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Heat transfer enhancement of Cu-water nanofluid in an inclined porous cavity with internal heat generation

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ABSTRACT

In this paper, the effect of internal heat generation on an unsteady laminar convection in a porous cavity filled with a Cu-water nanofluid has been reported numerically. Horizontal walls of the cavity are thermally insulated and different constant temperatures are imposed at the vertical walls. The transport equations for nanofluid saturated porous medium has been modeled by Darcy-Brinkman-Forchheimer equations and are solved by using SIMPLE algorithm. The influence of various non-dimensional parameters such as internal heat generation Q, inclination angle γ, Darcy number Da and solid volume fraction ϕ have been analyzed. The obtained results reveals that the utilization of nanofluid is insignificant at the presence of strong internal heat generation.

1. Introduction

Natural convection in a cavity with internal heat generation has received considerable attention because this type of problem finds many engineering applications in the field of heat removal from nuclear fuel debris, underground disposal of radioactive waste materials, storage of foodstuff and exothermic chemical reactions in packed-bed reactors. In the last few decades several numerical studies [1–5] dealt the natural convection heat transfer in a confined cavity with the presence of internal heat generation. Their numerical prediction reveals that the heat transfer rate decreases continuously as the value of internal heat generation is increased. Later the study of convection heat transfer with internal heat generation has been extended to porous cavities. This type of problem appears in the storage of agricultural products where the heat is produced by the occurrence of chemical reaction against them [6]. In natural convective cooling, the stored products inside the containers act as a porous medium. With this practical point of view many papers [7–9] have been reported on convection heat transfer in a porous filled cavity with internal heat generation. In all of the above studies, the authors studied the effect of internal heat generation with either a non-porous cavity or a porous cavity, but the influence of heat generation in a nanofluid filled cavity has also received little attention due to the emerging applications in various physical problems. Many authors had investigated the effect of heat generation on a natural convection heat transfer in a cavity [10–12] using highly thermal conducting fluid such as nanofluid. Their research work shows that the increase in solid volume fraction of nanoparticles produced an augmented heat transfer rate only for low values of internal heat generation parameter.

Transport of nanofluids in a porous medium is an important phenomenon in the recent years due to the noval applications in the field of oil recovery systems [13]. The main purpose of using nanofluid in a porous medium is to obtain an enhanced heat transfer. Since in the porous medium the fluid flow can be restricted by the presence of solid matrix which leads to the limited heat transfer performances and this can be overcome by the utilization of highly thermal conducting nanofluid. With this point of view few papers [14–16] have been conducted numerical examination on convection heat transfer in a porous cavity filled with a Cu-water nanofluid. Their observation informs that the presence of nanofluid significantly increased the performance of heat transfer in a porous cavity. But in the works mentioned above, the effect of internal heat generation is not considered, and in general the moving fluid generates heat continuously due to the action of metabolism and therefore it should be accounted. With this motivation, the present study deals with the effect of heat generation in a nanofluid filled porous cavity.

2. Mathematical formulation

Fig. 1 demonstrates the physical representation of the present problem. It is a two dimensional porous square cavity of size L filled with a heat generating Cu-water nanofluid with a uniform

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Nomenclature

C_p	specific heat, J kg^{-1} K^{-1}
Da	Darcy number
Fc	Forchheimer coefficient
g	gravitational acceleration vector, m s^{-2}
k	thermal conductivity, W m^{-1} K^{-1}
K	permeability, m^2
L	cavity length, m
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
p	fluid pressure, Pa
P	dimensionless pressure
Pr	Prandtl number
q	uniform volumetric heat generation, W m^{-3} K^{-1}
Q	dimensionless internal heat generation
Ra	Rayleigh number
t	time, s
T	temperature, K
u, v	velocity components in x, y directions, m s^{-1}
U, V	dimensionless velocity components
x, y	Cartesian coordinates, m
X, Y	dimensionless coordinates

Greek symbols

α	thermal diffusivity, m^2 s^{-1}
β	thermal expansion coefficient, K^{-1}
γ	inclination angle
θ	dimensionless temperature
ϵ	porosity
ϕ	solid volume fraction
σ	specific heat ratio
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
τ	dimensionless time

Subscripts

c	cold
f	fluid
h	hot
nf	nanofluid
p	nanoparticle
s	solid phase

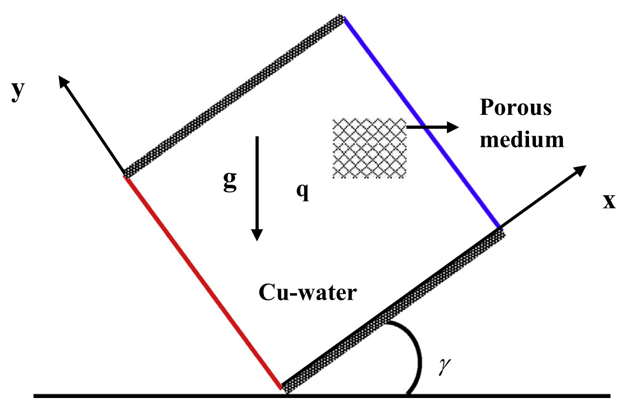

Fig. 1. Physical configuration of the problem.

volumetric heat rate q. The cavity is inclined at an angle γ with respect to the horizontal plane. The porous medium is assumed to be isotropic, homogeneous and in thermal equilibrium between the fluid and solid phases. The cavity is heated as well as cooled by a constant temperatures T_h and T_c $(T_h > T_c)$ for left and right active walls respectively, while the top and bottom horizontal walls are perfectly insulated. The Darcy-Brinkmann-Forchheimer model is adopted to analyze the flow characteristics in the fluid saturated porous medium. The nanoparticles are presumed to be in thermal equilibrium with the base fluid, and there is no slip occurs between them. The nanofluid properties are considered to be constant except the density variation due to the Boussinesq approximation.

Table 1
Thermo-physical properties of base fluid water and Cu nanoparticles [14–16].

Physical properties	Fluid phase (water)	Cu
c_p (J/kg K)	4179	385
k (W/m K)	0.613	401
ρ (kg/m^3)	997.1	8933
β (1/K)	21×10^{-5}	1.67×10^{-5}

The thermo-physical properties of the base fluid water and Cu nanoparticles are listed in Table 1.

Subject to the above assumptions, the governing equations for the system are:

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

$$\frac{1}{\epsilon}\frac{\partial u}{\partial t}+\frac{1}{\epsilon^2}\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x}+\frac{\nu_{nf}}{\epsilon}\nabla^2 u-\frac{\nu_{nf}}{K}u-\frac{Fc}{\sqrt{K}}u\sqrt{u^2+v^2}+\sin\gamma\, g\,\beta_{nf}(T-T_c) \tag{2}$$

$$\frac{1}{\epsilon}\frac{\partial v}{\partial t}+\frac{1}{\epsilon^2}\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y}+\frac{\nu_{nf}}{\epsilon}\nabla^2 v-\frac{\nu_{nf}}{K}v-\frac{Fc}{\sqrt{K}}v\sqrt{u^2+v^2}+\cos\gamma\, g\,\beta_{nf}(T-T_c) \tag{3}$$

$$\sigma\frac{\partial T}{\partial t}+\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\frac{k_{nf}}{(\rho c_p)_{nf}}\nabla^2 T+\frac{q}{(\rho C_p)_{nf}}(T-T_c), \tag{4}$$

where $Fc=\frac{1.75}{\sqrt{150\epsilon^{3/2}}}$ is the Forchheimer coefficient.

The appropriate initial and boundary conditions of the present study are:

$$\begin{aligned}
&t=0: u=v=0, \quad T=T_c, \quad 0\leqslant X\leqslant L, \quad 0\leqslant Y\leqslant L,\\
&t>0: u=v=0, \quad T=T_h, \quad X=0, \quad 0\leqslant Y\leqslant L,\\
&\qquad u=v=0, \quad T=T_c, \quad X=L, \quad 0\leqslant Y\leqslant L,\\
&\qquad u=v=0, \quad \tfrac{\partial T}{\partial Y}=0, \quad Y=0\ \&\ L, \quad 0\leqslant X\leqslant L.
\end{aligned}$$

Introducing the following non-dimensional variables

$$(X,Y)=\frac{(x,y)}{L}, \quad (U,V)=\frac{(u,v)}{\alpha_f/L}, \quad \tau=\frac{\alpha_f t}{L^2}, \quad P=\frac{pL^2}{\rho_{nf}\alpha_f^2}, \quad \theta=\frac{T-T_c}{T_h-T_c}$$

Using the non-dimensional variables, the Eqs. (1)–(4) can be rewritten in the form of non-dimensional equations as