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The EDL Effect in Microchannel Flow: A Critical Review

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Abstract

Microchannels are currently being used in many areas and have high potential for applications in many other areas. The application areas include Micro-Electro-Mechanical Systems (MEMS), microfuidics such as microchannel heat sinks for cooling micro-chips and laser diode arrays, Lab-On-Chip devices for chemical and bio-medical analyses, biotechnology, telecommunications, metrology, computer technology, office equipment and home appliances, safety technology, process engineering, robotics, automotive engineering and environmental protection and micro fluid pumps, etc. In this paper, a bibliographical review of the electric double layer effect in microchannels is presented. The effect of different parameters such as friction coefficient, Nusselt number, aspect ratio on the performance of microchannel with EDL is critically reviewed. The available numerical and experimental works quoted in the open literature are critically analysed in order to highlight the EDL effect in microchannel flow.

Keywords

Microchannel, Electric double layer, Microfluidics, Zeta potential

1. Introduction

Due to the rapid development of Micro-Electro-Mechanical Systems (MEMS) and microfuidics such as microchannel heat sinks for cooling micro-chips and laser diode arrays, Lab-On-Chip devices for chemical and biomedical analysis, and micro fluid pumps, etc., it is highly desirable to understand the fundamental characteristics of liquid flow in microchannels. It has been known that flow behaviour in microchannel is quite different from that in macro-pipeline. One of the most significant differences is that the flow rate of liquid in microchannel is less than that calculated based on conventional theory of fluid dynamics in the same pressure gradient. As dimensions of microchannel shrink, an additional flow resistance is generated to decrease the flow rate in microchannel. It is commonly believed that the physical interaction of insulated solid wall and electrolytic liquid is a main source of additional resistance in microchannel. Microchannel, with its high area to volume ratio and low liquid mass has a great potential in area heat transfer and bio-engineering. The effects of solid-liquid interface that can be ignored safely in macro flows become important in microchannel flows because of the large ratio of interfacial layer thickness to channel. The important microscale effects include the variation of electric potential near a surface Electric Double Layer (EDL), boundary slip, roughness, apparent viscosity. Electric double layer (EDL) effect has been proven to have significant effect in microchannel flow.

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2. Description of EDL

The electrically neutral solution contains an equal number of positively charged ions and negatively charged ions. While contacting an aqueous solution, most solid surfaces carry electrostatic charges or have a electrical surface potential. However, the electrostatic charges on the solid surface attract the counter-ions in the liquid. The concentration of counter-ions near the solid surface is higher than that in the bulk liquid far away from the surface. The concentration of co-ions near the surface is lower than that in the bulk liquid far away from the surface due to electric repulsion. Therefore, there is a net charge in the region close to the surface. This charge balances that on the surface. The surface and the layer of liquid containing the balancing charge is called the Electric Double Layer [12].

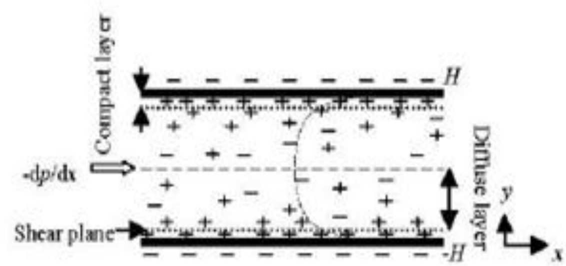

Fig. 1 The EDL, the compact and diffuse layers in parallel microchannel [You and Guo, 2010]

Next to the charged surface, there is a layer of immobile ions that are strongly attracted to the surface. This layer is called the compact layer, normally about several Angstroms thick. The potential distribution in the compact layer is mainly determined by the geometrical restrictions of the ion and molecule sizes, the short-range interactions between ions, and the wall and the adjoining dipoles. From the compact layer to the channel central line, the net charge density is gradually decreased to zero. The mobile ions in this region are less affected by the electrostatic interaction. This region is called diffuse layer. The thickness of diffuse layer depends on the bulk ionic concentration and electrical properties of the liquid, usually ranging from several nanometers for high ionic concentration solutions up to several microns for pure water and pure oils. The boundary between the compact layer and the diffuse layer is called the shear plane. Generally, the electrical potential at the solid-liquid interface is default to be measured directly. The electrical potential called the zita potential at the shear plane can be measured experimentally, which is considered as an approximation of the surface potential in most electrokinetic models [12].

3. Available Literatures

In this paper, a bibliographical review of the electric double layer effect in microchannels is presented. The effect of different parameters such as friction coefficient, Nusselt number, aspect ratio on the performance of microchannel with EDL is critically reviewed. The available numerical and experimental works quoted in the open literature are critically analysed in order to highlight the EDL effect in microchannel flow.

First researchers in this field, Mala et al. [1] have investigated the interfacial electrokinetic effects on characteristics of liquid flow through a microchannel between two parallel plates. Experiments are conducted to study the effects of electric double layer (EDL) on flow characteristics with different potassium chloride concentrations in water and with different plate materials. Microchannels with a height ranging from 10-280 µm are used in the measurement. A mathematical model has been developed for steady state liquid flow with the consideration of EDL effects. The predicated volume flow rates agree well with the measured data. The effects of the EDL field, the ionic concentration and the channel size on the velocity distribution and friction factor are also discussed. However, there is an ambiguity point about a backflow in the liquid velocity distribution near the channel wall by applying the ECB model. The backflow cannot be confirmed by their experimental results. Further, Mala et al. [2] have solved the two-dimensional, non-linear Poisson-Boltzmann equation in two ways: (i) analytically with the use of Debye-Huckel approximation; and (ii) numerically to obtain a complete solution without any assumption. The EDL potential distributions have been calculated by using two different solutions and are compared. They have observed that the linear solution may significantly overestimate the electric potential near the channel wall and in the corner regions, except for small zeta potential cases. The micro tube experiments of Mala and Li [3] indicate that there is an early transition from laminar to turbulent flows for Re > 112-338. Pointing at a plausible EDL effect, they have clearly stated that “there is an early transition from laminar to turbulent flow, and the range of critical Reynolds number varies somewhat, depending on the diameter and the material of the wall”.Ren et al. [4] have examined the magnitude of the additional flow resistance caused by the electrokinetic effect in microchannels. De-ionized ultra-filtered water and aqueous KCL solutions of two different concentrations are used as the testing liquids. Flow measurements are conducted in three silicon microchannels with a height of 14.1, 28.2 and 40.5 µm, respectively. It has been found that the measured the pressure gradient for pure water and the low concentration solution are to be significantly higher than that without eletro-viscous effect at the same Reynolds number. Such a difference strongly depends on the channel’s height and the ionic concentration of the liquids. The flow-induced streaming potential has also measured and the data confirm a higher electro-viscous effect on the flow of pure water and low concentration KCL solution. They have found a good agreement of the experimental results with the prediction of a theoretical electro-viscous flow model. Ng and Poh [5] have studied the flow and heat transfer characteristics of microchannels for developed 2-D flow field, with different bulk ionic concentration, zeta potential and the aspect ratio (AR) of the channel. Tardu [6] have investigated the effect of the electrostatic double layer (EDL) on the linear hydrodynamic stability of microchannel flows. It is shown that the EDL destabilizes the Poiseuille flow considerably. It is observed that the critical Reynolds number decreases by a factor when the nondimensional Debye-Huckel parameter (k) is around ten. Thus, the transition may be quite rapid for microchannel of a couple of microns heights in particular when the liquid contains a very small number of ions. The EDL effect disappears quickly for $k \geq 150$ corresponding typically to channels of heights 400 μm or larger. Tardu [7] has further shown that the microchannel flow under the electric double layer (EDL) effect is inviscidly unstable. A classical Orr-Sommerfeld analysis has revealed that the critical Reynolds number of the primary (linear) instability may decrease by a decade, provided that the liquid contains a very small amount of ions and is associated with large enough zeta potential and low continuity/viscosity. When the EDL layer is thick, the inflexion point moves away from the vioscous near wall region, and the inviscid instability mechanism becomes more dominant. The EDL modes are slower than the Poiseuille ones and the spectrum of the eign values shows its strong destabilizing effect. There are some strong arguments suggesting that the nonlinear stability mechanism under EDL effect is more severed compared with the macroscale flow. This study suggests that early transition in microchannel flows is plausible and can be checked through well controlled experiments. Tardu [8] has studied the effect of of the electric double layer (EDL) on the linear stability of Poiseuille planar channel flow. It has shown that the EDL destabilizes the linear modes, and that the critical Reynolds number decreases significantly when the thickness of the double layer becomes comparable with the height of the channel. First results coming from direct numerical simulations on the non-linear effects show that the by-pass transition is much more rapid in the presence of EDL. Several questions remain however unanswered such as the surface conduction effect on EDL. Lei and Jian-Kang [9] have numerically solved Poisson-Boltzmann equation for EDL and Navier-stokes equation for liquid flows to investigate the resistance effect of electric double layer on liquid flow in microchannels. The resistance effect of electric double layer has been estimated by an electric resistance number, which is found to be the proportional to the square of the liquid dielectric constant and the solid surface zeta potential and inverse-proportional to the liquid dynamic viscosity, electric conductivity and the square of the channel width. They have proposed an "electric current density balancing" (ECDB) condition to evaluate the flow-induced streaming potential, instead of conventional "electric current balancing" (ECB) condition which may induce spurious local bacflow in neighbourhood of the solid wall of the microchannel. Flow rate loss ratio and velocity profile are given to demonstrate the resistance effect of electric double layer in microchannel. Tan et al. [10] have studied the effect of aspect ratio with EDL in 3-D developing flow in microchannel. Parameters such as friction coefficient and Nusselt number are used to determine the performance of microchannel. Nernst and Plank model are used to model the EDL effect. They have found that the decrease in aspect ratio is resulted with an increase in the Nusselt number values. Ng and Tan [11] have used two EDL models coupled with Navier-Stokes equations to compute a 3-D developing microchannel flow. The Poisson-Boltzmann model (PBM) has been proven to be a promising tool in studying the EDL effect for developed microchannel flow, with respect to its accuracy and efficiency. Nernst-Planck model (NPM), with its two extra partial differential equations (PDEs) to predict the ion-concentration distribution, has reported to be a more appropriate model for developing microchannel flow through increased RAM and CPU are needed as compared to the PBM. The governing equations for both model are discretized for developing rectangular microchannel flows in Cartesian-coordinates. An additional source term, related to the electric potential, resulting from the EDL effect is introduced in the conventional z-axis momentum equation equation as a body force, thereby modifying the flow characteristics. A finite-volume scheme is used to solve the PDEs. The discrepancy in the results predicted by the two models is found to be more dominant in the near-wall region and not in the mainstream region. However, the performance of the microchannel has significantly been affected by the EDL effect. An increase in Schmidt number will lead to decrease in friction coefficient. A 3-D analysis has been concluded to be important and necessary for investigating the EDL effect in microchannels. You and Guo [12] have investigated the effects of the Electric Double Layer (EDL) on the liquid mean flow and the flow stability in microchannels by solving the Poisson-Boltzmann equation. The models of the traditional streaming electric current balance (ECB) and streaming electric current density (ECDB) are applied to determine the electrical streaming current. The numerical results show that the electrical streaming current backflow in the ECB model near the wall can be removed by using the ECDB model, which is suitable to study the effects of the EDL on the mean flow and the flow stability in microchannels. The flow is found more unstable if the ECDB model is applied. Jamaati [13] have presented an analytical solution for pressure-driven electrokinetics flows in planar microchannels with velocity slip at the walls. The Navier-Stokes equations for an incompressible viscous fluid have been solved along with the Poisson-Boltzmann equation for the electric double layer. Analytical expressions for the velocity profile, average electrical conductivity, and induced voltage are presented without invoking the Debye-Huckel approximation. It is known that an increase in the zeta potential leads to an increase in the flow-induced voltage; however, it is demonstrated that the induced voltage reaches a maximum value at a certain zeta-potential depending on the slip coefficient and the Debye-Huckel parameter, while decreasing rapidly at higher zeta-potentials. They have observed that liquid slip at the walls can increase the maximum induced voltage very significantly. You and Gou [14] have investigated the effects of an electric double layer (EDL), boundary slip and their combined effects on the microchannel flow stability. Electrical current density balance (ECDB) model is used to compute the conduction current when the effect of EDL is considered. The modified N-S equations and Poisson-Boltzmann equation together with the ECDB model and Navier slip boundary are the theoretical basis for the present approach. The stability analysis considering the modification of EDL and boundary slip is built up by the small perturbation method. They have observed that the effect of EDL results in inflexion on the mean velocity profile near walls and destabilizes the stability of flow. On the contrary, the effect of boundary slip stabilizes the stability of flow. The effectiveness of boundary slip on the mean velocity and flow stability is influenced strongly by the effect of EDL. The effect of boundary slip can be disspeared when zeta potential is large enough. Das et al. [15] have presented the consequence of field-dependent solvent polarization in the electric double layer (EDL) electrostatic potential distribution, the effective EDL thickness in narrow nanofluidic confinements with thick EDLs. They have found that the EDL, formed at the interface between a charged substrate and an electrolyte solution, induces a large electric field spanning across few nanometer distances from the interface. As a result, a polar solvent like water gets polarized, making its relative permittivity a function of the EDL electric field. This affects the overall EDL electrostatic potential distribution and most importantly, leads to a significant reduction of the effective EDL thickness, with the extent of the reduction being dictated by the value of the field, independent EDL thickness, strength of the solvent polarization, and the substrate-liquid interfacial electrostatic potential. Such finding necessitates redefining the classical EDL thickness, which is of overwhelming significance in nanofluidic transport.

Liquid flows through microchannels have wide industrial applications, such as design of microfluidic systems and microheat sinks. As characteristic dimensions of channels decrease to micro ranges, the fluid flow behaviour in these microchannels is strongly influenced by the wall/interfacial effects. The flow characteristics are different from the normal situation described by the Nvier-Stokes equations. For example, Eringen [16] has proposed a theory that states that fluid flow in microchannels will deviate from that predicted by Nvier-Stokes equations. Tuckermann and Pease [17, 18] have investigated experimentally and theoretically the fluid flow through microchannels. They have found that the flow friction measurements are slightly higher than those predicted by the classical theories. Pfahler [19] has measured the friction coefficient in microchannels and found a significantly higher flow rate than expected for both isopropanol and silicon oil. His results indicate that polar nature of the fluid may play a role in the change in the observed viscosity. Choi et al. [20] have measured friction factor in microtubes of inside diameters 3 to 81 µm using nitrogen gas. They have found that for diameters smaller than 10 µm, the friction coefficient, product of friction factor and Reynolds number Re, is equal to 53 instead of 64. Harley and Basu [21] have measured the friction factor in channels of trapezoidal and square cross sections. They have found experimentally that the friction coefficient ranged from 49 for square channels to 512 for the trapezoidal channels. Peng et al. [22, 23] and Wang and Peng [24] have found experimentally that fully turbulent convective heat transfer is reached at Re = 400 to 1500. They have also observed that transitional Re diminishes as the size of the microchannel decreases. Rice and Whitehead [25] have studied the effect of the surface electrical potential on liquid transport through narrow cylindrical capillaries with the assumption of the small surface electrical potential. Levine et al. [26] have extended the Rice and Whitehead model to higher surface electrical potential for flows in cylindrical capillaries. Mala et al. [27] have studied the surface potential effects on flow characteristics in microchannels theoretically. It has been concluded that the effect of the electric double layer (EDL) on velocity distribution, friction coefficient, apparent viscosity, and heat transfer cannot be neglected in microscale fluid flow and heat transfer. Most solid surfaces bear electrostatic charges; i.e., an electrical surface potential. If the liquid contains very small amounts of ions, the electrostatic charges on the solid surface attract the counterions in the liquid to establish an electric field. The arrangement of the electrostatic charges on the solid surface and the balancing charges in liquid is called the EDL. Microfluidic systems have become increasingly attractive in a variety of engineering fields such as micro power generation and biochemical processing due to recent advances in microfabrication technologies. Precise control of such systems often requires a complete understanding of the interaction between fluid dynamics and the electrical properties of the microchannel; usually referred to as electrokinetics. In every electrokinetic application, finding the accurate distribution of the prevailing electric potential is of fundamental importance, which is governed by the non-linear Poisson-Boltzmann (P-B) equation in many cases. The linear form, following the Debye-Huckel (D-H) approximation, is only valid when the electrical potential is small compared to thermal energy of the ions. Different methods have been developed for the solution of the P-B equation. Exact solution of the P-B equation between two dissimilar planar charged surfaces is presented by Behrens and Borkovec [28] in terms of Jacobian elliptic functions. A similar approach has been employed by other researchers [29-32] for the evaluation of streaming current and electrokinetic energy conversion. Although this semi-numerical scheme is capable of solving the non-linear P-B equation, the resulting potential field cannot be expressed in a closed form solution, and therefore, it is not suitable for fully analytical investigations of the flow field. There have been several attempts to extend the analytical solution of the P-B equation for a single flat plate [33] to a planar microchannel with overlapping electric double layers (EDLs) [34-37]. However, such a treatment requires a detailed examination of the key parameters, which has not received proper attention in the literature. Dutta and Beskok [37] have derived an analytical expression for the velocity distribution in mixed electro-osmotic/pressure-driven channel flows based on Hunter's solution [33] for a flat plate. Min et al. [36] have studied the electro-pumping effects in electro-osmotic flows and determined the flow rates both analytically and experimentally. In their analytical treatment, Hunter's solution is developed. Oscillating flows in two-dimensional microchannels are analytically studied by Wang and Wu [34]. Their analysis is also based on Hunter's non-linear P-B solution and velocity profiles are presented for thin EDLs; however, the conditions for the validity for the solution are not clearly discussed. For highly overlapped EDLs, the use of the Boltzmann equation may lead to inaccurate potential distributions as indicated by Qu and Li [38]. Yet, there are various studies involving strongly overlapped EDLs ($K<10$) in which the P-B equation has been used [28-30]. For these cases, a new set of governing equations and boundary conditions such as the charge regulation model have been proposed [38-41], where chemical equilibrium conditions in conjunction with overall charge and mass conservation of the ionic species are considered. However, the analytical treatment of these models is limited by the Debye-Huckel approximation [38, 39]. Experimental studies, which re well reviewed by Nato et al. [42], have shown the existence of significant liquid slip at the walls when low-energy (hydrophobic) surfaces are involved even at low Reynolds numbers ($Re<10$) [43-47]. Although slip is expected to occur preferentially over very smooth and poorly wetting surfaces, experiments on a variety of solid/liquid interfaces provide evidence of slip lengths up to micron levels in microchannels. [44, 45]. Slip over rougher walls in attributed to the presence of nano-bubbles trapped on the surface [42], and it is reported that hydrophobic surfaces enhance bubble formation [48].

Recent molecular dynamics simulations of water/solid interfaces indicate that the charged distribution is well approximated with the Poisson-Boltzmann equation in the presence of hydrodynamic slip [49]. Despite the fact that surface charge is expected to promote wetting and reduce slip, experimental observations indicate the presence of significant slip even highly charged surfaces [31]. Furthermore, Bouzigues et al. [50] have presented experimental evidence for slip-induced amplification effects on the wall zeta-potential. It is demonstrated that slip leads to amplification of the zeta-potential by a factor of ($1+\beta K$), which indicates considerable increase in zeta-potential especially for larger K. This fact is also confirmed by the theoretical model presented by Chakraborty [51] based on the free energy for binary mixtures. Slip effects have been studied in microchannel flows, and the results indicate an increase in the mass flow rate and considerable reduction in the applied voltage for electro-osmotic flows [52]. Recenrtly, Park and Choi [53] and Park and Kim [54] have studied electro-osmotic flows through hydrophobic microchannels employing an experimentally determined slip velocity at the walls and developed a method for the simultaneous evaluation of the zeta-potential and slip coefficient.

Electrokinetic flows have been mostly studied in the context of electro-osmotic flows, which involve applied electric fields but no externally applied pressure gradients. In electro-osmotic flows, the induced electric potential due to fluid motion is negligible in comparison to the applied electric potential. On the other hand, in purely pressure-driven flows, a significant electric potential can be generated due to the motion of charged fluid particles, which is called the streaming potential. This potential serves as the basis for possible micro-scale power generators or batteries. The efficiency of such systems is generally low and depends on the fluid properties and the channel geometry [29, 55-57]. Large efficiencies can be achieved when the overlapped EDL regime is considered. However, as mentioned earlier, the P-B equation is not consistent with the true physics of such problems, despite the fact that it has been used by several researches [28-30].

Rather limited information is available in the literature regarding the zeta-potential effects on the streaming potential in purely pressure-driven flows [58-60]. Mirbozorgi et al. [60] have performed analytical and numerical studies on the induced potential in planar microchannels. Their results show that, in fully-developed flow, the induced potential increases linearly along the microchannel at a fixed zeta-potential. However, the induced voltage varies in a non-linear manner with zeta such that a maximum voltage is developed with a certain zeta-potential. They have also used the Debye-Huckel approximation in their analytical treatment, which limits the validity of their results to relatively small zeta-potentials. Similar behaviour has been reported for flows with variable properties by the numerical study of Hwang and Soong [59]; however, the effect of slip on the induced voltage has not been considered in the above mentioned studies. Slip effects on the streaming potential have been studied in the context of electrokinetic energy conversion efficiency in nanochannels with highly overlapped EDLs. Davidson and Xuan [29] have numerically studied the electrokinetic conversion efficiency with slip in nanochannels using the Jacobian elliptic function for the potential field. A similar study has been performed by Ren and Stein [31], where strong enhancement in the energy conversion efficiency has been found in the presence of slip. It must be emphasized that these studies have been carried out for cases where an external load is applied and the net ionic current is not zero, in contrast to seeking the maximum induced voltage with zero net ionic current.

4. Problem domain, Analysis and Conclusion

A growing need to understand the electromechanics of systems with overlapping EDLs , and/or with very high ionic concentration, and/or with very zeta potential, has necessitated the underlying analysis. This review helps to understand the importance of the EDL effect on the flow characteristics of laminar flow in a microchannel. The microchannel performance based on the PBM prediction is evaluated and benchmarked with NPM. The discrepancy between two models is significant in the near wall region but not so in mainstream region. Thus, PBM is still an attractive model to compute the EDL effect in the microchannel, even when the flow is developing. The results available in literatures indicate that the appearance of EDL results in inflexion on the mean velocity profile near channel wall and destabilizes the flow stability. The effectiveness of boundary slip on the mean velocity and flow stability is influenced strongly by the effect of EDL. The effect of boundary slip is disappeared when the zeta potential is large enough. From the available literature, it has been observed that the analytical expressions are developed for the velocity field and the induced voltage without invoking the Debye-Huckel approximation. The models used are based on the non-linear P-B solution for an electrolyte over a single flat plate, which is extended to a planar microchannel. This approach has been previously employed for channel flows, while the precise validity conditions have not been thoroughly examined in the literature. In addition, the variation of electrical conductivity with zeta potential is not examined in detail. From the review of literatures it is clear that many researchers have performed the experimental and numerical work to understand the effect of EDL in microchannel flow. Experimental and numerical works for understanding of the effect of EDL on flow characteristics in microchannel is still lacking. Researchers have considered mainly

Newtonian fluid in their numerical investigation. The flow characteristics of non-Newtonian fluid in microchannel with EDL effect are very limited and there are huge scopes for further research work in this field.

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