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Chapter

Internal and External Influences on Hydro-Thermal Behavior of Micro-channel Flow

Naga Ramesh Korasikha, Thopudurthi Karthikeya Sharma, Gaddale Amba Prasad Rao and Kotha Madhu Murthy

Abstract

Microchannel flow is an effective solution for many engineering problems. Application of microchannels is found in various fields such as thermal management of electronics, micro-combustors, biomedical industries, MEMS. In microchannel flow, some internal and external influences such as surface roughness, electric and magnetic fields are very significant and commonly neglected in macro-scale flow. Early research works on microchannels stated that the conventional theories of macro-scale flow were not applicable for microscale flows. Finally, researchers are concluded that the deviation in conventional theories in the case of micro-scale flow is because of neglecting the internal forces, surface roughness, surface wettability, etc., which play a prime role in micro-scale flows. In this chapter, the behavior of microchannel flow under the internal and external influences is discussed. The heat transfer and hydrodynamic characteristics of microchannel flow under the external magnetic field and electric fields are presented. The effect of surface morphology, roughness, electro-osmotic effect, electrophoresis, internal heat generation, and analysis methods is discussed.

Keywords: microchannel flow, electronic cooling, MHD, surface roughness, surface wettability, electro-osmosis, electrophoresis

1. Introduction

With the rapid development of electronic technologies towards miniaturization and high power density, heat generation becomes a major problem in high-powered electronic systems, batteries, fuel cells, etc. High-temperature operation of these electronic devices reduces their performance, reliability, and life span, so thermal management has become the prime concern in modern electronic equipment. Researchers have developed various thermal management methods using compact heatsinks like mini-channel heatsinks, micro-channel heatsinks with forced and natural convection, flow boiling and phase change materials, etc.; according to the heat dissipation requirement, heat transfer modes were implemented. In the natural convection method, fluid was driven by buoyancy force generated by the temperature
gradient, and this was implemented for low heat dissipation applications. For large heat transfer requirements forced convection and flow boiling was used. Forced convection and flow boiling in microchannels are effective methods to deal with the immense heat dissipation requirement in modern electronics.

From the initial research on microchannel flows, there is uncertainty in implementing conventional theories of hydrodynamics and heat transfer to the micro, and mini channel flows. Some studies on microfluidics stated that the correlations applied for pressure drop in conventional channel flow were not valid for micro and mini channel flow. Finally, this ambiguity came to a concussion that the discrepancies in the outcomes when conventional theories are used for micro and mini channels are because of errors in channel measurements and neglected influences, which are significant microchannels flow.

The experimental study of J. Judy et al. [1] is evident that the uncertainties in the conventional flow theories are significantly influenced by the uncertainties in the diameter measurement, which may cause up to 20% discrepancy in Poiseuille’s number. In this analysis, from Poiseuille’s number data, it was observed that there is no distinguishable between the microscale and macroscale strokes flow. Bruno Agostini et al. [2] witnessed the 21% divergence in the friction factor due to the 3% error in estimating channel width and height. Apart from measurement errors, other possible causes for uncertainties are viscous dissipation, entrance effect, the influence of electric double layer and surface effects, etc. Some authors developed, advanced thermal characterization techniques for finding the probable sources of uncertainties in the microchannel flow [3]. Some external influences like electric field and magnetic field also show a noticeable influence on the hydrothermal behavior of the microchannel flow.

M.R. Akhtari and Nader Karimi [4] investigated the characteristics of microchannels with varying super-phobic surface roughness with four different micro-structured configurations. Outcomes of this work witnessed the decrease of Poiseuille number and Nusselt number with increasing the cavity fraction. They also reported that the triangular pattered structure showed the best performance among the four because in triangular patterned structure, the influence of shear-free interface on the drag reduction is more dominant than the reduction of heat transfer. Mohit Trivedi et al. [5] conducted a numerical study on electro-osmotic coupled pressure-driven flow of simplified Phan Thien Tanner fluids in a diverging micro-channel. They found that the velocity of the flow decreases moderately with the increasing the diverging angle when the other parameters were fixed.

Hang Xu [6] analyzed the mixed convection flow by buoyancy and pressure gradient in inclined micro-channel by considering the electric double layer effect and discussed the various parameters influence on the temperature distribution and velocity. It was noticed that the streaming potential raised with increasing the electrical-double-layer thickness and the zeta potential.

In this chapter, possible internal and external influences on microchannel flow are discussed (Figure 1). These influences can be also helpful to improve the heat transfer performance and development of innovative flow and heat transfer devices. Electro-osmosis was used in the development of electro-osmotic pumps, they have considerable advantages of no moving parts and less power requirement. Surface roughness of the channel has a considerable effect on the improvement of heat transfer. Surface wettability is also a significant parameter to enhance the boiling heat transfer. This chapter gives an overview of the recent works that have been done on electro-osmosis, surface roughness, surface wettability, external magnetic and electric field in micro-channel flow.
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DOI: http://dx.doi.org/10.5772/intechopen.105111

2. Internal influences

2.1 Electro-osmosis

Electro-osmosis refers to the movement of ionic fluid concerning the stationary charged surfaces with the development of an electric double layer (EDL) under the imposition of an external electric field [7–10]. Electro-osmotic actuated flow (electro-osmotic flow EOF) captured massive interest in the field of microfluidics because of its superior features of less pressure drop, no moving parts etc. Electro-osmosis is the modern pumping method for fluid transport and has advantages compared to the sure-driven flows [11, 12]. So much research work has been carried out on EOF-based micropumps and electronic cooling systems to analyze the thermo-hydraulic aspects [13]. V K Narla et al. [14] performed the theoretical analysis on EOF of nanofluid in curved microchannel. In this work, authors have studied the influence of Helmholtz-Smoulochowski velocity, inverse EDL thickness, Brinkman number, Joule Number, Curvature parameter, entropy generation and Nano particle concentration. It was found that the increasing inverse EDL thickness generates the flow acceleration in the microchannel upper region. The curved surface of the microchannel acts as the source of entropy generation. Schematic representation of pumping mechanism of electro-osmotic flow is presented in the Figure 2.

Michael O. Oni and Basant K. Jha [16] studied the viscous dissipation and Joule heating influence on the EOF in a vertical microchannel with asymmetric heating. Results of this work revealed that viscous dissipation and Joule heating reduces the temperature distribution and the asymmetric heating tends to increase the pressure gradient and induced electric potential. M Peralta et al. [17] was also examined the asymmetric zeta potential influence on the EOF of Maxwell fluid in parallel plate microchannel. They observed the fluctuations in the velocity profiles with increasing the angular Reynolds number and elasticity number because of viscous, elastic, electric and inertial forces in the flow.

An experimental and numerical study performed on the microfluidic chip witnessed the stable EOF on the super wettability surface [18]. M S Saravani and M Kalteh [19] conducted numerical study on combined pressure driven and electroosmotic flow of Newtonian nanofluid in the microchannel using Lattice-Boltzmann method. They have studied the influence of different parameters like slip coefficient, volume fraction of Nano-particles, Smolochowski velocity on the heat transfer. It was observed that the Nusselt number was decreases with increasing the pressure force at fixed electric field and Nusselt number was increases with increasing the electric field at fixed pressure force. Souvik Pabi et al. [20] investigated the hydrothermal and entropy generation characteristics of EOF in a hydrophobic
micro-channel. Schematic image of physical model developed by Souvik Pabi et al. shown in the Figure 3. It was found that the value flow velocity ($U$) reduces with rise in the viscoelectric coefficient ($f$). The Nusselt number was found to be enhanced under slip and percentage of enhancements achieved as 8.82% and 7.96% at the Brinkman number of $10^{-5}$ and 0.1 respectively. Variation of Nu with Peclet number ($Pe$) at different viscoelectric coefficient ($f$) and Brinkman number ($Br$) is presented in the Figure 4.

Edgar A. Ramos et al. [21] examined the EOF in rectangular microchannel by considering the temperature dependent absolute viscosity and slip boundary condition at the walls (Figure 5). In this study they implemented the asymptotic analysis by using the perturbation methods. The outcomes of this analysis revealed that the influence temperature depended viscosity and slip increases the flow rate in the microchannel. Jacky S.H. Lee et al. [22] studied the behavior of electro-osmotic flow in a cylindrical microchannel with non-uniform zeta potential distribution. Results of this study reveals that, the non-uniform distribution of zeta potential generates the various types of velocity profiles in both downstream and upstream sections. It was noticed that, flow circulation cannot be generated a simple step change, if such a change does not have polarity change of the surface charge. Various heterogeneous patterns with change in zeta potential polarity was observed to be able to produce different types of flow circulations.

Figure 3. Schematic image of the physical model developed by Souvik Pabi et al. [20].

Figure 4. Figure 5. Pumping Mechanism of electro-osmotic flow [15].
2.2 Electrophoresis

Electrophoresis is the phenomena of movement of charged particles in the colloidal solution under the influence of the imposed electric field. As a result of, applied electric field and viscous resistance imposed by the liquid on the colloidal particles, the stationary particles moves with constant velocity [23]. So many researchers has been working on the electrophoresis in straight and curved micro-channels with constant and variable cross-section by applying the uniform and non-uniform electric field [24–26]. Litao Liang et al. [27] performed the experimental demonstration on uniform straight rectangular microchannel with lateral migration in particle electrophoresis and developed an analytical model to predict the outcomes (Figure 6). The results of this work revealed that, the particle stream width at the exit of channel was noticed to be diminishes with the increment in either electric field or particle size and...
the predicted value of width of the steam through analytical model has good agreement with measured values.

P.H. Wiersema et al. [28] presented a correlation between the electrophoresis mobility and the Zeta potential of spherical shaped colloidal particles. They found that the correction for diminished values of dielectric constant in the double layer was negligible. Shizhi Qian et al. [29] performed numerical investigation on electrophoretic mobility generated in the convergent-divergent nanotube containing electrolyte solution with spherical charged particles by applying the electric field. Authors found that, when the nanotube wall was uncharged and the particle was charged the motion of the particle attained the noticeable acceleration and retardation as the particle moves in converging–diverging section in the direction of opposite electrode and achieved the maximum velocity at the throat. However, the mentioned effect is not always correct because when the charge density of wall of tube is of same sign and magnitude as the charge density of particle surface, the flow generated by the electrostatic force and the induced pressure gradient will reverse the direction of motion of particles. The schematic image of converging–diverging nano-tubes presented in Figure 7.

2.3 Surface effects

Surface of the fluid flowing channel have noticeable influence on the hydrothermal characteristics of the microchannel flow. Surface morphology, wettability, hydrophilic and hydrophobic behavior of the surface shows significant influence on the heat transfer [30]. Recent studies on surface effects on microchannel flow is presented in this section.

2.3.1 Surface roughness

Earliest investigations on the microchannel flows showed that the hydrothermal behavior of microchannel is differ from macrochannel. However, researchers concluded about this divergence as, some of the factors neglected in the macro scale shows significant effect on microscale and these factors are the reason for
discrepancies [1]. Surface roughness is an important factor which has considerable influence on microchannel flow. An experimental investigation done by Yuan Xing et al. [31] on microchannel surface roughness and witnessed the remarkable influence of roughness on heat transfer and hydraulic characteristics. At larger relative roughness, Nusselt number and the Poiseuille was found to be higher and the friction factor and Nusselt number increases with increasing the Reynolds number.
consistently. Benedikt Sterr et al. [32] performed the stochastic analysis on MCHS with random Roughness (Figure 8). It was revealed that the local surface height is inadequate to define the behavior of Nusselt number and the dependency of Nusselt number on various factors was increase with the value of roughness. The variation of normalized average Nusselt numbers, pressure drop and performance factor are depicted in the Figure 9.

Rahim Jafari et al. [33] conducted experimental analysis on flow boiling in microchannel to study the influence of surface roughness on micro-scale boiling. They found the 45% enhancement in heat transfer coefficient, when the roughness increased from 2.03 μm to 15.86 μm. Considerable increase of heat transfer during the phase change was obtained with low heatflux value at high roughness.
2.3.2 Surface wettability

Surface wettability is aptness of a fluid to spread over a surface. It is identified as an important factor in microfluidic devices, especially in case two-phase flows in microchannels, where the surface tension becomes presiding force as the channel size reduces [34]. Many researchers are focused on the influence of surface wettability on two-phase flow in microchannels. If water is considered, the characteristics of water droplets on a surface can be explored by surface energies and wettability. When surface energies are high, the water droplets area attracted towards the surface resulting low contact angle, it is called hydrophilic surface and in the reverse case surface is called hydrophobic surface [35]. Important findings of various researchers on surface wettability is discussed in this section. Figure 10 indicates the schematic representation of water contact angle on hydrophilic, hydrophobic surfaces.

Konstantinos Vontas et al. [37] studied the flow boiling in and hydrophobic surfaced microchannels under various heat fluxes and mass fluxes and observed the slug flow regime in the both cases. Authors revealed that liquid film and contact line evaporation are the prime heat transfer mechanism for hydrophilic and hydrophobic surfaces respectively. Prakash Rapolu and Sang Young Son [38] conducted an experimental analysis on geometry and wettability influence on pressure drop in 2-Phase microchannel flow and witnessed the rise in pressure drop with reducing the surface wettability (Figures 11 and 12). They also revealed that the effect of the capillary resistance on the pressure drop in a hydrophilic channel was comparatively less.
Ming Yu Zhou et al. [39] examined behavior of monodisperse poly n-isopropylacrylamide microspheres in microchannels with biphilic surfaces. Outcomes of this work disclosed that the mean fluid velocity in hydrophobic surfaced microchannel without microspheres is higher than hydrophilic surfaced microchannel. Wei Deng et al. [40] studied the bubble behavior and heat transfer in a boiling flow over the biphilic surfaces and found that at low heatflux values the bubbles prone to grow first on the hydrophobic surfaces because of low attractive force. Authors also stated that they noticed a different behavior of bubble characteristics at the wall temperature of 150 K and 200 K. Ali Heidarian et al. [41] conducted the hydrodynamic study on the nanofluid flow in the hydrophobic and super hydrophobic surfaced microchannel. Results of this study showed that the pressure drop of nanofluid flow in case of hydrophilic surface was increased by 74% and in case of hydrophobic surface was decreased by 47%. The wall shear stress was found to be reduced by 65%.

3. External influences

3.1 Magneto-hydrodynamics (MHD)

Magneto-hydrodynamics (MHD) is the study of behavior of an electrically conducting fluid under the magnetic field and it has many applications in engineering field including the cooling of liquid metals in nuclear reactors, design of MHD flow meters and MHD pumps etc. [42–44]. In the field of microfluidics, MHD is promising method for pumping applications because of its benefits of simple design,
no moving parts and less power consumption [45–48]. Chunhong Yang et al. [49] performed theoretical analysis on the thermal behavior of a incompressible MHD flow in a rectangular microchannel. In this study the cumulative influence of the Joule heating, viscous dissipation and electromagnetic coupled heat was considered. A gradual decrease of normal velocity was noticed with rising the Hartmann number (Ha) without implementing the lateral electric field. When lateral electric field was imposed, increasing-decreasing trend is observed for velocity and temperature but the Nu exhibited the adverse trend (Figure 13).

Velocity and temperature but the Nu exhibited the adverse trend.

Mehdi Kiyasatfar and Nader Pourmahmoud [50] studied the hydrothermal characteristics of non-Newtonian, conducting fluid flow in a square microchannel, imposed to the transfers magnetic field. In their study the decrease of velocity gradient was found near the wall with increasing the flow index of Power law which tend to decrease the Nu. Magnetic field showed the large influence on the velocity field, as Ha increases, maximum velocity was decreases and wall velocity gradient was increases. Nu variation with shear rate parameter for the dilatant fluids is presented in Figure 14. M.M. Rashidi et al.

Figure 13.
Lateral electric field influence on Nu with Br (K = 10). (a) Ha = 0.5. (b) Ha = 3 [49].

![Figure 13](image1.jpg)

Figure 14.
Nu variation with shear rate parameter for the dilatant fluids (Ha = 0) [50].

![Figure 14](image2.jpg)
[51] examined the mixed convective HT in sinusoidal microchannel with nanofluid flow under the influence of external magnetic field (Figure 15). From the results, improvement of average Nu and decrement in Poiseuille’s number was observed with increasing the concentration of nanoparticles. An enhancement of Nu and Poiseuille’s number was also noticed with increasing Ha at constant Re, Grashof number (Gr) and particles concentration. Basant Kumar Jha et al. [52] performed the magnetohydrodynamic analysis on natural convection flow formed in the micro-gap between two infinitely long parallel vertical plates. By the asymmetric heating of the plates, the natural convection is created between the plates in presence of the Hall current. The increase of fluid velocity was observed with the ratio of wall ambient temperature and rarefaction parameter.

3.2 Electro-hydrodynamics (EHD)

Electro-hydrodynamics (EHD) is the study of characteristics of electrically conducting fluid under the external electric field. The bulk fluid motion created due to the interactions between imposed electric field and the gradients electrical conductivity of the fluid is referred as the Electro-hydrodynamic (EHD) flow [53, 54]. In the field of microfluidics, EHD used for fluid pumping applications. Brian D. Storey [55]
conducted a numerical study on instabilities generated in microchannel flow between the two parallel plates due to the gradients of electrical conductivity of fluid. They also investigated the turbulence generated at low Reynolds number due to the instabilities in the flow by considering the electro-osmotic effect. Author found that the existence of shallow walls of the channel can modify the flow stability and flow characteristics remarkably. When walls are shallow with regard to the dimension of gradient of electric conductivity, the fluid motions are considerably suppressed and the wavenumber of instability increased. P. Zangeneh Kazemi et al. [56] investigated the performance of the EHD micro-pump under the influence of spacing of micro pillar electrode. Schematic representation of micropump with symmetric configuration of electrode is presented in Figure 16. Considerable higher pressure head was observed in case of micropump with asymmetric design compared to symmetric design of electrode under the equal applied voltage by consuming the lower power. The reduction in the spacing of the micro-pillar electrodes enhanced the performance of pump for the symmetric design, while diminished the performance for the asymmetric design.

Some researchers analyzed the combined effective applied magnetic field and electric field. Guillermo Ibáñez and Sergio Cuevas [57] investigated the electromagnetic interactions in the micro-channel by considering the influence of the Lorentz force generated by injected electric current and transvers magnetic field to diminish the entropy generation. Li Fengqina et al. [58] investigated the electro-magnetohydrodynamic flow in a microchannel with 3D corrugated walls. The flow in the present work was driven by a non-uniform electric field and uniform magnetic field. The effect of corrugations and Hartmann number (Ha) was analyzed by implementing the perturbation method. The results of this study reveal that maximum flow rate was achieved by increasing the Ha (magnetic field strength parameter).

Along with the mentioned influences, some other geometry-related effects like internal structure of the geometry, topology and internal fins etc., were also examined in some research works. Yongqi Lan et al. [59] performed the numerical simulation on effect of relative height and relative offset values of truncated and offset pin-fins on performance and entropy generation of MCHS. Enhancement of heat transfer and flow resistance was noticed in the MCHS with pinfins compared to the smooth MCHS. Increasing pinfin height ratio, increases the heat transfer and the flow resistance. Increasing the offset ratio also improved the heat transfer but extreme increase in offset ration leads to the decrease in heat transfer improvement. Prasenjit Dey et al. [60] conducted the experimental and numerical study on hydrothermal characteristics
of MCHS with bio-inspired novel fish scale structure. It was found that the fish scale structure can enhance the heat transfer compared to the plan structure. At 0.026 inclination angle of fish scale, friction factor was reduced by maximum 5% and Nusselt number increased by maximum of 14% compared to the plan surface structure. The performance evaluation factor was noticed as 1.75 at the inclination angle of 0.26 and Reynolds number of 1050. Xiaohu Li et al. [61] performed the topology optimization study on MCHS to augment its heat transfer performance by adopting iso-geometric analysis (IGA) approach. It was observed that the IGA approach produced the better outcomes compared to the traditional finite element analysis (FEA) approach.

4. Conclusions

The fluid flow and heat transfer behavior of the micro-channel flow under some internal and external influences is presented in this chapter. Latest works that has been performed on these influences are discussed so far. The prime conclusion from this chapter is,

- In micro-scale studies, the reason for the deviation of conventional theories and correlations was concluded as the neglected effects, which has a considerable influence on microscale flow.

- Electro-osmotic, MHD and EHD pumping methods have enormous significance in the field of microfluidics because of the advantages of no moving parts and low power consumption.

- Surface wettability plays key role hydrothermal performance of two-phase flow in microchannels.

- Surface roughness also has considerable influence on enhancing heat transfer in both single-phase and two-phase flow through micro-channels.

Author details

Naga Ramesh Korasikha¹, Thopudurthi Karthikeya Sharma¹*, Gaddale Amba Prasad Rao² and Kotha Madhu Murthy²

1 Department of Mechanical Engineering, NIT, Andhra Pradesh, India

2 Department of Mechanical Engineering, NIT, Warangal, India

*Address all correspondence to: tks@nitandhra.ac.in

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Internal and External Influences on Hydro-Thermal Behavior of Micro-channel Flow

DOI: http://dx.doi.org/10.5772/intechopen.105111


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