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Numerical analysis of the influence of tilt on natural convection in a double diffusive system within a square cavity containing a thermo-dependent Carreau fluid

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Abstract. This study examines the role of tilt in the temperature-dependent, double-diffusive natural convection process occurring in a tilted square cavity filled with a non-Newtonian Carreau fluid. The configuration setup includes impermeable (adiabatic) horizontal walls where no heat or mass transfer is possible, while the vertical walls are maintained at constant temperature and concentration. One of the main objectives of this research is to detail the influence of the cavity tilt angle on the heat and mass transfer rates for different values of the power-law index n and the Pearson number m, which reflects the rheological properties of the fluid. The results obtained, including stream function distributions and Nusselt and Sherwood numbers, indicate that convective transport processes are highly dependent on fluid rheology and cavity tilt angle. It is showed that, for a temperature-dependent viscosity fluid, pseudoplastic fluids strongly favour natural convection compared to Newtonian and dilatant fluids, leading to higher values of $|\Psi|_{max}$, Nu, and Sh. The cavity inclination is an effective control parameter for heat and mass transfer in double-diffusive natural convection systems involving temperature-dependent non-Newtonian fluids, where it depends strongly on the power-law index rather the thermo-dependent parameter.

1 Introduction

Natural convection in enclosed cavities remains a vital topic in heat and mass transport phenomena for a wide range of engineering and geophysical problems. In scenarios where both thermal and concentration differences are encountered, the problem of double-diffusive natural convection comes into play; the role of the coupling between thermal and solutal buoyancy forces remains highly significant. Though a vast amount of work has been performed using Newtonian fluids, many fluids work as non-Newtonian fluids; hence, such

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analyses are inadequate. Furthermore, the Carreau fluid remains an effective formulation in modeling the dependency of viscosity on shear rates. Kefayati and Tang [1] examined a Carreau fluid subjected to a thermal and mass gradient in a heated chamber containing an internal cold cylinder. They showed that increasing the Rayleigh number clearly amplifies convective cells and improves heat and solutal transport, while decreasing the power index n intensifies convective heat transfer at the expense of diffusive effects, with a significant impact on entropy generation. Kolsi et al. [2] analyzed a square cavity filled with a porous medium and a power-law fluid separated by a corrugated interface, highlighting that the non-Newtonian nature strongly modifies the intensity of the vortices, and that transfers increase with decreasing n, while porosity and corrugated geometry act as control mechanisms for thermo-solutal boundary layers. Kumar and Gangawane [3] looked into the issue of double-diffusion convection in a rectangular cavity that was subjected to a magnetic field and that contained a heated block. They found that the magnetic field reduced the convection process, whereas the block's geometry drastically changed the zones of active transfer, with solutal parameters being very influential. Lounis et al. [4] showed that in inclined cavities filled with Carreau-Yasuda fluids, the Soret and Dufour effects profoundly modify the coupled dynamics, and that the inclination accentuates the flow asymmetry. El Hadoui et al. [5] were interested in using the natural double diffusion convection in a horizontal rectangular cavity as a tool to study the effect of buoyancy parameters on the flow intensity and the rates of heat and mass transfers. They pointed out that using nanofluids in this configuration leads to an unexpected drop in both thermal and solutal performances. Erritali et al. [6] analyzed a heated cavity with temperature-dependent viscosity and their results revealed that the reduction of viscosity in hot areas leads to an enhancement of convection. Daghab et al. [7] provided an insight into the phenomenon of natural convection in an enclosure that was impacted by the heat sources placed at various points, concluding that the implicit relationship between temperature and viscosity leads to the large flow of heated fluid and consequently enhances the transfer of heat. Jalili et al. [8] numerically studied an inclined square cavity with a double porous layer and a homogeneous fluid, showing that the angle of inclination adjusts the competition between convection and diffusion: at low inclinations convection dominates, while at high inclinations transport becomes more diffusive, reducing the overall Nusselt. Devi et al. [9] analyzed an inclined cavity filled with nanofluid subjected to an external magnetic field and the presence of a heated internal blockage, showing that increasing the magnetic field strength reduces convective vigor while adding nanoparticles increases transfers, and that the inclination intensifies or weakens convection depending on the relationship between magnetic field, buoyancy, and heated geometry. Muhammad et al. [10] focused on the problem of double diffusion in channels that are either convergent or divergent and made up of a Carreau fluid with variable density. They concluded that the geometry plays a significant role in the formation of velocity gradients and that the non-Newtonian viscosity leads to thickness reduction of the boundary layer. Supti et al. [11] carried out a simulation of a non-Newtonian power-law nanofluid in an open cavity that had adiabatic fins attached to it. The results showed that the power index alters the convective cells' structure, and the fins are responsible for redirecting the streamlines and altering the distribution of heat flux. Sivasankaran et al. [12] examined the impact of walls' movement and entropy generation in a driven cavity filled with a Casson fluid; they found out that wall motion increases convection whereas high Casson parameter decreases internal flow strength and the amount of generated entropy. Bihiche et al. [13] numerically examined the doubly diffusive natural convection of non-Newtonian power-law fluids in an inclined square cavity, showing that the evolution of streamlines allows for the identification of flow transitions, and that increasing the Lewis number reduces heat transfer more than mass transfer. In a similar manner, Rahmoun et al. [14] revealed that with the increase in Lewis number, the mass transfer in the square cavities filled with Carreau-Yasuda fluids is decreased along with changing the convective structures particularly in the temperature-dependent configurations.

This literature review highlights the lack of studies dedicated to the numerical evaluation of the effect of the inclination on doubly diffusive natural convection with temperature-dependent viscosity in a square cavity filled with a Carreau fluid. To fill this gap, the present work focuses on the temperature-dependent behavior of non-Newtonian fluids described by Carreau model, confined in a square geometry and simultaneously subjected to imposed temperature and concentration gradients. The main objective is to examine how the orientation of the cavity modifies the flow mechanisms as well as heat and mass transfers, in order to provide a more detailed understanding of the role of inclination in doubly diffusive phenomena involving Carreau fluids.

2 Mathematical formulation

A two-dimensional square cavity with dimensions *H*×*H*, filled with a non-Newtonian fluid described by the Carreau rheological model, is investigated in the present work, as illustrated in Fig. 1. The two opposing vertical walls are maintained at constant temperature and concentration levels, whereas the remaining horizontal walls are assumed to be thermally insulated and impermeable to mass transfer.

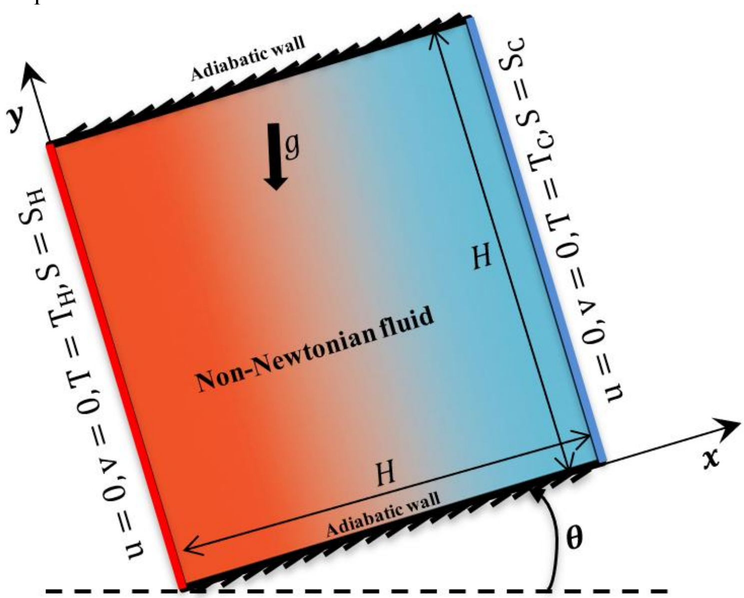

Fig. 1. Schematic representation of the problem.

The dimensionless equations describing the behaviour of the Carreau fluid are based on the fundamental principles of conservation of mass, momentum, energy, and concentration. These equations, formulated in dimensionless form to generalize the results and reduce the number of independent physical parameters, reflect the balance between the effects of convection and have the following expressions:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (1)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = Pr\left[\mu_a\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + 2\frac{\partial \mu_a}{\partial x}\frac{\partial u}{\partial x} + \frac{\partial \mu_a}{\partial y}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) + Ra_T(T + NS)sin(\theta)\right] - \frac{\partial p}{\partial x} \qquad (2)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=Pr\left[\mu_a\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+2\frac{\partial \mu_a}{\partial y}\frac{\partial v}{\partial y}+\frac{\partial \mu_a}{\partial x}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)+Ra_T(T+NS)cos(\theta)\right]-\frac{\partial p}{\partial y} \quad (3)$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2} \quad (4)$$

$$\frac{\partial S}{\partial t}+u\frac{\partial S}{\partial x}+v\frac{\partial S}{\partial y}=\frac{1}{Le}\left(\frac{\partial^2 S}{\partial x^2}+\frac{\partial^2 S}{\partial y^2}\right) \quad (5)$$

The apparent viscosity of the non-Newtonian fluid, modeled according to the Carreau law, is expressed by the following relation:

$$\mu_a=s+(1-s)[1+(\lambda\dot{\gamma})^2]^{\frac{n-1}{2}} \quad (6)$$

The effective shear rate $\dot{\gamma}$ is expressed as:

$$\dot{\gamma}=\left(2\left(\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2\right)+\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2\right)^{\frac{1}{2}} \quad (7)$$

In this setup, the *s* parameter stands for the ratio between the viscosities at infinite and zero shear rates, while the λ parameter stands for the dimensionless time relaxation parameter indicating the fluid's ability to recover from the application of forces. The power index *n* specifies the type of rheological response. The Carreau model was chosen due to its good compromise between physical accuracy and numerical simplicity. This Carreau model accurately captures the shear-thinning behavior of the fluid, particularly the transition between viscosity plateaus at low and high shear rates.

Those equations are ruled by the essential dimensionless numbers which determine fluid dynamics and thermal and diffusive exchanges. The following parameters are to be considered:

$$Ra_T=\frac{g\beta_T H'^3\Delta T}{\left(\frac{\mu'_0}{\rho}\right)\alpha}\ ;\ Pr=\frac{\left(\frac{\mu'_0}{\rho}\right)}{\alpha};\ N=\frac{\beta_S\Delta S}{\beta_T\Delta T}\ ;\ Le=\frac{\alpha}{D} \quad (8)$$

Pr is the Prandtl number, which correlates kinematic diffusivity and thermal diffusivity; *N* signifies the buoyancy ratio that indicates the degree of the influence of concentration and temperature gradients on convective motions; and lastly, *Le* is the Lewis number, which shows the relationship between thermal diffusivity and mass diffusivity in the form of a ratio.

The associated boundary conditions are:

$$\begin{cases}\frac{\partial T}{\partial y}=0,\frac{\partial S}{\partial y}=0\ \Rightarrow\ For\ y=0\ and\ y=1\ ,\forall x\\ T=T_H=1,\ S=S_H=1,\ \Rightarrow\ For\ x=0\ ,\forall y\\ T=T_C=0,\ S=S_C=0,\ \Rightarrow\ For\ x=1\ ,\forall y\end{cases} \quad (9)$$

The heat and mass transfer rates in proximity to the active walls are characterized by the dimensionless Nusselt and Sherwood numbers, which are given by:

$$Nu=-\int_0^1(\partial T/\partial x)_{x=0}\,dy\ \ ;\ Sh=-\int_0^1(\partial S/\partial x)_{x=0}\,dy \quad (10)$$

3 Numerical method

The objective of the current research is to accomplish a numerical solution of the equation system that governs double-diffusive natural convection in temperature-dependent viscosities of Carreau fluids. Hence, the dimensionless conservation equations for mass, momentum, energy, and concentration given by equations (1) to (5) were solved via the implicit alternating directions (ADI) method. This method is famous for its stability and efficiency in dealing with transient and strongly coupled problems and it demonstrated good numerical stability for all cases studied. To avoid any instability related to the strong viscosity gradients induced by temperature dependence, sufficiently small-time steps were adopted and a strict convergence criterion was imposed. No numerical oscillation or divergence was observed.

A mesh independence study was conducted by comparing the results obtained with different meshes. The results showed that variations in $|\Psi_{max}|$, Nu, and Sh become negligible beyond 101×101 mesh, even for the most shear-thinning case (n = 0.6) as listed in Table 1. The 101×101 mesh thus offers an optimal compromise between numerical accuracy and computational cost.

Table 1. Mesh independence study in terms of $|\Psi_{max}|$, Nu, and Sh for $Ra_T = 10^3$, $s = 0.01$, $\lambda = 0.2$, and n = 0.6.

	$|\Psi_{max}|$	Nu	Sh
41×41	-22.956	7.758	15.295
61×61	-22.324	7.472	14.896
81×81	-21.942	7.269	14.427
101×101	-21.916	7.197	14.077
121×121	-21.887	7.210	13.856
141×141	-21.862	7.229	13.734

3.1 Numerical code validation

The performance and robustness of the developed numerical program were assessed through the primary validation step that involved the comparison of the outcomes with reference data taken from literature. More specifically, the validation involves non-Newtonian Carreau-type fluids and compared to those of Makayssi et al. [15] for the characteristic parameters s = 0.01, λ = 0.2 and different values of the behavior index, which allowed us to assess the ability of our approach to faithfully reproduce the physical trends, as illustrated in Table 2. This agreement confirms not only the numerical accuracy of the developed code, but also the reliability of the methodological approach used for solving the fundamental equations of conservation of mass, momentum, energy, and concentration. Therefore, the implemented model can be considered valid and suitable for the analysis of double-diffusive natural convection phenomena in non-Newtonian fluids of the Carreau type.

Table 2. Comparison of $|\Psi_{max}|$, Nu, and Sh for $Ra_T = 10^3$, $s = 0.01$, $\lambda = 0.2$, and different values of n.

n	Makayssi et al. [15]			Present study		
	$|\Psi_{max}|$	Nu	Sh	$|\Psi_{max}|$	Nu	Sh
0.4	4.014	2.101	6.333	3,954	2,086	6,270
0.6	2,524	1,527	4,587	2,525	1,537	4,609
0.8	1,730	1,267	3,681	1,732	1,276	3,701

4 Results and discussion

Figure 2 highlights the combined influence of the tilt angle θ, the temperature dependence index m (Pearson number), and the behavior index n on the maximum flow intensity. For both values of n (n = 0.8 and n = 1.2), the flow intensity increases with θ until it reaches a maximum around θ = 80°. A slight local decrease observed between 80° and 90° can be explained by a readjustment of the flow structure rather than a reduction in buoyancy forces, and then decreases symmetrically. This evolution is linked to the fact that the optimal alignment of the thermal and solutal gradients with gravity maximizes buoyancy forces, favoring convective circulation. Increasing *m* systematically leads to an intensification of the flow. Physically, as *m* increases, the viscosity decreases sharply in the warm regions of the domain. This decrease in viscosity reduces the viscous forces opposing fluid motion, which facilitates flow acceleration and strengthens convective cells. Comparison between Figures 2a ($n = 0.8$) and 2b ($n = 1.2$) shows that the flow intensity is higher for $n = 0.8$. This behavior is typical of a pseudoplastic fluid, for which the apparent viscosity decreases with increasing shear rate, thus favoring convection compared to the dilatant case ($n > 1$), where viscous effects remain more significant.

Figures 3 and 4 illustrate respectively the evolution of the Nusselt (*Nu*) and Sherwood (*Sh*) numbers, characterizing the average heat and mass transfers at the walls, as a function of the angle of inclination θ for different values of the viscosity temperature-dependent parameter *m*, and this for two distinct rheological behaviors: a pseudo-plastic fluid ($n = 0.8$) and a dilatating fluid ($n = 1.2$). Overall, for both figures, *Nu* and *Sh* initially increase when θ changes from 0° to an intermediate value, then gradually decrease until reaching a minimum around $\theta = 90°$, before increasing again symmetrically as θ tends towards 180°. This symmetry with respect to $\theta = 90°$ is physically expected, as reversing the cavity's orientation relative to the gravity field leads to dynamically equivalent configurations in terms of buoyancy forces and flow structure. The observed decrease in *Nu* and *Sh* is explained by the near-horizontal alignment of the thermal and concentration gradients with respect to the direction of gravity. The buoyancy force's effective component that causes the convective flow is lessened, thus making natural circulation weaker in the cavity. Transport becomes slower and more dominated by diffusive mechanisms, consequently, a thickening of the thermal and mass boundary layers occurs and this results in a decrease of overall heat and mass transfer. The impact of the temperature-dependent parameter *m* is especially noticeable in all the results. In all cases of inclination and irrespective of *n* value, the rise in *m* yields a corresponding large rise in *Nu* and *Sh*. Theoretically, the larger *m* brings the reduction of viscosity in the hot spots of the cavity into prominence, which in turn lessens the viscous forces against the flow. The local viscosity reduction, therefore, drives fluid streaming, reinforces convection cells, and mixes thermally and with respect to mass. Hence near the active walls the boundary layers become thinner, which again leads to an increase in temperature and concentration gradients at the walls and thus higher values of *Nu* and *Sh*. In addition, the comparison of the two rheological behaviors justifies the constant higher *Nu* and *Sh* values of the pseudo-plastic fluid ($n = 0.8$) over the dilatating fluid ($n = 1.2$) irrespective of the angle of inclination or value of *m*. This is due to the fact that in a pseudo-plastic fluid apparent viscosity decreases with shear rate which, in turn, causes the generation of more vigorous convective structures. On the other hand, in the case of a dilatant fluid, the increase of viscosity with shear tends to hinder the flow which, in turn, limits the efficiency of heat and mass transport through convection.

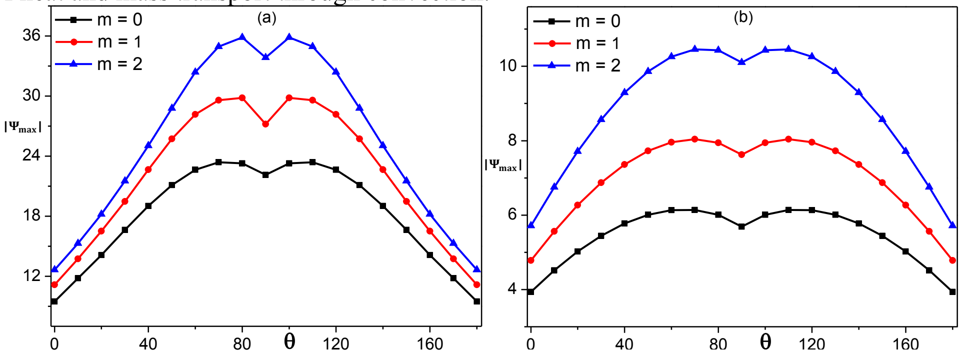

Fig. 2. Thermo-dependent influence on the intensity of the flow as a function of the inclination θ for $Ra_T = 10^4$, for $n = 0.8$ (a) and 1.2 (b).

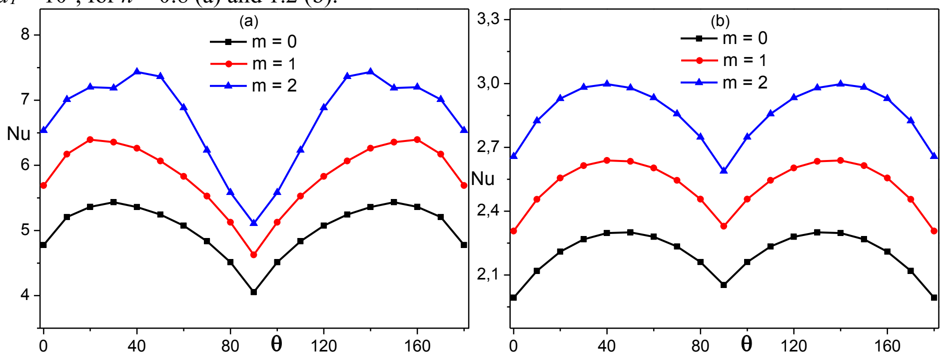

Fig. 3. Influence of thermo-dependent on heat transfer as a function of the inclination θ for $Ra_T = 10^4$, for $n = 0.8$ (a) and 1.2 (b).

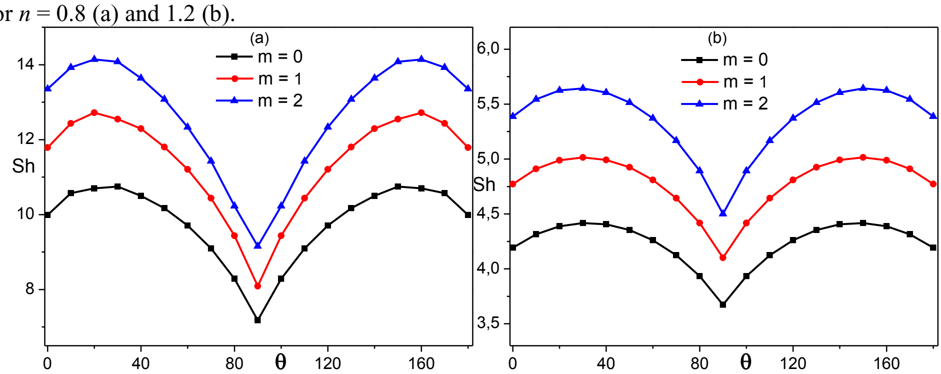

Fig. 4. Influence of thermo-dependent on mass transfer as a function of the inclination θ for $Ra_T = 10^4$, for $n = 0.8$ (a) and 1.2 (b).

Figure 5 illustrates the variation of the flow strength, represented by the maximum stream function value $|\Psi|_{max}$, together with the Nusselt number (*Nu*) and Sherwood number (*Sh*), versus the inclination angle θ for several values of the power-law index *n*, while keeping the temperature-dependent viscosity parameter fixed at $m = 1$. The decrease observed around $\theta = 90°$ is explained by the reduction in the effective component of the buoyancy force responsible for setting the fluid in motion. At the same time, the temperature and concentration gradients in this configuration are mainly aligned with the horizontal direction, which results in the suppression of natural convection and the prevalence of diffusive mechanisms. The flow reduction causes a decline in $|\Psi|_{max}$ to be associated with the thickening of the thermal and mass boundary layers, and thus this leads to decreased values of *Nu* and *Sh*. The influence of the power-law index on the optimum cavity inclination angle is clearly reflected in the behavior of the velocity, heat transfer, and mass transfer characteristics. For all cases, the extrema of $|\Psi|_{max}$, *Nu,* and *Sh* occur at intermediate inclination angles rather than at the horizontal or vertical configurations, indicating the existence of an optimal tilt where buoyancy forces are most effectively aligned with the thermal and solutal gradients. However, as the power-law index increases from n = 0.6 (shear-thinning fluid) to 1.4 (shear-thickening fluid), both the magnitude of these extrema and the sensitivity to the inclination angle decrease noticeably. Shear-thinning fluids exhibit stronger circulation and enhanced heat and mass transfer, leading to higher optimal values and a more pronounced dependence on θ, because the effective viscosity decreases in regions of high shear, facilitating flow development. In contrast, for shear-thickening fluids, the increased apparent viscosity suppresses convective motion, flattens the response curves, and weakens the effect of cavity inclination, making the optimal angle less distinct. The results in Figure 5 indicate that the direction of the cavity is a controlling parameter for the flow and heat and mass transfer with the symmetry about $\theta = 90°$. It also highlights that, for a thermo-dependent viscosity fluid, pseudo-plastic fluids strongly favor natural convection compared to Newtonian and dilatant fluids, leading to higher values of $|\Psi|_{max}$, *Nu* and *Sh*. These results underscore the importance of the coupling between cavity orientation, fluid rheology and the thermal dependence of viscosity in the optimization of transfers in double-diffusive natural convection systems.

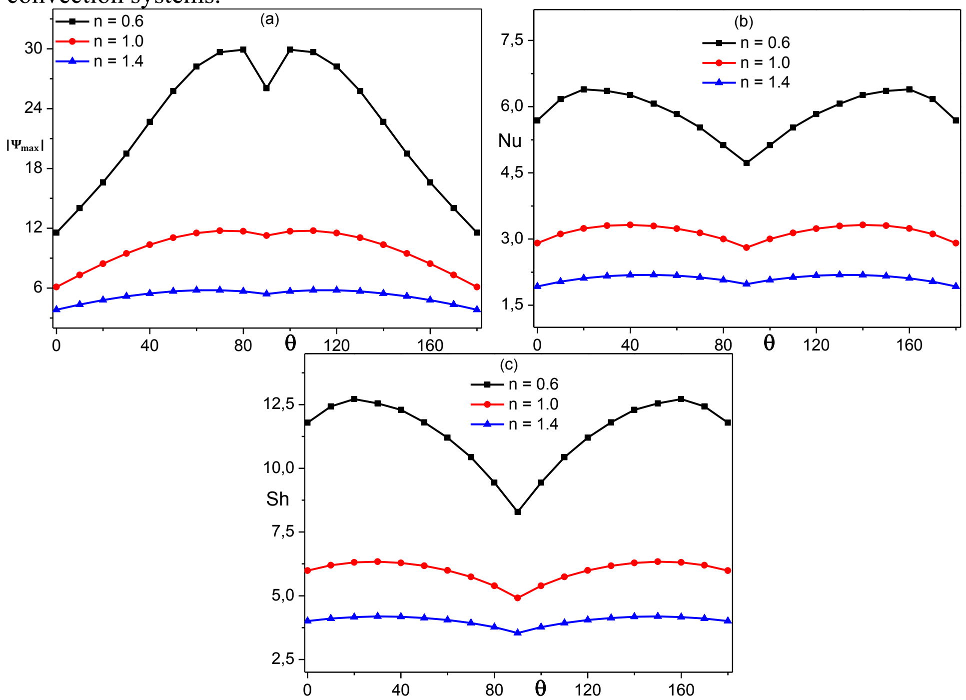

Fig. 5. Variation of *Ψ, Nu* and *Sh* as a function of the angle of inclination θ for different values of the power index n and for $m = 1$ and $Ra_T = 10^4$.

Figure 6 presents a comparative analysis of the flow structures, thermal fields, and concentration fields within the cavity for different orientations θ, considering two values of the thermo-viscous dependence index. The streamlines (left), isotherms (center), and isoconcentrations (right) do an excellent job of showing the temperature-dependent viscosity and cavity tilt's total effect that led the double-diffusive convection patterns. In the case of a horizontally positioned cavity ($\theta = 0°$), the flow pattern is characterized by one, rather centrally located, and nearly symmetrical convection cell from the surface of natural convection, where buoyancy forces are mainly in the vertical direction. The situation in this configuration keeps the flow light, with the largest value of the stream function $|\Psi|_{max} \approx 5.714$, while the isotherms and isoconcentrations are quite orderly, denoting a coexisting situation between convection and diffusion in the cavity core area. When the angle is increased to $\theta = 45°$, the gravity's effective position is altered, which causes the convection cell to rotate significantly, that it is now tilted and has longer stretching along the active walls. This configuration leads to a remarkable increase in the strength of convective motions, as indicated by the substantial rise in $|\Psi|_{max}$ to about 9.595. The isotherms and isoconcentrations become more distorted and more tightly packed near the walls, which demonstrates the increase in thermal and mass gradients and, consequently, the intensification of heat and mass transfer that is mainly due to convection. Finally, in the case of a vertical cavity ($\theta = 90°$), the influence of the tilt is at its peak: the buoyancy force acts only along the walls, leading to flow concentration within the layers and circulation that is more vigorous overall. This evolution is evident in the stream function's maximum value $|\Psi|_{max} \approx 10.103$, showing the ongoing increase in flow intensity with increasing θ. In this instance, the isotherms and isoconcentrations curves are almost completely aligned with the vertical walls and become extremely close to each other, referring to the intensified convective mechanisms as the main factor for the heat and mass transfer, the local drop in viscosity in the hot areas servicing it. Therefore, the increase in the angle of inclination together with the temperature dependence of viscosity results in more active flow dynamics and consequently better heat and mass transfer in the cavity. Moreover, the streamline analysis reveals the effect of the temperature-dependent viscosity. When the temperature is not a factor ($m = 0$), the convection cell has a mirrored structure around the cavity's geometric center almost entirely, which is the usual characteristic of a homogeneously natural flow. Conversely, when viscosity becomes a function of temperature ($m = 2$), this symmetry is broken. The convection cell gradually shifts towards the hot wall, a direct consequence of the local decrease in viscosity in high-temperature regions. This reduction in flow resistance promotes more intense circulation near the hot wall, leading to an asymmetric redistribution of velocity, temperature, and concentration fields.

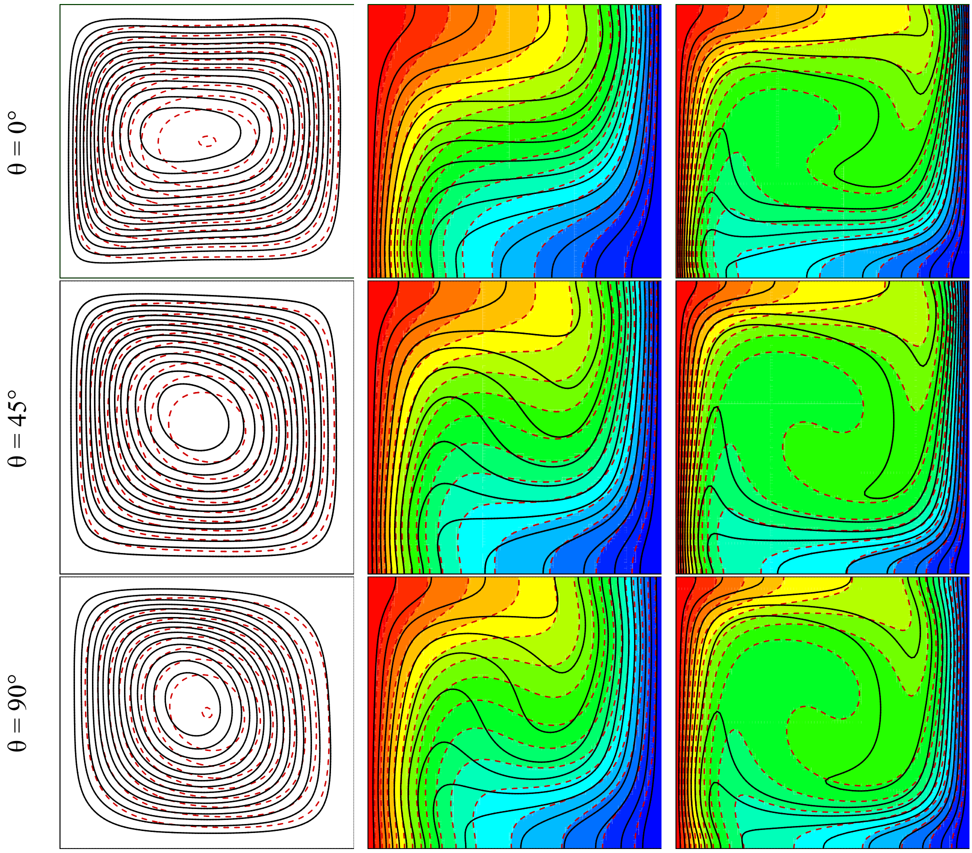

Fig. 6. Streamline patterns (left), temperature contours (middle), and concentration contours (right), for $m = 0$ (red curves) and $m = 2$ (black curves) at three inclination angles: $\theta = 0°$ (top row), $\theta = 45°$ (middle row), and $\theta = 90°$ (bottom row).

5 Conclusions

In this work, a numerical study was conducted to analyze the influence of inclination on natural double-diffusive convection in a square cavity filled with a non-Newtonian Carreau-type fluid whose viscosity depends on temperature. The cavity is bounded by horizontal walls assumed to be adiabatic and impermeable, while the vertical walls are maintained at constant temperature and concentration, thus imposing thermal and solutal gradients responsible for initiating fluid movement.

The findings presented above focus on the major properties of the thermal and rheological behavior of the system. The primary one is that the increase of the Pearson number m, which illustrates the viscosity temperature dependence, results in the substantial enhancement of the convective flow. Such transition in viscosity, occurring mostly in high-temperature zones, leads to the establishment of convection cells along with the flow of heat and mass being significantly intensified as shown by the rise in Nusselt and Sherwood numbers.

Moreover, the reduction of the power index n also contributes to the transport mechanisms positively. A fluid that displays a higher degree of pseudo-plasticity experiences a reduction in flow resistance in high-shear areas, which results in better fluid circulation inside the cavity. This pronounced flow activity not only enhances the transport of heat and mass but also clearly highlights the underlying exchange mechanisms, emphasizing the crucial role played by the rheological properties in controlling natural double-diffusive convection.

In summary, the present investigation demonstrates that the inclination of the cavity, together with the temperature-sensitive viscosity and the non-Newtonian nature of the Carreau fluid, significantly influences the flow structure and provides an effective means of controlling heat and mass transfer within confined convective configurations.

References

1. GH.-R. Kefayati, H. Tang, Double-diffusive natural convection and entropy generation of Carreau fluid in a heated enclosure with an inner circular cold cylinder (Part I: Heat and mass transfer). International Journal of Heat and Mass Transfer, 120, 731–750 (2018). doi:10.1016/j.ijheatmasstransfer.2017.12.080
2. L. Kolsi, S. Hussain, K. Ghachem, M. Jamal, & C. Maatki, Double diffusive natural convection in a square cavity filled with a porous media and a power law fluid separated by a wavy interface. *Mathematics*, *10*(7), 1060 (2022). https://doi.org/10.3390/math10071060
3. S. Kumar, & K.M. Gangawane, Double-diffusive convection in a rectangular cavity subjected to an external magnetic field with heated rectangular blockage insertion for liquid sodium–potassium alloy. *Physics of Fluids*, *34*(2) (2022). https://doi.org/10.1063/5.0080434
4. S. Lounis, R. Rebhi, N. Hadidi, G. Lorenzini, Y. Menni, H. Ameur, & N.A.C. Sidik, Thermo-solutal convection of Carreau-Yasuda non-Newtonian fluids in inclined square cavities under Dufour and Soret impacts. *CFD Letters*, *14*(3), 96-118 (2022). Doi : 10.37934/cfdl.14.3.96118.
5. B. El Hadoui, M. Kaddiri, M. Lamsaadi, & H. El Harfi, Effect of the thermal Rayleigh number on natural double diffusive convection in shallow rectangular cavities filled with nanofluids. In *AIP Conference Proceedings* (Vol. 2761, No. 1, p. 040002). AIP Publishing LLC (2023, October). https://doi.org/10.1063/5.0172067
6. I. Erritali, M. Kaddiri, I. Arroub, & H. Daghab, Effects of temperature dependent viscosity and Richardson number on mixed convection with the presence of thermal radiation in lid-driven square cavity. In *AIP Conference Proceedings* (Vol. 2761, No. 1, p. 040005). AIP Publishing LLC (2023, October). https://doi.org/10.1063/5.0171782

7. H. Daghab, M. Kaddiri, I. Arroub, I. Erritali, & R. Nouri, Natural convection for fluids with temperature-dependent viscosity in a square cavity subjected to discrete heating from below. In *AIP Conference Proceedings* (Vol. 2761, No. 1, p. 040029). AIP Publishing LLC (2023, October). https://doi.org/10.1063/5.0172255
8. B. Jalili, M. Emad, E.H. Malekshah, Investigating double-diffusive natural convection in a sloped dual-layered homogenous porous-fluid square cavity. *Sci Rep* **14**, 7193 (2024). https://doi.org/10.1038/s41598-024-57395-2
9. N. R. Devi, M. Gnanasekaran, A. Satheesh, P. R. Kanna, J. Taler, D. S. Kumar, & T. Sobota, Double-diffusive mixed convection in an inclined square cavity filled with nanofluid: A numerical study with external magnetic field and heated square blockage effects. *Case Studies in Thermal Engineering*, *56*, 104210 (2024). https://doi.org/10.1016/j.csite.2024.104210
10. M. Hamza, D. N. K. Marwat, Noureen. Double-diffusive convection in flow of Carreau fluid with variable density inside converging and diverging channels of rectilinear walls. *Results in Engineering*, *24*, 103053 (2024). https://doi.org/10.1016/j.rineng.2024.103053
11. I. J. Supti, M. J. Anee, M. M. Molla, & P. Nag, Multiple-relaxation-time lattice boltzmann simulation of natural convection of ethylene Glycol-Al2O3 power-law Non-newtonian nanofluid in an open enclosure with adiabatic fins. *South African Journal of Chemical Engineering*, *49*, 295-312 (2024). https://doi.org/10.1016/j.sajce.2024.06.002
12. S. Sivasankaran, M. Bhuvaneswari, & A. K. Alzahrani, Impact of moving walls and entropy generation on doubly diffusive mixed convection of Casson fluid in two-sided driven enclosure. *Entropy*, *26*(3), 245 (2024). https://doi.org/10.3390/e26030245
13. K. Bihiche, M. Lamsaadi, B. El hadoui, & Y. Tizakast, Double-diffusive natural convection of power-law fluids in an inclined square cavity with Soret effect. *Numerical Heat Transfer, Part A: Applications*, 1-26 (2025). https://doi.org/10.1080/10407782.2025.2520816
14. M. Rahmoun, B. El hadoui, T. Makayssi, & M. Lamsaadi, Lewis Number's Effect on Natural Double Diffusive Convection of Thermo-Dependent non-Newtonian Carreau-Yasuda Liquids in a Square Enclosure. In *ICTEA: International Conference on Thermal Engineering* (Vol. 1, No. 1), (2024, June).
15. T. Makayssi, M. Lamsaadi, and M. Kaddiri, Natural double-diffusive convection for the Carreau shear-thinning fluid in a square cavity submitted to horizontal temperature and concentration gradients. *Journal of Non-Newtonian Fluid Mechanics*, *297*, 104649 (2021). https://doi.org/10.1016/j.jnnfm.2021.104649