International Journal of Heat and Mass Transfer 102 (2016) 596–609

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Heat transfer and entropy generation in mixed convection of a nanofluid within an inclined skewed cavity

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ARTICLE INFO

Article history:
Received 22 February 2016
Received in revised form 21 May 2016
Accepted 17 June 2016

Keywords:
Mixed convection
Nanofluid
Tilted skewed cavity
Co-ordinate transformation
Entropy generation

ABSTRACT

The mixed convection of a Cu–water nanofluid in a skewed cavity which is slightly inclined from the horizontal is investigated. A co-ordinate transformation is used to transform the physical domain into the computational domain in an orthogonal co-ordinate system. A control volume method over a staggered grid arrangement is used to discretize the governing equations. The discretized equations are solved through a pressure-correction based SIMPLEC algorithm. Based on this algorithm a Fortran 95 computer code is developed, which has been executed in the IBM Power 7 server. The effects of relevant parameters such as, Richardson number ($0.1 \leqslant Ri \leqslant 5$), Reynolds number ($100 \leqslant \mathrm{Re} \leqslant 1000$), nanoparticle volume fraction ($0 \leqslant \phi \leqslant 0.2$) on the mixed convection of nanofluid is studied by considering acute to obtuse skew angle and inclination angle between $-30°$ to $30°$. We made a comparative study between several models for effective thermal conductivity and viscosity of a nanofluid. The entropy generation as well as the Bejan number is evaluated to illustrate the thermodynamic optimization of the mixed convection. Our results show that the flow and thermal fields within a skewed enclosure are sensible to the angle of inclination. The addition of nanoparticles produce an enhancement in the heat transfer but reduce the effect of buoyancy. The impact of the inclination angle on the heat transfer and entropy generation is analyzed for the considered range of the skew angle to determine the optimum heat transfer characteristics.
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1. Introduction

Nanofluids, which are suspensions of nanometre sized particles in the base fluid, are characterized by a higher thermal conductivity and heat transfer coefficient as compared to the base fluid. The heat transfer characteristics of nanofluids depend upon the shape, size, volume fraction and thermo physical properties of nanoparticles as well as the thermophysical properties of base fluid. The seminal work of Choi and Eastman [1] reports the benefits of nanofluids for augmenting heat transfer utilizing copper nanoparticles. Xuan and Li [2] have experimentally identified that increase in heat transfer of nanofluid is due to the enhanced thermal conductivity and the chaotic movement of nanoparticles. Studies on application and convective heat transfer characteristics of nanofluids and applications are made by Buongiorno [3], Kakac and Pramuanjaroenkij [4], Wong and Leon [5], Saidur et al. [6] and Mahian et al. [7]. The essence of the aforementioned studies is that, the heat transfer rate increases with the increase of nanoparticles volume fraction.

In modeling the heat transfer characteristics in nanofluids, two main approaches are adopted in literature. The one approach is the single-phase homogeneous flow model in which nanoparticles are assumed to be in a thermal equilibrium state and convect with the fluid. In the other approach which is the two-phase model [8], the nanofluid is treated as a two-component non-homogeneous mixture, including the base fluid and nanoparticles in which a relative velocity between the nanoparticles and fluid is considered. Buongiorno [3] described several slip mechanisms of which Brownian diffusion and thermophoresis are found to be the most important slip mechanisms in nanofluids. The Brownian diffusion effects dominate the thermophoretic effects for lower sized copper nanoparticles [9]. The single-phase model is simpler and computationally efficient to analyze the heat transfer characteristics of nanofluids [8].

Nanofluids can be considered as a single-phase fluid by considering an effective thermal conductivity and viscosity of nanofluids. Several experimental and theoretical studies were conducted in the literature to model the thermal conductivity and viscosity of nanofluids e.g., Corcione [10], Khanafer and Vafai [8], Arefmanesh

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.06.049
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Nomenclature

Be	Bejan number, S_h/S_{gen}
g	gravitational acceleration (m/s^2)
Gr	Grashof number, $\frac{g\beta_f \Delta\theta L^3}{\nu_f^2}$
K	thermal conductivity, (W/mK)
L	enclosure length, (m)
Nu	local Nusselt number
p	pressure, (N/m^2)
Pr	Prandtl number, ν_f/α_f
Re	Reynolds number, $\frac{U_0 L}{\nu_f}$
Ri	Richardson number, Gr/Re^2
S_f	dimensionless entropy generation due to fluid friction
S_{gen}	dimensionless local entropy generation
S_h	dimensionless entropy generation due to heat transfer
t	dimensionless time
T	temperature (K)
(u, v)	nondimensional cartesian Component of velocity
x, y	dimensionless Cartesian co-ordinates

Greek symbol

α	thermal diffusivity, (m^2/s)
β_f	coefficient of thermal expansion K^{-1}
η	transformed coordinate in y-direction
γ	inclination angle
λ	skew angle
μ	dynamic viscosity, (kg/m s)
ν	kinematic viscosity, (m^2/s)
ξ	transformed coordinate in x-direction
ρ	density, (kg/m^3)
θ	dimensionless temperature, $(T - T_C)/(T_H - T_C)$
ϕ	solid volume fraction

Subscripts

c	cold
h	hot
f	pure fluid
p	solid
nf	nanofluid
av	average
tot	total

Superscripts

$'$	dimensional quantity

et al. [11] and the reference there-in. The Mawell-Grenett (MG) model is a classical model for effective thermal conductivity. This model is a special case of the Hamilton–Crosser model [12]. Hamilton Crosser model considers the shape factor of the nanoparticles which accounts for the spherical as well as non spherical nanoparticles. However, the MG model is applicable for spherical shape nanoparticles and depends upon the thermal conductivity of nanoparticles, thermal conductivity of base fluid and the nanoparticles volume fraction. This restriction has given rise to a consideration of several new models, which accounts for the temperature, shape, size, particle mobility, Brownian motion, volume fraction and molecular level layering at the liquid-particle interface. Several models for thermal conductivity in nanofluids have been reported by Xuan et al. [13], Keblinski et al. [14], Koo and Kleinstreuer [15], Prasher et al. [16], Patel et al. [17], Corcione [10] and Chon et al. [18].

The effective viscosity in nanofluids is often evaluated by the Brinkman model [19]. It is applicable for spherical shape nanoparticles and depends on the viscosity of the base fluid and the nanoparticles volume fraction. However, it does not account for the nanoparticle size, temperature and Brownian motion. This inadequacy has given rise to a consideration of several new models as reported by Kebilinski et al. [14], Koo and Kleinstreur [15], Prasher et al. [16], Corcione [10] and Pak-Cho [20].

Khanafer and Vafai [8] made a comparative study on several correlation model based on the experimental data for the effective thermal conductivity and viscosity of the nanofluids. This study concludes that at room temperature, the effective thermal conductivity and viscosity for nanofluids can be evaluated through the classical models when the particle volume fraction is low. In the present analysis, we have made comparisons of several models and found that the MG model and the Brinkman model for approximating respectively, the thermal conductivity and viscosity is most convenient.

The study of natural/ mixed convection in cavity or duct has important practical relevance such as in electronics cooling, solar collector, solar pond, food processing etc. [21]. In several cases, these enclosures can have an inclination angle as compared to the gravity direction. The Study of natural convection in an inclined cavity also simulates a solar still device [22]. In the engineering design of a compact heat exchanger, solar collector, electronic cooling system, nuclear reactor and other thermal devices, it is important to consider the effects of enclosure inclination angle with respect to the horizontal. Depending on the inclination angle, the shear force may assist or oppose the buoyancy force. Understanding the heat transfer mechanisms in inclined enclosures is thus important for design purposes.

Abu-Nada and Oztop [12], Ghasemi and Aminossadati [23] and Kahveci [24] have studied natural convection of nanofluids in an inclined cavity. Abu-Nada and Oztop [12] found that a lower heat transfer rate occurs at an inclination angle $\gamma = 90°$ among the considered angle of inclination i.e., $\gamma = 0°$, 30°, 60° and 120°. They found that the effect of the inclination angle is insignificant at low Rayleigh number and the addition of nanoparticles produces an enhancement in the heat transfer rate. Ghasemi and Aminossadati [23] investigated the heat transfer performance of CuO-nanofluid in a vertically heated inclined square enclosure. They identified that the heat transfer rate is maximum at a specific inclination angle depending on the Rayleigh number and the nanoparticle volume fraction. Kahveci [24] studied the buoyancy driven heat transfer in a differentially heated tilted square enclosure and found that the average rate of heat transfer increase with the increase of the inclination angle up to a critical value of an inclination angle.

The mixed convection of nanofluids in an inclined lid-driven cavity has drawn the attention of several authors in recent years. The study by Abu-Nada and Chamkha [25] on the mixed convection of a nanofluid in a square cavity with a vertical temperature gradient shows that a significant enhancement in heat transfer occurs due to the presence of nanoparticles and the heat transfer is affected by the inclination angle when the Richardson number is not small ($Ri \geqslant 1$). Alina et al. [26] investigated the heat transfer performance of a nanofluid in an inclined two sided lid driven cavity with horizontal temperature gradient. They found that the effect of inclination angle on the heat transfer and flow field is more pronounced at higher values of Richardson number

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