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Heat transfer and entropy generation of mixed convection flow in Cu-water nanofluid-filled lid-driven cavity with wavy surface

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ABSTRACT

A numerical investigation is performed into the heat transfer effect and associated entropy generation of mixed convection flow in a lid-driven wavy-wall cavity filled with Cu-water nanofluid. In modeling the cavity, it is assumed that the left wall has a flat surface and a constant high temperature, while the right wall has a wavy surface and a constant low temperature. In addition, the left wall moves in the vertical direction, while the right wall remains stationary. Finally, the upper and lower walls are both flat and insulated. The simulations focus on the effects of the flow parameters and wavy-wall geometry conditions on the Nusselt number, entropy generation rate and Bejan number. In addition, the energy flux vectors are used in order to clarify the heat energy transport process. The results show that the mean Nusselt number and total entropy generation increase as the Richardson number, nanoparticle volume fraction and Reynolds number increase. The Bejan number reduces as the irreversibility distribution ratio increases, but increases as the Reynolds number increases. The mean Nusselt number and total entropy generation both increase as the amplitude of the wavy surface increases. Finally, an optimal heat transfer effect is obtained given an appropriate wavelength of the wavy surface depending on the Richardson numbers.

1. Introduction

Mixed convection flow and the associated heat transfer behavior in lid-driven cavities have numerous practical applications, including solar energy collectors, electronic device cooling, nuclear reactors, food processing, drying technologies, chemical processing, lubrication systems, crystal growth, and microchip cooling [1–3]. As a result, the problem of mixed convection flow in lid-driven cavities with regular surfaces has attracted significant attention in the literature [4–8]. Overall, the results have shown that the fluid flow behavior and heat transfer performance in such cavities are strongly dependent on the Richardson number and the shear-driving and buoyancy-driving directions.

Many researchers have shown that the heat transfer effect in lid-driven cavities can be improved by replacing the regular surfaces with wavy-wall surfaces. For example, Al-Amiri et al. [9] showed that for a lid-driven square cavity with a sinusoidal wavy bottom surface, the mean Nusselt number increased with an increasing Reynolds number and a higher amplitude of the wavy surface. In addition, it was shown that the optimal heat transfer performance was obtained under low Richardson number conditions using a wavy surface with two undulations. Nasrin [10] also investigated the problem of mixed convection heat transfer in a lid-driven square cavity with an undulating bottom surface. The results showed that the heat transfer performance improved with a larger wavy surface amplitude, a greater number of waves, and a higher cavity aspect ratio. Mekroussi et al. [11] examined the effects of the inclination angle on the mixed convection heat transfer performance in an inclined lid-driven cavity with a sinusoidal wavy bottom surface. It was shown that the mean Nusselt number improved with an increasing number of undulations or a greater inclination angle. Najafi et al. [12] also examined the effects of the inclination angle on the mixed convection heat transfer performance in a lid-driven cavity with an undulating base surface. The results showed that the local Nusselt number increased as the cavity was rotated in the clockwise direction or the aspect ratio of the cavity was reduced.

Traditional engineering systems use pure working fluids such as air, water or ethylene glycol for cooling purposes. However, such fluids have a low thermal conductivity, and therefore achieve only a limited heat transfer performance. Das et al. [13] showed that the heat transfer effect can be improved by adding metallic nanoparticles with a high thermal conductivity to the working fluid in order to form so-called nanofluids. Many studies have demonstrated the effectiveness of nanofluids in improving the heat transfer

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Nomenclature

Be	Bejan number, $Be = S^*_{l,h}/S^*_l$
C_p	specific heat, J kg^{-1} K^{-1}
E	energy flux vector
f	generalized variable
g	gravitational acceleration, ms^{-2}
Gr	Grashof number, $Gr = g\beta_{bf}(T_H - T_L)W^3/\nu_{bf}^2$
h	convection heat transfer coefficient, W m^{-2} K^{-1}
H	heat function
i, j	unit vectors in x- and y-directions
J	Jacobian factor
k	thermal conductivity, W m^{-1} K^{-1}
$\vec{n}$	normal vector
Nu	Nusselt number, $Nu = hW/k_{bf}$
Nu_m	mean Nusselt number, $Nu_m = \frac{1}{\lambda^*}\int_0^{\lambda^*} Nu d\eta$
p	pressure, N m^{-2}
Pr	Prandtl number, $Pr = \nu_{bf}/\alpha_{bf}$
Ri	Richardson number, $Ri = Gr/Re^2$
Re	Reynolds number, $Re = \rho_{bf}V_0W/\mu_{bf}$
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
S_ϕ	source term
T	temperature, K
T_0	mean temperature, K
T_H, T_L	high temperature and low temperature, K
u, v	velocity components along x- and y-axes, respectively, ms^{-1}
U, V	velocity components along ξ - and η-axes in transformed coordinate system, respectively
$\vec{V}$	velocity vector, ms^{-1}
V_0	lid-driving velocity, ms^{-1}
$\mathcal{V}^*$	dimensionless volume of cavity, m^3
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
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, $\theta = \frac{T - T_L}{T_H - T_L}$
λ	wavelength of wavy surface
μ	dynamic viscosity, N s m^{-2}
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
χ	irreversibility distribution ratio, $\chi = \frac{T_0\mu_{bf}}{k_{bf}}\left(\frac{V_0}{T_H - T_L}\right)^2$

Superscript

$*$	non-dimensional quantity

Subscripts

bf	base fluid
p	nanoparticle
nf	nanofluid
w	wall surface

performance of mixed convection in lid-driven cavities with regular surfaces [14–18]. The heat transfer performance of nanofluids in lid-driven cavities with wavy surfaces has also attracted growing interest in recent years. Arefmanesh et al. [19] showed that for the mixed convection of Al_2O_3-water nanofluid in a lid-driven square cavity with a wavy bottom wall, the heat transfer improved as the volume fraction of nanoparticles increased; particularly under lower Richardson numbers. Nasrin et al. [20,21] investigated the mixed convection heat transfer performance of CuO-water nanofluid in a double lid-driven cavity with vertical sawtooth wavy walls in the absence/presence of an internal heat source, respectively. The results showed that the flow patterns were increasingly perturbed and the heat transfer effect correspondingly improved as the quantity of nanoparticles added to the working fluid was increased. In addition, the flow behavior and heat transfer characteristics within the cavity were found to be strongly dependent on the Richardson number. Cho et al. [22] analyzed the mixed convection heat transfer performance of Cu-water, Al_2O_3-water and TiO_2-water nanofluids in a lid-driven wavy-wall cavity. The simulation results showed that the mean Nusselt number improved with an increasing volume fraction of nanoparticles and a higher Grashof number. In addition, it was shown that the optimal mean Nusselt number was obtained via an appropriate specification of the wavy surface geometry parameters. Abu-Nada and Chamkha [23] examined the mixed convection flow of CuO-water nanofluid in a lid-driven cavity with a wavy bottom wall, and showed that for all values of the Richardson number and wavy-surface geometry ratio, the use of nanoparticles resulted in a significant improvement in the heat transfer performance.

When analyzing thermofluidic systems, the flow streamlines and isotherms provide a useful understanding of the flow behavior and temperature distribution in the considered system. However, they do not fully explain the heat energy transport process. Thus, to better understand the heat energy flow path within the system, Kimura and Bejan [24] proposed a heatline visualization technique based on energy-analogs of the stream functions and streamlines used to visualize fluid flows. Many researchers have used the heatline technique to analyze the convection heat transfer behavior in cavities filled with nanofluids [25–29]. In a recent study, Hooman [30] extended the heatline visualization technique to produce a new tool for convection visualization based on energy flux vectors oriented tangentially to the heatline. Nayak et al. [31,32] showed that the energy flux vectors provide a complete explanation of the mixed convection heat transfer process in square and skewed enclosures.

In thermofluidic systems, irreversibilities inevitably occur and degrade the system efficiency. Bejan [33,34] showed that these irreversibilities can be quantified by the entropy generation rate. Thus, in practical systems, the entropy generation rate must be minimized in order to optimize the system performance. Mahian et al. [35] have reviewed the recent investigations on entropy generation in nanofluid flow of various geometries. Khorasanizadeh et al. [36] studied the entropy generation of Cu-water nanofluid mixed convection flow in a square cavity. The results revealed that the nanoparticles in the base fluid have a significant effect on the entropy generation. Nayak et al. [31,32,37] also investigated the entropy generation of Cu-water nanofluid in a lid-driven square cavity, and showed that the heat transfer and entropy generation rate both increased with an increasing volume fraction of nanopar-