Particle Concentration Distribution Control Based on Shear Rate Gradient and Marangoni Convection in Microchannel

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Abstract. The application of the microfluidic chip to the immunoassay has many advantages such as high efficiency, low cost, and high integration. It is of great significance to understand the flow characteristics of fluids in microchannel, which can improve the efficiency and accuracy of detection. In this paper, the effects of microchannel structure on the particle concentration distribution in two-phase flow and the flow behaviour of near-wall layer are studied by microfluidic observation technique. Also, a kind of microchannel structure was designed to increase the particle concentration in the front-end of microfluidic.

1. Introduction

In recent years, with the rapid development of Point-of-care Testing (POCT), a variety of microfluidic chips have emerged. The microfluidic chip is based on microfluidic technology. The fluid handling, device manufacturing and sample detection concerns many basic disciplines such as fluid mechanics, surface interface mechanics, biological reaction and chemical modification. At present, microfluidic chips are mostly used for immunoassay. It is necessary to study the flow behaviour of complex fluids in microchannel.

The research on fluid flow in microfluidic chips is generally divided into three aspects: theoretical analysis, experimental exploration and numerical simulation. Theoretical analysis is based on the basic theory of fluid mechanics, in which appropriate theoretical models are established according to the flow characteristics of fluids. Experimental research focuses on relative parameters such as velocity, pressure and particle concentration distribution in microfluidic chip systems. Numerical simulation is based on commercial software of fluid mechanics.

In the application of immunoassay, increasing the detected particle concentration in the front-end of two-phase flow can improve the efficiency and accuracy effectively. This research studied the approaches to improve the particle concentration distribution within meniscus in a microfluidic chip by adjusting the two-phase behaviour of near-wall layer. Several kinds of microchannel structures were designed to control the particle concentration distribution of two-phase flow in microchips.

2. Materials and methods

2.1. Observation platform of microfluidic

The observation platform of microfluidic is consisted of inverted fluorescence microscope, CCD and automatic objective table (Figure 1). Nanoscale antigenic molecules modified with fluorescent particles are applied in POCT. Antigenic molecules react with antibody coating in the detection area.
The nanoscale particles are enriched in the detection area and emit a fluorescent signal. The particle concentration in the detection directly determines the intensity of fluorescent signal, which determines the lower limit of detection of microchip.

![Detection Area](image1)

**Figure 1.** Observation platform of microfluidic.

### 2.2. Microfluidic chip

A new microfluidic chip structure is put forward in this research, which is low-cost and simple to manufacture. The chip consists of a three-layer structure (Figure 2). The material of the upper layer and the bottom layer is PMMA, which is hydrophilic material. The middle layer is a kind of double-sided tape with thickness of 80μm. It is hollowed out as the flow channel. So the height of channel is 80μm, which reaches the scale of microfluidic. The upper layer has an inlet and an outlet. The flow area of fluid can be limited by the micro-groove on the bottom layer, because the fluid in microchannel is driven by the capillary force.

![Structure of microfluidic](image2)

**Figure 2.** Structure of microfluidic chip.

### 2.3. Driving force

In the experiment, the fluid is driven by capillary force. According to the Laplace Capillary Pressure Formula:

\[ p \sim \frac{2\gamma}{R} \]

(\( \gamma \): Surface Tension, \( R \): Capillary Radius) Capillary pressure will decrease when the capillary radius increase. So we can limit the flow area of the fluid by the micro-grooves on the bottom layer. So the shape of micro-grooves is the shape of microchannel.
3. Results and discussion
Firstly, we set a lateral micro-protrusion on one side of the microchannel. The purpose is to speed up the flow of particles near the wall surface. The flow process is shown in Figure 3.

![Figure 3](image1)

**Figure 3.** The effect of micro-protrusion on particle concentration distribution. (a) before the fluid passed by the micro-protrusion. (b) after the fluid passed by the micro-protrusion.

According to the result of observing, we find that the fluid maintained the characteristics of laminar flow very well. Before the fluid passed by the micro-protrusion, the front-end of meniscus had a low particle concentration, and no convergence occurred. When the fluid passed by the micro-protrusion, the fluid near the wall speeded up. Finally, lots of particles gathered at the front-end of the fluid meniscus. And the particle concentration of the front-end of fluid got to a high level.

Based on this phenomenon, we set the micro-protrusion on both sides of microchannel to make it more effective. With this structure, the particles near the wall on both sides of microchannel can speed up and gather at the front-end. The flow process is shown in Figure 4.

![Figure 4](image2)

**Figure 4.** The Effect of Micro-protrusion on Both Sides of Microchannel. (a) Low concentration at the front-end of the fluid. (b) High concentration at the front-end of the fluid.

We explain this phenomenon as follows.
Under the condition of laminar flow characteristics, according to the Flow Continuity Equation, the fluid flow rate will be accelerated at smaller cross-sectional area to keep the fluid rate equivalent. The acceleration of the flow rate begins with the boundary layer, which increase the shear rate of boundary layer. Then it drives the fluid of the adjacent layer to accelerate under the action of shearing force. The shear rate between the apexes of the two micro-protrusions is shown in Figure 5. The fluid in the channel forms a velocity gradient from the boundary layer to the central of microchannel. It caused that in the front-end of fluid, the particle concentration in boundary layer is higher than central. And the surface tension in central is higher than in boundary layer because of the concentration distribution. So, the surface tension gradient is formed in the front-end of fluid. And particles will flow to the central part under the surface tension gradient. This phenomenon is called Marangoni Convection. Therefore, increased shear rate of boundary layer and Marangoni Convection phenomenon makes more particles gather at the front-end of the fluid. The schematic diagram of fluid flow is shown in Figure 6.

![Figure 5. Shear rate schematic diagram.](image)

![Figure 6. Flow process schematic diagram (Thicker streamlines represent higher speeds).](image)

![Figure 7. Detected particles gather at the detection area.](image)
In immunoassay, it’s hoped that the detected particles stay at the detection area for a period of time to improve the accuracy and efficiency. Therefore, the evolution of the above structure was made. The triangular micro-protrusions are changed to rectangular micro-protrusions, and a transverse groove is sculptured in the channel. So, the fluid is blocked by the change of capillary force temporarily. The particles are also blocked in this area temporarily because of the concentration phenomenon (Figure 7). And this area will be used as the detection area in immunoassay.

4. Conclusion
When microfluidic chips are applied to immunoassay, it’s hoped that detected particles can gather at the front-end of sample and stay at the detection area for a short time. It can be achieved by designing a special microchannel structure. In this research, an observation platform of microfluidic was built to study the influence of microchannel structure on two-phase flow. And it is confirmed that the micro-protrusions with a transverse groove structure was effective.

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