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Application of micro particle shadow velocimetry μPSV to two-phase flows in microchannels

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ABSTRACT

Micro particle shadow velocimetry (μPSV) is performed in the present study for simultaneous velocity measurement and interface tracking in both liquid–liquid and gas–liquid two-phase flows through circular microchannels of 500 μm diameter. The back-lit illumination using a non-coherent LED light source, combined with full refractive index matching of the liquid phases, the tube wall material and the channel exterior medium, allowed velocimetry to be done both within and around the liquid droplets, and even close to the interfaces and boundaries. Moreover, post-processing methods are proposed and implemented in order to resolve motion of isolated gas bubbles and immiscible liquid droplets in laminar flows quantitatively. In particular, simultaneous measurements of local instantaneous phase velocities and flow rates, liquid film dynamics and its thickness, shape and volume of the dispersed phase, and development length in front and at the back of the bubbles are obtained using one single sequence of gray scale shadowgraphy images. Such results are valuable for validation of corresponding numerical simulation codes. It is believed that this approach significantly reduces the size and cost of the experimental setup while increasing the accuracy and reliability of the measurements.

1. Introduction

Understanding the hydrodynamics of slug flow regime in micro-scale two-phase flows is an essential key to the efficient design and control of numerous fundamental operating systems in a broad range of applications, namely micro heat exchangers (Kreutzer et al., 2005; Wegmann and von Rohr, 2006; Kashid and Agar, 2007; Tung et al., 2009), fuel injectors, micro chemical and bio reactors (Waelchli and von Rohr, 2006; Abiev and Lavretsov, 2012; Seemann et al., 2012; Theberge et al., 2010; Teh et al., 2008), medical diagnostic test facilities, drug and blood delivery systems and fluid transport through porous media. However, these flows feature complex spatio-temporal physics which have for long been among the most challenging problems in fluid mechanics. While numerical approaches have been successful to a great extent in resolving some of the fundamental dynamics of such flows in the last two decades, reliable experimental measurements, which can assist in validating results of these simulations, have not been delivered at the same pace. The available experimental techniques are often very limited in both accuracy and range of measurements due to several technical problems, which will be addressed in the present study.

Non-intrusive optical velocimetry techniques are known to be among the most effective and reliable experimental approaches for resolving the complex dynamics of micro-scale multiphase flows with high spatio-temporal resolutions (Williams et al., 2010; Aubin et al., 2010). Among all, adaption of digital particle image velocimetry DPIV for micro-scale studies (μPIV) is perhaps by far the most established approach in the literature (Willert and Gharib, 1991; Santiago et al., 1998).

Despite being effective in quantifying important dynamics of the flow (Wang et al., 2007; King et al., 2007; Sarrazin et al., 2006; Kinoshita et al., 2007; Waelchli and von Rohr, 2006; Gunther et al., 2004; Fouilland et al., 2010; Luo and Wang, 2012; Zaloha et al., 2012), fluorescent μPIV still present multiple challenging limitations in micro-scale two-phase flow velocimetry:

- **Interface detection.** Simultaneous particle tracking and interface detection is perhaps the most challenging issue in experimental two-phase flow velocimetry techniques. Although fluorescent μPIV enhances the visibility of seeding particles close to the boundaries and interfaces, it provides no precise information on the interface dynamics and its location. Furthermore, the boundaries constraining the geometries cannot be

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captured on the final images obtained using this technique. Therefore, μPIV needs to be accompanied by shadowgraphy, especially in multi-phase flow studies, in order to compensate for this shortcoming. Despite the clear interface which appears in the images when following this approach, the image background gray level is also significantly raised, resulting in lower gray scale contrast levels in the final particle images. Moreover, this method is not very practical in micro-scale studies due to the limitations in space and optical access to the test section, and thus has been followed only by a few studies previously. It should be noted that the combined μPIV and shadowgraphy setups obviously demand accurate synchronization of the equipment and/or calibrations of the final images, which adds to the complexity of the final system, see Yamaguchi et al. (2009) and Smith et al. (2010).

- **High intensity reflections at the interface.** Light reflections at the interfaces, especially close to the sections with higher curvatures, can be eliminated by using fluorescent PIV to a great extent but not completely. Moreover, the emitted light from the particles can be reflected at any boundaries separating two media with different refractive indices within the test section, resulting in undesirable effects in the final images.
- **Intrusive effects.** Due to the low light efficiency of fluorescent imaging, high-power illumination sources are often employed in fluorescent μPIV. Therefore, intrusive effects are expected to interfere with the measurements, especially in smaller scales where the energy of the illuminating laser is focused on an extremely small volume within the fluid. This can result in local heating of the test section, and consequently local modification of the fluid properties such as viscosity, density and refractive index. Moreover, in most of the medical, biological and chemical applications, the experimental tests are required to be performed at precisely controlled temperatures and such effects can be destructive to the process or fluid sample of interest.

These shortcomings, in addition to the complexity and the price of a typical fluorescent μPIV system motivate us to seek a more practical and applicable technique which can be developed and employed by researchers in diverse fields of two-phase flows applications. Such a technique should allow simultaneous interface detection and velocity measurement using a relatively simple optical setup while inducing minimum intrusive effects.

In larger scales, Bröder and Sommerfeld (2007) employed a relatively simple shadowgraphy technique for simultaneous tracking of small droplets and bubbles, and velocimetry in the continuous phase. Similar particle shadow velocimetry PSV approach was later followed by Dietrich et al. (2008) and Tung et al. (2009), in micro-scale geometries, for resolving the flow around and within droplets, respectively. The optical configuration used in these investigations involved a fully-transparent test section placed between a low-power non-coherent light source and the imaging array. The working fluid was seeded with non-fluorescent particles whose refractive index was higher than that of the fluid. As the result, particles, phase interfaces and boundaries appeared as dark patterns over the light background created by back-lit illumination. Obviously, the potential capacity of this technique to resolve the interface dynamics and velocity of the tracer particles simultaneously, using only one low-power light source and a single high speed camera, is an appealing feature for micro-scale two-phase flow applications. This approach not only reduces the cost, size and complexity of the measurement setup but also eliminates the destructive effects of the commonly used high-power lasers in smaller dimensions as discussed earlier. Moreover, the errors due to the geometrical calibrations and synchronization of the multiple cameras and light sources, often used in micro-scale two-phase flow velocimetry systems, are also avoided in this technique. Despite all these advantages, this method, here referred to as μPSV, has not been commonly practiced in experimental studies of micro-scale two-phase flows before.

Regardless of their optical configurations, most of the velocimetry studies mentioned above mainly provided local velocity measurements in one of the phases, while simultaneous measurements of velocity fields in both phases and accurate determination of practical flow parameters, such as interface dynamics, film thickness and bubble shape, have never been performed experimentally in such investigations. Our main intention in the present study is to examine the effectiveness of μPSV by quantitatively characterizing the classic problem of confined isolated bubbles and immiscible droplets moving within circular microchannels as presented schematically in Fig. 1 (Fairbrother and Stubbs, 1935; Taylor, 1961; Bretherton, 1961). Furthermore, this study attempts to introduce an experimental measurement technique for creating valuable databases for verifying numerical simulations of adiabatic micro-scale multiphase flows, using a single sequence of gray scale images mainly via post-processing methods. In this context, firstly, feeding parameters for initialization of numerical simulations, such as flow rate and bubble volume are measured accurately; secondly, validity of the commonly assumed boundary conditions, such as no-slip condition at the wall and fully-developed flows far enough from the bubble/droplet, are investigated; thirdly, measurement methods which can assist in defining the required finest numerical resolution and domain of the simulation are suggested; and finally, precise quantification of important flow parameters are performed which can be used for validation purposes.

The following sections of the present paper discuss in detail the implementation of μPSV and present experimental results for liquid–liquid and gas–liquid flows: Section 2 covers the description of the experimental facility while Section 3 presents details of the experimental tests performed. Post-processing methods and results of the measurements are discussed in Section 4. Finally, important aspects and conclusions of the study are summarized in Section 5.

2. Experimental facility

A fully-transparent test section was used to allow back-lit illumination of the circular microchannel. This test section, shown in Fig. 2, was comprised of a straight circular tube. Tube material was chosen carefully so that its refractive index matched that of the working fluid used in each experiment. This tube was submerged inside a liquid bath, filled with a fluid of the same refractive index, and held within a transparent plexiglass container. Since the refractive indices of the working fluids, the tube material, and the surrounding liquid in the pool were all approximately the same, and the test section was observed through the horizontal flat surface of the liquid bath, optical distortions of the region of interest due to refraction at the outer and the inner curved surfaces of the tube were minimized. Furthermore, since the refractive index matching also prevented total internal reflection, the flow field close to the channel walls and the bubble/droplet interface could be resolved conveniently. The average of the working fluid temperatures measured before and after the water pool was used to determine the fluid physical properties at the region of interest ROI. Refractive indices n and viscosities μ of the liquids were measured using an E-line Tri 90 refractometer and a Bohlin C-VOR rheometer at the corresponding temperatures, respectively. Tube diameters were measured optically using a pre-calibrated Nikon Plan Fluor 40× infinity corrected objective. Specifications of the different tubes and working fluids used in this experimental study are listed in Table 1.