Flow Near the Meniscus of a Pressure-Driven Water Slug in Microchannels

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Micro-PIV system with a high speed CCD camera is used to measure the flow field near the advancing meniscus of a water slug in microchannels. Image shifting technique combined with meniscus detecting technique is proposed to measure the relative velocity of the liquid near the meniscus in a moving reference frame. The proposed method is applied to an advancing front of a slug in microchannels with rectangular cross section. In the case of hydrophilic channel, strong flow from the center to the side wall along the meniscus occurs, while in the case of the hydrophobic channel, the fluid flows in the opposite direction. Further, the velocity near the side wall is higher than the center region velocity, exhibiting the characteristics of a strong shear-driven flow. This phenomenon is explained to be due to the existence of small gaps between the slug and the channel wall at each capillary corner so that the gas flows through the gaps inducing high shear on the slug surface. Simulation of the shape of a static droplet inside a cubic cell obtained by using the Surface Evolver program is supportive of the existence of the gap at the rectangular capillary corners. The flow fields in the circular capillary, in which no such gap exists, are also measured. The results show that a similar flow pattern to that of the hydrophilic rectangular capillary (i.e., center-to-wall flow) is always exhibited regardless of the wettability of the channel wall, which is also indicative of the validity of the above-mentioned assertion.

Key Words: Microfluidics, Micro-PIV, Meniscus, Slug, Image Shifting Technique

1. Introduction

Over the past several years, as the understanding of microfluidics becomes more and more important in the design of microdevices, such as biochip, flow cytometer, capillary pumped loop (CPL), etc., a considerable number of theoretical and experimental studies have been performed on the capillary phenomena (Park et al., 2001; Höhmann and Stephan, 2002; Park et al., 2003; Buffone et al., 2004; Buffone and Sefiane, 2004a, 2004b).

Advance in the micro scale velocity measurement techniques, represented by micro-PIV, enables us to have a closer view of the micro scale flow. In particular, the flow near the meniscus is also one of the most important research topics regarding micro-scale heat transfer. Park et al. (2001) applied the MTFV (Molecular Tagging Fluorescence Velocimetry) to visualization of the three-dimensional flow occurring inside a heated capillary pore of 5-mm inner diameter with 5° inclination angle. The results show that the
thermocapillary stress plays an important role in the flow near the meniscus. Park et al. (2003) obtained optically-sectioned flow field mapping for the regions near an advancing bubble front, inside square microchannels using high-speed CLSM (Confocal Laser Scanning Microscopy) which suppresses all out-of-focus structures at image formation, thus eliminating the error caused by out-of-focus particle images in micro-PIV. The flow induced by naturally evaporating ethanol inside the glass capillary is also observed by Buflone et al. (2004).

However, the discrepancies between the known equations of capillary dynamics and the experimental results are still being reported. One reason of these discrepancies is thought to be the complexity of the actual flow near the meniscus in the capillary (Zhmud et al., 2000). Laminar flows in a pipe or a channel are usually characterized by a parabolic velocity profile, which for a capillary flow would hold far from the meniscus. However, it is obvious that the velocity profile is not parabolic near the meniscus. In particular, the flow pattern near the meniscus is expected to vary depending on the surface wettability, i.e., hydrophilicity or hydrophobicity because the shape of the meniscus also varies with it. The main objective of this study is to understand the fluid motion near the meniscus of a pressure-driven water slug advancing in microchannels with the rectangular and circular cross sections subject to hydrophilic and hydrophobic surface conditions, where micro-PIV technique is adopted to observe the flow structure and to obtain the velocity field near the meniscus. Because the pressure-driven water slug moves very fast, we apply time-resolved PIV setup (Sung and Yoo, 2001) which uses a high speed CCD camera. The problems arising from moving meniscus are overcome by fixing the meniscus position in the image using meniscus detection and image shifting technique.

2. Experimental Setup

A micro-PIV system, illustrated in Fig. 1, is assembled to measure instantaneous and time-averaged velocity field near the meniscus of a pressure-driven water slug in microchannels. Unlike the usual micro-PIV system, a mercury lamp combined with green filter cube (Olympus U-MWG2) is used as the light source. The white light which comes from the mercury lamp is filtered so that only the green light passes through the bandpass filter. This green light is then reflected at the dichroic mirror mounted on the filter cube. The main problem with using a continuous light source, such as the mercury lamp, is that a particle is captured as a streak image not as a dot image. This problem depends on the flow velocity and camera exposure time. That is, the streak becomes longer as the velocity becomes higher and as the exposure time becomes longer. This can be successfully overcome by controlling the exposure time of the high speed CCD camera. Used high speed CCD camera (NAC Inc. PCI2000s) allows us to regulate the exposure time to be short enough so that it does not make any streak images. The maximum frame rate of this camera is 250 frames per second with maximum resolution of $480 \times 420$ pixels. Another important reason that we use a high speed CCD camera and continuous light source is because the meniscus moves very fast. Under our experimental condition, the meniscus escapes the field of view within a few seconds. Therefore, to get as much data as possible, it is more desirable to use a high speed camera and a continuous light source.

Fluorescent polystyrene microspheres of $1-\mu m$

![Fig. 1 A schematic of the experimental setup](image-url)