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Electroosmosis modulated Darcy-Brinkman flow in sinusoidal microfluidic pipe: An analytical approach

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Abstract: Microfluidic devices utilize porous mediums for a wide range of applications, including micro-heat exchangers, microreactors, and various energy conversion systems, all of which involve intricate flow transport that directly influences the performance of reaction-fluid interactions. In the present investigation, we explore the electroosmotic flow characteristics in a sinusoidal micropipe with a porous medium. We obtain analytical approximate solutions for the governing flow equations by utilizing a perturbation method. The results for the potential field and flow characteristics are analyzed to examine the impact of micropipe waviness within an electrokinetic environment. This analytical study reveals that the periodic roughness on the surface of the micropipe generates periodic disturbances not only in the potential fields but also in the velocity profiles. An increase in the relative waviness of the pipe leads to the generation of corresponding waviness within the boundary layers of the flow. Additionally, it is observed that there is a decrease in the volumetric flow rate for higher permeability, as well as a reduction in the friction factor ratio for elevated Darcy numbers.

1. INTRODUCTION & OBJECTIVE

Surface waviness plays a pivotal role in microfluidic devices, finding applications in both the biomedical and industrial sectors of fabrication technology. This waviness etched onto the microchannel's surface introduces perturbations to the fluidic transport, thereby influencing its overall efficiency. In practice, the idealization of a smooth boundary often faces challenges due to the inevitable presence of surface roughness, particularly pronounced in fluid flow through microchannels. Notably, diverse microstructures such as surface roughness come into play in scenarios like fluid transport within porous media, cardiovascular systems, and micro-electro-mechanical systems (MEMSs), exerting a considerable influence on the underlying flow dynamics [1-5]. Consequently, a comprehensive exploration of the effects of surface roughness on fluid flow emerges as an imperative and significant pursuit.

In the intricate realm of microfluidics, the behaviour of fluids within narrow confinement takes on a fascinating complexity, governed by an interplay of various forces and phenomena. Among these, the marriage of electroosmosis and Darcy-Brinkman flow presents an intriguing puzzle that has captured the attention of researchers. Recent advancements in this field have begun to illuminate its potential: Trols et al. [6] conducted experimental studies on micro needle-based systems to enhance transdermal drug delivery efficiency. Hunt et al. [7] examined the combined characteristics of heat and mass transport in a microchannel-based reactor featuring a porous catalyst. Kumar et al. [8] explored theoretical models concerning nutrient transport through channels with deformable porous linings for diverse biological applications.

However, the study of mass transport under the influence of electroosmotic flow through wavy microchannel or pipes with porous walls remains limited. Reza et al. [9] directed their theoretical explorations toward the analysis of heat transfer within a corrugated microchannel featuring a porous medium under an electromagnetic environment. In pursuit of biomedical innovation, Rana et al. [10] discussed the influence of wall roughness on Electromagnetohydrodynamic flow within a porous microchannel. Expanding the canvas, the realm of rough microtubes has also been investigated by certain researchers, unmasking the consequences of surface roughness on electroosmotic flow, analytically scrutinizing these microtubular configurations. Keramati et al. [11] further enriched the discourse by providing an analytical solution for electroosmotic flow within rough microtubes. The quest for knowledge ventured even into the territory of slightly corrugated walls, as Chang et al. [12] undertook a perturbation analysis of electroosmotic flow within a microtube. However, the studies mentioned earlier focused on electroosmotic flow within corrugated microchannels or pipes. Specifically, the effect of waviness on the transport of electrolytes in sinusoidal micropipe with porous media remains unexplored.

This study delves into the captivating realm using an analytical approach, with the objective of unravelling the intricate dynamics of fluid motion within sinusoidal microfluidic pipes. The analytical methodology employed facilitates a systematic exploration of the underlying physics, shedding light on the intricate relationship between electroosmotic phenomena and the Darcy-Brinkman flow regime. The primary aim of this study is to theoretically investigate the impact of surface waviness on fully developed Darcy-Brinkmann flow in the presence of electroosmotic force, achieved through the unification of perturbation techniques. A refined perturbation theory is formulated to calculate the velocity distribution and flow rate in a circular micropipe with periodic surface irregularities. Additionally, the friction factor ratio between sinusoidal and smooth micropipes is approximated and expressed, with these formulations subsequently validated against prior results.

2. RESULTS & HIGHLIGHTS OF IMPOINTANT POINTS

In this study, we delve into a perturbation analysis of electroosmosis-modulated Darcy-Brinkman flow through a micropipe featuring sinusoidal roughness. We thoroughly investigate steady, fully developed, laminar flow of a Newtonian fluid, employing the perturbation technique to derive the governing equations for potential and velocity distribution. Furthermore, we approximate and express the friction factor ratio between sinusoidal and smooth micropipes. The three key parameters influencing the friction factor are identified as the Darcy number, relative waviness and the wave number. For various wave amplitudes, changes in flow patterns and the occurrence of recirculations manifest near the wavy wall of the pipe. Notably, the middle layer of the flow remains unaffected by the wave amplitude, with disturbances confined primarily to the boundary layers due to the resistance imposed by the pipe's waviness. Additionally, we observe a decrease in the volumetric flow rate for higher permeability, and a reduction in the friction factor ratio for elevated Darcy numbers.

In conclusion, this rigorous analysis of electroosmosis-modulated Darcy-Brinkman flow through sinusoidal micropipes unveils a realm of intricate fluid dynamics. As we unravel the interplay between waviness, flow patterns, and friction factors, our findings hold promise for enhancing microfluidic systems in diverse fields, from biomedical devices optimizing drug delivery to advanced engineering solutions for efficient fluid transport in porous media.

REFERENCES

1. C. Ng, Combined pressure-driven and electroosmotic flow of Casson fluid through a slit microchannel, J. Non-Newtonian Fluid Mech. 198 (2013) 1-9.
2. C. Vargas, J. Arcos, O. Bautista, F. Mendez, Hydrodynamic dispersion in a combined magnetohydrodynamic-electroosmotic driven flow through a microchannel with slowly varying wall zeta potentials, Phys. Fluids 29 (2017) 092002.
3. Y. Zhang, Y. Chen, X. Yu, A flexible device for ocular iontophoretic drug delivery. Biomicrofluidics, 10(1) (2016) 011911.
4. N. C. Tsai, C. Y. Sue, Review of MEMS-based drug delivery and dosing systems. Sensors Actuators A Phys. 134(2) (2007) 555-564.
5. L. Wang, Y. Jian, Q. Liu, F. Li, L. Chang, Electromagnetohydrodynamic flow and heat transfer of third grade fluids between two micro-parallel plates, Colloids Surf. A: Physicochem. Eng. Asp. 494 (2016) 87-97.
6. A. Tröls, M. A. Hintermüller, M. Saeedipour, S. Pirker, B. Jakoby, Drug dosage for microneedle-based transdermal drug delivery systems utilizing evaporation-induced droplet transport, Microfluid Nanofluidics. 23(7) (2019) 91.
7. G. Hunt, N. Karimi, M. Torabi, Two-dimensional analytical investigation of coupled heat and mass transfer and entropy generation in a porous, catalytic microreactor. Int J Heat Mass Transf. 119 (2018) 372-391.
8. P. Kumar, B. Dey, G. P. Raja Sekhar, Nutrient transport through deformable cylindrical scaffold inside a bioreactor: An application to tissue engineering. Int J Eng Sci. 127 (2008) 201-216.
9. M. Reza, A. Rana, G.C. Shit, Thermo-fluidic transport of electromagnetohydrodynamic flow in a corrugated porous medium microchannel, Eur. Phys. J. Plus. 136 (2021). 496.
10. A. Rana, G. C. Shit, M. Reza, Electromagnetohydrodynamic thermo-fluidic transport in a porous microchannel with wall roughness, Colloids Surf. A: Physicochem. Eng. Asp. 650, (2022) 129336 (2022).
11. H. Keramati, A. Sadeghi, M. H. Saidi, S. Chakraborty, Analytical solutions for thermo-fluidic transport in electroosmotic flow through rough microtubes, International Journal of Heat and Mass Transfer 92 (2016). 244-251.
12. L. Chang, Y. Jian, M. Buren, Q. Liu, Y. Sun, Electroosmotic flow through a microtube with sinusoidal roughness, Journal of Molecular Liquids 220 (2016). 258-264.