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Characterization and pressure drop correlation for sprays under the effect of micro scale cavitation

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A B S T R A C T

In this study, spray formation and atomization, droplet evolutions, break-up, and corresponding cavitating flows at the outlet of a short micro-channel with an inner diameter of 152 µm were experimentally studied at different injection pressures with the use of a high speed visualization system. High speed visualization was performed at five different segments to cover a ∼27.5 mm distance beginning from the micro-channel outlet (Five segments, at distances of 0–5.5, 5.5–11, 11–16.5, 16.5–22 and 22–27.5 mm from the micro-channel outlet) to assess the spray formation mechanism. High speed visualization revealed that droplet evolution is initiated from the second segment at low upstream pressures (5–30 bars), whereas droplets are discretized from the liquid jet in the fourth and fifth segments at medium and high upstream pressures (40–100 bars). Bigger size droplets formed at the outlet up to an injection pressure of 30 bars, while cavitation effect of intensified cavitating flows became dominant beyond this injection pressure, leading to smaller droplet sizes and a more conical spray. Pressure drop was correlated together with Martinelli parameter for cavitating flows and a new correlation for two-phase pressure drop was developed. Moreover, in order to segment the discretized droplets at low upstream pressure (5–30 bars) from captured images and to perform an in-depth analysis on them, an active contour approach utilizing curve evolution and level set formulation was implemented. As shown by experimental results, droplets were successfully segmented at different low pressure levels. The droplet/bubble evolution can be exploited in biomedical and engineering applications, where destructive effects of bubbly cavitating flows are needed.

1. Introduction

Spray formation downstream of micro flow restrictive elements strongly depends on the flow regimes inside them. Recently, high velocity jets along the spray, bubble evolution, collapse of the bubbles, and droplet segmentation in the spray have become popular due to their exploitation in engineering and biomedical applications. It is crucial to identify the appearance of the spray and to concentrate on the whole shape of the spray in such a way that the spray length and energy released from the collapse of resulting bubbles could be applied on a possible target at the optimum distance for such applications. For this, rigorous studies are necessary to assess flow characteristics downstream of the micro flow restrictive elements, and experimental investigations are required to gain insight into cavitating flow physics with visualization as well as with numerical approaches.

Spray formation was studied both numerically and experimentally in conventional orifices within a wide range of operating conditions [41,42,35,36,43]. Although some of the studies included experiments on mini/micro nozzles [23,24,44,10], there is still a considerable lack of information about spray characteristics in micro scale and exploitation of potential applications such as biomedical treatment with cavitation erosion. In this regard, different techniques have been employed to investigate the effect of cavitating flow on the spray in micro scale. For example, Im et al. [19] took X-radiography measurements to investigate the influence of the internal geometry of a nozzle on the morphology of a high speed liquid jet immediately downstream of the nozzle. They found that cavitation inside the nozzle was strongly affected by internal geometry variations in micro scale.

While major properties of the spray and significant locations along the spray were mainly investigated from a numerical point of view

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[46,48,13], spray visualization displaying the spray morphology has not been considered within a wide range of working conditions in the micro scale. Recently, some studies on droplet breakup and spray behavior in cavitating flows in small scale were considered from an experimental point of view [16]. Che et al. [8] focused on droplet breakup to measure the size and number of the daughter droplets. They observed that the breakup process was dependent on the interaction between interfacial tension and shear force. They also observed that the breakup process could be controlled by varying the flow and mother droplet size.

The micro scale flow regimes are different and much less known compared to their counterparts in macroscale. In the study of Mishra and Peles [32], it was emphasized that cavitation phenomenon in micro scale differs from conventional scale. Moreover, most of the studies on the transition from liquid jet to separated droplets were performed in macro scale and are rather numerical or theoretical. Therefore, it is essential to characterize the spray structure in micro scale with the aid of non-dimensional numbers and spray features, which constitutes the motivation of the current study. The experimental studies in micro scale such as the study of Xing et al. [47] on a jet flow with a diameter of 20 μm reported a non-dimensional Ohnesorge number ($Oh = \mu/(\rho\sigma R) \wedge (1/2)$, where μ is the viscosity, ρ is density, σ is surface tension and R is the droplet radius) of 0.24 for the initial separation and wave number of 0.64, while the Ohnesorge number in this study is 0.013. The Ohnesorge number extracted from a linear analysis [12] for a mini jet flow with a radius of 1 mm was reported as approximately 1, where deformation of the separated droplets was presented as the initial condition. Saroka et al. [40] in a computational nonlinear three-dimensional study obtained a slow growth of the droplets. The maximum Reynolds number ($Re = \rho v D/\mu$, where v is the flow velocity) was 100 and the reported Ohnesorge number was 0.1, while the minimum Reynolds number in this study is 2200. Most of studies in this field considered the instability behavior of the jet flow from a numerical point of view, and the detailed characteristics of the discretized droplets such as their shape, size and eccentricity still need to be experimentally addressed in order to utilize the droplets/bubbles characteristics in an efficient way.

Dumouchel [15] in his review paper included several experimental investigations on primary breakup in the process of the spray atomization, tried to gather almost all the information gained in the literature and addressed significant achievements in this early step spray process. The author indicated that the nozzle geometry and the flow inside the orifice play a crucial role in the formation of the spray at the outlet of the orifices. However, the author claimed that there exists a considerable lack of reliable data related to this region, and therefore, the whole structure of the spray atomization and behavior should be assessed. Thus, besides the visualization of the spray downstream of a micro-channel or a micro flow restrictive element, detailed analysis of the recorded images is necessary using image processing techniques. Therefore, precise advanced image processing techniques are required to analyze the captured images/videos to help reveal the ongoing phenomenon. For this, different methods have been proposed. A robust image/ video processing technique was developed by Bilen and Unel [3], Bilen et al. [4] to investigate microscopic images and retrieve information about the underlying phenomena. Previously, a novel tracking method was developed by the authors [1,2], which could track droplets in a jet flow through handling the merging and splitting cases. However, this method, which included a thresholding based segmentation, could suffer from inefficient contrast of the acquired shadow images.

Kass et al. [21] introduced a ground breaking image segmentation method called “active contour”, also known as “snake”, which localizes the nearby edges accurately based on energy minimization. Lines and edges belonging to the region of interest are extracted with the help of internal and external constraint forces. This seminal work has been the focus of several research studies to detect the object boundaries and track them accurately. Chan and Vese [6] proposed a new model for active contours based on Mumford-Shah functional, which can detect object boundaries without using gradient information. To compensate active contours' slow convergence rates and some misconvergences in complex scenes, Mishra et al. [31] developed a decoupled active contour DAC) approach. The method separates the internal and external terms and employs Hidden Markov Models HMM) and Viterbi search, which facilitates quicker convergence and makes it less likely to misconverge. Recently, Marquez-Neila et al. [30] developed a morphological approach to curvature-based evolution of curves and surfaces to handle the computational complexity and numerical instabilities of classical PDE partial differential equations) based active contours. More recently, Dubrovina-Karni et al. [14] proposed a novel multi-region active contour method to segment an image into an arbitrary number of regions by using a variational approach based on a single level set function.

As a potential application of this study, the emerged spray can be employed in fragmentation of urinary stones, which will act as the targeted area. For this application, it is required to characterize the spray structure and to display flow morphology along its length in order to identify the optimum distance between the tip of the short micro-channel and targeted stone. There are also some investigations focusing on the effect of the sprays on small targeted areas [25,37,45,20]. In this regard, Liao et al. [27] used the VOF (Volume of Fluid) model to simulate the collapse process in order to determine the optimum stand-off between the targeted point and probe. They showed that this model was capable of measuring the jet velocity and pressure impulse. Moreover, they illustrated that the major parameter in cavitation erosion is the high pressure rather than the jet velocity. Furthermore, it should be noted that the characterization of spray structure in micro scale will help to identify the liquid jet length and primary-secondary breakups, which are crucial in micro-jet cooling systems. The interaction between cavitating flows at the outlet of the micro-channel and a solid target may also be utilized to harvest energy.

In the current study, the spray structure was characterized with the aid of non-dimensional numbers, and a new correlation based on the Martinelli parameter was developed for high Reynolds numbers, which could predict two phase pressure drop inside the micro-channel for sprays under the effect of cavitation. The spray formation at five different segments starting from the outlet of a short micro-channel/micro orifice with an inner diameter of 152 μm was visualized using the high accuracy visualizing equipment. The spray patterns were extracted for different injection pressures, which were varied between 5 and 100 bars. Moreover, for injection pressures less than 30 bars, the droplets downstream of the spray were characterized with the use of an active control approach based on curve evolution theory, which can successfully segment individual droplets from the captured images. The results of this study will help to visualize the formation of spray and to capture separated droplets in micro scale, which could offer new insights into possible biomedical and engineering applications.

2. Methods and materials

2.1. Experimental setup and procedure

A schematic of the experimental setup and micro-channel configuration along with spray structure at the low upstream pressure is shown in Fig. 1. The experimental setup consists of a high pressure pure nitrogen tank (Linde Gas, Gebze, Kocaeli), a liquid container (Swagelok, Erbusco BS, Italy), pressure sensors (Omega, USA), fine control valves (Swagelok) at different locations, a micro filter (Swagelok), a turbine-meter (Omega, USA), a Phantom high speed camera (Phantom v310, a trademark of Vision Research) with appropriate lenses, a workstation with visualization software (Phantom PCC 2.0 software), fittings (Swagelok), and micro-channel (Small Parts, USA) connected to the setup with appropriate fittings for cavitation formation. The tank was