International Journal of Heat and Mass Transfer 100 (2016) 835–850

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Heatline visualization of conjugate natural convection in a square cavity filled with nanofluid with sinusoidal temperature variations on both horizontal walls

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ARTICLE INFO

Article history:
Received 9 November 2015
Received in revised form 3 May 2016
Accepted 6 May 2016

Keywords:
Conjugate natural convection
Heatline
Nanofluid
Sinusoidal conditions
Finite difference method

ABSTRACT

The problem of conjugate natural convection in a square cavity filled with a nanofluid with sinusoidal temperature variations on both horizontal walls is visualized by heatlines. Water-based nanofluids with Ag, Cu, Al_2O_3, or TiO_2 nanoparticles are chosen for investigation. The governing equations together with the specified boundary conditions are solved numerically using the finite difference method over a wide range of Rayleigh number ($10^5 \leqslant Ra \leqslant 10^8$), nanoparticle volume fractions ($0 \leqslant \phi \leqslant 0.2$), phase deviations ($0 \leqslant \gamma \leqslant \pi$), amplitude ratios ($0 \leqslant \varepsilon \leqslant 1$), wall to nanofluid thermal conductivity ratios ($0.44 \leqslant K_r \leqslant 23.8$) and wall thickness to height ratios ($0 \leqslant S \leqslant 0.7$). Comparisons with previously published work verify good agreement with the proposed method. Detailed computational results for the influence of the various parameters on streamlines, heatlines, isotherms, and the overall heat transfer are shown graphically. It is found that the heat transfer rate is significantly enhanced by incrementing the solid wall thickness. Different values of the thermal conductivity ratio are shown to depict a variety of enhancements for the heat transfer rate.

1. Introduction

Natural convection heat transfer is an important phenomenon in engineering systems because of its wide range of applications in electronic cooling, heat exchangers, and double pane windows [1]. Natural convection heat transfer occurs in cavities and is caused by temperature differences and buoyancy forces. It can be analysed by using cavities filled with a clear fluid [2] or nanofluid [3]. The low thermal conductivity of conventional heat transfer fluids such as water and oils is a primary limitation to enhancing the performance and compactness of many electronic engineering devices. Solids typically have a higher thermal conductivity than liquids. For example, copper (Cu) has a thermal conductivity 700 times greater than water and 3000 times greater than engine oil. A new innovative technique to enhancing heat transfer is by using solid nanoparticles with diameters of 10–50 nm in a base fluid (i.e. nanofluids) [4]. Because of the small size and very large specific surface area of the nanoparticles, nanofluids have superior properties such as high thermal conductivity, minimal clogging of flow passages, long-term stability, and homogeneity. Thus, nanofluids have a wide range of potential electronic, automotive, and nuclear applications where improved heat transfer or efficient heat dissipation is required. An early study considered heat transfer enhancement in a differentially heated cavity by using the finite volume method [5]. The suspended nanoparticles were found to substantially increase the heat transfer for all of the given Grashof numbers. Jou and Tzeng [6] investigated natural convective heat transfer enhancement in rectangular cavities filled with an Al_2O_3–water nanofluid. Tiwari and Das [7] studied the mixed convection heat transfer in a two-sided lid-driven differentially heated square cavity filled with a nanofluid. Alloui et al. [8] analytically and numerically investigated the natural convection and heat transfer in a shallow rectangular cavity filled with an Al_2O_3–water nanofluid. They applied the Neumann boundary conditions for temperature to the horizontal walls of the cavity. Their study was considered five nanoparticles, they concluded that the strength of the fluid flow decreased with the presence of

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.05.031
0017-9310/

Nomenclature

A	amplitude
Cp	specific heat capacity
g	gravitational acceleration
k	thermal conductivity
K_r	thermal conductivity ratio
L	width and height of cavity
$\overline{Nu}$	average Nusselt number
Pr	Prandtl number
Ra	Rayleigh number
S	dimensionless solid wall thickness
T	temperature
u, v	velocity components in the x-direction and y-direction
U, V	dimensionless velocity components in the X-direction and Y-direction
x, y & X, Y	space coordinates & dimensionless space coordinates

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
γ	phase deviation
ε	amplitude ratio
θ	dimensionless temperature
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
ϕ	solid volume fraction
ψ & Ψ	stream function & dimensionless stream function
ω & Ω	vorticity & dimensionless vorticity

Subscript

b	bottom
bf	base fluid
c	cold
h	hot
i	interface between the solid wall and the nanofluid
nf	nanofluid
sp	solid nanoparticle
t	top
w	wall

nanoparticles. Oztop et al. [9] studied the effect of a non-uniform wall heating condition on the natural convection and heat transfer in a square inclined cavity filled with a CuO nanofluid by using the finite volume method. They showed that the heat transfer in the cavity is clearly increased with the addition of nanoparticles and low Rayleigh numbers.

Conjugate natural convection heat transfer in cavities has received much attention because of its importance to many engineering systems, such as solar energy collectors, material processing, heat preservation of thermal transport circuits, building energy components, and the cooling of electrical units. Kaminski and Prakash [10] numerically studied the effect of conjugate natural convection heat transfer in a square cavity with a finite thickness vertical wall to compare different models of wall heat conduction. Their results indicated that the temperature distribution in the solid wall shows significant two-dimensional effects at high Grashof number and the temperature of the interface tended to be quite non-uniform. House et al. [11] investigated the effect of a centred heat-conducting body on the natural convection heat transfer in a square cavity. The two vertical walls were maintained at a constant temperature and the horizontal walls were adiabatic. The results showed that the heat transfer decreased with the increase of the solid body. Ha et al. [12] investigated the effect of unsteady natural convection processes in similar vertical cavities with a centred heat-conducting body. Baytaş et al. [13] numerically studied the conjugate natural convection heat transfer in a square cavity filled with a porous medium and have two finite-thickness horizontal plates. Ben-Nakhi and Chamkha [14] studied the effect of conjugate natural convection around a finned pipe in a square cavity. Zhao et al. [15] studied the effect of a centred heat-conducting body on the conjugate natural convection heat transfer in a square cavity. Ben-Nakhi and Chamkha [16] analysed the effect of conjugate natural convection in a square cavity with inclined thin fin of arbitrary length by using the Gauss–Seidel point-by-point method. Saleh et al. [17] investigated the effect of conjugate natural convection at the bottom wall on Darcy–Bénard convection in a square porous cavity. The horizontal walls of the cavity were maintained at a constant temperature while the vertical walls were kept insulated. The results indicated that the average Nusselt number increased with the increase of the thermal conductivity or decrease the thickness of the solid wall. Chamkha and Ismael [18] numerically investigated the conjugate heat transfer in a porous cavity heated by a triangular thick wall. Chamkha and Ismael [18] studied the effect of conjugate natural convection heat transfer in a porous cavity filled with nanofluids and heated by a thick triangular wall. Their study showed that the heat transfer was significantly enhanced at low Rayleigh number with the increase of the nanoparticles volume fraction. Very recently, Ismael and Chamkha [19] investigated conjugate natural convection in a differentially heated composite cavity filled with a nanofluid.

Recently, the problem of natural convection in closed cavities with various thermal boundary conditions has been given considerable attention by several studies. Sarris et al. [20] used the finite-volume method to study the natural convection in a 2-D cavity with sinusoidal temperature profile on the upper wall while the other walls are adiabatic. The upper horizontal wall heated with sinusoidal temperature profile while the bottom and vertical walls of the cavity were kept adiabatic. They concluded that the intensity of the fluid circulation and thermal penetration depth were highly increased with the increase of the cavity aspect ratio. Saeid and Yaacob [21] numerically considered natural convection in a square cavity filled with pure fluid with a non-uniformed hot-wall temperature and a uniformed cold-wall temperature. The left vertical wall of the cavity was heated by a spatial sinusoidal temperature and the right vertical wall was maintained at a constant temperature, while the horizontal walls were adiabatic. Their results indicated that the average Nusselt increased with an increase in the nondimensional amplitude which appeared clearly with low wave number. Bilgen and Yedder [22] numerically considered natural convection in a rectangular cavity heated and cooled from the left vertical sidewall by sinusoidal temperature profiles and all the other walls are kept insulated. Deng and Chang [23] numerically studied the natural convection in a rectangular cavity filled with pure fluid and heated by two sinusoidal temperature distributions on the vertical left and right sidewalls. The left and right vertical walls heated with sinusoidal temperature distributions and the top and bottom horizontal walls were thermally insulated. They