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Numerical study of the flow in a square cavity filled with Carbopol-TiO_2 nanofluid

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ABSTRACT

The present paper investigates numerically the free convection of a non-Newtonian carbopol-TiO_2 nanofluid confined in a square cavity with vertical walls subject to uniform and constant heat flux and insulated horizontal walls. The rheological behavior is taken into account by combining the regularized Herschel-Bulkley-Papanastasiou model with the model of He et al. [1]. The partial differential equations governing fluid flow and heat transfer are discretized using the Finite Volume Method. The numerical experiments are carried out for a range of parameter values, namely, Rayleigh number 10^3–10^6, Herschel-Bulkley number 0–20, Prandtl number 10–1000, power law index 0.4–1.0 and nanoparticle solid volume fraction 0.0–0.09. The numerical results are presented in terms of streamlines, isotherms, unyielded plugs, velocity profiles and average Nusselt number. It is found that, all the problem parameters, except for the Prandtl number, have a significant effect on both the hydrodynamic and the thermal fields.

1. Introduction

Since the 90s, nanoparticles have been used in many fields including electronics, coatings, textiles, sports articles, pharmaceutical applications, food processing, aerospace domain, automotive industry, chemicals, construction, cosmetics and optics. Today, they are present in more than one thousand products. The addition of nanoparticles in a fluid medium gives rise to a new category called nanofluid that has aroused the interest of researchers. Combining nanoparticles with a non-Newtonian fluid has been the focus of several studies in order to analyze the rheological behavior of this mixture and its potential applications in industry.

Ternik and Rudolf [2] studied natural convection for an aqueous solution of Carboxymethyl Cellulose (CMC) as base fluid, and one of Au, Al_2O_3, Cu and TiO_2 as nanoparticles. Such a mixture follows the power law model. They found that the average Nusselt number increases with the nanofluid Rayleigh number for all types of nanoparticles. Kefayati [3] used copper nanoparticles with water in a square lid driven cavity. He observed that the mixture has a shear-thinning behavior. He noticed that nanoparticles do increase the heat transfer for several values of the power law index. Using the same mixture, Kefayati [4] analyzed the entropy generation due to both heat transfer and fluid friction. He observed that entropy generation increases with volume fraction and decreasing the power law index. The heat transfer and fluid flow of SA-TiO_2 non-Newtonian nanofluid in a porous medium has been investigated by Hatami and Ganji [5]. They used two analytical approaches, namely, Least Square Method (LSM) and Collocation Method (CM) as well as a numerical method. They concluded that LSM is more accurate for problems involving a mixture of non-Newtonian fluid and nanoparticles. Considering a sinusoidal boundary condition, Kefayati [6] investigated via the Finite Difference Lattice Boltzmann Method (FDLBM) the mixed convection of a water-Al_2O_3 mixture which exhibits a shear-thinning behavior. He concluded that the effect of nanoparticles on the heat transfer increases with the power law index. Recently, Kefayati [7] investigated a two-side lid driven cavity under the same conditions. The thermal boundary conditions were hot left wall and cold right wall.

Non-Newtonian nanoparticle fluid flow through a circular tube has been investigated for a wide set of thermal conditions. Kamali and Binesh [8] performed a numerical investigation in order to understand the non-Newtonian Carbon Nanotube (CNT) nanofluid behavior in the case of the power law model. Moawed et al. [9] studied blood-Au non-Newtonian nanofluids. They observed that the Nusselt number increases with nanoparticle concentration. They also proposed an equation for the Nusselt number. Similar studies were conducted by Hojjat et al. [10] and Moraveji et al. [11].

A numerical study was performed by Li et al. [12] in order to examine the thermal performance of nanoparticles in a non-Newtonian base fluid by considering discrete heating and cooling sections. They noticed that, for heating sections, the heat transfer improvement due to presence of the nanoparticles is higher for larger values of the power law index. The same trend was observed in cold sections for nanofluid

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Nomenclature

A	cavity aspect ratio (H/L)
c_p	heat capacity (J kg^{-1} K^{-1})
g	gravitational acceleration (m s^{-2})
H	cavity height (m)
HB	Herschel-Bulkley number
k	thermal conductivity (W m^{-1} K^{-1})
K	consistency factor (Pa s^n)
L	cavity width (m)
m	stress growth exponent (s)
M	dimensionless stress growth exponent
n	power law index
Nu	Nusselt number
Nu_m	average Nusselt number
p	pressure (Pa)
P	dimensionless pressure
Pr	Prandtl number
q	constant heat flux density (W m^{-2})
Ra	Rayleigh number
t'	time (s)
t	dimensionless time
T	temperature (K)
u, v	velocity components (m s^{-1})
U, V	dimensionless velocity components
x, y	Cartesian coordinates (m)
X, Y	dimensionless Cartesian coordinates

Greek letters

α	thermal diffusivity (m^2 s^{-1})
β	thermal expansion coefficient (K^{-1})
$\dot{\gamma}$	shear rate (s^{-1})
θ	dimensionless temperature
μ	dynamic viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
τ	dimensionless shear stress
τ_0	yield stress (Pa)
ϕ	volume fraction of nanoparticles
ψ	dimensionless stream function (ψ'/α)

Subscripts

a	atmospheric
c	cold
f	fluid
nf	nanofluid
s	solid nanoparticle

Superscript

'	dimensional variables

cooling effect. Baheri Islami et al. [13] investigated the heat transfer of a non-Newtonian nanofluid flow in the presence of baffles. They concluded that the heat transfer is enhanced by nanoparticle addition. Furthermore, the enhancement is more significant for a Newtonian base fluid.

The work of Roberts and Barnes [14] showed that the carbopol exhibits both yield stress and shear-thinning properties, a behavior corresponding to the Herschel-Bulkley model. It is interesting to note that the Herschel-Bulkley model describes well the experimental fluid flows in [15,16]. In addition, the Herschel-Bulkley model exhibits five fluid category limiting cases, which depend on the values of three parameters as summarized in Table 1.

Table 1
Limit cases of the Herschel-Bulkley model.

	Herschel-Bulkley	Newtonian	Power law	Bingham	Shear-thickening
K	>0	>0	>0	>0	>0
n	]0, ∞[	1	]0, 1[	1	]1, ∞[
$\tau 0$	>0	0	0	>0	0

To our knowledge, there is no published work dealing with natural convection in a cavity filled with a Herschel-Bulkley nanofluid. In the present study, we evaluate the hydrodynamic and thermal performances of a two-dimensional square enclosure filled with TiO_2-carbopol nanofluid exhibiting both yield stress and shear-thinning behaviors. The cavity is differentially heated with Neumann boundary conditions on the vertical walls while the horizontal walls are insulated.

2. Methodology

2.1. Problem definition

The physical setup involves natural convection in a square enclosure with adiabatic horizontal walls and differentially heated vertical walls. The left wall is heated with uniform and constant heat flux density while the right wall is cooled with the same flux. The cavity is filled with a homogeneous aqueous solution of carbopol (0.02–0.08 wt% [17]) that contains titanium dioxide nanoparticles. The resulting mixture is a nanofluid which presents yield stress and shear-thinning behavior after yielding. Hence, it is modeled as a non-Newtonian nanofluid. It is assumed that both base fluid (carbopol) and nanoparticles (TiO_2) are in thermal and chemical equilibrium. It is also assumed that the thermophysical properties of the nanofluid, which are shown in Table 2, are constant except for the density which follows the Boussinesq approximation. Over the range of conditions encompassed here, the resulting flow is laminar and incompressible. The computations are performed with the following parameter range values: Prandtl number $Pr = 10$–1000, Rayleigh number $Ra = 10^3$–10^6, Herschel-Bulkley number $HB = 0$–20, solid volume fraction $\phi = 0.0$–0.09 and power law index $n = 0.4$–1.0. The nomenclature for the numerical setup, which includes both dimensions and boundary conditions, is displayed in Fig. 1. We consider an aspect ratio $A = L / H$ equal to one.

2.2. Mathematical formulation

The flow is described by the Navier–Stokes equations. Considering the above assumptions, the two-dimensional continuity, momentum and energy equations for an incompressible non-Newtonian nanofluid flow are written as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t'} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x} + \frac{1}{\rho_{nf}}\left[2\frac{\partial}{\partial x}\left(\mu'_{nf}\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu'_{nf}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right)\right] \tag{2}$$

Table 2
Thermophysical properties of carbopol solution and TiO_2.

	ρ (kg m^{-3})	k (W m^{-1} K^{-1})	c_p (J kg^{-1} K^{-1})	$\beta \times 10^5$ (K^{-1})
Carbopol solution	997.1	0.613	4179	21
TiO_2	4250	8.9538	686.2	0.9