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Heat transfer and entropy generation of natural convection in nanofluid-filled square cavity with partially-heated wavy surface

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ABSTRACT

A numerical investigation is performed into the heat transfer performance and entropy generation of natural convection in a partially-heated wavy-wall square cavity filled with Al_2O_3–water nanofluid. The simulations focus specifically on the effects of the nanoparticle volume fraction, the Rayleigh number and the wavy-surface geometry parameters on the mean Nusselt number, total entropy generation and Bejan number. The results show that the mean Nusselt number increases and the total entropy generation decreases as the volume fraction of Al_2O_3 nanoparticles increases. By contrast, the mean Nusselt number reduces and the total entropy generation increases as the amplitude and wavelength of the wavy-surface increase. Moreover, the Bejan number increases with an increasing amplitude and increasing wavelength of the wavy-surface. Finally, for all values of the Rayleigh number, the Nusselt number increases and the entropy generation reduces as the peak in the wavy surface approaches the horizontal center-plane of the cavity. Overall, the results presented in this study provide a useful source of reference for enhancing the natural convection heat transfer performance in partially-heated wavy-wall cavities while simultaneously reducing the entropy generation.

1. Introduction

Natural convection in cavities has many important engineering applications, including electronic cooling devices, heat exchangers, MEMS devices, electric machinery, solar energy collectors, and so on [1]. However, natural convection has a poor heat transfer performance in confined spaces since conventional working fluids (e.g., water, oil and ethylene glycol) have a low thermal conductivity. Accordingly, the problem of improving the heat transfer effect in such environments has attracted significant attention in the literature. It was shown in [2] that the heat transfer performance of traditional working fluids can be improved via the addition of metallic nanoparticles with a high thermal conductivity (e.g., Al_2O_3, Cu or TiO_2). Note that the mixture is called to nanofluid. Many researchers have investigated the problem of natural convection in square/rectangular cavities filled with nanofluids [3–12]. In general, the results have shown that the heat transfer performance depends primarily on the type of nanoparticles added to the working fluid. However, for all nanoparticles, the heat transfer performance improves with an increasing nanoparticle addition and an increasing Rayleigh number. In addition, for a rectangular cavity, the heat transfer effect is enhanced as the aspect ratio is used appropriately.

The problem of natural convection heat transfer in partially-heated cavities is important in many practical applications, such as the cooling of buildings or flush-mounted electronic heaters. Oztop and Abu-Nada [13] investigated the natural convection heat transfer performance of different nanofluids in a cavity heated only along the left vertical wall. The results showed that for all of the considered nanofluids, the mean Nusselt number increased with an increasing Rayleigh number and an increasing volume fraction of nanoparticles. Moreover, it was shown that the heat transfer performance improved as the height of the heater was increased. Ghasemi and Aminossadati [14] studied the natural convection phenomenon in a nanofluid-filled square cavity containing an oscillating heat source. The results showed that the optimum position of the heat source varied as a function of the Rayleigh number. Sheikhzadeh et al. [15] examined the natural convection heat transfer performance of Cu-water nanofluid in a square cavity with partially-active side walls. It was shown that for a given Rayleigh number, the mean Nusselt number could be optimized by adjusting the locations of the active regions of the cavity walls. Jmai et al. [16] investigated the natural convection phenomenon

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Nomenclature

Be	Bejan number $\left(Be = \frac{S^*_{l,h}}{S^*_l}\right)$
C_p	specific heat (J kg^{-1} K^{-1})
Ec	Eckert number $\left(Ec = \frac{\alpha^2_{bf} k_{bf}}{W^3 C_{p,bf} q''_0}\right)$
f	generalized variable
g	gravitational acceleration (m s^{-2})
h	convection heat transfer coefficient (W m^{-2} K^{-1})
H	height of cavity (m)
J	Jacobian factor
k	thermal conductivity (W m^{-1} K^{-1})
l_w	length of wavy surface (m)
$\vec{n}$	normal vector
Nu	Nusselt number $\left(Nu = \frac{hW}{k_{bf}}\right)$
Nu_m	mean Nusselt number $\left(Nu_m = \frac{1}{l^*_w} \int_{y^*_p - \lambda^*/2}^{y^*_p + \lambda^*/2} Nu d\eta\right)$
P	pressure (N m^{-2})
Pr	Prandtl number $\left(\Pr = \frac{\nu_{bf}}{\alpha_{bf}}\right)$
q''_0	heat flux (W m^{-2})
Ra	Rayleigh number $\left(Ra = \frac{g\beta_{bf} W^3 (q''_0 W)/k_{bf}}{\nu_{bf}\alpha_{bf}}\right)$
S_l	local entropy generation ($S_l = S_{l,h} + S_{l,f}$)
$S_{l,h}$	local entropy generation due to heat transfer irreversibility
$S_{l,f}$	local entropy generation due to fluid friction irreversibility
S_t	non-dimensional total entropy generation per unit volume
T	temperature (K)
T_L	low temperature (K)
T_r	parameter-estimated entropy generation $\left(T_r = \frac{T_L k_{bf}}{q''_0 W}\right)$
u, v	velocity components along x- and y-axes, respectively (m s^{-1})
U, V	velocity components along ξ- and η-axes in transformed coordinate system, respectively
$\vec{V}$	velocity vector (m s^{-1})
$\forall$	volume of cavity (m^3)
W	width of cavity (m)
x, y	x- and y-axis coordinates, respectively
y_p	distance between peak in wavy surface and lower flat cavity wall

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
α_w	amplitude of wavy surface
α_ϕ, β_ϕ, γ_ϕ	parameters of transformed coordinate system
β	thermal expansion coefficient, (K^{-1})
ϕ	nanoparticle volume fraction (%)
ξ, η	axes of transformed coordinate system
θ	dimensionless temperature $\left(\theta = \frac{T - T_L}{(q''_0 W)/k_{bf}}\right)$
λ	wavelength of wavy surface
μ	dynamic viscosity (N s m^{-2})
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})

Superscript

$*$	non-dimensional quantity

Subscripts

bf	base fluid
p	particle
nf	nanofluid
s	surface

within square cavities containing different water-based nanofluids and two partially-heated side walls. The results showed that the heat transfer performance was fundamentally dependent on the type of nanoparticles used and the location of the heat source on the two walls.

Besides using metallic nanoparticles, the heat transfer performance of traditional working fluids can also be enhanced through a careful design of the cavity geometry. For example, in many engineering applications (e.g., solar collectors, condensers in refrigerators, and so on), the heat transfer performance is improved by means of wavy surfaces. The literature contains many investigations into the natural convection heat transfer performance of traditional working fluids such as air or water in wavy-wall cavities [17–21]. Overall, the results show that the heat transfer performance 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 and Rayleigh number).

Recently, the problem of natural convection heat transfer in nanofluid-filled cavities with wavy surfaces has attracted increasing attention. Abu-Nada and Oztop [22] examined the natural convection heat transfer performance of Al_2O_3–water nanofluid in a square cavity bounded by wavy upper and lower surfaces with adiabatic conditions and left and right vertical surfaces with different constant temperatures. The results showed that the Al_2O_3 nanoparticles yielded a significant improvement in the mean Nusselt number compared to that achieved using a pure water working fluid. Moreover, it was shown that the geometry parameters of the wavy surfaces had a critical effect on the heat transfer performance. Cho et al. [23] investigated the natural convection heat transfer phenomenon in a nanofluid-filled cavity comprising vertical isothermal walls with a complex-wavy surface and flat upper and lower walls with adiabatic conditions. The results showed that the heat transfer performance was dependent on the wavy-surface geometry parameters and could be improved by increasing the volume fraction of nanoparticles.

All thermofluidic processes involve irreversibilities and therefore incur an efficiency loss. In practice, the extent of these irreversibilities can be measured by the entropy generation rate. In designing practical systems, it is desirable to minimize the rate of entropy generation so as to maximize the available energy [24–26]. Many researchers have studied the entropy generation due to natural convection in square/rectangular/wavy-wall cavities filled with air or water [27–36]. Overall, the results have shown that the rate of entropy generation increases as the Rayleigh number and irreversibility distribution ratio increase. Moreover, for given values of the Rayleigh number and irreversibility distribution ratio, the entropy generation rate is determined by the heat transfer irreversibility and/or fluid friction irreversibility.

The problem of entropy generation in square or wavy-wall cavities filled with nanofluids has attracted significant attention in recent years. Shahi et al. [37] investigated the entropy generation induced by natural convection heat transfer in a square cavity containing Cu–water nanofluid and a protruding heat source. The results showed that the Nusselt number increased and the entropy generation reduced as the nanoparticle volume fraction was increased. In addition, it was shown that the heat transfer performance could be maximized and the entropy generation minimized by positioning the heat source on the lower cavity wall. Esmaeilpour and Abdollahzadeh [38] examined the natural convection heat transfer behavior and entropy generation rate in a Cu–water