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Non-homogeneous model for a side heated square cavity filled with a nanofluid

Michele Celli *

Dipartimento di Ingegneria Industriale, Alma Mater Studiorum, Università di Bologna, Viale Risorgimento 2, I-40136 Bologna, Italy

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ABSTRACT

A side heated two dimensional square cavity filled with a nanofluid is here studied. The side heating condition is obtained by imposing two different uniform temperatures at the vertical boundary walls. The horizontal walls are assumed to be adiabatic and all boundaries are assumed to be impermeable to the base fluid and to the nanoparticles. In order to study the behavior of the nanofluid, a non-homogeneous model is taken into account. The thermophysical properties of the nanofluid are assumed to be functions of the average volume fraction of nanoparticles dispersed inside the cavity. The definitions of the nondimensional governing parameters (Rayleigh number, Prandtl number and Lewis number) are exactly the same as for the clear fluids. The distribution of the nanoparticles shows a particular sensitivity to the low Rayleigh numbers. The average Nusselt number at the vertical walls is sensitive to the average volume fraction of the nanoparticles dispersed inside the cavity and it is also sensitive to the definition of the thermophysical properties of the nanofluid. Highly viscous base fluids lead to a critical behavior of the model when the simulation is performed in pure conduction regime. The solution of the problem is obtained numerically by means of a Galerkin finite element method.

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1. Introduction

In the last few decades an increasing attention has been focused on the heat transfer performances of a particular kind of colloids called nanofluids. A nanofluid is a suspension of metallic nanoparticles (or nanotubes) dispersed inside a base fluid. These colloids have been proposed as highly-effective heat transfer media (Choi and Eastman, 1995; Lee and Choi, 1996; Nguyen et al., 2007). Experimentally, great efforts have been spent in measuring the thermophysical properties of the nanofluids. Different kind of base fluids and dispersed nanoparticles have been tested in order to measure the thermal conductivity (Eastman et al., 1997; Lee et al., 1999; Wang et al., 1999; Xuan and Li, 2000; Eastman et al., 2001), the viscosity (Li et al., 2002; Prasher et al., 2006; Kwak and Kim, 2005) and the convective heat transfer coefficient (Xuan and Li, 2003; Wen and Ding, 2004; Heris et al., 2006). The thermophysical properties of the nanofluids have also been deeply studied from the theoretical point of view. A number of correlations have been proposed and employed in order to model the thermophysical properties (Das and Choi, 2006; Wang and Mujumdar, 2007). While the heat transfer performances of nanofluids have been widely studied, relatively few efforts have been undertaken with respect to the investigation of the sensitivity of the nanoparticles distributions to the heat transfer processes.

In this contribution, a two dimensional square cavity filled with a nanofluid and subjected to side heating is studied. A nanofluid composed of Water as base fluid, and Alumina as nanoparticles dispersed into the base fluid, is investigated. The cavity walls are assumed to be impermeable to the base fluid and to the nanoparticles. The lower and upper boundary walls are assumed to be adiabatic. The side heating conditions are obtained by imposing two different temperatures at the vertical boundary walls. The model that is most frequently employed to simulate the nanofluids behavior is the homogeneous model. This model considers the nanofluid as a clear fluid with the only difference that the thermophysical properties of the nanofluid itself are modified in their values as functions of the average volume fraction of nanoparticles dispersed inside the base fluid. Magyari (2011) pointed out that, with a little rescaling effort, the homogeneous model produces the same results already obtained with the clear fluids models. Moreover, the assumption of homogeneity of the nanoparticles distribution may not hold when particle migration phenomena occur (Ding and Wen, 2005; Wen et al., 2009; Kang et al., 2007). The arguments just presented lead to the choice of employing a non-homogeneous model for the present analysis.

The non-homogeneous model prescribes a dedicated mass balance equation for the dispersed nanoparticle. The mathematical model is thus characterized by four balance equations: the mass

* Tel.: +39 051 2098330.
E-mail address: michele.celli3@unibo.it

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Nomenclature

c	specific heat (J/(kg K))
D_B	Brownian motion coefficient (m^2/s)
d_p	nanoparticles diameter (m)
D_T	thermophoresis coefficient (m^2/s)
$F(\Phi_0)$	nondimensional function
$\mathbf{g}$	gravity acceleration (m/s^2)
$G(\Phi_0)$	nondimensional function
$H(\Phi_0)$	nondimensional function
$I(\Phi_0)$	nondimensional function
$\mathbf{j}$	nanoparticles mass flux (m/s)
k	thermal conductivity (W/(mK))
k_B	Boltzmann constant (J/K)
L	lenght of the cavity side (m)
MES	nondimensional maximum size of the grid elements
$\mathbf{n}$	normal unit vector
N	number of grid elements
P	nondimensional pressure
r	radius of the neighborhood of $\phi = 1$
S	nondimensional cavity surface
T	nondimensional temperature
T_c	cold wall temperature (K)
T_h	hot wall temperature (K)
T_0	reference temperature (K)
$\mathbf{v}$	nondimensional velocity field (u, v)
$\mathbf{x}$	nondimensional position vector (x, y)

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K^{-1})
β_T	nondimensional constant
ΔT	reference temperature jump (K)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
ϕ	rescaled volume fraction of nanoparticles
Φ	local volume fraction of nanoparticles
Φ_0	average volume fraction of nanoparticles

Nondimensional numbers

Le	Lewis number
N_{BT}	nondimensional number
$\overline{Nu}$	average Nusselt number
Pr	Prandtl number
Ra	Rayleigh number

Subscripts, Superscripts

–	dimensional quantity
$\sim$	rescaled quantity
f, p, nf	fluid, nanoparticle, nanofluid
max	maximum value

balance equation for the base fluid, the momentum balance equation for the nanofluid, the energy balance equation for the nanofluid and the mass balance equation for the nanoparticles, Buongiorno (2006). Moreover, the thermophysical properties of the nanofluid are here expressed by means of phenomenological correlations as functions of the average volume fraction of the nanoparticles. The thermophysical properties of the base fluid are, in fact, unavoidably modified by the presence of the dispersed nanoparticles. On the other hand, the nondimensional governing parameters (Rayleigh number, Prandtl number and Lewis number) are defined exactly as for clear fluids. This choice allows an easier comparison between the results obtained by the mathematical model here employed and the results for clear fluids found in the literature. The contribution of the average volume fraction of nanoparticles, coming from the definitions of the thermophysical properties, is thus taken into account by means of a number of *ad hoc* nondimensional parameters.

The non-homogeneous model is here studied for different range of values of the nondimensional parameters involved. The main goals of this study are looking for possible non-homogeneities of the nanoparticles distribution and investigating the heat transfer performances of the nanofluid at the cavity side walls. Particular attention is focused on the low Rayleigh numbers regimes. The nanoparticles distribution shows indeed a strong sensitivity to the heat transfer processes for low Rayleigh numbers. The non-homogeneous model is here also tested for a particular highly viscous base fluids (Propylene Glycol) in the limit case of pure conduction and pure diffusion regime. The numerical solution of the problem is obtained by Galerkin's finite element method.

2. Mathematical model

The two dimensional side heated square cavity here investigated is sketched in Fig. 1. The cavity is assumed to be impermeable and the horizontal walls are assumed to be adiabatic. The side heating condition is obtained by imposing two different temperatures at the walls: the hot wall, T_h, is assumed to be on the left vertical boundary and the cold wall, T_c, is assumed to be on the right vertical boundary. The cavity walls are subjected to the no-slip condition. The boundary conditions are shown in their dimensional form in Table 1.

A nanofluid composed of Water as base fluid, and Alumina (Al_2O_3, Auerkari, 1996) as nanoparticles dispersed inside the base fluid, is here studied. In order to analyze the nanoparticles distribution, a non-homogeneous model is employed, Buongiorno (2006). The following hypotheses are assumed:

- Non-homogeneous nanofluid model.
- Brownian motion and thermophoresis as leading physical transport mechanisms for the nanoparticles diffusion.
- Thermophysical properties of the nanofluid are expressed as functions of the average volume fraction of nanoparticles dispersed inside the base fluid.

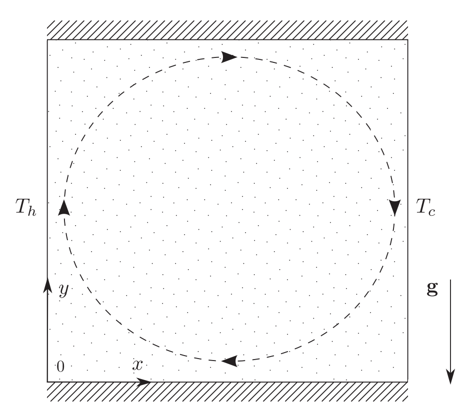

Fig. 1. Sketch of the system.

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