**Radiative Transport Analysis of Magnetized Casson Hybrid nanofluid Flow with Multi-slip Condition on a Stretching/Shrinking Sheet**

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**Abstract:** The ongoing study examines the integration of inclined magneto-radiative and multi-slip constraints on the motion and thermal attributes of Casson hybridised fluid via a stretchy/contracting heated boundary layer sheet. The proposed hybrid nanofluid employs water as the base solvent integrated with carbon nanotubes, characterized through the Casson fluid formulation to depict its non-Newtonian flow properties. The analysis includes the impact of multiple slip effects, arising from simultaneous velocity, thermal slips at boundary. Additionally, the influence of an inclined magnetism is examined to explore behavior in the system. The resulting nonlinear coupled equations are solved numerically via appropriate computational techniques. The study thoroughly analyzes the role of key factors such as slip conditions, magnetic field inclination, and thermal radiation on the fluid’s momentum and energy profiles.

**Keywords:** Casson Hybrid nanofluid; Radiative thermal transport; Inclined magnetic field; CNT nanoparticles; Multiple slip.

**INTRODUCTION**

Fluids are essential for heat transmission in chemical reactors, oil and gas pipelines, food preparation, paper production, energy storage, textile manufacture, paint production, bioengineering, solar thermal energy, & jet thermal control. A fluid is considered a nanofluid if it includes particles smaller than 109 m. Colloidal suspensions of tiny particles are called nanofluids. The most often utilized materials for creating nanofluids are metals, oxides, carbides, or carbon tubes. The many applications of nanofluids in the chemical industry, health, electronics, agriculture, and many other fields have attracted the attention of engineers and scientists. Due to their many optical, surface adsorption, rheological, heat-transfer, along with electrochemical characteristics, nanoparticles are highly useful.

Hybrid nanofluids are altered versions of nanofluids that are made in two ways: first, by drooping more than a combination of dissimilar nanoparticles in the desired fluid; second, by arranging the nanoparticles in a conjoined suspension in the base fluid. To intensify the process of heat conveyance and the ideal cost of manufacturing, researchers are interested in nanofluids composed of two distinct nanoparticles. Choi and Eastman [1] initiated the investigation of nanofluid by demonstrating that the addition of nanoparticles to ordinary fluids significantly enhances their heat-conducting capacity. The basis for sophisticated heat transference applications for engineering & operational systems was established by their groundbreaking work. Magneto-fluidic flow analysis of Casson fluid on a stretched cylinder was investigated by Tamoor et al. [2] indicated that the momentum & heat fields acted against one other at larger Hartman numbers. Khan et al. [3] also performed a computer study on Casson fluid convection interacting with a yaw-oriented cylindrical geometry that included the thermal transmission. In the work of Raje et al. [4], attention was given to heat exchange and entropy generation phenomena in a transient magnetism-induced Casson fluid over a porous cylinder. The Bejan number with the entropy generation is the falling function of the Prandtl number, they found. Waqas et al. [5] consider the effect of the magnetism on the bioconvective Casson nanofluid along with gyrotactic microorganism.

Freidberg [6] analysed on the magnetohydrodynamics (MHD) studies how electrically conductive fluids, particularlywith high effective electrical, behave when flowing in a magnetic field. Sreedevi et al. [7] considered the Maxwell magnetohydrodynamics convective flow nanofluid between the rotating and stretched disks, and also analysed impact single as well as multi wall carbon nanotubes. Srinivasacharya et al. [8] emphasized the generalized behaviour of thermo-solutal transmission in MHD flow over a Wedge Surface. The primary focous of their research was to analyzed the influence of concentration gradients, thermal conductivity of the nanoparticle, and the nanoparticle dispersion on the overall convective transport in the occurrence of a magnetisation. Ganapathirao and Ravindran [9] conducted a comprehensive evaluation of magnetised nanofluid flow in a vertical wedge, focusing on the synergistic effects of suction and injection processes. Their study specifically looked at how mixed convection works when there are both heat and concentration gradients, as well as how chemical processes inside the boundary layer affect it. Pandey and Kumar [10] studied how nanofluid flows near a stretched cylindrical surface, taking into account the effects of slip boundary conditions, a porous medium, and heat radiation. Their research aimed to demonstrate the influence of natural convection and viscous dissipation on the thermal and flow characteristics of the nanofluid, with a particular focus on the effects of heat radiation. Kandasamy et al. [11] considered the transient dynamics of MHD flow of nanofluids through a porous wedge. Their research showed how important radiation and porosity are for heat transfer and flow properties.

Bhatti et al. [12] investigated the transient three-dimensional MHD boundary-layer motion of a viscous nanofluid hosting motile microbes over a stretching porous cylinder. Their study took into account how mass transport and heat properties are impacted by the interaction of chemical reactions and nonlinear thermal radiation. In order to improve heat transfer properties, Pattnaik et al. [13] examined the circulation of a water-based nanofluid containing magnetically conducting FeO₄ over a radially stretched matertial. The study focused on how radiative heat energy affects the thermal behavior of the flow of nanofluids. The movement of a hydromagnetic nanofluid via a porous substrate under the action of radiative heat energy and thermal stratification was examined by Goud et al. [14]. The motion of a second-grade nanofluid throughout a moving flat horizontal surface was examined by Jamshed et al. [15] while accounting for thermal radiation, viscous dissipation, Joule heating, and porous media. Entropy analysis was also used in the study to assess the system's thermodynamic irreversibilities.

The mechanism that adds or subtracts thermal energy from the fluid flow is referred to as the heat source or sink. A heat sink draws energy from the fluid to reduce its temperature, whereas a heat source raises it. In a variety of engineering systems, these thermal effects are essential for altering heat transfer, flow characteristics, and the overall energy balance. The Darcy–Forchheimer circulation of a water CNT nanofluid in three dimensions was examined by Upreti et al. [16]. They examined the 3D magnetohydrodynamic behavior of water-based nanofluids with CNTs paying particular attention to the effects of ohmic heating and a non-uneven heat source or sink. The effects of double dispersion, a systematically varying heat source/sink, as well as a higher-order chemical reaction upon the transient, free convection MHD flow of a Casson fluid over a flat plate and vertical cone immersed in a porous substrate were investigated by Benazir et al. [17]. Makinde et al. [18] scrutinized steady 2d MHD free convective boundary-layer flows within an electrically conducting nanofluid over a non-linear stretching sheet, they considered the effects of chemical reactions as well as a heat source/sink. An extensive computational study of three-dimensional rotating hybrid nanofluid flow over a stretching sheet under the influence of an external magnetic field is presented by Anjum et al. [19]. The study emphasises in particular on the effects of spatially varying heat sources or sinks and nonlinear radiation, which complicates the heat transfer process. A comprehensive numerical investigation was carried out by Aziz et al. [20], focusing on, the role of heat sources and sinks, across a stretching surface.

**MATHEMATICAL FORMULATION**

A Casson hybrid nanofluid's two-dimensional magnetohydrodynamic (MHD) flow over an steretchy or contracting thermal surface is the main focus of the proposed study. Here we consider that the material lies in along the direction of axis, as illustrated in **FIGURE 1.** A magnetic field of uniform strength  is applied at an inclination angle ξ relative to the axis is to represents the effect of inclination magnetic of the flow dynamics.

The thermal boundary condition is governed by a convective heating mechanism, where the sheet's surface temperature is influenced by a heat transfer coefficient *h*. The surrounding fluid is maintained at a constant ambient temperature . This configuration allows for the simultaneous investigation of magnetohydrodynamic effects, convective heating, and flow control mechanisms due to sheet motion.

The rheological expression for Casson fluid ( for incompressible)is:



 (2.1)

Here, the deformation components are indicating as , and  is the nonnewtonian fluid’s critical parameter.  and  represents the rate of deformation for the  component.,

Hence, following [21] the governing equation of the standard boundary is,

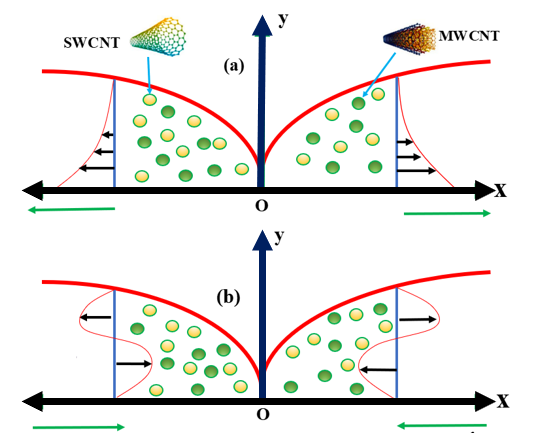
 (2.2)

 (2.3)

 (2.4)

subject to boundary requirements,

 (2.5)



**FIGURE 1** Diagrammatic view of the flow domain: (a) stretching case, (b) shrinking case

The thermophysical models for hybrid nanofluids are

 (2.6)

 (2.7)

 (2.8)

 (2.9)

 (2.10)

These are the following similarity parameters,

 (2.11)

So that,

 (2.12)

Here,  the constant mass flux, indicates suction and injection . The radiative heat flux proposed by Rosseland - approximation is defined as,

 (2.13)

By adopting Taylor series and managing the higher order terms is,

 (2.14)

Eq. (4) reduces to,

 (2.15)

After implementing the similarity transformation (11), Eqns. (2.3) – (2.5) are redesigned as,

 (2.16)

 (2.17)

 (2.18)

where,

 (2.19)

Prandtl number,  is the 1st and 2nd order momentum slip,  is Biot number,  thermal radiation factor  heat source/sink factor,  Eckert number,  constant magnetic parameter.

The physical specified quantities are specified as

 (2.20)

where,

 (2.21)

By using Eqns. (2.20) and (2.21), we get,

 (2.22)

Here,  is local Reynolds number

**TABLE 1:** Thermal properties

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***Physical properties*** | Density | Specific heat | Thermal conductivity | Electrical conductivity |
| ***Water (H2O)*** |  |  |  |  |
| ***SWCNT*** |  |  |  |  |
| ***MWCNT*** |  |  |  |  |

**TABLE 2:** Validation with previous study at



|  |  |  |
| --- | --- | --- |
|  | Rate of shear stress | |
| Mahabaleshwar et al. [21] | Current work |
| 5% | 1.005377436 | 1.005377387 |
| 10% | 0.998771987 | 0.998771857 |
| 15% | 0.981844545 | 0.981843539 |

**RESULTS AND DISCUSSION**

This research specifically investigates water-based hybrid nanofluids composed of “single-walled carbon nanotubes” (SWCNTs) and “multi-walled carbon nanotubes” (MWCNTs). The study focuses on analysing the association of generalized slip surface conditions and an oblique magnetism on the movement of a Casson hybrid nanofluid via a stretchy–contracting thermal surface. **TABLE 1** presents the thermodynamic traits of the nanoparticles and water, which forms the basis for evaluating thermophysical performance. The simulated outputs showcased in **TABLE 2** assist to validate the prior findings of the prior study (Mahabaleshwar et al. [21]) based on the computation of shear rates for different volume fractions of nanoparticles. The fixed amounts of the key terms , , , , , , ,, , , , , , are carried out in the work.

**FIGURE 2** illustrates the interpretation of a magnetism on the velocity distribution of a Casson hybridised fluid composed of SWCNTs and MWCNTs suspended in H2O, under both stretching and shrinking surface scenarios. In this context, a positive stretching parameter (λ > 0) corresponds to a stretching sheet, while a negative value (λ < 0) represents a shrinking sheet. The involvement of magnetism produces Lorentz forces that restrict the fluid motion, resulting in a dampening effect on the momentum patern. The magnetic aspects slow the momentum in both stretching and shrinking situations owing to Lorentz forces. However, under shrinking situation this influence is more substantial. **FIGURE 3** visualizes the interpretation of the magnetised inclination angle on the momentum pattern in both stretching and shrinking situations. In the stretching situation, deviation in the inclination angle alter the direction and strength of the drag force, which integrates with the immersed nanocomposites and substantially declines the momentum of the fluid pattern. In the context of contracting situation, the inclined magnetism leading to a moderate growth in fluid momentum. **FIGURE 4** deliberates the integration of 1st-order slip on the momentum pattern under both stretching and shrinking situations. In stretching situation, this slip slows down the momentum of the fluid near the surface, leading to a thinner boundary layer thickness. Similarly, in shrinking scenario, the first-order slip elevates the momentum of the fluid near the wall. **FIGURE 5** showcases the integration of second-order slip on the momentum pattern of the fluid. Under the situation of stretching, the integration of second-order slip leads to a more substantial growth of the momentum pattern than first-order slip. Additionally, in shrinking scenario, second-order slip has a declination effect on the momentum pattern. Understanding these higher-order boundary interactions is crucial for precise control of flow behaviour in advanced fluidic systems. **FIGURE 6** explains the interpretation of suction and injection on the velocity pattern of the fluid. Due to the suction motion of the fluid attenuation near the wall, diminishing the boundary layer thickness. Similarly, the case of injection upsurges the speed of the fluid. In shrinking context, the effects are reversed. **FIGURE 7** explores the combined effects of *SWCNT* and *MWCNT* nanoparticle concentrations ranging from 0% to 3% on the momentum pattern of the fluid. An elevation in nanoparticle concentration enhances the fluid’s effective viscosity and alters its rheological behavior. Higher concentrations lead to more resistance to flow due to increased interactions among nanoparticles. It is disclosed that momentum pattern of SWCNT-based nanofluids tend to surpass those of MWCNTs due to their higher aspect ratio and better dispersion, resulting in improved flow characteristics. **FIGURE 8** explores the interpretation of the Biot’s number on the energy field. An elevation in Biot number intensifies convective heat exchange, leading to higher surface heat absorption in both stretching and shrinking scenarios. **FIGURE 9** explains the integration of the Eckert number, which quantifies the ratio of kinetic energy to enthalpy. A higher Eckert number implies more kinetic energy is converted into thermal energy, increasing the energy pattern near the surface. This effect is prominent in both stretchy and contracting situations, with the shrinking configuration displaying slightly higher thermal augmentation due to flow compression. **FIGURE 10** showcases the role of thermal radiation on the energy pattern. Thermal radiation, which represents energy transfer on electromagnetic waves, increases the fluid temperature near the surface by enhancing energy absorption. Regardless of stretching or shrinking behavior, stronger radiation leads to significant temperature elevation and alteration in thermal boundary thickness. This effect is important in high-temperature environments or radiation-dominant systems. **FIGURE 11** evaluates the imposition of a uneven heat source on the temperature distribution. A heat source introduces energy into the system, raising the fluid temperature and expanding the thermal boundary layer. Conversely, a heat sink removes energy, leading to a energy drop and a thinner thermal layer. The position and magnitude of the source/sink strongly influence the resulting profile and can be tailored to enhance thermal management in practical systems. **FIGURE 12** analyzes the association of CNTs nanomolecules on the energy pattern of the Casson hybridised fluid. The involvement of these nanoparticles elevates the effective thermal conductivity of the fluid, improving heat transfer performance. SWCNTs, due to their higher aspect ratio and superior thermal conductivity, demonstrate better temperature enhancement than MWCNTs. The effectiveness depends on particle concentration, size, thermal conductivity, and dispersion stability. **FIGUREs 13–15** present the streamline patterns of Casson hybridised fluid flow. Streamline patterns showcases trajectories that fluid particles follow. In Casson fluids, which exhibit yield stress behavior, streamline patterns are influenced by the presence of suspended nanoparticles. Under a critical shear stress, fluid acts like a solid; above it, it flows. Nanoparticles modify the fluid's rheological and thermal properties, altering streamline density and curvature. Denser streamlines imply higher velocity regions, while distorted streamlines near walls indicate boundary layer effects. These visualizations are instrumental in understanding complex flow structures and boundary-layer evolution under different nanoparticle influences.

**TABLE 3** outlines the changes in shear rate profiles under various parameter values. It is disclosed that higher magnetic strength tilt amplifies influences in both scenarios. First-order slip reduces, while 2nd order slip boosts shear rate. CNT concentration promotes the rate coefficient. **TABLE 4** displays the integration of key attributes on Nusselt number. Stronger thermal radiation boosts the rate constant for both scenarios. Thermal slip from the Biot number also elevates it. In constrant, CNTs concentrations reduce the rate. Higher Prandtl and Eckert numbers, along with extra heat input, likewise diminish the rate coefficients.

**TABLE 3:** Computational evaluation of 

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  | |
|  |  |
| 0.5 |  |  |  |  |  |  | 1.4769 | -0.9854 |
| 1 |  |  |  |  |  |  | 1.5349 | -1.0376 |
| 1.5 |  |  |  |  |  |  | 1.5936 | -1.09 |
| 0.5 |  |  |  |  |  |  | 1.4769 | -0.9854 |
|  |  |  |  |  |  |  | 1.5349 | -1.0376 |
|  |  |  |  |  |  |  | 1.653 | -1.1425 |
|  |  | 0.1 |  |  |  |  | 1.5349 | -1.0376 |
|  |  | 0.2 |  |  |  |  | 1.3224 | -0.9657 |
|  |  | 0.3 |  |  |  |  | 1.1658 | -0.9005 |
|  |  | 0.1 | 0.1 |  |  |  | 1.5349 | -1.0376 |
|  |  |  | 0.2 |  |  |  | 1.8108 | -1.04 |
|  |  |  | 0.3 |  |  |  | 2.3614 | -1.042 |
|  |  |  | 0.1 | 0.1 |  |  | 1.3724 | -0.9086 |
|  |  |  |  | 0.15 |  |  | 1.3915 | -0.9239 |
|  |  |  |  | 0.2 |  |  | 1.4109 | -0.9395 |
|  |  |  |  | 0.1 | 0.01 |  | 1.5349 | -1.0376 |
|  |  |  |  |  | 0.02 |  | 1.7071 | -1.1933 |
|  |  |  |  |  | 0.03 |  | 1.9052 | -1.3744 |
|  |  |  |  |  | 0.01 | 0.01 | 1.5349 | -1.0376 |
|  |  |  |  |  |  | 0.02 | 1.7271 | -1.1942 |
|  |  |  |  |  |  | 0.03 | 1.9444 | -1.3762 |
|  |  |  |  |  |  | 0.04 | 2.1909 | -1.5877 |

**TABLE 4:** Computational evaluation of 

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  | |
|  |  |
| 0.2 | 1 | 0.1 | 0.1 | 0.01 | 0.01 | 0.1 | 0.1061 | 0.1025 |
| 0.4 |  |  |  |  |  |  | 0.1234 | 0.1201 |
| 0.6 |  |  |  |  |  |  | 0.1408 | 0.1378 |
| 0.2 | 1 |  |  |  |  |  | 0.135 | 0.1345 |
|  | 2 |  |  |  |  |  | 0.1333 | 0.1316 |
|  | 3 |  |  |  |  |  | 0.1321 | 0.129 |
|  | 1 | 0.1 |  |  |  |  | 0.1321 | 0.129 |
|  |  | 0.2 |  |  |  |  | 0.1206 | 0.1175 |
|  |  | 0.3 |  |  |  |  | 0.1092 | 0.106 |
|  |  | 0.1 | 0.1 |  |  |  | 0.1321 | 0.129 |
|  |  |  | 0.2 |  |  |  | 0.2492 | 0.2388 |
|  |  |  | 0.3 |  |  |  | 0.3554 | 0.335 |
|  |  |  | 0.1 | 0.01 |  |  | 0.1321 | 0.129 |
|  |  |  |  | 0.02 |  |  | 0.1308 | 0.1272 |
|  |  |  |  | 0.03 |  |  | 0.1292 | 0.1251 |
|  |  |  |  | 0.01 | 0.01 |  | 0.1321 | 0.129 |
|  |  |  |  |  | 0.02 |  | 0.1297 | 0.1264 |
|  |  |  |  |  | 0.03 |  | 0.1271 | 0.1238 |
|  |  |  |  |  | 0.01 | 0.1 | 0.1321 | 0.129 |
|  |  |  |  |  |  | 0.2 | 0.1318 | 0.1285 |
|  |  |  |  |  |  | 0.3 | 0.1316 | 0.128 |
|  |  |  |  |  |  | 0.4 | 0.1313 | 0.1275 |



**FIGURE 2.** on 



**FIGURE 3.** on 



**FIGURE 4.**  on 



**FIGURE 5.** on 



**FIGURE 6.**  on 



**FIGURE 7.**  on 



**FIGURE 8.** on 



**FIGURE 9.**  on 



**FIGURE 10.** on 



**FIGURE 11.** on 



**FIGURE 12.**  on 



**FIGURE 13.** Flow trajectory pattern at 



**FIGURE 14.** Flow trajectory pattern at 



**FIGURE 15.** Flow trajectory pattern at 

**CONCLUSION**

This work emphasized the analysis of diverse slip boundary formulations and an oblique magnetism under radiant energy–driven flow process. The study addressed this flow behavior in a Casson hybridized fluid over a thermally convective surface experiencing expansion or contraction. The nanofluid considered in this research was a hybrid mixture comprising water and carbon nanotubes (CNTs), chosen for their enhanced thermal characteristics.

* The presence of CNTs in the Casson hybrid nanofluid enhanced its thermal efficiency, which led to elevated heat transfer rates.
* Suction reduces the boundary layer thickness, while injection elevates fluid speed, with opposite effects in shrinking situation.
* First-order slip declines velocity near the surface, while second-order slip elevates momentum, specifically in stretching scenarios.
* Higher Biot number, Eckert number, and thermal radiation elevates temperature patterns and heat transfer rates.

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