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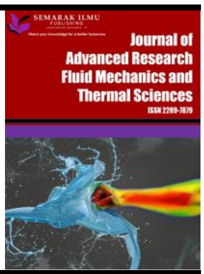

Nanofluid Flow and Heat Transfer between a Stationary Nonpermeable Disk and a Permeable Rotating Shrinking Disk with Radiation and Heat Generation Effects

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ABSTRACT

The flow between bounded surfaces is known as internal flow. The internal flow between disks has many significant applications, such as gas turbine rotors, rotating machinery, food processing technology, and air cleaning machines. In the current study, the nanofluid flow between two disks, nonpermeable and stationary, and the other permeable, rotating and shrinking, is analysed. The governing partial differential equations and boundary conditions are proposed with the inclusion of radiation and heat generation effects. Then, similarity transformations are utilised in deriving the nonlinear ordinary differential equations and boundary conditions for computation using the bvp4c solver. Multiple solutions are obtained, and only the first solution is stable. The combination Mn-$ZnFe_2O_4$/$C_2H_6O_2$ nanofluid is found to produce the lowest magnitude of skin friction coefficient and the highest heat transfer rate.

1. Introduction

Choi and Eastman [1] proposed nanofluid, which is composed of nanometer-sized particles (*e.g.,* metallic nanoparticles, metallic oxide nanoparticles, and nanotubes) suspended in a base fluid (*i.e.,* conventional heat transfer fluid such as water, ethylene glycol, and engine oil). Following the pioneering work by Maxwell [2], this study was done to find a better heat transfer fluid with high thermal conductivity. Applications of nanofluid range from manufacturing processes to biomedical applications, such as in heat exchangers, as a coolant in nuclear systems and automobiles, drug delivery systems, medicine, nanorefrigerants, sunscreen products, magnetic sealing, and building heating systems [3-6]. Researchers conducted various studies on the external and internal flows of the nanofluids to identify the flow behaviour and thermophysical properties of this fluid [7-16].

External flow is unbounded flow over a surface, while internal flow is a flow between bounded surfaces, for example, through a pipe, duct, or channel with confining walls. Fluid flow between

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rotating disks was initially studied by Batchelor [17]. In this work, it was predicted that a boundary layer would form on both disks, and the main body of the fluid would rotate. However, Stewartson [18] found that the boundary layer only forms on the rotating disk, with the main body of fluid being essentially stationary when the disks rotate in a different direction or one of the disks is static. Later, Mellor *et al.,* [19] presented a theoretical and experimental study on the flow between a stationary and a rotating disk. Then, Narayana and Rudraiah [20] extended this study by considering a uniform suction on the static disk. Next, Lopez [21] considered a corotating cylinder surrounding the stationary and rotating disk and studied the fluid flow in this geometry. Kavenuke *et al.,* [22] then produced approximate solutions for flow between an impermeable stationary disk and a porous rotating disk. Further extension of this study was conducted by Upadhya *et al.,* [23] by considering nanofluid, as the working fluid, in the presence of a magnetic field and internal heating. Numerical solutions were generated in this study. Bilal *et al.,* [24] recently expanded this study with a nanofluid containing gyrotactic microorganisms and magnetic nanoparticles. The radial wall friction along the gyrating disk was found to be elevated by heat generation. Meanwhile, the augmentation of the chemical reaction boosted the mass transfer rate in the internal flow of the nanofluid.

The present study will analyse the nanofluid flow between two disks, with one disk stationary while the other is rotating and shrinking. This study is extended from Kavenuke *et al.,* [22] and Upadhya *et al.,* [23] to the case of a nanofluid and shrinking disk. Partial differential equations and boundary conditions that govern this flow problem will be simplified and solved numerically in MATLAB. The results, represented by tables and graphs, will be scrutinised and discussed.

2. Mathematical Formulation

Consider a steady nanofluid flow between a stationary nonpermeable disk (lower disk) and a permeable rotating shrinking disk (upper disk). The stationary and rotating disks are separated by a distance l, as shown in Figure 1, where (r, φ, z) are cylindrical coordinates with $r-$ axis measured in the vertical direction and $z-$ axis measured in the horizontal direction. However, the angle φ will not appear in the mathematical formulation due to rotational symmetry, and the distance l is very small compared to the radii of the disks [22]. Meanwhile, the upper permeable disk rotates about the $z-$ axis with a velocity $\Omega\,\varepsilon$, where Ω is the angular velocity and ε $(0 < \varepsilon \leq 1)$ is a regulator which controls the rotation of the disk. The rotation occurs when $\varepsilon > 0$ and is at rest for $\varepsilon = 0$. Here, w_0 is the constant mass flux velocity with $w_0 > 0$ for suction and $w_0 < 0$ for injection. Thermal radiation and internal heating effects are considered in the heat transfer analysis.

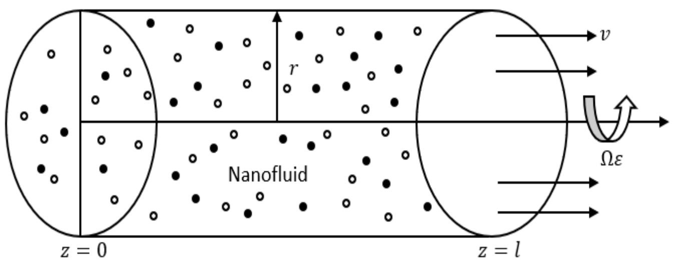


Fig. 1. Physical model and coordinate system

Under these assumptions, the following set of boundary layer equations governing the flow of water (H_2O) and ethylene glycol ($C_2H_6O_2$) suspended by cobalt ferrite ($CoFe_2O_4$) and Mn-Zn ferrite (Mn-$ZnFe_2O_4$) nanoparticles can be expressed as [23]

$$\frac{1}{r}\frac{\partial\,(r\,u)}{\partial\,r}+\frac{\partial\,w}{\partial\,z}=0, \tag{1}$$

$$u\,\frac{\partial\,u}{\partial\,r}+w\,\frac{\partial\,u}{\partial\,z}-\frac{v^2}{r}=-\frac{1}{\rho_n}\frac{\partial\,p}{\partial\,r}+\frac{\mu_n}{\rho_n}\left[\left(\frac{\partial}{\partial\,r}\left(\frac{u}{r}\right)\right)+\frac{\partial^2 u}{\partial\,z^2}\right], \tag{2}$$

$$\frac{u}{r}\,\frac{\partial\,(r\,v)}{\partial\,r}+w\,\frac{\partial\,v}{\partial\,z}=\frac{\mu_n}{\rho_n}\left[\left(\frac{\partial}{\partial\,r}\left(\frac{v}{r}\right)\right)+\frac{\partial^2 v}{\partial\,z^2}\right], \tag{3}$$

$$u\,\frac{\partial\,w}{\partial\,r}+w\,\frac{\partial\,w}{\partial\,z}=-\frac{1}{\rho_n}\,\frac{\partial\,p}{\partial\,z}+\frac{\mu_n}{\rho_n}\left[\frac{1}{r}\,\frac{\partial\,w}{\partial\,r}+\frac{\partial^2 w}{\partial\,z^2}\right], \tag{4}$$

$$u\,\frac{\partial\,T}{\partial\,r}+w\,\frac{\partial\,T}{\partial\,z}=\frac{k_n}{\left(\rho\,C_p\right)_n}\left[\frac{1}{r}\,\frac{\partial\,T}{\partial\,r}+\frac{\partial^2 T}{\partial\,z^2}\right]-\frac{1}{\left(\rho\,C_p\right)_n}\frac{\partial\,q_r}{\partial\,z}+\frac{Q_0}{\left(\rho\,C_p\right)_n}\,(T-\,T_2), \tag{5}$$

along with the boundary conditions given by

- he nonpermeable stationary disk at $z=0$

$$u(r,0)=0,\qquad v(r,0)=0\,,\qquad w(r,0)=0,\qquad T(r,0)=\,T_1. \tag{6}$$

- The permeable rotating shrinking disk at $z=l$

$$u(r,l)=0,\qquad v(r,l)=r\,\Omega\,\lambda,\qquad \mathrm{w}(r,l)=\,\varepsilon\,w_0,\qquad T(r,l)=\,T_2. \tag{7}$$

In the above equations, $u, v,$ and w are the velocity components along the $r-, \varphi-$ and $z-$directions, respectively. The nanofluid temperature is given by T, while the temperature of the lower and upper disks is T_1 and T_2 , respectively. Meanwhile, Q_0 is the heat generation/absorption coefficient, p is the pressure, q_r is the radiation heat flux, and $\lambda(< 0)$ is the shrinking parameter.

Further, μ is the dynamic viscosity, ρ is the density, k is the thermal conductivity, and ρC_p is the effective heat capacity with C_p as the heat capacity at constant pressure

$$\left.\begin{aligned} \frac{\mu_n}{\mu_f}&=\frac{1}{(1-\,\phi)^{2.5}},\\ \rho_n&=(1-\phi)\,\rho_f+\,\phi\,\rho_s,\\ \frac{k_n}{k_f}&=\frac{k_s\,+2\,k_f\,-2\,\phi\,(k_f\,-\,k_s)}{k_s\,+2\,k_f\,+\,2\,\phi\,(k_f\,-\,k_s)},\\ \left(\rho C_p\right)_n&=(1-\,\phi)\left(\rho\,C_p\right)_f+\,\phi\left(\rho\,C_p\right)_s. \end{aligned}\right\}. \tag{8}$$

Here, the suffixes n, s, and f represent the nanofluid, nanoparticles, and base fluid, respectively. Table 1 contains the thermophysical properties of the base fluids and nanoparticles. Meanwhile, the nanoparticle volume fraction is ϕ.

Table 1
Thermophysical properties of water, ethylene glycol, $CoFe_2O_4$ and Mn-$ZnFe_2O_4$ nanoparticles [25]

Properties	Water	Ethylene glycol	$CoFe_2O_4$	Mn-$ZnFe_2O_4$
Thermal conductivity, k [W/m K]	0.613	0.349	3.7	5
Heat capacity, C_p [J/kg K]	4 179	2 382	700	800
Density, ρ [kg/m^3]	997.1	1 116.6	4 907	4 900
Prandtl number, Pr	6.96	204	-	-

From the Rosseland approximation, the radiative heat flux, q_r can be expressed as follows

$$q_r = -\frac{4\,\sigma^*}{3\,k^*}\frac{\partial T^4}{\partial\, y}, \tag{9}$$

with σ^* and k^* denote the constant of Stefan-Boltzmann and the coefficient of mean absorption, respectively. Using the Taylor series and ignoring higher-order terms, T^4 is expanded about T_∞ to obtain $T^4 \approx 4T_\infty^3 T - 3T_\infty^4$. Then, Eq. (5) can be written as

$$\begin{aligned} u\,\frac{\partial\, T}{\partial\, r} + w\,\frac{\partial T}{\partial\, z} = {} & \frac{1}{\left(\rho\, C_p\right)_n}\left[\left(k_n\left(\frac{1}{r}\left(\frac{\partial\, T}{\partial\, r}\right) + \frac{\partial^2 T}{\partial\, z^2}\right) + \frac{16\,\sigma^*\,T_2^3}{3\,k^*}\,\frac{\partial^2 T}{\partial\, z^2}\right)\right] \\ & + \frac{Q_0}{\left(\rho\, C_p\right)_n}\,[(T - T_2)\theta(\eta)] \end{aligned} \tag{10}$$

It is suitable to introduce the following similarity variables [23]

$$\left.\begin{aligned} u = r\Omega\, f'(\eta), \quad v = r\,\Omega\, g(\eta), \quad w = -2\,w_0 f(\eta), \;\; \theta(\eta) = \frac{T - T_2}{T_1 - T_2}, \\ p = -\frac{1}{2}\rho_f\, r^2\,\Omega^2\, A + \rho_f\, w_0^2\, P(\eta), \quad \eta = \frac{z\,\Omega}{w_0}, \end{aligned}\right\}, \tag{11}$$

where the prime denotes differentiation with respect to η and A is an arbitrary constant, and substituting (11) into Eqs. (2) to (4), and (10), we obtain the following ordinary (similarity) differential equations

$$\frac{1}{Re}\frac{\mu_n/\mu_f}{\rho_n/\rho_f} f'''' + 2\,f f''' + 2gg' = 0, \tag{13}$$

$$\frac{1}{Re}\frac{\mu_n/\mu_f}{\rho_n/\rho_f} g'' + 2fg' - 2gf' = 0, \tag{14}$$

$$\frac{1}{PrRe}\frac{1}{\left(\rho C_p\right)_n/\left(\rho C_p\right)_f}\left(\frac{k_n}{k_f} + \frac{4}{3}\,Rd\right)\theta'' + 2f\,\theta' + \frac{Q\,\theta}{\left(\rho C_p\right)_n/\left(\rho C_p\right)_f} = 0, \tag{15}$$

subject to the boundary conditions

$$\left.\begin{aligned} f(0) = 0, \;\; f'(0) = 0\,, \;\; g(0) = 0, \;\; \theta(0) = 1, \\ \theta(1) = 0, \;\; f'(1) = 0, \;\; g(1) = \lambda, \;\; f(1) = -\varepsilon/2\,. \end{aligned}\right\}. \tag{16}$$

Here, Pr is the Prandtl number, Re is the Reynolds number, Rd is the radiation parameter, and Q is the heat generation/absorption parameter, which are given by

$$Pr = \frac{(\mu C_p)_f}{k_f}, \quad Re = \frac{w_0^2}{\Omega \, \nu_f}, \quad Rd = \frac{4 \, \sigma^* \, T_2^3}{k_f \, k^*}, \quad Q = \frac{Q_0}{\Omega \, (\rho C_p)_f}, \tag{17}$$

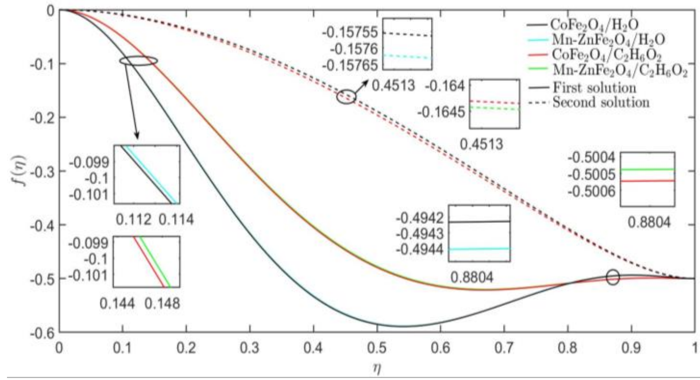
where $\nu = \mu/\rho$ is the kinematic viscosity.

4. Results and Discussion

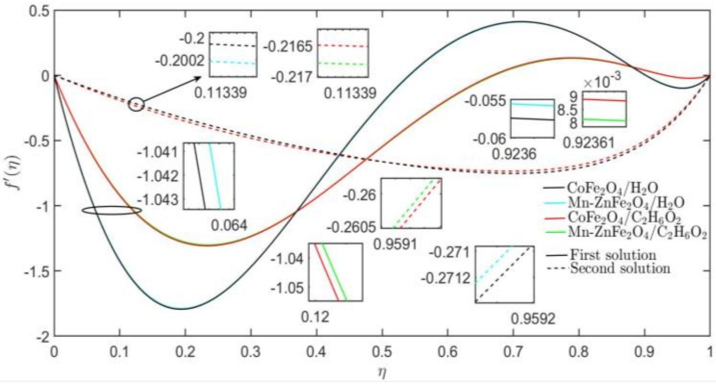
In the present study, water- and ethylene glycol-based nanofluids containing cobalt ferrite ($CoFe_2O_4$) and Mn-Zn ferrite ($Mn\text{-}ZnFe_2O_4$) nanoparticles are considered. Only the first solution is determined to be stable and physically significant, based on the stability analysis of multiple solutions carried out in the prior studies [26–28]. The physical quantities of interest for these nanofluids are tabulated in Table 2. As noted in Table 2, the $CoFe_2O_4/H_2O$ nanofluid produces the largest magnitude of skin friction coefficient, followed by the $Mn\text{-}ZnFe_2O_4/H_2O$, $CoFe_2O_4/C_2H_6O_2$, and $Mn\text{-}ZnFe_2O_4/C_2H_6O_2$ nanofluids. Based on these observations, the combination of $Mn\text{-}ZnFe_2O_4$ nanoparticle with $C_2H_6O_2$ produces the most efficient nanofluid for this flow problem, as it has the lowest magnitude of skin friction coefficient and the highest heat transfer rate. Next, the axial velocity profile in Figure 2a shows that the $Mn\text{-}ZnFe_2O_4/C_2H_6O_2$ nanofluid has the highest velocity near the stationary impermeable disk. However, near the permeable rotating disk, $CoFe_2O_4/H_2O$ nanofluid exhibits the highest axial velocity compared to the other nanofluids. Meanwhile, the $Mn\text{-}ZnFe_2O_4/C_2H_6O_2$ and $CoFe_2O_4/C_2H_6O_2$ nanofluids have the highest radial velocities near the stationary and rotating disks, respectively, as shown in Figure 2b. At the same time, in Figure 2c, the $Mn\text{-}ZnFe_2O_4/C_2H_6O_2$ nanofluid shows the highest tangential velocity near the stationary and rotating disks. From Figure 2d, the $CoFe_2O_4/C_2H_6O_2$ and $Mn\text{-}ZnFe_2O_4/H_2O$ nanofluids have the highest and lowest temperature profiles, respectively.

Table 2
Coefficients of skin friction (radial and tangential directions) at the lower and upper disks when $\phi = 0.2, \lambda = -1, \varepsilon = 1, Re = 9, Rd = 0.3$, and $Q = 0.1$

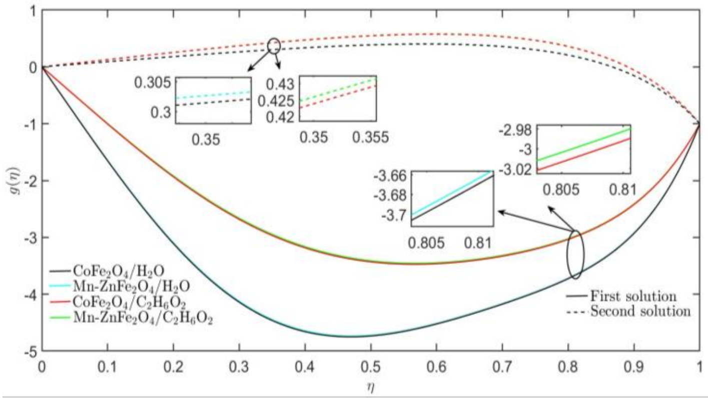
Nanofluid	$\frac{\mu_{hn}}{\mu_f} f''(0)$ (lower disk)		$\frac{\mu_{hn}}{\mu_f} g'(0)$ (lower disk)		$\frac{\mu_{hn}}{\mu_f} f''(1)$ (lower disk)		$\frac{\mu_{hn}}{\mu_f} g'(1)$ (upper disk)	
	First solution	Second solution	First solution	Second solution	First solution	Second solution	First solution	Second solution
$CoFe_2O_4/H_2O$	-35.62302	-3.32474	-29.23075	1.58930	9.22210	13.75794	51.70404	-22.26607
$Mn - ZnFe_2O_4/H_2O$	-35.47872	-3.32798	-29.11240	1.59553	9.11525	13.74935	51.56424	-22.28368
$CoFe_2O_4/C_2H_6O_2$	-21.53147	-3.67576	-17.68497	2.23249	2.94548	13.12263	37.10216	-24.34233
$Mn - ZnFe_2O_4/C_2H_6O_2$	-21.37439	-3.68210	-17.55654	2.24338	2.92835	13.11506	36.91246	-24.38100



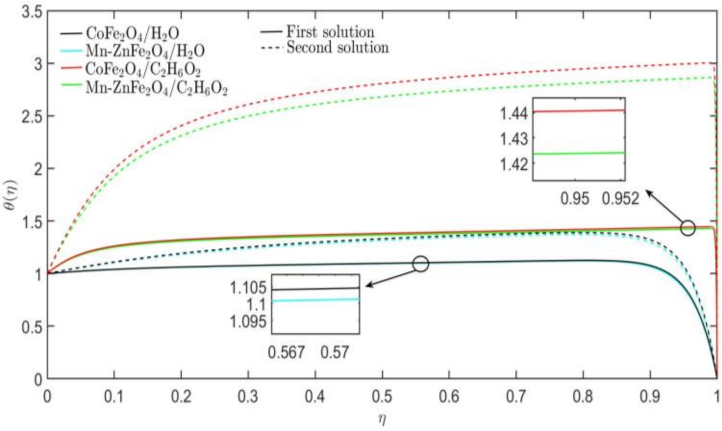
(a)



(b)



(c)



(d)

Fig. 2. Profiles of (a) axial velocity, (b) radial velocity, (c) tangential velocity, and (d) temperature for various nanofluid when $\phi = 0.2, \lambda = -1, \varepsilon = 1, Re = 9, Rd = 0.3$, and $Q = 0.1$

5. Conclusions

The nanofluid flow between a nonpermeable stationary disk and a rotating permeable shrinking disk is scrutinised in this study. Various nanofluids such as the $CoFe_2O_4/H_2O$, Mn-$ZnFe_2O_4/H_2O$, $CoFe_2O_4/C_2H_6O_2$, and Mn-$ZnFe_2O_4/C_2H_6O_2$ are considered as the working fluid in this flow problem. Dual solutions are generated from numerical computation. The combination Mn-$ZnFe_2O_4/C_2H_6O_2$ nanofluid has the lowest magnitude of skin friction coefficient and the highest heat transfer rate. The temperature profile of the ethylene-glycol-based nanofluids (*i.e.,* $CoFe_2O_4/C_2H_6O_2$ and Mn-$ZnFe_2O_4/C_2H_6O_2$) rises with the addition of nanoparticle volume fraction, contrary to the water-based nanofluids (*i.e.,* $CoFe_2O_4/H_2O$ and Mn-$ZnFe_2O_4/H_2O$).

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References
[1] Choi, S. US, and Jeffrey A. Eastman. *Enhancing thermal conductivity of fluids with nanoparticles*. No. ANL/MSD/CP-84938; CONF-951135-29. Argonne National Lab.(ANL), Argonne, IL (United States), 1995.
[2] Maxwell, James Clerk. *A treatise on electricity and magnetism*. Vol. 1. Clarendon press, 1873.
[3] Yu, Wei, Huaqing Xie, and Li-Hong Liu. "A review on nanofluids: Preparation, stability mechanisms, and applications." *Journal of Nanomaterials* 2012, no. 711 (2011): 128. https://doi.org/10.1155/2012/435873
[4] Ali, Naser, Joao A. Teixeira, and Abdulmajid Addali. "A review on nanofluids: fabrication, stability, and thermophysical properties." *Journal of Nanomaterials* 2018 (2018). https://doi.org/10.1155/2018/6978130
[5] Halim, Nur Fazlin Che, and Nor Azwadi Che Sidik. "Nanorefrigerants: A Review on Thermophysical Properties and Their Heat Transfer Performance." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 20, no. 1 (2020): 42-50. https://doi.org/10.37934/araset.20.1.4250
[6] Latib, Muhammad Azamuddin, and Natrah Kamaruzaman. "Simulation Study on the Heat Performance of Different Nanofluids for Rotating Detonation Engine Cooling." *Journal of Advanced Research in Micro and Nano Engineering* 5, no. 1 (2021): 1-8.
[7] Roslan, Rozaini, I. R. Ali, Ammar I. Alsabery, and N. A. Bakar. "Mixed Convection in a Lid-Driven Horizontal Rectangular Cavity Filled with Hybrid Nanofluid By Finite Volume Method." *Journal of Advanced Research in Micro and Nano Engineering* 1, no. 1 (2020): 38-49.
[8] Jowsey, Mohamad Hafzan Mohamad, Natrah Kamaruzaman, and Mohsin Mohd Sies. "Heat and Flow Profile of Nanofluid Flow Inside Multilayer Microchannel Heat Sink." *Journal of Advanced Research in Micro and Nano Engineering* 4, no. 1 (2021): 1-9.
[9] Akaje, Wasiu, and B. I. Olajuwon. "Impacts of Nonlinear thermal radiation on a stagnation point of an aligned MHD Casson nanofluid flow with Thompson and Troian slip boundary condition." *Journal of Advanced Research in Experimental Fluid Mechanics and Heat Transfer* 6, no. 1 (2021): 1-15.
[10] Elfaghi, Abdulhafid MA, Alhadi A. Abosbaia, Munir FA Alkbir, and Abdoulhdi AB Omran. "CFD Simulation of Forced Convection Heat Transfer Enhancement in Pipe Using Al2O3/Water Nanofluid." *Journal of Advanced Research in Numerical Heat Transfer* 8, no. 1 (2022): 44-49.
[11] Dzulkifli, Nor Fadhilah, Norfifah Bachok, Nor Azizah Yacob, Ioan Pop, Norihan Arifin, and Haliza Rosali. "Stability Solution of Unsteady Stagnation-Point Flow and Heat Transfer over a Stretching/Shrinking Sheet in Nanofluid with Slip Velocity Effect." *CFD Letters* 14, no. 1 (2022): 66-86. https://doi.org/10.37934/cfdl.14.1.6686
[12] Sunitha, Cheela, Prathi Vijaya Kumar, Giulio Lorenzini, and Shaik Mohammed Ibrahim. "A Study of Thermally Radiant Williamson Nanofluid Over an Exponentially Elongating Sheet with Chemical Reaction Via Homotopy Analysis Method." *CFD Letters* 14, no. 5 (2022): 68-86. https://doi.org/10.37934/cfdl.14.5.6886
[13] Cherifa, Benygzer, Bouzit Mohamed, Mokhefi Abderrahim, and Khelif Fatima-Zohra. "Unsteady Natural Convection in a Porous Square Cavity Saturated by Nanofluid Using Buongiorno Model: Variable Permeability Effect on Homogeneous Porous Medium." *CFD Letters* 14, no. 7 (2022): 42-61. https://doi.org/10.37934/cfdl.14.7.4261
[14] Bosli, Fazillah, Alia Syafiqa Suhaimi, Siti Shuhada Ishak, Mohd Rijal Ilias, Amirah Hazwani Abdul Rahim, and Anis Mardiana Ahmad. "Investigation of Nanoparticles Shape Effects on Aligned MHD Casson Nanofluid Flow and Heat

Transfer with Convective Boundary Condition." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 91, no. 1 (2022): 155-171. https://doi.org/10.37934/arfmts.91.1.155171

[15] Ismail, Nurul Syuhada, Yong Faezah Rahim, Norihan Md Arifin, Roslinda Nazar, and Norfifah Bachok. "Stability Analysis of The Stagnation-Point Flow and Heat Transfer Over a Shrinking Sheet in Nanofluid in The Presence of MHD and Thermal Radiation." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 91, no. 2 (2022): 96-105. https://doi.org/10.37934/arfmts.91.2.96105

[16] Yahaya, Rusya Iryanti, Norihan Md Arifin, Ioan Pop, Fadzilah Md Ali, and Siti Suzilliana Putri Mohamed Isa. "Steady Flow of Burgers' Nanofluids over a Permeable Stretching/Shrinking Surface with Heat Source/Sink." *Mathematics* 10, no. 9 (2022): 1580. https://doi.org/10.3390/math10091580

[17] Batchelor, Go K. "Note on a class of solutions of the Navier-Stokes equations representing steady rotationally-symmetric flow." *The quarterly journal of mechanics and applied mathematics* 4, no. 1 (1951): 29-41. https://doi.org/10.1093/qjmam/4.1.29

[18] Stewartson, K. "On the flow between two rotating coaxial disks." In *Mathematical Proceedings of the Cambridge Philosophical Society*, vol. 49, no. 2, pp. 333-341. Cambridge University Press, 1953. https://doi.org/10.1017/S0305004100028437

[19] Mellor, G. L., P. J. Chapple, and V. K. Stokes. "On the flow between a rotating and a stationary disk." *Journal of fluid mechanics* 31, no. 1 (1968): 95-112. https://doi.org/10.1017/S0022112068000054

[20] Narayana, C. L., and N. Rudraiah. "On the steady flow between a rotating and a stationary disk with a uniform suction at the stationary disk." *Zeitschrift für angewandte Mathematik und Physik ZAMP* 23, no. 1 (1972): 96-104. https://doi.org/10.1007/BF01593206

[21] Lopez, Juan M. "Flow between a stationary and a rotating disk shrouded by a co-rotating cylinder." *Physics of Fluids* 8, no. 10 (1996): 2605-2613. https://doi.org/10.1063/1.869047

[22] Kavenuke, D. P., E. Massawe, and O. D. Makinde. "Modeling laminar flow between a fixed impermeable disk and a porous rotating disk." *African Journal of Mathematics and Computer Science Research* 2, no. 7 (2009): 157-162.

[23] Upadhya, S. Mamatha, R. L. V. Devi, C. S. K. Raju, and Hafiz Muhammad Ali. "Magnetohydrodynamic nonlinear thermal convection nanofluid flow over a radiated porous rotating disk with internal heating." *Journal of Thermal Analysis and Calorimetry* 143, no. 3 (2021): 1973-1984. https://doi.org/10.1007/s10973-020-09669-w

[24] Bilal, Muhammad, Hamdi Ayed, Anwar Saeed, Ameni Brahmia, Taza Gul, and Poom Kumam. "The parametric computation of nonlinear convection magnetohydrodynamic nanofluid flow with internal heating across a fixed and spinning disk." *Waves in Random and Complex Media* (2022): 1-16. https://doi.org/10.1080/17455030.2022.2042621

[25] Ahmed, Naveed, Asifa Tassaddiq, Rana Alabdan, Umar Khan, Saima Noor, Syed Tauseef Mohyud-Din, and Ilyas Khan. "Applications of nanofluids for the thermal enhancement in radiative and dissipative flow over a wedge." *Applied Sciences* 9, no. 10 (2019): 1976. https://doi.org/10.3390/app9101976

[26] Yahaya, Rusya Iryanti, Norihan Md Arifin, Ioan Pop, Fadzilah Md Ali, and Siti Suzilliana Putri Mohamed Isa. "Dual solutions for MHD hybrid nanofluid stagnation point flow due to a radially shrinking disk with convective boundary condition." *International Journal of Numerical Methods for Heat & Fluid Flow* ahead-of-print (2022). https://doi.org/10.1108/HFF-05-2022-0301

[27] Wahid, Nur Syahirah, Norihan Md Arifin, Najiyah Safwa Khashi'ie, Ioan Pop, Norfifah Bachok, and Mohd Ezad Hafidz Hafidzuddin. "Hybrid nanofluid stagnation point flow past a slip shrinking Riga plate." *Chinese Journal of Physics* (2022). https://doi.org/10.1016/j.cjph.2022.05.016

[28] Wahid, Nur Syahirah, Norihan Md Arifin, Najiyah Safwa Khashi'ie, Ioan Pop, Norfifah Bachok, and Mohd Ezad Hafidz Hafidzuddin. "Hybrid Nanofluid Radiative Mixed Convection Stagnation Point Flow Past a Vertical Flat Plate with Dufour and Soret Effects." *Mathematics* 10, no. 16 (2022): 2966. https://doi.org/10.3390/math10162966