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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

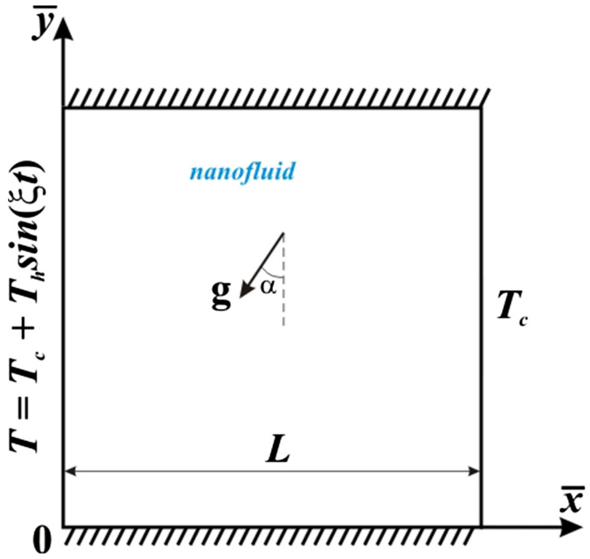

Fig. 1. A scheme of the system.

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·kg^{-1}·K^{-1})	4179	765
ρ (kg·m^{-3})	997.1	3970
k (W·m^{-1}·K^{-1})	0.613	40
$\beta \times 10^{-5}$ (K^{-1})	20.7	0.846