A Numerical Investigation of Solar Thermal Radiation and Non-Fourier Heat Conduction in Solar Aircraft Wings Using Ternary Hybrid Nanofluids

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Abstract

The aim of this study is to enhance the operating thermal efficiency of solar aircraft through the use of solar thermal radiation and ternary hybrid nanofluids (THNF). The study inspects the convective thermal transfer in wings of solar aircraft using a noble innovative THNF which consists of has Copper (Cu), SiO2 Silicon dioxide, Zirconium dioxide (Zr02) nanoparticles and in Propylene glycol (C3H8O2) as the basic fluid. The model used to analyze the problem uses a parabolic trough solar collector (PTSC) to model the solar thermal radiation and makes use of Cattaneo-Christov heat flux model in order to account for the non-Fourier heat conduction phenomena. Wavelets and Gegenbauer wavelets methods was uses to solve the system of ODEs. The study results display that the improvement of thermal transport via THNF is due to the advanced thermal conductivity of the nanoparticles and elevated capability of the THNF to collect and absorb solar power energy. The Cattaneo-Christov model offers a better representation of heat flux with the incorporation of thermal time delay resulting in the enhanced prediction of thermal behavior in the aircraft wings. Also, PTSC is significantly beneficial in the enhancement of the thermal management procedure of the solar energy harvesting process.

Keywords: solar aircraft, nanoparticles, Cattaneo-Christov model, Solar-powered ships, Porous Medium, Propylene glycol

1. Introduction

Realizing the impact of heat radiation in various disciplines, including industrial processes, biotechnology, pharmaceuticals, environmental applications, and so on, has advanced significantly in recent years. In physics, engineering, and other sciences, thermal radiation greatly impacts how various systems behave [1]. They also serve as the foundation for figuring out how to design and operate various applications, including biological systems, mechanical systems, equipment, and environmental phenomena, among many others. Radiation is simply energy in motion, either as electromagnetic waves or as fast-moving particles [1]. The term

"radiation" usually refers to ionizing radiation, such as beta particles and gamma rays, which have enough energy to liberate electrons in the substance they contact with. All of the things we touch, eat and breathe naturally include radioactive elements, which are chemicals that emit radiation. Cosmological radiation continuously bombards Earth's atmosphere; some of it even reaches the surface [1, 2]. Every person on the earth is exposed to radiation, a recognized carcinogen and mutagen, for every second of the day. In addition to being a necessary component of our surroundings, radiation is used extensively in scientific, industrial, and medical research. Many authors from across the world have recently looked at heat radiation in different situations. Among the significant authors are [3–7]. The impact of heat radiation on an MHD maxwellian fluid flow over an expanding surface was investigated by Aliakbar et al. [8]. The resultant ordinary differential equation was examined using the homotopy analysis approach, and the study's findings showed that the flow model's temperature increases as thermal radiation grows. Misra and Sinha [9] conducted a thorough investigation on the effects of heat radiation on MHD blood flow while taking a porous stretching sheet into account. The flow problem was analyzed using a developed numerical approach, and the outcome showed that the temperature of the MHD blood fluid rises with increasing radiation parameter. An electrically conducting magnetohydrodynamic nanofluid flow across an expanding surface was studied by Daniel et al. [10] in relation to the impact of heat radiation. Using partial differential equations to describe the flow issue, an appropriate similarity variable was used to convert the partial differential equations into ordinary differential equations, which were then solved implicitly using the finite difference method. Improved thermal radiation parameter results in higher nanofluid temperature, according to analysis.

The technological equipment known as a parabolic trough solar collector (PTSC) gathers solar radiation and transforms it into thermal energy at temperatures between 150 and 500°C on an industrial scale [11, 12]. The capacity to focus incident sunlight onto an absorber tube in the collectors' focal line is provided by the reflecting surface's cylindrical trough form and parabolic mirror section. Such PTSC typically have a width of 0.5–10 m. PTSC is mostly used in the production of solar electricity [13]. Recently, several writers from all around the world have examined PTSC in various contexts. Some of the important writers are [14–16]. Also, a numerical analysis of wind flow over a parabolic trough solar collector is conducted by Hachicha et al. [17]. Sandeep and Arunchala [18] reviewed PTSC in 2017 while taking heat augmentation methods into account. The study and manipulation of matter at dimensions roughly between 1 and 100 nm that permit special size-dependent features is known as nanotechnology, according to the US National Nanotechnology Initiative [19]. Higher-order assemblages into nanoparticles can also fall within this 1–100 nm size range, which can equate to individual molecules for polymers or other macromolecules. This size range includes tiny clusters or nanoparticles for atoms and molecules that are smaller, angstrom-sized [19]. The broader development of hybrid nanofluids has garnered significant attention in recent decades. By adding three different types of nanoparticles to the base fluid, researchers have made an incredible discovery that has led to the creation of a special nanofluid known as a ternary hybrid nanofluid [20].

There are some really intriguing features to this nanofluid. Because of their better thermophysical characteristics, ternary hybrid nanofluids have piqued the interest of many researchers [21]. In terms of their capacity to transfer heat, ternary hybrid nanofluids are far more advantageous than binary and mono nanofluids. Because of the primary characteristics of nanofluids, including their enhanced variants (ternary nanofluids), engineers and industrialists have been satiated by their extremely rich thermal mechanism. Chemical, mechanical, applied thermal, and biotechnological engineering are among the domains where these are widely applied [20]. A number of authors from throughout the globe have recently looked at ternary hybrid nanofluid in a variety of settings. Among the notable authors are [22–25]. Oladapo et al. [26] examined a comparison of ternary and tetra hybrid nonofluids that contained iron oxide, copper, zirconium dioxide, and aluminum oxide in an ethylene glycol base fluid. The flow model including variable attributes was analyzed using a time-dependent variable.

The homotopy analysis method was used to numerically analyze this work. An improvement in the thermal field was noted upon increasing the solar radiation parameter. Solar-powered aircraft are electric vehicles that run on solar energy. They can be airships, blimps, or airplanes [26]. The energy generated by the solar cells is stored in the form of hydrogen or batteries, which is then used at night when the sun doesn't shine. Solar-powered aircraft can fly for months at a time at heights of over 20 to 100 kilometers because they don't need fuel, which means they don't need oxygen [26].

Solar-powered aircraft could therefore be utilized for telecommunication, video/imagery, weather radar-based precipitation detection, flight control, geopositioning Global Positioning Systems, and other pseudo satellite applications that relay data back to ground stations. An energy plane fueled by the sun is shown in Figure 1 [27].

The aim of this study is to enhance the thermal efficiency and energy management of solar aircraft by employing solar thermal radiation and ternary hybrid nanofluids (THNF) composed of copper (Cu), silicon dioxide (SiO_2), and zirconium dioxide (ZrO_2) nanoparticles in a propylene glycol base fluid. This is achieved through the integration of the Cattaneo-Christov heat flux model and a parabolic trough solar collector (PTSC) to optimize heat transfer in the aircraft wings. Figure 1 display the innovative solar aircraft design

Figure 1a: Innovative Solar Aircraft Design

2. Flow model

The following outlines the norms and settings used to describe the movement across the horizontal surface.

- Copper (Cu), SiO_2 Silicon dioxide, Zirconium dioxide (ZrO_2) nanoparticles,
- Thermal radiation, second law of thermodynamics, Tiwari & Das nanofluid scheme.
- Propylene glycol, Viscous dissipation, Steady, Laminar, Slip velocity,
- Porous media, non-regular extending velocity, Cattaneo Christov heat flux.

The non-regular extending speed is defined as $U_w(x, t) = bx$, and surface temperature $T_w(x,0)$ $= T_\infty + b^*x$. Where T_∞(Surrounding temperature), b(Initial extension rate), b^*(Rate of thermal variation). The ternary hybrid nanofluid was created by initially introducing Copper (Cu), (SiO_2) Silicon dioxide, Zirconium dioxide (ZrO_2) nanoparticles into Propylene glycol at an optimal volume fraction β_{SiO_2}, β_{Cu}, β_{ZrO_2} and kept constant at 0.09 throughout the experiment. Figure 3 illustrates the geometric representation of the flow.
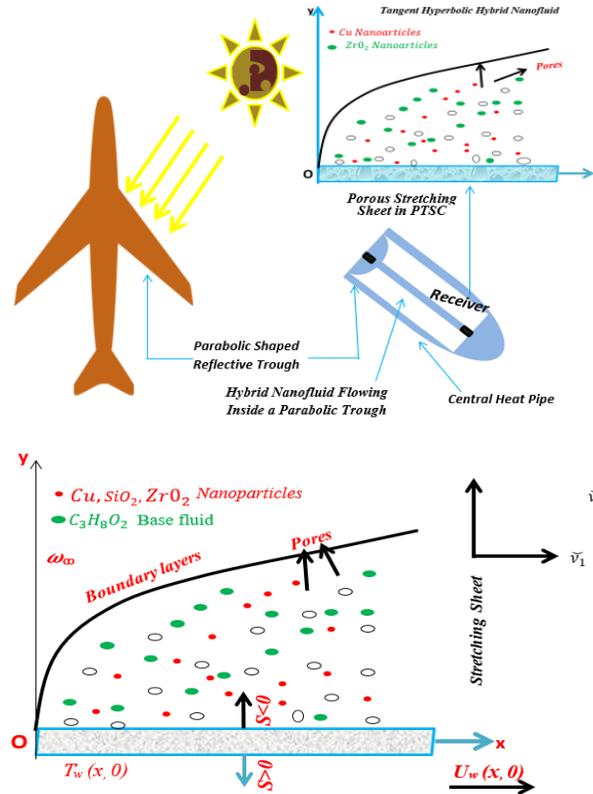
Figure 1b: The systematic diagram

The governing equations for tangent hyperbolic ternary hybrid nanofluid are:

$$\frac{\partial \breve{v_1}}{\partial x} + \frac{\partial \breve{v_2}}{\partial y} = 0, \tag{1}$$

$$\breve{v_1}\frac{\partial \breve{v_1}}{\partial x} + \breve{v_2}\frac{\partial \breve{v_2}}{\partial y} = \frac{\mu_{thnf}}{\rho_{thnf}}\left[(1-n) + n\sqrt{2}\varsigma\left(\frac{\partial \breve{v_2}}{\partial y}\right)\right]\frac{\partial^2 \breve{v_1}}{\partial y^2} - \frac{\mu_{thnf}}{\rho_{thnf}k}\breve{v_1}, \tag{2}$$

$$\breve{v_1}\frac{\partial T}{\partial x} + \breve{v_2}\frac{\partial T}{\partial y} = \tag{3}$$

$$\frac{1}{(\rho C_p)_{thnf}}\left[k_{thnf}\left(\frac{\partial^2 T}{\partial y^2}\right) - \left(\frac{\partial q_2}{\partial y}\right) + \mu_{thnf}\left(\frac{\partial \breve{v_1}}{\partial x}\right)^2\right] - \varepsilon^*\left[\breve{v_1}\left(\frac{\partial \breve{v_1}}{\partial x}\frac{\partial T}{\partial x}\right) + \breve{v_2}\left(\frac{\partial \breve{v_2}}{\partial y}\frac{\partial T}{\partial y}\right) + \breve{v_1}\left(\frac{\partial \breve{v_2}}{\partial x}\frac{\partial T}{\partial x}\right) +$$

$$\breve{v_2}\left(\frac{\partial \breve{v_1}}{\partial y}\frac{\partial T}{\partial y}\right) + \breve{v_1}^2\left(\frac{\partial^2 T}{\partial x^2}\right) + \breve{v_2}^2\left(\frac{\partial^2 T}{\partial x^2}\right) + 2\breve{v_1}\breve{v_2}\frac{\partial^2 T}{\partial x\partial y}\right]$$

,

$$E_G = \frac{k_{hnf}}{T_\infty^2}\left[1 + \frac{16\sigma^* T_\infty^3}{k^* v_f(\rho C_p)_f}\right]\left(\frac{\partial \breve{v_1}}{\partial y}\right)^2 + \frac{\mu_{hnf}}{\omega_\infty}\left(\frac{\partial \breve{v_1}}{\partial y}\right)^2 \tag{4}$$

With boundary conditions

$$\breve{v_1}(x,0) = U_w + \mu_{thnf}\left(\frac{\partial \breve{v_1}}{\partial y}\right), \breve{v_1}(x,0) = v_w,$$

$$-B_g\left(\frac{\partial T}{\partial y}\right), = P_g(T_w - T),$$

$$\breve{v_1} \rightarrow 0, \quad T \rightarrow T_\infty, \quad \text{as} \quad y \rightarrow \infty.$$

Here, T is the Temperature of the fluid, (n) Index of the power-law, (P_g) Thermal conductivity of the solid material, ($\varepsilon^\wedge*$) thermal relaxation time.

3. Similarity transformations

Streaming functions are defined as this:

$$\breve{v_1} = \frac{\partial \psi}{\partial y}, \text{ and } \breve{v_2} = -\frac{\partial \psi}{\partial x}, \Pi(x,y) = \sqrt{\frac{b}{v_f}}\, y, \qquad (2)$$

$$\phi(\Pi) = \frac{T - T_\infty}{T_w - T_\infty}, \quad \psi(x,y) = \sqrt{v_f b}\, x f(\Pi),$$

into equations (1) - (4). We obtain

$$(1\text{-}n)\, f''' + f''' f'' m We + f'' f \delta_a \delta_b - f'^2 \delta_a \delta_b - f' K = 0, \qquad (3)$$

$$\left(1 + \frac{1}{\delta_d} PrNr\right)\theta'' + \frac{\delta_c}{\delta_d} Pr\, f\theta' - \frac{\delta_c}{\delta_d} Pr\, f' + \frac{PrEc}{\delta_a \delta_d} f''^2 + \frac{\phi_c}{\phi_d} Pr\, \varepsilon^* f f' \theta' + \frac{\delta_c}{\delta_d} Pr\, \varepsilon^* f^2 \theta'' = 0, \qquad (4)$$

$$N_G = Re\left[\delta_d(1 - Nr)\theta'^2 \frac{1}{\delta_a} + \frac{Br}{\Omega}(f''^2 + Kf'^2)\right],$$

With

$$f(0) = S, \theta'(0) = -B_i\big(1 - \theta(0)\big), \qquad f'(\Pi) \rightarrow 0, f'(0) = 1 + \frac{Y}{\phi_a} f''(0), \theta(\Pi) \rightarrow 0, \quad (5)$$

as $\Pi \rightarrow \infty$.

Physical concern parameters

Surface Drag Coefficient and heat transfer rate are defind as:

$$C_f = \frac{\tau_w}{\rho_{thnf} U_w^2} \text{ where } \tau_w = \mu_{hnf}(1 - n)\left(\frac{\partial v_1}{\partial y}\right)_{y=0} + n\sqrt{\varsigma x}\left(\frac{\partial v_1}{\partial y}\right)^2_{y=0}, \qquad (6)$$

and

$$Nu_x = \frac{x q_w}{k_f(T_w - T_\infty)}, q_w = -k_{thnf}\frac{16}{3}\frac{\sigma^* T_\infty^3}{k^* v_f(\rho C_p)_f}\left(\frac{\partial T}{\partial y}\right),$$

Using the nondimensional equation, we obtain:

$$Re_x^{1/2}C_f = \frac{1}{\delta_a \delta_b}\left[f''(0)(1-n) + (f''(0))^2\frac{nW_e}{2}\right], \text{ and } Re_x^{1/2}Nu_x = -\frac{k_{hnf}}{k_f}[(1-Nr)\theta'(0)], \qquad (7)$$

Numerical solution

Application of Wavelets and Gegenbauer wavelets Method.

Wavelets and Gegenbauer wavelets methods are two of kinds mathematical methods employed in the solving of ODE, signal processing, and data compression; Wavelets are specialized in the decomposition of signals into the various frequencies that are useful in multiresolution analysis while Gegenbauer wavelets solve other intricate problems with boundary conditions and singularities involving use of orthogonal polynomials. The Flow chart of the algorithm of the present work is displayed in figure 1d.
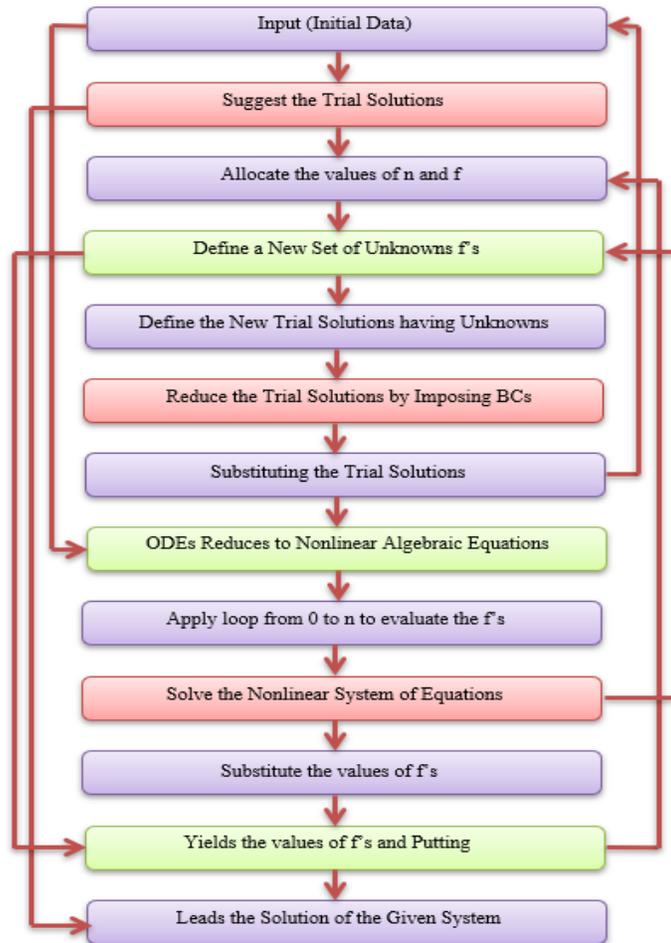
Figure 1d: Flow chart of the algorithm.

Result and conclusion

The results of this study reveal significant improvements in the thermal transfer capabilities of solar aircraft wings when employing ternary hybrid nanofluids (THNF) consisting of copper (Cu), silicon dioxide (SiO$_2$), and zirconium dioxide (ZrO$_2$) nanoparticles in a propylene glycol base. The Nusselt number (Nux) is crucial for evaluating the heat transfer rate to the core. The Nusselt number values shown in Table below confirm the anticipated result of achieving more effective heat transport with ternary hybrid nanofluids than with hybrid nanofluids, which aims to enhance heat transmission. Improving factors like Nr raises the Nusselt number at the plate wall, whereas factors such as We, and Ec lower it. In summary, THNF show better heat transfer performance than HNF.

The solar radiation parameter measures the energy received by a system from the sun. When more energy is transferred into a fluid or medium, it increases the thermal energy. As this

parameter goes up, the temperature profile rises, especially in systems that use nanofluids or in applications like solar collectors and aircraft wings (See figure 2). In nanofluid-based systems, heat transfer can be enhanced even further by solar radiation. This is because nanoparticles improve the thermal conductivity of the fluid. Together, these factors contribute to an overall increase in the temperature of the flowing fluid
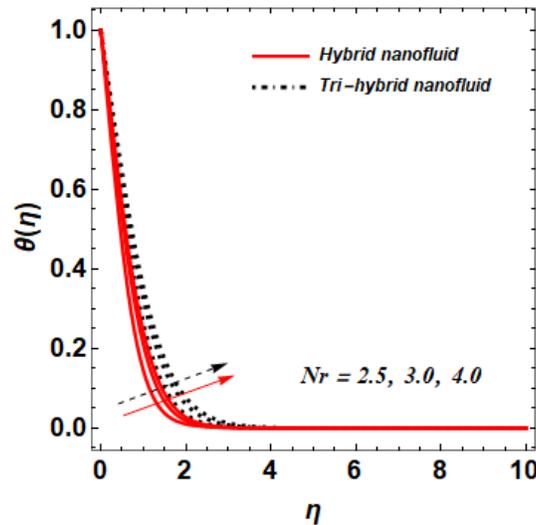

Figure 2: Effect of solar radiation parameter on temperature profile.

It has been observed that as the Reynolds number and Brinkman number increase, the generation of entropy also rises. The Reynolds number indicates the balance between inertial forces and viscous forces within a fluid. When the Reynolds number (Re) is high, the fluid flow becomes faster and more turbulent. This turbulence causes the layers of fluid to move more randomly, which increases friction between them. As this friction increases, so does the rate of irreversibility (dissipative effects), leading to higher entropy production. On the other hand, the Brinkman number relates to heat dissipation due to viscous action. It represents the ratio of heat generated by viscous effects to the heat transported through conduction in the fluid. A higher Brinkman number (Br) indicates that viscous heating is more significant compared to heat conduction. This results in additional irreversibilities and increased entropy, particularly in situations where viscous dissipation is a major factor, such as with highly viscous fluids or at high flow rates. This performance is display in Figure 3 and Figure 4.
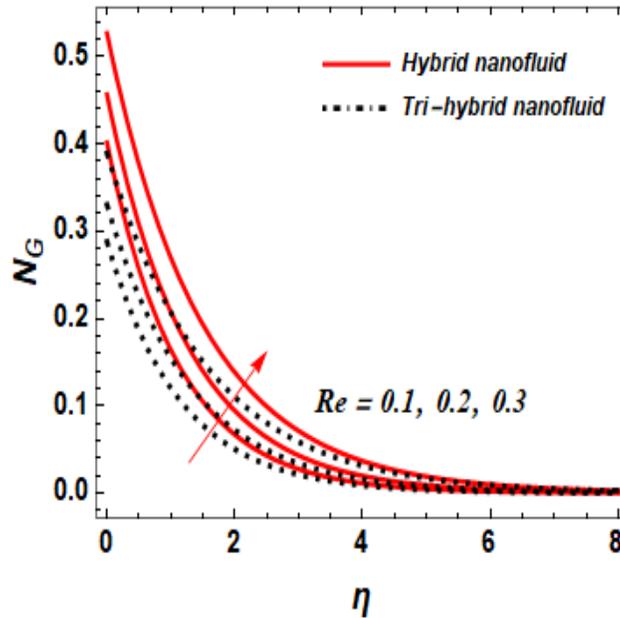
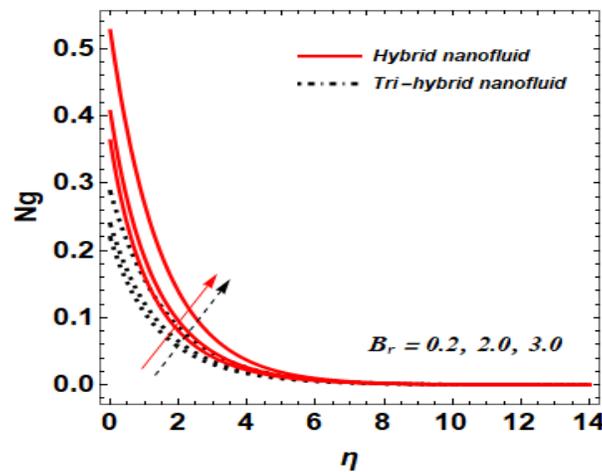Figure 3: Effect of Reynolds number on entropy generation.

Figure 4: Effect of Brinkman number on entropy generation.

The velocity slip parameter (γ) measures how much the fluid's velocity at the wall's velocity. When γ increases, the no-slip condition becomes less strict. This means that the interaction between the fluid and the wall decreases, which reduces the shear stress at the wall. In fluid flow, a higher velocity slip parameter indicates less friction or drag force on the wall. This reduction in drag means there is less momentum exchange between the fluid and the surface. Additionally, layering effects slow down the velocity gradient near the boundary, leading to a decrease in the overall fluid flow velocity close to the surface. An increase in the velocity slip parameter (γ)

results in fewer interactions between the fluid and the wall, ultimately reducing the fluid flow rate within the boundary layer. This performance is display in Figure 5.
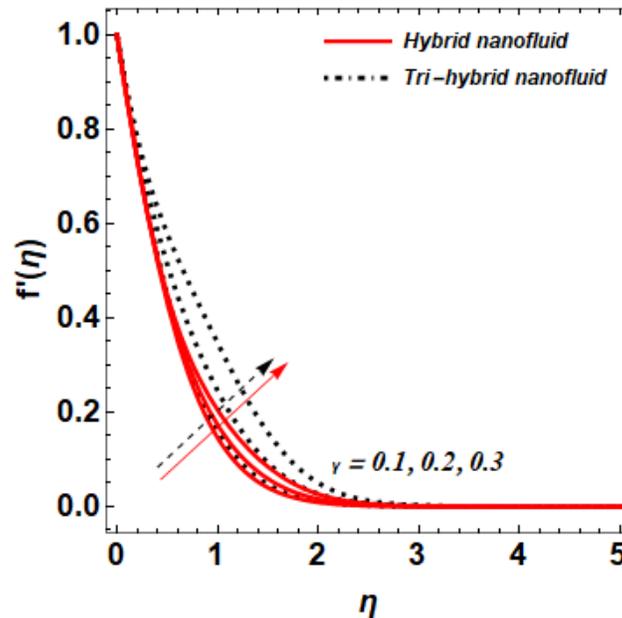

Figure 5: Effect of velocity slip parameter on fluid flow.

Suction helps stabilize the boundary layer by making it thinner. This thinning increases the velocity gradient near the surface, leading to a higher shear rate. As a result, fluid flow gets closer to the surface, which increases the velocity. On the other hand, injection creates a thicker boundary layer by adding mass to the flow, which decreases the velocity gradient. Consequently, the velocity profile fluid flow slows down, reducing the overall velocity near the surface. Suction also aids in the cooling process by drawing in cooler fluid from the edges of the boundary layer. This action thins the thermal boundary layer and causes the temperature distribution temperature profile to decrease more sharply near the surface. When considering injection (where $S < 0$ \$), warmer fluid is introduced into the boundary layer. This tends to energize the thermal boundary layer, causing the temperature profile decrease at a slower rate, which results in lower heat transfer rates. In the suction scenario, the boundary layer becomes thinner, leading to a sharp rise in the velocity gradient. This increase results in higher viscous dissipation and generates more entropy due to fluid friction. For injection (again, where $S < 0$), while it aims to reduce thickness, it increases the boundary layer thickness and decreases the velocity gradient. Thus, the contribution of viscous dissipation to entropy decreases. This reorganized version presents the information in a more digestible way while maintaining the original meaning. This performance is display in Figure (6-10).
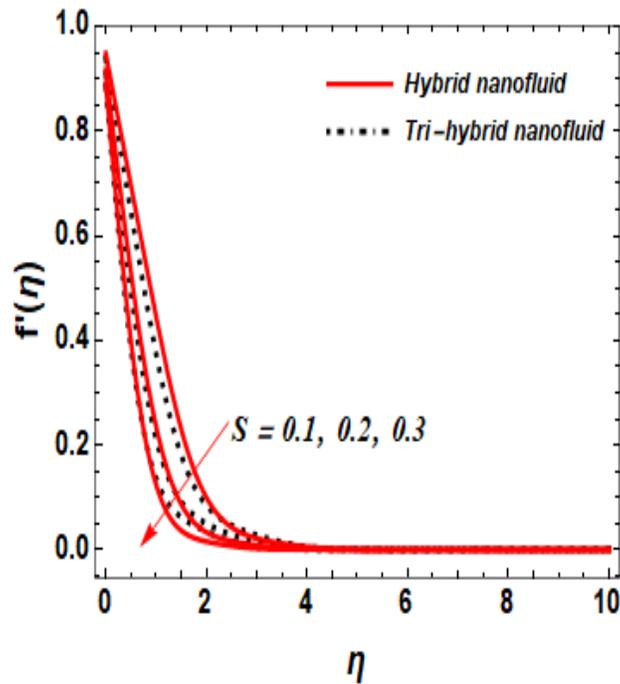
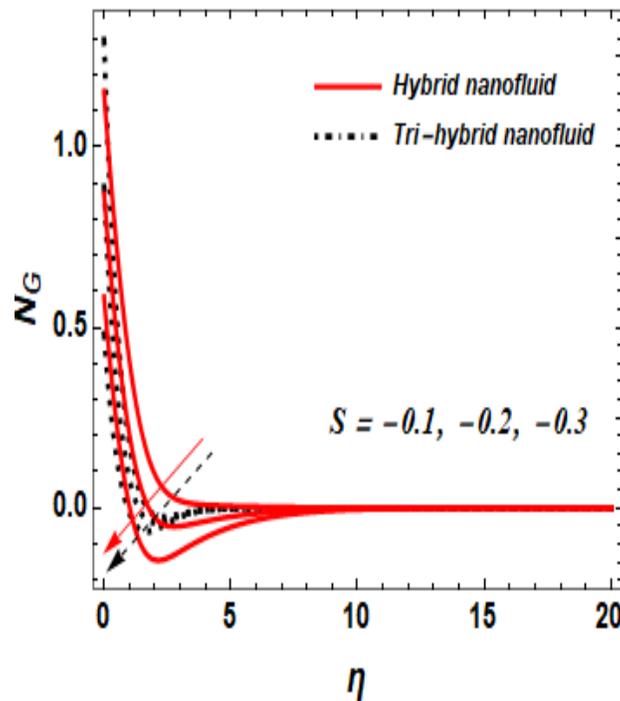Figure 6: Effect of S parameter on fluid flow.

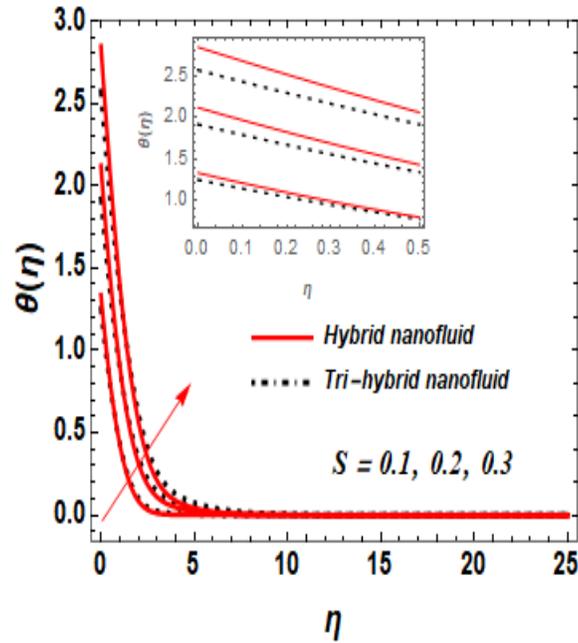Figure 7: Effect of S parameter on entropy generation.

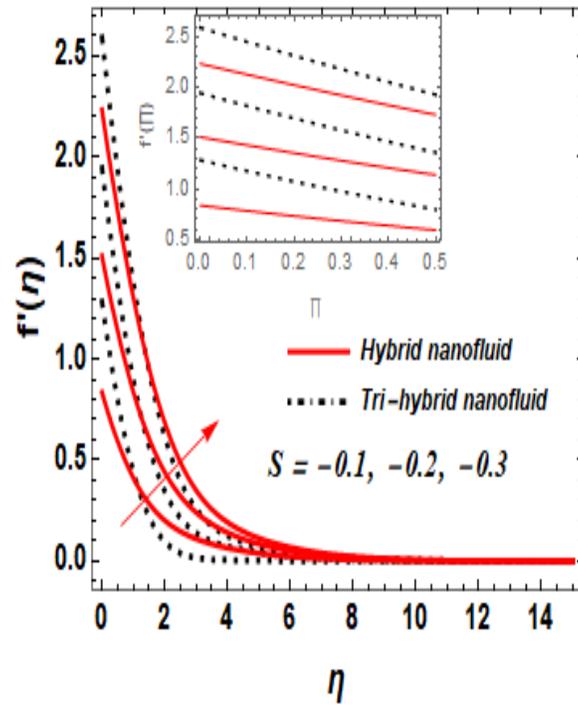Figure 8: Effect of S parameter on temperature profile.

Figure 9: Effect of S parameter on fluid flow.

Conclusion

In conclusion, this study successfully demonstrates the potential of ternary hybrid nanofluids (THNF) in enhancing the thermal efficiency of solar aircraft. The combination of copper (Cu), silicon dioxide (SiO_2), and zirconium dioxide (ZrO_2) nanoparticles in a propylene glycol base fluid improves thermal conductivity and enhances the ability to capture and store solar energy. The use of the Cattaneo-Christov heat flux model effectively incorporates non-Fourier heat conduction, accounting for thermal time delay and offering a more accurate prediction of heat transfer in solar aircraft wings. Additionally, the integration of a parabolic trough solar collector (PTSC) further optimizes solar energy harvesting. Together, these innovations provide a robust solution for advancing the thermal management system in solar aircraft, contributing to improved operational efficiency. Future studies should explore other nanoparticle combinations or fluid bases to evaluate their performance and potential for further enhancing thermal conductivity and energy absorption..

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