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Natural convection heat transfer in a nanofluid-filled cavity with double sinusoidal wavy walls of various phase deviations

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ABSTRACT

In the present study, a new 2D quarter-circular enclosure with two sinusoidal wavy walls and two straight walls was proposed. Natural convection heat transfer in such cavities filled with various kinds of nanofluids was investigated and the phase deviation between two sinusoidal wavy walls was paid special attention. With the given shape of inner wall, the effect of shape regulation of the outer wavy wall was studied by a combined Finite volume method (FVM) and response surface method (RSM) method. Sinusoidal amplitude of outer wall (A) and phase deviation (γ) between the inner and outer walls were found to have significant effects on surface heat transfer coefficient h. The isothermal lines deform and fluctuate much more intensively with the increase of γ. RSM optimization manifested that the highest h appears at $A = 0.11$ and $\gamma = 1.77$ rad for water-Ag nanofluid. In the optimal enclosure, the surface heat transfer coefficient increases as the volume fraction of nanofluid increases. With the increasing of Ra, mass flow rate increases greatly. Water-Ag, water-CuO, water-Al_2O_3, water-TiO_2 nanofluids have been studied and it shows that water-Ag nanofluid has higher surface heat transfer coefficient than the others. For the cavity with double sinusoidal wavy walls, a periodical fluctuation of local Nusselt number at different locations of the outer wavy wall has been found and the net result is that the outer wall Nusselt number is evidently larger than that with only single sinusoidal wavy wall.

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1. Introduction

Natural convection heat transfer in a cavity induced by temperature and density gradients has found various promising applications such as in electronic devices, aerospace and automotive industry [1–4]. The physics of natural convection in cavities (circular, rectangular, etc.) has many applications especially in solar collectors, in special design of two-walled windows. It is also widely applied in heat exchanger, caliduct, nuclear reactor cooling pipes and so on. Therefore, enhancing the heat transfer efficiency in cavity is the key issue for these applications. Nanofluids, or nanoparticle suspensions, have attracted increasing attention in recent years for their excellent performance compared to its base liquid when applied in heat and mass transfer [5–7]. In this respect, replacing of the initial pure liquid in cavity by an appropriate nanofluid has been widely attempted and it is expected that the addition of the nanoparticles could significantly increase the thermal conductivity, Nusselt number and surface heat transfer coefficient of the working fluid in the designed cavity.

Kefayati et al. have investigated in detail natural convection heat transfer in nanofluid using Lattice Boltzmann Method [8–13]. Study on turbulent natural convection in tall enclosures using Cu/Water nanofluid using Lattice Boltzmann Method shows that the increment of the aspect ratio causes heat transfer to decline in different Rayleigh numbers. The effects of a magnetic field on natural convection flow in filled long enclosures with Cu/water nanofluid have also been analyzed by lattice Boltzmann method [9]. It shows that heat transfer decreases with the growth of the aspect ratio but this growth causes the effect of the nanoparticles to increase. Kefayati et al. studied the two-dimensional steady mixed convection in a square enclosure with differentially heated sidewalls [13]. Heat transfer and entropy generation on laminar natural convection of non-Newtonian nanofluids in a porous square cavity have been analyzed by Finite Difference Lattice Boltzmann Method (FDLBM) [14]. Results indicated that heat transfer and different irreversibilities enhance as Rayleigh number increases. The enhancement of the volume fraction augments heat transfer and the entropy generations due to heat transfer and fluid friction. Natural convection and entropy generation of non-Newtonian nanofluid have also been investigated using the Finite Difference Lattice Boltzmann method (FDLBM) [15]. The total

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Nomenclature

a	amplitude (m)
A	A = 2A′ for convenience
A'	dimensionless amplitude
C_p	heat capacity (J/kg K)
F	total force acting on nanoparticle (N)
g	gravitational acceleration (m/s^2)
h	surface heat transfer coefficient (convection coefficient) (W/m^2 K)
I	unit vector
k	thermal conductivity (W/m K)
m	mass (kg)
N	number of sinusoidal undulations
Nu	Nusselt number
Pr	Prandtl number
r	radius of spherical nanoparticle (m)
Ra	Rayleigh number
S_p	source term
t	time (s)
T	temperature (K)
v	velocity (m/s)

Greek symbols

τ	stress tensor (Pa)
B	thermal expansion coefficient (K^{-1})
γ	phase deviation (rad)
ζ	Rotation angle with respect to horizontal plane (°)
φ	volume fraction
ρ	Density (kg/m^3)
v	kinematic viscosity (m^2/s)
μ	shear viscosity (Pa s)

Subscripts

ave	average
c	cold wall
h	hot wall
in	inner wall
l	pure water
loc	local
p	particle
v	virtual mass
out	outer wall

entropy generation increases as the buoyancy ratio number augments. It was shown that the increase in the Brownian motion and Thermophoresis parameters enhances the total irreversibility.

Magneto-hydrodynamic(MHD) flow has also been given particular attention [16–20]. Khan et al. studied the shape effect of nanoparticle on heat transfer in magneto-hydrodynamic flow [16]. It is noticed that the temperature of the fluid is maximum for the platelet-shaped particles followed by the cylinder- and brick-shaped particles. Magneto-hydrodynamic effects are incorporated along with the passive control model of nanofluids that also takes into account the Brownian motion and thermophoresis effects in their another study [17]. Kefayati investigated the effect of a magnetic field on natural convection flow in a nanofluid-filled cavity with sinusoidal temperature distribution on one side wall [19]. He also simulated heat transfer and entropy generation of MHD natural convection of non-Newtonian nanofluid in an enclosure [20]. It is noted that the augmentation of the power-law index causes heat transfer to drop in the absence of the magnetic field, by contrast, the heat transfer increases with the rise of power-law index in the presence of the magnetic field. Besides, Nanofluid heat transfer characteristics have been studied when it flow in different channels and cavities [21,22]. Khan et al. studied heat transfer effects of carbon nanotubes suspended nanofluid flow in a channel with non-parallel walls [21]. They also conducted numerical investigation for three dimensional squeezing flow of nanofluid in a rotating channel with lower stretching wall [22]. We have employed a response surface methodology (RSM) combined with FEM methods to find an optimal performance for a circular-wavy cavity (CWC) filled by nanofluid under the natural convection heat transfer condition [23]. The results show that the effect of Lewis number on Nusselt number can be considered significant only for the high buoyancy ratio numbers. As for the geometry of the cavity, natural convection in circular-wavy cavity has been studied by Sheikholeslami et al. [24]. Sheikholeslami studied the heat transfer characteristics when the inner wall amplitude is 0.2 and the undulation number is 2. By using RSM it is found that the optimal amplitude of 0.3 and undulation number of 3 for such enclosure. Sheremet et al. investigated the natural convective heat transfer and nanofluid flow in a cavity with top wavy wall and corner heater. It was found that nanoparticle volume fraction essentially affects both fluid flow and heat transfer while undulation number only significantly changes the heat transfer rate [25]. Further study of such kind of enclosure was conducted by Motlagh et al. using Buongiorno's two-phase model [26]. It was found that the inclination of such enclosure can greatly enhance the Nusselt number. Buongiorno's two-phase model is also used by Kefayati et al. in mixed convection [27]. Moreover, Esfandiary et al. investigated natural convection of Al_2O_3-water nanofluid in an inclined enclosure considering the effect of Brownian motion and thermophoresis and the highest value for Nusselt number has been achieved when the inclination angle of the cavity is 30° [28].

In spite of many studies on natural convection heat transfer of nanofluids in various cavities, more numerical and experimental investigations on cavity of various geometries are still needed considering the very complicated conditions and rigorous requirements during their practical applications [27–29]. Besides the work introduced above, Rostami et al. also found that the Nusselt number for the wavy micro-channel is larger than that for flat walls micro-channels [30]. There is an optimal geometry for wavy-walls micro-channels which leads to the maximum Nusselt number. Deng et al. studied natural convection in a rectangular enclosure with sinusoidal temperature distributions on both side walls [31]. The results showed that the natural-convection heat transfer in enclosures with sinusoidal temperature distributions on both walls is superior to that with the sinusoidal temperature distribution only on one side. In their study, phase deviation of the sinusoidal temperature distributions on the two side walls are also taken into consideration and found to be crucial for the enhancement of heat transfer of the cavity. Alsabery et al. have investigated the conjugate natural convection in a square cavity filled with nanofluid which has sinusoidal temperature variations on both horizontal walls [32]. They found that the streamlines, isotherms and heatlines can be significantly affected by phase deviation of two sinusoidal temperature profiles. The heat transfer performance at outer wall can be enhanced by simply changing the phase deviation of temperature distribution at two walls without increasing the total volume of cavity. As mentioned above, circular-wavy cavity (CWC) has been studied by Sheikholeslami et al. [24] and us [23] and the significantly improved heat transfer performance has been achieved over such geometry. In our previ-

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