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Enhancing heat transfer performance in non-mixing liquid slug flow with the use of alumina nanoparticles in microchannels: a numerical study

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ABSTRACT

Because of the superior thermal performance and manufacturing readiness, non-mixing two-phase flows in microchannels have recently gained popularity as a method for the implementation of cooling applications. Due to internal fluid recirculation within the slugs, slug-flow is one of the two-phase flow regimes that facilitates greater heat transfer rates in microfluidic devices than other types of two-phase flows. This is because the ratio of surface area to volume of slugs is greater than that of other two-phase flow types. Because of this, the present study is focused on increasing heat transfer capability of two-phase slug flow further by introducing nanoparticles. The nanofluid-based liquid-liquid slug-flow was investigated throughout this research using numerical investigations. The software ANSYS Fluent® was utilised for doing the research in a numerical format. In order to explore the impact that nanoparticles have on the transport of heat, set of numerical investigations were carried out. Nanoparticles made out of aluminium oxide (Al_2O_3) were used for the simulations because of their high heat conductivity, which is also one of the reasons for its excellent physical and chemical stability as a nanofluid. The numerical results were validated against the experimental data that were already published in the literature. The VOF (Volume-of-Fluid) and Eulerian–Eulerian models were utilised in order to successfully capture the interface of a two-phase flow. Using nanoparticles in either phase led to a considerable improvement in heat transport, as demonstrated by the CFD findings. The incorporation of nanoparticles into the secondary phase has resulted in an increase of more than eightfold the Nusselt number compared to two-phase liquid-liquid slug flow. Furthermore, adding nanoparticles to the fluid has a significant increase in its thermal conductivity.

KEYWORDS: *Numerical Modelling, Nanofluid, CFD, Flow Simulation, Alumina nanoparticles*

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1 INTRODUCTION

In recent years, microfluidics technology has grown and matured. Its high surface area to volume ratio makes microchannel fluid flow a promising heat transporter. These results are related to microchannel cooling. Thus, heat exchangers, MEMS, microreactors, and LoCs use microchannel-based flows. Tuckerman and Pease (1981) proposed using liquid in microchannels to cool electronic components. According to the findings of the research conducted by Asthana et al. (2011), integrating a microchannel into a heat sink with one-phase flow removed heat at 0.79 kW/cm^2. Using heat sinks with channels and fluid flow to remove heat from electronic components is proven and efficient. Single-phase microchannel flows are laminar, so their heat extraction is limited. Two-phase flows were used to overcome these constraints. Two-phase flow can be gas-liquid or liquid-liquid, but microdevices with superior thermal transport and easy flow generation have become more popular. There are several two-phase flow patterns, but the slug flow has the best thermal performance. Nanofluids are promising heat transmission options because they increase liquid thermal conductivity by adding nanoparticles. Colloidal dispersion nanoparticles have one dimension of 1 to 100 nanometers and are used in nanofluids at low concentrations and densities (less than 1.0 volume percent) (Albadr et al. 2013). This study primarily aims to examine the impact of nanoparticle volume fraction on heat transfer in microchannels. This was accomplished by integrating different volume fractions of nanoparticles into the liquid-liquid slug flow in two occurrences: nanoparticles in the primary phase and nanoparticles in the secondary phase.

1.1 Heat transport in two-phase flow using nanoparticles

The immiscible slug flow is the most common flow type utilised in heat removing applications that employ the utilisation of the flows with two phases. Bandara et al. (2017), He et al. (2010), Mi et al. (2001) and Tan et al. (2021) define slug flow as the movement of set of plugs from a secondary flow through a primary flow. The flow that occurs when a fluid phase is located around the secondary phase plug and the channel wall is referred to as Taylor flow (Gupta et al. 2010; Liu et al. 2005). Janes et al. (2010) investigated heat transport in liquid-gas and liquid-liquid flow systems with plug pattern.

Their study focused on liquid-liquid two-phase and heat transmission. Experiments involving oil–air, water–air, and water–oil have been conducted as part of their research. It was seen that the flows almost acted in the same way that Taylor flows do.

The majority of the experimental research that has been done by researchers focused on determining the influence that friction has on two-phase liquid-liquid flow (Abdollahi et al. 2017; Özdemir and Sözbir 2018; Triplett et al. 1999). A study on the features of heat transport and flow visualisation of gas-liquid two-phase flow in microchannels with continuous heat intensity at the wall carried out by Lim et al. (2013) was able to find two correlations: one between the Nusselt number and void fraction, and the other between the Nusselt number and axial location.

Nanofluids' convective heat transport has received a large amount of interest as a technique for boosting heat transport capability in recent years. This is due to the increasing demand for excessive heat extraction rates in a wide range of heat removal applications. Mohammed Adham et al. (2013) explored the numerous facets of nanofluids that are based on heat sinks with microchannels. They claimed that more study is required to determine the impact that the kind of nanofluid and the microchannel geometries have on the heat transmission mechanism. According to Rea et al. (2009)'s experiments, heat transport rates were improved in the fully formed zone including nanoparticles in the convective heat transport of alumina/water nanofluids in the laminar flow regime. Experimental research conducted by Zeinali Heris et al. (2007) on the forced convection of alumina/water nanofluids revealed that the Nusselt number increases in proportion to the volume fraction of the fluid. Experiments and computer simulations were used in the research carried out by Kalteh et al. (2012) on the topic of nanofluids heat transport in microchannels. They demonstrated a high heat transport with increasing particle concentration percentage and the Reynolds number by using alumina/water as the nanofluid, and they did this by showing an increase.

In the available context of research on two-phase flow with nanofluids, only a small number of experiments have been conducted. The heat transport in a two-phase nanofluid flows were the focus of a numerical study that was conducted by Guan et al. (2018). They used alumina/water as the nanofluid and simulated numerically under two primary cases: a cavity filled with water-alumina nanofluid and a rising drop of silicone oil; and a channel with stratified flows of water-alumina nanofluid, water, and silicone oil (Guan et al. 2018). They demonstrated that the distribution of nanoparticles was primarily driven by convection, while diffusion of nanoparticles had a relatively minor role. In addition to this, they demonstrated that the presence of nanoparticles close to the wall promotes increased heat transmission, however the presence of nanoparticles within the bulk had no effect on the rise of internal heat transport. A numerical investigation of nanofluid-based two-phase slug flow heat transport in a square micro sized channel was carried out by Bayareh et al. (2020). A water-alumina mixture was used as the nanofluid in this experiment, and air functioned as the subordinate phase. They were able to shorten the computing time required to show the presence of fluctuations and vortices in the liquid film region by employing a technique known as boundary mesh adaption. They discovered that there was a 10% increase in the rate of heat transport compared to a water-air two-phase flow, and that the Nusselt number depends on the length of the unit cell and the slug. Zong and Yue (2022) carried out an experiment to find out how adding nanoparticles affected the pressure drop and flow patterns of gas-liquid slug flow in microreactors. In their experiment, they used nitrogen gas as the secondary phase and water containing nanoparticles as the main phase. The water-based nanofluids employed were composed of TiO_2/water, TiO_2/water combined with ethylene glycol, and alumina/water. They demonstrated the presence of film with liquid around nitrogen bubbles in the gas and nano based fluid cases, but there was no film with liquid present in the two-phase flow involving water and gas. This demonstrated that the incorporation of nanoparticles has resulted in a modification of the wall's wetting capabilities, resulting in a greater hydrophilicity. It was claimed that the pressure drops that were measured in their studies were closely aligned with the model that had been presented by Kreutzer et al. (2005).

To gain a complete understanding of the field of hydrodynamic and transport of heat in two-phase based on nanofluids in microdevices, additional research is necessary. Therefore, computational simulations and numerical analysis of the fluid flow and heat transport related to nanofluid-based two-phase slug flow in microchannels are the main focus of this research.

2 RESEARCH METHODOLOGY

A two-phase flow including nanoparticles is modelled numerically in this investigation using a circular microchannel as the setting. The simulations are run in a two-dimensional space that is axisymmetric. According to Cheng and Xia (2018) research, the primary and secondary working fluids, respectively, consisted of water and light mineral oil. The effect of the inclusion of nanoparticles on slug flow heat transport was studied by adding Al_2O_3 nanoparticles to each phase on its own in order to conduct the experiment (see figure 1). A multiphase (3 phases) flow model was used to mimic this, allowing for the independent study of the performance of the nanoparticles (alumina) without being influenced by the chemical and physical characteristics of the base phase or the secondary phase. To explore the influence of the nanoparticles, the phase containing more nanoparticles was often treated as a single phase by changing its thermal and physical properties. Since CFD solutions handle the problem as if it were a single-phase flow, this can cut the amount of time needed for the computation by a significant amount (Nazififard et al. 2012). The difficulty in determining the effect of nanoparticles on their own is a limitation of this methodology, which is otherwise advantageous. The presence of the Brownian force, friction force, thermophoresis, gravity, and Brownian diffusion, show that nanofluids are naturally two-phase fluids. As a result, using multiphase models can lead to the acquisition of more precise calculations. Consequently, the utilisation of multiphase models can result in the achievement of more accurate predictions. The major two-phase modelling methodologies for nanofluids that were utilised were called Lagrangian-Eulerian models and Eulerian-Eulerian models.

ANSYS Fluent® (ANSYS, Inc 2009) was used in this research to solve the general continuity, momentum and energy equations as well as certain interaction equations between the phases like forces, surface tension and pressure field. This software was developed by ANSYS, Inc. During the investigation of nanoparticles in the microchannel, a Eulerian model was utilised. Additionally, this investigation is broken up into two primary subcases, which are referred to as nanoparticle inclusion in primary phase (slug phase domain) and nanoparticle inclusion in secondary phase (plug/droplet forming phase) respectively. We examined several different behaviours, each including a different combination of the volume fractions of nanoparticles present in the secondary phase and the primary phase. Prior to the simulation commencing, the secondary phase was patched with silicon oil to convert the domain into a phase slug regime.

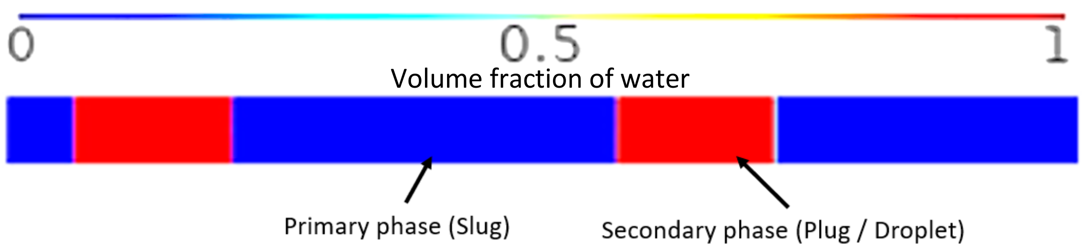

Figure 1. Initial Setup of the domain

2.1 Heat transport in two-phase flow using nanoparticles

In order to verify the precision of the mesh elements that are being used in this simulation, a mesh independence analysis has been carried out. Figure 2 depicts the similar findings that were achieved from simulations using different mesh sizes. According to figure 2, the difference in the percentage of values that can be found between the cases of 0.5-micron mesh and 1.0-micron mesh is 6%, whereas the difference that can be found between the cases of 5.0-micron element size and 1.0-micron mesh was greater than ten percent.

For this reason, 1-micron structured mesh components were used for the duration of the study. The mesh sections at the interface between the two phases were continually and automatically modified based on the gradient of the volume fraction. The coarsening and refining threshold values were set at 0.1 and 0.15, respectively. Figure 3's element size mesh used complex gradient adaptation to track the thin interface between the phases at a resolution of 1 micron. In order to provide a more thorough comprehension, Figure 4 depicts the mesh superimposed above the phase contour. Figure 5 shows the adapted mesh during the simulation.

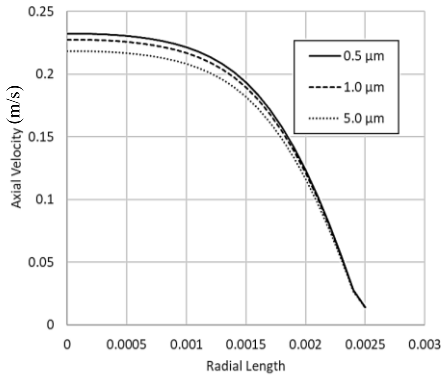

Figure 2. Distribution of velocities in water along the channel radius

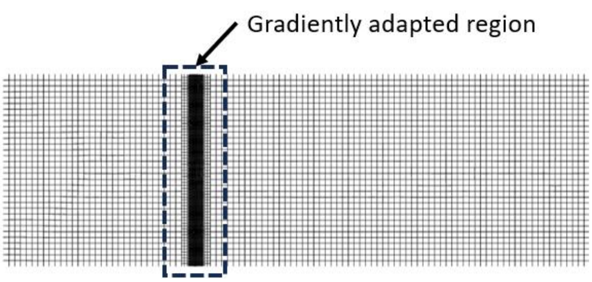

Figure 3. Mesh generated using computation with gradient-adapted refinements

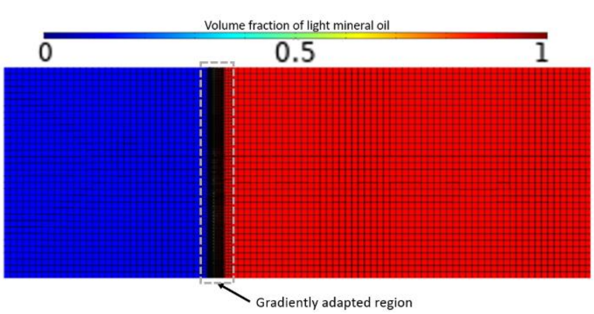

Figure 4. Mesh generated using computation with gradient-adapted refinements with phase contour overlay

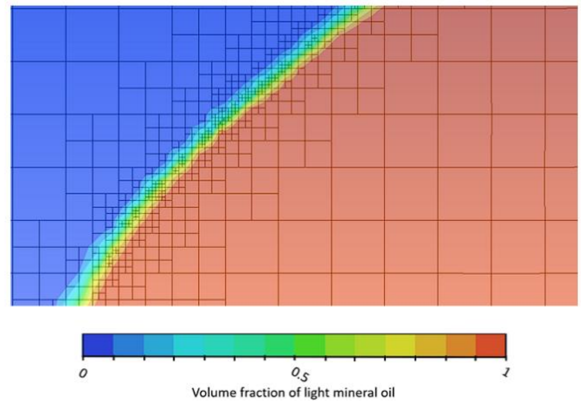

Figure 5. Adapted mesh during the simulation

2.2 Phase properties and boundary conditions

The primary components of the numerical model are the flow-developing region and the wall with constant temperature, which is the location where heat transport is taken into consideration. In this particular model, a microchannel with a length of 3000 microns and a diameter (D) of 100 microns was chosen since it offers a suitable amount of space for flow development according to the study done by Bandara et al. (2017, 2015). Each and every one of the physical properties of the fluids and the nanoparticles are exactly the same as those listed in Table 1. The cases that have been completed are summarised in Table 2, which has been presented here. The value of 0.04925 N/m was chosen for the numerical analysis to represent the interfacial tension with water (Bandara et al. 2017, 2015).

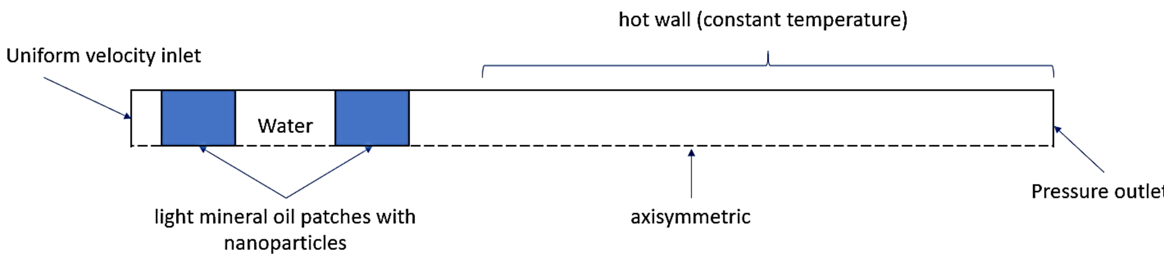

Figure 6. Schematic diagram of multiphase flow model

The slug stream will have formed across a span of ten times the channel diameter (1000 microns) and the wall temperature will have reached 300 K before to entering the heating region. The temperature of the heated section is about the same as that of the heating wall (2000 microns), which is continuously maintained at 350 K. The inlet's boundary condition is specified as a velocity inlet with a fixed velocity of 0.2 m/s for each example according to the greatest Nusselt number measurement in two-phase slug flow (Bandara et al. 2017, 2015). The velocity inlet is the set boundary condition for the inlet, while the 0 Pa gauge pressure outlet is the specified boundary condition for the channel's output. The selection of nanoparticle concentration was guided by experimental and numerical findings in the literature (Alshehri et al. 2020; Hemmat Esfe et al. 2014; Heyhat et al. 2013; Hwang et al. 2009). The results of those additional studies were taken into consideration as an additional source of support for this investigation's conclusions. The boundary conditions applied to the fluid domain are depicted in Figure 6.

Table 01. Material properties including nanophase

Material	Density (kg/m^3)	Specific Heat (J/kg.K)	Thermal Conductivity (W/m.K)	Dynamic Viscosity (Pa.s)
Water	998	4182	0.6	0.001002
Light Mineral Oil	838	1670	0.17	0.023
Aluminium	2690	917	239	N/A
Al_2O_3 Nanoparticle (Alshehri et al., 2020)	3970 50 nm spherical	765	40	N/A

Table 02. Tested cases

Case No.	Inlet Velocity (m/s)	Nanoparticle Domain	Nanoparticle concentration (v/v %)
01	0.2	Light mineral oil	0.2
02	0.2	Light mineral oil	0.5
03	0.2	Water	0.2
04	0.2	Water	0.5

3 RESULTS & DISCUSSION

In this section, the outcomes that were reached through the use of numerical simulations are discussed. The findings are broken down into two primary categories: nanoparticles in the secondary fluid and nanoparticles in the base or primary fluid. Both of these categories are presented below. The first part of this study will discuss the research that was done on nanoparticles in the secondary phase. The second part will discuss how the nanoparticles affect heat transport when they are added to the base phase.

3.1 Heat transport impacts from secondary phase nanoparticles

The droplet formation that occurs during a two-phase flow with Al_2O_3 nanoparticles is depicted in Figure 7, and the temperature distribution that occurs within a droplet is depicted in Figure 8. The Nusselt number was computed in order to conduct a quantitative investigation of the effect of heat transmission.

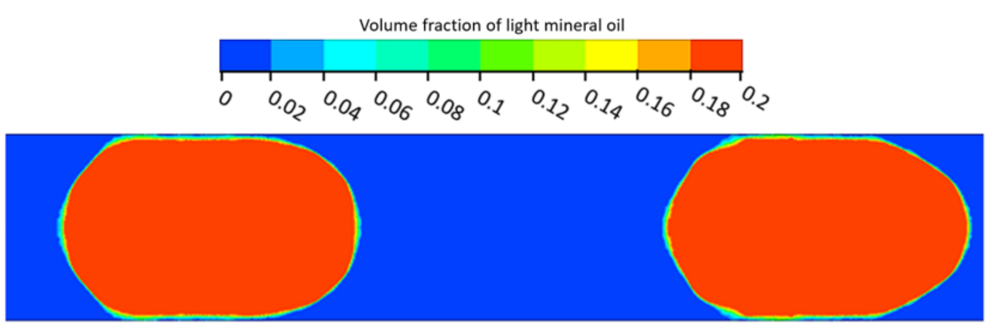

Figure 7. Volume fraction of the Al_2O_3 nanophase.

The Nusselt number was determined by employing the correlation that was presented in equation (1) and was proposed by Ramirez-Tijerina et al. (2018). They conducted their studies inside of a tube that was perfectly straight, and they came up with a correlation for the Nusselt number of nanofluid in cases where the flow was subjected to a temperature that was maintained along the wall. Using equation (2), we were able to determine the local Nusselt number based on the CFD findings. The correlations that were published by Sharma et al. (2012) can be used to compute the parameters of the nanofluid, such as its viscosity and thermal conductivity. These correlations are given in equations (3) and (4), respectively. As part of the process to validate the study, these computed values were compared with the attributes that were acquired by CFD simulation.

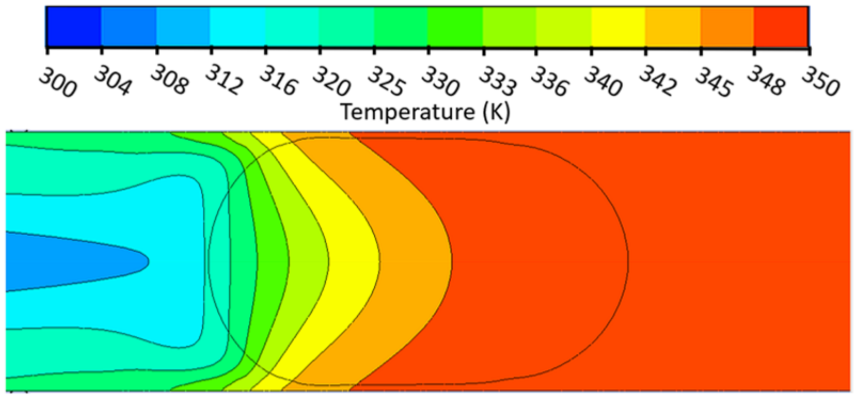

Figure 8. Temperature distribution within a bubble (nanoparticles in secondary phase)

The CFD study's properties of the nanophase have been compared to the previously mentioned correlation and experimentally measured effective heat conductivity (k_{eff}) values, which were 1.130 and 1.274 for instances one and two, respectively. These experimental values were taken from the research conducted by Hemmat Esfe et al. (2014). The effective thermal conductivity of the nanofluid phase is compared across the various scenarios in figure 9, which can be found here. All of the CFD results had a range of between 3.0% and 4.0% with both the values found in the literature and the experimental data. Table 3 provides an overview of the findings that were gathered.

$$Nu_{nf} = h_{nf} D_h / k_{nf} = 0.073 Re^{0.702} Pr_{nf}^{0.4} \tag{1}$$

$$Nu_x = q D_h / k(T_w - T_m) = h D_h / k \tag{2}$$

$$\mu_{nf}/\mu_w = \mu_{eff} = C(1 + \varphi/100)^{11.3} \left(1 + T_{nf}/70\right)^{-0.038} \left(1 + d_p/170\right)^{-0.061} \tag{3}$$

$$k_{eff} = k_{nf}/k_w = \left[0.8938(1 + \varphi/100)^{1.37} \left(1 + T_{nf}/70\right)^{0.2777} \left(1 + d_p/150\right)^{-0.0366} \left(\alpha_p/\alpha_w\right)^{0.01737}\right] \tag{4}$$

Table 03. Effect of nanoparticles in secondary phase on heat transfer case parameters

Case No.	Al_2O_3 Volume Fraction	Property	CFD Result (Nano domain)	Sharma et al. Model	Nanofluid
01	2.00% (v/v)	Dynamic viscosity	0.0225412 (Pa.s)	0.0220279 (Pa.s)	Light mineral Oil / Al_2O_3
		Thermal conductivity	0.1997 (W/m.K)	0.1974 (W/m.K)	
		Average Nusselt Number	17.1245 Using Eq. (2)		
02	5.00% (v/v)	Dynamic viscosity	0.0228117 (Pa.s)	0.0221027 (Pa.s)	
		Thermal conductivity	0.2236 (W/m.K)	0.2057 (W/m.K)	
		Average Nusselt Number	20.524 Using Eq. (2)		

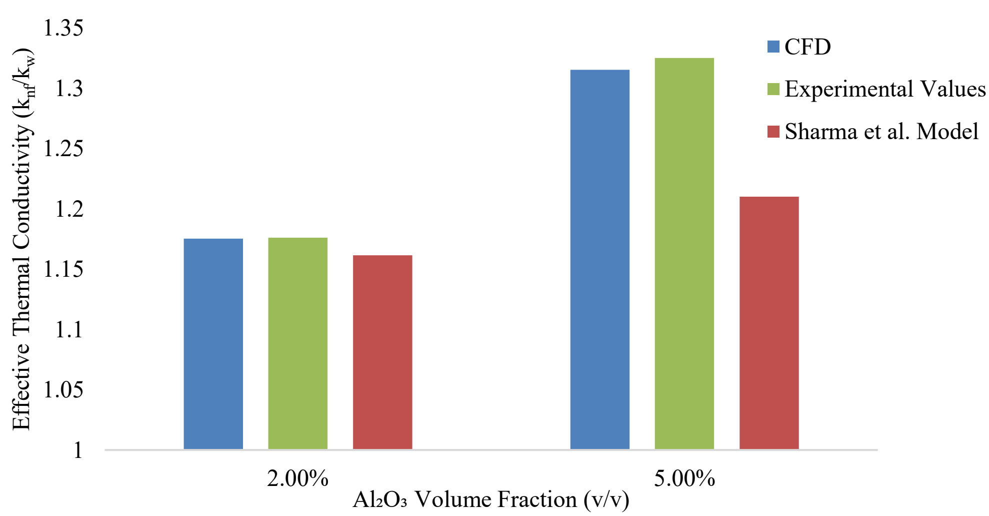

Figure 9. Effective thermal conductivity comparison

Figure 10 presents a comparison of the Nusselt number of single-phase and liquid-liquid two-phase slug flows with and without nanoparticles. This comparison is made using the nanofluid as the basis for the liquid-liquid two-phase slug flow. In comparison to the two-phase liquid-liquid slug flow, the nanofluid Nusselt number was found to have a significantly higher value when the analysis was completed. This is because there has been no change in the primary phase's thermal conductivity since the nanoparticles were added to the secondary phase. This results in the observed phenomenon. As a result, the proportion of heat that is transferred by convection as opposed to heat that is transferred via conduction has increased. As a direct consequence of that fact, the typical Nusselt number now stands at an increased value. Figure 11 depicts the fluctuation in the Nusselt number with respect to the axial length. This helps to explain the change in the Nusselt number along with two successive droplets. Because there is less of a temperature gradient in the middle of the droplet, the Nusselt number there has dropped by a significant amount in a short amount of time. The circulation of nanoparticles is responsible for the increased convective heat transport that contributes to the higher Nusselt numbers observed in nanofluids. The relative velocity magnitude of the Al_2O_3 nanoparticles in relation to the host phase is depicted in Figure 12, which depicts a single droplet. Convective heat currents are produced as a result of the relative motion of the nanoparticles inside the bubble, which contributes to an increase in the total amount of heat transferred via convection in the two-phase flow. When applied in a two-phase liquid-liquid slug flow, the utilisation of Al_2O_3 nanoparticles will unquestionably result in an enhancement in the total thermal conductivity of the fluid flow. Because of this, the overall rate of heat transport that occurs with the flow of fluid increased. Consequently, the average Nusselt number was 2.1 times higher than it would be in a two-phase liquid-liquid slug flow when nanofluid was not present, and it was 5.1 times higher than it would be in a single-phase laminar flow.

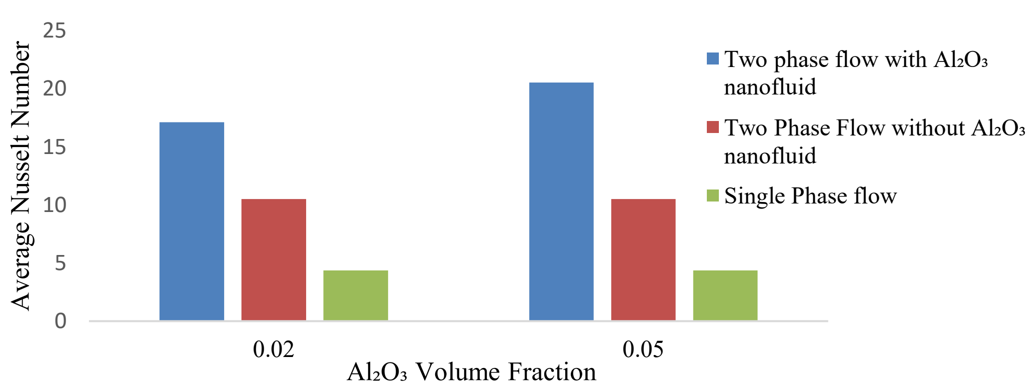

Figure 10. Comparison of the Nusselt number for nanofluid-based liquid–liquid two-phase slug flow (where the droplet phase is a nanofluid) relative to that of a single-phase flow and a conventional liquid–liquid two-phase slug flow without nanoparticles.

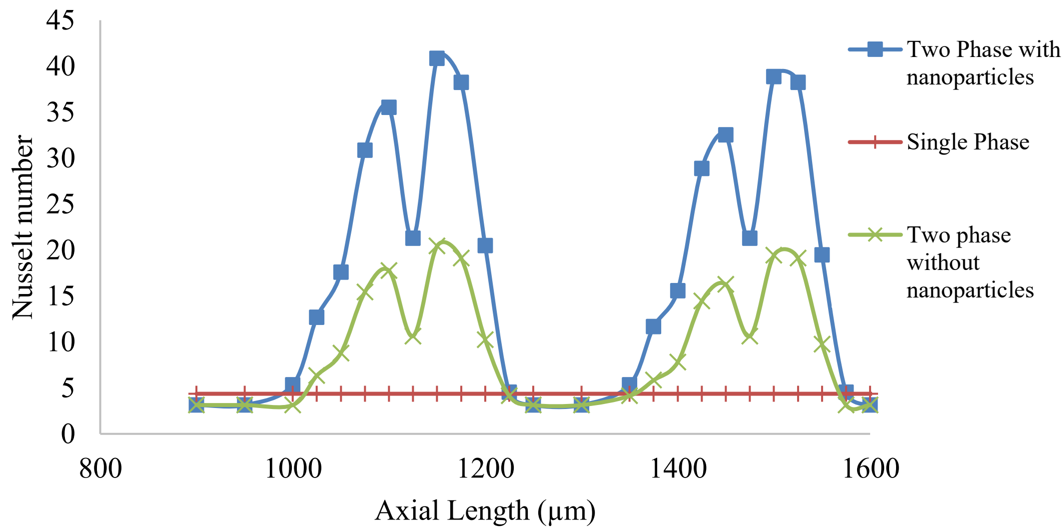

Figure 11. Axial Nusselt number variation (Case 03)

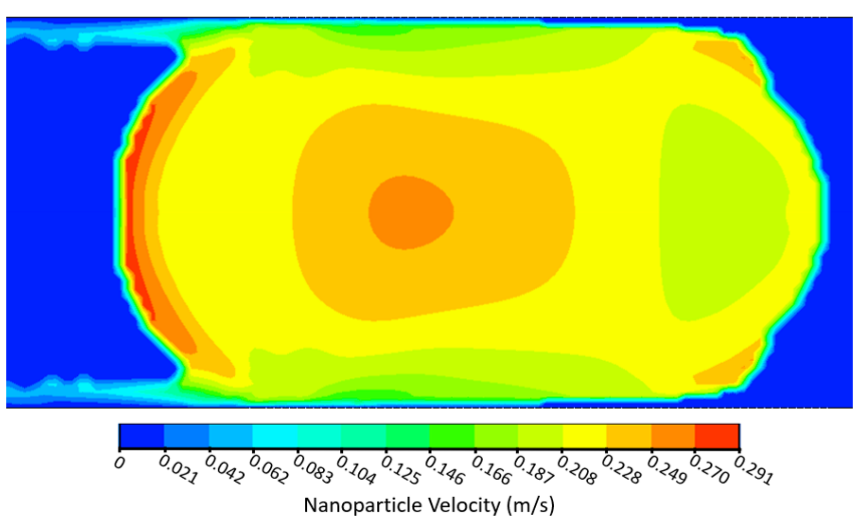

Figure 12. The magnitude of the velocity of Al_2O_3 nanoparticles relative to the surrounding fluid within a single bubble

3.2 Impact of nanoparticles on heat transport when present in primary phase

Taking into account the water's nominal thermal conductivity, the Nusselt number increased in the flow, as shown in Table 4, in comparison to the two-phase liquid-liquid slug flow that did not contain nanoparticles. In spite of the fact that the nanoparticles were added to the primary phase, for the purposes of this investigation, we did not take them into account as being a component of the primary phase (Jama et al. 2016; Wang and Mujumdar 2008; Yu and Xie 2012). The Nusselt number was computed with both the nominal and revised thermal conductivities as reported in Table 4. This was done in order to ensure accuracy.

The temperature gradients that can be found within a single droplet are depicted in Figure 13. According to Bandara et al. (2017), this shows that the temperature distribution of the droplet is the same as that of the two-phase liquid-liquid slug flow that does not contain nanoparticles. According to the findings, the typical value of the Nusselt number has dropped in comparison to a two-phase liquid-liquid slug flow in which nanoparticles were not present.

Table 04. Effect of nanoparticles in primary phase on heat transfer case parameters

Case No.	Al_2O_3 Volume Fraction	Property	CFD Result (Nano domain)	Sharma et al. Model	Nanofluid
01	2.00% (v/v)	Dynamic viscosity	0.0009829 (Pa.s)	0.0009596 (Pa.s)	Water / Al_2O_3
		Thermal conductivity	0.7051 (W/m.K)	0.6969 (W/m.K)	
		Average Nusselt Number	20.874* 16.6769** Using Eq. (2)		
02	5.00% (v/v)	Dynamic viscosity	0.0095285 (Pa.s)	0.0096291 (Pa.s)	
		Thermal conductivity	0.7891 (W/m.K)	0.7251 (W/m.K)	
		Average Nusselt Number	22.231* 16.903** Using Eq. (2)		

* Using 0.6 W/m.K as thermal conductivity (nominal) of primary phase
** Using respective thermal conductivity of nanofluid

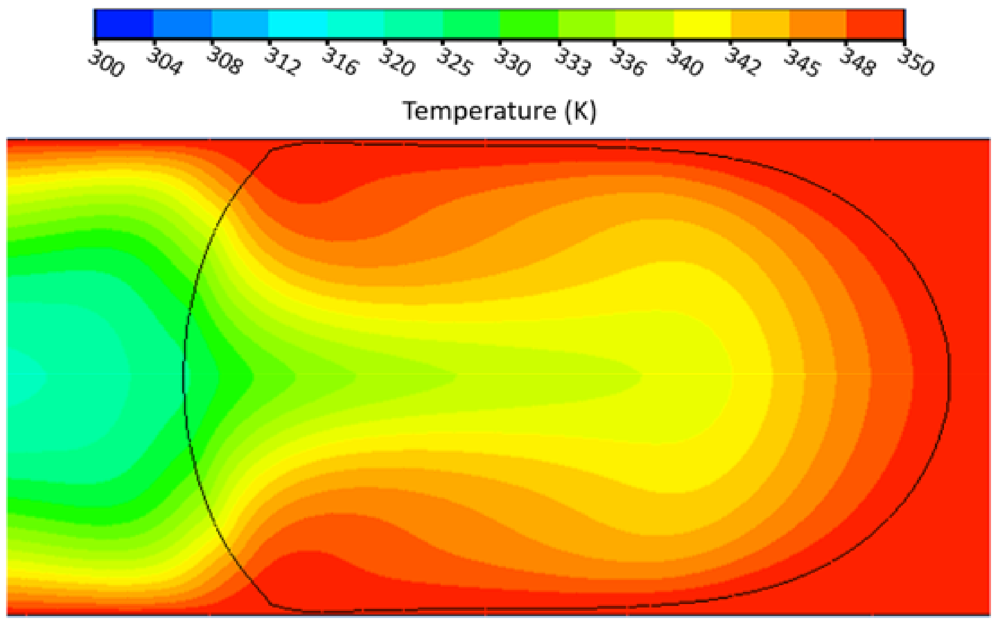

Figure 13. Fluctuating temperatures observed within a bubble (Nanoparticles in primary phase)

The comparison of the Nusselt number due to the presence of nanoparticles in the primary fluid is depicted in the Figure 14. According to the figure, adding nanoparticles to the primary phase clearly impacts on the mean Nusselt number in the fluid.

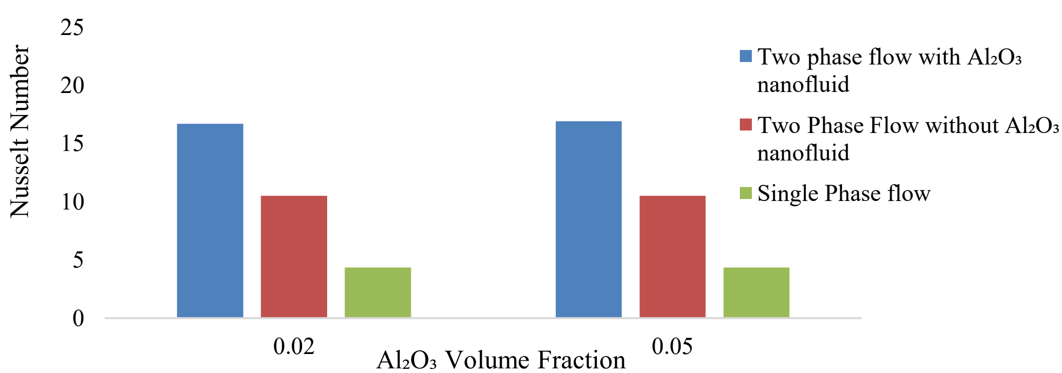

Figure 14. Comparison of the Nusselt number for nanofluid-based liquid–liquid two-phase slug flow (with the slug phase consisting of nanofluid) against single-phase flow and conventional liquid–liquid two-phase slug flow without nanoparticles.

Nusselt number variation along the axis is illustrated in Figure 15. Despite giving low Nusselt numbers because of the strong heat conductivity of the nanophase, the two-phase flow with nanoparticles has reached the maximum temperature over a shorter distance than the two-phase flow without nanoparticles. This is because the nanophase has a higher thermal conductivity.

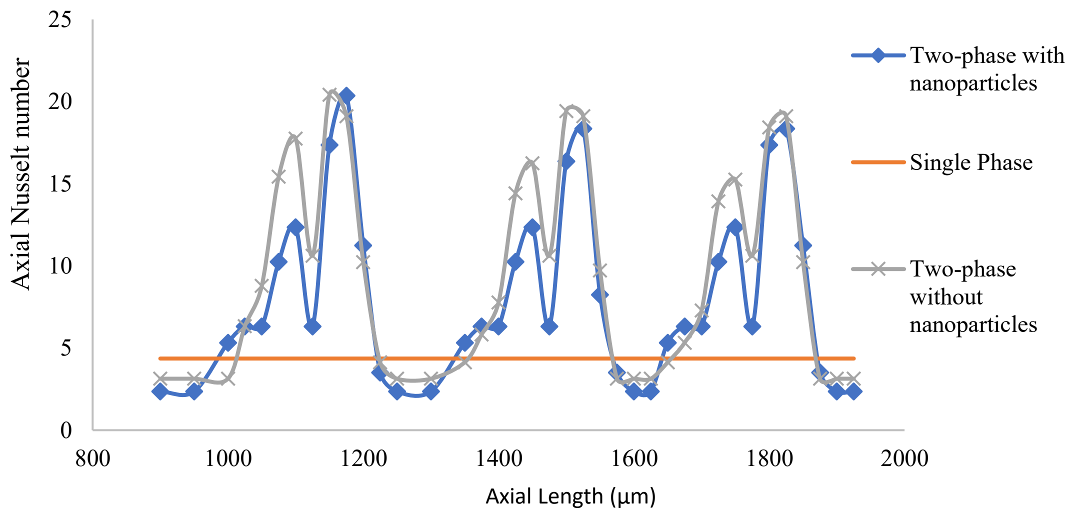

Figure 15. Axial Nusselt number variation (Case 01)

4 CONCLUSION

In order to explore the influence that nanoparticles have on heat transmission, studies were carried out in which nanoparticles were introduced to both the primary and secondary phases. The size of the nanoparticles was held steady throughout the studies at a value of 50 nm. The nanoparticles were dealt with as if they were their own separate solid phase. The addition of nanoparticles to the secondary phase resulted in a rise in the Nusselt number that was greater than the value seen in the two-phase liquid-liquid slug flow. With a volume proportion of Al_2O_3 nanoparticles comprising 5% of the total, the greatest Nusselt number value recorded in the findings was around 40, while the average value remained around 20. This occurred as a direct result of the nanoparticle circulation that took place within the droplet. Because of the movement of the fluid, nanoparticles were able to more effectively transfer heat.

In the final step of this series of CFD study, nanoparticles were added to the primary phase in order to conduct the tests. According to the findings, the greatest

Nusselt number recorded was 16, and it was achieved with a 2% volume-to-volume concentration of Al_2O_3 nanoparticles in relation to the changed thermal conductivity of the primary phase. When the volume fraction was 5% v/v, the maximum Nusselt number reported was 22. This occurred when the nanophase was considered as an independent solid phase.

By introducing nanoparticles into one phase and using a two-phase liquid-liquid slug flow, the flow's overall heat transmission was enhanced. The addition of nanoparticles to the secondary phase resulted in a significant increase in the Nusselt number. Even though there were significantly fewer nanoparticles when they were added to the primary phase, the same event still happened. This increase in heat transmission happened directly as a result of the nanoparticles' impact on the fluid's thermal conductivity. The material's thermal conductivity increased by 1.3 times when 5% nanoparticles were added to the main phase. As a result, it took noticeably less time to achieve the saturation temperature. Based on the results, it can be concluded that the heat transport efficiency, as determined by the Nusselt number, increased by 2.1 times when nanoparticles were incorporated into the base phase. These observations and results are consistent with the current study's findings and can be found in the literature (Ghashim 2021; Rashid et al. 2023).

NOMENCLATURE

Symbols	**Acronyms**
Nu − Nusselt number (Local)	$MEMS$ − Micro electromechanical systems
q − Heat flux [W/m^2]	VOF − Volume of Fluid
T − Temperature [K]	CFD − Computational Fluid Dynamics
k − Phase Thermal Conductivity [W/m. k]	LoC − Lab on a Chip
Re − Reynolds number	CHF − Critical heat transfer
d − Nanoparticle diameter [nm]	
α − Thermal diffusivity [m^2/s]	**Subscripts**
C − Nanoparticle constant (= 1 for Al_2O_3 h −	nf - Nanofluid
Coefficient of Heat transfer [W/m^2. K]	p - Nanoparticle
D − Pipe Diameter [m]	$wall$ - Wall
Pr − Prandtl number	w - Water
μ − Dynamic viscosity [Pa.s]	v/v - Volume/volume
φ − Volume fraction	m - Mean / bulk
	eff - Effective

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