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Conduction and convection heat transfer characteristics of water–Au nanofluid in a cubic enclosure with differentially heated side walls

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ABSTRACT

The present work deals with the steady-state natural convection in a cubic enclosure filled with the water–Au nanofluid. The enclosure is heated on the vertical and cooled from the adjacent wall, while the other walls are adiabatic. The governing differential equations have been solved by the standard finite volume method and the hydrodynamic and thermal fields were coupled together using the Boussinesq approximation. The effects of the volume fraction of nanoparticles in the range $0\% \leqslant \varphi \leqslant 5\%$ on the heat transfer characteristics of Au nanofluids are investigated for the nominal values of base-fluid Rayleigh number $\left(10^1 \leqslant Ra_{bf} \leqslant 10^6\right)$.

It is shown that adding nanoparticles in a base-fluid delays the onset of convection. Contrary to what is argued by many authors, we show by numerical simulations that the mean Nusselt number $\overline{Nu}$ values for nanofluids $(\varphi > 0\%)$ are smaller than those obtained in the case of pure fluid with the same nominal value of Rayleigh number Ra_{bf} due to the weakening of convective transport.

1. Introduction

Today more than ever, ultrahigh-performance and controlled heat transfer plays an important role in the development of energy-efficient heat transfer systems (e.g. cooling system for wind turbines [1]) and fluids which are required in many industries and commercial applications. The idea of improving the heat transfer performance of inherently poor conventional heat transfer fluids (e.g. water, oil or ethylene glycol) with the inclusion of solid particles was first introduced by Maxwell [2]. However, suspensions involving milli- or micro-sized particles create problems (such as sedimentation, clogging of channels, high pressure drop, and severe erosion of system boundaries) and cannot be used in micro channel flow passages. For that, nano-sized particles dispersed in a base-fluid, known as nanofluid [3], have been developed, used and researched extensively to enhance heat transfer.

Many of the researchers have studied the heat transfer characteristics of nanofluids in last decade experimentally as well as computationally. There have been concerns that if the nanofluids can be studied as a single-phase fluid or they have to be treated as a two-phase mixture [4]. Although they are more accurate in predicting heat transfer, two-phase models are computationally more expensive than single-phase models due to the increased number of equations to be solved. Using a single-phase model for nanofluids simplifies the application of computational fluid dynamics as only the material properties in governing equations need to be modified with appropriate correlations and this simplicity has attracted the attention of researchers for investigating the flow and heat transfer behavior of various nanofluids.

The majority of available studies on convective heat transfer in nanofluids are related to the forced convection flows, showing an unquestionable heat transfer enhancement [5]. On the other hand, much less studies performed on the buoyancy-induced heat transfer in nanofluids opened the question if the use of nanoparticle suspensions is actually advantageous with respect to the pure fluids. As a matter of fact, according to some authors, the addition of nanoparticles to a base fluid implies an enhancement of the heat transfer rate, while, according to others, a deterioration may occur.

Natural convection (i.e. flow caused by the temperature induced density variations) is one of the most extensively analyzed configurations because of its fundamental importance as the benchmark problem for studying convection effects (and comparing as well as validating numerical techniques). In addition to the obvious academic interest, thermally driven flow is preferred strategy by heat transfer designers when a small power consumption, a negligible operating noise, and a high reliability of the system, are main concerns (e.g. reduction of cooling time, manufacturing cost and improvement of product quality [6]). Although quite some various configurations of the enclosure problem are possible [7–10], one of the most studied cases (involving nanofluids) is the

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two-dimensional square enclosure with differentially heated isothermal vertical walls and adiabatic horizontal walls [11–14]. When the vertical walls are insulated to ensure adiabatic conditions and the lower horizontal wall held at the higher temperature then one has the classical Rayleigh–Bénard configuration [15,16].

To date, most of the authors (e.g. [11–13,17,18]) performed numerical studies in a 2-dimensional enclosures and they claim that the presence of nanoparticles in a fluid alters the flow structure and increases the natural convection mean Nusselt number for any given characteristic (i.e. *Ra* or *Gr*) number. Convective heat transfer enhancement using nanofluids was also observed in experimental works of Nanna et al. [19] and Nanna and Routhu [20].

On the other hand, an apparently paradoxical behavior of heat transfer deterioration was observed in experimental studies [21–24]. For example, Putra et al. [21] reported that the presence of Al_2O_3 and CuO nanoparticles in a base-fluid reduce the natural convective heat transfer for the natural convection inside a horizontal cylinder heated from one end and cooled from the other. However, they did not explain clearly why natural convective heat transfer is decreased with an increase in volume fraction of nanoparticles. Hwang et al. [23] theoretically studied the thermal characteristics of natural convection of water based nanofluids in a rectangular cavity. They used two different models to calculate the effective viscosity of nanofluid and compare the results obtained from these models. They showed that the ratio of heat transfer coefficient of nanofluid to that of base fluid is decreased as the size of nanoparticle increases. Ho et al. [22] experimentally investigated natural convection heat transfer of a nanofluid in a vertical enclosure for different particle sizes and various volume fractions of nanoparticles. Systematic heat transfer degradation was observed in their measurements for nanofluids containing nanoparticles with volume fractions greater than 2% over the entire range of Rayleigh numbers. Furthermore, a decreasing trend of the mean Nusselt number with the increase of nanoparticles' volume fraction was reported by Li and Peterson [24].

The reason for such conflicting results can be explained by the fact that the heat transfer performance of nanofluids in natural convection applications is a direct consequence of the increase of the thermal conductivity and viscosity that occur as the nanoparticle volume fraction is augmented [25]. Actually, one of the commonest causes of conflicting conclusions is the use of the Brinkman equation for predicting the nanofluid dynamic viscosity [26,27], whose values are notably underestimated by this viscosity model. Furthermore, the thermal conductivity is often calculated by the Maxwell–Garnett model or other classical mean-field theories (e.g. Hamilton–Crosser model), that fail to predict the significant enhancement in the thermal conductivity of nanofluids [28]. As a matter of fact, Ho et al. [26] studied numerically the effects of uncertainties of dynamic viscosity and thermal conductivity on natural convection in a square enclosure filled with Al_2O_3 water nanofluid. Significant difference in the effective dynamic viscosity enhancement of the nanofluid calculated from the two adopted formulas, other than that in the thermal conductivity enhancement, was found to play a major role, thereby leading to contradictory results concerning the heat transfer efficacy of using nanofluid in the enclosure. Recent numerical studies [16,29] pointed out another possible cause for such conflicting results. The increasing trend of the mean Nusselt number (as observed by many authors) was because of their using the base fluid thermal conductivity in a definition of the nanofluid Nusselt number.

The above review of existing literature shows that the problem of natural convection in a three-dimensional enclosure filled with nanofluid is an issue still far from being tackled and solved. Framed in this general background, the purpose of the present study is to examine the effect of adding Au nanoparticles to Newtonian base fluid on the conduction and convection heat transfer characteristics in a differentially heated cubic enclosure over the wide range of the base-fluid Rayleigh number ($10^1 \leqslant Ra_{bf} \leqslant 10^6$) and volume fraction of nanoparticles ($0\% \leqslant \varphi \leqslant 5\%$). In contrast to most previous studies, where the classical models of Brinkman and Maxwell–Garnett were utilized, more accurate correlations (suggested by Corcione [30]) for thermal conductivity and viscosity of nanofluids are used.

The rest of the paper is organized as follows. The necessary mathematical background and numerical details are presented Sections 2 and 3, which is followed by the grid refinement, numerical accuracy assessment and validation study (Section 4). Following this analysis, the results are presented and subsequently discussed (Section 5). The main findings are summarized and conclusions are drawn in the final section of this paper.

2. Methodology

The standard finite volume method is used to solve the coupled conservation equations of mass, momentum and energy. The diffusion terms in momentum and energy equations are approximated by a second-order central differencing scheme which gives a stable solution. Furthermore, a second-order linear upwind differencing scheme is adopted for the convective terms. Coupling of the pressure and velocity is achieved using the well-known SIMPLE algorithm. The convergence criteria were set to 10^{-8} for all residuals.

2.1. Governing equations

For the present study a steady-state laminar flow of an incompressible water-based Au nanofluid is considered. It is assumed that both the fluid phase and solid nanoparticles are in thermal equilibrium and there is no slip between them. The thermo-physical properties of the base-fluid and nanoparticles are taken to be constant with the exception of the density which varies according to the Boussinesq approximation. Table 1 presents the thermo-physical properties of water and Au nanoparticles at the reference temperature.

The governing equations (mass, momentum and energy conservation) for a steady, laminar and incompressible flow are:

$$\frac{\partial v_i}{\partial x_i} = 0 \tag{1}$$

$$\rho_{nf} v_j \frac{\partial v_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + (\rho\beta)_{nf} g (T - T_C) + \frac{\partial}{\partial x_j}\left[\eta_{nf}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)\right] \tag{2}$$

$$(\rho c_p)_{nf} v_j \frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_j}\left(k_{nf}\frac{\partial T}{\partial x_j}\right) \tag{3}$$

where the cold wall temperature T_C is taken as the reference temperature for evaluating the buoyancy term $(\rho\beta)_{nf} g(T - T_C)$ in the momentum equation.

Relationships between the properties of nanofluid (nf) to those of base-fluid (bf) and pure solid (s) are given with the following empirical models [17,31,32]:

Table 1
Thermo-physical properties of water and Au nanoparticles [16,29].

	Pure water	Au
c_p (J/kg K)	4179	128.8
ρ (kg/m^3)	997.1	19320
k (W/m K)	0.613	314.4
β (1/K)	2.100×10^{-4}	1.416×10^{-7}
η (kg/m s)	1.003×10^{-3}	–