Experimental Techniques for Bubble Dynamics Analysis in Microchannels: A Review

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Experimental studies employing advanced measurement techniques have played an important role in the advancement of two-phase microfluidic systems. In particular, flow visualization is very helpful in understanding the physics of two-phase phenomenon in microdevices. The objective of this article is to provide a brief but inclusive review of the available methods for studying bubble dynamics in microchannels and to introduce prior studies, which developed these techniques or utilized them for a particular microchannel application. The majority of experimental techniques used for characterizing two-phase flow in microchannels employs high-speed imaging and requires direct optical access to the flow. Such methods include conventional brightfield microscopy, fluorescent microscopy, confocal scanning laser microscopy, and micro particle image velocimetry (micro-PIV). The application of these methods, as well as magnetic resonance imaging (MRI) and some novel techniques employing nonintrusive sensors, to multiphase microfluidic systems is presented in this review. [DOI: 10.1115/1.4023450]

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1 Introduction

Over the past two decades, microfluidic devices have received significant attention because of certain inherent characteristics, such as high heat and mass transfer efficiencies. They have been employed in numerous applications in microelectromechanical systems (MEMS), electronic cooling, chemical reactors and separators, lab-on-a-chip devices, etc. [1,2].

In particular, gas-liquid two-phase flow in microchannels provides many advantages for chemical microreactors and micro-mixers. It offers small-volume confinement and the ability to control the bubble/droplet size and distribution [3]. Segmentation improves the mixing behavior and reduces the axial dispersion in the liquid phase [4]. The enhanced mixing drives the reactions to the required concentrations in shorter times while maintaining a narrow residence time distribution [5]. For performing reactions at high temperatures, gas-liquid flow is preferable over liquid-liquid flow since most liquids show increased miscibility at higher temperatures. Moreover, unlike liquid-liquid emulsions, it is possible to obtain uniform segmentation in gas-liquid flows over a very large range of bubble velocities and reaction timescales [5]. Some applications of the gas-liquid two-phase flow in microchannels involving reactions include fluorination, hydrogenation, biochemical reactions such as DNA analysis, and material synthesis [6,7]. Effective design of these devices requires knowledge of some of the flow characteristics in the microdevice such as bubble formation mechanisms, bubble shape, bubble size, two-phase flow patterns, mixing behavior, and flow velocity fields.

Two-phase flow in micro-heat exchangers is also an area of significant interest. Heat transfer to liquids in microchannels is quite different from that for macroscale channels since bubbles cause significant volume change and pressure fluctuations [8]. An understanding of the bubble dynamics is critical to the design and optimization of two-phase microchannel heat sinks [9].

For the design of gas-liquid two-phase microfluidic devices, the relevant characteristics of the flow inside the channels have to be

understood. The system can be studied analytically, numerically, or experimentally. Flow visualization is often the first method used in experimental study of fluid dynamics in microdevices [1]. The characteristics that may be obtained experimentally include bubble size and shape, bubble formation and growth rate, contact angle, liquid film thickness around the Taylor bubbles, 3D reconstruction of the bubble shape, mixing behavior, bubble velocity, and liquid velocity field.

The measured bubble velocity can be used in the calculation of the Reynolds, capillary, and Weber numbers for the gas-liquid two-phase flow. The capillary number, the most significant dimensionless number for characterizing multiphase microfluidics, is the ratio of viscous forces to surface tension forces across the gas-liquid interface [4]. This number is equivalent to the ratio of the Weber number to the Reynolds number. In addition to the aforementioned numbers, Nusselt, Prandtl, Jacob, boiling, and confinement (Co) numbers may also play important roles for boiling heat transfer in microchannels. According to Cornwell and Kew [10], if $Co \geq 0.5$, the bubble diameter approaches the channel diameter and confinement effects distinguish the boiling phenomenon from the one in macroscale channels. Extensive discussion of dimensionless numbers related to multiphase microfluidics and boiling heat transfer in microchannels has been presented by Gunther and Jensen [4] and Kandlikar [11], respectively.

In this paper, we present a review of experimental techniques used to study gas-liquid two-phase flow in microchannels. Some of the techniques for studying bubble dynamics in microchannels are also commonly used for studying single-phase flow in microdevices. The most often used flow visualization technique in microfluidic devices is high-speed¹ photography and microscopy, which when combined properly can achieve high spatial and temporal resolutions and capture fast transient phenomena. Fluorescent microscopy, advantageous for increasing the contrast between the liquid and gas phases and studying the mixing

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¹"High-speed" can be interpreted as thousands of frames per second; however, this term was also used in the cited literature for frame rates down to one hundred frames per second.

processes, is also discussed. Another reviewed method is confocal scanning laser microscopy, which provides insight to the 3D structure of the flow and also improves the image quality by eliminating out-of-focus blur. Moreover, micro particle image velocimetry, the most well-established method for investigating the liquid flow velocity field in microdevices, is discussed. All the aforementioned techniques, to varying extent, involve high-speed imaging and require direct optical access to the flow. Magnetic resonance imaging, as a technique for studying the flow in optically-opaque microdevices, is also included herein. Finally, some novel alternatives for characterizing two-phase flow in microchannels are reviewed.

2 Brightfield Microscopy and High-Speed Photography

Flow visualization using a high-speed camera coupled with a microlens or an optical microscope is the most universal technique for characterizing two-phase flows in microdevices with direct optical accessibility. Conventional optical microscopy can provide valuable information about the pattern and size of the microstructures in transparent microchannels. Combined with high-speed photography, it is possible to achieve high spatial and temporal resolutions and capture fast transient phenomena in microscale. Conventional optical microscopy can be used to qualitatively identify and characterize bubble patterns, two-phase flow processes ongoing in the microdevice, such as bubble formation and break up, and also flow regimes (if applicable) often described as bubbly, slug, and annular. Processing the sequential images, it is possible to acquire quantitative information including bubble generation frequency, size distribution and velocity, and bubble growth rate.

The limit of resolution of a microscope refers to its ability to differentiate between two closely-located points on a specimen. The optical resolution, which determines the minimum distance between two resolvable points, is diffraction-limited and depends on the numerical aperture of the objective and the wavelength spectrum of the light used for illumination. Neglecting the optical aberrations, the Rayleigh criterion estimates the optical resolution as $0.61 \lambda/NA$, where λ is the wavelength of the illumination, and NA is the numerical aperture of the objective [12]. The highest achievable numerical aperture is ~ 0.95 for a dry objective. Using the shortest wavelength of the visible light spectrum ($\lambda \sim 400$ nm) and a dry objective, the best optical resolution achievable is ~ 200 nm, which is sufficient to resolve typical bubble dynamics phenomena in microchannels. Immersion oil objectives can provide even higher optical resolution since they have a larger numerical aperture ($NA \sim 1.4$) [13].

The spatial resolution of a combined system of digital photography and microscopy, which refers to the size of the smallest possible feature that can be detected, depends both on the camera pixel size and the optical resolution. In order to accurately record the size of this minimum feature and avoid aliasing, its projected image must overlap a minimum of two pixels on the sensor following the Nyquist criterion. If such an overlap does not occur, the limit of spatial resolution is dictated by the sensor rather than the optics [14]. The temporal resolution is equal to the exposure time (shutter speed); using pulsed illumination, the temporal resolution is equal to the pulse duration.

A review of various digital camera types and their use in droplet and bubble dynamics studies is presented by Thoroddsen et al. [15]. Some of the well-known companies providing scientific high-speed CCD and CMOS cameras include Dantec Dynamics, LaVision, TSI, Vision Research, Photron, NAC, and Integrated Design Tools. Software such as IMAGE PRO, IMAGEJ, MATLAB image processing toolbox, as well as commercial programs provided by some of the aforementioned companies, are widely used for image processing. Digital imaging technologies have been rapidly improving in terms of sensitivity, resolution, and frame rate. Scientific CMOS (sCMOS) technology, a recently emerged high-performance imaging breakthrough, provides a better solu-

tion for low-light scientific imaging. sCMOS sensors simultaneously offer high performance for key parameters in quantitative scientific measurements including extremely low read out noise, wide dynamic range, high quantum efficiency, high resolution, and rapid frame rates.

To obtain sharp images and “freeze” motion, the object should move less than one pixel during the exposure time. At a spatial resolution of $1 \mu\text{m}$ (which means each pixel corresponds to $1 \mu\text{m}$ of the physical object), at flow velocities $\sim 1 \text{ cm s}^{-1}$, the exposure time must be less than $100 \mu\text{s}$, the time required for $1 \mu\text{m}$ movement of the object on the image sensor [15].

Today, ultra-high-speed digital cameras can acquire several hundreds of thousand frames per second with exposure times as small as $1 \mu\text{s}$ (e.g., Phantom v-series cameras by Vision Research²). Therefore, when combined with the proper lens, high-speed cameras can solely accommodate the resolution requirements of a system with low velocity microscale phenomena. However, at velocities more than 1 m s^{-1} , the exposure time of $1 \mu\text{s}$ is not short enough to freeze motion and results in blurry pictures. In that case, the use of a stroboscopic or pulsed light source with pulse durations less than $1 \mu\text{s}$ synchronized with the camera is necessary to obtain high-quality images. Employing a double-pulsed laser synchronized with a double-frame camera, it is possible to measure the instantaneous changes more accurately. Moreover, the use of high intensity light sources such as lasers, can generally improve the image quality for low exposure times in that they enable more signal (light) to reach the image sensor. However, if the laser power is set too high, image detectors will be saturated and some features in the images will be lost. The sensor can also be irreversibly damaged.

Shadowgraphy or backlighting is the most common type of illumination for microscopy. Shadowgraphy works based on the refraction of light in an inhomogeneous medium. Differences in refractive indices of gas and liquid phases distort parallel light beams and produce spatial variations in the intensity of light, which can be visualized on a screen or sensor on the other side of the medium. To obtain clear images, it is necessary to have a homogenous and parallel illumination source with a proper intensity [16].

For a bubble, light refraction is strongest at the gas-liquid interface [17]. No refraction occurs in the liquid or exactly at the center of a spherical bubble; and the interface reflects a considerable amount of backlight. Gases have a smaller refractive index than liquids, as light travels more rapidly inside the bubble than surroundings. As a result, the rays of light scattering from the spherical bubble in a liquid medium are diverging while a droplet in a gaseous medium acts like a converging lens. Regardless, a dark shadow marks the periphery of the bubble on the screen, which can be an image sensor. Figure 1 represents the basics of shadowgraphy for a spherical gas bubble in a liquid medium. Shadowgraphy provides much more accurate information on the bubble (droplet) shape and size than frontlighting photography and is a suitable method to investigate bubbles (droplet) dynamics in fluid mechanics.

High-speed microscopy with backlighting has been widely used to study gas-liquid two-phase flow in microchannels. Visualizing the boiling behavior and bubble nucleation always has been a popular area of research. High-speed imaging has been used to measure bubble formation rate, bubble growth rate, and departure size at different heat flux rates and temperatures in microchannels [8,18–22]. A range of boiling flow patterns in microchannels have been visualized in several studies [23–26]. Moreover, bubble dynamics in boiling heat transfer in a single microchannel and an array of two and three parallel microchannels has been studied and compared [18–20]. Bubble visualization has also been employed to study flow boiling stability in microchannels [27].

²Phantom v-series camera data sheets are available at <http://www.visionresearch.com/Service-Support/Downloads/Documents/Camera-Specific-Downloads/>.

Fig. 1 Schematic of shadowgraphy for a gas bubble in a liquid medium, adapted from Settles [17]

T-junctions, flow-focusing, and coflowing devices provide the primary avenues for droplet and bubble generation in microfluidics. The formation and break up mechanisms, bubble shape and bubble size, and the effect of volumetric flow rates and the micro-mixer geometry have been widely studied (for T-junction devices, see Refs. [28–36]; for flow-focusing devices, see Refs. [2,6,7,37–42]; for coflowing devices, see Refs. [43–46]; for a Y-junction device, see Ref. [47]; and for a novel geometry-based device, see Ref. [48]). The effect of ultrasonic irradiation on bubble formation in a T-junction was investigated by Ichikawa et al. [49]. The motivation for this study was incorporating ultrasound for active mixing and producing smaller bubbles in microchannels.

Using bubble generator devices, several researchers have visualized different gas-liquid two-phase flow patterns in circular, rectangular, and triangular microchannels [50–62]. Visualizing the bubbles, it is also possible to construct the flow pattern transition map according to the velocities of the two phases in microchannel. Serizawa et al. [54] calculated the cross-sectional averaged void fraction by assuming symmetrical bubble shapes within the bubbly and slug regimes. It has been shown that the flow patterns are strongly correlated to the surface wettability and gas/liquid, gas/solid, and liquid/solid interface properties [54,55]. Fu et al. [56] investigated the evolution of two-phase flow patterns in converging and diverging microchannels.

Using two high-speed cameras at different angles and stereoscopic backlighting, it is possible to reconstruct 3D images from microbubbles. The 3D reconstruction of the bubble bursting process and the measurement of the bursting rims velocity was demonstrated by Wang and Zhang [63]. Voisin et al. [64] reconstructed the 3D geometry of Taylor bubbles trapped inside hollow cellulose fibers from 2D shadowgraph images taken with only one camera. They used the intensity profile of the bubble shadowgraph to find the orientation of the bubble for 3D reconstruction.

A novel fluorescent shadowgraphy technique to study bubble shapes and positions in a microchannel device has been developed by Takeuchi et al. [16]. In the experiment, due to the existence of optical heating on the back of the device, applying a homogenous and parallel light source from behind was unfeasible. Instead, a layer of fluorescent solution in parallel cover glasses was located on the back of the microchannels. The concentration of the solution and intensity of the excitation light could be adjusted to control the fluorescent illumination intensity. More studies involving bubble imaging with backlighting are presented in Refs. [65–70].

The main drawback of backlighting is that any particle between the light source and the camera will cast a shadow on the image sensor and out-of-focus bubbles will appear on the images. Such bubbles can introduce significant errors to not only size measurements but also void fraction measurements. According to Ren et al. [71], sizing errors can be as large as 100% for small bubbles. In microchannel devices, the measuring volume is limited by the depth of the microchannel and the probability of bubble overlap occurrence depends on the two-phase flow regime. For bubbly flows containing bubbles with diameters smaller than the depth of

the microchannel, there is a possibility that some bubbles will be partially or totally covered by another bubble in the upper part of the channel, which introduces errors to the measurements.

To overcome the aforementioned drawback of backlighting and eliminate the out-of-focus shadows, some other bubble/droplet measurement techniques have been developed. These methods were applied to experiments involving bubbles moving in a relatively large volume of liquid (e.g., bubble columns). Although these methods are not characterized for bubble dynamics study in microchannels, introducing them as relevant bubble visualization and measurement techniques is appropriate.

Interferometric laser imaging for bubble sizing, which can give the spatial distribution of velocity and diameters of spherical bubbles, has been developed over the past decade [72–76]. This method is an adaptation of interferometric laser imaging for droplet sizing (ILIDS), a well-known method in the field of droplet and spray studies. An interferogram pattern is generated by the interference of external reflection and direct refraction of an incident light sheet on the bubble. The number of fringes on the pattern projected on an out-of-focus plane can be correlated to the particle size, and velocimetry measurements are based on cross-correlating two pulsed out-of-focus images. The main advantage of this technique is its ability to look at large fields of view, but it has a limitation on the number of bubbles per volume since only a minimal overlap of images is allowed. Another technique named glare point velocimetry and sizing (GPVS) for bubbly flows, was proposed by Hess [77] and developed by Dehaeck et al. [78]. In GPVS, the glare points (reflection and refraction spots) on the bubble surface are being observed on an in-focus plane, and the distance between the two glare points can be correlated to the bubble size. Figure 2 presents the principles of the ILIDS and GPVS methods. The main advantage of GPVS over ILIDS and backlighting is its ability to measure higher bubble concentration flows. More recently, Dehaeck et al. [79] proposed the laser marked shadowgraphy method, a combination of backlighting and GPVS, which obtains a more robust image processing compared to GPVS and a well-defined measuring volume compared to backlighting.

Fig. 2 Principles of GPVS and ILIDS techniques, courtesy of Dehaeck and van Beeck [76]

3 Fluorescent Microscopy

Fluorescent microscopy is another nonintrusive technique that can be used for two-phase flow visualization in microchannels. The main advantage of performing fluorescent microscopy for two-phase flow is the contrast enhancement between the liquid and gas phases and the possibility of studying mixing. Typically, the liquid phase is fluorescently labeled, and the microscopy reveals the phase distribution in the channels. This method requires an intense near-monochromatic illumination with a certain excitation wavelength, which causes fluorescence in the sample. During the process, the fluorophores absorb photons and jump to the excitation state where they remain for typically 1–10 ns before returning to their ground state by releasing photons [80]. Due to the energy dissipation, the light emitted by fluorophores has a lower energy and, subsequently, a longer wavelength compared to the excitation light. Typical fluorescent dyes are fluorescein-based and rhodamine-based compounds [81].

Laser induced fluorescence (LIF) is the most common type of fluorescent visualization technique. Nonlaser illumination sources include xenon arc, mercury arc, and high intensity light-emitting diode (LED) lamps. An excitation filter must be paired with xenon and mercury lamps since they are not single-wavelength sources. To obtain the highest signal-to-noise ratio, only the emitted light should reach the image sensor. For that reason, an emission filter is placed in the imaging path to filter out the entire range of excitation wavelengths. Figure 3 presents the arrangement of filters in a widefield fluorescent microscope with a xenon or mercury arc light source. The term “widefield” implies that the entire depth of the specimen over a wide area is illuminated.

Implementing LIF, excessively high laser powers should be avoided since they can excite all of the fluorophores within the volume and lead to excited-state saturation. In the case of excited-state saturation, excess light does not improve the contrast and signal intensity in the image plane, but introduces more out-of-focus fluorophore emission, reducing the axial resolution [82].

To obtain sharp images, short exposure times are necessary. As with other optical techniques, pulsed lasers such as Nd:YAG or Nd:YLF with short pulse durations (<10 ns) are typically employed for obtaining high-quality LIF data when flow velocities are high [4]. False-color images can be helpful for visualization purposes since the human eye is more sensitive to colors and cannot discern more than about 50 levels of gray.

LIF has been widely used to characterize gas-liquid flow patterns (bubbly, slug, annular, etc.) in microchannels and to measure the physical parameters including bubble and liquid slug lengths [4,83–86]. Some fluorescent images from different flow patterns are presented in Fig. 4. Due to differences in refractive indices of gas and liquid phases, the light emitted by the fluorophores beneath the bubble front and back curvatures is refracted. Identifying the exact location of a bubble edge might be an issue in the presence of strong refractions [87].

Fig. 3 Arrangement of the filters in a widefield fluorescent microscope with xenon/mercury arc light source

Fig. 4 Fluorescent images from different flow patterns in microchannels, (a) slug and plug flow, (b) annular flow, and (c) bubbly flow, courtesy of Waelchli and Rudolf von Rohr [84]

fying the exact location of a bubble edge might be an issue in the presence of strong refractions [87].

Fluorescent labeling of the gas phase is a more complicated option for this technique because of the challenge of producing fluorescent microbubbles. Fluorescent microbubbles were used in the experiment of Meng et al. [88]; the bubbles labeled with fluorescein isothiocyanate were composed of octafluoropropane (C_3F_8) gas encapsulated by a phospholipid shell. These fluorescent microbubbles were injected into microcavities and manipulated with a surface acoustic wave.

Fluorescent microscopy is also a powerful technique used to study mixing in microfluidic devices including two-phase microfluidic systems. Fluorescent tracers have been used to study mixing in the liquid phase of a segmented gas-liquid flow in straight and meandering microchannels, where mixing is considered complete when the concentration of the dye is uniform within the liquid slug [83]. A more complicated configuration was used by Hellman et al. [89] where laser-generated cavitation bubbles were used to mix two microchannel streams; LIF and confocal microscopy were utilized to visualize the fluid patterns produced upon bubble collapse. The spreading of the dye-containing liquid stream into the uncolored liquid stream was visualized to characterize the mixing process. The light intensity can be correlated to the concentration value, which enables quantitative measurements on the mixing. In widefield fluorescence microscopy, the visualization is conducted perpendicular to the flow direction; therefore, the concentration information represents an integration of intensities through the depth of the microchannel. To the contrary, by using confocal scanning laser microscopy it is possible to obtain point measurements of the fluorescent dye concentration as a function of the depth of the microchannels [81]. For more information about the measurement of mixing in microfluidic systems, the reader is referred to a review paper by Aubin et al. [81].

4 Confocal Scanning Laser Microscopy

Confocal scanning laser microscopy (CSLM) is an optical microscopy technique that is used to improve the fluorescent image quality. In point-scanning confocal microscopy, in contrast to widefield fluorescent microscopy, the specimen is scanned by a focused illumination spot; the laser is first expanded to fill the objective and then focused to a very fine spot centered at the focal plane [90]. The laser light source moves rapidly from point to point over the sample, and the fluorescent emitted light is detected by a photomultiplier tube through a pinhole. The pinhole prevents the light being emitted from the regions above and below the in-focus points from reaching the photomultiplier. The image is, subsequently, rebuilt from the recorded point intensities via software algorithms.

The main advantage of CSLM over widefield fluorescence microscopy is higher axial resolution (smaller depth of the field) and less out-of-focus blur, leading to the enhancement of

signal-to-noise ratio [91]. Figure 5 presents the principles of point-scanning confocal microscopy and the out-of-focus blur elimination by the confocal pinhole.

The point-by-point scanning limits the temporal resolution to approximately 1 s, a serious limitation for many microfluidic applications [92]. However, spinning disk confocal microscopes have thousands of moving pinholes on a scanner, which provide simultaneous scanning and higher temporal resolutions. An image acquisition rate of up to 120 fps with a spinning disk confocal microscope is reported by Park et al. [93]. Optical sectioning and high axial resolution allow for accurate signal discrimination and avoid superimposing the structures on top of each other. Combining the information content of all optical sections enables reconstruction of the 3D images. Similar to brightfield optical microscopy, the spatial resolution of the CSLM measurements depends on the numerical aperture of the optical system and the wavelength of light. According to Aubin et al. [81], in the upper limit 3D CSLM can resolve ~ 200 nm in the focal plane and ~ 500 – 800 nm along the optical axis.

For the first time, Park et al. [93] proposed combining CSLM with micro-PIV to obtain optically sectioned flow field mapping in microchannels. Velocity data for CSLM micro-PIV and wide-field fluorescence micro-PIV for Poiseuille flow in circular microchannels have been directly compared [94]. CSLM showed significantly improved particle image contrast, and the fluid vector fields agreed more accurately with the Poiseuille flow analytical solution. Some of the results of the study are presented in Fig. 6.

In an application of CSLM to two-phase flow, Fries et al. [85] measured time-averaged liquid film thickness at the wall and in the corner of the microchannels with slug flow regime. Figure 7 represents the data analysis process for the determination of the film thickness. The result showed that by increasing the capillary number within the range of 2×10^{-4} to 10^{-1} , the film thickness decreased. Experimental measurement of the film thickness in two-phase flow regimes is important since numerical methods can encounter difficulties in resolving the thin films, which rearrange over a long axial length scale [85].

In addition to the poor temporal resolution, the other disadvantage of CSLM includes the limited number of available laser lines and their narrow bands. To the contrary, in widefield fluorescent microscopes, the use of xenon or mercury arc lamps provides a full range of excitation wavelengths in the ultraviolet, visible, and infrared spectral regions and allows for the selection of different fluorophores [90]. Another drawback is the harmful nature of a high intensity laser on living cells, which is not often an issue for gas-liquid two-phase flow studies [90].

Fig. 5 Schematic illustration of confocal microscopy

Fig. 6 Particle images taken by (a) CSLM and (b) widefield fluorescent microscopy, courtesy of Park et al. [94]

Fig. 7 Scheme of data analysis for the determination of the film thickness: (a) optical slices in direction of the channel depth recorded with the CSLM. (b) Reconstruction of yz slices. (c) Average image of all yz slices in channel length direction. (d) Average image of the channel cross section with a schematic outline of the channel wall and sectioned films. Film thicknesses at the channel top (δ_f) and in the corner (δ_c) were measured, courtesy of Fries et al. [85].

5 Micro Particle Image Velocimetry

Micro particle image velocimetry was initially developed for quantitative flow visualization and characterization in microchannels by Santiago et al. [95] and Meinhart et al. [96,97]. The principles of micro-PIV are similar to conventional PIV. Two successive images separated by a known short time interval, are taken from the illuminated seed particles. The two images are then analyzed by dividing the images into hundreds or thousands of small areas called interrogation windows. A cross correlation is applied on the interrogation windows with a selected percentage area overlap. The displacement vector can be calculated from the location of the correlation peak for the group of particles inside

each interrogation area, and subsequently, the instantaneous velocities of the flow field may be obtained. Typically, the two velocity vectors normal to the camera axis are measured. The main difference between micro-PIV and PIV methods lies in the illumination techniques. In micro-PIV, volume illumination is typically used instead of planar illumination since optical access is often limited to one direction, and it is difficult to make laser sheets thin enough and furthermore to align them in microdevices [97]. In particular, silicon-based microchannels fabricated by bonding the glass wafer onto the silicon structure have optical access on one side only [98]. The use of fluorescently labeled seed particles and imaging of the emitted light is a common approach in micro-PIV technique. A schematic view of a micro-PIV setup is presented in Fig. 8. Extensive discussion of the micro-PIV technique is included in several review papers [1,80].

In general, applying micro-PIV to the disperse phase in two-phase flows is challenging due to differences in refractive indices of gas and liquid phases and the refraction of light at curved interfaces. The light scattered from the particles inside a droplet is refracted at the interface, which affects the measured velocity field. This situation does not happen when the seeded phase is the continuous phase [4].

In two-phase flow experiments employing PIV methods, the accurate measurement of bubble size and bubble shape as well as bubble velocity can be obtained by shadowgraphy techniques. Lindken and Merzkirch [99] combined a double-pulsed laser light sheet for fluorescent particle illumination and a double-pulsed high-power LED array for shadow imaging of the gas bubbles in a bubble column experiment. Using a different light wavelength for shadowgraphy along with a PIV/LIF method allows the acquisition of bubble and seed particle images simultaneously. The emission filter eliminates the fluorescent excitation light, but the wavelength used for shadowgraphy must be selected in a way that it passes the emission filter. In microdevices with side access, it is also possible to project a laser sheet into the device [100,101]. Use of an ultrathin illumination sheet with the thickness of $5\ \mu\text{m}$ [100] allows for high axial resolutions regardless of the depth of field of the image acquisition system. The described technique employs the conventional PIV with planar illumination, which is not always practicable in microfluidic devices; however, the principles of the combined technique will be the same for micro-PIV studies.

Stroboscopic backlighting has been used for micro-PIV measurements in T-junction and cross-junction flow-focusing devices

Fig. 8 Schematic of a micro-PIV setup using a microscope, adopted from Lindken et al. [1]

[2,42,102]. These experiments were performed on an inverted microscope, and they used the shadowgraphs of the relatively large 880 nm calibrated latex seed particles for PIV analysis. A different light source was not required for bubble imaging since the method did not involve fluorescence microscopy.

Shadowgraphy is not applicable to microdevices with optical access on one side only. For such devices, one approach to visualizing the gas-liquid interface in micro-PIV images is by adding fluorescent dye to the liquid phase already seeded with fluorescent particles to illuminate the whole volume of liquid [103].

The primary role of micro-PIV studies in gas-liquid two-phase flow in microchannels is to determine the liquid-phase velocity field. For example, micro-PIV and high-speed photography were used concurrently to investigate the role of inertial, viscous, and interfacial forces on the bubble formation process in various types of flow focusing devices [7]. Knowledge of the flow field upstream of the bubble pinch off is useful for the evaluation of shear stress for comparison with the surface tension and pressure distribution. The same technique is applied to determine the liquid-phase velocity field around the gaseous thread of the bubbles formed in a flow focusing device [2] and to characterize the bubble formation at a T-junction [43,104]. Park et al. [93] showed that bubble shape and proximity to the channel walls undergo a transition with increasing flow rate. Using micro-PIV, the effects of channel dimensions and capillary number on the transition of the bubble shape as well as flow field ahead of the bubble was investigated. For more particular applications, micro-PIV is applied to study a liquid slug moving in and out of a microfabricated reservoir in a microchannel network [105] and the characteristics of a two-phase flow resulting from gas jet injection into a microchannel [106].

The velocity distribution in the liquid phase influences the mixing and the mass transfer in liquid slugs inside microchannels. Meandering microchannels are attractive for the design of micro-mixers since they create asymmetric counter rotating vortices in the liquid slug, which enhance the mass transfer over the channel centerline [107]. Micro-PIV has been used to investigate and compare the velocity vector field and the streamlines in the liquid phase around the bubbles in straight and meandering microchannels [83,84,107,108].

Kwak et al. [103] evaluated the velocity deficit in a fractal-like branching microchannel network using the micro-PIV technique. The primary purpose of the branching microchannel flow network was for a heat sink application; however, the experiment was performed with injected bubbles to avoid complications.

Micro particle tracking velocimetry (micro-PTV), a technique similar to micro-PIV, has been employed in microchannel devices on a more limited basis. In this technique, instead of cross-correlating the interrogation windows, the velocity field is determined by tracking the individual particles. A two-dimensional velocity vector can be obtained for each of the tracked particles. Necessarily, for the best particle recognition in sequential images, a lower particle concentration is used [109]. Micro-PTV can provide a higher spatial resolution than micro-PIV in that it computes the velocity vectors of single particles not a group of particles inside the interrogation window [81].

In one application to a two-phase flow in a microchannel, Park and Kihm [110] used deconvolution microscopy and a single camera, in the development of a micro-PTV technique able to calculate the three-dimensional velocity field around a bubble. The method tracks the out-of-plane location of the seed particles by correlating the diffraction ring pattern size of the particles with the defocus distance from the focal plane.

6 Magnetic Resonance Imaging

Magnetic resonance imaging is a tomographic technique to obtain information from optically opaque and magnetically heterogeneous systems. In this technique, a varying electromagnetic field with a “resonance” frequency flips the spin of the protons of

the molecules. During the relaxation, the protons generate radio frequency signals, which will be measured for image productions. Local magnetic properties let the substances become distinguished from one another in the image; therefore, systems with significant magnetic susceptibility variations and rapid nuclear spin relaxation times can be robustly characterized with this technique [111]. In microfluidic devices, MRI has been used to characterize single and multiphase flows in multilayered stacked microchannel reactors, where direct optical access, if possible, is restricted to the first layer of channels and not the interior ones.

Gladden's research group developed a variant of rapid acquisition with relaxation enhancement (RARE) pulse sequence termed SEMI-RARE [112,113]. In this technique, multiple images (up to ~ 120) can be acquired from a single radio frequency excitation [114]. In comparison to other MRI techniques, SEMI-RARE can achieve higher spatial and temporal resolution in combination with high signal to noise ratio [113]. Several studies used SEMI-RARE to visualize Taylor flow bubbles in an array of parallel microchannels in ceramic monolith reactors [111–113,115]. Figure 9 presents the image processing steps for two-phase flow visualization. The size and velocity of the bubbles were obtained with the temporal resolutions around 150 ms and in plane spatial resolution around $390\ \mu\text{m} \times 790\ \mu\text{m}$. One of the drawbacks of SEMI-RARE technique is the inability to compute velocity in liquid filled channels, since velocities can be calculated from gas-liquid interface tracking in two or more successive images. Moreover, due to the low temporal resolution, SEMI-RARE cannot be used to image bubble velocities greater than $\sim 10\ \text{m/s}$ [114]. Sederman et al. [114] proposed “line excitation TOF” and “displacement tracking” techniques to overcome these drawbacks. These methods, however, sacrifice the information on the gas-liquid interfaces along the channels and are unable to image bubble distributions. In spite of the resolution limitations of the MRI methods, they are fairly successful in basic multiphase flow characterization in multilayer microreactors.

7 Novel Two-Phase Flow Visualization Alternatives

In an attempt to overcome some of the disadvantages of the high-speed imaging, such as high cost and the necessity of having optical access to the device, some innovative nonintrusive sensors for characterizing gas-liquid flows in microchannels have been developed [81]. These methods do not involve image acquisition and employ sensors responsive to the phase difference to detect the bubbles. Although these methods cannot “visualize” the bubbles inside the channels, they can provide some information about the flow characteristics.

An integrated nonintrusive sensor that works based on the total internal reflection of the laser beam at the gas-liquid interface has been developed by Kraus et al. [116]. The technique allows for detection of the structure of two-phase flows as well as slug length, bubble velocity, and frequency. The sensor can be used to

Fig. 9 (a) Gas-liquid distribution within a ceramic monolith. (b) The map produced by correction to the image intensities arising from resonance frequency inhomogeneity and averaging the signal intensities across the width of each channel. (c) The ternary-gated map showing gas (black), solid (gray), and liquid (white), courtesy of Gladden et al. [112].

characterize the flow in the interior channels as well as the top channels of a multiplate structure [117].

Another method, developed by Leung et al. [118], employs a laser beam, which passes through a gas or liquid medium in the channel and becomes refracted to varying degrees. The refracted light is collected by a position sensitive detector producing voltage signals. This technique enables obtaining the information on the size and frequency of bubbles.

Using IR sensors at different streamwise positions in capillaries, Wolffenbuttel et al. [119] developed a method to measure velocity and slug length in gas-liquid and gas-liquid-liquid flows. The IR sensor's signal is low for high absorbance, indicating a liquid slug and high for low absorbance, indicating a gas slug. The technique does not require optical access to the flow.

Lastly, another cost-effective optical technique has been demonstrated by Revellin et al. [120–123]. The setup consisted of two laser beams, directed through the microchannel and the fluid inside, at two different locations. Two lenses were used to focus the laser beams at the middle of the microchannels. On the opposite side of the channel, two photodiodes measured the intensity of light at a rate of 10 kHz. The laser beams interact with the structure of the flow and produce different voltage signals in the diodes. Processing the voltage allows the determination of the characteristics of the gas-liquid flow regimes (bubbly, slug, semi-annular, and annular flows) in addition to the velocity, length, and frequency of the bubbles.

8 Conclusions

This review discusses current experimental techniques for bubble dynamic studies in microchannels. The report provides a concise discussion of each of the methods including main principles, the advantages, limitations, and documented implementation of the technique to study two-phase flows in microchannels. High-speed imaging coupled with microscopy and backlighting is the most widely used technique to study microchannel flows. Fluorescent microscopy can be used to provide high contrast between the two phases and, in addition, to enable the study of mixing phenomenon. Fluorescent imaging also can be employed in other techniques, such as confocal scanning laser microscopy and particle image velocimetry, to enhance the image quality. CSLM allows selection of the image plane and acquisition of 3D information on two-phase flow structures. Dynamic low-velocity microfluidic systems require a spinning disk confocal microscope, which provides higher temporal resolutions than a scanning one. The micro-PIV technique, which was originally developed for single-phase flow in microchannels, has been used to provide complementary velocity field and shear stress in the liquid phase of gas-liquid flows in microchannels.

Moreover, magnetic resonance imaging has been used to characterize two-phase flows in opaque microchannel devices, such as monolith reactors. A few innovative methods, which do not involve image acquisition but employ nonintrusive sensors, have been presented. These methods are relatively cheap and can provide some characteristic properties of the two-phase flow; however, they are not able to “visualize” the flow in the common sense. The authors hope that the review will guide the users in the choice of appropriate visualization techniques for microchannel devices to obtain required information.

There are still opportunities for contributions to the characterization of two-phase flow in microchannels. As microtechnology moves toward commercialization, there is a necessary evolution of fabrication techniques from those feasible for laboratory-based research to those suitable for commercial mass-production. Commercial devices are not necessarily made from transparent materials. Furthermore, many industrial microdevices consist of multiple layers and do not provide optical accessibility. Further development of nonintrusive sensors, which do not require optical

access for characterizing two-phase flow in opaque and multilayer devices, is anticipated.

It is interesting to think about techniques that can easily align an ultra-thin laser sheet within the depth of microdevices. Such capability would allow performing the conventional PIV with high signal-to-noise ratio and, hence, high accuracy. Moreover, noting that the low temporal resolution of CSLM technique has limited its applicability to very low-velocity flows, advances in the temporal resolution of CSLM would be promising to enable its application to a wider range of systems. Such an improvement also enables obtaining high quality PIV data by CSLM.

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