전자기장을 이용한 마이크로시스템에서의 유동제어

강인석, 윤병준
포항공과대학교 화학공학과/기계.산업공학부

Electromagnetic Flow Control in Microfluidic Systems

In Seok Kang, Byung Jun Yoon
Dept. of Chem. Eng./Div. of Mech. Eng., POSTECH

Introduction

Recently microfluidic systems are of great interest to many researchers because of several advantages in heat and mass transport over conventional systems [1]. For successful design and operation of such microsystems, the control of microfluids is the key and great efforts have been done to find effective means of control. In the present talk, we are concerned with the control of microfluids by using the electromagnetic fields. But the main focus will be given in this extended abstract to the electrostatic force due to the space limitation.

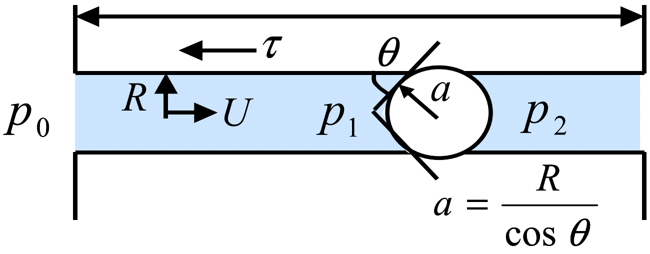
Under electric field, a common linear isotropic fluid is subject to the force

$$f^{(e)} = \rho_f E - \frac{E^2}{2} \nabla \varepsilon$$

where the first term is the force on the free charges and the second term is due to the force on the polarized charges [2]. The electro-kinetic phenomena, which includes electro-osmosis and electrophoresis, are mainly due to the free charge effect. On the other hand, the dielectrophoresis is in the second category. Here we want to introduce several ways of control of microfluid flows by using the electrostatic forces after briefly mentioning the characteristics of microfluidic systems.

Characteristic scales in microfluidic systems

The characteristics of microfluidic systems can be best recognized by considering the characteristic scales. To do that, let us consider first the pressure driven flow in a capillary shown below. If we consider the typical flow parameters such as $L = 0.1\,m$, $\gamma = 10^{-1}\,N/m$,



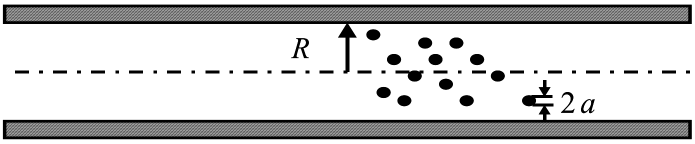
$\mu = 10^{-3}\,kg/m\cdot s$, $U = 10^{-2}\,m/s$, the pressure drops and the surface tension stress are as shown in Table 1. In the table, τ_c is the characteristic tangential stress at the wall. As we can see in the table, the pressure drop is inversely proportional to the square of radius and increases drastically if the same velocity is to be maintained. Therefore, if we want to use the same pressure drop, the velocity decreases drastically.On the other hand, that is not the case for the surface tension driven flow.

Table 1. Characteristic pressure drops and surface tension stress in micro-capillary.

$R(m)$	10^{-3} (1mm)	10^{-4} (100 μm)	10^{-5} (10 μm)	10^{-6} (1μm)
$\tau_c\,(N/m^2)$	2×10^{-2}	2×10^{-1}	2	2×10
$\Delta p\,(N/m^2)$	4	4×10^{2}	4×10^{4}	4×10^{6}
$\frac{2\gamma}{R}\,(N/m^2)$	2×10^{2}	2×10^{3}	2×10^{4}	2×10^{5}

The surface tension stress is inversely proportional to the radius and becomes very large as the radius decreases and it may be used as the driving force for the micro-channel flow. For example, the surface tension may drive the micro-channel flow to the O(1cm/s) for the 10μm channel, and O(0.1cm/s) flow even for the 1μm channel.

Another important characteristics is for the diffusion process. Differently from the heat conduction process, the diffusion process is a slow process even for microsystems. That is the case especially for the diffusion process of particles of nano-meter or larger such as DNA particles. To appreciate this fact, let us consider the diffusion of particle of radius "a" as shown below.



If we apply the Stokes-Einstein diffusivity, $D=kT/6\pi\mu a$, to compute the diffusion timescale, $t_c=R^2/D$, for particles dispersed in water flowing in a channel of radius of 100μm, we have the result shown in Table 2.

Table 2. Typical diffusion timescales in a micro-channel

a	10 nm	1nm	0.1nm
$D\,(m^2/s)$	2×10^{-11}	2×10^{-10}	2×10^{-9}
$t_c\,(s)$	5×10^{2}	5×10	5

As we can see in the table, diffusion of particles takes a quite long time and this fact indicates the importance of efficient mixing even in microsystems. That is the case when we consider the dispersed system of particles.

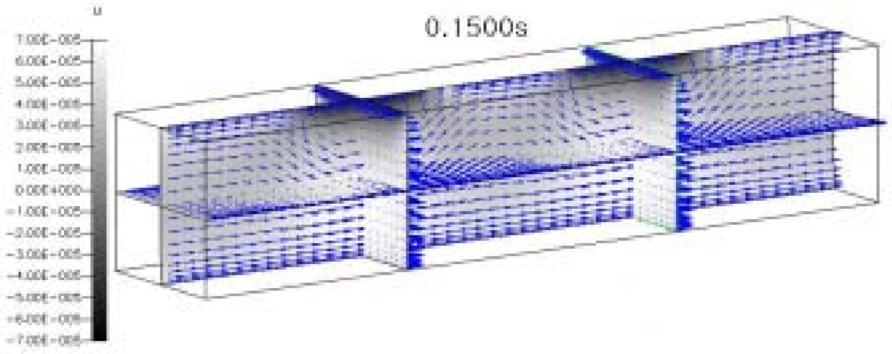
Electro-osmosis

One common way of driving fluid in a micro-channel is based on the electro-osmosis. Electro-osmosis is nothing but the use of electrical force exerted on the free charges dispersed in the electrical double layer near the charged surface. When the charged surface has the zeta-potential ζ, the flow generated outside the double layer is

$$u_\infty = -\frac{\varepsilon\zeta}{\mu}E_\infty .$$

However, the flow generated by the electro-osmosis is usually quite slow because the zeta potential is low (usually $\zeta \sim O(100mV)$) and the external electric field, E_∞, is limited by the electrolysis. So, the research interests in electro-osmosis are focused to how to control the zeta potential and how to maximize the applied potential without inducing electrolysis.

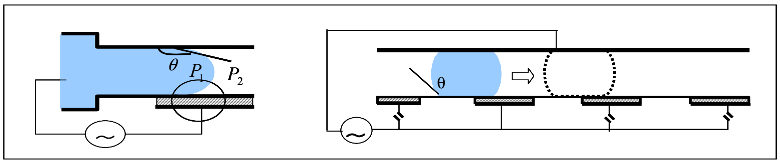
Regarding the first problem, there has been a considerable progress. By using a similar idea as the solid-state field-effect transistor in electronics, a very useful idea has been developed for the control of zeta potential [3]. Incorporating this nice idea, the methods of efficient mixing have been devised. From the formula for the electro-osmosis velocity, we can imagine a certain mixing strategy. In the following figure, electro-osmotic flow is shown for the channel of which the top layer has locally positive zeta potential while the bottom layer is negatively charged. We can clearly see the circulating flows near the top layer, which is expected to improve the mass transfer efficiency. This idea has been further developed to generate chaotic mixing. Recently Qian and Bau showed that chaotic mixing can be induced by using the time-periodic zeta potential [4]. Of course, their idea is based on the field-effect flow control.

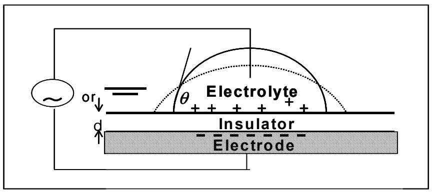


Electrowetting

As mentioned in the section of characteristic scales, the capillary force may play a major role.

Thus it would be very nice, if we may control the surface tension as we want. In that direction, we have a nice idea called "electro-wetting". By applying strong electric field across the dielectric layer, we collect the charges near the fluid-solid interface which in turn changes the fluid-solid interfacial free energy. The free energy change results in the contact angle change via the force balance at the triple point. The change of contact angle is predicted by the Young Lippmann equation



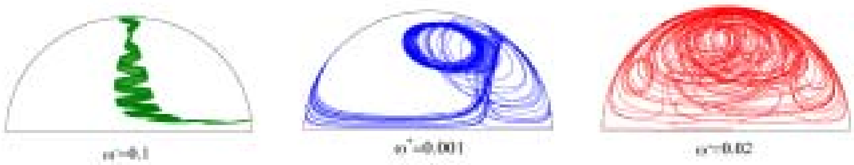


$$\cos\Theta(V) = \cos\Theta(0) + \frac{\varepsilon}{2d\gamma_{LV}} V^2$$

where ε and d are the electrical permittivity and the thickness of the dielectric (insulating) layer between the fluid and the external electrode, and γ_{LV} is the interfacial tension of the vapor-liquid interface. Since the contact angle change has a significant effect on the flows in micro-channels, electro-wetting has drawn much attention of researchers [5]. Nevertheless, the basic understanding on the fundamentals of the phenomena is still far from being complete and awaits the challenge of bright researchers. One of such unresolved problems is the explanation of contact angle saturation [6].

Dielectrophoresis

As mentioned in electro-osmosis, the applied potential is limited by the electrolysis. But in the case of dielectric liquid, we do not have to worry about that and we may apply very strong field to induce various interesting electrohydrodynamic(EHD) phenomena. One of such phenomena is the generation of electrical stress at the interface, which results in the flow to satisfy the continuity of tangential stress across the interface. The basic idea underlying this interesting phenomenon was discussed earlier in the classic paper by Melcher and Taylor [2]. Recently, the same idea has been incorporated with the chaos theory for devising a way rapid mixing of microfluids [7].



Remarks

Due to the space limitation, many other interesting problems have not been touched in this extended abstract. Those problems will also be discussed in the talk.

References

1. D. R. Meldrum and M. R. Holl, Science, Vol 297, pp. 1197-1198, 2002
2. J. R. Melcher and G. I. Taylor, Ann. Rev. Fluid Mech., Vol 1, pp. 111-146, 1969
3. R. B. M. Schasfoort, S. Schlautmann, J. Hendrikse, A. van den Berg, Science, Vol 286, pp. 942-945, 1999
4. S. Qian and H. H. Bau, Anal. Chem., Vol 74, pp. 3616-3625, 2002
5. C. Quilliet and B. Berge, Current Opinion in Colloid and Interface Science, Vol 6, pp. 34-39
6. M. Vallet, M. Vallade and B. Berge, Eur. Phys. J. B., Vol 11, pp. 583-591, 1999
7. S. M. Lee, D. J. Im and I. S. Kang, Phys. Fluids, Vol 12, pp. 1899-1910, 2000