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Natural convection of water-based nanofluids in an inclined enclosure with a heat source

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ABSTRACT

This study investigates natural convection heat transfer of water-based nanofluids in an inclined square enclosure where the left vertical side is heated with a constant heat flux, the right side is cooled, and the other sides are kept adiabatic. The governing equations are solved using polynomial differential quadrature (PDQ) method. Calculations were performed for inclination angles from 0° to 90°, solid volume fractions ranging from 0% to 20%, constant heat flux heaters of lengths 0.25, 0.50 and 1.0, and a Rayleigh number varying from 10^4 to 10^6. The ratio of the nanolayer thickness to the original particle radius is kept at a constant value of 0.1. The heat source is placed at the center of the left wall. Five types of nanoparticles are taken into consideration: Cu, Ag, CuO, Al_2O_3, and TiO_2. The results show that the average heat transfer rate increases significantly as particle volume fraction and Rayleigh number increase. The results also show that the length of the heater is also an important parameter affecting the flow and temperature fields. The average heat transfer decreases with an increase in the length of the heater. As the heater length is increased, the average heat transfer rate starts to decrease for a smaller inclination angle (it starts to decrease with inclination at 90° for $\varepsilon = 0.25$, 60° for $\varepsilon = 0.50$, 45° for $\varepsilon = 1.0$, respectively).

1. Introduction

In order to manage the growing demand from a variety of industries (electronics, automotive and aerospace industries, for example), heat exchanger devices have to become smaller in size and lighter in weight, and they must provide ever higher performance. Fluids in common use, such as water oil and ethylene glycol, often have low thermal conductivity of conventional heat transfer, a primary limitation in enhancing the performance and the compactness of many electronic devices for engineering applications. To overcome this impediment, there is a strong motivation to develop fluids with advanced heat transfer properties and, in particular, substantially higher conductivities. One innovative way to improve the thermal conductivity of a fluid is to suspend metallic nanoparticles within it. The resulting mixture, referred to as a nanofluid, possesses a substantially larger thermal conductivity than that typical of traditional fluids [1]. Choi [2] was the first to use the term “nanofluid” to refer to a fluid in which nanoparticles are suspended. The term “nanofluid” does not simply refer to a specific liquid–solid mixture, but also to the necessity of other special characteristics, such as even suspension, stable suspension, durable suspension, low agglomeration of particles, and no chemical change of the fluid. Keblinski et al. [3] proposed that the thermal conductivity increase of nanofluids is due to the Brownian motion of particles, the molecular-level layering of the liquid at the liquid/particle interface, the nature of heat transport in the nanoparticles, and the effect of nanoparticle clustering.

One of the most significant parameters regarding the enhancement of heat transfer of nanofluids is the effective thermal conductivity of the nanofluid. Since there is currently a lack of sophisticated theories for predicting the effective thermal conductivity of a nanofluid, several researchers have proposed different correlations to predict the apparent thermal conductivity of two-phase mixtures. The models proposed by Hamilton and Crosser [4], Wasp [5], Maxwell-Garnett [6], Bruggeman [7] and Wang et al. [8] are all meant to determine the effective thermal conductivity of a nanofluid, but all have failed to predict it accurately. To be specific, experimental results have shown much higher thermal conductivities than those predicted by these models. An alternative expression for calculating the effective thermal conductivity of solid–liquid mixtures was proposed by Yu and Choi [9]. They claimed that a structural model of nanofluids might consist of a bulk liquid, solid nanoparticles and solid-like

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Nomenclature

c_p	specific heat at constant pressure
g	gravitational acceleration
Gr	Grashof number
H	height of the enclosure
k	thermal conductivity
L	width of the enclosure
Nu	Nusselt number
p	pressure
Pr	Prandtl number
q	heat flux
R	residue
Ra	Rayleigh number
T	temperature
u	velocity component in the x direction
v	velocity component in the y direction
w	length of heat source
x	cartesian coordinate
y	cartesian coordinate

Greek symbols

α	thermal diffusivity
η	ratio of the nanolayer thickness to the original particle radius
β	thermal expansion coefficient
γ	kinematic viscosity
ε	dimensionless length of the heat source
ξ	outward variable normal to the surface
ϕ	solid volume fraction
μ	dynamic viscosity
φ	inclination angle
ρ	density
ψ	stream function
ω	vorticity

Subscripts

a	average
c	cold
eff	effective
f	fluid
o	reference value
s	solid

Superscript

*	dimensional variable

nanolayers. The solid-like nanolayer acts as a thermal bridge between the solid nanoparticles and the bulk liquid. This is the model that has been used in this study to determine the effective thermal conductivity of a nanofluid.

The past decade has witnessed several studies of convective heat transfer in nanofluids. Khanafer et al. [10] were the first to investigate the problem of buoyancy-driven heat transfer enhancement of nanofluids in a two-dimensional enclosure. Jou and Tzeng [11] numerically investigated the heat transfer performance of nanofluids inside two-dimensional rectangular enclosures. Their results show that increasing the volume fraction causes a significant increase in the average heat transfer coefficient. Santra et al. [12] have conducted a similar kind of study, up to $\phi = 10\%$, using the models proposed by Maxwell-Garnett [6] and Bruggeman [7]. Their results show that the Bruggemann model [7] predicts higher heat transfer rates than the Maxwell-Garnett model [6]. Hwang et al. [13] have carried out a theoretical investigation of the thermal characteristics of natural convection of an alumina-based nanofluid in a rectangular cavity heated from below using Jang and Choi's model [14] for predicting the effective thermal conductivity of nanofluids (and various models for predicting the effective viscosity). Oztop and Abu-Nada [15] investigated heat transfer and fluid flow due to buoyancy forces in a partially heated enclosure using nanofluids using various types of nanoparticles. It was found that the heat transfer enhancement due to using a nanofluid is more pronounced at a low aspect ratio than at a high aspect ratio.

Natural convection heat transfer in a partially heated enclosure is an issue of practical importance. Air-cooling is one of the preferred methods for cooling computer systems and other electronic equipments, due to its simplicity and low cost. The electronic components are treated as heat sources embedded on flat surfaces [16]. In many applications, natural convection is the only feasible mode of cooling such sources.

For conventional fluids, convective heat transfer in a partially heated enclosure has been studied in the literature. A numerical study on natural convection in a glass-melting tank heated locally from below has been performed by Sarris et al. [17]. More recently, Calcagni et al. [18] made an experimental and numerical study of free convective heat transfer in a square enclosure characterized by a discrete heater located on the lower wall and cooling from the lateral walls. A numerical investigation of the natural convection of air in a vertical square cavity with localized isothermal heating from below and symmetrical cooling from the sidewalls was carried out by Aydin and Yang [19]. The top wall as well as the non-heated parts of the bottom wall were considered to be adiabatic. Sharif and Mohammad [20] studied the same configuration as Aydin and Yang, [19] where the localized isothermal heat source at the bottom wall is replaced with a constant flux heat source, a scenario that is physically more realistic for electronic component cooling applications. They investigated the effect of aspect ratio and inclination of the cavity on the heat transfer process. Cheikh et al. [21] studied the natural convection cooling of a localized heated plate embedded symmetrically at the bottom of an air-filled square enclosure.

The problem of natural convection heat transfer of nanofluids in an enclosure with a constant flux heater has not yet been analyzed.

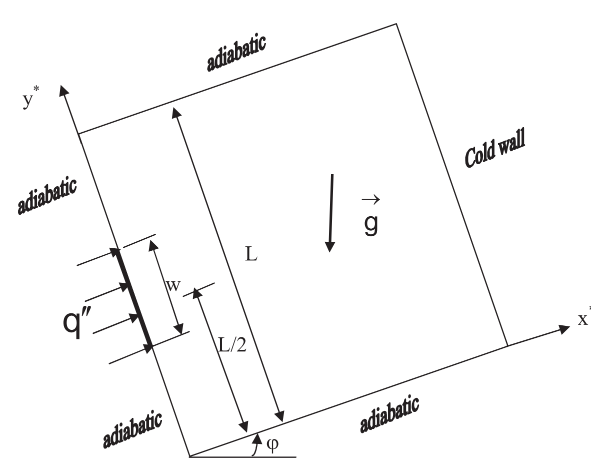

Fig. 1. Geometry and coordinate system.