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# RECENT EXPERIMENTAL STUDIES ON MICROSCALE CHANNEL FLOWS

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**ABSTRACT:** *In this paper, we review recent experimental studies on single-phase and multiphase flows in microchannels. Brief overviews of physical phenomena of fluid flow in microchannels, and measurement techniques mainly in conjunction with the flow visualization, are given. Regarding the studies of single-phase flows, the current state-of-the-art of electrokinetics and optofluidics is outlined. Then the studies of multiphase flows are reviewed in terms of solid-liquid, liquid-liquid and gas-liquid flows, and in view of their appropriate functionalities and applications. In particular, a systematic evaluation of lateral migration of particles in microchannel flows is discussed.*

## 1. INTRODUCTION

Microfluidics, often referred to as a method of controlling fluids in microscale devices with length scales less than a millimeter, has attracted considerable attention for the past few decades because of its wide range of scientific and engineering applications toward lab-on-a-chip (LOC) devices. The use of integrated microfluidic devices or LOC systems offers numerous advantages such as small operating volume, ease of use, point-of-care diagnostics, fast reaction of a sample, and so forth, for engineers and scientists in the fields of bio-engineering, medicine, biology and chemistry. With the advances in the MEMS technology, the ability to fabricate and pattern micro structures has been enhanced and has achieved the promotion of microfluidics. In the late 90's, Whiteside's group [1] introduced a novel channel fabrication technique called 'Soft Lithography' which represents a non-photolithographic strategy based on replica molding for formation of micro- and nano-sized channel architectures. It provides a convenient, effective, and low-cost method, which has been widely employed. There are also a number of journals, which highlight applications and functionalities embodied on chip-sized devices powered by microfluidics (e.g., *Journal of Micromechanics and Microengineering*, *Microfluidics and Nanofluidics*, *Biomicrofluidics*, *Lab on a Chip*, and *Small*).

Indeed, versatile control of fluid flows enables researchers to create a wide variety of functional elements in chip-based devices, such as mixers, valves, pumps, sensors, separators, concentrators, and many others. These functionalities in microfluidic devices operate in single phase as well as in multiphase. Single-phase flow in microchannels often contains single-phase liquid flows or two (or more) miscible liquid flows, while multiphase flow involves solid-liquid flow, two or more immiscible liquid-liquid flow and gas-liquid flow. Prior to fabrication of channel structures for the above-mentioned functionalities, one must understand physical phenomena of fluid flows in microchannels, which are quite unique from those observed in macroscale flows and thus can be fully understood by diagnosing, for example, flow patterns and temperature distributions.

In this paper, we describe flow physics and visualization techniques regarding microscale flows. Then, we review recent studies on single-phase and multiphase flows in microchannels, while we focus on their applications. As for the single-phase flow, we mainly deal with two subjects: electrokinetic flow and optofluidics, while for the multiphase flow, we review current issues on solid-liquid flow, liquid-liquid flow and gas-liquid flow.

## 2. FLOW PHYSICS

In this section, we deal with the characteristics of flow phenomena regarding microchannels and their importance toward applications. For more comprehensive and extensive review on this subject, reference can be made to Stone et al. [2].

Low-Reynolds-number operation due to the scale-down effect of a microchannel is the most typical characteristic in microscale flows. Commonly, laminar flow maintains the Reynolds number (*Re*) typically ranging below 30 in a microchannel. This sometimes brings about adverse effects. For example, mixing is an important issue in microchannels, but it is hindered due to low *Re* operation. On the other hand, laminar flows enable engineers to sort, separate or filter macromolecules in microchips. Surface tension is dominant when the length scale of the microchannel is less than say one millimeter. The capillary force, i.e., the driving force in droplet-based microfluidic actuators, basically results from the surface tension. High surface-to-volume ratio is another characteristic of a microchannel flow, which exhibits the importance of surface force and other surface effects. For example, high surface-to-volume ratio induces capillary electrophoresis to be more efficient in microchannels. However, when transporting fluids by way of electrokinetic flow, it makes macromolecules quickly diffuse and adsorb to channel surfaces, reducing the efficiency of pumping. Diffusion is a spontaneous movement of fluid molecules by Brownian motion. Diffusion length in microchannel flows is much shorter than that of macroscale flows, which may be utilized to create gradually varying concentration distributions of miscible fluids for LOC applications.

## 3. MEASUREMENT TOOLS

Along with the increase of interest in LOC devices, rapid development of flow measurement techniques has been made. Recent review on microscale flow visualization is presented in Sinton [3]. Velocity measurement techniques inside microchannels can be typically divided into three categories: bulk-flow measurement, field measurement and pointwise measurement.

Bulk-flow measurement includes in-line flowmeter, the timed collection of fluid and pressure taps between inlet and outlet of a channel. This type of the measurement is very simple-minded because no optical access is required. However, it does not provide detailed velocity information inside a channel.

On the other hand, field measurement is subdivided into two categories: particle-based measurement and scalar-based measurement. Particle-based measurement technique is powerful and widely adopted, where fluorescent particles are seeded in the flow field and consecutive particle image sets are obtained. This particle-based measurement is again mainly subdivided into particle image velocimetry (PIV) and particle tracking velocimetry (PTV) depending on the application of interest. The first PIV technique was applied to a rectangular microchannel by Santiago et al. [4] and in a circular microchannel by Koutsiaris et al. [5]. Molecular tagging velocimetry (MTV) is typical of scalar-based measurement, which uses fluorescent dye rather than fluorescent particles. This method has been applied to the diagnosis of microscale flow by numerous researchers [6].

Laser Doppler velocimetry (LDV) has been widely adopted in macroscale flows as a pointwise measurement technique. However, it has been applied to microscale flows by reducing the probe volume through which the particles pass [7]. This method requires an effort of traversing the probe volume to scan the velocity field.

Microfluidic devices sometimes require a simultaneous measurement of velocity and temperature. Several measurement techniques such as MTV&T [8], PIV correlation algorithm method [9] and single camera PTV-LIF method [10] have been reported. Charmathy et al. [11] presented an advancement of simultaneous velocity and temperature measurement method without calibration procedures. However, they are still in their early stage of progress.

## 4. SINGLE-PHASE FLOWS

### 4.1 Electrokinetic flow

Electrokinetic process was first attributed to Reuss [12] who demonstrated electroosmotic flow through a sand column. Electrokinetics involves two important phenomena: electroosmosis and electrophoresis. The former is the bulk fluid motion due to the electrical double layer of the solid wall, while the latter is the particle motion due to the electrical double layer on the particle surface. The advent of MEMS technology has seen an application of electrokinetics as a technique for fluid pumping. Electrokinetic flow reveals quite different characteristics from pressure-driven flow, because surface charge plays an important role in electrokinetic flow. Electrokinetics has been widely adopted in LOC devices, since it realizes various functions, such as pumping, mixing, flow direction control and separation, without complicated auxiliary parts.

Based on DC-electrokinetics, Chen and Santiago [13] developed an analytical model for planar electroosmotic micropump. Takamura et al. [14] proposed a low-voltage electroosmotic pump for stand-alone microfluidics devices, and Schönfeld et al. [15] proposed electroosmotic flow patterning using microfluidic delay loops. DC-electroosmotic pump has some limitations, such as generation of undesired gas bubbles, unwanted reactions of species, electrode dissolution, and/or hydrodynamic instability. Thus, AC voltage is used to pump fluids, which is called AC-electroosmotic (ACEO) pumping. Brown et al.

[16] demonstrated symmetry breaking in the widths and spacings of each electrode pair in the array, so that this concept was utilized to achieve ACEO pump with nonplanar electrodes [17], and asymmetric pairs of electrodes [18]. Next, electrophoresis is one of the most widely used techniques for handling macromolecules in various engineering and scientific applications. For example, this technique can be applied to LOC devices for sampling, transport, separation and detection. In addition, dielectrophoresis is another widely used method for controlling particulate materials, DNAs, cells, carbon nanotubes (CNTs) and so forth [19]. Combination of IC chip and microfluidics even allows trapping and moving of individual living cells and droplets along the programmable paths using dieletrophoresis.

## 4.2 Optofluidics

The integration of fluidics and optics has led to a new emerging technology referred to as 'Optofluidics'. The goal of optofluidics is to realize highly versatile, flexible, and compact LOCs integrating optical components, such as light sources, sensors, lenses, waveguides and so forth. Currently, numerous optical devices have been proposed. More extensive review on this subject is provided in the work of Monet et al. [20]. Here, we present a brief review of the current representative optofluidic devices, such as waveguide, flexible lens and so forth.

Waveguide from the optofluidic technique is the optical element which transmits rays into the integrated microchip by using total internal reflection (TIR) methods or interference methods. A number of waveguides with different approaches for increasing sensitivity have been reported, e.g., a waveguide based on low-loss light propagation [21], a waveguide using a nanoporous cladding [22], and liquid-core/ liquid-cladding optical waveguides [23]. Recently, liquid-core ARROW waveguide has been developed for ultra-high sensitivity detection, such as a single molecule sensitivity. Current devices using an optofluidic waveguide as a light source is somehow bulky due to the limitation in combining waveguides with detectors. Further, Optofluidic technology replaces a conventional solid lens by flexible liquid lens, enabling control of liquid meniscus by pressure, electrowetting or magnetic force, which provides a novel application for use in mobile phone [24] and has a great impact on miniaturized optical devices. In addition, as a manipulation tool using electromagnetic force from laser source, optical tweezers have been employed in molecular biology research. Currently, it is applied to handle microparticles according to the wave guidance of a laser in a microchannel [25]. This concept provides a novel method of controlling macromolecules for sorting, purification, drug screening and so forth.

# 5. MULTI-PHASE FLOWS

Microfluidic devices frequently operate with multiphase flows. In this section, multiphase flows in microchannels, such as solid-liquid flow, liquid-liquid flow, and gas-liquid flow are reviewed. We highlight lateral migration of neutrally buoyant particles in solid-liquid flow, and droplet dynamics (e.g., generation, merging, and breakup) in liquid-liquid flow, respectively. Further, current state-of-the-art of gas-liquid flow in microchannels will be presented.

## 5.1 Solid-liquid flow

Microchannels often contain fluid flows with solid particles, where the particle size relative to the channel diameter is small but not negligible. Under such flow conditions, particles will not necessarily follow fluid streamlines, so that lateral migration is frequently observed. Lateral migration of solid particles in dilute suspensions, has been extensively and systematically investigated in macroscale flows since Segré and Silberberg's experiment [26]. However, it is not fully understood in microscale flows so far [27].

Very recently, a study on lateral migration of neutrally buoyant particles transported through microchannels over a broad range of Reynolds numbers has been carried out. Flow Reynolds numbers are obtained from tracer particles using PTV algorithm by separating particle images according to their sizes, as shown in Figure 1. By analyzing the spatial distributions of spherical particles, it is revealed that lateral migration of particles markedly occurs even at very low $Re$, which is induced by high shear rate due to small-scale effect, as shown in Figure 2. Particle equilibrium position is obtained as a function of $Re$, and the critical $Re$, at which the particle equilibrium position starts to increase, is found in the range of $20 < Re < 30$ [27]. As an application of this lateral migration, a novel device is proposed for generating the particle beam axisymmetrically (3-D focusing) in a single capillary without sheath flows. Focusing of spherical particles was successfully made with a particle beam diameter of about 10 μm [28].

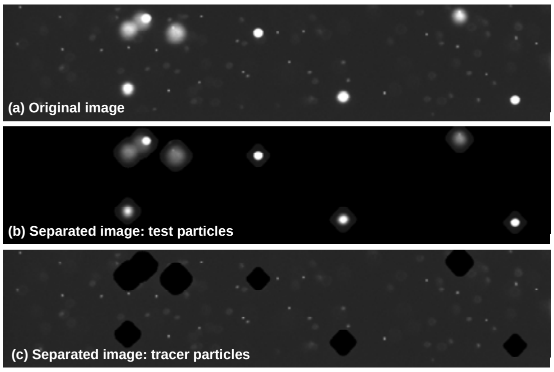


Figure 1 Particle image separation according to the particle sizes: (a) original particle image where both tracer and target particles are mixed for the simultaneous measurement, (b) 1-μm tracer particle image, and (c) 10-μm target particle image separated from the original image by using morphological operations.

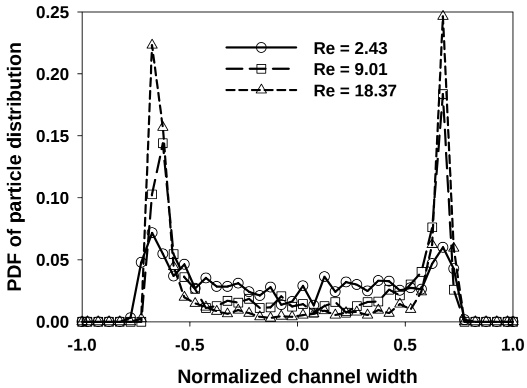


Figure 2 Spatial distributions of large test particles over normalized lateral positions at various *Re*'s for channel hydraulic diameter $D_h$ = 140.9 $\mu$m. Particle distribution is somewhat uniform across the channel cross section. However, as *Re* increases, particles drift away from the wall and away from the center of the channel.

Proposed device is expected to provide crucial solutions for simple and innovative 3-D particle focusing method to be applied to the MEMS-based micro-flow cytometry.

## 5.2 Liquid-liquid flow

The use of droplets in microfluidic devices has many advantages: need of only small sample volume, precise detection and ease of control in reaction kinetics. Droplet-based microfluidic devices perform numerous functions, such as rapid mixing, micro/nano particle synthesis, cell encapsulation, protein crystallization study and so forth. Further, one of the prospective applications employing droplets in microchannels is automatic control of fluid flows using logic gates such as AND, OR, XOR, NAND and NOR gates [29]. Here, we focus on the droplet controlling method in microfluidic platforms: generation, merging and breakup.

The first droplet generation in microfluidic platform was made by Thorsen et al. [30]. In accordance with the channel geometry, droplet generation can be performed in T-junction microfluidic channel, focusing channel or coaxial type channel. However, there are some limitations in the generation of droplets. For example, it is generally difficult to produce droplets of size less than about 10 μm. On the other hand, generation of Janus particles is currently of great interest, since Janus particle powered by the cells adherent to it have seen biomedical applications [31].

Droplet coalescence technique plays an important role in droplet-droplet mixing. In the work of Wang et al. [32], two droplets are generated and merged at the confluence region in their microchannels containing two T-junctions. Brouzes et al. [33] has employed two focusing channels to generate and merge droplets using an electrode. Above-mentioned techniques involve some complicated channel geometries, and droplets may not be generated sequentially and alternately. A novel microfluidic device has been proposed, which is capable of generating droplets alternately and merging them in pairs. This channel involves one cross junction with a diverging section attached to the downstream branch, where droplets are merged, so that mixing occurs inside the droplet.
In fact, flow visualization of moving droplet inside a microchannel provides a better understanding of this mixing phenomenon [34, 35]. Flow

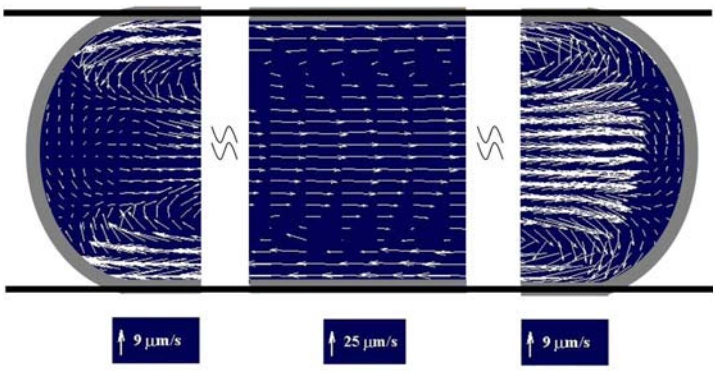


Figure 3 Velocity vectors at the center plane of the droplet through straight channel region.

patterns inside a droplet might be influenced by droplet speed, droplet size, contactability with walls, channel geometry and so forth. Finally, several methods of geometrically mediated passive breakup were reported [36]. In practice, the unit element, such as, generation, merging and breakup should be integrated on a single chip to realize the functionalities, e.g., mixing, particle synthesis and so forth.

## 5.3 Gas-liquid flow

Gas-liquid two-phase flow is encountered in a variety of engineering processes such as MEMS systems, electronic cooling and genetic engineering, bioengineering and so forth. Recent studies of gas-liquid flows have focused on two-phase flow regimes, void fraction and pressure drop in micro- and mini-channels. Interactions at the interfaces between gas, liquid, and solid introduce nonlinearity and instabilities [37]. Cubaud et al. [37] showed the flow map and the transition lines between flow regimes for 200- and 525-μm channels. Two-phase flow patterns, void fraction and pressure drop have been studied in a circular channel [38], in a single trapezoid microchannel [39] and the converging and diverging microchannels [40]. Although these works have brought up some interesting findings about two-phase flow phenomena, more detailed database on two-phase structures and characteristics should be needed.

## 6. CONCLUSIONS

This paper reviews current experimental studies on the microscale flows which are uniquely different from those in macroscale. A general view has been made of the flow phenomena and the measurement techniques in conjunction with single phase flows and multiphase flows, encountered in micro-chips. Electrokinetics proves to be an essential technique for transporting fluids through microchannels. Optofluidics promises highly integrated photonic devices with a wide variety of applications. Solid particles transported through a microchannel exhibit lateral migration, i.e., cross-stream motion with respect to the fluid. The use of droplets in microfluidic platform provides various bioengineering applications. Flows in microscale fully reflect the transport phenomena in lab-on-a-chip devices that will bring further development in biomedical systems.

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