SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

CFD Letters

Journal homepage:
https://semarakilmu.com.my/journals/index.php/CFD_Letters/index
ISSN: 2180-1363

MHD Hybrid Nanofluid Flow Past A Stretching/Shrinking Wedge With Heat Generation/Absorption Impact

Nurul Amira Zainal[1,2 *], Iskandar Waini[2,3], Najiyah Safwa Khashi'ie[1,2], Roslinda Nazar[4], Ioan Pop[5]

[1] Fakulti Teknologi dan Kejuruteraan Mekanikal, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal, Malaysia
[2] Forecasting and Engineering Technology Analysis (FETA) Research Group, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal, Malaysia
[3] Fakulti Teknologi dan Kejuruteraan Industri dan Pembuatan, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal, Malaysia
[4] Department of Mathematical Sciences, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi Selangor, Malaysia
[5] Department of Mathematics, Babes-Bolyai University, Cluj-Napoca, Romania

ARTICLE INFO

Article history:
Received 27 June 2023
Received in revised form 22 July 2023
Accepted 19 August 2023
Available online 21 January 2024

Keywords:
Hybrid nanofluids; Wedge surface; MHD; Heat generation

ABSTRACT

Heat transfer is commonly utilized in diverse industrial applications, including the manufacturing of paper, the cooling of electrical devices, and the synthesis of new substances. Hence, this study aims to investigate the effect of heat generation/absorption on the steady magnetohydrodynamic (MHD) flow and heat transfer of Al_2O_3-Cu/H_2O hybrid nanofluids over a permeable stretching/shrinking wedge. By using similarity transformation techniques, the governing equations of the hybrid nanofluids are transformed into similarity equations. The similarity equations are numerically solved using the MATLAB software's built-in bvp4c package. The findings show that hybrid nanofluids are seen to improve thermal efficiency in comparison to conventional fluid. In relation to heat transfer rate, the increase of magnetic parameters from 0.00 to 0.10 and 0.15 contributes approximately 12.3% and 18.8%, respectively. Meanwhile, as the heat generation parameter increases, the heat transfer rate decreases leading to an inefficient thermal system. The findings of this study are anticipated to contribute to the knowledge base of scientists and researchers in the field.

1. Introduction

The properties of mono nanofluids can be customized by varying the ratio or concentration of the nanoparticles. However, mono nanofluids showed continuous thermophysical characteristics in a restricted range utilizing just one kind of nanoparticle (metallic or non-metallic). In recent years, hybrid nanofluids have been developed to improve the thermophysical and heat-transporting properties of fluids [1, 2]. Hybrid nanofluids are made by mixing a range of nanoparticles to improve the heat transfer fluid's thermal properties. The continuing development and significant advancements in thermal management are essential for the use of electronic devices in every element of human activity, including the manufacturing, heating, and cooling sectors. However, selecting the appropriate nanoparticles is still questionable [3]. Hence, investigating the maximum capabilities of this potent nanofluid combination needs continuous exploration.

---

[*] *Corresponding author.*
E-mail address: nurulamira@utem.edu.my (Nurul Amira Zainal)

https://doi.org/10.37934/cfdl.16.6.146156

The effectiveness of hybrid nanofluids as heat-transfer fluids in various flows and surfaces, including wedge-shaped surfaces, has recently been the subject of numerous investigations. This is driven by its widespread applications in the industrial and chemical sectors, including the geothermal and aviation sectors [4, 5]. Previously, Falkner and Skan [6] initially suggested this kind of flow to illustrate how Prandtl's idea of boundary layers could be applied. The similarity transformation techniques were used to obtain the ordinary (similarity) differential equations. Zainal *et al.,* [7] demonstrated that when the wedge angle parameter is enhanced, the concentration of chemical species in the boundary layer increases. According to Rehman *et al.,* [8], the desired heat transfer rate can be obtained by choosing various and suitable nanoparticle proportions in the hybrid nanofluids over a wedge. Following the literature cited above, we believe that hybrid nanofluids may help to advance the thermal process of the stretching/shrinking wedge.

The magnetic field effects are also recognized for their ability to modify the rate of fluid flow and heat transfer. The applications of MHD in various industries, medical settings, and natural environments are extensive [9]. The presence of such elements is also recognized for its ability to modify the behaviour of flow within the boundary layer. Hence, the incorporation of these effects in the investigation of fluid dynamics renders it more captivating and convincing. Ali *et al.,* [10] investigated the impact of nanoparticle diameter in Darcy-Forchheimer MHD flow. It has been observed that the fluid has restrictions because of the weakened magnetic field caused by viscous forces, which also act in opposition to the aggressive forces. In another study, Ali *et al.,* [11] performed a study using the finite element method to investigate the behaviour of magnetic parameters in a tangent hyperbolic nanofluid flow past a stretching wedge. The study also considered the influence of activation energy on the flow characteristics. There are various recent papers relevant to the above discussion that are now published in various fields [12-15].

Since most engineering processes frequently involve extremely high temperatures, the impact of heat generation and absorption should not be disregarded. Applications like semiconductor wafers, rocket thrusters, combustion models, electronic chips, and endothermic chemical reactions are among the useful ones that take heat generation in the flow field into account [16]. In boundary layer flows with heat transmission, the presence of heat generation is critical because heat generation affects boundary layer temperature, which in turn affects product quality. Based on the study conducted by Manohar *et al.,* [17], the temperature of the hybrid nanofluids is consistently greater than the temperature of the nanofluids. Garia *et al.*, [18] spotted that the heat generation parameter exhibits contrasting effects with suction, resulting in a decrease in the heat transfer coefficient on the temperature distribution. Rawat *et al.,* [19] concluded that the thermal profile rises due to an increment in the heat generation parameter on titania–ethylene glycol nanofluid flow over a wedge. Negi *et al.,* [20] investigated the effects of heat generation on the stagnation point of the MHD nanofluid flow past a stretching sheet while Yaseen *et al.,* [21] performed a research investigation on the flow of ternary hybrid nanofluid over three distinct geometries, namely a flat plate, cone, and wedge. The study also incorporated the use of the Cattaneo–Christov Model and accounted for the presence of heat generation. According to the findings, the rate of heat transmission is highest as the flow moves towards the cone.

In accordance with the previous reviews of relevant literature, the primary objective of this study is to address a gap in existing knowledge, specifically in the field of hybrid nanofluid flow, by investigating the impact of heat generation/absorption on a stretching/shrinking wedge surface. The key contribution of this paper involves the formulation of a novel mathematical model for hybrid nanofluids, incorporating the heat source/sink parameter as well as additional variables such as the magnetic field and suction effect. Additionally, this investigation observed the occurrence of many solutions. The study presented in this work demonstrates the application of a mathematical approach in the thermal extrusion manufacturing process. More specifically, it focuses on the production of plastic films through drawing or the extrusion of polymer sheets from a die. The findings of this study are anticipated to contribute to the knowledge base of scientists and researchers in the field, specifically in the areas of boundary layer analysis and thermal systems, by providing valuable insights into the characteristics and behavior of this promising heat transfer fluid.

2. Methodology

A steady magnetohydrodynamics (MHD) $Al_2O_3 - Cu/H_2O$ hybrid nanofluids flow with the effect of heat generation/ over a stretching/shrinking wedge is studied which shown in Figure 1. The free-stream velocity is given by $u_e = U_e x^m$ with $u_w(x) = U_w x^m$ is the velocity of the stretching/shrinking wedge. Next, U_e is a constant, $U_w > 0$ and $U_w < 0$ denote as the stretching wedge and shrinking wedge, respectively. Further, we have $m = \beta/(2-\beta)$ where m and β denoted as wedge angle and the Hartree pressure gradient parameter. The flow over a wedge is modelled mathematically when m remains within the range of 0 to 1 [22,23]. Thus, m is set to 0.1 representing the acute wedge angle. The fluid's ambient temperature is represented by the stretching/shrinking wedge temperature, where both temperatures are set to be constant. In the y-direction, a magnetic field is set up with $B(x) = B_0 x^{(m-1)/2}$ where B_0 is the applied magnetic field intensity.

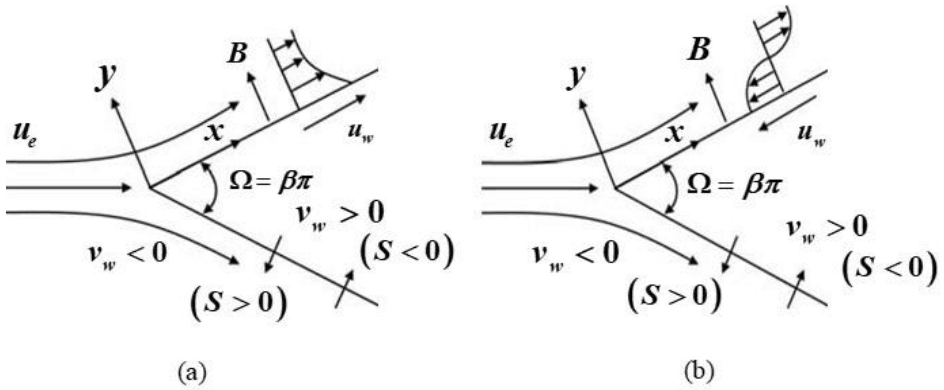


Fig. 1. The coordinate systems for (a) stretching wedge (b) shrinking wedge

Based on the above assumption, the governing equations of the hybrid nanofluids mathematical model can be written as (Awaludin *et al.,* [24]):

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = u_e \frac{du_e}{dx} + \frac{\mu_{hnf}}{\rho_{hnf}}\frac{\partial^2 u}{\partial y^2} - \frac{\sigma_{hnf}}{\rho_{hnf}} B^2 \left(u - u_e\right), \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k_{hnf}}{\left(\rho C_p\right)_{hnf}}\frac{\partial^2 T}{\partial y^2} - \frac{Q_0}{\left(\rho C_p\right)_{hnf}}\left(T - T_\infty\right). \tag{3}$$

Meanwhile, the boundary conditions of the above mathematical assumption are given as follows

$$\begin{aligned} &v = v_w(x), u = u_w(x), T = T_w, \ \text{at}\, y = 0, \\ &u \to u_e(x), T \to T_\infty(x), \quad \text{as} \ y \to \infty. \end{aligned} \tag{4}$$

The heat generation/absorption variable is denoted as $Q_0 = Q^* u_e x^{(m-1)}$ with constant Q^*. The thermophysical characteristics of related fluids are portrayed in Table 1 while Table 2 demonstrates the correlation coefficient that applies to the hybrid nanofluids.

Table 1
Properties of the base fluid and nanoparticles (Oztop and Abu Nada [25])

Component	$\rho\,(\text{kg/m}^3)$	$k\,(W/mK)$	$C_p\,(\text{J/kgK})$
Al_2O_3	3970	40	765
H_2O	0.613	21	4179
Cu	8933	400	385

Table 2
Nanofluids with hybrid thermal properties (Raza *et al.,* [26])

Thermophysical properties	Alumina-Copper/Water (Al_2O_3–Cu/H_2O)
Thermal conductivity, k_{hnf}	$\frac{k_{hnf}}{k_f} = \left[\frac{\left(\frac{\phi_1 k_{Al_2O_3} + \phi_2 k_{Cu}}{\phi_{hnf}} \right) + 2k_f + 2\left(\phi_1 k_{Al_2O_3} + \phi_2 k_{Cu}\right) - 2\phi_{hnf} k_f}{\left(\frac{\phi_1 k_{Al_2O_3} + \phi_2 k_{Cu}}{\phi_{hnf}} \right) + 2k_f - \left(\phi_1 k_{Al_2O_3} + \phi_2 k_{Cu}\right) + \phi_{hnf} k_f} \right]$
Heat capacity, $\left(\rho C_p\right)_{hnf}$	$\left(\rho C_p\right)_{hnf} - \left(1-\phi_{hnf}\right)\left(\rho C_p\right)_f = \phi_1 \left(\rho C_p\right)_{Al_2O_3} + \phi_2 \left(\rho C_p\right)_{Cu}$
Electrical conductivity, σ_{hnf}	$\frac{\sigma_{hnf}}{\sigma_f} = \left[\frac{\left(\frac{\phi_1 \sigma_{Al_2O_3} + \phi_2 \sigma_{Cu}}{\phi_{hnf}} \right) + 2\sigma_f + 2\left(\phi_1 \sigma_{Al_2O_3} + \phi_2 \sigma_{Cu}\right) - 2\phi_{hnf} \sigma_f}{\left(\frac{\phi_1 \sigma_{Al_2O_3} + \phi_2 \sigma_{Cu}}{\phi_{hnf}} \right) + 2\sigma_f - \left(\phi_1 \sigma_{Al_2O_3} + \phi_2 \sigma_{Cu}\right) + \phi_{hnf} \sigma_f} \right]$

The following similarity variables now presented as (Sparrow *et al.,* [27]):

$$\psi = \left(U_e \nu_f\right)^{1/2} x^{(m+1)/2} f(\eta), \ \eta = \left(U_e/\nu_f\right)^{1/2} x^{(m-1)/2} f(\eta) y, \ \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \tag{5}$$

Thus,

$$v_w = -\frac{m+1}{2}\left(U_e \nu_f\right)^{1/2} x^{(m-1)/2} S. \tag{6}$$

For further details, S in the Eq. (6) is the parameter of constant mass flux and in this study, we only considered the positive values where $S > 0$ which represents the suction parameter. By utilizing the similarity variables Eq. (5) and Eq. (6), the subsequent ordinary differential equations are then developed. These equations are known as similarity equations such as

$$\frac{\mu_{hnf}/\mu_f}{\rho_{hnf}/\rho_f} f''' + \frac{m+1}{2} ff'' + m\left(1-f'^2\right) - \frac{\sigma_{hnf}/\sigma_f}{\rho_{hnf}/\rho_f} M\left(f'-1\right) = 0, \tag{7}$$

$$\frac{1}{\Pr}\left(\frac{k_{hnf}/k_f}{\left(\rho C_p\right)_{hnf}/\left(\rho C_p\right)_f}\right)\theta'' + \frac{m+1}{2} f\theta' + \frac{H}{\left(\rho C_p\right)_{hnf}/\left(\rho C_p\right)_f}\theta = 0, \tag{8}$$

$$\begin{gathered} f(0)=S,\ f'(0)=\lambda,\ \theta(0)=1, \\ f'(\eta)\to 1,\ \theta(\eta)\to 0, \end{gathered} \tag{9}$$

Where $M=\sigma_f B_0^2/\rho_f U_e$ is the magnetic coefficient, $\Pr=\nu_f/\alpha_f$ is the Prandtl number, and $\lambda=U_w/U_e$ represents the stretching/shrinking wedge parameter. The heat generation/absorption parameter is denoted as $H=Q^*/\left(\rho C_p\right)_f$. The physical quantities related to this study is declared as $Nu_x=\frac{xk_{hnf}}{k_f\left(T_w-T_\infty\right)}\left(-\frac{\partial T}{\partial y}\right)_{y=0}$ and $C_f=\frac{\mu_{hnf}}{\rho_f u_\infty{}^2}\left(\frac{\partial u}{\partial y}\right)_{y=0}$. Then, we get

$$\mathrm{Re}_x^{1/2} C_f = \frac{\mu_{hnf}}{\mu_f} f''(0), \quad \mathrm{Re}_x^{-1/2} Nu_x = -\frac{k_{hnf}}{k_f}\theta'(0), \tag{10}$$

Where $\mathrm{Re}_x = u_e(x)x/\nu_f$.

3. Numerical Procedure

The modified similarity systems in Eq. (7) – Eq. (8) were solved numerically to the desired level of accuracy using the bvp4c tools in MATLAB software. Due to its consistency and precision, this technique is chosen and has attracted the attention of many researchers. For additional information, a comprehensive discussion on this approach can be found in the work of Shampine *et al.,* [28]. In order to start up the bvp4c routine, Eq. (7) – Eq. (8) must be transformed into a set of first-order ordinary differential equation which can be rewritten as

$$\begin{aligned} &f=y(1), \quad \theta=y(4), \\ &f'=y(2), \ \theta'=y(5), \\ &f''=y(3), \end{aligned} \tag{11}$$

hence,

$$f'''=\frac{\rho_{hnf}/\rho_f}{\mu_{hnf}/\mu_f}\left(-\left(\frac{m+1}{2}\right)y(1)\,y(3)-m\left(1-y(2)^2\right)+\frac{\sigma_{hnf}/\sigma_f}{\rho_{hnf}/\rho_f}M\left(y(2)-1\right)\right), \tag{12}$$

$$\theta''=\Pr\frac{\left(\rho C_p\right)_{hnf}/\left(\rho C_p\right)_f}{k_{hnf}/k_f}\left(-\left(\frac{m+1}{2}\right)y(1)\,y(5)-\frac{H}{\left(\rho C_p\right)_{hnf}/\left(\rho C_p\right)_f}y(4)\right), \tag{13}$$

Meanwhile, the boundary conditions Eq. (9) is declared as

$$\begin{aligned}
[\, & y_a(1)-S \\
& y_a(2)-\lambda \\
& y_a(5)-1 \\
& y_b(2)-1 \\
& y_b(4)];
\end{aligned} \tag{14}$$

where the subscript a and b reflect the condition as $t=0$ and $t\to\infty$, respectively.

4. Results and Discussions

In this section, the results obtained from the numerical approach is discussed thoroughly. The results' reliability is compared with Sparrow *et al.,* [27] and Ishak *et al.,* [29] as provided in Table 3. It is found that the present findings are very much in line with previous investigations. Hence, we are confident that the intended mathematical model can accurately anticipate the behaviour of dynamic fluid flow for this particular study.

A diverse application of ϕ is carried out to differentiate between the conventional heat transfer fluid and the hybrid nanofluids. Furthermore, a diversity of parameter value specifications is made to the prior scope where the angle of the wedge and suction parameter are fixed to $m=0.1,$ and $S=2.0$, respectively, while the magnetic are set within $0.0\le M\le 0.05$ and the heat generation/absorption parameter is classified in the range of $0.0\le H\le 0.5$ to ensure that the solutions that were found are compatible with one another. This study employs a Prandtl number of 6.2, which is consistent with a nanofluid based on water (except for comparisons to earlier data). It should also be noted that to accomplish the desired outcome, the supplied parameter values must be used to generate a precise computation of the outcome.

Table 3
Approximation values of $f''(0)$ by certain values of S when $\lambda=M=H=\phi_1=\phi_2=0,$ and $\Pr=m=1$

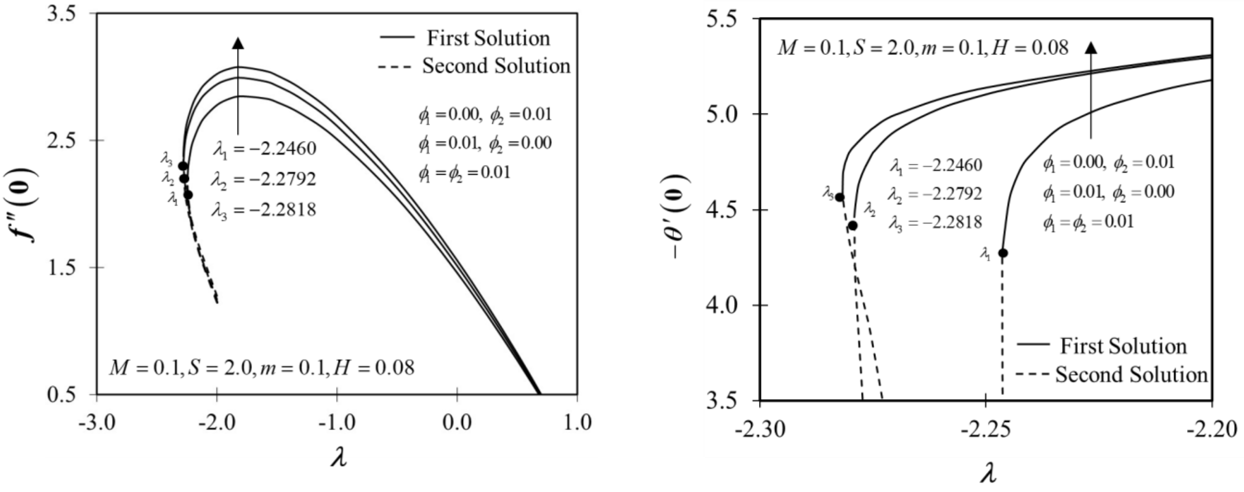
S	Present result	Sparrow *et al.,* [27]	Ishak *et al.,* [29]
1.0	1.889313	-	1.8893
0.5	1.541752	-	1.5418
0.0	1.232589	1.2310	1.2326
−0.5	0.969231	0.9697	0.9692
−1.0	0.756576	0.7605	0.7566

Figure 2 describes the influence of nanoparticles concentration when ϕ is varied as the wedge shrinks. When $\phi_1=0.00,\phi_2=0.01$, the alumina-water nanofluid (Al_2O_3/H_2O) is formed, meanwhile $\phi_1=0.01,\phi_2=0.00$ denoted the copper-water nanofluid (Cu/H_2O) and the combination of $\phi_1=\phi_2=0.01$ produced the alumina-copper/water hybrid nanofluids (Al_2O_3-Cu/H_2O). The improvement in the skin friction coefficient $(f''(0))$ trend is obvious as the value of ϕ improves over the shrinking wedge, as illustrated in Figure 2(a). According to the findings, the Al_2O_3-Cu/H_2O displayed the dominant trend of $(f''(0))$, followed by Cu/H_2O and Al_2O_3/H_2O. This process allows the boundary layer separation to proceed at a slower rate because of the frictional drag that is being exerted upsurges in the Al_2O_3-Cu/H_2O. The improvement in the heat transfer rate coefficient $-\theta'(0)$ corresponds to the increment in ϕ is accessible in Figure 2(b). It is proven that the Al_2O_3-Cu/H_2O shows better performance in heat transfer efficiency, followed by Cu/H_2O and Al_2O_3/H_2O. Aluminium is inferior to copper in terms of processor cooling since copper has better thermal conductivity. But due to its lower density as compared to copper, aluminium can radiate heat into the air more effectively. As a result, the combination of these heat conductor fluids performs better than a monofluid.

Figures 3(a) and 3(b) depict the velocity profile $f'(\eta)$ and temperature profile $-\theta'(0)$, respectively. Figure 3(a) appears to indicate that the boundary layer thickness of the first solution increases as the nanoparticle volume concentration ϕ in Al_2O_3-Cu/H_2O increases. However, the second solution showed a reduction trend as ϕ increases. The same characteristic trend is observed in the temperature distribution profile $\theta(\eta)$ which presents an upward trend in the first solution, while a downward trend is displayed in the second solution of the shrinking wedge, as exhibited in Figure 3(b). As can be seen, the thickness of the thermal boundary layer declines in both profiles. In general, the velocity and temperature distribution profiles were able to meet the requirements of the far-field boundary conditions (13) asymptotically when $\eta_\infty = 10$ is employed.

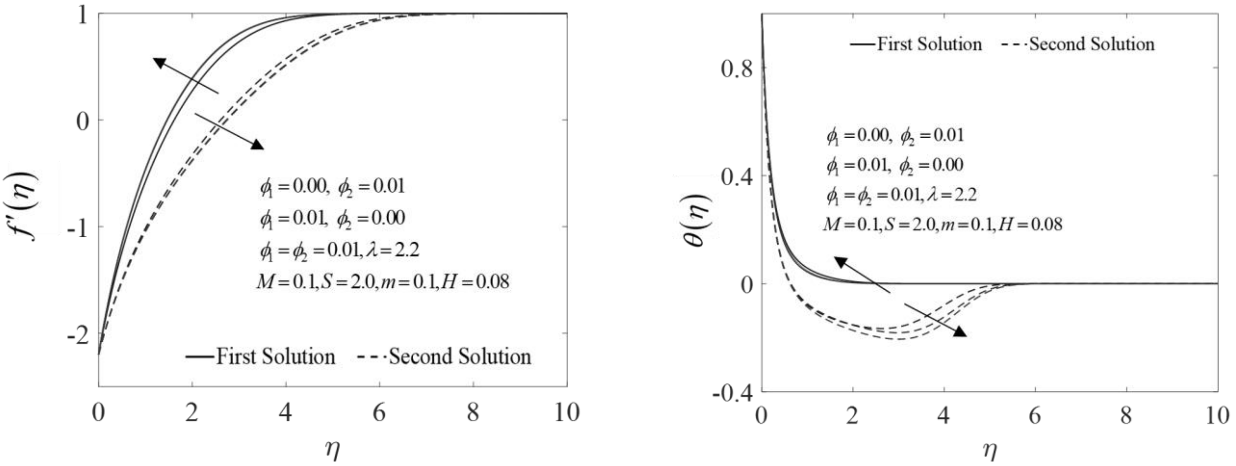
The impact of magnetic effect M in Al_2O_3-Cu/H_2O is available in Figure 4(a) and 4(b) with respect to $f''(0)$ and $-\theta'(0)$, respectively. Figure 4(a) displays that as M improved, $f''(0)$ increases in both solutions. On the other hand, Figure 4(b) illustrates an increasing pattern of $-\theta'(0)$ when M improves in the first solution, hence we can conclude that the thermal performance quality has progressed as the magnetic parameter enhances. Also, it should be noted that the proliferation of M has increased the solutions range as seen in Figure 4, hence granting for a prolonged delay in the process of boundary layer separation. From a fundamental standpoint, the magnetic field created a drag/resistance Lorentz force that delayed the velocity of the fluid and retarded the separation of the boundary layer.

Figure 5 illustrates the effect that the heat generation/absorption parameter has on this problem with the entire system. Figure 5(a) shows the variations of $-\theta'(0)$ for H such that $H = 0.0, 0.3, 0.5$ while the temperature distributions profile $\theta(\eta)$ is displayed in Figure 5(b). It has been observed that H has a significant effect on the temperature of the working fluid. To a significant extent, $-\theta'(0)$ improves whenever there is an increase in the heat generation as a result of the existence of extra heat supplied by the working flow, hence slow down the heat transmission of the system. This is due to the fact that a greater amount of heat is produced and then released into the flow, which has the effect of improving the thickness of the momentum boundary layer. The temperature of the hybrid nanofluids rises because of the thermal diffusion layer that formed when heat is generated, and this rises in conjunction with a decrease in the thermal rate.



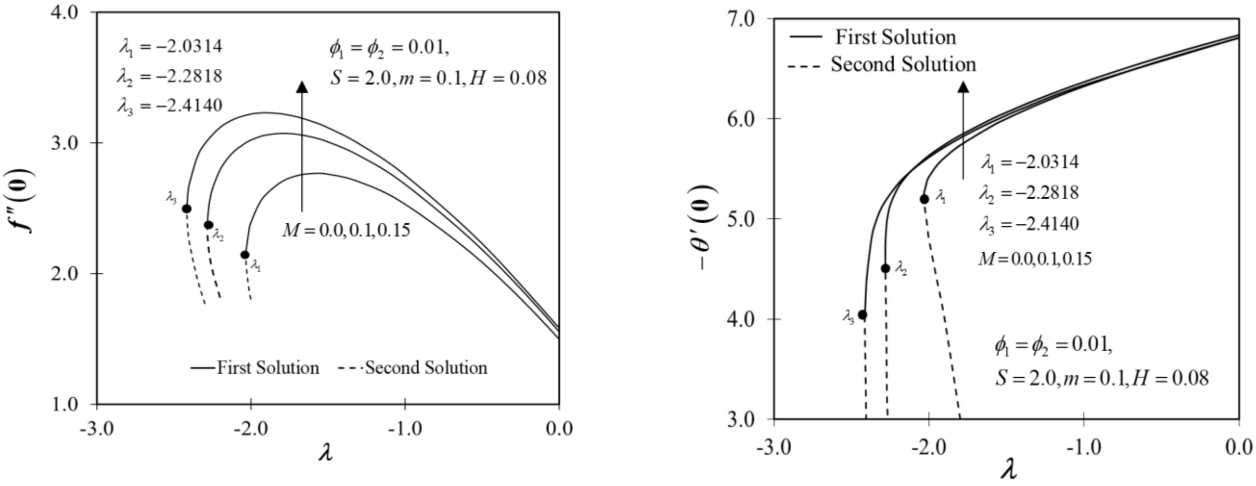
(a) (b)

Fig. 2. Different values of ϕ with λ (a) reduced skin friction coefficient (b) reduced heat transfer coefficient



(a) (b)

Fig. 3. Different values of ϕ with η (a) velocity profile (b) temperature profile



(a) (b)

Fig. 4. Different values of M with λ (a) reduced skin friction coefficient (b) reduced heat transfer coefficient

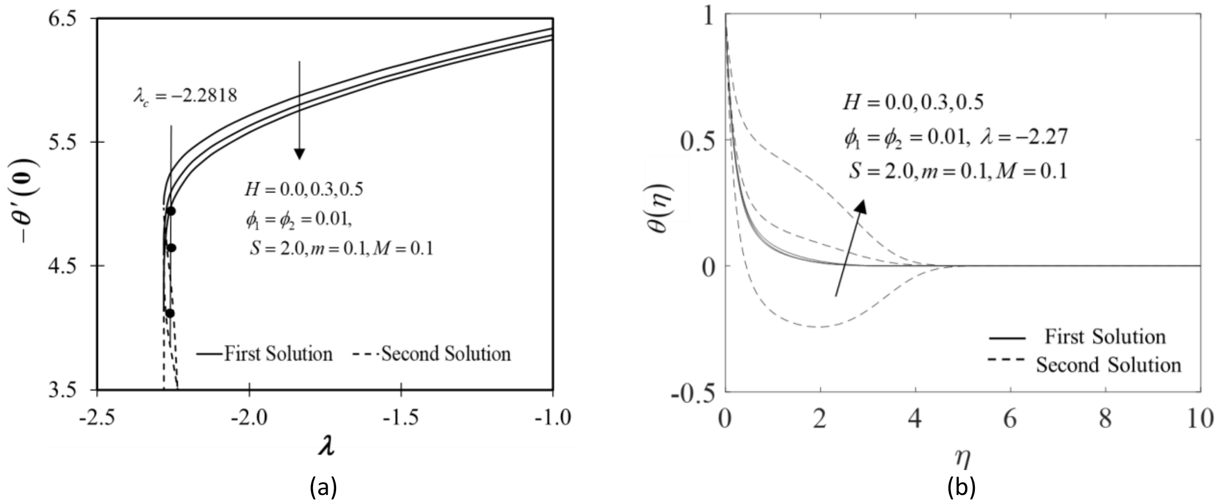


Fig. 5. Different values of H with λ and η (a) reduced heat transfer coefficient (b) temperature profile

5. Conclusions

Recent research verified a numerical simulation of the Al_2O_3-Cu/H_2O hybrid nanofluid's response to heat generation/absorption impact along a shrinking wedge with the addition of other governing parameters. Apparently, raising the magnetic parameter and nanoparticle volume fraction concentration may boost thermal efficiency. In relation to heat transfer rate, the increase of magnetic parameters from 0.00 to 0.10 and 0.15 contributes approximately 12.3% and 18.8%, respectively. This demonstrates that the Al_2O_3-Cu/H_2O hybrid nanofluids have better thermal conductivity than Cu/H_2O and Al_2O_3/H_2O when the magnetic and suction impacts incorporate in the working flow. In contrast, due to the formation of the thermal diffusion layer, the thermal performance of the working fluid degraded as the heat generation parameter increased, which dissipated the extra heat into the working flow.

Acknowledgement

The authors would like to acknowledge Fakulti Teknologi dan Kejuruteraan Mekanikal, Universiti Teknikal Malaysia Melaka for the financial and technical support.

References

[1] Salman, S., AR Abu Talib, S. Saadon, and MT Hameed Sultan. "Hybrid nanofluid flow and heat transfer over backward and forward steps: A review." *Powder Technology* 363 (2020): 448-472. https://doi.org/10.1016/j.powtec.2019.12.038

[2] Muneeshwaran, M., G. Srinivasan, P. Muthukumar, and Chi-Chuan Wang. "Role of hybrid-nanofluid in heat transfer enhancement–A review." *International Communications in Heat and Mass Transfer* 125 (2021): 105341. https://doi.org/10.1016/j.icheatmasstransfer.2021.105341

[3] Mercan, Hatice. "Thermophysical and rheological properties of hybrid nanofluids." In *Hybrid Nanofluids for Convection Heat Transfer*, pp. 101-142. Academic Press, 2020. https://doi.org/10.1016/B978-0-12-819280-1.00003-3

[4] Waini, Iskandar, Anuar Ishak, and Ioan Pop. "MHD flow and heat transfer of a hybrid nanofluid past a permeable stretching/shrinking wedge." *Applied Mathematics and Mechanics* 41, no. 3 (2020): 507-520. https://doi.org/10.1007/s10483-020-2584-7

[5] Dinarvand, Saeed, Mohammadreza Nademi Rostami, and Ioan Pop. "A novel hybridity model for TiO2-CuO/water hybrid nanofluid flow over a static/moving wedge or corner." *Scientific reports* 9, no. 1 (2019): 16290. https://doi.org/10.1038/s41598-019-52720-6

[6] Falkneb, V. M., and Sylvia W. Skan. "LXXXV. Solutions of the boundary-layer equations." *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 12, no. 80 (1931): 865-896. https://doi.org/10.1080/14786443109461870

[7] Zainal, Nurul Amira, Roslinda Nazar, Kohilavani Naganthran, and Ioan Pop. "Flow and heat transfer over a permeable moving wedge in a hybrid nanofluid with activation energy and binary chemical reaction." *International Journal of Numerical Methods for Heat & Fluid Flow* 32, no. 5 (2022): 1686-1705. https://doi.org/10.1108/HFF-04-2021-0298

[8] Rehman, Rabia, Umar Khan, Hafiz Abdul Wahab, and Basharat Ullah. "Second law analysis for the flow of hybrid nanofluid over a wedge." *Waves in Random and Complex Media* (2022): 1-16.https://doi.org/10.1080/17455030.2022.2155726

[9] Rawat, Sawan Kumar, Himanshu Upreti, and Manoj Kumar. "Comparative study of mixed convective MHD Cu-water nanofluid flow over a cone and wedge using modified Buongiorno's model in presence of thermal radiation and chemical reaction via Cattaneo-Christov double diffusion model." *Journal of Applied and Computational Mechanics* (2020). https://doi.org/0.22055/JACM.2020.32143.1975

[10] Ali, Liaqat, Ye Wang, Bagh Ali, Xiaomin Liu, Anwarud Din, and Qasem Al Mdallal. "The function of nanoparticle's diameter and Darcy-Forchheimer flow over a cylinder with effect of magnetic field and thermal radiation." *Case Studies in Thermal Engineering* 28 (2021): 101392. https://doi.org/10.1016/j.csite.2021.101392

[11] Ali, Bagh, Rizwan Ali Naqvi, Amna Mariam, Liaqat Ali, and Omar M. Aldossary. "Finite element study for magnetohydrodynamic (MHD) tangent hyperbolic nanofluid flow over a faster/slower stretching wedge with activation energy." *Mathematics* 9, no. 1 (2020): 25. https://doi.org/10.3390/math9010025

[12] Ali, Bagh, Anum Shafiq, Imran Siddique, Qasem Al-Mdallal, and Fahd Jarad. "Significance of suction/injection, gravity modulation, thermal radiation, and magnetohydrodynamic on dynamics of micropolar fluid subject to an inclined sheet via finite element approach." *Case Studies in Thermal Engineering* 28 (2021): 101537. https://doi.org/10.1016/j.csite.2021.101537

[13] Rosaidi, Nor Alifah, Nurul Hidayah Ab Raji, Siti Nur Hidayatul Ashikin Ibrahim, and Mohd Rijal Ilias. "Aligned magnetohydrodynamics free convection flow of magnetic nanofluid over a moving vertical plate with convective boundary condition." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 93, no. 2 (2022): 37-49. https://doi.org/10.37934/arfmts.93.2.3749

[14] Janapatla, Pranitha, and Anomitra Chakraborty. "Mixed convection nanofluid flow using lie group scaling with the impact of MHD radiation thermophoresis and brownian motion." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 101, no. 2 (2023): 85-98. https://doi.org/10.37934/arfmts.101.2.8598

[15] Yaseen, Moh, Manoj Kumar, and Sawan Kumar Rawat. "Assisting and opposing flow of a MHD hybrid nanofluid flow past a permeable moving surface with heat source/sink and thermal radiation." *Partial Differential Equations in Applied Mathematics* 4 (2021): 100168. https://doi.org/10.1016/j.padiff.2021.100168

[16] Khashi'ie, Najiyah Safwa, Iskandar Waini, Nur Syahirah Wahid, Norihan Md Arifin, and Ioan Pop. "Unsteady separated stagnation point flow due to an EMHD Riga plate with heat generation in hybrid nanofluid." *Chinese Journal of Physics* 81 (2023): 181-192. https://doi.org/10.1016/j.cjph.2022.10.010

[17] Manohar, G. R., P. Venkatesh, B. J. Gireesha, J. K. Madhukesh, and G. K. Ramesh. "Dynamics of hybrid nanofluid through a semi spherical porous fin with internal heat generation." *Partial Differential Equations in Applied Mathematics* 4 (2021): 100150. https://doi.org/10.1016/j.padiff.2021.100150

[18] Garia, Rashmi, Sawan Kumar Rawat, Manoj Kumar, and Moh Yaseen. "Hybrid nanofluid flow over two different geometries with Cattaneo–Christov heat flux model and heat generation: A model with correlation coefficient and probable error." *Chinese Journal of Physics* 74 (2021): 421-439. https://doi.org/10.1016/j.cjph.2021.10.030

[19] Rawat, Sawan Kumar, Moh Yaseen, Umair Khan, Manoj Kumar, Amal Abdulrahman, Sayed M. Eldin, Samia Elattar, Ahmed M. Abed, and Ahmed M. Galal. "Insight into the significance of nanoparticle aggregation and non-uniform heat source/sink on titania–ethylene glycol nanofluid flow over a wedge." *Arabian Journal of Chemistry* 16, no. 7 (2023): 104809. https://doi.org/10.1016/j.arabjc.2023.104809

[20] Negi, Anup Singh, Ashok Kumar, Moh Yaseen, Sawan Kumar Rawat, and Akshay Saini. "Effects of heat source on the stagnation point flow of a nanofluid over a stretchable sheet with magnetic field and zero mass flux at the surface." *Forces in Mechanics* 11 (2023): 100190. https://doi.org/10.1016/j.finmec.2023.100190

[21] Yaseen, Moh, Sawan Kumar Rawat, Nehad Ali Shah, Manoj Kumar, and Sayed M. Eldin. "Ternary hybrid nanofluid flow containing gyrotactic microorganisms over three different geometries with Cattaneo–Christov model." *Mathematics* 11, no. 5 (2023): 1237. https://doi.org/10.3390/math11051237

[22] Yaseen, Moh, Sawan Kumar Rawat, and Manoj Kumar. "Falkner–Skan problem for a stretching or shrinking wedge with nanoparticle aggregation." *Journal of Heat Transfer* 144, no. 10 (2022): 102501. https://doi.org/10.1115/1.4055046

[23] Rawat, Sawan Kumar, Moh Yaseen, Umair Khan, Manoj Kumar, Amal Abdulrahman, Sayed M. Eldin, Samia Elattar, Ahmed M. Abed, and Ahmed M. Galal. "Insight into the significance of nanoparticle aggregation and non-uniform heat source/sink on titania–ethylene glycol nanofluid flow over a wedge." *Arabian Journal of Chemistry* 16, no. 7 (2023): 104809. https://doi.org/10.1016/j.arabjc.2023.104809

[24] Awaludin, Izyan Syazana, Anuar Ishak, and Ioan Pop. "On the stability of MHD boundary layer flow over a stretching/shrinking wedge." *Scientific reports* 8, no. 1 (2018): 13622. https://doi.org/10.1038/s41598-018-31777-9

[25] Oztop, Hakan F., and Eiyad Abu-Nada. "Numerical study of natural convection in partially heated rectangular enclosures filled with nanofluids." *International journal of heat and fluid flow* 29, no. 5 (2008): 1326-1336. https://doi.org/10.1016/j.ijheatfluidflow.2008.04.009

[26] Raza, Jawad, Azizah Mohd Rohni, and Zurni Omar. "Numerical investigation of copper-water (Cu-water) nanofluid with different shapes of nanoparticles in a channel with stretching wall: Slip effects." *Mathematical and Computational Applications* 21, no. 4 (2016): 43. https://doi.org/10.3390/mca21040043

[27] Sparrow, E. M., E. R. G. Eckert, and W. J. Minkowycz. "Transpiration cooling in a magneto-hydrodynamic stagnation-point flow." *Applied Scientific Research, Section A* 11 (1963): 125-147. https://doi.org/10.1007/BF03184718

[28] Shampine, Lawrence F., Ian Gladwell, and Skip Thompson. *Solving ODEs with matlab*. Cambridge university press, 2003. https://doi.org/10.1017/CBO9780511615542

[29] Ishak, Anuar, Roslinda Nazar, and Ioan Pop. "Falkner-Skan equation for flow past a moving wedge with suction or injection." *Journal of Applied Mathematics and Computing* 25, no. 1-2 (2007): 67-83. https://doi.org/10.1007/BF02832339