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Entropy generation and natural convection of nanoparticle-water mixture (nanofluid) near water density inversion in an enclosure with various patterns of vertical wavy walls

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ABSTRACT

Entropy generation due to laminar natural convection of Cu–water nanofluid near the density maximum of water in a two-dimensional enclosure with various patterns of vertical wavy walls is investigated numerically. In order to study the nature of irreversibility in terms of entropy generation in the presence of nanoparticle near water density inversion, the second law of thermodynamics is applied. The governing equations are formulated using both the Boussinesq and non-Boussinesq homogenous models and solved on a non-uniform mesh using a pressure-based finite volume method. The calculations are performed for Ra number of 10^5, 10^6 and a range of nanoparticle volume fraction from 0 and 0.05. The results are presented and discussed in terms of streamlines, isotherms patterns, contours of local entropy generation, average Nusselt number and average entropy generation. It was found that both the density inversion and the presence of nanoparticles play a significant role in the flow field structure, heat transfer characteristics and entropy generation. It was concluded that the Boussinesq approximation gave rise to the higher average heat transfer rate and entropy generation as compared to non-Boussinesq approximation. In addition, the average Nusselt number and entropy generation were found to decrease as the volume fraction of nanoparticle increased. Finally, the formation of bi-cellular flow structure substantiates the effective role of density inversion of water in the free convection characteristics.

1. Introduction

Natural convection is an important heat transfer mechanism induced by density differences. It has received substantial attention in recent years due to its broad range of engineering applications such as domestic heating, solar ponds, solar collectors and food storage to name a few. Many researchers have attempted to explore the heat transfer enhancement approaches to optimize the thermal performance of the fluid-filled enclosures involving natural convection heat transfer. One of the significant deficiencies of the conventional heat transfer fluids such as water, oil, and ethylene glycol mixture is that they have an inherently poor thermal performance due to their low thermal conductivity. Various methods have been

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Nomenclature

A	aspect ratio, = H/W
C_p	specific heat at constant pressure (J/kg K)
C	constant
d_p	nanoparticle diameter (m)
g	gravitational acceleration components (m/s^2)
H	cavity height (m)
k	fluid thermal conductivity (W/m K)
L	cavity width (m)
M	molecular weight of the base fluid (kg)
N	Avogadro number = 6.022×10^{23} mol^{-1}
$\overline{Nu}$	average Nusselt number
p	pressure (kg/m s^2)
P	non-dimensional pressure
Pr	Prandtl number
Ra	Rayleigh number
$\dot{S}_l$	entropy generation
$\dot{S}_{l,a}$	non-dimensional local entropy generation
$\dot{S}_{T,a}$	non-dimensional total entropy generation
T	temperature (K)
u, v	velocity components (m/s)
U, V	non-dimensional velocities
x, y	Cartesian coordinates (m)
X, Y	non-dimensional Cartesian coordinates
W	average width of the cavity

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K^{-1})
θ	non-dimensional temperature
μ	Dynamic viscosity (Pa.s)
υ	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
ϕ	particle volume fraction
φ	irreversibility distribution ratio
λ	surface waviness
ζ	dimensionless time

Subscripts

c	cold
f	fluid
h	hot
nf	nanofluid
s	solid
0	reference value
$*$	Non-dimensional

developed to overcome this weakness. Nanotechnology offers great potential in this area and is already being widely used to great success. Recently, new heat transfer fluids, such as nanofluids (homogenous suspensions of nanoparticles in a base fluid), have proven to be highly promising in increasing the thermal performance of heat transfer devices due to their increased thermal conductivity and heat transfer area. The pioneering theoretical work on the new class of fluids, namely, high- thermal-conductivity nanofluids was carried out by Choi [1] in order to develop advanced heat transfer fluids with substantially higher conductivities. A numerical study on natural convection in a two-dimensional rectangular enclosure filled with copper–water nanofluid was conducted by Khanafer et al. [2]. It was found that the heat transfer rate increases with an increase in the nanoparticle volume fraction for different Grashof numbers. In contrast with the results of Khanafer, experimental results of Putra et al. [3] showed that dispersion of nanoparticle into pure fluid may lead to decrease in heat transfer. Natural convection heat transfer enhancement in a horizontal cylindrical annulus filled with nanofluids was investigated by Abu-Nada et al. [4] for a wide range of nanoparticle volume fractions and different Rayleigh (Ra) numbers. Mahmoudi et al. [5] studied numerically the natural convection cooling of horizontal heat source mounted in a square cavity filled with