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Free convection heat transfer in complex-wavy-wall enclosed cavity filled with nanofluid☆

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ABSTRACT

A numerical investigation is performed into the natural convection heat transfer characteristics within an enclosed cavity filled with nanofluid. The left and right walls of the cavity have a complex-wavy geometry and are maintained at a low and high temperature, respectively. Meanwhile, the upper and lower walls of the cavity are both flat and insulated. The nanofluid is composed of Al_2O_3 nanoparticles suspended in pure water. In performing the analysis, the governing equations are formulated using the Smoothed Particle Hydrodynamics and the complex-wavy-surface is modeled as the superimposition of two sinusoidal functions. The simulations examine the effects of the volume fraction of nanoparticles, the Rayleigh number and the complex-wavy-surface geometry parameters on the flow streamlines, isotherm distribution and Nusselt number within the cavity. The results show that for all values of the Rayleigh number, the Nusselt number, increases as the volume fraction of nanoparticles increases. In addition, it is shown that the heat transfer performance can be optimized by tuning the wavy-surface geometry parameters in accordance with the Rayleigh number. Overall, the results presented in this study provide a useful insight into potential strategies for enhancing the convection heat transfer performance within enclosed cavities with complex-wavy-wall surfaces.

1. Introduction

Natural convection phenomena, due to their relevance to many scientific issues such as nuclear reactor systems, foundry devices, heat exchangers, geophysical and astrophysical processes, etc., have been studied in the literature, in particular, due to geometrical simplicity, minimum cost, low noise smaller size and reliability [1–3]. However, the traditional working fluids used in such systems (e.g., water, oil or ethylene glycol) have a low thermal conductivity, and thus their heat transfer performance is inevitably limited. Consequently, a requirement exists for new working fluids with a higher thermal conductivity. The recent discovery of "nanofluids," which is an important kind of fluid suspension consisting of uniformly dispersed and suspended nanometer-sized (10–50 nm) particles and fibers in base fluid, proposes the next approach as cooling technology. This is because nanofluids have fascinating features. Putra et al. [4] conducted the experiment for observation on the natural convective characteristics of water based Al_2O_3 nanofluids. They reported that the presence of nanoparticles suspended in base fluid systematically deteriorates the natural convective heat transfer with increasing nanoparticle concentration. The degradation of natural convective heat transfer with increasing particle concentration characterized by decreasing the Nusselt number for a given Rayleigh number was experimentally observed. However, they did not clearly explain why natural convective heat transfer in a cavity is decreased with the increment of the volume fraction of nanoparticles. Kim et al. [5] analytically researched the convective instability driven by buoyancy and heat transfer characteristics of nanofluids with theoretical models which are used to estimate properties of nanofluids. They chose both Einstein's model [6] and Brinkman's model [7] for predicting the effective viscosity of nanofluids, and both Hamilton and Crosser's model [8] and Bruggeman's model [9] for the effective thermal conductivity of nanofluids. In recent years, the problem of natural convection heat transfer in square or rectangular cavities filled with nanofluid has attracted significant attention. Khanafer et al. [10] investigated the problem of buoyancy-driven heat transfer enhancement in a two dimensional square enclosure filled with Cu-water nanofluid. Hwang et al. [11] studied the problem of buoyancy-driven heat transfer within a rectangular cavity filled with water–Al_2O_3 nanofluid. Oztop and Abu-Nada [12] examined the problem of natural convection heat transfer in partially heated square enclosures containing different nanofluids. Ghasemi and Aminossadati [13] investigated the natural convection heat transfer performance of Cu–water nanofluid in an inclined enclosure, while Kahveci [14] examined the heat transfer performance of various buoyancy-driven nanofluids in a differentially heated tilted enclosure. Kefayati et al. [15] investigated the problem of natural convection in a tall enclosure filled with SiO_2–water nanofluid. Overall, the results presented in the literature [10–15] showed that the heat transfer performance can be enhanced by increasing the volume fraction of nanoparticles in the base fluid. The problem of natural convection heat transfer within enclosures with wavy-walls is of interest in many

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Nomenclature

H	altitude of the cavity [m]
W	distance between the wave-walls [m]
C_p	specific heat at constant pressure [J kg^{-1} K^{-1}]
g	acceleration due to gravity [ms^{-2}]
k	thermal conductivity [W m^{-1} K^{-1}]
Nu	local Nusselt number
P	pressure of the fluid [Nm^{-2}]
Pr	Prandtl number
Ra	Rayleigh number
q_w	heat flux at the surface [W m^{-2}]
T	temperature of the fluid [K]
T_H	maximum temperature on wall [K]
T_L	minimum temperature on wall [K]
u, v	dimensional velocity components along the (x, y) axes [ms^{-1}]
x, y	axis in the direction along and normal to the tangent of the surface

Greek symbols

α	thermal diffusivity
β	volumetric coefficient of thermal expansion [K^{-1}]
θ	dimensionless temperature function
ϕ	solid volume fraction
μ	viscosity of the fluid [kg m^{-1} s^{-1}]
ν	kinematic viscosity [m^2 s^{-1}]
ρ	density of the fluid [kg m^{-3}]
λ	wave length
η	parameter to avoid the zero domenator

Subscripts

i,j	positions in the grid
w	wall
eff	effective value
L	the minimum temperature
H	the maximum temperature
f	fluid particle
p	solid particle
nf	nanofliud property
m	mean value

engineering applications, e.g., cooling systems for microelectronic devices, heat exchangers or solar collectors, underground cable systems, and so forth. Accordingly, the heat transfer performance of traditional working fluids such as water and air within wavy-wall enclosures has been widely studied. Ching-Chang Cho et al. [16] studied the natural convection heat transfer within an enclosure bounded by two isothermal wavy-walls and two adiabatic straight walls. Mahmud et al. [17] performed a numerical investigation into the natural convection heat transfer characteristics within an enclosure bounded by two isothermal wavy-walls and two adiabatic straight walls. In later studies, the same group examined the natural convection heat transfer performance within an inclined wavy enclosure [18] and an enclosure with different wavy structures [19]. Abdelkader et al. [20] examined the problem of natural convection heat transfer within a shallow horizontal enclosure, in which the lower surface was a wavy-wall with a constant high temperature, the upper surface was a flat wall with a constant low temperature, and the left and right surfaces were flat and symmetrical. Rostami [21] studied the unsteady natural convection heat transfer phenomenon within an enclosure bounded by two vertical isothermal wavy-walls and two horizontal adiabatic straight walls. Varol and Oztop [22] conducted a numerical investigation into the natural convection heat transfer phenomenon in a shallow wavy enclosure comprising a lower wavy surface with a constant hot temperature, an upper straight surface with a constant cold temperature, and two vertical flat surfaces with thermal insulation. In a later study, Oztop et al. [23] examined the natural convection heat transfer behavior in wavy-walled enclosures containing volumetric heat sources. Overall, the results presented in the literature [15–23] showed that the heat transfer performance within wavy-walled enclosures depends strongly on both the geometry parameters of the wavy surface (e.g., the wave amplitude and wavelength) and the flow parameters (e.g., the Grashof number, Rayleigh number, and so forth). As discussed earlier, the natural convection heat transfer performance of nanofluids in enclosures with flat surfaces has been extensively examined. Moreover, natural convection in wavy-wall enclosures filled with traditional working fluids (e.g., air or water) has also been widely researched. However, the natural convection heat transfer performance of nanofluids within enclosed cavities with wavy-walls has attracted little attention. Accordingly, the present study performs a numerical investigation into the natural convection heat transfer performance of a wavy-wall enclosed cavity filled with Al_2O_3–water nanofluid. In modeling the cavity, the right and left walls are assumed to have a complex-wavy-surface and a constant high and low temperature, respectively, while the upper and lower walls are assumed to be flat and insulated. In performing the simulations, the governing equations are formulated using the Smoothed Particle Hydrodynamics and the wavy-wall surfaces are modeled as the superimposition of two sinusoidal functions. The simulations focus specifically on the effects of the nanoparticle volume fraction, Rayleigh number, and wavy-surface geometry parameters (i.e., the wave amplitude, wavelength and waveform) on the flow streamlines, isotherm distribution, and local and mean Nusselt numbers within the enclosure.

2. Governing equations

2.1. Thermophysical properties of Al_2O_3 nanofluid

In analyzing the flow behavior and heat transfer characteristics in the cavity shown in Fig. 1, where the computational domain, is a square cavity. The heat source is located on the bottom wall of the cavity which is thermally insulated. The vertical walls and the horizontal top wall of the cavity are maintained at a relatively low temperature (T_L). The fluid filled cavity is assumed to be Newtonian, incompressible and laminar; the governing equations are simplified via the following assumptions [16]:

(i) The nanofluid is Newtonian, incompressible and laminar.
(ii) The thermophysical properties of the nanofluid are all constant other than the density which varies in accordance with the Boussinesq approximation.

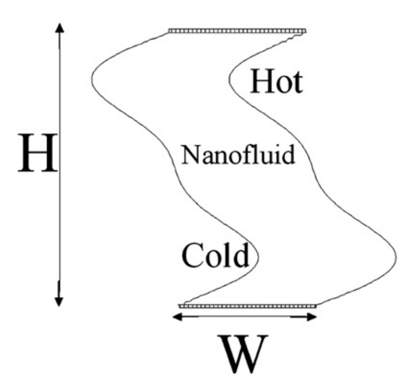

Fig. 1. Physical model of the problem.