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Effect of solid-to-fluid conductivity ratio on mixed convection and entropy generation of a nanofluid in a lid-driven enclosure with a thick wavy wall

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ABSTRACT

A numerical study on the conjugate heat transfer by mixed convection of a Cu-water nanofluid and conduction in a solid region is conducted in an enclosure with a thick wavy heated wall. The upper lid of the enclosure is made to slide horizontally at a constant speed, along with that the condition of heated outer boundary of the thick bottom wall leads to a mixed convection within the enclosure. The impact of the wavy fluid-solid interface, solid-to-fluid thermal conductivity ratio and nanoparticle volume fraction on the heat transfer characteristics is analyzed for different choice of the Richardson number. The computational domain is transformed into an orthogonal co-ordinate system. The transformed governing equations along with the specified boundary conditions are solved through a finite volume method for a wide range of Richardson number, nanoparticle volume fraction, wave amplitude, wave number and wall-to-fluid conductivity ratio for different Reynolds number. Results show that the heat transfer rate increases substantially due to the inclusion of nanoparticles. Heat transfer rate varies due to the variation of the solid-to-fluid conductivity ratio, amplitude and wave number of the wavy wall. The impact of the wavy surface is stronger when the solid conductivity is in the order of the conductivity of the fluid. The Bejan number and the entropy generation are determined to analyze the thermodynamic optimization of the conjugate mixed convection.

1. Introduction

The conjugate heat transfer in a fluid filled thick wall enclosures due to the buoyancy/shear driven flows has drawn attention of many researchers due to its wide applications in building design [1], cooling of electronic equipments [2], heat exchangers [3], nuclear reactors [4] and float glass production [5]. In electronic cooling system, where electronic components are placed on a circuit board and heat load from the circuit board are to be removed, relates to a conjugate heat transfer problem. Kim et al. [6] studied numerically the free convection in channels formed by a series of parallel plates embedded with line heat sources.

In recent years, utilization of nanofluid as a cooling fluid for enhanced heat transfer becomes an emerging area of investigation. Nanofluid is a colloidal mixture/solution of nano-sized (1–100 nm) particles with a base fluid. Nanofluid differs in thermo-physical properties from base fluid due to these suspended nano-particles and it exhibits higher thermal conductivity compared to the low thermal conductive base fluid such as oil, water etc. Several studies are made to analyze the potential benefits of nanofluid. Choi and Eastman [7], who suggested the term “nanofluid” in 1995, studied theoretically the thermal conductivity of nanofluid consisting of copper nanophase materials and conclude that not only nanofluid exhibit high thermal conductivity compared to the conventional base fluid (oil, water, ethylene glycol etc.), it also reduces heat exchanger pumping power. Xuan and Li [8] made a detailed study on the convective heat transfer and flow field of nanofluids and concluded that suspension of nanoparticles into base fluid produces an enhanced rate of heat transfer. Tiwari and Das [9], Abu-Nada and Chamkha [10], Salari et al. [11] and Rahman [12] studied mixed convection of nanofluid in an enclosure and concluded by positive remarks that the average Nusselt number of nanofluid is larger than that of the base fluid at the same Richardson number. Effect of nanoparticles on heat transfer and entropy generation in natural convection within an enclosure is studied by Parvin and Chamkha [13]. Chamkha and his collaborators [14,15] analyzed

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Nomenclature

Be	Bejan number, S_h/S_{gen}
g	gravitational acceleration (m/s^2)
Gr	Grashof number, $g\beta_f\Delta\theta L^3/\nu_f^2$
H	enclosure height (m)
k	thermal conductivity (W/mK)
K_r	wavy solid wall to nanofluid thermal conductivity ratio, k_s/k_{nf}
K_{ro}	wavy solid wall to base fluid thermal conductivity ratio, k_s/k_f
Nu	local Nusselt number
p^*	pressure (N/m^2)
Pr	Prandtl number, ν_f/α_f
Re	Reynolds number, $\rho_f U_0 H/\mu_f$
Ri	Richardson number, Gr/Re^2
S_f	dimensionless local entropy generation due to fluid friction irreversibility
S_{gen}	dimensionless total entropy generation
S_h	dimensionless local entropy generation due to heat transfer irreversibility
t^*	time (s)
t	dimensionless time
T	temperature (K)
(u^*, v^*)	velocity components in x,y direction respectively (m/s)
(u, v)	dimensionless velocity components in x,y direction respectively
U_0	upper wall velocity (m/s)

Greek symbols

α	thermal diffusivity (m^2/s)
α_s	dimensionless wave amplitude of wavy wall
β_f	coefficient of thermal expansion (K^{-1})
μ	dynamic viscosity (kg/m $\cdot$ s)
ξ	transformed coordinate in x-direction
η	transformed coordinate in y-direction
ν	kinematic viscosity (m^2/s)
θ	dimensionless temperature
Π	dimensionless heat function
ρ	density (kg/m^3)
ϕ	nanoparticle volume fraction
ω_n	wave number of wavy wall

Subscripts

av	average
c	cold
f	clear fluid
h	hot
nf	nanofluid
p	solid particle
s	solid wall

Superscripts

$*$	dimensional quantity
0	clear fluid ($\phi = 0$)

the heat transfer due to natural convection in a nanofluid saturated porous media as well as MHD mixed convection of nanofluids within a lid-driven cavity [16].

In the homogeneous model, which neglects the relative flux of nanoparticles in the base fluid, the nanofluid is assumed to be a single phase medium whose thermophysical properties are modified due to the presence of the nanoparticles. The Brinkman model [17] for the viscosity and the Maxwell [18] model for the thermal conductivity are widely adopted for theoretical analysis of nanofluids based on a homogeneous model. It may be noted that both these models do not depend on the temperature and nanoparticles size. It has been established through several experiments [19] that the Maxwell-Garnetts model for thermal conductivity agrees well with the experimental results. Based on the experimental data several empirical models are proposed for nanofluids [20]. Khanafer and Vafai [21] compared the results based on classical models with several empirical correlations for viscosity and thermal conductivity and concluded that at the room temperature the results based on the classical models are in close agreement with the experimental data. Parvin et al. [22] compared the MG model with the Chon et al. [23] model for the thermal conductivity of nanofluids and found a discrepancy in the results.

Most of the experimental studies [24,25] found that a more nanoparticles concentration creates enhanced thermal conductivity. Several experimental studies [26,27] considered nanoparicle volume fraction above 10% and found that the thermal conductivity of the nanofluid enhances with the increase of nanoparticle volume fraction. However, in recent years most of the experiments [28] on nanofluids restricted the volume fraction below 10%. The mass fraction of the nanoparticles is taken to be sufficiently small so as to treat the nanofluid as Newtonian and incompressible. At higher volume concentration the nanoparticles can agglomerate. In a recent review article, Murshad and Estellé [28] has cited several experimental works where it is found that the nanofluids exhibits non-Newtonian nature for a larger particle volume fraction.

The experimental studies such as, Wen and Ding [29] shows that the distribution of nanoparticles in fluid are nonuniform, which suggest a relative velocity between the nanoparticles and fluid. Buongiorno [30] developed a two-phase non-homogeneous model by considering the slip velocity of nanoparticles. This study shows that for the tiny size nanoparticles, the Brownain diffusion and themophoresis are the two main mechanisms to generate the relative velocity of the nanoparticles with respect to the base fluid. The thermophoretic force tries to induce the nanoparticle migration in the opposite direction of the imposed temperature gradient, whereas the Brownian diffusion tends to create a homogeneous distribution of nanoparticles when a concentration gradient of nanoparticle arise. However, the study of Choi [31] shows that the difference between the computed average Nusselt number based on the homogeneous model and the non-homogeneous model is negligible. The non-homogeneous model as proposed by Buongiorno [30] consider the theromphysical parameters are constant and do not depend on the nanoparticle distribution. Several authors [32,33] proposed modification of this non-homogeneous model. In the present study, we have adopted a homogeneous model for the nanofluids and found an insignificant difference with the corresponding non-homogeneous model.

In many engineering applications such as micro-electronic devices, refrigerators and solar collectors the geometric shape of the bounding surfaces are often irregular or wavy structured. The bounding surfaces of the enclosures are often modulated to enhance heat transfer by increasing the inter-facial contact area between the bounding surface and the fluid layer. The effect of different shapes and size of enclosure and channel on the heat transfer are studied by many researchers [34–37]. Song et al. [34] studied the heat transfer optimization based on the constructal