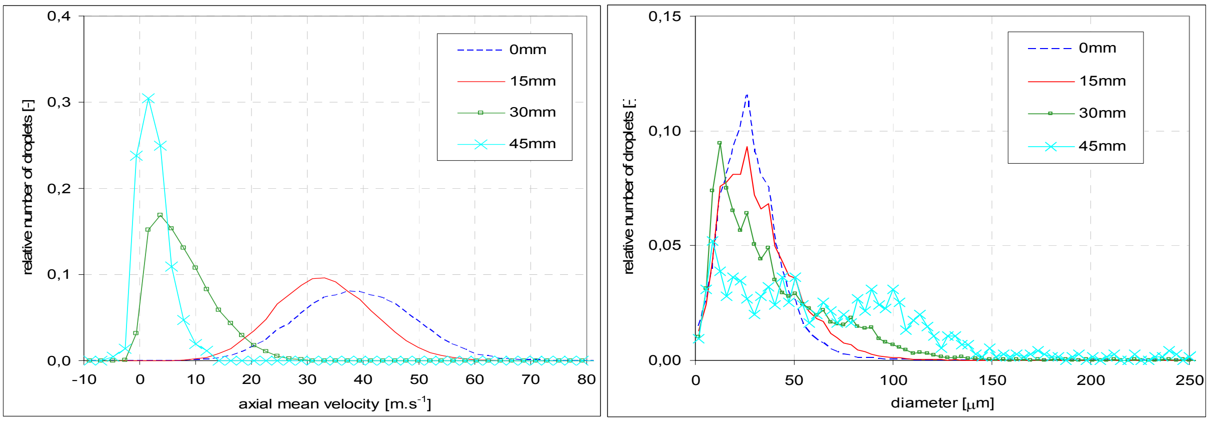

Fig.7: Particle velocity distribution (left), particle size distribution (right), atomizer E10: p_a=0.6MPa, GLR=0.05, position Y=0mm, Z=152mm, various X-axis positions

Particle velocity distribution can be described by log-normal statistical distribution. Near the nozzle axis the distribution is almost symmetrical, in larger radial distances, where lower droplet velocities occur the distribution is highly asymmetrical - see Fig.7. Particle size distribution in the nozzle axis can be described by Rosin-Rammler distribution with R-R exponent α_R=2.06. R-R mean drop diameter D_R= 25µm is in agreement with [14]. Also log-normal distribution with standard geometric deviation s_g= 0.58µm^{-1} and geometric mean drop diameter D_{ng}=21.5µm gives good correlation. The Rosin-Rammler and log-normal distribution are defined as follows:

$$f(D) = \frac{1}{\sqrt{2\pi}D \cdot s_g} \exp - \left[\frac{1}{2s_g^2} (\ln D - \ln \overline{D}_{ng})^2 \right] \quad (2)$$

$$g(D) = \left(\alpha_R / D_R^{-\alpha_R}\right) \cdot D^{(\alpha_R - 1)} \cdot \exp - \left(D/D_R\right)^{\alpha_R} \quad (3)$$

In larger radial distances larger droplets occur and the distribution changes to bimodal. The second peak corresponds with drop diameter 100µm. Comparison of D_{32} for atomizers E8, E9, E10 and E12 is seen in Fig.8. The curves for air pressure 0.6MPa are shifted by -10µm and for air pressure 1.0MPa are shifted by -20µm for better resolution. D_{32} generally decreases with increasing GLR and air pressure for all atomizers and pressures. The differences between nozzles don't have a uniform trend for all pressures and GLR. Atomizer E8 (E9) has lower D_{32} at pressure 0.2 and 1.0MPa then atomizer E10 (E12), but higher D_{32} at pressure 0.6MPa. The values differ by less than ±3µm in the entire measurement range. We assume that differences in cross section area of aerator holes and different two-phase flow conditions don't influence D_{32}. As D_{32} of atomizer E8 has almost the same values as atomizer E9 we can conclude that different angle of nozzle exit orifice axis to main atomizer axis has no influence on spray quality. Also comparison between E10 and E12 indicates no significant influence of tangential air entrance into the aerator.

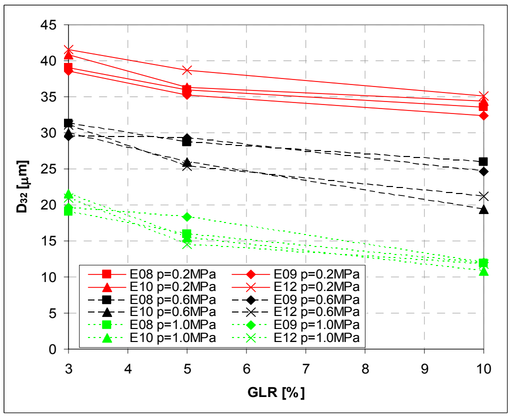

Fig.8: Air pressure and GLR influence on D_{32}, position X=Y=0mm, Z=152mm.

4. Two-phase flow parameters and conditions

Mixing process and two-phase flow inside the effervescent atomizer is an important step to atomization. Understanding the behaviour of mixture inside of atomizer is prerequisite for a good atomizer design. Little works deals with influence of operational and design parameters on two-phase flow patterns and relation between two-phase flow patterns and spray quality and stability [4,7,13,18-20].

Two-phase flow inside atomizers is presented here using Baker's map for horizontal two-phase flow published in [21]. Atomizer E8 has the same operational conditions as E9 and also differences between atomizer E10 and E12 are negligible, so that only two-phase flow regimes for E8 and E10 are presented here. The atomizers were developed to operate in bubbly flow regimes. The coordinates in Baker's two-phase flow map (see Fig.9) follows from values mentioned in Tab.1, detailed description of calculation procedure is published in [4].

Both the pressure and GLR influence the flow pattern, as can be observed in Fig.9. As for geometrical parameters, only the cross-sectional area of mixing chamber has an influence. Larger mixing chamber cross-sectional area of the atomizer E8 shifts the two-phase flow regime closer to slug flow than for the atomizer E10.

Simplified transparent atomizer was designed to observe two-phase flow with high-speed video camera. More can be found in [4]. Main conclusion was that the two-phase flow patterns were not always in a good agreement with the patterns predicted by maps published for fully developed two-phase flow. The atomizer mixing chamber elevation has not large effect on the flow pattern, but the horizontal flow can lead to vertical liquid separation under some operational conditions. This latter should be considered in case of multi-hole atomizers used in burners in horizontal position, where it can induce a non-homogenous spray in individual exit orifices. The results also indicated that non-homogenous mixture in case of low GLR could lead to unsteadiness. These results were supported by flame observation in combustion chamber. Heterogeneous flame indicated non-uniform GLR distribution caused by fluid vertical separation.

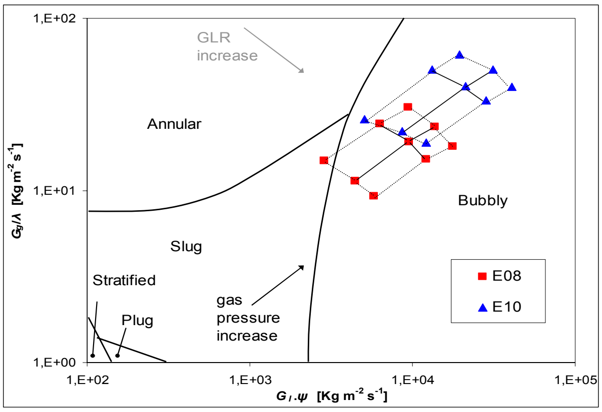

Fig.9: Field of operation regimes of E8 atomizer for combinations of air pressure 0.2, 0.6, 1.0 MPa and GLR 3, 5 and 10 %.

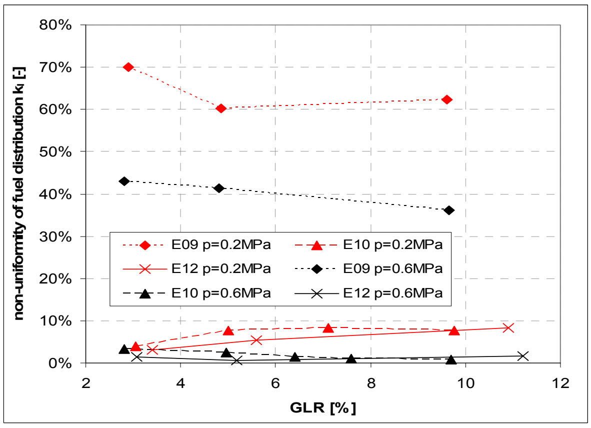

Fig.10: Non-uniformity of fuel distribution on exit orifices of multi-hole effervescent atomizer.

5. Spray heterogeneity

Based on these finding a distribution of fuel volumetric flow rate by individual exit orifices was measured. The atomizer was run in horizontal position with a special collector that enabled measuring the fuel volumetric flow rate Q_l of individual nozzle orifices without significant influence on atomizer operation. Fuel flow rate of the uppermost and the lowermost orifice was measured. The non-uniformity of fuel distribution was defined as:

$$k_l = \frac{2(Q_{lb} - Q_{lt})}{Q_{lb} + Q_{lt}}, \qquad (4)$$

where the subscript b belong to the lower orifice and the subscript t to the upper one. Results for atomizers E9, E10 and E12 are seen in Fig.10. The non-uniformity is much higher for atomizer E9 than for E10 and E12. We assume that lower area of air holes leads to higher air injection velocity and it improves mixing of two-phase flow and prevent the gas-liquid separation. Operation at lower pressure, where lower fluid velocities inside the mixing chamber are achieved, always leads to higher non-uniformity of fuel distribution. For lower pressure the two-phase flow regime is also closer to slug and stratified regime as it is seen in Fig.9. Differences between atomizer E10 and E12 are not significant, the tangential air input to the mixing chamber does not influence the non-uniformity. Using a swirler inside the mixing chamber could also improve the spray homogeneity.

6. Spray unsteadiness

During development of effervescent atomizers unsteady behaviour of spray was observed under some operational conditions of atomizer. A method of the unsteadiness evaluation was developed based on measurement of mixture pressure near the exit nozzle orifice. Band pass RMS pressure value serves as a measure of the unsteadiness; detailed description of the method is in [4]. Results for atomizers E8, E10 and E12 are presented in Tab.1. Values of p_{RMS} higher than 2kPa usually mean an unsteady spray. It is seen that at lower pressure the atomizers have higher tendency to unsteady behaviour. For these operational conditions, atomizers operates closer to slug flow as it is seen in Fig.9.

7. Conclusions

D_{32} profiles of developed effervescent atomizer are inverse bell-shaped, which is not in agreement with some researchers. The minimum D_{32} about 35µm is at nozzle axis. Size-velocity correlation is negligible with regard to position in spray. Particle size distribution in the nozzle axis can be described by Rosin-Rammler distribution. In larger radial distance larger droplets occur and the distribution changes from uni- to bi-modal.

Horizontal operation of multi-hole effervescent atomizers can lead to gravitational gas-liquid separation. Decreasing of number of aerator holes can prevent this negative effect. Tendency to spray unsteadiness at lower pressure and GLR probably corresponds with a shift from bubbly flow to slug flow and can be prevented by thorough design of atomizer.

Acknowledgement

We greatly acknowledge a financial support from the Ministry of Education of the Czech Republic through the project Eureka E! 2517 BURNER, from Brno University Research Plan No. MSM262100001 and project GA 101/03/P020 funded by the Czech grant agency.

References

[1] Jicha, M.-Jedelsky, J.-Otahal, J.-Slama, J.: Influence of some geometrical parameters on the characteristics of effervescent atomization, Int. Conf. ILASS Europe, pp.345-350, 2002.

[2] Jedelsky, J.-Jicha, M.-Slama, J.: Characterisation of Spray Generated by Effervescent Atomizers, ICLASS 2003, pp.0311, 2003.

[3] Jedelsky, J.-Jicha, M.-Slama, J.: Discharge Coefficient and Operational Flow characteristics of Multihole Effervescent Atomizers, ICLASS 2003, pp.0310, 2003.

[4] Jedelsky, J.-Jicha, M.: Characteristics of a Two-phase Flow Inside the Mixing Chamber of an Effervescent Atomizer, 3rd International Symposium on Two-Phase Flow Modelling and Experimentation, 2004.

[5] Chen, S.K.-Lefebvre, A.H.: Discharge coefficient for plain orifice effervescent atomizers, Atomization and Sprays, vol.4, pp.275-290, 1994.

[6] Chin, J.S.-Lefebvre, A.H.: Design Procedure for effervescent atomizers, J. of Eng. For Gas Turbines and Power, vol.117, pp266-271, 1995.

[7] Lorcher, M.-Schmidt, F.-Mewes, D.: Flow Field and Phase Distribution Inside Effervescent Atomizers, 9th International Conference on Liquid Atomization and Spray Systems - ICLASS 2003, pp.12-9., 2003.

[8] Lorcher, M.-Mewes, D.: Atomization of Liquids by Two - Phase Gas – Liquid Flow through A Plain – Orifice Nozzle, Ilass-Europe 2000.

[9] Jicha, M.-Jedelsky, J.-Slama, J.: Technical report, Project E! 2517 Burner, 2001-2003 (in Czech)

[10] Panchagnula, M. V.-Sojka P. E: Spatial droplet velocity and size profiles in effervescent atomizer-produced sprays, Fuel 78, 729-741, 1999.

[11] Morelli, F.-Ligasacchi, S.-Bizzarri, M.: Development of Effervescent atomizers for Oil-Fired Power Stations. 9th International Conference on Liquid Atomization and Spray Systems - ICLASS 2003, 2003.

[12] Sankar, S.V.-Robart, D.M.-Bachalo, W.D.: A swirl effervescent atomizer for spray combustion. Proceedings of the ASME HTD-vol.317-2, pp.175-182, IMECE 1995.

[13] Kufferath, A.-Wende, B.-Leuckel, W.: Influence of liquid flow conditions on spray characteristics of internal-mixing twin-fluid atomizers. International J. of Heat and Fluid Flow. Vol.20, Issue 5, pp.513-519, 1999.

[14] Whitlow, J.D.-Lefebvre, A.H.: Effervescent Atomizer Operation and Spray Characteristics, Atomization and Sprays, Vol.3, No.2, pp137-155, 1993.

[15] Chen, S.K.-Lefebvre, A.H.: Spray Cone Angles of Effervescent Atomizers, Atomization and Sprays, Vol.4, No.3, pp291-301, 1994.

[16] Wade, R. A.-Weerts, J.M.-Sojka, P. E.-Gore, J.P.-Eckerle, W.A.-Crofts, J.D.: High pressure effervescent atomization: effect of ambient pressure on spray cone angles. Fuel, 80(3), pp427-435, 2000.

[17] Sovani, S.D.-Chou, E.-Sojka, P.E.-Gore, J.P.-Eckerle, W.A.: Effervescent atomization at injection pressures in MPa range, Atomization and Sprays, Vol.9, No.6, pp651-667, 1999.

[18] Chin, J.S.-Lefebvre, A.H.: Flow patterns in internal-mixing, twin-fluid Atomizers, Atomization and Sprays, Vol.3, pp.463-475, 1993.

[19] Catlin C.A.-Swithenbank J.: Physical Processes Influencing Effervescent Atomizer Performance in the Slug and Annular Flow Regimes, 2001, Atomization and Sprays, Vol.5, pp.575-595, 2001.

[20] Chin, J.S.-Lefebvre, A.H.: Flow Regimes in Effervescent Atomization.5th annual conference on Liquid Atomization and Spray Systems, pp.210-214, San Ramon, CA, 1992.

[21] Wallis, G.B.: One Dimensional Two Phase Flow, McGraw Hill Book Co., New York, 1969.

[22] Sovani, S.D.-Sojka, P.E.-Lefebvre, A.H.: Effervescent Atomization, Progress in Energy and Combustion Science 27, pp.483-521, 2001.