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Review

Buoyancy-driven heat transfer of water–Al_2O_3 nanofluid in a closed chamber: Effects of solid volume fraction, Prandtl number and aspect ratio

Rehena Nasrin [a,*], M.A. Alim [a], Ali J. Chamkha [b]

[a] Department of Mathematics, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh

[b] Manufacturing Engineering Department, The Public Authority for Applied Education and Training, Shuweikh 70654, Kuwait

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ABSTRACT

This paper analyzes heat transfer and fluid flow of natural convection in a vertical closed chamber filled with Al_2O_3/water nanofluid that operates under differentially heated walls. The Navier–Stokes and energy equations are solved numerically using the finite element technique with Galerkin's weighted residual simulation. The heat transfer rates are examined for parameters of nanoparticle volume fraction (ϕ), Prandtl number (*Pr*) and cavity aspect ratio (*AR*). Enhanced and mitigated heat transfer effects due to the presence of nanoparticles are identified and highlighted. Based on these insights, the impact of fluid temperature on the heat transfer of nanofluid are determined. Decreasing the Prandtl number results in amplifying the effects of nanoparticles due to increased effective thermal diffusivity. The results highlight the range where the heat transfer uncertainties can be affected by the volume fraction of the nanoparticles. In addition, a correlation is developed graphically for the average Nusselt number as a function of the cavity aspect ratio.

Contents

* Corresponding author.
E-mail addresses: rehena@math.buet.ac.bd (R. Nasrin), maalim@math.buet.ac.bd (M.A. Alim), achamkha@yahoo.com (A.J. Chamkha).

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Nomenclature

C_p	specific heat at constant pressure ($J\ kg^{-1}K^{-1}$)
d_p	mean nanoparticle diameter (m)
g	gravitational acceleration (ms^{-2})
H	height of the chamber (m)
K	thermal conductivity ($W\ m^{-1}K^{-1}$)
L	length of the chamber (m)
Nu	Nusselt number
Nu^*	normalized Nusselt number
P	dimensional pressure ($N\ m^{-2}$)
P	non-dimensional pressure
Pr	Prandtl number
Ra	Rayleigh number
T	dimensional temperature (K)
T	time
u, v	velocity components ($m\ s^{-1}$) along x, y direction respectively
U, V	dimensionless velocity components along X, Y direction respectively
x, y	Cartesian coordinates (m)
X, Y	non-dimensional Cartesian coordinates

Greek symbols

α	thermal diffusivity ($m^2\ s^{-1}$)
β	thermal expansion coefficient (K^{-1})
ϕ	solid volume fraction
θ	non-dimensional temperature
μ	dynamic viscosity of the fluid ($kg\ m^{-1}s^{-1}$)
ν	kinematic viscosity of the fluid ($m^2\ s^{-1}$)
ρ	density of the fluid ($kg\ m^{-3}$)
ω	dimensionless velocity field

Subscripts

av	average
c	less heated wall
f	base fluid
h	heated wall
nf	water–Al_2O_3 nanofluid
s	solid particle

1. Introduction

Heat transfer materials like water, ethylene glycol, engine oil, alumina, copper and silver have been widely used in numerous important fields, such as heating, ventilating, air-conditioning system, micro-electronics, transportation, manufacturing and nuclear engineering. Cooling or heating performances for thermal systems play vital roles in the development of energy-efficient heat transfer equipments, such as MEMS and NEMS (Micro and Nano Electro Mechanical Systems, respectively). Natural convection heat transfer is an important phenomenon in engineering systems due to its wide applications in electronic cooling, heat exchangers, double pane windows etc. Enhancement of heat transfer performance in these systems is an essential topic from an energy saving perspective. The low thermal conductivity of conventional fluids such as water and oils is a primary limitation in enhancing the heat transfer performance and the compactness of such systems.

Over the last years, it has been demonstrated that thermal conductivity of fluids suspended with metallic nanoparticles (nanofluids) is significantly higher than that of pure fluids by Choi et al. [1]. Additional benefits of nanofluids include high stability with low sedimentation, no clogging in micro-channels, reduction in pumping power and design of small heat exchanger systems by Murshed et al. [2] where research conducted by different groups on heat transfer characteristics of nanofluids showed little agreement. A great amount of experimental research in this field has recently been reported in literature. Eastman et al. [3] observed that Al_2O_3/water and CuO/water with 5% nanoparticle volume fractions increased the thermal conductivity by 29% and 60%, respectively. In addition, Xie et al. [4] showed that Al_2O_3/ethylene glycol with 5% nanoparticle volume fraction enhanced thermal conductivity by 30% and Patel et al. [5] reported that Au/toluene and Au/water with 0.0013–0.011% nanoparticle volume fractions increased the thermal conductivity by 4–7% and 3.2–5%, respectively. Recently, in the natural convection of nanofluids inside a horizontal cylinder, Putra et al. [6] observed the paradoxical behavior of heat transfer due to different particle concentrations, types of particles and different shapes of the containing cavity. Kim et al. [7] analyzed the convective instability driven by buoyancy and heat transfer characteristics of nanofluids and indicated that as the thermal conductivity and shape factor of nanoparticles decrease, the convective motion in a nanofluid sets in easily. At the same year, in a series of experiments in laminar tube flows, Wen and Ding [8] showed that the local heat transfer coefficients increased 41% and 46% at Re = 1050 and 1600, respectively in the presence of nanoparticle volume fraction of 0.016. Jung et al. [9] reported that the heat transfer coefficient increased 32% by dispersing 1.8% nanoparticles in a micro-rectangular channel with Al_2O_3/water nanofluid.

The computational studies reported in this area include two main approaches: (1) a two-phase model, in which both liquid and solid heat transfer behaviors are solved in the flow fields [10,11] and (2) a single-phase model, in which solid particles are considered to behave as fluids, because the nanoparticles are easy fluidized [12–17]. The model of nanofluids in a cavity was first proposed by Khanafer et al. [12] and the authors investigated the natural convection effect on the enhancement of heat transfer. Tiwari and Das [13] further studied the forced convection effect with two-sided lid-driven differentially heated square cavity. A theoretical study on a heated cavity reported by Hwang et al. [18] showed that the heat transfer coefficient of Al_2O_3/water nanofluids reduced when there was an increase in size of nanoparticles and a decrease in average temperatures. Particle concentration and tube size dependence of viscosities of Al_2O_3–water nanofluids flowing

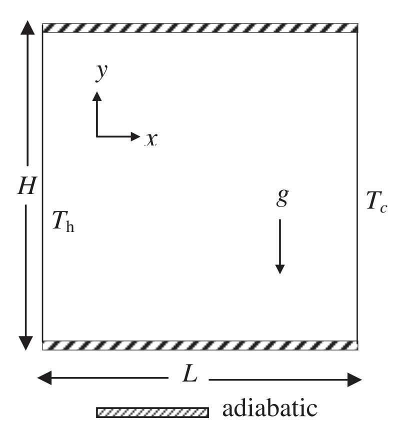

Fig. 1. Schematic diagram of the square chamber.