DOI: https://doi.org/10.14311/TPFM.2025.022

POD ANALYSIS OF STABLE AND UNSTABLE EFFERVESCENT SPRAY

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Abstract

Effervescent atomization is influenced by the atomizer's internal geometry, operational parameters, and additional components, such as bubble-breakers or velocity profile modifying inserts. This study investigates the liquid discharge of three effervescent atomizers with a central liquid inlet at gas-to-liquid mass ratios (*GLR*) from 1 to 10%. The atomizers differ by having inserts in the liquid inlet line. These inserts aim to improve discharge stability by changing liquid velocity profile at the aeration point and reducing pressure waves through increase in liquid pressure-drop. Proper orthogonal decomposition (POD) analysis shows that the inserts reduce spray unsteadiness and change dominant flow patterns. This results in finer sprays without presence of liquid jets. The stable configurations also show less variance concentrated in the dominant modes.

Keywords: effervescent, atomizer, spray, proper orthogonal decomposition, POD

1 Introduction

The internal geometry of the effervescent atomizers plays a crucial role in determining the stability and quality of the resulting spray. Effervescent atomization, widely used in various industrial applications due to its low energy consumption, involves the mixing of gas and liquid within the atomizer to create a two-phase flow that exits through a discharge orifice. The air-bubble expansion tears the liquid and forms ligaments, which break up into droplets as a result of the aerodynamic force acting upon their surface. The design and configuration of the internal components of the atomizer, such as the mixing chamber, aerator orifice, and exit orifice, significantly influence the internal flow patterns, which, in turn, affect the spray characteristics.

Past studies have shown that different internal geometries can lead to varying flow regimes within the atomizer, such as bubbly, slug, churn, and annular flows, each impacting the spray stability differently. The configuration of the inlet ports in effervescent atomizers can lead to different internal flow patterns and spray qualities. The configuration with liquid supplied by aeration ports to gas (OIL, central gas) has been shown to produce more stable sprays with smaller droplet sizes compared to the opposite configuration. In this case, the liquid flows directly on the mixing chamber wall, which forces more stable annular flow regime [1]. The design of the aerator, including the diameter and angle of aeration holes, can affect the spray unsteadiness and quality. Larger aeration orifices have been associated with lower spray unsteadiness for water spray, but increased fluctuation rate for more viscous liquids [2].

The internal flow regime is also influenced by operational parameters such as the gas-to-liquid mass ratio (*GLR*) and operating pressure. An increase in *GLR* leads to formation of more bubbles [3]. For values above *GLR* > 1%, a transition to more complex regimes occurs, such as elongated jetting, which stabilizes the spray and reduces droplet size [4], or slug flow, which is inherently unstable [5]. The internal flow can be also affected by introduction of various types of inserts like bubble breakers or swirlers. Bubble breakers act in the mixing chamber with aim to reduce size of generated bubbles. A wire mesh bubble breaker in the mixing chamber has been found to improve spray quality by reducing droplet size and enhancing stability through the formation of small-scale bubbles [6]. Perforated plate bubble breakers were found to be effective in reduction of bubble sizes and improving spray parameters for *GLR* regimes from 1 to 6% [7, 8].

This paper focused on spray structure analysis from three effervescent atomizers with central liquid (OIG), which used an insert in the liquid inlet line. This atomizer is unstable, but for very low *GLR*, this configuration is more likely to generate bubbly flow than the OIL. The aim of this study is to alternate liquid velocity profile prior its mixing with gas. This should change the sheer rate at the aerator location, as the higher sheer rate is beneficial for even bubble creation [9]. Further, the pressure drop increases, which could be beneficial for atomizer stability as the pressure wave propagates throughout the length of the atomizer and even to the inlet tubes [10].

2 Experimental setup

Experiments were performed in the spray laboratory at Brno University of Technology on a cold test bench. The water was fed by a centrifugal pump through the Coriolis mass flow meter Mass 2100 Di3, fitted with a Mass 6000 transmitter (Siemens AG, GE) with an accuracy of ± 0.1% of actual value, to the atomizer. The liquid line was fitted with a piezo-resistive BD sensor DMP 331i (BD SENSORS s.r.o., CZ) for pressure detection with an accuracy of ± 0.4 kPa and a sampling frequency of 200 Hz.

A Plexiglas effervescent atomizer with a mixing chamber diameter of 6 mm and an exit orifice diameter of 1 mm was used in this study; see schematic drawing in Figure 1, which shows the 4-diamond atomizer. The second atomizer included gyroid porous media with a porosity of 0.7, pore size of approx. 0.8 mm and a height of 4 mm, placed at the top of the mixing chamber. The third atomizer served as a reference and did not contain any inserts.

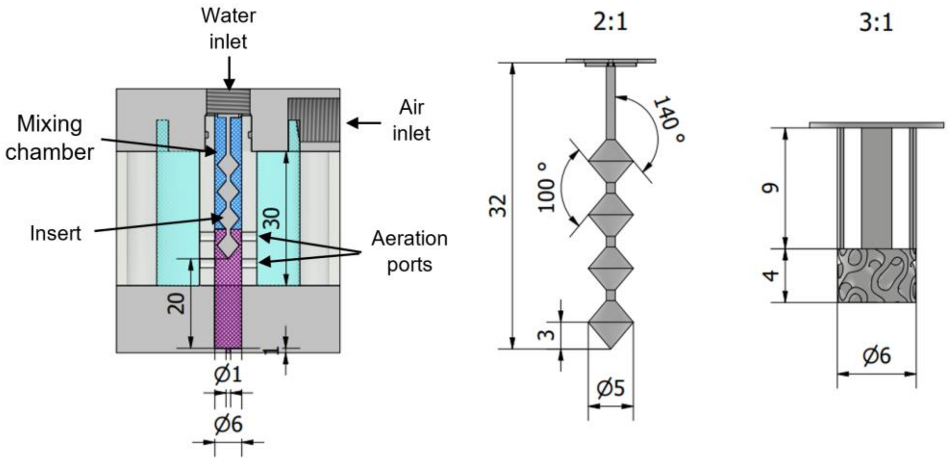

Figure 1: From left: schematic drawing of the atomizer with 4-diamond insert, detail on 4-diamond insert, detail on gyroid insert.

Liquid discharge was recorded using a FASTCAM SA-Z high-speed camera (Photron, JP) equipped with a long-distance microscope 12× zoom lens (Navitar, New York, US). Backlit illumination of the spray was provided by an LED light source (model HPL3-36DD18B, Lightspeed Technologies, US) with a pulse duration of 600 ns. Images were acquired at a frame rate of 20,000 fps, with a resolution of 1024 × 1024 pixels. A total of 2,500 frames were captured, covering 0.125 seconds of recording time. The POD analysis was performed using every fourth image, resulting in 625 frames in total.

3 Results and Discussion

The discharge coefficient (C_D) is discussed first, followed by an analysis of the spray structure using POD. The spray from the atomizer without insert demonstrate an unstable nature characterized by rapid changes in the spray cone angle and spray structure. Two distinct phases are observed: the first is dominated by excess atomizing air, producing a very fine spray, while the second has a high liquid content, which can result in a liquid stream forming at the spray center (see the following sections).

The addition of an insert in the liquid inlet line changes both the liquid pressure drop and the liquid velocity profile in the mixing chamber. The C_D was calculated to assess the influence of spray fluctuations on liquid discharge. It was based the gas pressure (p_g), which remained constant throughout the study and closely represent pressure inside the mixing chamber, the liquid flow rate, $\dot{m}_l$, the liquid density, ρ_l, and the exit orifice area A_o:

$$C_D = \frac{\dot{m}_l}{A_o\sqrt{2\rho_l p_g}} \tag{1}$$

The atomizer without an insert shows C_D values about 4% higher for GLR = 1% and 2.5% than the atomizers with inserts. This difference decreases at GLR = 5 and 10%, where it approaches the measurement uncertainty. The slightly higher C_D of the no-insert atomizer can be attributed to its unstable discharge nature. Rapid changes in the discharge structure resemble more separated flow, which typically exhibits higher C_D values compared to homogeneous discharge [11].

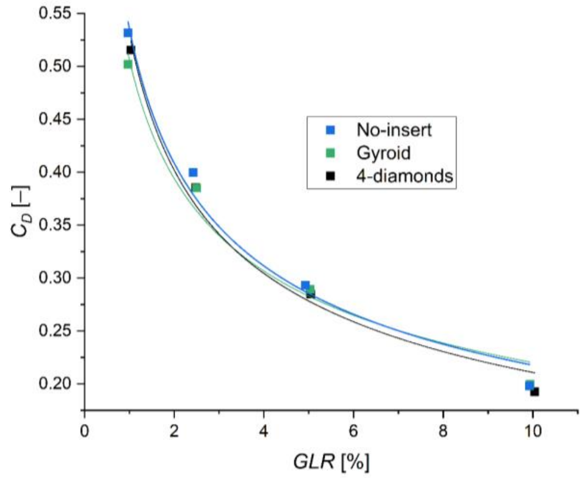

Figure 2: C_D as a function of *GLR*

The liquid inlet pressure, p_l, increases with the addition of inserts. For example, at *GLR* = 2.5% the p_l/p_g ratio increases from 0.99 for the no-insert atomizer to p_l/p_g = 1.00 and 1.06 for 4-diamonds and gyroid inserts, respectively. This increase in pressure drop may help dampen pressure waves originating in the mixing chamber, preventing them from propagating through the inlet line.

The POD is used to identify dominant flow patterns. In this paper, it was applied on raw images from high-speed camera and represents pixel intensity variance in the images; a decrease in pixel intensity corresponds to the presence of more liquid in the image. The relative mode variance, often represented as energy, shown in Figure 3 reflects the significance of each mode in the overall spray behavior. Since spray discharge is a highly turbulent process, the most significant modes account for only a portion of the total variance. For example, the four most dominant modes represent approximately 25% of the total variance at *GLR* = 1%, decreasing to 5% at *GLR* = 10%. Atomizers with more fluctuating behavior tend to concentrate more variance in the first few modes as these significantly differs from mean image. For example, the no-insert atomizer at *GLR* = 2.5% concentrates 18% of the total mode variance in the first four modes, compared to the more stable gyroid and 4-diamond atomizers, which each concentrate only about 5%. Differences between the atomizers are most pronounced at *GLR* = 2.5% and 5%.

Figure 4 provides a detailed view of the first four modes at *GLR* = 2.5%, while Figure 5 shows the real spray shape corresponding to the maximum amplitude of each mode, as illustrated in Figure 6. For the no-insert atomizer, the first mode represents a liquid jet discharge, which is typical for the low-gas regime in an unsteady atomizer. Mode 3 represents a gas-dominant regime with fine atomization. Modes 2 and 4 are regimes with liquid concentrations falling between modes 1 and 3 and exhibit some degree of asymmetry and fluctuations: mode 2 shows more liquid discharged on the left side of the spray, while mode 4 shows the opposite.

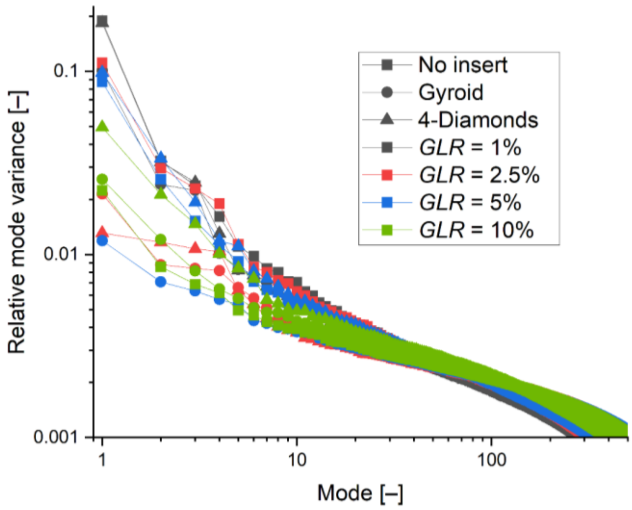

Figure 3: Relative mode variance

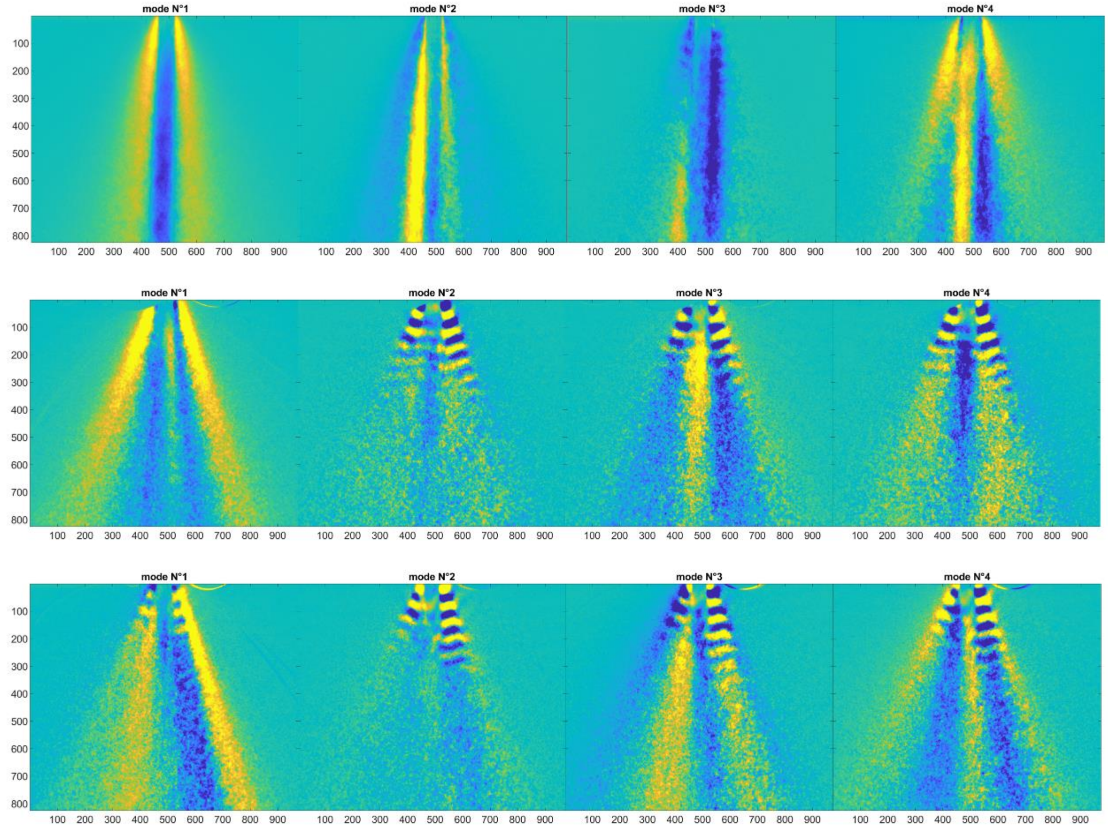

Figure 4: The first four modes of POD analysis for *GLR* = 2.5 %. From top to bottom: no-insert, gyroid, 4-diamonds. The image is color-mapped: yellow regions represent pixel intensity above the mean image, blue regions represent intensity below the mean, and green regions are close to the mean intensity.

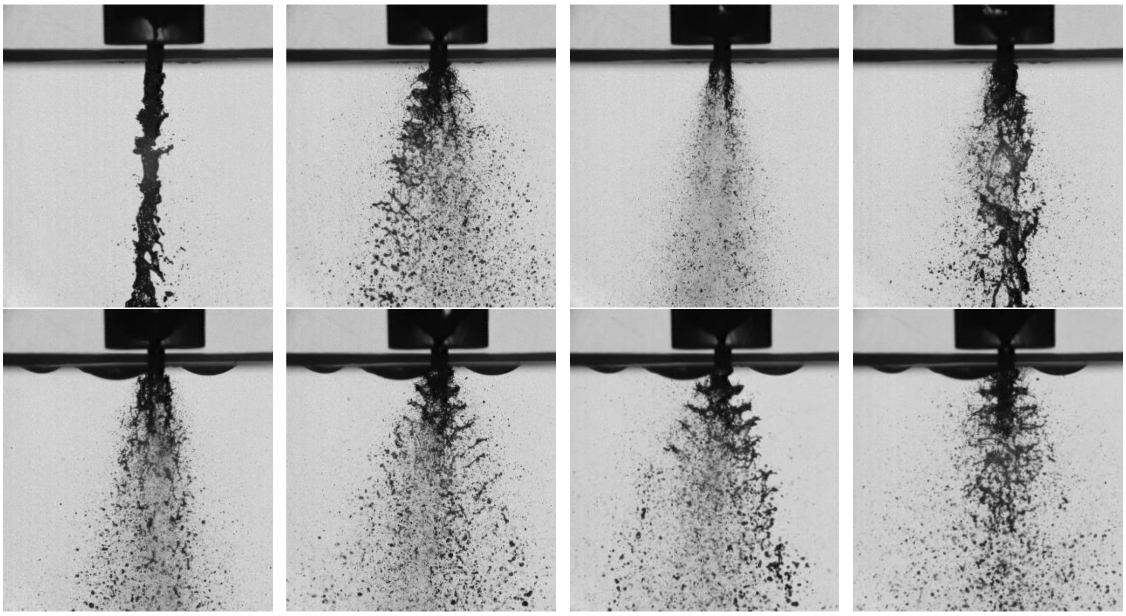

Figure 5: Snapshots of spray structure corresponding to the maximum amplitude of modes 1 to 4 (from left). Top: no-insert atomizer at *GLR* = 2.5%, bottom: gyroid atomizer at *GLR* = 2.5%

The gyroid and 4-diamond atomizers exhibit very different liquid structures compared to the no-insert version. In these atomizers, mode 1 represents a standard spray shape, while modes 2–5 show periodic wavy structures on the discharged liquid. Since no liquid jet is present in these regimes, the resulting sprays are generally finer. The self-excited, high-frequency waves are not expected, possibly indicating another type of internal oscillation. The wavelength of these waves is approximately 1 mm, which is comparable to the exit orifice diameter, and fluctuate with a frequency of around 10 kHz. There is notable phase-shift in wave structure between modes 2-4, indicating periodically travelling wave. The similar waves are typical for sinusoidally-exited liquid jets [12]. The characteristics of these waves are nearly identical for both the gyroid and 4-diamond atomizers. At *GLR* = 1% and 5%, the gyroid atomizer still exhibits these wavy structures. However, the 4-diamond atomizer shows this structure only at *GLR* = 2.5%. At *GLR* = 1%, the behavior of the 4-diamond atomizer is similar to that of the no-insert atomizer, which is confirmed by their identical relative mode variance at this operating regime.

Mode dominance and frequency alone cannot fully uncover the spray structure. A more complete understanding is revealed by observing the temporal variation of the mode amplitude, as shown in Figure 6. Although spray instabilities are often discussed in terms of frequency, the duration of individual phases might not be equal. For similar atomizers as tested in this study, typical fluctuation frequencies are around 10–30 Hz and their frequency is inversely proportional to the mixing chamber length [10]. In this case, the frequency of mode 1 in the unstable no-insert atomizer is approximately 40 Hz. However, the duration of mode 1 is much shorter than its period suggests. The atomizer with gyroid insert also exhibits these low-frequency with modes 1-3 oscillating at around 30 Hz, while modes 2-4 shows additional modulation at a higher frequency of 1-2 kHz. It should be noted that these results come from a short measurement period of 0.13 seconds, which may not fully capture the irregular fluctuating behavior of the atomizer. More advanced methods such as dynamic mode decomposition (DMD) or oscillating pattern decomposition (OPD) might provide additional results and will be tested in future research.

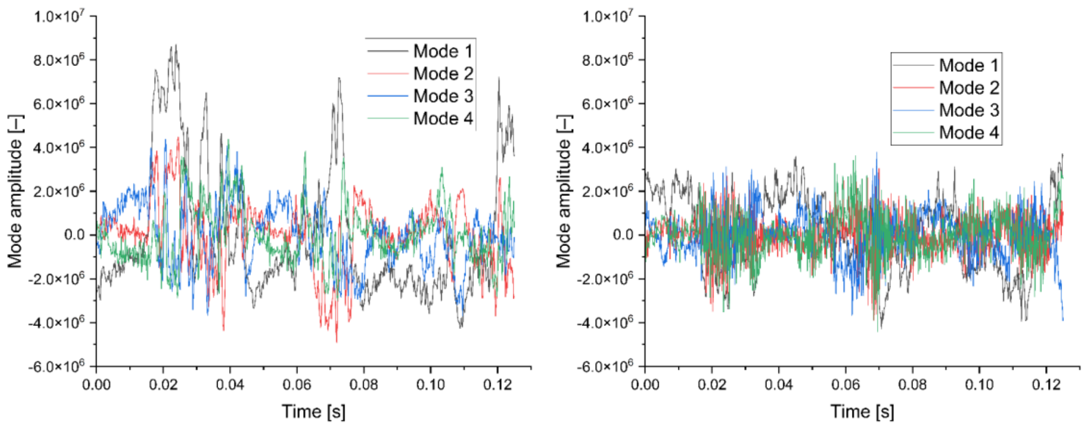

Figure 6: Time variation of mode amplitude for *GLR* = 2.5%. From left: no-insert, gyroid

4 Conclusion

This study analysed the influence of liquid inlet inserts on the spray stability and characteristics of effervescent atomizers with central liquid inlet configurations. The addition of inserts altered the liquid distribution inside the mixing chamber, leading to improved spray stability. Proper Orthogonal Decomposition (POD) analysis revealed significant differences in flow patterns between the no-insert and insert configurations. The gyroid and 4-diamond inserts demonstrated more stable sprays, with less variance concentrated in the dominant modes. However, high-frequency self-excited waves were observed in the discharged liquid.

These findings highlight the potential of simple internal atomizer modifications, such as porous media inserts in the liquid inlet line, to optimize spray parameters of effervescent atomizer. Future research will focus on the propagation of pressure fluctuations inside the mixing chamber to better understand the behavior described in this paper.

Acknowledgement

The authors acknowledge the financial support from the project no 23-07722S funded by the Czech Science Foundation

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