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Numerical study of periodic natural convection in a nanofluid-filled enclosure due to transitional temperature of heat source

E. Sourtiji *, D.D. Ganji, M. Gorji-Bandpy, S.M. Seyyedi

Babol University of Technology, Department of Mechanical Engineering, Babol, Mazandaran, Iran, P.O. Box 484

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ABSTRACT

A numerical study of unsteady periodic natural convection flows through an alumina–water nanofluid in a square cavity due to a sinusoidal time-dependent temperature of a thin heat source located at the center of the enclosure is performed. It is found that an oscillating time-dependent temperature of the heat source cased to create a periodic variation in the fluid flow and temperature field in the cavity after certain time duration. The influence of the nanoparticle on the flow and temperature fields have been plotted and discussed. It is observed that the average Nusselt number is an increasing function of nanoparticle volume fraction and Rayleigh number for all the oscillation periods and Rayleigh numbers investigated. It is also found that the performance of the nanoparticle utilization on the enhancement of the heat transfer at higher Rayleigh numbers ($Ra = 10^6$) is less than that of lower Rayleigh numbers ($Ra = 10^3$).

1. Introduction

Increasing the heat transfer rate while incurring acceptable pressure drop is an important objective in many industrial applications such as electronic device cooling, microfluidic components, heat exchangers, and so on. Conventional heat transfer fluids such as water, oil and ethylene glycol possess low thermal conductivity values thus limiting their utilization in challenging conditions. Adding some solid nanoparticles with high thermal conductivity to the fluid is one of the ways to overcome this problem. The resulting fluid is a suspension of the solid nanoparticle in the base fluid which is called a “nanofluid”. The thermal conductivities of nanofluids are believed to be greater than the base fluid due to the high thermal conductivity of the nanoparticles. In the recent years, many experiments have been carried out by researchers to identify the thermal conductivity of nanofluids [1–3]. The results revealed that the thermal conductivity of nanofluids depends to various parameters such as interfacial layer at the particle/liquid interface [4], nanoparticle size and shape [5], nanoparticle clustering [6], Brownian motion of the nanoparticle in the base fluid [7], temperature and volume fraction concentration of the nanoparticles in the base fluid [8].

In the recent years many researches have investigated numerically and experimentally the enhancement of heat transfer utilizing nanofluids [9–14]. Aminossadati [15] performed a numerical analysis of natural cooling of a right triangular heat source by a water–CuO nanofluid in a right triangular cavity that is under the influence of a horizontal magnetic field. It was found that the presence of nanoparticles in the base fluid drastically impressed the fluid flow and enhanced heat transfer rate. Khanafer et al. [16] carried out a numerical study of laminar natural convection in a square cavity. They have used three theoretical models for the prediction of viscosity and thermal conductivity of nanofluids and deduced that the variances within different models have substantial effects on the results. Cho et al. [17] performed a numerical study of mixed convection heat transfer characteristics of water-based nanofluids confined within a lid-driven cavity with wavy walls. They considered three different nanofluids of Cu–water, Al_2O_3–water and TiO_2–water to explore the effects of utilization of nanofluids and deduced that the heat transfer is augmented in the presence of nanofluids. Several researchers have investigated the effects of nanofluid in transitional flows [18–20]. Ghasemi and Aminossadati [21] examined the periodic natural convection in an enclosure filled with nanofluids numerically. They used a heat source with oscillating heat flux on the left wall of the cavity to generate periodic behavior on the fluid flow and temperature field in the cavity. It was deduced that the utilization of nanoparticles enhances the heat transfer especially at low Rayleigh numbers. Rahman et al. [22] studied unsteady natural convection heat transfer in an isosceles triangular enclosure filled with Al_2O_3 nanoparticle numerically. They found that the addition of the

* Corresponding author at: Babol University of Technology, Babol, Mazandaran, Iran, P.O. Box 484. Tel.: +98 1113234205; fax: +98 1113212268.
E-mail addresses: Esourtij@gmail.com (E. Sourtiji), ddg_davood@yahoo.com (D.D. Ganji), Gotji@nit.ac.ir (M. Gorji-Bandpy), mostafa_5054@yahoo.com (S.M. Seyyedi).

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Nomenclature

f	frequency of oscillation (s^{-1})
g	gravitational acceleration (m/s^2)
H	length of the cavity sides (m)
k	thermal conductivity (W/mK)
Nu	Nusselt number
p	pressure (N/m^2)
P	dimensionless pressure
Pr	Prandtl number, υ/α
Re	Reynolds number, ($(u_n 2w/\upsilon)$)
Ra	Rayleigh number, ($g\beta H^3 \Delta T/\upsilon\alpha$)
T	temperature (K)
t	time (sec)
u, v	components of velocity (m/s)
u_m	the mean inlet velocity (m/s)
U, V	dimensionless of velocity component, ($U = u/u_m$, $V = v/u_m$)
x, y	cartesian coordinates (m)
X, Y	dimensionless of Cartesian coordinates, ($X = x/H$, $Y = y/H$)

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (k^{-1})
ϕ	particle volume fraction
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
θ	dimensionless temperature
τ	dimensionless time ($t\, u_0/H$)
τ_p	period of oscillation

Subscripts

Avg	average
eff	effective
f	fluid
m	mean
nf	nanofluid
S	surface

nanoparticle into the base fluid (water) affects both heat transfer and fluid flow and deduced that heat transfer is increased with the addition of nanoparticle for all Rayleigh number investigated.

The aim of this study is to simulate numerically the unsteady free convection heat transfer of alumina (Al_2O_3)–water nanofluid in a square enclosure subjected to an oscillating temperature of a thin heat source located at the center of the cavity. The buoyancy force has been induced by a higher temperature on the surface of the heat source and lower temperature of the left wall of the enclosure. The effective thermal conductivity and the viscosity of nanofluid have been determined by the models which were presented by Murshed [23] and Nguyen et al. [24] respectively. The consequence of varying the Rayleigh number, the temperature oscillation frequency and the nanoparticle concentration on the fluid flow and heat transfer will be presented and discussed.

2. Problem formulation

Fig. 1 shows a two-dimensional square cavity with a thermal heat source located at its center. The height and width of the cavity are denoted by *H* and *L*, respectively and are assumed to be identical ($H = L$). The length of the heat source is specified by L_C which $L_C = 0.3H$. The heat source is thin enough so its height can be neglected. The depth of the enclosure perpendicular to the plane of the diagram is assumed to be long. Hence, the problem can be considered to be two-dimensional. The left wall of the cavity is maintained at a constant law temperature of T_C, whereas the other walls of the enclosure are insulated. The surface temperature of the heat source has a sinusoidal variation with time as follows:

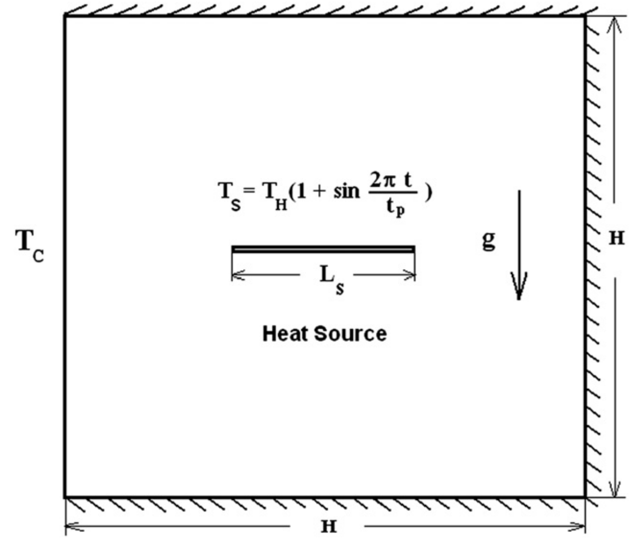

Fig. 1. Schematic diagram of the problem.

$$T_S = T_H\left(1 + \sin\frac{2\pi t}{t_P}\right). \quad (1)$$

Where t_P is the oscillation period and T_H is the constant high temperature of the hot wall corresponding to the steady state of the problem. The enclosure is filled with a water-based Al_2O_3 nanofluid. It is assumed that the base fluid and the nanoparticles are in thermal equilibrium, incompressible, Newtonian and the thermophysical properties of the fluid are constant (Table 1) except for the density which is estimated by the Boussinesq approximation. With these assumptions, the dimensional transport equations are as follows:

Continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0. \quad (2)$$

Momentum:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho_{nf}}\frac{\partial P}{\partial x} + \upsilon_{nf}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \quad (3)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y} + \upsilon_{nf}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \frac{1}{\rho_{nf}} g(\rho\beta)_{nf}(T - T_C). \quad (4)$$

Table 1
Thermophysical properties of the base fluid and the Cu nanoparticles.

	C_P [J kg^{-1} K^{-1}]	ρ [kg m^{-3}]	K [Wm^{-1} K^{-1}]	$\beta.10^{-5}$ [K^{-1}]
Water	4179	997.1	0.613	21
Cu	385	8933	401	1.67