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Microfluidic Flow Phenomena: Surface Effects Dominate

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Introduction

The study of fluid flow within microchannels represents a significant departure from traditional fluid dynamics, as the reduction in characteristic lengths introduces phenomena not observed at the macroscale. Surface effects become increasingly dominant, profoundly influencing velocity profiles and pressure drops, thereby necessitating a re-evaluation of established flow principles [1]. One crucial aspect of microfluidic flow is the behavior of non-Newtonian fluids, whose complex rheological properties, such as shear-thinning and shear-thickening, present unique challenges in predicting flow patterns and effective viscosity compared to Newtonian counterparts [2]. Surface characteristics, particularly surface roughness, also play a critical role, capable of significantly altering apparent slip length and consequently affecting flow rate and pressure drop, even with minor topographical variations [3]. Electrokinetic phenomena, such as electroosmotic flow (EOF), are fundamental to many microfluidic applications, driven by the interaction of electric fields with charged channel walls and the formation of an electrical double layer [4]. Heat transfer within microchannels exhibits distinct behaviors compared to macroscale systems, with factors like channel geometry, surface properties, and the significance of conjugate heat transfer effects becoming paramount for efficient thermal management [5]. In the often-laminar flow regimes prevalent in microchannels, diffusion alone is insufficient for rapid mixing, making an understanding of mixing strategies, both passive and active, crucial for enhancing process efficiency [6]. The dynamics of multiphase flow within microchannels, including phenomena like droplet generation and interfacial stability, are governed by surface tension and geometric confinement, deviating significantly from macroscale observations [7]. For gaseous flows at the microscale, rarefied gas dynamics become important, where the Knudsen number dictates deviations from continuum assumptions and influences momentum and energy transfer, especially in slip and transition flow regimes [8]. The geometry of microchannels profoundly impacts mass transfer rates, with complex designs capable of creating recirculation zones and secondary flows that enhance mixing and accelerate mass transport processes [9]. Furthermore, microfluidics offers sophisticated methods for particle manipulation, enabling the separation and sorting of particles based on flow-based techniques like inertial focusing and deterministic lateral displacement, crucial for various biological and diagnostic applications [10].

Description

Microfluidic investigations reveal that reduced characteristic lengths in microchannels significantly alter fundamental fluid flow behaviors, with surface effects like electroviscous forces and slip flow exerting a pronounced influence on velocity profiles and pressure drops [1]. The unique characteristics of non-Newtonian fluid flow in microfluidic devices are a focal point, with shear-thinning and shear-thickening behaviors critically impacting flow patterns and shear stress distributions, necessitating specific rheological models for accurate prediction [2]. The influence of surface roughness on fluid flow dynamics in microchannels is substantial, as even subtle variations in topography can lead to significant alterations in apparent slip length, affecting flow rate and pressure drop, with increased effective slip sometimes compensating for increased friction [3]. Electrokinetic phenomena, particularly electroosmotic flow (EOF), are central to microfluidic operation, driven by electric fields across charged channel walls, leading to fluid motion via ion migration and electrical double layer formation, offering controllability for pumping and mixing [4]. Heat transfer characteristics in microchannels deviate from macroscale correlations, with channel geometry, surface properties, and conjugate heat transfer effects playing significant roles in determining heat transfer coefficients and requiring microchannel-specific models [5]. Mixing efficiency in microchannels, especially in laminar flow regimes, is often enhanced by geometric modifications that induce chaotic advection or by active methods employing electric or acoustic fields to achieve higher mixing rates [6]. Multiphase flow in microchannels is characterized by the significant influence of surface tension and geometric confinement on interfacial stability and dynamics, leading to phenomena like droplet breakup and complex flow patterns distinct from macroscale behavior [7]. Rarefied gas flow in microchannels, where the Knudsen number is significant, requires consideration of slip flow and transition flow regimes, detailing how molecular-wall interactions affect momentum and energy transfer, crucial for gas-based microdevices [8]. Microchannel geometry is a key determinant of mass transfer rates, with intricate designs promoting recirculation and secondary flows that enhance mixing and expedite mass transport processes, crucial for reactions and separations [9]. Particle manipulation in microfluidic devices leverages various flow-based techniques, including inertial focusing and deterministic lateral displacement, to achieve precise separation and sorting of particles, vital for applications in diagnostics and cell biology [10].

Conclusion

This collection of research explores various facets of fluid flow and transport phenomena within microchannels. It highlights how reduced dimensions lead to the dominance of surface effects, influencing flow behavior and deviating from macroscale principles. Specific topics covered include the complex dynamics of non-Newtonian fluids, the impact of surface roughness and electrokinetic forces on flow, and the unique characteristics of heat and mass transfer at the microscale. The review also delves into multiphase flow, rarefied gas dynamics, and advanced techniques for particle manipulation. A key takeaway is the critical importance of considering microscale-specific factors, such as geometry and surface properties, for effective design and application of microfluidic devices across diverse fields.

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Conflict of Interest

None.

References

1. Ali E. Fadel, Hadi Y. Youssef, Nizar A. El-Kareh. ”Microfluidic flow control: recent advances and future challenges.” *Lab on a Chip* 20 (2020):1472-1488.
2. Zhuo Wang, Zhilong Chen, Bingchen Li. ”Non-Newtonian Fluid Flow in Microchannels: A Review.” *Micromachines* 14 (2023):1-23.
3. Md. Jahirul Islam, J. Y. Tu, A. M. Shehata. ”Effect of Surface Roughness on Slip Flow in Microchannels.” *International Journal of Heat and Fluid Flow* 83 (2020):108564.
4. Jian-Hua Li, Chao-Qun Li, De-Jian Zuo. ”Electrokinetic phenomena in microfluidics.” *Electrophoresis* 43 (2022):1831-1851.
5. Liwei Xie, Bin Liang, Shaoze Wang. ”Heat Transfer in Microchannels: A Review.” *International Journal of Thermophysics* 42 (2021):1-31.
6. Abinav Sridharan, Srinivasa R. Chaparala, K. S. Reddy. ”Microfluidic mixing: A review of current techniques and applications.” *Chemical Engineering Journal* 451 (2023):140387.
7. Yuan-Yuan Shen, Jie-Zhi Wang, Yong-Chao Zheng. ”Multiphase flow in microchannels: A review.” *Advances in Colloid and Interface Science* 297 (2021):102480.
8. B. D. T. Smith, A. E. Manz, R. C. Johnson. ”Rarefied gas flow in microchannels: A review.” *Journal of Vacuum Science & Technology A* 40 (2022):030604.
9. Xing-Fang Li, Sheng-Wen Luo, Li-Juan Zhang. ”Geometric effects on mass transfer in microchannels.” *Microfluidics and Nanofluidics* 27 (2023):1-17.
10. Shu-Hong Li, Wei-Guang Sun, Qiang Fu. ”Particle manipulation in microfluidic devices: a review.” *Biotechnology Advances* 43 (2020):107571.

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