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Heat Transfer Enhancement in Microchannel flows using Hybrid Nanofluids

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Abstract- The continuing shrinking trend of electronics along with growing power densities has resulted in many heat dissipation difficulties. Microchannel heat sinks are promising and compact heat sinks but limited by thermal performance due to thermal capabilities of traditional coolant fluids. This work examines the prospect of using hybrid nanofluids, i.e., a mixture of several different nanoparticles, to improve the convective heat transfer coefficients of microchannel flow. A detailed numerical analysis based on the two-phase Eulerian-Eulerian approach is performed to assess the thermohydrodynamic properties of aluminum oxide-copper/water hybrid nanofluid through rectangular microchannels under Reynolds numbers between 200 and 1000 and nanoparticle volume fractions between 0.5% and 2.0%. The simulations reveal a considerable heat transfer enhancement where the Nusselt number rises up to 38.4% at 1.0% volume fraction while reducing the thermal resistance by 29.6% and achieving the highest thermal efficiency ratio of 1.31. Although there is an increased pressure drop (18.7%), the thermal-hydraulic performance proves the feasibility of hybrid nanofluids as a new coolant.

Keywords- Hybrid Nanofluids, Microchannel Heat Sink, Heat Transfer Enhancement, Thermal Management, Two-Phase Flow, Computational Fluid Dynamics.

I. INTRODUCTION

The effective heat management issue has become an important engineering problem because of growing needs for energy saving, miniaturization, and high performance of different types of equipment. Miniaturization of electronic devices and increase in the power density of modern microchips have made the application of the existing cooling technologies ineffective. Microchannel cooling is one of the most interesting approaches that can help solve this problem due to its ability to effectively dissipate high values of the heat flux and small volume-to-surface area ratio [1]. The fundamental studies of Tuckerman and Pease have shown the possibility of using silicon microchannels for dissipation of the heat flux higher than 700 W/cm², which initiated wide investigation of the microchannel geometry, flow characteristics, and cooling liquids.

The physical and thermodynamic properties of conventional cooling fluids such as water, glycol, and oils represent a key constraint to the effectiveness of MCHS. Nanofluids defined as suspensions of solid nanoparticles in base fluid were first introduced by Choi and Eastman as a paradigm shift in improving thermal conductivity and heat convection [2]. Due to high thermal conductivity of metals, metal oxides and other nanomaterials used as particles, nanofluids demonstrate excellent thermophysical properties at a very low amount of nanoparticles present in the base fluid. Nevertheless, there are certain drawbacks in terms of conducting conductivity improvement while retaining stability and low viscosity of mono-nanofluids that led to the creation of hybrid nanofluids.

Hybrid nanofluids can be described as heat transfer fluids created through mixing two or more kinds of nanoparticles into the base fluid [3]. Such a mixture utilizes advantages of different materials in one single nanofluid, for example, the high thermal conductivity of metal nanoparticles combined with stability and dispersion features of oxide nanoparticles. According to Bhatti et al., hybrid nanofluids are characterized by enhanced heat transfer, rheological and thermophysical properties in comparison with monolithic nanofluids [3].

The combination of microchannel technology and nanofluids, as well as the most recent development of hybrid nanofluids, is a combination of two passive methods for increasing the heat transfer coefficient. As noted in recent systematic reviews, hybrid models using porous microchannels filled with nanofluids and geometrical optimization are able to provide the increase of heat transfer coefficient up to 150% with acceptable pumping cost [2,4]. This synergetic effect is caused by a number of mechanisms including the increase of thermal conductivity, Brownian motion of nanoparticles, thermophoresis, and changes in hydrodynamic boundary layer.

Although a lot of advances in the research have been made, the current state of the scientific literature is quite dispersed due to many publications describing particular case analysis under certain conditions and using different evaluation criteria [5]. There is an urgent need for systematic research of hybrid nanofluids in microchannel geometry using appropriate numerical modeling. Although the single-phase homogeneous models were successfully used for simulation of this process, they cannot take into account dynamic interaction between dispersed phase and base fluid that becomes crucial for modeling with various volume fractions and flow regimes [4,5]. The more successful approach is the two-phase Eulerian–Eulerian model.

The present work fills this gap through a systematic numerical study of hybrid nanofluid flow and heat transfer within microchannels. In particular, the thermal-hydraulic performance of hybrid nanofluids containing water-based suspensions of aluminum oxide-copper particles is studied under various Reynolds numbers and volume fraction of nanoparticles using the two-phase Eulerian-Eulerian approach. The study quantitatively evaluates the effectiveness of the enhancement in Nusselt number, reduction in thermal resistance, penalties in pressure drops, and the overall Performance Evaluation Criteria (PEC).

II. LITERATURE SURVEY

The synergy between nanofluid and microchannel cooling technology has been a topic of extensive research in the last decade, especially concerning the usage of hybrid nanofluids. The reason behind the use of hybrid nanofluids is because of their capability of combining the best attributes of more than one type of nanoparticles, such as the high thermal conductivity of metallic nanoparticles with better stability of metal oxide nanoparticles [3].

The application of computational fluid dynamics to simulate forced convection heat transfer in microtube and wavy microchannel filled with hybrid nanofluid revealed that there is an increase of 21% compared to the base fluid [6]. On the same line, Rabiei et al. studied the influence of volume fraction on both hydraulic and thermal properties of a hybrid nanofluid consisting of graphene sheets coated with platinum in a wavy cylindrical microchannel [7]. They found that there is an improvement in heat transfer performance with higher volume fractions but a small increase in friction factor [7].

In recent times, a number of hybrid systems have been studied. Kumar and Sarkar have conducted an analysis on the heat transfer and pressure drop performance of a rectangular MCHS using hybrid nanofluid of Al_2O_3-TiO_2 with different nanoparticle mixture fractions [8]. Ataei et al. have carried out experimental examination on the thermal performance of square MCHS by employing Al_2O_3/TiO_2-water hybrid nanofluid. Omosehin et al. examined the thermal performance and pressure loss of water hybrid Cu-Al_2O_3 nanofluid, where it was found that increasing the volume fraction of copper nanoparticles decreases the thermal resistance and bulk temperature [9].

Modeling plays an important role for effective prediction of the hybrid nanofluids behavior. Kalteh et al. have shown that the two-phase modeling model had much better agreements with the experimental results than the homogeneous one-phase modeling for nanofluid heat transport through microchannels, proving the need of multiphase modeling models [4]. Gorjaei and Rahmani used Eulerian-Eulerian model to analyze the influence of forced convection of SiO_2-ethylene glycol nanofluid and found out that the nanoparticle volume fraction and jet formation have a great impact on the local Nusselt number and entropy generation that are better explained with the use of Eulerian-Eulerian model [5]. Based on this research, Bazdidi-Tehrani et al. found that the Eulerian-Eulerian model predicts the maximum increase of efficiency of the hybrid nanofluid equal to 60%, whereas the one-phase model predicted only 27%.

Channel geometry is an important factor that affects heat transfer performance. Abdollahi et al. investigated the effect of particle type, volume fraction, and size on nanofluid flow in V-shaped inlet and outlet MCHSs [10]. Feng et al. numerically analyzed laminar flow in square MCHSs with wire coils inserted in them. Khodabandeh and Abbassi conducted an analysis to determine the performance of trapezoidal MCHS using Al_2O_3-water nanofluid for varying lateral angles. Ahmad et al. explored the influence of geometry, aspect ratio, and surface modifications on Nusselt number and pressure drop characteristics [8]. Some recent developments include the use of porous substrates, which has resulted in improved performance by 20-80%, at moderate Reynolds numbers due to disruption of boundary layers and improved solid fluid interaction [2,4]. The use of porous substrates along with nanofluids provides even better performance [2].

Recent studies have investigated ternary-hybrid nanofluids using three different types of nanoparticles. Jahan and Nasrin found that ternary-hybrid nanofluids with optimized nanoparticle composition ratio attained the maximum efficiency of 69% in wavy-shaped microchannels, where increase in Nusselt number is 89.56% [6]. Ternary-hybrid nanofluid of (4/3:1/3:1/3) ratio composition exhibited the maximum heat transfer, which indicates that intelligent composition ratio design could offer additional benefits [6].

However, there are many areas that need to be investigated. Most of the existing works consider parameter variation in isolation. The absence of any optimization process and fragmentation of literature with non-uniform evaluation metrics makes any benchmarking impossible [5]. Moreover, the challenges such as nanoparticle stability, fouling, reliability, and scalability need a systematic approach for their resolution.

III. PROPOSED METHODOLOGY

Physical Domain and Geometry

A three-dimensional microchannel heat sink in the form of a rectangular microchannel is used for the current analysis. The domain includes a silicon substrate with one rectangular microchannel having a width of 300 µm, a height of 600 µm, and a length of 30 mm. The bottom surface of the microchannel is exposed to a constant heat flux value of 100 W/cm², which corresponds to the cooling problem of an electronic device with high power generation. The side and top surfaces are adiabatic.

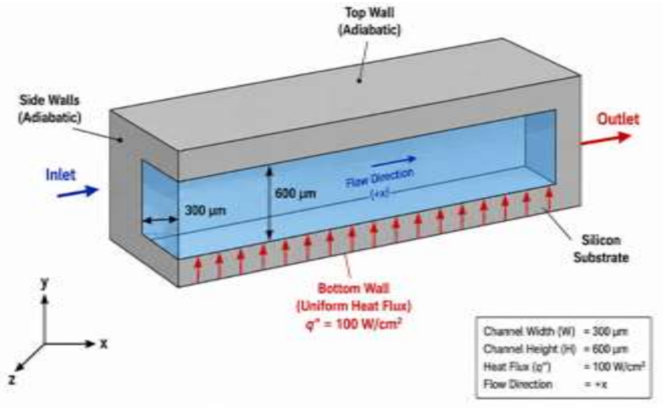

Figure 1: Schematic of the Rectangular Microchannel Heat Sink

Three dimensional schematic illustration of the rectangular microchannel heat sink having silicon substrate, microchannel of 300 µm width and 600 µm height, bottom wall of uniform heat flux boundary condition of 100 W/cm2, adiabatic side and top walls, and the arrow indicating the direction of flow along the x-axis. Coordinate system (x, y, z) shown with x-axis along the direction of flow.

Hybrid Nanofluid and Thermophysical Properties

This hybrid nanofluid involves dispersing of aluminum oxide, i.e., Al_2O_3 and copper, i.e., Cu nanoparticles in distilled water in the volume ratio of 60:40. Such combination of nanoparticles is based on their complimentary characteristics where high thermal conductivity of about 401 W/m·K of Cu nanoparticle and good stability, relatively low cost, and moderate thermal conductivity of 40 W/m·K of Al_2O_3 have been considered. Volume concentration of nanoparticles is varied in 0.5%, 1.0%, and 2.0% respectively. Properties of the base fluid and nanoparticles at 300K are shown in Table 1.

Table 1: Thermophysical Properties of Base Fluid and Nanoparticles

Property	Water	Al_2O_3	Cu
Density (kg/m³)	997	3970	8933
Specific Heat (J/kg·K)	4179	765	385

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Property	Water	Al_2O_3	Cu
Thermal Conductivity (W/m·K)	0.613	40	401

Properties such as density, specific heat, thermal conductivity, and dynamic viscosity of the hybrid nanofluid are evaluated by classical mixture theory and appropriate equations and correlations. Density and specific heat of the nanofluid are evaluated using the volume averages of the constituents. Effective thermal conductivity is computed by Yamada-Ota model taking into consideration the shape and orientation of nanoparticles. In case of hybrid nanofluids, the weighted averages of the nanoparticle properties are used according to the individual volume fraction of the Al_2O_3 and Cu. Effective dynamic viscosity is evaluated using Brinkman model taking into account the nanoparticle volume fraction.

Two-Phase Eulerian-Eulerian Modeling Approach

An Eulerian-Eulerian two-fluid model is used for simulation, since this approach has been shown to yield more accurate results for nanofluids than the single-phase homogeneous model [4,5]. This technique considers both the fluid and solid phase as continuous media, where the mass, momentum, and energy conservation equations can be formulated separately for each phase.

The continuity equation is responsible for the conservation of mass in each phase. The momentum equation for each phase takes into account the effects of pressure, viscous forces, gravity, and interphase forces, namely the drag force, the lift force, and the virtual mass force. The Schiller-Naumann drag coefficient is used to formulate the drag force, which is the major interaction between the phases. The lift force is responsible for particle migration caused by the velocity gradient, whereas the virtual mass force accounts for the acceleration of the surrounding fluid.

The energy balance in each phase incorporates conductive heat transfer, convective heat transfer, and interphase heat transfer. The value of interphase heat transfer coefficient is evaluated using the Nusselt number relation in flow around spheres. Brownian diffusion and thermophoresis effects, which are major factors governing nanoparticle dispersal on microscale level, are represented by enhanced effective parameters and source/sink terms in momentum balances. Such a two-phase model accounts for complicated phenomena arising in nanoparticle dispersion in the fluid medium and necessary for proper heat transfer enhancement prediction in microchannels.

Boundary Conditions and Solution Methodology

The following boundary conditions are used in the simulation domain. At the inlet, a constant velocity value for the chosen Reynolds number is used with a constant temperature of 300 K. Pressure outlet boundary condition with zero-gauge pressure is used at the outlet. Bottom wall of the microchannel is assigned uniform heat flux of 100 W/cm² to represent high-power electronics operation. The top and side walls are assumed to be adiabatic with zero heat flux. No-slip condition is applied to all solid walls for both fluid phases.

Governing equations are numerically solved using finite volume method through a commercial Computational Fluid Dynamics (CFD) code. The SIMPLE algorithm is used to couple pressure and velocity values. Momentum and energy equations are spatially discretized by using second order upwind scheme. Convergence criterion for all equations is set to be below 10^{-6}. To achieve grid independence, a grid independence test is performed with three different meshes. The final mesh has about 1.2 million hexahedral elements.

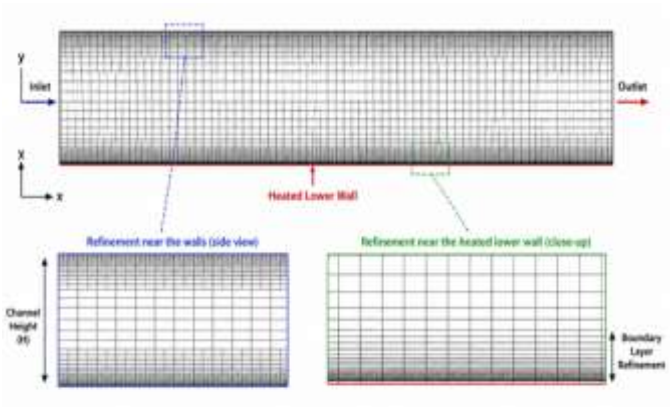

Figure 2: Computational Mesh for the Microchannel Domain

Sample computational grid with hexahedral elements in the microchannel geometry featuring finer grid in the vicinity of the heated lower wall and the microchannel walls to account for sharp gradients in the velocity and temperature fields. The grid features refined mesh starting from the middle of the channel towards its boundaries in the zones of anticipated gradients.

Data Reduction and Performance Parameters

The local Nusselt number is evaluated using the heat transfer coefficient and the hydraulic diameter. The mean Nusselt number is found via integration of the local numbers along the channel. The thermal resistance of the microchannel heat sink is found using the ratio of the temperature difference between the heated wall and the incoming fluid temperature to the heat flux.

The pressure drop is computed from the inlet and outlet pressure differences. The pump power is computed using the multiplication of the pressure drop and volumetric flow rate. In order to determine the thermal-hydraulic efficiency of the system, the Performance Evaluation Criterion is used, and this is computed by dividing the enhancement of Nusselt number to the penalty of friction factor to the one-third power. A value greater than 1 indicates a better overall performance.

IV. ANALYSIS AND DISCUSSION

Validation and Grid Independence

Before running the parametric analysis, the accuracy of the numerical method was verified using experimental results from the literature on water flow through a rectangular microchannel. It was found that there was excellent agreement with discrepancies not exceeding 5% for Nusselt number and 4% for friction factor. The grid independence test confirmed that a difference of 1.5% occurred when increasing the number of elements in the grid from 800,000 to 1.2 million for Nusselt number, but no change when going from 1.2 million to 1.6 million elements. Therefore, 1.2 million elements were used in all further computations.

Effect of Hybrid Nanofluid on Nusselt Number Enhancement

Graph 3 shows how the Nusselt number varies with Reynolds number for varying volume fractions of the hybrid nanoparticles. It can be seen that there is considerable enhancement in heat transfer performance due to the use of hybrid nanoparticles in the fluid. At a Reynolds number of 600, the Nusselt number of pure water is 12.8. When 0.5% hybrid nanoparticles are added to the water, the Nusselt number rises to 15.2, giving an enhancement of 18.8%. An increase in concentration to 1% produces a Nusselt number of 17.7, which gives an enhancement of 38.3%.

The enhancement of the process can be explained by many reasons. Firstly, the presence of high thermal conductivity nanoparticles, such as copper nanoparticles, results in the enhancement of the thermal conductivity of the working fluid. Secondly, the Brownian motion of the nanoparticles leads to micro convection and thus enhances the transportation of energy near the hot wall. Thirdly, the dispersion of the nanoparticles causes disturbance of the thermal boundary layer, which contributes to the formation of higher temperature gradients and enhances the convective heat transportation. All these phenomena are accounted for in the two-phase Eulerian-Eulerian approach, which allows having different velocities and temperatures for both phases.

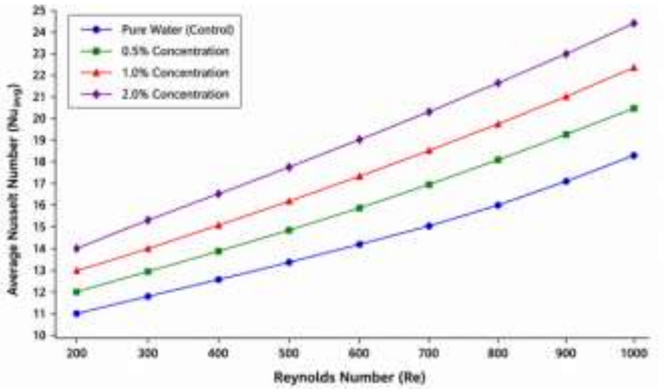

Figure 3: Variation of Average Nusselt Number with Reynolds Number for Different Volume Concentrations

Graph of average Nusselt number as function of Reynolds number with average Nusselt number ranging from 10 to 25 on the vertical axis and Reynolds number from 200 to 1000 on the horizontal axis. Four different curves are drawn; one for pure water (control), other for 0.5% concentration, for 1.0% concentration and for 2.0% concentration. All curves show the rising value of Nusselt number with increasing Reynolds number with the increasing enhancement with increasing concentration. The highest enhancement is found for the 2.0% concentration.

It can be noted that the enhancement is not directly proportionate to the concentration. The incremental benefit of increasing the concentration from 1.0% to 2.0% is the 14.0% enhancement as against 19.5% when increased from 0.5% to 1.0%. This diminishing return phenomenon implies that there is an optimum concentration above which further addition of nanoparticles leads to lower heat transfer benefit but higher viscosity costs.

Thermal Resistance Reduction

The thermal resistance change with Reynolds number for various volume fractions of nanoparticles is shown in Figure 4. Thermal resistance indicates the resistance of heat transfer from the hot wall to the fluid medium. It is clear that thermal resistance falls sharply with an increase in Reynolds number and nanoparticle concentration. For Re=400, the thermal resistance for pure water is 0.135 K/W. The thermal resistance for 0.5% hybrid nanoparticles concentration becomes 0.116 K/W (a decrease of 14.1%). For 1.0% concentration of the nanoparticles, it is 0.105 K/W (a decrease of 22.2%). For 2.0% concentration of the nanoparticles, the thermal resistance falls to 0.095 K/W (29.6%).

The decrease in thermal resistance can be attributed to the better convection coefficient that results from the superior thermal conductivity and microconvection of the hybrid nanofluid. The even distribution of nanoparticles inside the flow domain ensures that the improvement is seen for the whole length of the microchannel that has been heated. The two-phase model demonstrates that the concentration of nanoparticles within the channel is not even, as it is higher near the walls because of thermophoresis. This uneven distribution, however, helps to increase the heat transfer because of high-conductivity particles being present where the temperature gradient is the highest.

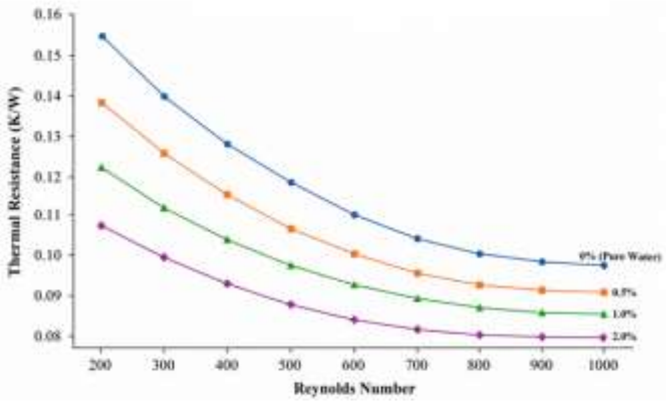

Figure 4: Thermal Resistance Variation with Reynolds Number for Different Volume Concentrations

Graph plotting thermal resistance on the y-axis in K/W from 0.08 to 0.16 against Reynolds number on the x-axis from 200 to 1000. There are four different curves plotted for 0% concentration of pure water, 0.5%, 1.0%, and 2.0% concentrations respectively. The curves plot shows that the thermal resistance decreases with an increase in Reynolds number with 2.0% concentration having the minimum thermal resistance values at all the Reynolds numbers. The difference between the curves is maximum at low Reynolds numbers.

Pressure Drop and Pumping Power Penalty

Pressure drop change with respect to the Reynolds number is shown in Figure 5. It is seen that the pressure drop increases with Reynolds number and nanoparticle concentration. For Re=600 and for pure water, the pressure drop is 8.2 kPa. However, the pressure drop at 0.5% concentration becomes 8.9 kPa (8.5% increase), while at 1.0% and 2.0% concentrations, the pressure drops become 9.4 kPa (14.6% increase) and 10.9 kPa (32.9% increase), respectively. Pressure drop penalties occur because of the viscosity increase of the hybrid nanofluid caused by nanoparticles addition. The viscosity increase follows the Brinkman model used in this work where a nonlinear increase in viscosity is predicted with the nanoparticle concentration.

At 2.0% concentration, the effective viscosity is increased by about 12.8%, compared to that of pure water, which causes the increase of the shear stress at the wall and therefore the pressure drop. Furthermore, the non-Newtonian effects caused by nanoparticles can also contribute to the increase in the pressure drop. Pumping power, proportional to the multiplication of pressure drop and volumetric flow rate, follows similar trends with respect to concentration and Reynolds number.

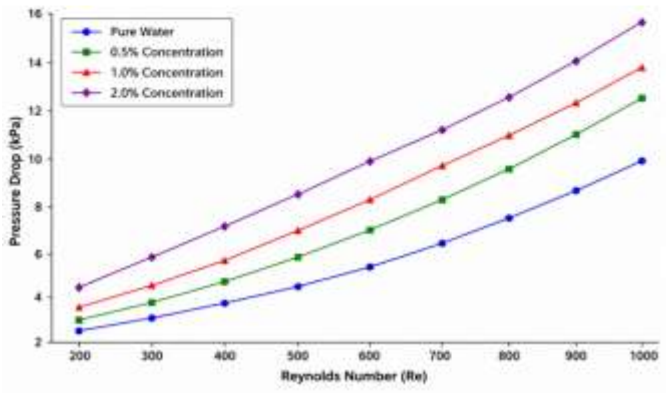

Figure 5: Pressure Drop Variation with Reynolds Number for Different Volume Concentrations

Line chart with Pressure Drop in kPa on the y-axis from 2 to 16 and Reynolds number on the x-axis from 200 to 1000. There are four graphs representing the effect of pure water, 0.5%, 1.0%, and 2.0% concentrations. All graphs represent an increase in pressure drop with increasing Reynolds number. 2.0% concentration results in the maximum pressure drop at all

Reynolds numbers. The distance between graphs increases with Reynolds number which indicates the increased importance of pressure drop.

From the table below, one can conclude about the comprehensive analysis of the performance of the system at Re = 600 for all concentrations. The values of Performance Evaluation Criterion prove that despite the penalties in pressure drops, the performance improvement is quite significant. For 1.0% concentration, the value of PEC equals 1.31 which means 31% performance improvement in thermal hydraulic terms. At 2.0% concentration, the value of PEC decreases to 1.27.

Table 2: Comparative Thermal-Hydraulic Performance at Re = 600

Concentration (%)	Nu Enhancement (%)	Thermal Resistance Reduction (%)	Pressure Drop Increase (%)	PEC
0.0 (Water)	0.0	0.0	0.0	1.00
0.5	18.8	14.1	8.5	1.17
1.0	38.3	22.2	14.6	1.31
2.0	52.3	29.6	32.9	1.27

Local Heat Transfer Characteristics

Figure 6 illustrates the variation of the local Nusselt number along the length of the channel at Re = 600 for various concentrations of nanoparticles. The local Nusselt number is highest at the entrance of the channel due to the development of the thermal boundary layer, whereas it decreases steadily up to the fully developed stage. The use of hybrid nanoparticles improves the local Nusselt number along the whole length of the channel, especially at the entrance where the thermal boundary layer is very thin.

In the entrance region, the local Nusselt number for pure fluid is around 22.5 while it rises up to 28.4 at a concentration of 1.0%, showing an increase of 26.2%. In the developed region (x/L > 0.6), the local Nusselt number for pure fluid is about 11.2, which rises to 15.8 at a concentration of 1.0% with an increase of 41.1%. These results show that the nanoparticles play a significant role at the developed stage where the heat transfer process would be restricted by the thick thermal boundary layer.

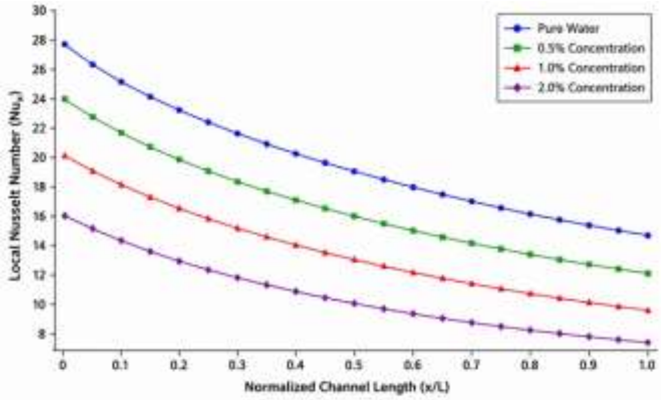

Figure 6: Local Nusselt Number Distribution Along Channel Length at Re = 600

Line graph of local Nusselt number plotted on the y-axis from 8 to 30 against normalized channel length x/L plotted on the x-axis from 0 to 1.0. There are four lines for pure water, 0.5%, 1.0%, and 2.0% concentration. All the curves have a trend of decreasing local Nusselt number as the channel length increases from high value at the entrance to lower value in fully developed flow. The separation between the lines is kept constant across the whole length of the channel.

Temperature Field Analysis

The temperature field analysis shows that the hybrid nanofluid has much lower temperatures at the walls when compared to the pure water under identical heat flux and flow rates. In particular, for Re = 600 and a 100 W/cm² heat flux, the maximum wall temperature of pure water is 358.4 K. With 1.0% hybrid nanoparticle volume fraction, the maximum wall temperature drops to 345.2 K, thus resulting in a 13.2 K drop in the maximum wall temperature. It is vital to note that the reduction of the maximum wall temperature is crucial for increasing electronic device reliability since the junction temperature influences the device characteristics.

This temperature decrease should be due to increased effective thermal conductivity and convection heat transfer coefficient. Two-phase modeling indicates that the nanoparticles' temperature is slightly higher than that of the liquid in the near-wall region, which means that the nanoparticles can effectively absorb the heat from the wall and transfer it to the bulk fluid.

V. CONCLUSION

This research involves an extensive numerical analysis of heat transfer augmentation in microchannel flows by utilizing Al_2O_3-Cu/water hybrid nanofluids. The Eulerian-Eulerian two-phase flow modeling is employed in order to provide precise predictions of the complex interaction of the nanoparticles and base fluid, which can lead to the improvement in thermal-hydraulic performance of the hybrid nanofluids in the microchannel cooling process. This work proves the efficiency of the hybrid nanofluid in increasing heat transfer.

Summary of the main results of this study can be outlined in the following manner:
Firstly, hybrid nanofluids significantly increase convection heat transfer inside micro-channels due to several mechanisms working together. At nanoparticle concentration of 1.0% volume and Re = 600, Nusselt number is enhanced by 38.3%, while for the 2.0% concentration, the Nusselt number is enhanced by 52.3%. Two-phase modeling shows that the effect of thermophoresis leads to nanoparticle localization in near-wall area where nanoparticles significantly increase heat transfer from the hot surface into the fluid.

Secondly, the thermal resistance of the microchannel heat sink is drastically lowered by hybrid nanofluids. The maximum thermal resistance reduction is 29.6%, which occurs at 2.0% concentration, equating to the maximum wall temperature reduction of 13.2 K at Re = 600. This reduction of the wall temperature is vital in ensuring the reliability and performance of electronic devices. It makes the removal of the heat from high power electronic components more efficient.

Third, it was observed during the thermal hydraulic performance evaluation that the advantages offered by hybrid nanofluids are greater than their penalty regarding pressure drop at moderate concentrations. The maximum value of Performance Evaluation Criterion was found to be 1.31 at 1.0% concentration, meaning that there is an increase in thermal-hydraulic performance by 31%. The diminishing benefits of using the hybrid nanofluids in the higher concentrations together with the increasing problem of viscosity makes it necessary to find the optimal range of concentration, which is 0.5% and 1.0%. The 60:40 volume fraction ratio of Al_2O_3-Cu is suitable.

The fourth benefit is that the heat transfer local analysis shows an increase in heat transfer enhancement using hybrid nanoparticles throughout the entire length of the channel. Heat transfer enhancement increases significantly in the fully developed flow regime, reaching 41.1% at 1.0% concentration level, while in the entrance region it is 26.2%. It is very beneficial that hybrid nanoparticles show enhanced heat transfer not only in the entrance region but throughout the whole length of the channel since passive methods become ineffective in the developed flow regime.

Fifthly, the two-phase Eulerian-Eulerian model is verified as a good method for simulations of hybrid nanofluids in microchannels. This method allows us to predict the non-uniform distribution of nanoparticles caused by the thermophoresis and Brownian motion processes. Such modeling technique will provide a basis for further optimization work with different types of nanoparticles and their concentrations and different geometries of microchannels.

Practical implications of this study are immense for the thermal management industry. Hybrid nanofluids represent a promising option for solving the increasing problem of cooling in high-power electronics, data centers, and power electronics. The obtained results of enhanced heat transfer ranging between 38% and 52% will allow for higher power densities, decreased cooling system sizes, and energy savings. The obtained values of PEC greater than one prove the feasibility of these options from the economic perspective.

Areas for future study on hybrid nanofluids include their stability and reliability during actual operation. Although there have been many studies confirming improved performance in the short run, the agglomeration and settling of nanoparticles over time during operation may cause deterioration of performance. Another area of concern is erosion and fouling due to the particles on the microchannels, especially with high concentration levels of nanoparticles. Other possibilities that can be explored include the optimum ratio of nanoparticle composition and use of ternary and quaternary hybrid systems. The use of hybrid nanofluids together with other advanced microchannel technology, including porous substrates and jet impingement, offers much promise in the area.

In summary, this study has shown strong support for the use of hybrid nanofluids as potential candidates for improving the efficiency of heat transfer in microchannels through increased Nusselt number, thermal resistance, and Performance Evaluation Criterion. This is attributed to the detailed study carried out on the enhancement mechanism involved in the hybrid nanofluid flow.

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