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Effect of uniform and nonuniform heat source on natural convection flow of micropolar fluid

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ABSTRACT

Natural convection of micropolar fluid in a square cavity with uniform and nonuniform heated thin plate built in horizontally or vertically is investigated numerically. The non-uniform heating is due to the non-linearly varying temperature of the plate. The vertical walls are cooled while the top and bottom walls are insulated. The flow with in the cavity is assumed to be two dimensional. The governing equations were solved by finite volume method using second order central difference scheme and upwind differencing scheme. The computational results are presented in the form of isotherms, streamlines and average Nusselt numbers. The study was performed for different Rayleigh numbers, Prandtl numbers, length of the heat source, location of the plate, vortex viscosity parameter and source non-uniformity parameters. The result shows that the presence of vortex viscosity parameter retards the fluid velocity and hence the heat transfer rate is decreased. Also, the non-uniformity parameter affects the fluid flow and heat transfer rate especially for higher Rayleigh numbers.

1. Introduction

Micropolar fluids are fluids with micro structure. They belong to a class of fluids with non-symmetrical stress tensor that we shall call polar fluids, and include, as a special case, the well-established Navier-Stokes model of classical fluids that we shall call ordinary fluids. Physically, micropolar fluids may represent fluids consisting of rigid, randomly oriented (or spherical) particles suspended in a viscous medium, where the deformation of fluid particles is ignored. In recent years analysis of flow and heat transfer of micropolar fluids in cavities has been of great interest because of the Newtonian fluids cannot successfully describe the characteristic of fluid with suspended particle. Unlike the other fluids, micropolar fluids may be described as non-Newtonian fluids consisting of dumb-bell molecules or short rigid cylindrical element, polymer fluids, fluid suspension, etc. In addition with the classical velocity field, a micro-rotation vector and a gyration parameter are introduced in the micropolar fluid model in order to investigate the kinematics of micro-rotation. From the theory of micropolar fluid, it is also expected to successfully describe the non-Newtonian behavior of certain fluids, such as liquid crystals, ferro liquids, colloidal fluids, liquids with polymer additives, animal blood carrying deformable particles (platelets), clouds with smoke, suspensions, slurries and liquid crystals. The model of micropolar fluids introduced by Eringen [1,2] is worth studying as a very well balanced one. First, it is a well-founded and significant generalization of the classical Navier-Stokes model, covering, both in theory and applications, many more phenomena than the classical one. The fluid flow and heat transfer behavior of such systems can be predicted by the mass, momentum and energy conservation equation with appropriate boundary condition. A comprehensive analysis of the fluid flow and heat transfer patterns in fundamentally simple geometries, such as the buoyancy driven cavity is a necessary precursor to the evaluation of better designs for more complex industrial applications. The importance of natural convection in cavities can be found in many engineering applications, such as heating and ventilation of living space, cooling in nuclear reactors and electronic packaging, and as energy transfer in solar collectors [3,4]. Therefore, natural convection in cavities has been extensively investigated over the past several decades. A brief review of some important studies on natural convection in enclosures is outlined below. Ostrach [5] provided a comprehensive review article and extensive bibliography on natural convection in cavities. Natural convection in a rectangular cavity with differentially heated side walls and insulated horizontal surfaces was investigated numerically and experimentally by Keyhani et al. [3] and Davis [6] respectively. Ganzarolli and Milanez [7] per-

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Nomenclature

Alphabetics

L	length of the cavity (m)
l	length of the heat source (m)
g	gravitational acceleration (m/s^2)
h	local heat transfer coefficient (W/m^2 K)
P	pressure (N/m^2)
p	dimensionless pressure (N/m^2)
k	thermal conductivity (W/m K)
Nu	Nusselt number ($Nu = hH/k$)
N	angular velocity (s−1)
Pr	Prandtl number (ν/α)
p_l	dimensional location of the plate (m)
P_l	dimensionless location of the plate
q_w	heat flux (W/m^2)
Ra	Rayleigh number ($g\beta L^3 \Delta T/\nu\alpha$)
t	time (s)
T	temperature (K)
x, y	dimensional coordinates
u, v	dimensional velocity components (m/s)
U, V	dimensionless velocity components
X, Y	dimensionless coordinates

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K^{-1})
λ	source non-uniformity parameter ($(T_{h1} - T_{h2})/2\Delta T$)
ν	kinematic viscosity (m^2/s)
μ	dynamic viscosity (kg/m s)
θ	dimensionless temperature
ρ	density (kg/m^3)
τ	dimensionless time
ϵ	dimensionless length of the heat source (l/L)
ω	dimensional vorticity (s^{-1})
ψ	dimensional stream function (m^2/s^1)
Ψ	dimensionless stream function
Ω	dimensionless vorticity

Subscripts

avg	average
c	cold wall
h	hot wall

formed a numerical study of steady natural convection in rectangular enclosures heated from below and symmetrically cooled from the sides. They observed that for the square cavity, the flow and thermal fields are not strongly affected by the isothermal or constant heat flux boundary condition at the bottom heat source. However, distinct differences were observed between the isothermal and constant heat flux conditions for the shallow cavity. Aydin and Yang [8] numerically investigated natural convection of air in a cavity with localized isothermal heating from below and symmetrical cooling from sidewalls. The average Nusselt number at the heated part of the bottom wall is shown to increase with increasing Rayleigh number as well as with increasing length of the heat source.

A numerical study to investigate the free convection micropolar fluid flow in an square cavity with boundary element method is performed by Zadravec et al. [9]. They observed that micropolar fluid flow produces lesser heat transfer rate compared to the Newtonian fluids. Sathiyamoorthy et al. [10] numerically investigated steady natural convection flows in a square cavity with linearly heated side walls. They found that average Nusselt numbers smoothly increase as Ra increases with an exception for $Pr = 10$ at the left wall due to the presence of a strong secondary cell near the top edge of the left wall. Natural convection heat transfer in a square cavity with a heated plate built-in vertically and horizontally is studied by Oztop et al. [11]. They showed that heat transfer rate increase at both vertical and horizontal position of the plate as Gr increases. Natural convection in tilted rectangular enclosures with a vertically situated hot plate inside is studied by Altac and Kurtul [12]. They found that the heat transfer rate increases with an increase in the aspect ratio for all tilt angles and Rayleigh numbers.

Laminar natural convection in a two dimensional square cavity filled with micropolar fluid and differentially heated on the vertical sidewalls is numerically investigated by Aydin and Ioan Pop [13]. They found that, when the Rayleigh number and Prandtl number increases the heat transfer is increased. Obviously, an increase of material parameter condensed the heat transfer rate. Saleem et al. [14] numerically investigated steady two-dimensional natural convection flow of micropolar fluid in a rectangular cavity heated from below with cold sidewalls. It was found the heat transfer rate from heated surface, in the case of micropolar fluid is less than that of the Newtonian fluid under the same physical conditions. The effects of both rotation and magnetic field of a micropolar fluid through a porous medium induced by sinusoidal peristaltic waves traveling down the channel walls are studied analytically and computed numerically by Abd-Alla et al. [15]. MHD free convection in an inclined enclosure filled with a micropolar nanofluid by Bourantas and Loukopoulos [16]. It can be observed that the average Nusselt number of micropolar nanofluid was smaller compared with that of a pure nanofluid model. Transient buoyancy-opposed double diffusive convection of micropolar fluids in a square enclosure numerically investigated by Jena et al. [17]. They revealed that flow field and rotation velocities increase with an increase in the Rayleigh number. The presence of the vortex viscosity parameter leading monotonic decrease in the flow strength and heat transfer rates. The vortex viscosity parameter enhance the viscous force on the fluid which reduce the fluid velocity and micro-rotation.

On the basis of the literature review, it appears that no work was reported on the natural convection flow of micropolar fluids in enclosure with nonuniform heating source placed inside. Therefore, due to its practical interest in the engineering fields such as building design, cooling of electronic components, solar energy systems, solar collectors, liquid crystals, animal blood, colloidal fluids and polymeric fluids [4,19,20], the topic needs to be further explored. Hence, the aim of this study is to investigate natural convection square cavity in a vertically localized nonuniform heat plate filled with micro-polar fluid.

2. Mathematical formulation

Consider a two dimensional square cavity of sides of length L as shown in Fig. 1. The top and bottom walls of the cavity are adiabatic and two vertical walls have constant temperature T_c. A thin vertical plate is placed at the center of the cavity. The temperature of the plate T_h is varying linearly from T_{h1} to T_{h2}. The cartesian