

Thermal Performance Analysis of Ternary Hybrid Nanofluids in Solar-Powered Ships Using Parabolic Trough Solar Collectors

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Abstract. The impact of Cattaneo–Christov heat flux on cylindrical surfaces using Carbon Nanotube (CNT) ternary Hybrid Nanofluids with convective boundary conditions is investigated in this work, especially within the context of solar-powered ships. A numerical simulation is performed to assess the thermal characteristics and effectiveness of CNT ternary Hybrid Nanofluids over traditional fluids. The thermal relaxation effects and the heat flux are attained using the Cattaneo–Christov heat flux model which leads to a better prediction of heat transfer processes in the nanofluids. By assessing the existing behaviors and energy transfer characteristics of CNT ternary hybrid nanofluids, the findings perfectly show that the nanoparticle impacts improving the thermal conductivity and heat transfer efficiency. This is useful for optimization of cooling systems of ships driven by solar energy. This work is beneficial to the efforts put towards designing and optimal thermal management strategies for solar-powered ships using nanofluid and novel heat transfer.

Keywords: Cattaneo–Christov heat flux, CNT ternary Hybrid, Thermal relaxation effects, Solar-powered ships, Porous Medium, Cylindrical surfaces.

1 Introduction

Recent advancements in ternary nanofluids (TNFs) have significantly enhanced the sustainability of various engineering systems in numerous manufacturing industries, particularly in the area of thermal transfer. Researchers in the industrial sector have shown significant interest in the combination of base fluids, nanoparticles, and surfactants or stabilizers, owing to their intricate thermal properties [1-4]. This profound curiosity stems after probable proceeds that TNFs offer in increasing heat transportation process. The importance of TNFs in electronics such as computers, telephones, and LED lights cannot be over emphasized by frequently regulating the thermal generated during their operation. This high level of thermal conductivity does not only increase the efficiency of electronic devices but also reassure their dependability by enhancing heat dissipation effectiveness. Moreover, the application of TNFs exceeds the prerogative of electronics, with broader applications as thermal transmission techniques in strenuous solar power systems [5]. Incorporating TNFs into thermal energy storage systems offers a dual benefit of improving energy density and refining heat transfer efficiency. By their movement within solar collectors, these nano fluids

efficiently transport absorbed solar energy to both thermal exchangers and storage tanks, subsequent in an important improvement in the general efficacy of solar energy transformation measures [6-10]. This strategic use of TNFs not only modifies the functioning of thermal energy storage systems, meanwhile this is very important at driving progress within sustainable energy technologies through the enhancement of energy transfer and storage abilities. The research on the heat efficiency of TNFs (Aluminum oxide, copper oxide, copper in water) and hybridized nano-fluids (Aluminum oxide, copper oxide in water), studying the causes of convective heat conditions and the use of a magnetic force on improving heat performance were study by [11]. This study aimed to evaluate the heat storage capacity of hybrid and tri-hybrid nano-fluids. Through the application of novel approach like building an empirical correlation, applying a consistent magnetic field, and engaging convective thermal transfer methods, they required to develop the holding of heat energy in between those fluids. This research highpoint the likeliness of nano fluid-based arrangements in improving efficiency and storage ability, making them well-suited for different renewable energy uses. The efficiency of an electrically conductive hybrid nanofluid made up of water with (iron oxide and carbon

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nanotube) in a trapezoidal vessel featuring wavy walls. Their research incorporated different forces such as Lorentz hydro magnetized body force, Darcian, and Forchheimer drag force factors in a three-dimensional scenario of free convection were study by [12]. the mixed convection flow over a lengthy surface, taking into justification convection thermal transfer influenced by the Joule effect and considering nth-order chemical reactions were study by [13]. The research applied entropy generation analysis to assess the flow dynamics. The hydrothermal properties of a hybrid nano liquid slip flow over a permeable surface that expands, or contracts were study by [14]. The simulation involved copper alumina nanoparticles in water as the base liquid and introduced Joule heating and viscous dissipative flux for a more detailed model. By examining new cooling method, it is likely to reduce energy usage in cooling systems. One of the ways to achieve this involves researching on vapor, compression-vapor absorption cascade refrigeration systems as a way to traditional single-stage vapor compression cooling systems. These methods make use of geothermal and solar heat, as well as waste heat from operations, to generate cooling effects. In this regard they consume less electricity compared to vapor compression cycles using diverse refrigeration fluids. Furthermore, adopting such innovative cooling methods not only saves energy but also supports sustainable practices by utilizing renewable energy sources. With the combination of earth energy, solar energy, and waste heat recovery systems, these cooling methods of technologies cover the way for more adequate and eco-friendly cooling solutions [15]. The integration of nanoparticles with extraordinary heat properties into fluids are called hybridized nano-fluids, this can help develop cooling and energy management. This technique is useful in commercial cooling, biotechnology applications, and medical usages such as tumor treatment and controlling the outbreaks [16]. The benefits of CNT nanoparticles in thermal transfer offers many benefits in different manufacturing industry and technologies. These benefits include improving thermal dissipation in integrated circuit technology, improving polymer heat conductivity, and providing lightweight clarifications for aircraft heat control [17]. CNT nanoparticles contribute to the efficiency in heat energy storage, filtering thermal transfer in fluid arrangements, and evolving biomedical treatments such has cancer therapy and heat stress in the human body. CNT-based tools are very important in heat exchangers, thermal energy storage systems, thermal barricade coats, and thermal boundary tools [18 - 19]. By refining heat control, avoiding overheating, and improving the total performance, these materials provide meaningful assistances in different applications. In a different research Salawu et al. [20] studied the heat, temperature and physical properties of a carbon nanotube nanofluid formed from kerosene oil under circumstances of unstable mixed convection. Their examination seized into radiative heat flux and magneto hydrodynamics.

The aim of this research is to analyse the thermal performance of ternary hybrid nanofluids in solar-powered ships utilizing parabolic trough solar collectors (PTSC). The study seeks to optimize heat transfer

efficiency and energy conversion processes by leveraging the enhanced thermal properties of ternary hybrid nanofluids, thereby improving the overall performance and sustainability of solar-powered maritime vessels. To examine the thermal conductivity, viscosity, and heat transfer coefficients of ternary hybrid nanofluids under varying concentrations and compositions.



Figure 1a: Solar-Powered Ships

2. Designing and Formulating the Problem

The following outlines the norms and settings used to describe the movement across the horizontal surface [20 - 25].

- MWCNT, SWCNT, silver (Ag), Cattaneo–Christov heat flux.
- Velocity slip, porous medium, solar thermal radiation.
- steady-state, Non-Newtonian Maxwell nanofluid.
- viscous dissipation, boundary-layer approximations.
- The systematic diagram is display in Figure 1b.

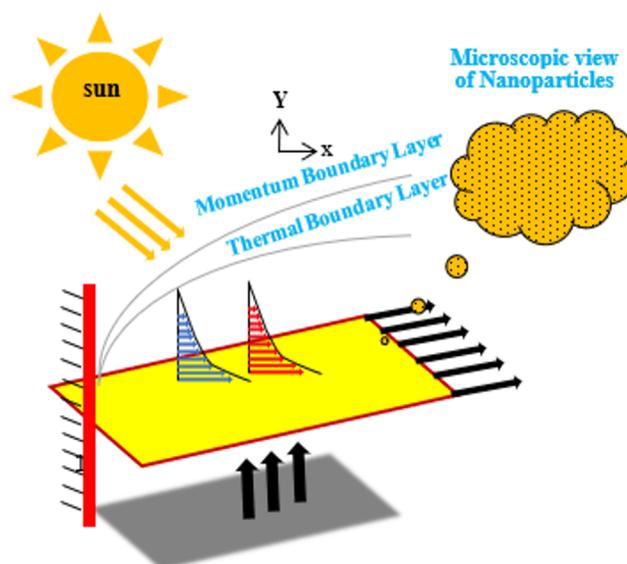


Figure 1b: The systematic diagram

The governing equations derived are as follows:

$$\frac{\partial \tilde{v}_1}{\partial x} + \frac{\partial \tilde{v}_2}{\partial y} = 0, \tag{1}$$

$$\tilde{v}_1 \frac{\partial \tilde{v}_1}{\partial x} + \tilde{v}_2 \frac{\partial \tilde{v}_1}{\partial y} = \frac{\mu_{thnf}}{\rho_{thnf}} \left[\frac{\partial^2 \tilde{v}_1}{\partial y^2} \right] - \frac{\mu_{thnf}}{\rho_{hnfk}} \tilde{v}_1 - \zeta \left[2\tilde{v}_1 \tilde{v}_2 \frac{\partial^2 \tilde{v}_1}{\partial x \partial x} + \tilde{v}_1^2 \frac{\partial^2 \tilde{v}_1}{\partial x^2} + \tilde{v}_2^2 \frac{\partial^2 \tilde{v}_1}{\partial x^2} \right] \tag{2}$$

$$\tilde{v}_1 \frac{\partial \omega}{\partial x} + \tilde{v}_2 \frac{\partial \omega}{\partial y} = \frac{1}{(\rho c_p)_{thnf}} \left[k_{thnf} \left(\frac{\partial^2 \omega}{\partial y^2} \right) - \left(\frac{\partial q_r}{\partial y} \right) + \mu_{thnf} \left(\frac{\partial v_1}{\partial x} \right)^2 + Q(\omega - \omega_w) \right] + \gamma \left[\tilde{v}_1 \left(\frac{\partial v_1}{\partial x} \frac{\partial \omega}{\partial x} \right) + \tilde{v}_2 \left(\frac{\partial v_2}{\partial y} \frac{\partial \omega}{\partial y} \right) + \tilde{v}_1 \left(\frac{\partial v_2}{\partial x} \frac{\partial \omega}{\partial x} \right) + \tilde{v}_2 \left(\frac{\partial v_1}{\partial y} \frac{\partial \omega}{\partial y} \right) + \tilde{v}_1^2 \left(\frac{\partial^2 \omega}{\partial x^2} \right) + \tilde{v}_2^2 \left(\frac{\partial^2 \omega}{\partial x^2} \right) + 2\tilde{v}_1 \tilde{v}_2 \frac{\partial^2 \omega}{\partial x \partial y} \right], \tag{3}$$

Subjected to:

$$\tilde{v}_1(x,0) = U_w + P_w \left(\frac{\partial v_1}{\partial y} \right), v_2(x,0) = R_w, -k_0 \left(\frac{\partial \omega}{\partial y} \right) = h_f(\omega_H - \omega) \tag{4}$$

$$v_1 \rightarrow 0, \omega \rightarrow \omega_\infty, \text{ as } y \rightarrow \infty.$$

Figure 1c illustrates the properties of the ternary hybrid nanofluid, and Figure 1c shows the thermo-physical characteristics of the ternary hybrid nanofluid [26 - 30].

Table 1: The properties of ternary hybrid nanofluid.

Thermophysical	$C_p/(J.kgK)$	$k/(W.mK)$	$\rho/(kg.m^{-3})$
MWCNT	796	3000	1600
SWCNT	425	6000	2600
Engine oil (EO)	1910	0.14	884
silver (Ag)	235	10500	10500

Figure 1c displays the properties of ternary hybrid nanofluid.

Table 2: The thermo-physical characteristics of the ternary hybrid nanofluid

Property	Ternary hybrid nanofluid
Dynamic viscosity	$\frac{\mu_{thnf}}{\mu_f} = \frac{\mu_f}{\left((1 - \beta_{SiO_2})(1 - \beta_{Cu})(1 - \beta_{ZrO_2}) \right)^{2.5}}$
Density	$\frac{\rho_{thnf}}{\rho_f} = (1 - \beta_{SiO_2}) \left[1 - \beta_{Cu} \left\{ (1 - \beta_{ZrO_2}) + \beta_{SiO_2} \frac{\rho_a}{\rho_f} \right\} + \beta_{Cu} \frac{\rho_a}{\rho_f} \right] \beta_{ZrO_2} \frac{\rho_a}{\rho_f}$
Thermal conductivity	$k_{nf3} = \frac{(k_3 + 2k_{nf2}) - 2\beta_{ZrO_2}(k_{nf2} - k_3)}{(k_3 + 2k_{nf2}) + \beta_{ZrO_2}(k_{nf2} - k_3)}$ $\frac{k_{thnf}}{k_f} = \frac{(k_{nf1}\beta_{SiO_2} + k_{nf2}\beta_{Cu} + k_{nf3}\beta_{ZrO_2})}{\vartheta_{thnf}}$
Heat capacity	$(\rho c_p)_{nf3} = (1 - \beta_{SiO_2}) + \frac{(\rho c_p)_a}{(\rho c_p)_f} \beta_{Cu}$ $\frac{(\rho c_p)_{thnf}}{(\rho c_p)_f} = (\rho c_p)_{nf1} + (\rho c_p)_{nf2} + (\rho c_p)_{nf3}$

Figure 1d: Thermo-physical attributes of ternary hybrid nanofluid.

2.1. Transformed Problems

Streaming functions are defined as this [31 - 33]:

$$\psi(x, y) = \sqrt{v_f b x} f(\gamma), \tilde{v}_1 = \frac{\partial \psi}{\partial y}, \text{ and } \tilde{v}_2 = -\frac{\partial \psi}{\partial x} \theta(\gamma) = \frac{\omega - \omega_\infty}{\omega_H - T_\infty}, \gamma(x, y) = \sqrt{\frac{b}{v_f}} y \tag{5}$$

Using the above streaming functions, we obtain,

$$f''' f^2 \Lambda_N + f'^2 + K_N f' \frac{1}{\theta_a \theta_b} - \frac{K_N f'' f'}{\theta_a \theta_b} + (2f f' f'') \Lambda_N = 0 \tag{6}$$

$$\theta'' \left(1 + \frac{1}{\phi_d} Pr Nr \right) + \delta_N Pr \frac{\theta_c}{\theta_d} (\theta f'' + \theta^2 f^2 + f f'' \theta'') + Pr \frac{\theta_c}{\theta_d} f \theta' - Pr \frac{\theta_c}{\theta_d} f' \theta + Ec Pr \frac{\theta_c}{\theta_d \phi_a} f'^2 + \theta \frac{Q_N}{\phi_c} + \delta_N f'^2 \theta \tag{7}$$

$$N_G = Re \left[\phi_a (1 - Nr) \theta'^2 + \frac{1}{\phi_a} \frac{B_N}{\beta} (f'^2 + K f'^2) \right], \tag{8}$$

with

$$\theta'(0) = -B_i(1 - \theta(0)), f(0) = S, f'(0) = 1 + \varpi_N f''(0), f'(\gamma) \rightarrow 0, \theta(\gamma) \rightarrow 0, \text{ as } \gamma \rightarrow \infty. \tag{9}$$

The formula with the parameter as well as the symbols are listed in table 3:

Table 3: The formula with the parameter

Parameters	Formula	Symbols
Biofilm number	$B_i = \frac{h_f}{k_0} \sqrt{\frac{\mu_f}{b}}$	B_i
Eckert number	$E_N = \frac{u_\infty^3}{(c_p)_f (\omega_H - T_\infty)}$	E_N
Heat generation	$Q_N = \frac{Q_0}{(\rho c_p)_f b}$	Q_N
Solar radiation parameter	$R_N = \frac{16}{3} \frac{\sigma^* T_\infty^3}{k^* \nu_f (\rho c_p)_f}$	R_N
Suction/Injection Parameter	$S = R_w \sqrt{\frac{1}{\nu_f b}}$	S
velocity slip	$\varpi_N = \sqrt{\frac{\mu_f}{\rho_f}} P_w$	ϖ_N
Prandtl number	$Pr = \frac{\mu_f c_p}{k_f}$	Pr
Porous medium	$K_N = \frac{\nu_f}{bk}$	K_N
Non-Newtonian Maxwell Volume fraction	$\Lambda_N = b\zeta$	Λ_N
Relaxation time parameter	$\delta_N = b\delta$	δ_N
thermal diffusivity	$\alpha_f = \frac{k_f}{(\rho c_p)_{hnf}}$	α_f
Entropy generation	$N_G = \frac{Ec b^2 u_\infty^3}{k_f (\omega_H - T_\infty)^2}$	N_G

3. Wavelets and Chebyshev Wavelets Method

Wavelets are mathematical instruments to decompose data into different frequencies and analyze all these frequencies with the resolution proportional to its frequency [33-37]. Another important advantage of them is their applicability to detection of signals which have non-stationary nature, in which frequency content varies with time. The overall concept is to use the wavelets which are just oscillations in data and or functions and these oscillations are limited to both space and frequency. Chebyshev Wavelets Method is a numerical technique used in the solution of differential

equations, integral equation and other mathematics related problems base on wavelet theory and chebyshev polynomials. The method is also very effective particularly in the situations where the boundary conditions are quite complicated or there are nonlinearities in the problem. In the present work, we utilized the Wavelets and Chebyshev Wavelets Method. The flow diagram utilizing the avelets technique are display in Figure 1e.

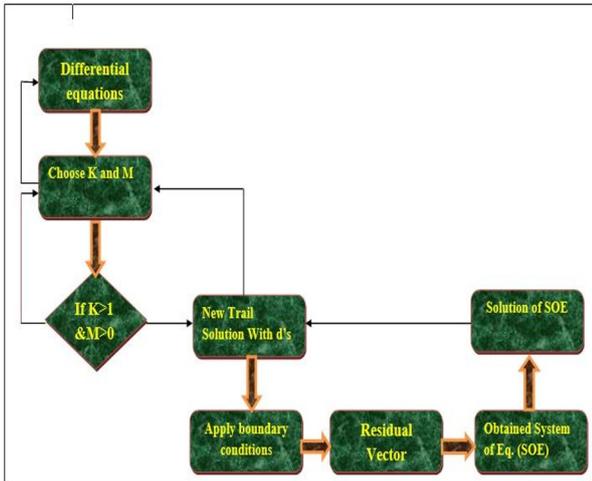


Figure 1c: Flow diagram utilizing the Wavelets technique

4. Results and Discussion

A comparative examination of the imposed constraint on the temperature distribution was carried out for both skin resistance (C_f) and wall heat gradient (Nu_x). It is crucial to assess the influence of different physical parameters, including the drag force (C_f) and skin resistance (C_f) and wall heat gradient (Nu_x). The corresponding comparative percentages are shown in Table 1 below. The Result disclosed that an increase in Ec , led to a boost in the relative percentage, which was establishing a base ranging from 2. 4% at its basic level, to 2 percent, thus indicating the competition or threat from the new entrants. 6% at the highest. Likewise, comparing the percentages shown in the table, there is a positive correlation between solar radiation and its increase wherein the comparative percentages are reduced to 2. 4% at the minimum to 2. 7% at the maximum. Further it was illustrated that the range of minimum and maximum relative percentages incorporated in the ternary hybrid nanofluid and hybrid nanofluid liquids are 2. 3% to 2. 7% with increasing in $\delta_N = 0. 01, 0. 2, 0. 3$. In the case of increasing B_i values the relative percentage variation is recorded between 2%. 2% and 2. 7%. Examining the results of nanofluids heat transfer rate the minimal relative percentage is between 2. 2% to 2. The B_i is represented here to mean: 6% as the B_i value increases. In conclusion, all the physical parameter studied has an enhancing effect on heat transfer rate.

Table 4: Comparative percentages of the physical parameter

Ec	R_N	δ_N	ϕ_2	B_i	C_f		Nu_x	
					Hybrid-	Tenary	Hybrid-	Tenary
					Nanofluid	Hybrid-	Nanofluid	Hybrid-
2	0.1	0.01			5.4422	6.6777	4.5024	4.6123
4					5.4422	6.6777	4.3531	4.4689
6					5.4422	6.6777	4.3049	4.4229
		0.1			5.3111	6.1100	4.4030	4.5140
		0.3			5.3111	6.1100	4.4299	4.6531
		0.5			5.3111	6.1100	4.5740	4.7049
			0.01		5.2437	6.3755	4.4639	4.5679
			0.2		5.5412	6.6442	4.5030	4.6119
			0.4		5.6459	6.7197	4.5480	4.6650
				0.02	-	6.3552		4.4039
				0.03	-	6.4467		4.4658
				0.05	-	6.6971		4.5029
				0.1	5.4812	6.7373	4.4570	4.5581
				0.2	5.5215	6.8352	4.5025	4.6136
				0.4	5.6970	6.8913	4.5569	4.6802

It has been observed that rise in the values of B_N often implies the enhanced viscous dissipation. From eq. (8) it becomes clear that an increase in B_N results in a proportional increase in the viscous characteristics and heat dissipation takes place (see figure 2). This often leads to the creation of more entropy since more energy in converted to thermal energy caused by friction. This is because if an increase in Re usually shows that flow is unnatural and more turbulent in nature. Turbulence increases the rate of mixing, and it is followed by an increased rate for heat transfer. Nevertheless, turbulence comes with extra shear forces that add further energy losses in the system, therefore, lead to more entropy generation. Highly turbulent flows, therefore, realize large entropy generation because of viscous dissipation effects. B_N means that more energy is going into viscous dissipation and hence more heat is generated. Also, it is observed that turbulent mixing by Higher Re increases the rate of entropy generation due to higher flow disruptions, and interfacial shear forces [40- 43]. simultaneously both higher Brinkmann and Reynolds numbers are responsible for the flow entropy generation due to both larger viscous dissipation and turbulence effects (see Figure 2).

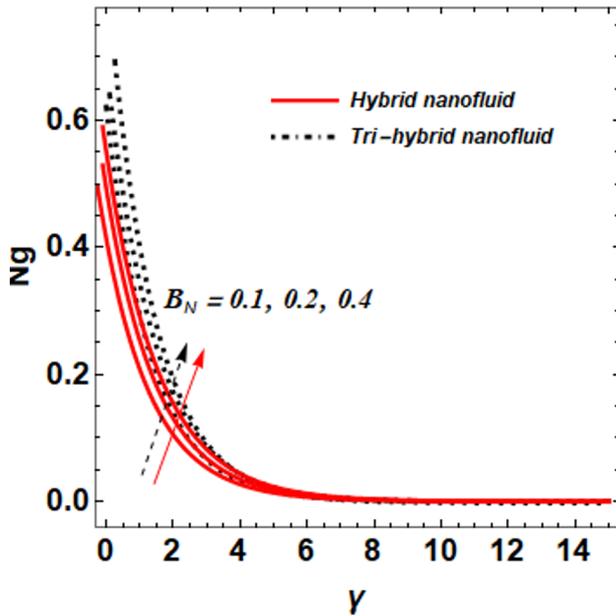


Figure 2: Effect of B_N on entropy generation

Eckert number is a non-dimensional parameter that characterizes the ratio of viscous dissipation to thermal conduction in a fluid flow. This directly leads to more temperatures recorded in the flow due to fluid motion and transformation in which kinetic energy is converted to thermal energy by viscosity. The values of higher Eckert number are usually related to high temperatures in the fluid as the kinetic energy of fluid flow is dissipated into thermal energy because of the viscous effects. The analysis shows that the thickness of the thermal boundary layer increases as the Eckert number rises [37-40]. This occurs because the temperature gradient within the thermal boundary layer becomes more pronounced, and the thermal factor is influenced by the effects of viscous dissipation (see Figure 3). It was seen that the effect of heat generation parameter increases the temperature profile (see Figure 4).

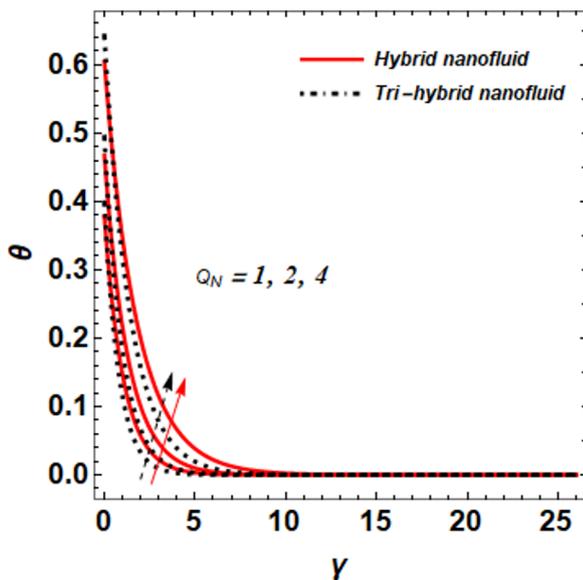


Figure 3: Effect of heat generation on fluid temperature.

When the permeability parameter K_N is high, the porous structure of the medium allows fluid to pass through more easily, reducing resistance and resulting in an increase in the velocity profile, especially in laminar flow. Conversely, when K_N is low, the porous medium offers greater resistance to fluid flow, leading to a reduction in the velocity profile as the fluid encounters more frictional forces within the medium. This increased resistance smooths out and elongates the velocity profile (see figure 5). In summary, an increase in the permeability parameter K_N corresponds to an increase in fluid velocity, while a decrease in K_N leads to a reduction in velocity. This relationship is influenced by the type of fluid, the nature of the porous material, the velocity field, pressure changes, and other conditions.

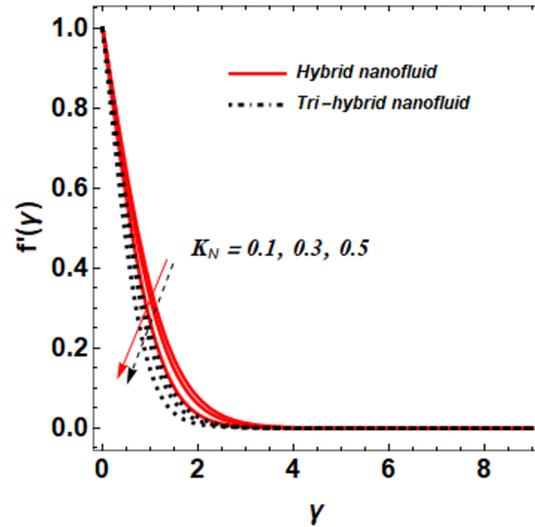


Figure 4: Effect of permeability parameter

Solar radiation is a direct source of thermal energy for several reasons. When the value of the solar radiation parameter increases, it indicates that more energy from the sun is being harnessed within the system. This additional energy raises the thermal load on the fluid or surface, leading to an increase in temperature (see Figure 5). For example, in solar collectors, an increase in solar radiation enhances heat transfer to the fluid, resulting in a higher fluid temperature. This rise in temperature directly benefits the efficiency of the system. In applications such as radiative heating, such as in solar airplane wings or other solar-based thermal systems, an increase in the solar radiation parameter leads to higher temperatures, improving overall performance.

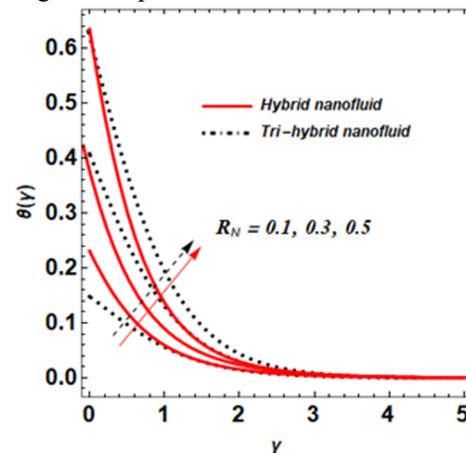


Figure 5: Effect of permeability parameter

5. Conclusion

This paper investigates the impacts of heat flux in cylinders using the Cattaneo–Christov model with CNT hybrid nanofluids under convective boundary conditions, specifically for spacecraft applications. The results demonstrate an improvement in thermal performance when CNT hybrid nanofluids are used, compared to ordinary fluids. The Cattaneo–Christov heat flux model effectively captures the characteristics of heat transfer, incorporating thermal relaxation and heat flux key factors in accurately representing the thermal behavior of nanofluids. It was found that the use of CNT hybrid nanofluids enhances thermal conductivity and energy transport characteristics, which are crucial for efficient heat rejection and energy savings in solar-powered ships. The study shows that convective boundary conditions contribute to the increased thermal conductivity of these nanofluids, suggesting that proper control of these conditions can lead to significant advancements when using CNT-based nanofluids. Additionally, the findings offer insights into best practices for applying advanced cooling systems in ships that utilize solar power generation.

Future research should focus on experimental validation of the simulated results, as well as the study of static and dynamic stability of flows involving CNT hybrid nanofluids, alongside an analysis of their efficiency and cost performance in various practical applications. In conclusion, this work opens new horizons for thermal system applications in solar ships, utilizing sustainable nanofluids and enhanced heat transfer methods.

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