Proceedings of the 18th UK Heat Transfer Conference

9-11 September 2024, Birmingham

UKHTC2024-148

NUMERICAL MODELLING OF MULTI-PHASE TAYLOR FLOW WITH NANOPARTICLES USING MPPIC-VOF APPROACH FOR HEAT TRANSFER ENHANCEMENT

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1. ABSTRACT:

This study numerically investigates heat transfer characteristics of multi-phase Taylor flow containing nanoparticles in millimetric channels using a newly customised OpenFOAM solver, thermalMPPICInterFOAM. Simulations were conducted to analyse the thermal field and average Nusselt numbers for four cases, which are single-phase flow, two-phase Taylor flow, and three-phase flow with and without thermophoretic and Brownian motion effects. Results showed that while Taylor flow improved heat transfer, adding 100 nm nanoparticles at low volumetric concentration of 10^{-4} decreased efficiency due to nanoparticle migration effects. This outcome indicates the need for further optimization of nanoparticle concentration and diameter in nanofluid cooling systems.

2. INTRODUCTION:

Taylor flow, characterized by elongated gas bubbles separated by liquid slugs, offers notable benefits for heat transfer in laminar flow mini- and micro-scale devices due to the internal circulation generated within the liquid slugs [1]. This flow pattern is prevalent in applications such as pulsating heat pipes, microfluidic devices, and fuel cells. However, conventional methods for improving heat transfer often rely on fluids with intrinsically low thermal conductivity. Nanofluids, which are mixtures of nanoparticles suspended in a base fluid, have emerged as a promising solution. Due to their enhanced thermophysical properties, particularly thermal conductivity, nanofluids are well-suited for a range of heat transfer applications, including mini/microchannel heat sinks [2]. The presence of nanoparticles in the liquid phase can also significantly modify the hydrodynamic characteristics of two-phase flow in Taylor bubbles.

Exploring the synergy between Taylor flow and nanofluids holds the potential to discover novel techniques for improving heat transfer in mini channels, thereby reducing heat build-up and maintaining optimal operating temperatures, especially in electronic devices. Although the individual benefits of Taylor flow hydrodynamics and nanofluids are well-established, their combined effect on heat transfer enhancement has not been extensively investigated and is a challenging area given the wide range of spatial scales involved (~1 mm to ~ 100 nm) [3]. This study aims to address this gap by simulating and examining the heat transfer properties of Taylor flows containing nanoparticles in millimetric channels through a newly developed OpenFOAM solver. By focusing on multi-phase flows involving gas, liquid, and solid phases, and the accompanying heat transfer phenomena, this research seeks to provide new insights into the enhancement of heat transfer in mini channels.

3. METHDOLOGY:

To investigate the heat transfer properties of Taylor flows containing nanoparticles in millimetric channels, a new customized OpenFOAM solver, thermalMPPICInterFOAM, was developed. This solver combines the Volume of Fluid (VOF) method for capturing the gas-liquid interface with the MPPIC Lagrangian approach for solid particle tracking [4]. The modifications included adding the energy equation and updating the properties of water, air, and nanoparticles iteratively throughout the simulation. Additionally, thermophoretic and Brownian forces affecting the nanoparticles were incorporated into the solver which already manages the basic forces such are drag, lift, gravity, pressure gradient and viscous forces. The governing equations employed in this study encompass the continuity equation, which ensures mass conservation within the flow, the momentum equation,

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which accounts for the forces acting on the fluid, including the effects of nanoparticles, and the energy equation, which is essential for analysing heat transfer within the multiphase flow system.

The simulations were performed on a High-Performance Computing (HPC) system, encompassing a series of cases to analyse local and average Nusselt numbers comprehensively. Initially, a fully developed single-phase water flow was simulated, serving as a baseline with an expected theoretical Nusselt number of 3.6. Subsequently, the investigation progressed to a two-phase Taylor flow consisting of water and air, to evaluate the influence of the gas-liquid interface on heat transfer. The study further examined a three-phase flow involving water, air, and nanoparticles without considering thermophoretic and Brownian forces, to isolate the impact of nanoparticles on heat transfer. Finally, a full model was employed that included these forces, providing a holistic view of their effects on the system. Throughout these simulations, the solver dynamically updated the properties of the three phases (water, air, and nanoparticles) with each iterative solution loop, ensuring an accurate representation of the complex multiphase dynamics.

4. RESULTS:

The study examined the effects of 100 nm nanoparticles with a volumetric concentration of $\phi = 1 \times 10^{-4}$ in the liquid phase, with a channel wall temperature of 325 K and a fluid temperature of 300 K at the start of the flow. Figure 1 shows the domain temperature distribution for the four study cases. As in laminar flow, the thermal boundary layer formed as expected for single-phase flow (water only). In Taylor flow without nanoparticles (two-phase), flow circulations in the slug region caused boundary layer disruption, increasing heat extraction from walls. In the last two nanoparticle cases, the particle presence in the flow significantly affected the domain temperature distribution. This, in turn, influenced heat transfer from the walls to the flow system, as shown in Figure 2-a. However, the temperature distribution for the latter two cases is almost similar, as also confirmed by the variation in the local Nusselt number in Figure 2-b. Brownian motion and thermophoresis effects are absent when the particle diameter $d_p = 100\ nm$ or greater, which may explain this behaviour [5]. Hence, it is crucial to investigate these effects at particle diameters below this value. The variation of average Nusselt numbers over time suggests incomplete thermal development in all cases. However, a specific time of 0.08 seconds was selected for all cases to compare differences in the thermal behaviour. It was found that Taylor flow, with and without nanoparticles, improved heat transfer over single-phase flow. However, adding nanoparticles to Taylor flow decreased heat transfer indicated by Nusselt numbers. In Figure 2-b, it is noted that the jumps in the local Nusselt number for the two-phase Taylor flow case, in the front and back regions of the bubbles, are higher than for the cases of nanoparticles presence, which explains the higher average Nusselt number for that case. According to Zhang et. al. [3], the low nanoparticle concentration in the current study may explain this. Thus, nanoparticle concentration and diameter effects on Taylor flow heat transfer require further investigation, specifically in the front and back regions of the bubbles. Brownian motion and thermophoresis also slowed heat transfer reduction. This could be due to the migration of nanoparticles from high to low-temperature regions, especially near the wall where the thermal gradient is high, reducing the heat transfer effect.

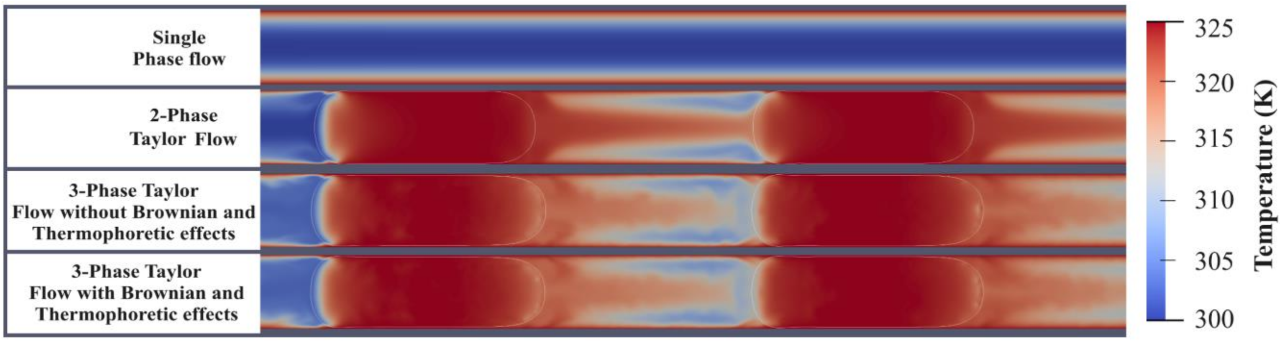
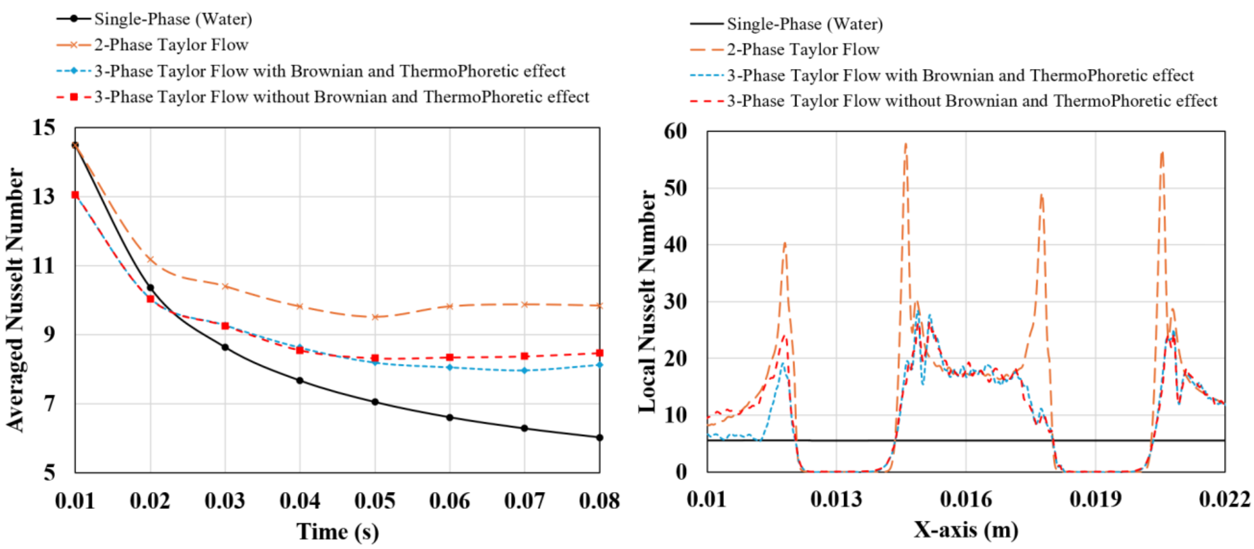


Figure 1: Temperature distribution for the domain of study cases. $Re = 100, \phi = 1 \times 10^{-4}, d_p = 100\ nm.$



(a) (b)

Figure 2: Averaged (a) and Local (b) Nusselt number variation for the study cases. $Re = 100$, $\phi = 1 \times 10^{-4}$, $d_p = 100\ nm$.

5. CONCLUSIONS:

Taylor flow significantly enhances heat transfer compared to single-phase flow due to increased mixing in the slug regions. However, adding 100 nm nanoparticles at a low concentration $\phi = 1 \times 10^{-4}$ reduces heat transfer efficiency, as indicated by lower Nusselt numbers, likely due to insufficient nanoparticle concentration. Accordingly, there is a logical need for further optimization of nanoparticle concentration and diameter to maximize heat transfer in multiphase flows. Brownian motion and thermophoresis affect temperature distribution by causing nanoparticle migration from high to low temperature regions, particularly near the walls, reducing heat transfer.

ACKNOWLEDGMENT

This research was supported by the Higher Committee for Education Development in Iraq (HCED) Scholarship program, a Royal Academy of Engineering/Leverhulme Trust Research Fellowship [LTRF2122-18-108], and an EPSRC research grant [EP/Z002540/1].

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