ZAJESE
ZARIA JOURNAL OF EMPIRICAL STUDIES IN EDUCATION

EFFECT OF AN ISOTHERMAL WALL AND THE CHARACTERISTIC PROPERTIES OF SELECTED NANOFLUIDS IN A MIXED CONVECTION FLOW

Luqman, A. Azeez & Zubairu, H. Kaseem
Department of Mathematics
Federal University of Education, Zaria
Luqmant14@mail.com

Abstract
This research investigates the effect of an isothermal wall and the characteristic properties of selected nanofluids in a mixed convection flow. The coupled partial differential equations (PDEs) are derived as governing equations and solved using the Laplace transform technique. The study evaluates nanofluid's velocity, temperature, penetration distance, heat transfer rate, and shear stress based on dimensionless parameters. Additionally, the study correlates the effects of heat transfer and shear stress near the plate surface, presenting the findings in a suitable table. The results indicate that Ag-water and Cu-water exhibit similar profiles, while oxides differ. Furthermore, an increase in nanoparticle volume fraction over time leads to an increase in the Nusselt number and shear stress. This research recommends the use of high heat transfer to give a low change in porosity, permeability and nanoparticle concentration. High heat should also be used as it affects the velocity and temperature profiles inside the boundary layer.
.

Keywords: Mixed convection, Isothermal, Nanofluid, Vertical plate

Introduction

Mixed convection flow, which combines the effects of buoyancy-driven natural convection and externally forced convection, plays a crucial role in numerous engineering applications, including electronic cooling systems, heat exchangers, and thermal management devices. The introduction of nanoparticles into base fluids has further enhanced heat transfer efficiency due to their superior thermal conductivity, making nanofluids a key focus in contemporary thermal-fluid research (Habib et al. 2024). A fundamental configuration for studying mixed convection involves flow near an isothermal vertical plate, where the interplay between buoyancy forces and external flow significantly influences the development of the thermal boundary layer (Basant & Gabriel, 2022). The isothermal condition where the plate maintains a constant temperature creates a temperature gradient that drives natural convection, while forced convection modifies the flow dynamics. Recent studies (Muhammad et al. 2021; Habib et al. 2024) have explored how nanoparticle properties (such as type, volume fraction, and distribution) and base fluid characteristics affect heat transfer performance in such flows. Additionally, the influence of boundary conditions including velocity slip, temperature jump, plate inclination, and magnetic effects has been extensively investigated to optimize thermal performance (Shi et al. 2023).

Recent advancements in nanofluid research have expanded the understanding of mixed convection in complex scenarios. For instance, Turkyilmazoglu (2013) and Wahid et al. (2021, 2022) examined hybrid nanofluids over shrinking permeable inclined plates with thermal radiation effects. Similarly, Garoosi and Talebi (2017), Shi et al. (2023) and Helel and Boukadida (2024) all conducted numerical analyses of mixed convection near isothermal vertical surfaces, emphasizing nanoparticle size and distribution effects. Other studies, such as those by Ramana et al. (2015) and Khan et al. (2022), explored magnetohydrodynamic (MHD) effects, thermophoresis, and chemical reactions in porous media. The interaction between mixed convection flow and solid boundaries, particularly an infinite isothermal vertical wall, presents both challenges and opportunities for improving heat transfer efficiency. This configuration allows for a detailed examination of how buoyancy and forced convection interact, providing insights into the underlying mechanisms governing thermal transport. Earlier foundational studies established key models for nanofluid behaviour and subsequently works further refined the understanding of mixed convection in vertical channels (Hang & Pop, 2012; Xu et al. 2013 & Fakour et al. 2014).

Recent investigations have also explored specialized conditions, such as MHD effects (Yasin et al., 2015 & Alamirew et al., 2024), entropy generation (Cho, 2018), and non-Newtonian nanofluids (Yan et al., 2017). Additionally, studies on convective boundary conditions (Ramreddy et al., 2013), rotating systems (Hassan & Harmand, 2015), and radiative heat flux (Sowmya et al., 2023) have contributed to a more comprehensive understanding of mixed convection in nanofluids. Given these developments, this study aims to systematically analyze the effects of an isothermal wall and the characteristic properties of selected nanofluids on mixed convection flow, bridging existing knowledge gaps and offering new insights for thermal engineering applications.

Objectives of the Study

The objectives of the study are to:

1. determine the temperature profile for Nano fluids
2. determine the velocity profile of Nano fluids
3. determine the penetration distance (xp) profile for Nano fluids

Research Questions

The following research questions were raised to guide the study:

1. What are the variations in the temperature profiles of various nanofluids
2. What are the variations in the velocity profiles of some nanofluids
3. What is the effect of the leading-edge parameter (xp) on the behavior of certain nanofluids

METHODOLOGY

This article simulates the mixed convection flow with nanofluids around an infinite isothermal vertical plate. Four nanofluids are considered based on their thermophysical properties, and comparative studies are carried out on the effectiveness of the nanofluid. The governing equations are derived and analytical solutions are offered in terms of exponential and complementary error functions. The solutions obtained are graphically represented using MATLAB software. Throughout the analysis, the nanoparticle volume fraction is taken between 0.0-0.5 and the time is taken so small to study the transient state as shown in Figure 1.

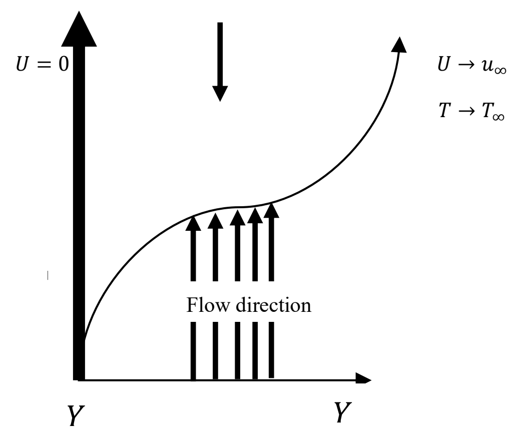

Figure 1: Schematic of the prm.

Mathematical formulation and solutions

Consider the unsteady free and forced convection flow of an incompressible viscous fluid past an infinite vertical plate with a constant heat source. The x'-axis is oriented vertically along the plate, while the y-axis is perpendicular to it. The governing equations for this flow, incorporating the effects of porosity and a constant heat source, are derived under the Business approximation. Using the Laplace transform method, these equations are reformulated in a dimensionless form to analyze the unsteady forced and free convection behavior.

$$\frac{\partial U}{\partial \omega} = \nu_{nf}\left(\frac{\partial^2 U}{\partial Y^2}\right) + g\beta_{nf}(T - T_\infty) \quad (1)$$

$$\frac{\partial U}{\partial \omega} = \frac{k_{nf}}{(\rho C_p)_{nf}}\left(\frac{\partial^2 T}{\partial Y^2}\right) \quad (2)$$

$$\omega < 0 \qquad U(y,t) = 0, \qquad T(y,t) = T_\infty \quad at\ y = 0$$

$$\omega \geq 0 \qquad U(0,t)=0, \qquad T(0,t)=T_w \tag{3}$$

$$U(y,\omega)\to U_\infty,\ T(y,t)\to T_\infty \quad at\ Y\to\infty$$

$$t=\frac{v_f}{L^2}\omega,\ y=\frac{Y}{L},\ u=\frac{v_f}{sL^2}U, \theta=\frac{T-T_\infty}{T}, u_\infty=\frac{sL^2}{v_f} \tag{4}$$

Substituting eqn. (4) into (1), (2) and (3) we have

$$\frac{\partial U}{\partial t}=a_1\frac{\partial^2 u}{\partial y^2}+a_2\theta \tag{5}$$

$$\frac{\partial \theta}{\partial t}=a_3\frac{\partial^2 \theta}{\partial y^2} \tag{6}$$

$$t<0 \quad u=0,\ \theta=0 \quad \forall\, y\geq 0$$

$$t\geq 0\begin{cases} u=0 \quad \theta=1\ \forall\, y\geq 0\\ u\to 0 \quad \theta\to 0\ as\ \forall\, y\to\infty\end{cases} \tag{7}$$

Where notations $a_1, a_2\ and\ a_3$ in Eqs. (5) and (6) denote Nanofluids parameters.

$$a_1=\frac{1}{(1-\varphi)^{2.5}}\frac{1}{1-\varphi+\varphi\frac{\rho s}{\rho_f}}, a_2=\frac{1-\varphi+\varphi\frac{(\rho\beta)_s}{(\rho\beta)_f}}{1-\varphi+\varphi\frac{\rho_s}{\rho_f}}, a_3=\frac{1}{Pr}\frac{knf}{kf}\frac{1}{1-\varphi+\varphi\frac{(\rho C p)}{(\rho C p)}} \quad (8$$

Where ρ_f the density of the base fluid is, ρ_{nf} is the density of nanofluid, β_{nf} is the thermal expansion coefficient of the nanofluid, β_f is the thermal expansion coefficient of the base fluid. For nanofluid expressions ρ_{nf}, $(\rho cp)_{nf}$, $(\rho\beta)_{nf}$ are respectively the effective density, specific heat capacity and thermal expansion of the nanofluid and given as:

$$\rho_{nf}=(1-\varphi)\rho_f+\varphi\rho_s \tag{9}$$

$$(\rho C_p)_{nf}=(1-\varphi)(\rho C_p)_f+\varphi(\rho C_p)_s \tag{10}$$

$$(\rho\beta)_{nf}=(1-\varphi)(\rho\beta)_f+\varphi(\rho\beta)_s \tag{11}$$

$\frac{k_{nf}}{k_f}$ from eqn. (8) is the ratio of the thermal conductivity of the nanofluid for spherical nanoparticle, and according to Vajravelu et al. (2011), it can be written as:

$$\frac{k_{nf}}{k_f}=\frac{k_s+2k_f-2\varphi(k_f-k_s)}{k_s+2k_f+\varphi(k_f-k_s)} \tag{12}$$

Solution to the problem

The governing equations (5-7) are solved using the Laplace transform method to transform the governing partial deferential equation to ordinary deferential equation and then solved using the method of undetermined coefficients as follows:

$$\bar{\theta}=\frac{1}{p}exp\left(-y\sqrt{\frac{p}{a_3}}\right) \tag{13}$$

$$\bar{u}=\frac{b_1}{p^2}\left[exp\left(-y\sqrt{\frac{p}{a_1}}\right)-exp\left(-y\sqrt{\frac{p}{a_3}}\right)\right]+\frac{1}{p}\left[1-exp\left(-y\sqrt{\frac{p}{a_1}}\right)\right] \tag{14}$$

Taking Laplace inverse of (13) and (14) we have

$$\theta=erfc\left(-\frac{y}{2\sqrt{ta_3}}\right) \tag{15}$$

$$u=b_1[F_1(t,a_1,y)-F_1(t,a_3,y)]+1-erfc\left(-\frac{y}{2\sqrt{ta_3}}\right) \tag{16}$$

To obtain the penetration distance we take the Laplace inverse of (14) as

$$XP=L^{-1}\left[\frac{\bar{u}}{p}\right]$$

Then we have

$$XP=L^{-1}\left[\frac{b_1}{p^3}\left[exp\left(-y\sqrt{\frac{p}{a_1}}\right)-exp\left(-y\sqrt{\frac{p}{a_3}}\right)\right]+\frac{1}{p^2}\left[1-exp\left(-y\sqrt{\frac{p}{a_1}}\right)\right]\right] \tag{17}$$

$$XP=b_1[F_2(t,a_1,y)-F_2(t,a_3,y)]+t-F_1(t,a_3,y) \tag{18}$$

where

$$b_1=\frac{a_1a_3}{a_1-a_3} \tag{19}$$

$$F_1(t,a_1,y)=\left(\frac{y^2}{2a_1}+t\right)erfc\left(\frac{y}{2\sqrt{ta_1}}\right)-\sqrt{\frac{t}{\pi a_1}}yexp\backslash \tag{20}$$

$$F_2(t,a_1,y)=\frac{1}{2}\left(\frac{y^4}{12a_1^2}+\frac{y^2t}{a_1}+t^2\right)erfc\left(\frac{y}{2\sqrt{ta_1}}\right)-\frac{y}{6}\sqrt{\frac{t}{\pi a_1}}\left[\frac{y^2}{2a_1}+5t\right]exp\left(\frac{-y^2}{4ta_1}\right) \tag{21}$$

The Nusselt number and skin friction are obtained when Eqn. (15) and Eqn. (16) are differentiated with respect to y

$$Nu=-\frac{1}{\sqrt{\pi t a_3}}\bigg|_{y=0} \tag{22}$$

$$\tau=\sqrt{\frac{t}{\pi a_3}}-\sqrt{\frac{t}{\pi a_1}}\bigg|_{y=0} \tag{23}$$

Table 1 Thermo-physical properties of water and nanoparticles

	$\rho(kg/m^3)$	$C_p(J/kgK)$	$k(W/mK)$	$\beta \times 10^5(K^{-1})$
Water	997.1	4179	0.613	21
Cupper (Cu	8933	385	400	1.67
Silver (Ag)	10500	235	429	1.89
sAlumina (Al_2O_3)	3970	765	40	0.85
Titanium oxide (TiO_2	4250	686.2	8.9538	0.9

From the information in Table 1, the graphs were obtained and presented in Figures 2,3 and 4

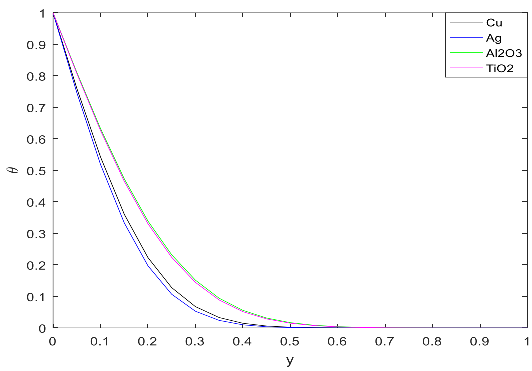

Figure 2: Temperature profile for Nano fluids when values of $\phi = 0.2$ $\Pr = 0.71$ $t = 0.02$

Figure 2 illustrates the variations in the temperature profiles of various nanofluids. It is observed that Ag-water exhibits the highest peak in the temperature profile, with both Ag-water and Cu-water displaying steeper temperature gradients.

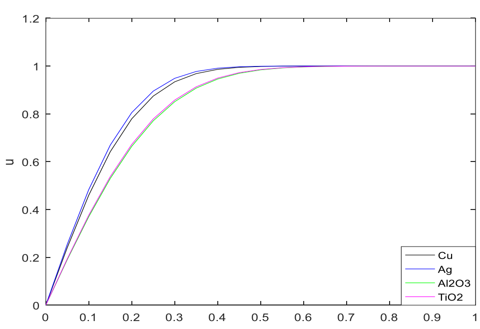

Figure 3: Velocity profile of Nano fluids when values of $\phi = 0.2$ $\Pr = 0.71$ $t = 0.02$

Figure 3 clarifies the variations in the velocity profiles of some nanofluids. It clearly shows that Ag-water and Cu-water reach the peak of their velocity profiles faster than alumina and titanium oxides, exhibiting highly similar velocity profiles.

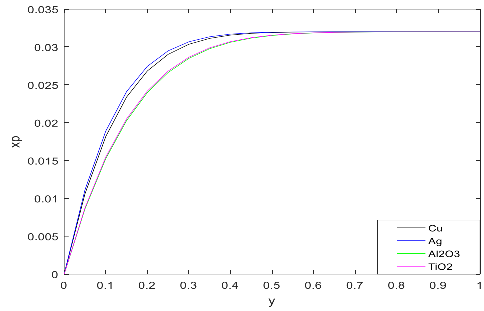

Figure 4: Penetration distance (xp) profile for Nano fluids when values of $\phi = 0.2$ $\Pr = 0.71$ $t = 0.02$

Figure 4 illustrates the effect of the leading-edge parameter (xp) on the behavior of certain nanofluids. A steeper slope is observed for the Cu-water profile, which indicates faster penetration. Similarly, the higher peak of the Ag-water profile signifies greater penetration distances.

Table 2: Numerical values of skin friction coefficient and Nusselt number around the channel

			Cu		Ag		Al_2O_3		TiO_2	
Pr	ω	ϕ	Nu	τ	Nu	τ	Nu	τ	Nu	τ
7.0	0.01	0.0	-4.7539	4.7451	-4.7539	4.7451	-4.7539	0.7451	-4.7539	4.7451
	0.03	0.1	-2.2235	2.1754	-2.1968	2.1430	-2.2310	2.2004	-2.2912	2.2613
	0.05	0.3	-0.0392	0.9425	-0.9999	0.8912	-1.0613	1.0032	-1.1840	1.1296
	0.07	0.5	-0.0823	-0.0520	-0.0742	-0.0713	-0.2523	0.1709	-0.5220	0.4567

Table 2 presents the numerical values of heat transfer and shear stress of water taken as the base fluid. It is observed that both heat transfer and shear stress decrease with an increase in time t and nanoparticle volume fraction, although heat transfer occurs away from the fluid.

DISCUSSION

Figure 2 illustrates high thermal conductivity of Ag-water enhances its temperature profile, while Cu-water's steeper gradients indicate rapid temperature changes. Ag and Cu, having lower heat capacities, require less energy to undergo temperature changes. On the other hand, alumina and titanium nanofluids, due to their lower thermal conductivity, show more gradual temperature gradients, resulting in intermediate temperature changes. From a practical perspective and the research of Choon et al (2024), Ag and Cu nanofluids are suitable for high-performance cooling systems, such as radiators, air conditioning units, and cooling towers, because of their superior thermal conductivity. In contrast, alumina and titanium nanofluids are more applicable to moderate temperature control systems, such as cryogenics and refrigeration, where gradual temperature changes are preferred.

Figure 3 clarifies the variations in the velocity profiles of some nanofluids. The high thermal conductivity of silver and copper nanoparticles significantly enhances heat transfer within the fluid, reducing thermal resistance and allowing the fluid to stabilize more quickly. From the research of Ershard et al (2021), the lower thermal conductivity of alumina and titanium oxides results in less efficient energy transfer, causing a slower rate of velocity change and delaying flow stabilization. Physically, Ag-water and Cu-water are ideal for applications requiring high-performance heat dissipation and rapid flow stabilization, such as radiators, cooling towers, and electronics cooling systems. Their quick thermal and velocity responses also make them suitable for high-efficiency heat exchangers and forced convection systems. Conversely, alumina and titanium oxides are better suited for applications demanding steady and controlled fluid flow, such as cryogenic systems, refrigeration, and precision thermal management in sensitive environments. Their gradual flow stabilization ensures uniform and controlled heat transfer in scenarios that require long-term thermal stability.

Figure 4 illustrates the effect of the leading-edge parameter (xp) on the behavior of certain nanofluids. A steeper slope is observed for the Cu-water profile, which indicates faster penetration. Similarly, the higher peak of the Ag-water profile signifies greater penetration distances. Physically, from the research of Can et al (2021) this behavior reflects the lower viscosity of both Cu-water and Ag-water nanofluids, which facilitates easier flow and results in greater penetration of the fluid. These characteristics make them ideal for applications requiring high-speed and long-range heat transfer, such as advanced cooling systems and heat exchangers. The profiles of Al_2O_3-water and TiO_2-water intersect, indicating that the penetration distance of one nanofluid occasionally surpasses the other. This behavior suggests changes in flow dynamics or thermal properties at different positions. Additionally, most oxide-based nanofluids, such as Al_2O_3-water and TiO_2-water, exhibit higher viscosities, which can hinder fluid flow and affect their penetration behavior. In inference , the lower viscosity and superior penetration properties of Ag-water and Cu-water nanofluids make them highly suitable for applications demanding efficient heat transfer over long distances, such as in advanced cooling systems and heat exchangers.

Table 2 presents the numerical values of heat transfer and shear stress of water taken as the base fluid. It is observed that both heat transfer and shear stress decrease with an increase in time t and nanoparticle volume fraction, although heat transfer occurs away from the fluid. It is well known that shorter time values result in transient flow, during which shear stress and heat transfer may not reach a steady state. Conversely, longer time values lead to stabilized flow, reflecting a quasi-steady state. The Nusselt number Nu increases in both Ag-water and Cu-water as the volume fraction ϕ increases due to enhanced thermal conductivity. However, Nu may decline if increased viscosity reduces fluid motion. In disparity, Al_2O_3 and TiO_2-based nanofluids exhibit lower Nu and higher shear stress at larger volume fractions ϕ, reflecting an increase in viscosity. Additionally, the data in the table show that as Nu decreases, shear stress increases. This observation physically highlights the dominant role of viscosity. In practical applications such as cooling systems, maximizing Nu is prioritized for efficient heat transfer, while maintaining manageable shear stress is essential to minimize energy loss.

CONCLUSION

The study of mixed convection flow with nanofluids around an infinite isothermal vertical plate offers valuable insights for optimizing heat transfer in various modern technological applications. The unique thermal properties of nanofluids, combined with their fluid dynamics, make them suitable for use in advanced cooling systems, energy-efficient devices, and numerous industrial applications where heat management is essential. Cu-water and Ag-water nanofluids exhibit similar temperature and velocity profiles, while Aluminum Oxide and Titanium Dioxide nanofluids display distinct profiles. Cu-water and Ag-water nanofluids perform better in applications requiring deeper penetration, whereas Aluminum Oxide (Al_2O_3) and Titanium Dioxide (TiO_2) are more suitable for applications with shorter penetration requirements. The numerical results in Table 2 indicate that an increase in the volume fraction of nanoparticles over time enhances heat transfer and shear stress. From the table, it is observed that the Nusselt number (Nu) decreases, while shear stress (τ) increases with time.

RECOMMENDATIONS

This research recommends the following:

1. The use of high heat transfer to give a low change in porosity, permeability and nanoparticle concentration
2. The use of high heat transfer affect the velocity and temperature profiles inside the boundary layer of pipes.

REFERENCES

Alamirew, W., Zergaw, G. & Gorfie, E. (2024). Mixed Convection Flow of MHD Casson Nanofluid over a Vertically Extending Sheet with Effects of Hall, Ion Slip and Nonlinear Thermal Radiation. *International Journal Thermofluids*, 23, 100762. *doi: 10.1016/j.ijft.2024.100762*.

Basant K. J. & Gabriel, S. (2022). "Mixed convection flow from a convectively heated vertical porous plate with combined effects of suction/injection", internal heat generation and nonlinear thermal radiation. *Journal of Process Mechanical Engineering,*1–10. *doi: 10.1177/09544089221116963.*

Buongiorno, J. (2005) Convective Transport in Nanofluids. *Journal of Heat Transfer*. 128 (3), 240–250. *doi: 10.1115/1.2150834.*

Can, J., Qibai, W., Gaoiang, Y., Haiyan, Z. and Yufery, Z.(2021). "investigation on hybrid nanofluid based on carbon nanotubed with metal nanoparticles; stability, thermal, conductiviity and viscosity J*ournal of Powder Technology, 389(1), 1-10.*

Cho, C. C. (2018). Mixed convection heat transfer and entropy generation of Cu-water nanofluid in wavy-wall lid-driven cavity in presence of inclined magnetic field. *International Journal of Mechanical Science*, 151. *doi: 10.1016/j.ijmecsci.2018.12.017.*

Cho, C. C.M, Chen, C. L. & Chen, C. K. (2013). "Mixed convection heat transfer performance of water-based nanofluids in lid-driven cavity with wavy surfaces. *International Journal of Mechanical Science*, 68, 181–190. *doi: 10.1016/j.ijthermalsci.2013.01.013.*

Choi, S. U. S., Zhang, Z. G., Yu, Wl., Lockwood, F. E. & Grulke, E. A. (2001). Anomalous thermal conductivity enhancement in nanotube suspensions. *Applied Physics Letters,* 79(14), 2252–2254.

Ershadul, H., Sanower, H and Hafiz, M. A. (2021). Laminar force convection heat transfer of nanofluid inside non-circular ducts. J*ournal of Powder Technology, 378(8), 808-830.*

Fakour, M., Vahabzadeh, A. & Ganji, D. D. (2014). Scrutiny of mixed convection flow of a nanofluid in a vertical channel. *Case Studies in Thermal Engineering*, 4, 15–23.

Garoosi, F. & Talebi, F. (2017). Numerical analysis of conjugate natural and mixed convection heat transfer of nanofluids in a square cavity using the two-phase method. *Advances in Powder Technology*, 28. *doi: 10.1016/j.apt.2017.04.006*.

Habib, B. B., Najeem, U., Aamir, H. and Nahad, A. S. (2024). "A Comprehensive Review On Nano fluids: Synthesis Cutting Edge Application And Future Prospective". *International Journal of thermal fluids, 22,100595. https://doi.org/10.1016/j.ijft.2024.100595*

Hang, X. & Pop, I. (2012). Fully developed mixed convection flow in a vertical channel filled with nanofluids, *International Journal of Heat Mass Transfer,* 39 (8) 1086–1092. *doi: https://doi.org/10.1016/j.icheatmasstransfer.2012.06.003.*

Hassan, H. & Harmand, S. (2015). Effect of using nanofluids on the performance of rotating heat pipe. *Applied Mathematical Modelling*, 39(15) 4445–4462. *doi: 10.1016/j.apm.2014.12.023*.

Helel., D. & Boukadida, N. (2024). Numerical Investigation of Heat and Mass Transfer in Nanofluid-Filled Porous Medium. *Advances in Nanoparticles*, 13(3), 29–44.

Khan, U., Waini, I., Zaib, A., Ishak, A. & Pop, I. (2022). MHD Mixed Convection Hybrid Nanofluids Flow Over a Permeable Moving Inclined Flat Plate in the Presence of Thermophoretic and Radiative Heat Flux Effects. *Mathematics*, 10, 1164. *doi: 10.3390/math10071164.*

Muhammed, A., Najeeb, Y., Javid, A., Faizan, S., Mohammed, M. E., Sayedus, S. and Arafat, A. B. (2021). Heat Transfer and Pressure Drop Performance of Nanofluid: A State of the Art Review. *International Journal of Thermal Fluids, 9,100065. doi.org/10.1016/j.ijft.2021.100065*

Oztop, H. F. & Abu-Nada, E. (2008). Numerical study of natural convection in partially heated rectangular enclosures filled with nanofluids, *International Journal of Heat Mass Flow*, 29(5), 1326–1336.

Ramreddy, C., Murthy, P., Chamkha, A. & Rashad, A. (2013). Soret effect on mixed convection flow in a nanofluid under convective boundary condition. *International Journal of Heat Mass Transfer,* 64, 384–392. *doi: 10.1016/j.ijheatmasstransfer.2013.04.032.*

Ramreddy, J. V Vangala, S., Sandeep, D. N. & Sulochana, C. (2015). Influence of chemical reaction, radiation and rotation on MHD nanofluid flow past a permeable flat plate in porous medium. *Journal of Nigeria. Mathematical. Society,* 35. *doi: 10.1016/j.jnnms.2015.08.004.*

Sharma, K. Vijay, N., Mabood, F. & Badruddin, I. A. (2022). Numerical simulation of heat and mass transfer in magnetic nanofluid flow by a rotating disk with variable fluid properties. *International. Communication on Heat Mass Transfer*, 133, 105977. *doi: 10.1016/j.icheatmasstransfer.2022.105977.*

Shi, L., TaoW., Zheng, N., Zhou, T. & Sun, Z. (2023). "Numerical study of convective heat transfer and particle distribution subject to magneto-static field in a square cavity," *International. Journal of Thermal. Science*, 185, 108081. *doi: https://doi.org/10.1016/j.ijthermalsci.2022.108081.*

Sowmya, S. B., Nalinakshi, N. & Sravan, K. T.(2023). Mixed Convection Nanofluid Flow Past An Exponential Permeability Plate With Radiation Effect. *Journal of Propulsion Technology*, 44(4), 8650–8664

Turkyilmazoglu, M. (2013), "Unsteady Convection Flow of Some Nanofluids Past a Moving Vertical Flat Plate With Heat Transfer. *Journal of Heat Transfer*, 136, 31704. *doi: 10.1115/1.4025730.*

Wahid, N. S., Arifin, N. M., Khashi, N. S., Pop, I., Bachok, N. & Hafidzuddin, M. (2022). MHD Mixed Convection Flow of a Hybrid Nanofluid Past a Permeable Vertical Flat Plate with Thermal Radiation Effect. *Alexandria Engineering Journal*, 61(4) 3323–3333. *doi: https://doi.org/10.1016/j.aej.c.08.059.*

Wahid., N. S., Arifin., N., Khashi'ie., N., Pop., I., Bachok., N. & Hafidzuddin., M. (2022). Mixed Convection Magnetic Nanofluid Flow past a Rotating Vertical Porous Cone. *Journal of Applied Fluid Mechanics*, 15, 1207–1220. *doi: 10.47176/jafm.15.04.1063.*

Xu, H., Fan, T. & Pop, I. (2013). "Analysis of Mixed Convection Flow of a Nanofluid in a Vertical Channel with the Buongiorno Mathematical Model," *International. Communication on Heat Mass Transfer,* 44, 15–22. *doi: https://doi.org/10.1016/j.icheatmasstransfer.2013.03.015.*

Yasin, M., Arifin, N., Nazar, R., Ismail, F. & Pop, I. (2013). Mixed Convection Boundary Layer Flow Embedded in a Thermally Stratified Porous Medium Saturated by a Nanofluid. *Advances in Mechanical Engineering. doi: 10.1155/2013/121943.*