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IMPINGING EFFERVESCENT ATOMIZERS: DESIGN INSIGHTS

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Abstract

Design and performance of an impinging effervescent atomizer are investigated in this study. Effervescent atomizers were adapted to a multi-orifice design to address limitations in single orifice setups as small spray cone angle (*SCA*) and small area coverage. High-speed imaging and Phase Doppler anemometry were used to assess liquid discharge behaviour, droplet size, and spray stability. The experiments analysed various design parameters, including the diameter of the mixing chamber, the diameter of the exit orifice, and pitch circle diameter, under different gas-to-liquid ratios (*GLR*) and inlet fluid configurations (central air vs. central liquid). Results indicate that the inlet fluid configuration significantly affects discharge stability, with the central liquid configuration showing low-frequency oscillation, which lowers spray quality. Although the discharge coefficient was unaffected by design variations, the droplet size was influenced by the pitch circle diameter and the *GLR*, with the latter being the dominant factor. The findings provide insight into optimizing the design for stable and efficient operation of the impinging effervescent atomizer.

Keywords: effervescent atomization, impinging effervescent atomizer, Phase Doppler anemometry

1 Introduction

The effervescent atomizer is an internally mixed twin-fluid atomizer, where liquid and gas mix within the atomizer. The primary breakup is caused by the rapid expansion of the gas, which tears the liquid into ligaments and droplets. Effervescent sprays typically exhibit a relatively narrow spray cone angle, with high-velocity droplets concentrated at the spray core [1]. To enhance atomization, the impinging effervescent atomizer (EFI) was introduced in [2]. The EFI atomiser incorporates collisions of liquid jets or ligaments after exit orifice with the aim of modifying the spray characteristics.

Certain EFI atomizer design parameters remained constant in [2], and their effects on the spray were not examined. This study focuses on investigating the influence of design parameters, including the exit orifice diameter (d_o), the mixing chamber diameter (d_m), the pitch circle diameter (d_{pitch}), and the configuration of the inlet fluids. The typically used configurations, referred to as OIL and OIG in [3], are designated here as central air and central liquid.

These design aspects are relatively well explored for a single orifice effervescent atomizer. The effect of the inlet fluid configuration was investigated by [3,4], who found that the air central configuration resulted in more temporally stable liquid discharge and lower pressure fluctuation amplitudes. Mlkvik et al. [3] reported that the central air configuration produced smaller droplet sizes, but it was less stable than a Y-jet atomizer at a low gas to liquid ratio (*GLR*). The central air configuration is more likely to induce annular internal flow, characterized by an air core at the mixing chamber central. However, the behaviour of annular flow in a multi-orifice atomizer remains unclear. Does the annular flow evenly distribute among all exit orifices, or does it fluctuate, leading to unstable discharge trough individual orifices?

The liquid discharge is highly dependent on the type of internal flow, which is influenced by the inlet pressure (*pl*) and *GLR* [5]. At low *GLR*, bubbly flow dominates, producing the largest droplets. As the *GLR* increases, slug and plug flows emerge, transitioning to annular flow at higher *GLRs*. Internal flow is spatially and temporally unstable. Jedelský and Jícha [6] observed a non-uniform liquid distribution among individual orifices in horizontal operation of an effervescent atomizer, due to uneven internal two-phase flow and the occurrence of slug flow. It remains unclear how different internal flow regimes interact with a multi-hole orifice configuration, or whether variations in d_{pitch} affect liquid discharge and spray characteristics.

Ansari and Azadi [7] observed that a larger tube diameter minimizes the slug flow region, but shifts the boundary from churn to annular flow to a higher *GLR*. The internal two-phase flow differs for different d_m [8], therefore the influence of d_m is investigated here. It was found that d_o has little to no effect on the mean drop size for the single orifice effervescent atomizer [9, 10]. It was also found by Li et al. [11] that the number of discharge orifices has no effect on the mean droplet size. The effect of the multi hole arrangement on other parameters as the discharge coefficient (C_D) was not discussed and is presented here.

2 Experimental setup

Atomizer design, experimental conditions, experimental techniques are described in this section. Experiments were carried out in the Multiphase-flow laboratory at Brno University of Technology.

2.1 Test rig

The water was pumped from the storage tank to the effervescent atomizers by the gear pump. The water flow rate was measured by a Coriolis mass flow meter (Mass 2100 Di3 containing Mass 6000 transmitter, Siemens AG, GE) with an accuracy of ± 0.1% from the actual flow rate. The atomization gas was supplied from the pressurized vessel. The gas flow rate was measured by FMA-A2100 mas flow meter (Omega Engineering, USA) with an accuracy of ± 1% of the full scale (full scale is 100 SLPM). Inlet liquid and atomization air pressures were measured with piezo-resistive BD Sensor DMP 331i (BD SENSORS s.r.o., CZ) with sampling frequency of 200 Hz, mounted close to the atomizer inlet. Pressure measurement accuracy was ± 2 kPa. This experimental setup yields repeatability of $C_D \pm 0.386 \cdot 10^{-3}$.

2.2 Atomizer and operating conditions

Several EFI atomizers were designed. The EFI design atomizer is outlined in Fig. 1 and the dimensions are described in Table 1. Atomizers were tested at 100 kPa with *GLR* within the range of 2.5 to 10%. The selected atomizers were tested at two inlet fluid configurations, central air and central liquid.

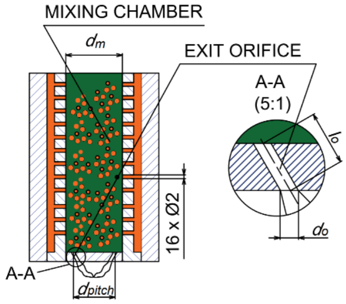


Figure 1: Schematic design of impinging effervescent atomizer

Table 1: Dimensions of EFI atomizer

Atomizer	d_o [mm]	d_m [mm]	l_o/d_o [–]	d_{pitch} [mm]
EFI1	0.9	12	5.8	10.4
EFI2	0.9	24	8	22.4
EFI3	1.7	12	2.15	9.8
EFI4	1.7	24	4	21.8
EFI5	1.7	24	2.15	9.8
EFI6	1.7	24	2.15	15.8

2.3 High speed visualization and Phase Doppler anemometry setup

Liquid discharge at 20,000 fps with shutter speed of 1.25 µs was recorded with a FASTCAM SA-Z (Photron, Japan) high-speed camera equipped with a long-distance microscope 12 X Zoom lens (NAVITAR, New York, USA). The LED light model HPL3-36DD18B (Lightspeed Technologies, USA) was used to illuminate the spray with a pulse duration of 600 ns.

Droplet sizes and velocities were determined using a two-component fibre-based PDA measurement system (Dantec Dynamics A/S Skovlunde, Denmark). The two-component velocity measurement was performed in the coincidence mode simultaneously with the drop sizing. Either 40 000 samples were acquired, or a 20-second acquisition duration was achieved, depending on whichever occurred first. Dantec BSA software 7.5 was used to control the measurement. The PDA setup is described in Table 2. Several repeated measurements were performed and repeatability of ID_{32} is ± 1.4 µm.

Table 2: PDA setup

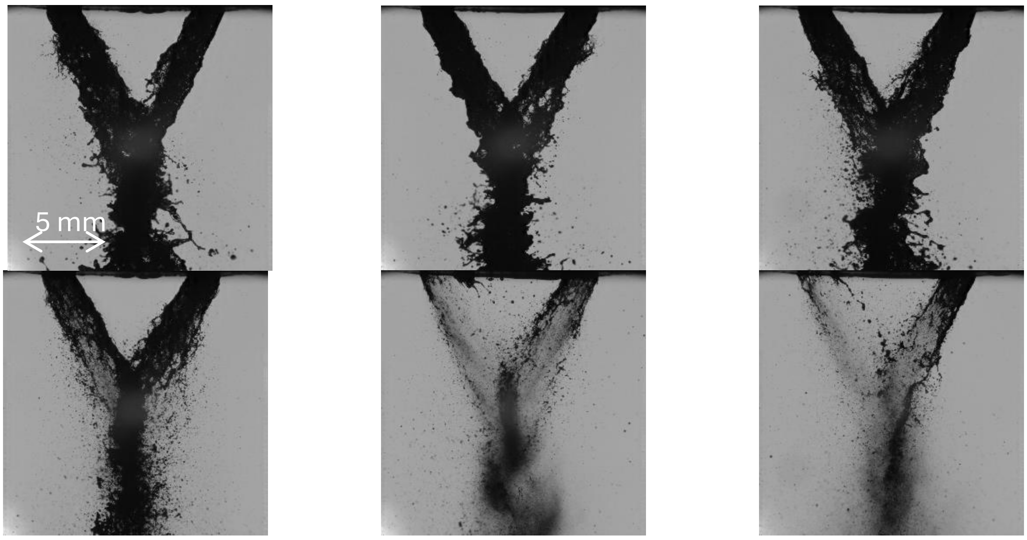
Parameter	Value	
Laser power output	0.26 W	
Scattering angle	70°	
Receiver mask	C	
Receiver spatial filter	0.2 mm	
The focal length of transmitting/receiving optics	500/500 mm	
Wavelength	532 nm	561 nm
Velocity component	**Axial**	**Radial**
Velocity centrale	19.94 m/s	0 m/s
Velocity span	39.89 m/s	21.03 m/s
Sensitivity	800 V	850 V
SNR	0 dB	0 dB
Signal gain	12 dB	14 dB
Level validation ratio	4	4

3 Results and Discussion

The experimental data obtained by the measurements described in Chapter 2 were analysed and the main results and findings are presented in this chapter.

3.1 Liquid discharge

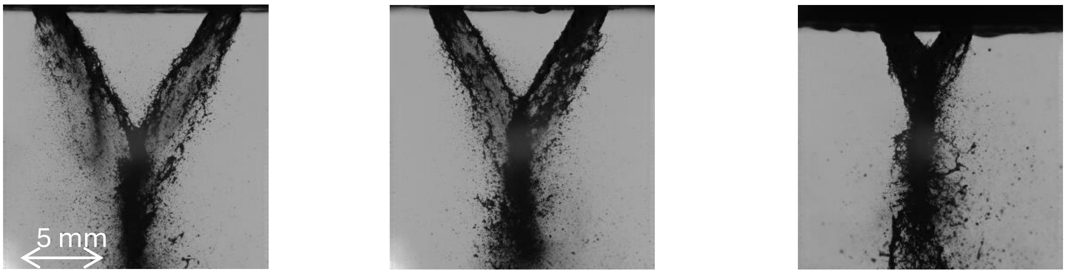
The primary breakup behaviour was comparable for central air and central liquid configurations. However, unstable behaviour was observed in the central liquid configuration, where the liquid discharge oscillated between multiple modes. This instability is depicted in Fig. 2. It appears that the *GLR* differs between modes, leading to unstable operation. The observed fluctuations occurred at frequencies below 6 Hz across all *GLR* regimes for the central liquid configuration.



GLR = 2.5% *GLR* = 5% *GLR* = 10%

Figure 2: Unstable behaviour of liquid discharge, for EFI6 for central liquid configuration (top = unstable mode, bottom = stable discharge)

Atomizers with different d_{pitch} (Fig. 3) were analyzed. For $d_{pitch} \geq 15.8$ mm the liquid discharge remained consistent. However, for smaller d_{pitch}, the primary breakup mechanism differed. In these cases, compact liquid jets collided to form a liquid sheet, with its primary breakup driven by the rapid expansion of air trapped within the liquid. A side view of EFI5 is shown in Fig. 4. Additionally, a shorter liquid sheet breakup length was observed at higher *GLR*.



d_{pitch} = 21.8 mm d_{pitch} = 15.8 mm d_{pitch} = 9.8 mm

Figure 3: Liquid discharge for different d_{pitch} (central liquid configuration)

Figure 4: EFI5 side view with (central liquid configuration) for *GLR* = 2.5, 5 and 10%

3.2 Discharge coefficient

C_D is a key parameter for atomizers, representing the ratio of the actual mass flow rate to the ideal mass flow rate. C_D is insensitive to d_{pitch} and d_m Since $d_m \geq d_o$, most friction losses occur in the exit orifices. No significant differences in the mean C_D were observed between the central air and central liquid configurations, despite the fact that the central liquid configuration exhibited greater instability. This finding aligns with the results of [4], who also reported no difference in mean C_D but noted a larger standard deviation in the void fraction for the central liquid configuration. C_D is typically correlated with *GLR*, *pl*, and l_o/d_o. Equation (1) was developed to describe C_D and the comparison between computed and measured C_D is illustrated in Fig. 5. The influence of *GLR* and l_o/d_o on C_D was found to be higher than reported in [2]. However, the computed values are consistently 0.02 higher than the measured values.

$$C_D = 0.18 GLR^{-0.5} Re_L^{-0.07} (l_o/d_o)^{-0.3} \quad (1)$$

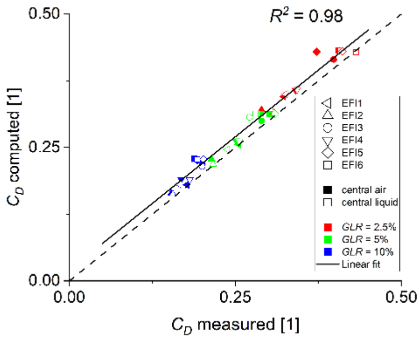


Figure 5. Comparison of measured and computed C_D according to equation (1)

3.3 Droplet size

The mean integral Sauter diameter (ID_{32}) was computed by equation (2) to represent the overall droplet size. ID_{32} account for the uneven droplet size spatial distribution for effervescent atomizer. Description of equation (2) can be found in [12].

$$ID_{32} = \frac{\sum_i r_i f_i D_{30}^3}{\sum_i r_i f_i D_{20}^2} \quad (2)$$

The ID_{32} for different atomizers is shown in Fig. 6 left. It has a decreasing trend with increasing *GLR*. ID_{32} is the same for central liquid and central air configuration. The only difference was observed for EFI3 at 5 and 10% *GLR* and EFI5 at 5% *GLR*. These atomizers have a d_{pitch} = 9.8 mm and exhibited the largest fluctuations. Smaller ID_{32} was observed for higher d_{pitch}. It is illustrated in Fig. 6 right for the central air configuration. Note here that this trend was obtained only for 10% *GLR* in the central liquid configuration.

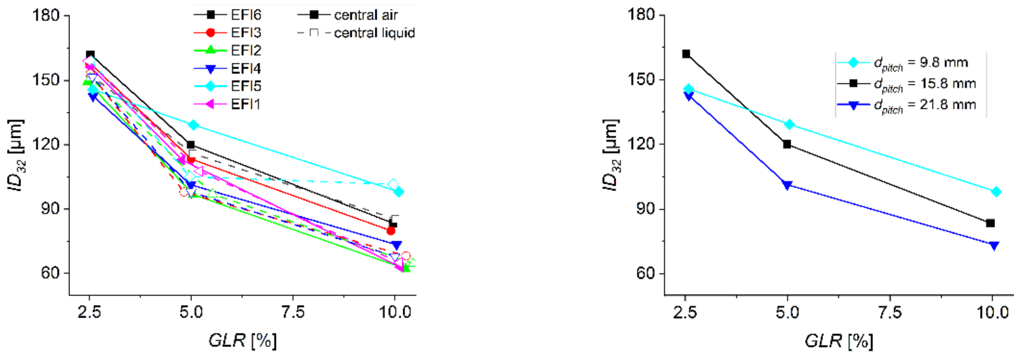


Figure 6: ID_{32} for different EFI (left), ID_{32} for different d_{pitch}, central air configuration (right)

Empirical equation (3) was obtained for ID_{32}, which is usually governed by *GLR* and p_l. Note that atomizers were tested in a relatively narrow *GLR* range. Influence of *GLR* is the same as reported in [2]. ID_{32} was also correlated with ratio of d_{pitch}/d_m, but *GLR* remains dominant. The corelation is illustrated in Fig. 7. The corelation is constantly about 20 μm higher than the measured values, but follows a correct trend.

$$ID_{32} = 32GLR^{-0.44}\left(d_{pitch}/d_m\right)^{-0.2} \tag{3}$$

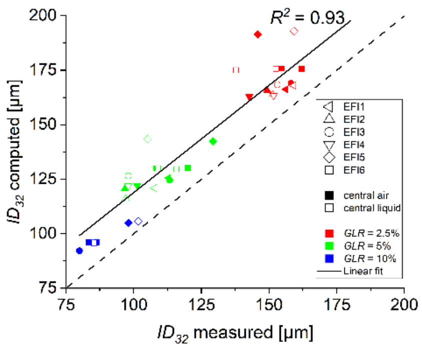


Figure 7: Comparison of measured and computed ID_{32}

3.4 Pressure fluctuations

The comparison of the standard mean deviation of inlet liquid pressure (pl_{std}) for the EFI3 and EFI5, which experienced a different ID_{32} between central air and central liquid configuration, is presented in Fig. 8. pl_{std} is much higher for central liquid configuration. Observed fluctuations causes differences in the liquid discharge (see Fig. 3) and affects the created droplets, mainly their size and sphericity. Droplets created in the unstable regime may have a larger size and non-spherical shape and can't be accurately measured with PDA.

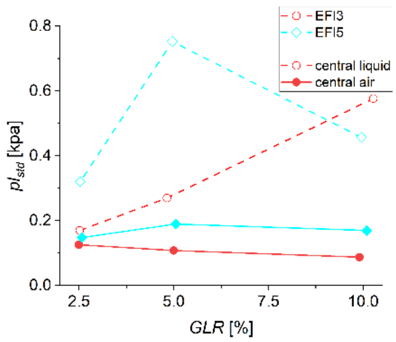


Figure 8: Comparison of pl_{std} for central air and central liquid configuration for EFI3 and EFI5

4 Conclusions

The design parameters of an impinging effervescent atomizer were investigated in this study. The effects of the inlet fluid configurations (central liquid and central air), exit orifice pitch circle diameter, mixing chamber diameter, and exit orifice diameter on liquid discharge, discharge coefficient, and droplet size were analyzed. Experiments were conducted using high-speed imaging, Phase Doppler anemometry, and a cold test rig to measure pressure, liquid flow rate, and gas flow rate. The results showed that the liquid discharge exhibited low-frequency fluctuations in the central-liquid configuration. The primary breakup behavior was distinct for the atomizer with the smallest pitch circle diameter, where collisions of liquid jets occurred. Design variations did not have a significant impact on the discharge coefficient, which was mainly influenced by the gas to liquid ratio, the liquid Reynolds number in the discharge orifice, and the length to diameter ratio of the exit orifice. The discharge coefficient correlation aligned well with the findings from previous studies on impinging atomizers. Both the discharge coefficient and the Integral Sauter mean diameter behaved similarly for the central-liquid and central-air configurations. Differences in the Integral Sauter mean diameter were observed only for the most unstable liquid discharge cases (EFI3 and EFI5). It was demonstrated that Integral Sauter mean diameter is partially dependent on the ratio of pitch circle diameter to mixing chamber diameter, although *GLR* remained the most influential factor.

Acknowledgements

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References

[1] Zaremba, M., et al.: An experimental analysis of the spraying processes in improved design of effervescent atomizer. *International Journal of Multiphase Flow*, vol. 103: (2018) pp. 1–15.

[2] Cejpek, O., Maly, M., Dhinasekaran, V. K., Avulapati, M. M., Dacanay, L., & Jedelsky, J.: Novel atomizer concept for CCS applications: Impinging effervescent atomizer. *Separation and Purification Technology*, vol. 311: (2023) p. 123259.

[3] Mlkvik, M., Jedelsky, J., Karbstein, H. P., & Gaukel, V.: Spraying of viscous liquids: Influence of fluid-mixing mechanism on the performance of internal-mixing twin-fluid atomizers. *Applied Sciences*, vol. 10, no. 15: (2020) Art. no. 15.

[4] Hammad, F. A., Sun, K., Jedelsky, J., & Wang, T.: The effect of geometrical, operational, mixing methods, and rheological parameters on discharge coefficients of internal-mixing twin-fluid atomizers. *Processes*, vol. 8, no. 5: (2020) Art. no. 5.

[5] Hammad, F. A., Sun, K., Che, Z., Jedelsky, J., & Wang, T.: Internal two-phase flow and spray characteristics of outside-in-liquid twin-fluid atomizers. *Applied Thermal Engineering*, vol. 187: (2021) p. 116555.

[6] Jedelský, J. & Jícha, M.: Spray characteristics and liquid distribution of multi-hole effervescent atomisers for industrial burners. *Applied Thermal Engineering*, vol. 96: (2016) pp. 286–296.

[7] Ansari, M. R. & Azadi, R.: Effect of diameter and axial location on upward gas–liquid two-phase flow patterns in intermediate-scale vertical tubes. *Annals of Nuclear Energy*, vol. 94: (2016) pp. 530–540.

[8] Chen, L., Tian, Y. S., & Karayiannis, T. G.: The effect of tube diameter on vertical two-phase flow regimes in small tubes. *International Journal of Heat and Mass Transfer*, vol. 49, no. 21: (2006) pp. 4220–4230.

[9] Roesler, T. C. & Lefebvre, A. H.: Studies on aerated-liquid atomization. *International Journal of Turbo and Jet Engines*, vol. 6: (1989) pp. 221–229.

[10] Spray characteristics of aerated-liquid pressure atomizers. *Journal of Propulsion and Power*. Accessed: Dec. 03, 2024. [Online]. Available: https://arc.aiaa.org/doi/10.2514/3.23066.

[11] Li, J., Lefebvre, A. H., & Rollbuhler, J. R.: Effervescent Atomizers for Small Gas Turbines. Presented at the ASME 1994 International Gas Turbine and Aeroengine Congress and Exposition, American Society of Mechanical Engineers Digital Collection: (2015).

[12] Jedelsky, J., Jicha, M., Slama, J., & Otahal, J.: Development of an Effervescent Atomizer for Industrial Burners. *Energy Fuels*, vol. 23, no. 12: (2009) pp. 6121–6130.