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SIMULATION OF HEAT TRANSFER AND A NEW NANOFLUID FLOW INSIDE A HORIZONTAL CHANNEL

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ABSTRACT

The current investigation aims to simulate the heat transfer of conventional fluid and various types of nanofluids inside a horizontal heated tube exposed to a constant heat flux. This study implemented Ansys Fluent release 2021 R1 with a single-phase model that used nearly spherical nanoparticles with a constant diameter of 20 nm and 50 nm for Alumina ($Al2O3$) and Ceria ($CeO2$), respectively. The investigation used a volume concentration of nanoparticles from 0.1% to 2% Vol and a Reynolds number range of 400-2000. The findings indicate that, in all situations for hybrid nanofluid, the Nusselt number increased due to an increase in the Reynolds number and the volume concentration compared to the base fluid (Deionized water DI). The improvement ratio between the hybrid nanofluids and conventional fluid at varying volume concentrations was analyzed. Alumina and Ceria hybrid nanofluid with a 2% volume fraction showed the most increased heat transfer ratio, around 13.12%, compared to DI water. The outcomes of this study might be used to fabricate a new generation of nanofluids.

KEYWORDS

New nanofluid; Heat transfer; Horizontal channel; Ceria nanoparticles; Alumina nanoparticles and Hybrid nanofluid.

1. INTRODUCTION

Throughout recent decades, many investigators have concentrated their attention on making liquids that play better with heating or cooling performance over typical thermal transfer fluids like water, engine oil, ethylene glycol, and salt liquids. Suspending a small number of certain types of metallic or non-metallic nanoscale with relatively high thermal conductivity in these typical fluids is one of the latest modern techniques to boost heat exchange systems (Junhao Li, 2021, Jahar Sarkar, 2015, Hamza Babar, 2019). Due to their noticeable benefits, such as better thermo-physical properties, long-term stability, tremendous heat transfer rate augmentation, as well as a slight penalty in pressure drop raise, numerous studies have been done in past years on the heat transfer and fluid flow characteristics of nanofluids for convective and multiphase flow heat transfer studies such as (Thong Le Ba, 2022, Mohammed Saad Kamel, 2020a, Mohammed Saad Kamel, 2020b, Al-Mayahi, 2018). Nanofluids present a new class of thermal fluid prepared by dispersing nanoscale particles in conventional liquids. There are two techniques to prepare those new thermal fluids: one-step and two-step. The standard one-step technique refers to the fabrication of the nanoparticles and suspension happening together. The two-step technique is the most widely utilized and suitable for large-scale applications. The researchers considered suspending various combinations of nanoscale materials in conventional liquids after discovering that mono nanofluids worked effectively and produced good results for heat transfer systems. These new suspensions were eventually developed and termed hybrid nanofluids. The previous studies in the field of nanofluids have shown that when compared to mono nanofluid, hybrid nanofluid performed better and offered a higher heat transfer rate due to superior thermophysical properties, especially the thermal conductivity (Mohammed Saad Kamel, 2021b, K.Y. Leong, 2017, Gaurav Bharadwaj, 2024).

(D. Madhesh, 2015) experimentally studied the enhancement of heat transfer and fluid flow for hybrid nanofluids, which consist of titanium oxide and copper (TiO2 and Cu) through tubular heat exchangers. They noticed that up to a particle volume fraction of 0.7 vol.%, the Nusselt number revealed an increasing trend. However, they observed the drop in Nusselt number due to clustering after they passed the 0.7 vol.% limit because the higher particle concentration decreases the distance between particles, so the Van der Waals forces increase among the particles, and then the chance of clustering increases. (K.Y. Leong, 2017) addressed the difficulties, synthesis methods, thermal conductivity, and potential applications of hybrid nanofluids. In accordance with the concluding comments, published work has demonstrated that the thermal conductivity of hybrid nanofluids increases with temperature and particle concentration. The primary barrier restricting hybrid nanofluid usage across various industries, especially on a large scale, is stability. The selection of appropriate hybrid nanomaterials, the intricate production process, and the availability of thermal conductivity models capable of predicting thermal conductivity precisely or within a reasonable error range were additional obstacles.

(Mohammad Hemmat Esfe, 2017) measured the thermal conductivity of single-walled carbon nanotube SWCNTs with oxide magnesium MgO-based ethylene Glycol EG as a base fluid. The temperature range for producing and testing hybrid nanofluids runs from 30 to 50°C, with a concentration of 0.05-2%. The results show that with a volume concentration increase of up to 1%, the thermal conductivity gradient rises, and then the sensitivity drops. (Al-Mayahi, 2018) the effect of copper/ water nanofluid on laminar mixed convection flow for a lid-driven cavity was studied. The findings demonstrate that the Nusselt number rises as the Reynold number, Rayleigh number, and nanofluid concentration increase.

(Salih and Yaseen, 2020) numerically investigated the laminar forced convective flow with mono nanofluids. Their study estimated the thermal and fluid flow characteristics of an Al2O3-water nanofluid in a circular tube with a constant heat flux. The impact of the nanoparticle's volume concentration of less than 5% and Reynolds number on thermal-hydraulic performance was studied. The numerical results reveal that using Al2O3 nanoparticles greatly increases the average coefficient of heat convection, which is raised by 10% compared to the base fluid.

(Firas Aziz Ali, 2023) investigated the performance of hybrid nanofluids, which consist of Al2O3 and ZnO (50:50), with low concentrations (0.1-0.5 Vol.%) inside the heat exchange system. Their results presented that the heat transfer and friction factor were enhanced with high concentration.

According to the previous studies that were reviewed regarding the utilizing of nanofluids to enhance the heat transfer of heat exchange systems, prior works have mostly concentrated on various mono nanofluid types with vertical and horizontal tubes, with little attention paid to using hybrid nanofluids such as a combination of Alumina and Ceria hybrid nanocomposites based deionized water as a new nanofluid inside a heated horizontal channel. However, with the balanced contribution made by Alumina nanofluid's thermal conductivity and Ceria nanofluid stability, the Al2O3 – CeO2 nanofluid combination regularly provides superior heat transfer performance compared to other nanoparticles (such as copper or silver). Over time, improved thermal performance results from the stable suspension and higher thermal conductivity were found in many studies in the literature. In addition, Alumina and Ceria nanoparticles combined in nanofluids provide a unique combination of boosted thermal conductivity, superior stability and dispersion, cost-effectiveness, and potential catalytic characteristics. Because of these benefits, it is a very promising option in several applications, such as energy systems, cooling, and heat transmission. Therefore, a nanofluid of Alumina and Ceria nanomaterials-based deionized water with a low range of volume concentration inside a horizontal heated channel with constant heat flux was numerically investigated. Also, the flow condition was assumed to be a laminar regime, and the Reynolds number was varied in the range of 400-2000.

2. MATHEMATICAL MODEL AND THERMOPHYSICAL PROPERTIES

In the current work, the governing differential equations (continuity, momentum, and energy) for the single-phase model can be expressed as follows (Mohammed Saad Kamel, 2018, Adnan M. Hussein, 2017):

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}=0 \tag{1}$$

$$U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}=-\frac{1}{\rho_{HNFs}}\frac{\partial p}{\partial x}+v_{HNFs}\left(\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}\right)-grav_x,$$

$$U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}=-\frac{1}{\rho_{HNFs}}\frac{\partial p}{\partial x}+v_{HNFs}\left(\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}\right)-grav_y, \tag{2}$$

where p is the static pressure and ($grav = \rho \mathbf{g}$) is the gravitational force term; U and V are velocity components, and x and y are coordinates in Cartesian space.

$$U\frac{\partial T}{\partial x}+V\frac{\partial T}{\partial y}=\alpha_{HNFs}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{3}$$

where ρ_{HNFs}, v_{HNFs}, $\alpha_{HNFs}=\frac{\lambda_{HNFs}}{\rho_{HNFs}\cdot C_{p,HNFs}}$ are the hybrid nanofluids density, kinematic viscosity, and thermal diffusivity, respectively.

This simulation takes into account the following simplifications and assumptions:

- The case is a fully developed laminar flow.
- Heat transfers only from the channel wall to the fluid within forced convection.
- Steady-state flow inside the horizontal channel.
- The fluid is incompressible and viscous.
- The geometry is symmetrical and 2-D.
- The thermophysical properties of the fluids are constant.

The thermophysical properties of the nanomaterials and working liquid utilized in this work are presented in Table 1. as stated in previous work (Al-Oran et al., 2020, Mohammed Saad Kamel, 2021a).

Table 1. Thermophysical properties of the nanomaterials and working liquids utilized in this simulation (Al-Oran et al., 2020, Mohammed Saad Kamel, 2021a) .

Property	Deionized water (DI)	Alumina (Al_2O_3)	Ceria (CeO_2)	Al_2O_3+CeO_2 Mixing (50:50)
Density $\left[{kg}/{m^3}\right]$	996.56	3970	7220	5595
Specific heat $\left[{J}/{kg.K}\right]$	4180	765	460	612.5
Thermal conductivity $\left[{W}/{m.K}\right]$	0.609	40	12	26
Dynamic viscosity [**Pa s**]	0.00085	-	-	-

The concentrations of the Alumina-Ceria hybrid nanofluids were proposed to be dilute with a range of (0.1-2) Vol.%, and for this reason, the simulation was considered to be in the single-phase model as many studies mentioned that using proper thermal properties correlations could give accurate results (Hanafizadeh et al., 2015, Eshgarf et al., 2023).

In the single-phase model, the nanofluids are treated as normal fluids but with modified thermophysical properties due to the presence of the nanoparticles, and hence, the stability and agglomeration issues of the nanofluid can be avoided. The thermophysical characteristics of hybrid nanoparticles are averaged, and their mixing ratio is set at 50:50 to mimic this work. This simulation incorporates the thermophysical properties of deionized water at 300 K with isobaric properties from the NIST Chemistry Web-Book. The thermophysical properties of the new hybrid nanofluids were calculated in this work with an acceptable degree of accuracy using Eq. 4 to Eq. 7, which depend on various parameters, including the volume concentration, conditions, and types of nanomaterials used in the present investigation (Mohammed Saad Kamel, 2021b, Mohammed Saad Kamel, 2022).

$$\rho_{HNFs} = \varphi\rho_{HNMs} + (1-\varphi)\rho_{DI\,water} \tag{4}$$

$$C_{p,HNFs} = \frac{\varphi(\rho C_p)_{HNMs} + (1-\varphi)(\rho C_p)_{DI\,water}}{\varphi\rho_{HNMs} + (1-\varphi)\rho_{DI\,water}} \tag{5}$$

$$k_{HNFs} = (1.21 - 0.00958T - 0.223\varphi + 0.0001223T^2 + 0.006598T\varphi) \times k_{DI\,water} \tag{6}$$

$$\mu_{HNFs} = (1 + 7.3\varphi + 123\varphi^2)\mu_{DI\,water} \tag{7}$$

The improvement ratio in the heat transfer is calculated as:

$$\text{Improvement Ratio} = \frac{Nu_{HNFs} - Nu_{Fluid}}{Nu_{HNFs}} \times 100\% \tag{8}$$

The physical structure of this work is a horizontal heated channel with a circular cross-section of 1 m in length and 10 mm in diameter, as presented in Fig. 1. The length of the channel was increased by 0.5 mm from the inlet to the heated wall within an adiabatic condition to ensure a fully developed condition (Doherty et al., 2007). The working liquids used in this simulation were the deionized water and (Alumina + Ceria) hybrid nanofluid with different volume fractions. Since dividing the computational domain into smaller symmetric subdomains does not affect the results and would minimize computing time, the thermal zone and fluid flow are considered to be two-dimensional axisymmetric concerning the flow along the x-axis. Concerning the boundary conditions of this simulation, a constant temperature of 300 K and uniform velocity were assumed at the inlet of the tube. In addition, non-slip conditions with a constant heat flux of 2000 W/m^2 on the heated section of the channel were adopted. A pressure outlet condition at the point of exit zones and a uniform velocity profile at the inlet were used for the CFD study. Moreover, for the single-phase model assumption with no slip velocity between the phases, the velocity of a solid phase (nanoparticles) and the liquid phase (DI water) is assumed to be the same at the entrance of the channel.

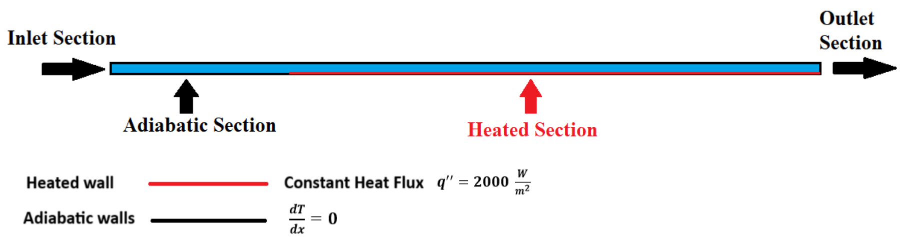


Fig. 1. Physical geometry for the present model.

In this simulation, the heat transfer of a hybrid nanofluid inside a horizontal heated channel with a constant heat flux is introduced for the purpose of predicting and evaluating the performance of the hybrid nanofluids compared to the base fluid. The Computational Fluid Dynamic (CFD) program represented by ANSYS Fluent Release 2021R1, which is widely used to investigate the performance of nanofluids (Eshgarf et al., 2023), was adopted to simulate the heat transfer performance in current work. The control volume method was utilized to solve the governing single-phase conservation equations. The SIMPLEC method is applied to set up the coupling between velocity and pressure. Second-order upwind discretization algorithms are employed in the single-phase calculations to minimize computational errors in this simulation. Mesh sensitivity was studied using a structured grid based on a quadrilateral mesh via ANSYS 2021R1, as illustrated in Fig.2.

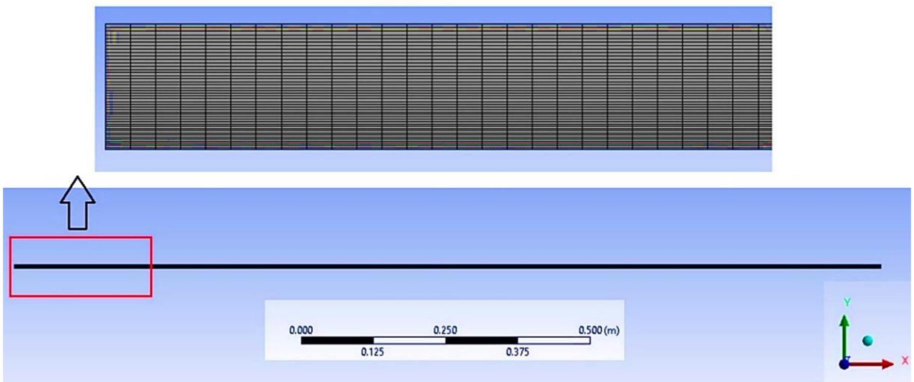


Fig. 2. The computational meshes utilized in the present simulation using ANSYS 2021R1.

The impact of grid size on the outcomes was examined using deionized water as the working fluid. Four sets of the meshes were investigated: 30,000, 45,000, 60,000, and 90,000 cells at a Reynolds number of 1500. Convergence criteria were utilized to decide when the solution could be considered suitable; for the current simulation, the residual monitors were set to be 10^{-5} for continuity, momentum, and energy equations to confirm the accuracy and reliability of the findings. Fig. 3 illustrates the mesh independence test for deionized water at different numbers of cells. It was found that the relative error percentage for the average Nusselt number comparison for all four-grid sizes was less than 0.3%. Therefore, to achieve an acceptable balance between the computing time and the data accuracy, the second mesh consisting of 45,000 cells was used in this simulation.

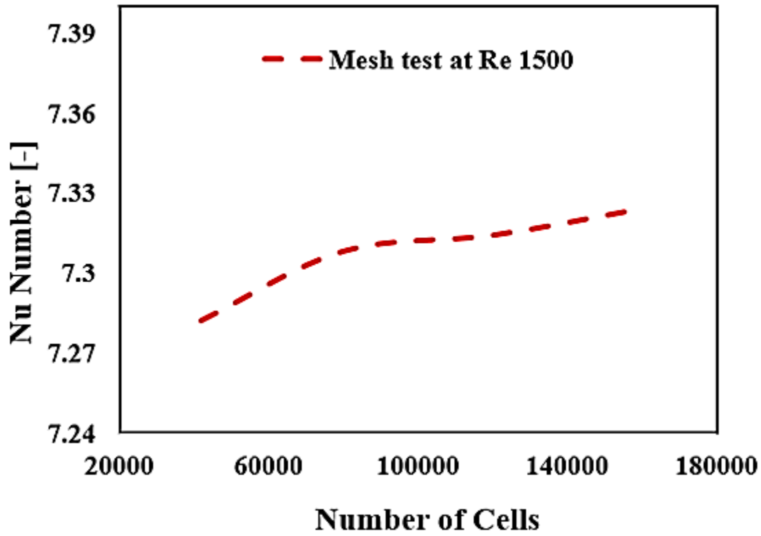


Fig. 3. The model mesh independence test.

3. RESULTS AND DISCUSSION

In the present work, the heat transfer performance of a new hybrid nanofluid inside a horizontal heated channel was numerically investigated. Several hybrid nanofluids consisting of Alumina and Ceria nanomaterials with a mixing ratio of 50:50 at different volume concentrations with a base fluid of DI water were studied. The average Nusselt number of DI water inside the horizontal channel with constant heat flux has been validated and compared to the results of a well-known correlation, namely the Shah correlation (Mohammed Saad Kamel, 2018, Hwang et al., 2009, Hussein, 2017). Also, the experimental data of (S. Zeinali Heris, 2013) was used to validate the numerical results of the present simulation. Fig. 4 introduced the average Nusselt number versus Reynolds number of the present CFD model, Shah correlation, and experimental results. It can be seen that the predicted CFD results agree well with the Shah equation and are acceptable to the experimental results of the literature. The standard error of the mean (SEM) for obtained results was calculated for the data points; the SEM measures the amount that the sample mean might shift if the sampling procedure were carried out several times with the same characteristics. In addition, the Mean Absolute Percentage Error (MAPE), which is a typical statistical index for assessing a predictive model's accuracy, was calculated. The MAPE of the CFD results compared to the Shah correlation results was 3.25%.

After verifying the accuracy and reliability of the present model, heat transfer performance was presented for DI water and hybrid nanofluids at Reynolds numbers (400, 500, 1000, 1500, and 2000) and concentration values of 0.1%, 0.5%, 1%, and 2% Vol.

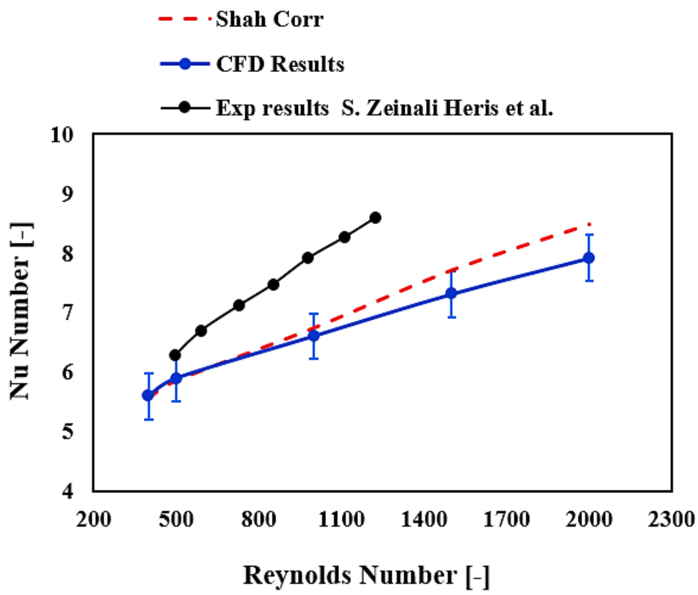


Fig. 4. Nusselt number versus Reynolds number of the present model, Shah correlation, and experimental data.

Fig. 5 depicts the results of the average Nusselt number and Reynolds number at various volume concentrations of Alumina-Ceria hybrid nanofluids (0.1%, 0.5%, 1%, and 2% Vol.). The outcomes demonstrate that the average Nusselt number increased when hybrid nanofluids were used compared to DI water. Nusselt number was also shown to increase when the concentration of hybrid nanofluids for all Reynold numbers was increased. The Brownian motion of the hybrid nanoparticles was the main reason for improving the thermal conductivity of nanofluid, as stated in many research works in the literature. Several investigations in the literature (Mohammed Saad Kamel, 2021b, Mohammad Hemmat Esfe, 2017, K.Y. Leong, 2017) have suggested several explanations for the rising thermal conductivity of nanofluids, such as particle-liquid layering interaction and kinetic movement of energy carriers. The impact of the particles on the growth of the hydrodynamic and thermal zones throughout the entire length of the channel was one of the main justifications for enhancing the heat transfer performance. The outcomes match the increase in Nusselt number of nanofluid at various volume fractions obtained by some studies (Mohammed Saad Kamel, 2018, Hussein, 2017).

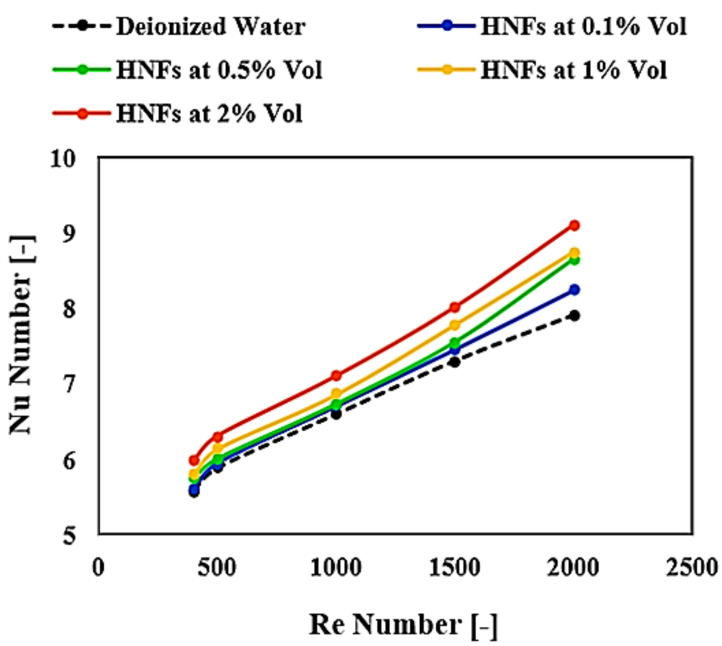


Fig. 5. Nusselt number versus Reynolds number for DI water and hybrid nanofluids at various volume concentrations.

Fig. 6 demonstrates the results of heat transfer performance represented by the Nusselt number with respect to the Reynolds number for mono nanofluids, including Alumina and Ceria nanofluids with various concentrations. The finding showed that the thermal performance of mono nanofluids differs from hybrid nanofluids at the same concentrations (0.5% and 1%) and the same flow regime. The Alumina (Al_2O_3) nanofluid has an increase in Nusselt number compared to DI water at a high Re number, and this is due to the high thermal conductivity for this type of nanofluid compared to the CeO_2 nanofluid. On the other hand, the Ceria nanoparticles have higher density compared to Alumina nanoparticles, which leads to a decrease in the stability of prepared nanofluid as stated in previous studies (Mohammed Saad Kamel, 2021b, Mohammed Saad Kamel, 2021a, K.Y. Leong, 2017). It can be concluded that the hybrid nanofluid has better heat transfer performance than a single nanofluid at the same conditions, and this could be attributed to the proper mixing ratio and the high thermal conductivity for used concentrations.

Fig. 7 shows the improvement ratios in heat transfer for various hybrid nanofluids versus the Reynolds number. It is obvious that the hybrid nanofluid with a 2% volume fraction has the highest heat transfer ratio of approximately 13.12% when compared to DI water at a high Reynolds number (2000). The findings of the simulation of the improvement in heat transfer for the Al_2O_3-CeO_2/ water hybrid nanofluid with current volume fractions under laminar flow conditions within a circular channel seemed to be somewhat closer to the experimental data of (S. Zeinali Heris, 2013) and simulation results of (Mohammed Saad Kamel, 2018).

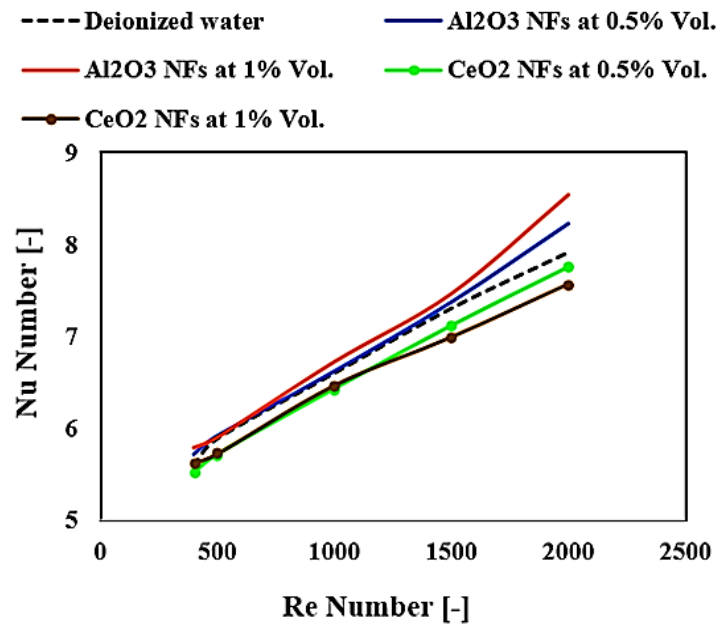


Fig. 6. Nusselt number versus Reynolds number for DI water and hybrid nanofluids at various volume concentrations.

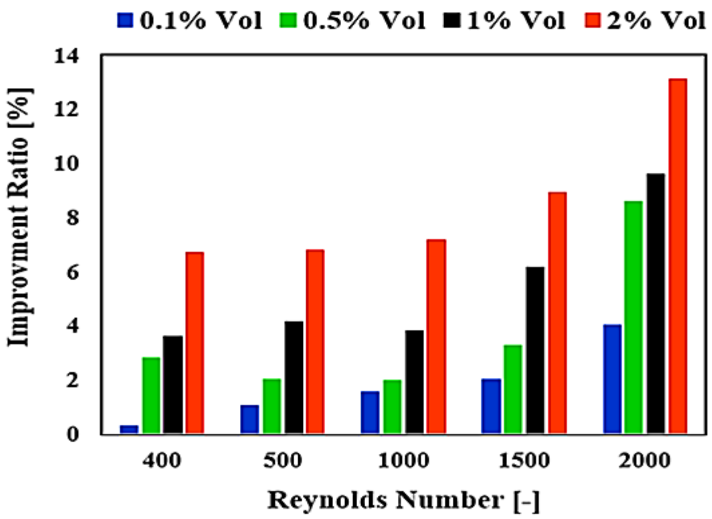


Fig. 7. Improvement ratio versus Reynolds number for hybrid nanofluids at various volume concentrations.

Fig. 8 illustrates the improvement ratios for mono nanofluids at different concentrations and Re numbers, including Alumina and Ceria nanofluids. The results demonstrate that for the Alumina nanofluid, there was an increase in this ratio of about (3.7% and 7.3%) for 0.5% and 1% volume concentrations, respectively. While for Ceria nanofluid, there was a decrease in the improvement ratio compared to Alumina and hybrid nanofluid, and this reduction was about (-2% and -6.2%) for 0.5% and 1% volume concentrations, respectively.

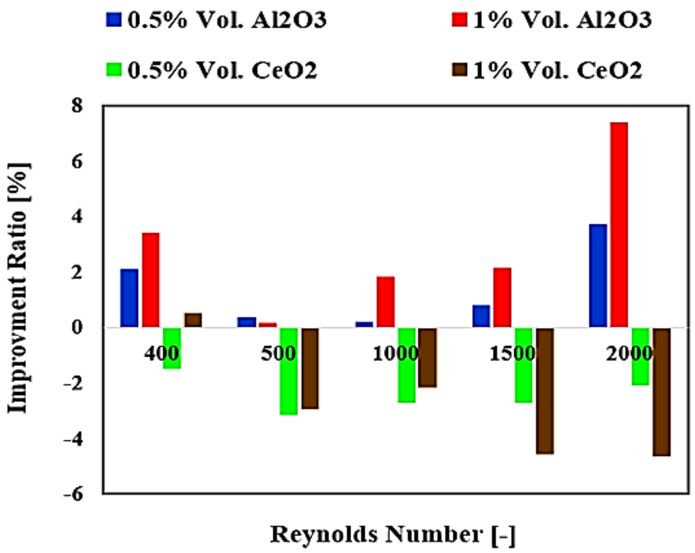
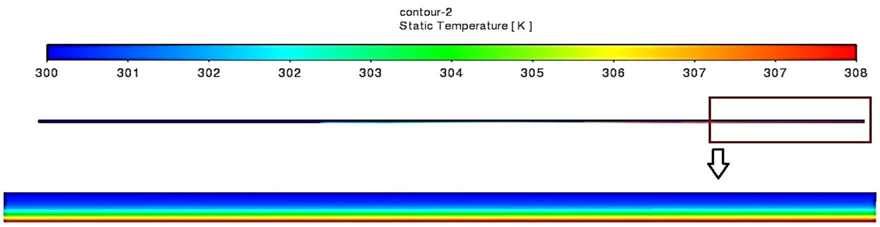


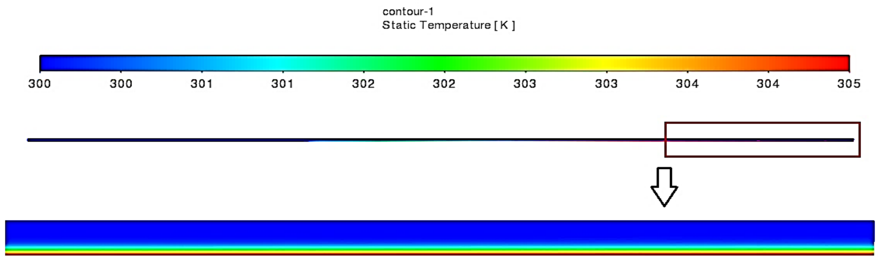
Fig. 8. Improvement ratio versus Reynolds number for mono nanofluids (Alumina and Ceria) nanofluids at 0.5% and 1% volume concentrations.

Fig. 9 shows the contours of static temperature for different cases of DI water and hybrid nanofluid at a constant concentration of 2% Vol and different Reynolds numbers along the heated horizontal channel. For DI water at a Reynolds number of 400, the average temperature inside the thermal boundary layer close to the heated wall is 308 K. In contrast, the average temperature of the free streams outside the thermal boundary layer at the tube's core is 302K. However, the average temperature inside and outside the thermal boundary layer is about 305 K and 301 K, respectively, for a Reynolds number of 2000. This is because the velocity of the fluid increases with an increasing Reynolds number, which means less time for the fluid to dissipate the heat from the wall. Hence, the temperature of the fluid decreases with increasing Reynolds number. It is worth mentioning that the temperature of the hybrid nanofluid follows the same behaviour of DI water; however, the value of temperature for all cases is higher compared to the DI water due to the improvement in the thermophysical properties of the hybrid nanofluid compared to the base fluid.

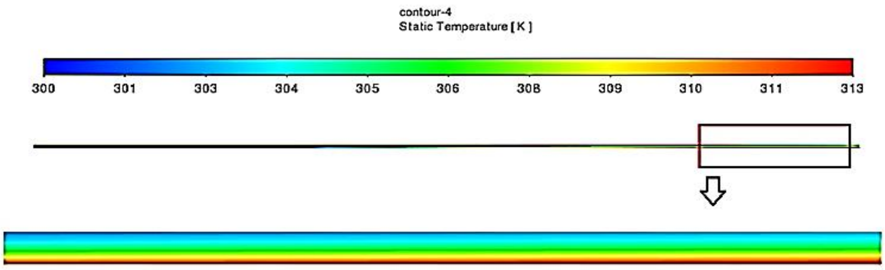
The numerical studies that addressed the utilization of hybrid nanofluids in the applications of heated tube or channels are listed in Table 2. The heat transfer performance of this study was compared to previous research findings in the literature. Other relevant studies from the literature were selected to compare with the obtained results, with an emphasis on studies that used conditions similar to current work, in order to gain a better understanding of the enhancement mechanisms during the laminar convective heat transfer flow of Alumina-Ceria/water nanofluids. The comparison of the current results and previous works shows that the heat transfer performance represented by Nusselt (Nu) or the heat transfer coefficient (h) depends on the bulk effect that is related to the thermophysical properties of the fluid and the type of flow regime as well as the surface characteristics of the heated tube. However, if a nanofluid is employed until the nanoparticle concentration reaches an optimal value, these parameters can result in improved heat transfer performance.



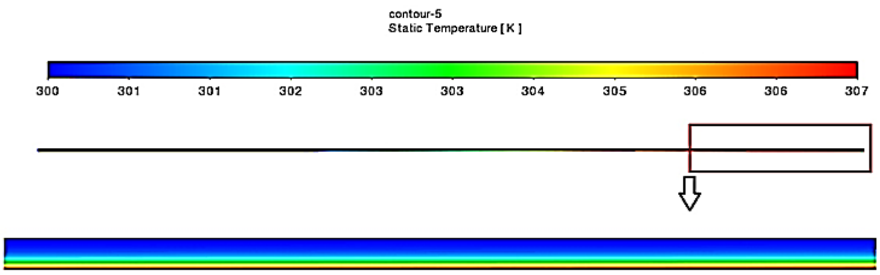
DI water at Re 400



DI water at Re 2000



HNFs at Re 400 for 2% Vol.



HNFs at Re 2000 for 2% Vol.

Fig. 9. Contours of static temperatures for DI water and hybrid nanofluid with 2% concentrations at different Reynolds numbers.

Reference	Hybrid NF	Reynolds No./ Concentration	Application	Key findings
(Wong and Tiong, 2021)	Al_2O_3-Cu/water	Re: 10000-100000/ 0.1-2%	Heated tube	At Re of 10000 and HNF concentration of 2%, ***Nu*** and ***h*** increased by 37.47% and 58.6% compared to pure water values.
(Lanka et al., 2023)	$ZnFe_2O_4$/water	Re:1275, 1500, 1875 and 2200/ 0.1-2%	Heated tube	At Re of 2200 and HNF concentration of 2%, ***h*** increased by 42.09% and 34.07% compared to pure water and Fe_2O_4/water.
(Moghadassi et al., 2015)	Al_2O_3-Cu/water	Re:800-2300 /0.1%	Heated tube	The average increases in Nu were 13.46% and 4.73% compared to pure water and Al_2O_3/water.
(Gupta et al., 2020)	$ZnFe_2O_4$/water	Re:1275, 1500, 1875 and 2200 /0.02-0.5%	Heated tube	At Re of 2200 and HNF concentration of 0.5%, ***h*** and pressure drop increased by 42.99% and 72% compared to pure water.
(Kaska et al., 2019)	AlN - Al_2O_3 /water	Re:5000-17000/ 1-4%	Heated tube	At Re of 17000 and HNF concentration of 3%, ***Nu*** increased by 50% compared to pure water.
(Garud and Lee, 2021)	Al_2O_3-Cu/water	Re:2000-12000 /0.5-2%	Heated tube	At Re of 12000 and HNF concentration of 2%, ***Nu*** increased by 14.8% compared to pure water.
Present study	Al_2O_3-CeO_2/water	Re:500-2000 /0.1-2%	Heated channel	At Re of 2000 and HNF concentration of 2%, ***Nu*** increased by 13.12% compared to pure water.

4. CONCLUSIONS

The present study examined numerically the heat transfer of laminar forced convection of deionized water DI and new hybrid nanofluids based on Al_2O_3 and CeO_2 nanoparticles with a mixing ratio (50:50) inside a horizontal channel. The results of this study demonstrate that the use of new hybrid nanofluids made of Al_2O_3 and CeO_2-based DI water nanofluids in a horizontal channel enhances the performance of heat transfer determined by the Nusselt number when compared to DI water. It was also noticed that the heat transfer of the nanofluids improved with increasing Reynolds number and volume concentrations. Furthermore, the improvement ratio for prepared nanofluid (Alumina-Ceria/ water) at various volume concentrations was demonstrated. The hybrid nanofluid with a 2% volume concentration exhibited the highest enhancement, at around 13.12%. However, for the future direction of using hybrid nanofluids, it is possible to use other combinations of two or more nanoparticles suspended in another base fluid, such as carbon-based nanoparticles and metal oxides, to optimize their synergistic effects.

Examining how hybrid nanofluids behave in laminar and turbulent flow scenarios by focusing on the effects of heat transfer under the various Reynolds numbers and flow regimes will also benefit future studies. Extending the investigations to cover more performance, including hydrodynamic and thermodynamic analyses, would be useful for practical applications. In addition, the study of hybrid nanofluids affecting convective heat transfer, evaporation, and flow boiling in forced and free convection systems will be important because these processes are used in many applications, such as heat exchangers and electronic cooling systems. Finally, the results of this study might guide the fabrication of a new type of nanofluid and enhance the heat transfer efficiency of different heat exchange systems.

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