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Natural convection in an inclined cavity with time-periodic temperature boundary conditions using nanofluids: Application in solar collectors

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ABSTRACT

Natural convection of alumina-water nanofluid inside a square cavity with time-sinusoidal temperature is studied numerically. The domain of interest is an inclined square cavity having isothermal wall at $\bar{x} = L$, while temperature of the wall $\bar{x} = 0$ is changed as a sinusoidal function of time, other walls are adiabatic. Dimensionless governing equations formulated using stream function, vorticity and temperature have been solved by finite difference method of the second order accuracy. The effects of Rayleigh number, oscillating frequency, cavity inclination angle and nanoparticles volume fraction on fluid flow and heat transfer have been analyzed. It has been found that a growth of boundary temperature oscillating frequency leads to an increase in the average Nusselt number oscillation amplitude and reduction of oscillation period. At the same time, the boundary temperature oscillating frequency is a very good control parameter that allows to intensify convective flow and heat transfer.

1. Introduction

Fluid flow and heat transfer induced by natural convection in cavities are important from theoretical as well practical point of view in many engineering applications. Some often given cited include nuclear and chemical reactors, cooling of electronic devices, polymer technology, solar power collectors, and in thin film solar energy collector device. The effective cooling techniques are needed for cooling any sort of high energy devices. Representative studies in this field have been very well summarized in the books by Kulacki [1] and Bejan [2]. Thus natural convection in cavities occurs naturally in a wide range of scientific fields which in the past has attracted the attention of researchers from a diverse range of fields such as mechanical and chemical engineering, oceanography, astrophysics, geology, and biology.

Natural convection in a system with time oscillating boundary conditions has received much attention in the past two decades. Kazmierczak and Chinoda [3] studied the buoyancy-driven flow in an enclosure with time-periodic boundary conditions. Lage and Bejan [4] considered the resonance of natural convection in an enclosure heated periodically from the side. They found that the convection intensity within the enclosure increases linearly with heating amplitude for a wide range of parameters. The Prandtl number effect on the optimum heating frequency of an enclosure filled with a viscous fluid or with a saturated porous medium has been considered by Antohe and Lage [5]. Kwak and Hyun [6] investigated the natural convection in an enclosure having a vertical sidewall with time-varying temperature, while Kwak et al. [7,8] numerically investigated the resonant enhancement of natural convection heat transfer in a square enclosure and in an enclosure with time-periodic heating imposed on one sidewall. It was found that a large-amplitude wall temperature oscillation causes an augmentation of the time-mean heat transfer rate. The maximum gain of the time-mean Nusselt number in the interior occurs at the resonance frequency, at which maximal fluctuations of the Nusselt number are found. Further, Sarris et al. [9] studied the natural convection in a 2D enclosure with sinusoidal upper wall temperature and Bilgen and Ben Yedder [10] considered the natural convection in an enclosure with heating and cooling by sinusoidal temperature profiles on one side. Kalabin et al. [11] analyzed natural convective heat transfer within an inclined square cavity with a side wall temperature varying with sine function of time. It was revealed that a growth of oscillations frequency leads to a reduction of average Nuisselt number amplitude for wall without time effect. Zargartalebi et al. [12] studied unsteady conjugate natural convection in a porous cavity sandwiched by finite conductive walls considering time-periodic boundary conditions and local

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Nomenclature

Roman letters

c_p	specific heat at constant pressure
f	dimensionless oscillation frequency
$\mathbf{g}$	gravitational acceleration vector
H_1, H_2, H_3	special functions
k	thermal conductivity
L	length and height of the cavity
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
$\overline{\overline{Nu}}$	time-averaged Nusselt number
$\bar{p}$	dimensional pressure
Pr	Prandtl number
Ra	Rayleigh number
T	dimensional temperature
t	dimensional time
T_c	low temperature
T_h	high temperature
u, v	dimensionless velocity components
$\bar{u}$, $\bar{v}$	dimensional velocity components
x, y	dimensionless Cartesian coordinates
$\bar{x}$, $\bar{y}$	dimensional Cartesian coordinates

Greek symbols

α	cavity inclination angle
β	thermal expansion coefficient
θ	dimensionless temperature
μ	dynamic viscosity
ρ	density
ρc_p	heat capacitance
$\rho\beta$	buoyancy coefficient
τ	dimensionless time
ξ	dimensional oscillation frequency
ϕ	nanoparticles volume fraction
ψ	dimensionless stream function
ω	dimensionless vorticity

Subscripts

c	cold
f	fluid
h	hot
max	maximum value
nf	nanofluid
p	(nano) particle

thermal non-equilibrium. It was found that apart from non-dimensional frequency and wall thickness, the amplitude of periodic fluid Nusselt number is an increasing function of all aforementioned parameters. Furthermore, aside from Rayleigh number and heat transfer coefficient, the behavior of the solid Nusselt number is the same as fluid Nusselt number.

The particular problem of natural convection in an inclined enclosure has received considerable attention due to its relevance to a wide variety of applications in engineering and science. Ozoe et al. [13,14] studied the problem of natural convection in inclined rectangular channels heated on one side and cooled on the opposing side. Their results indicated that as the angle of inclination increased, a minimum and then a maximum heat transfer occurred. Later, Rahman and Sharif [15] examined the laminar natural convection in differentially heated inclined rectangular enclosures of various aspect ratios. Chamkha and Al-Naser [16] considered laminar double-diffusive convective flow of a binary gas mixture in an inclined rectangular enclosure filled with an uniform porous medium.

Conventional heat transfer fluids such as water, ethylene glycol mixture and engine oil have limited heat transfer capabilities due to their low thermal conductivity in enhancing the performance and compactness of many engineering devices [17,18]. In contrast, metals have thermal conductivities up to three times higher than these fluids. Thus it is naturally desirable to combine two substances to produce a medium for heat transfer that would behave like a fluid, but has the thermal conductivity of a metal. Therefore, there is a strong need to develop advanced heat transfer fluids with substantially higher conductivities to enhance thermal characteristics. Small particles (nanoparticles) stay suspended much longer than larger particles. The presence of the nanoparticles in the fluids increases appreciably the effective thermal conductivity and viscosity of the base fluid and consequently enhances the heat transfer characteristics. The discovery of nanofluids, which is a new kind of fluid suspension consisting of uniformly dispersed and suspended nanometer-sized (10–50 nm) particles and fibers in base fluid. Thus, nanofluids may be used in various applications which include electronic cooling, vehicle cooling transformer and coolant for nuclear reactors. Choi [19] seems to be the first who indicated engineered colloids composed of nanoparticles dispersed in a base fluid. Choi et al. [20] showed that the addition of small amount (less than 1% by volume) of nanoparticles to conventional heat

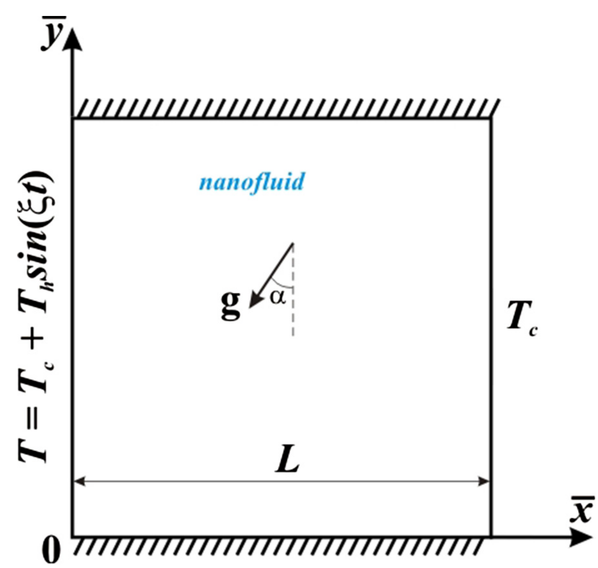

Fig. 1. A scheme of the system.

Table 1
Physical properties of base fluid and Al_2O_3 nanoparticles (Oztop and Abu-Nada [44]).

Physical properties	Base fluid (water)	Al_2O_3
c_p ($J\cdot kg^{-1}\cdot K^{-1}$)	4179	765
ρ ($kg\cdot m^{-3}$)	997.1	3970
k ($W\cdot m^{-1}\cdot K^{-1}$)	0.613	40
$\beta \times 10^{-5}$ (K^{-1})	20.7	0.846

transfer liquids which enhanced the thermal conductivity of the fluid up to approximately two times. Experimental studies by Das [21], Xuan and Li [22] and Minsta et al. [23] showed that even with small volumetric fraction of nanoparticles (usually less than 5%) the thermal conductivity of the base fluid is enhanced by 10–50% with a remarkable improvement in the convective heat transfer coefficient. Putra et al. [24] conducted the experiment for observation on the natural convective characteristics of alumina-water (Al_2O_3) based nanofluids. They reported that the presence of nanoparticles suspended in base fluid systematically deteriorates the natural convective heat transfer with increasing nanoparticle concentration.

Different mathematical models have been employed by several authors to describe heat transfer in nanofluids [25–42]. Among all these models, the most used are those where the concentration of the nanoparticles is constant and the addition of the nanoparticles into the base fluid improved their physical properties [25,26]. Moreover, a more complex mathematical nanofluid model has been developed by Buongiorno [27] and Buongiorno et al. [28] to explore the thermal properties of base fluids. Xuan and Roetzel [29] proposed homogeneous flow model where the convective transport equations of pure fluids are directly extended to nanofluids. It is worth mentioning that many references on nanofluids can be found in the books by Das et al. [30], Nield and Bejan [31], and Shenoy et al. [32], and in the review papers by Kakaç and Pramuanjaroenkij [33], Manca et al. [17], Mahian et al. [34], Sheikholeslami and Ganji [35], etc.

The objective of the present study is a numerical analysis of natural convection in an inclined square cavity filled with an alumina-water nanofluid under the effect of time-periodic boundary conditions using the mathematical nanofluid model proposed by Tiwari and Das [26]. Since using classic models to calculate thermal conductivity and viscosity of nanofluids might affect the accuracy of results, we used experimental-based correlations to calculate the properties of nanofluids. The results of present study can be helpful in design of solar energy devices like solar collectors in which the boundary conditions vary with time due to changes in weather conditions including solar radiation and ambient temperature during a typical day. It is worth pointing out that Sheremet and Pop [43] have studied the natural convection in a wavy porous cavity with sinusoidal temperature distributions on both side walls filled with a nanofluid using the mathematical nanofluid model proposed by Buongiorno [27].

2. Mathematical formulation

The physical model of natural convection in an inclined square cavity filled with Al_2O_3-water nanofluid and the coordinate system are schematically shown in Fig. 1. The domain of interest includes the nanofluid-filled cavity (shown in Fig. 1) with a time-varying left wall temperature. Horizontal walls are supposed to be adiabatic, while right vertical wall is kept at constant low temperature T_c. Temperature of left wall varies sinusoidally in time with a cold temperature T_c. It is assumed in the analysis that the thermophysical properties of the fluid are independent of temperature, and the flow is laminar.

The nanofluid is Newtonian and the Boussinesq approximation is valid. The base fluid and the nanoparticles are in thermal equilibrium. The thermophysical properties of the base fluid and the nanoparticles are given in Table 1. It is considered that viscous dissipation and thermal radiation are neglected. Taking into account the abovementioned assumptions the governing equations can be written in dimensional Cartesian coordinates as follows

$$\frac{\partial \bar{u}}{\partial \bar{x}}+\frac{\partial \bar{v}}{\partial \bar{y}}=0 \tag{1}$$

$$\rho_{nf}\left(\frac{\partial \bar{u}}{\partial t}+\bar{u}\frac{\partial \bar{u}}{\partial \bar{x}}+\bar{v}\frac{\partial \bar{u}}{\partial \bar{y}}\right)=-\frac{\partial \bar{p}}{\partial \bar{x}}+\mu_{nf}\left(\frac{\partial^2 \bar{u}}{\partial \bar{x}^2}+\frac{\partial^2 \bar{u}}{\partial \bar{y}^2}\right)+(\rho\beta)_{nf}g(T-T_c)\sin(\alpha) \tag{2}$$

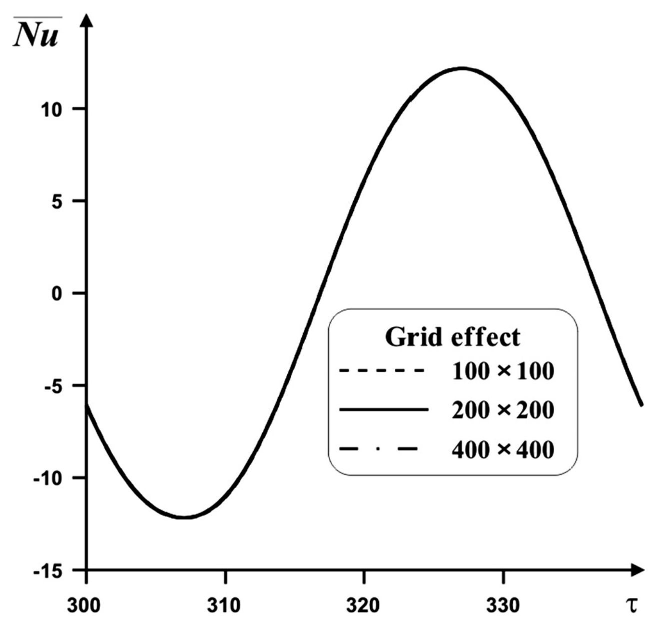

Fig. 2. Time variations of average Nusselt number during one full period for $Ra = 10^5$, $Pr = 7.0$, $\phi = 0.03$, $f = 0.05\pi$ and different mesh parameters.

Table 2
Comparison of average Nusselt number for natural convection of nanofluid in a differentially heated square cavity.

			Average Nusselt number			
ϕ	Ra	Pr	Ho et al. [45]	Present study	Saghir et al. [49] (FDM)	Saghir et al. [49] (FEM)
1%	7.74547×10^7	7.0659	32.2037	30.6533	30.657	31.8633
2%	6.6751180×10^7	7.3593	31.0905	30.5038	30.503	31.6085
3%	5.6020687×10^7	7.8353	29.0769	30.2157	30.205	28.216

Table 3
Grid independence results of $\overline{\overline{Nu}}$ for $Ra = 10^5$, $Pr = 7.0$, $\phi = 0.03$, $f = 0.05\pi$.

Grid	50 × 50	100 × 100	200 × 200	300 × 300	400 × 400
$\overline{\overline{Nu}}$	−0.000759	−0.000861	−0.000919	−0.000959	−0.000989

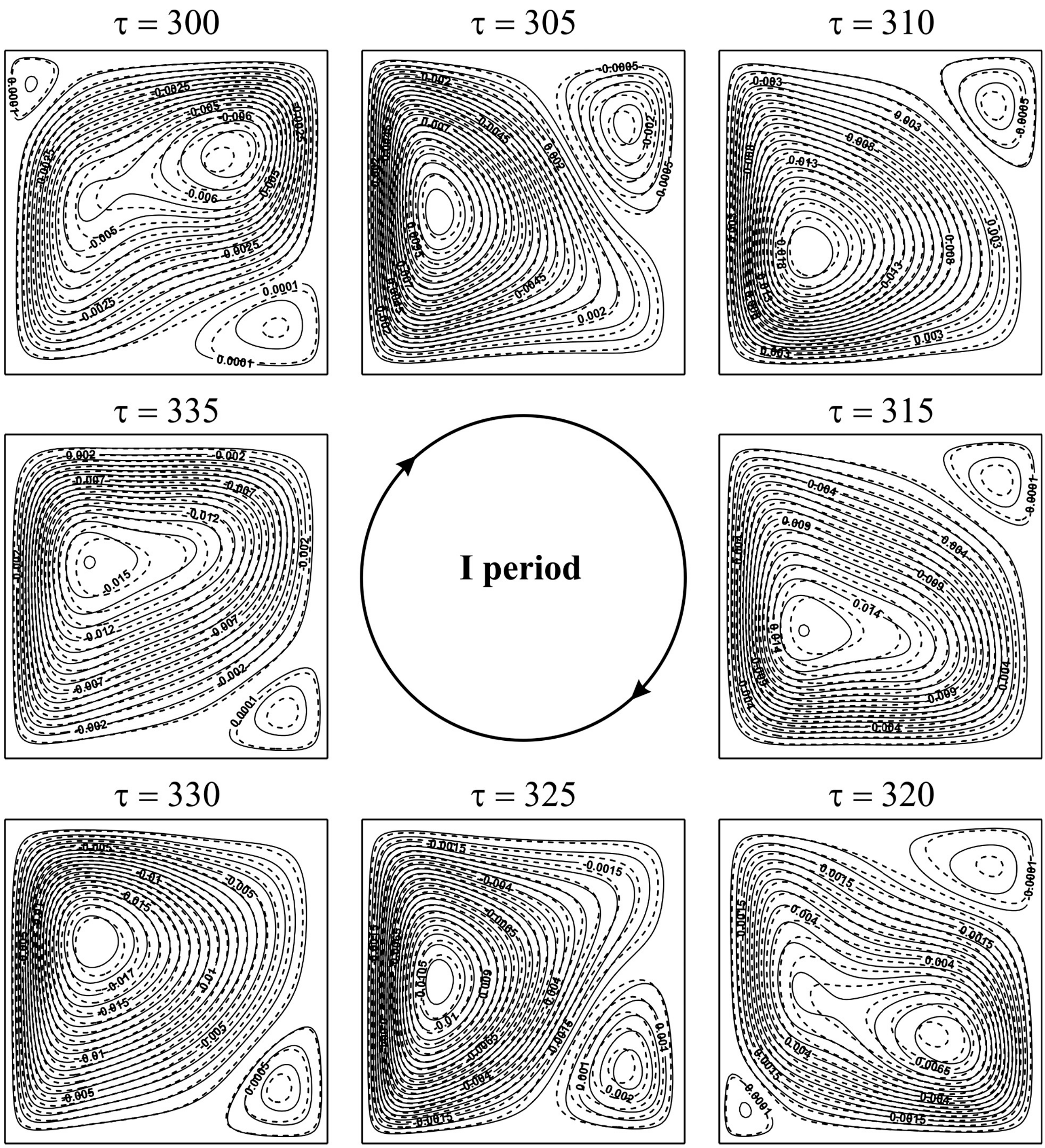

Fig. 3. Streamlines for a period of oscillations for $Ra = 10^5$, $f = 0.05\pi$, $\alpha = 0$ and $\phi = 0.0$ (solid lines), $\phi = 0.03$ (dashed lines).

$$\rho_{nf}\left(\frac{\partial \bar{v}}{\partial t}+\bar{u}\frac{\partial \bar{v}}{\partial \bar{x}}+\bar{v}\frac{\partial \bar{v}}{\partial \bar{y}}\right)=-\frac{\partial \bar{p}}{\partial \bar{y}}+\mu_{nf}\left(\frac{\partial^2 \bar{v}}{\partial \bar{x}^2}+\frac{\partial^2 \bar{v}}{\partial \bar{y}^2}\right)+(\rho\beta)_{nf}g(T-T_c)\cos(\alpha) \tag{3}$$

$$(\rho c_p)_{nf}\left(\frac{\partial T}{\partial t}+\bar{u}\frac{\partial T}{\partial \bar{x}}+\bar{v}\frac{\partial T}{\partial \bar{y}}\right)=k_{nf}\left(\frac{\partial^2 T}{\partial \bar{x}^2}+\frac{\partial^2 T}{\partial \bar{y}^2}\right) \tag{4}$$

with the following boundary conditions

$$\begin{aligned}
&t=0:\bar{u}=\bar{v}=0,\quad T=T_c \text{ at } 0\leqslant \bar{x}\leqslant L,\quad 0\leqslant \bar{y}\leqslant L;\\
&t>0:\bar{u}=\bar{v}=0,\quad T=T_c+T_h\sin(\xi t) \text{ at } \bar{x}=0,\quad 0\leqslant \bar{y}\leqslant L;\\
&\qquad\bar{u}=\bar{v}=0,\quad T=T_c \text{ at } \bar{x}=L,\quad 0\leqslant \bar{y}\leqslant L;\\
&\qquad\bar{u}=\bar{v}=0,\quad \frac{\partial T}{\partial \bar{y}}=0 \text{ at } \bar{y}=0,\quad L, 0\leqslant \bar{x}\leqslant L
\end{aligned} \tag{5}$$

The effective density, specific heat and thermal expansion coefficient of nanofluid are given by using the following equations (see Oztop and Abu-Nada [44])