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Natural convection heat transfer and entropy generation in wavy-wall enclosure containing water-based nanofluid

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ABSTRACT

A numerical investigation is performed into the natural convection heat transfer characteristics and entropy generation of water-based nanofluids in an enclosure bounded by wavy vertical walls and flat upper and lower surfaces. In performing the analysis, it is assumed that the left wall is heated by a constant heat flux while the right wall is maintained at a constant low temperature. In addition, the upper and lower walls are both assumed to be insulated. The analysis considers three different nanofluids, namely Cu–water, Al_2O_3–water and TiO_2–water. The governing equations are modeled using the Boussinesq approximation and are solved using the finite-volume numerical method. The analysis examines the effects of the nanoparticle volume fraction, the type of nanofluid, the Rayleigh number and the wavy surface geometry parameters on the mean Nusselt number and total entropy generation. The results show that for all values of the Rayleigh number considered in the present study ($Ra = 10^4{\sim}10^6$), the mean Nusselt number increases and the total entropy generation reduces as the volume fraction of nanoparticles increases. In addition, it is shown that the Cu–water nanofluid yields the best heat transfer performance and the lowest total entropy generation of the three nanofluids. Finally, it is shown that for a given nanofluid, the mean Nusselt number can be maximized and the total entropy generation minimized via an appropriate tuning of the wavy surface geometry parameters. Overall, the results presented in this study provide a useful source of reference for enhancing the natural convection heat transfer performance in wavy-wall enclosures while simultaneously reducing the entropy generation.

1. Introduction

Natural convection heat transfer in regular enclosures (e.g., square or rectangular enclosures) has long been of interest in developing engineering systems such as electronic cooling devices, heat exchangers, MEMS devices, electric machinery, solar energy collectors, and so on [1]. However, the problem of natural convection heat transfer in enclosures with irregular wall surfaces has attracted growing interest in recent years due to the potential for an enhanced heat transfer performance [2–6]. Overall, the results have shown that the heat transfer characteristics of fluids confined within enclosures with irregular wall surfaces depend on both the flow conditions and the geometry parameters.

The studies presented in [2–6] all take water or air as the working fluid. However, such fluids have a low thermal conductivity, and thus the heat transfer performance is inevitably limited. Choi [7] showed that the heat transfer performance can be significantly improved by adding metallic nanoparticles with a high thermal conductivity to the working fluid (e.g., water) in order to form so-called nanofluids. The literature contains many investigations into the natural convection phenomenon in regular enclosures containing nanofluids. For example, Khanafer et al. [8] investigated the buoyancy-driven heat transfer enhancement obtained in a two-dimensional square enclosure filled with Cu–water nanofluid. The results showed that the heat transfer performance improves as the volume fraction of Cu nanoparticles in the base fluid is increased. Hwang et al. [9] examined the same problem for a rectangular cavity filled with Al_2O_3–water nanofluid. Their results have also shown that nanofluid can effectively enhance the heat transfer effect. Oztop and Abu-Nada [10] and Sheikhzadeh et al. [11] examined the problem of natural convection heat transfer in partially-heated enclosures containing different nanofluids. The results showed that the flow and temperature fields are dependent on the length and location of the heat source. Ghasemi and Aminossadati [12] and Abu-Nada and Oztop [13] investigated the natural convection heat transfer performance of nanofluids in an inclined enclosure, while Ogut [14] and Kahveci [15] examined the heat transfer performance of various buoyancy-driven nanofluids in a differentially-heated tilted enclosure. In general, the results showed that the inclination angle of the enclosure has a significant

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Nomenclature

C_p	specific heat ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
Ec	Eckert number $\left[Ec = \frac{\alpha_{bf}^2 k_{bf}}{W^3 C_{p,bf} q_0''}\right]$
f	generalized variable
g	gravitational acceleration ($\mathrm{m\,s^{-2}}$)
h	convection heat transfer coefficient ($\mathrm{W\,m^{-2}\,K^{-1}}$)
J	Jacobian factor
k	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
l_w	length of wavy surface (m)
n	normal direction
Nu	Nusselt number $\left[Nu = \frac{hW}{k_{bf}}\right]$
Nu_m	mean Nusselt number $\left[Nu_m = \frac{1}{l_w^*}\int_0^{\lambda^*} Nu d\eta\right]$
p	pressure ($\mathrm{N\,m^{-2}}$)
Pr	Prandtl number $\left[Pr = \frac{\nu_{bf}}{\alpha_{bf}}\right]$
q_0''	heat flux ($\mathrm{W\,m^{-2}}$)
Ra	Rayleigh number $\left[Ra = \frac{g\beta_{bf}W^3(q_0''W)/k_{bf}}{\nu_{bf}\alpha_{bf}}\right]$
$\dot{S}_l$	local entropy generation
$\dot{S}_t$	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 ($\mathrm{m\,s^{-1}}$)
U, V	velocity components along ξ- and η-axes in transformed coordinate system, respectively
$\vec{V}$	velocity vector ($\mathrm{m\,s^{-1}}$)
$\forall$	volume of enclosure ($\mathrm{m^3}$)
W	width of enclosure (m)
x, y	coordinates in x- and y-axis directions, respectively

Greek symbols

α	thermal diffusivity ($\mathrm{m^2\,s^{-1}}$)
α_1, α_2	amplitude of wavy surface
α_ϕ, β_ϕ, γ_ϕ	parameters of transformed coordinate system
β	thermal expansion coefficient, ($\mathrm{K^{-1}}$)
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 ($\mathrm{N\,s\,m^{-2}}$)
ν	kinematic viscosity ($\mathrm{m^2\,s^{-1}}$)
ρ	density ($\mathrm{kg\,m^{-3}}$)
Φ	viscous dissipation function

Superscript

$*$	non-dimensional quantity

Subscripts

bf	base fluid
p	particle
nf	nanofluid
s	surface

effect on the flow behavior and heat transfer performance of the nanofluid.

In optimizing the thermal systems, it is necessary to minimize the entropy generation [16–18]. Yilbas et al. [19] examined the natural convection performance and entropy generation in a square cavity with different top and bottom wall temperatures. Erbay et al. [20] and Magherbi et al. [21] investigated the transient entropy generation in square enclosures with completely- or partially-heated left-side walls, respectively, and a completely cooled right-side wall. Ilis et al. [22] examined the effect of the aspect ratio on the entropy generation in a rectangular cavity with a high-temperature left-side wall and a low-temperature right-side wall. Dagtekin et al. [23] studied the natural convection characteristics and entropy generation in a Γ-shaped enclosure containing a heated step. Mukhopadhyay [24] analyzed the entropy generation caused by natural convection in a square enclosure heated from below by two isoflux sources. Mahmud et al. [25,26] examined the natural convection heat transfer characteristics and entropy generation in wavy-walled enclosures having left and right walls with different temperatures. The studies presented in [19–26] considered water or air as the working fluid and the results showed that for given values of the Rayleigh number, the entropy generation is determined primarily by the heat transfer irreversibility or / and the fluid friction irreversibility. Recently, Shahi et al. [27] investigated the entropy generation induced by natural convection heat transfer in a square cavity containing a nanofluid and heated by a protruding heat source. It was shown that the Nusselt number increased and the entropy generation reduced as the nanoparticle volume fraction was increased. Furthermore, the results showed that the heat transfer performance could be maximized and the entropy generation minimized by positioning the heat source on the lower wall of the enclosure.

The natural convection heat transfer characteristics and entropy generation in regular enclosures filled with conventional working fluids (i.e., air or water) or nanofluids are well-understood. However, the effects of natural convection heat transfer on the entropy generation in irregular enclosures containing nanofluids are less clear. Accordingly, the present study performs a numerical investigation into the natural convection heat transfer characteristics and entropy generation within a wavy-wall enclosure filled with various water-based nanofluids. In simulating the flow and temperature fields within the enclosure, the left and right walls are assumed to have a wavy surface, while the upper and lower walls are assumed to be flat. In addition, the left wall is assumed to be heated by a constant heat flux, the right wall is maintained at a constant low temperature, and the upper and lower walls are both insulated. In performing the analysis, the governing equations are modeled using the Boussinesq approximation and are solved using the finite-volume numerical method. The simulations focus specifically on the effects of the nanoparticle volume fraction, the nanofluid type, the Rayleigh number and the wavy-wall geometry parameters on the flow streamlines, isotherm distribution, mean Nusselt number and local and total entropy generation within the enclosure. The results provide a useful source of reference for the design and development of efficient heat transfer systems with minimal energy loss.

2. Mathematical formulation

Fig. 1 illustrates the wavy-wall enclosure considered in the present study. As shown, the enclosure has a width W and a height λ The related mathematical formulations and numerical solution procedure are described in the following.

2.1. Governing equations

The flow behavior and heat transfer characteristics in the enclosure shown in Fig. 1 are governed by the continuity, momentum