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Natural convection and entropy generation of Al_2O_3–water nanofluid in an inclined wavy-wall cavity

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ABSTRACT

A numerical investigation is performed into the natural convection heat transfer performance and entropy generation of Al_2O_3–water nanofluid in an inclined wavy-wall cavity. The simulations focus specifically on the effects of the cavity inclination angle, nanoparticle volume fraction, Rayleigh number and wave amplitude of the wavy surface on the flow streamlines, isotherm distribution, Nusselt number and entropy generation within the cavity. The range of the studied parameters is as follows: cavity inclination angle from 0° to 360°, nanoparticle volume fraction from 0% to 4%, Rayleigh number from 10^2 to 10^6, wavy-surface amplitude from 0.0 to 0.5. The results show that the inclination angle has a strong effect on the flow streamlines, isotherms, local entropy generation and heat transfer performance; particularly at higher Rayleigh numbers. In addition, it is shown that for a given Rayleigh number and cavity inclination angle, the mean Nusselt number increases and the total entropy generation decreases as the volume fraction of Al_2O_3 nanoparticles increases. Finally, it is shown that for a constant Rayleigh number and inclination angle, the Nusselt number in a wavy-surface cavity is higher than that in a regular cavity, while the total energy generation is lower.

1. Introduction

The phenomenon of natural convection heat transfer in regular cavities (e.g., square or rectangular cavities) has attracted enormous attention in the literature due to its many important applications in engineering systems, including electronic cooling devices, heat exchangers, MEMS devices, electric machinery, and so on [1–6]. Overall, the results have shown that the flow and geometry parameters (e.g., the Rayleigh number, Prandtl number, and cavity aspect ratio) have a significant effect on the flow characteristics and heat transfer behavior in the cavity. Natural convection heat transfer in inclined cavities also has many important applications, such as solar energy collectors, double-glazed windows, car batteries, electronic cooling systems, and crystal growth [7]. Thus, the literature also includes many investigations into the flow field characteristics and heat transfer performance of natural convection in inclined cavities [8–12]. In general, the results have shown that the optimal heat transfer performance occurs at a specific inclination angle of the cavity.

Wavy-surface geometry structures are used to improve the heat transfer performance within cavities in many engineering applications, including cooling systems for microelectronic devices, heat exchangers, solar collectors, underground cable systems, and so forth. Previous studies have shown that the heat transfer performance in such cavities depends strongly on both the wavy-surface geometry parameters (e.g., the waveform, wave amplitude and wavelength) and the flow conditions (e.g., the Grashof number and the Rayleigh number) [13–17]. In addition, for an inclined cavity, the heat transfer performance is affected not only by the wavy-surface geometry parameters and flow conditions, but also the inclination angle [18–21].

Besides using wavy-surface geometry structures, the heat transfer performance in cavities can also be enhanced by changing the thermophysical properties of the working fluid. Many studies have shown that the thermal conductivity of traditional working fluids (e.g., air, water and oil) can be improved through the addition of metallic nanoparticles [22–27]. Thus, the problem of natural convection heat transfer in regular cavities filled with nanofluids has attracted significant interest in recent years [28–32]. It has been shown that the heat transfer performance depends primarily on the type of nanoparticle added to the working fluid. In addition, the results have shown that the heat transfer performance generally increases with an increasing nanoparticle volume fraction.

Recently, many researchers have investigated the problem of natural convection in regular nanofluid-filled inclined cavities and nanofluid-filled wavy-surface cavities. For example, Gasemi and Aminossadati [33] performed a numerical investigation into

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Nomenclature

Be	Bejan number, $Be = \frac{S^*_{l,h}}{S^*_l}$
C_p	specific heat, J kg^{-1} K^{-1}
f	generalized variable
g	gravitational acceleration, ms^{-2}
h	convection heat transfer coefficient, W m^{-2} K^{-1}
H	height of cavity, m
i, j	unit components in x- and y-directions, respectively
J	Jacobian factor
k	thermal conductivity, W m^{-1} K^{-1}
l^*_w	non-dimensional length of wavy surface
$\vec{n}$	normal vector
Nu	Nusselt number, $Nu = \frac{hW}{k_{bf}}$
Nu_m	mean Nusselt number, $Nu_m = \frac{1}{l^*_w}\int_0^H Nu d\eta$
p	pressure, N m^{-2}
p_0	reference pressure, N m^{-2}
Pr	Prandtl number, $Pr = \frac{\mu_{bf}}{\alpha_{bf}\rho_{bf}}$
q	heat flux, W m^{-2}
Ra	Rayleigh number, $Ra = \frac{g\beta_{bf}W^3(T_H - T_L)}{(\mu_{bf}/\rho_{bf})\alpha_{bf}}$
S_l	local entropy generation
$S^*_{l,h}$	non-dimensional local entropy generation due to heat transfer irreversibility
$S^*_{l,f}$	non-dimensional local entropy generation due to fluid friction irreversibility
S_t	non-dimensional total entropy generation per unit volume
T	temperature, K
T_0	mean temperature, K
T_H, T_L	high temperature and low temperature, respectively, K
u, v	velocity components along x- and y-axes, respectively, m s^{-1}
$\vec{V}$	velocity vector, m s^{-1}
$\bar{V}^*$	dimensionless volume of cavity, m^3
U, V	velocity of transformed coordinates along ξ- and η-axes, respectively
W	width of cavity, m
x, y	coordinates in x- and y-axis directions, respectively

Greek symbols

α	thermal diffusivity, m^2 s^{-1}
α_w	amplitude of wavy surface
β	thermal expansion coefficient, K^{-1}
ϕ	nanoparticle volume fraction, %
ξ, η	axes of transformed coordinates
θ	dimensionless temperature
ϑ	inclination angle of cavity, °
μ	dynamic viscosity, Ns m^{-2}
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, Kg m^{-3}
Φ	irreversibility distribution ratio, $\Phi = \frac{T_0\mu_{nf}}{k_{nf}}\left[\frac{\alpha_{bf}}{W(T_H - T_L)}\right]^2$

Superscript

*	non-dimensional quantity

Subscripts

bf	base fluid
p	nanoparticle
nf	nanofluid
w	wall

natural convection heat transfer in an inclined square cavity filled with CuO–water nanofluid. Ogut [34] studied the natural convection heat transfer of water-based nanofluids in an inclined square cavity with a partially-heated side wall. Bouhalle and Abbassi [35] analyzed the heat transfer behavior and fluid flow characteristics of natural convection in an inclined cavity filled with CuO–water nanofluid, heated from one side, and cooled from the ceiling. Abu-Nada and Oztop [36] examined the natural convection behavior of Al_2O_3–water nanofluid in a cavity with differentially-heated wavy surfaces. Kashani et al. [37] examined the effects of the surface waviness and nanoparticle dispersion on the solidification of Cu–water nanofluid in a vertical cavity with differentially-heated wavy-surface side walls. Nikfar and Mahmoodi [38] analyzed the natural convection behavior in an Al_2O_3–water nanofluid-filled square cavity with wavy side walls maintained at constant high and low temperatures, respectively. Esmaeilpour and Abdollahzadeh [39] examined the natural convection heat transfer performance and entropy generation rate in a Cu–water nanofluid-filled cavity comprising two vertical wavy surfaces with different temperatures and two horizontal flat surfaces with thermal insulation. Cho et al. [40] investigated the natural convection heat transfer performance of Al_2O_3–water nanofluid in a wavy-wall cavity in which the left and right walls had a complex-wavy geometry and were maintained at high and low temperatures, respectively. In general, the results presented in [33–40] showed that the heat transfer performance is significantly enhanced when nanofluids are used to accomplish heat transfer.

To optimize an energy system, it is necessary to minimize the entropy generation caused by heat transfer irreversibility and fluid friction irreversibility [41,42]. The literature contains many investigations into the entropy generation rate in air/water-filled square/rectangle cavities [43–47] or inclined cavities filled with air/water [48–52]. The results have shown that the entropy generation is minimized when the cavity is inclined at a particular angle. In recent years, the problem of entropy generation in nanofluid-filled square/rectangle cavities has also attracted significant attention [53–56]. Overall, the results have shown that for given geometry and flow parameters, nanofluid-filled cavities have a lower entropy generation than base fluid-filled cavities. In addition, the entropy generation rate within wavy-wall cavities filled with nanofluid has also been investigated in several recent studies [39,57–59]. The effect of wavy geometry parameters on the entropy generation was studied.

As discussed above, the problem of heat transfer in inclined cavities is of interest in many practical engineering applications. Many studies have shown that the heat transfer performance can be improved by using wavy-surface geometry structures or nanofluids. However, the literature contains very few investigations into natural convection heat transfer within nanofluid-filled inclined cavities with wavy surfaces. In addition, to optimize an energy system, the entropy generation must be reduced. Accordingly, the present study investigates the natural convection heat transfer performance and entropy generation behavior in an inclined wavy-wall cavity filled with Al_2O_3–water nanofluid. In modeling the cavity, the left and right walls are assumed to have a complex wavy surface and a high and low temperature, respectively, while the upper and lower walls are assumed to be flat and insulated. The flow behavior and heat transfer characteristics in the cavity are assumed to be governed by the continuity equation, momentum equation, energy equation