Mechanics Research Communications 66 (2015) 34–43

Contents lists available at ScienceDirect

Mechanics Research Communications

journal homepage: www.elsevier.com/locate/mechrescom

Two numerical modelings of free convection heat transfer using nanofluids inside a square enclosure

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ARTICLE INFO

Article history:
Received 5 January 2015
Received in revised form 27 March 2015
Accepted 28 March 2015
Available online 4 April 2015

Keywords:
Water–copper nanofluids
Natural convection heat transfer
Numerical approximation
Galerkin least-squares method

ABSTRACT

This work describes the numerical simulation of natural convection heat transfer of Cu–water nanofluids in a square enclosure for Rayleigh numbers varying from 10^3 up to 10^5. Two different numerical approaches were used: the finite volume method and the finite element method. The nanofluids were assumed to be single-phase fluids with modified thermal properties obtained from experimental results and theoretical models. The results showed that the Nusselt number for nanofluids was basically the same as that obtained for the base fluid. Therefore, the enhancement observed in the heat transfer coefficient was significant due to the augmentation in the thermal conductivity.

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1. Introduction

Heat transfer by natural convection is applied in several types of heat exchangers that do not require fans or pumps, ensuring very low noise levels. A common application of natural convection heat transfer is in electrical and electronic components and in electrical transformers. Interesting works conducted on thermal convection were developed by [1] and [2]. With miniaturization and the need to increase the operational performance of these types of equipment, it has become necessary to increase the capacity of heat exchangers. However, in many cases it is not possible to enlarge the exchange surfaces of these systems. An alternative is to improve the thermal properties of the heat exchange fluids, e.g., liquids with a dispersion of nanoscale particles.

The idea of dispersing solid particles in liquids has its beginnings in the studies of [3], who developed an equation based on the theory of an effective medium for the electrical resistance of a dispersion of particles in a fluid, which can analogously be applied to the thermal conductivity of dispersions. However, due to sedimentation problems, abrasion, and clogging of the millimetric pipelines resulting from the size of the particles used, research on particle dispersions in liquids to increase the heat exchange capability has been stagnate for some time.

With the advent of nanotechnology, it has become possible to produce nanosize particles (1–100 nm), and improvements on the thermal properties of fluids are again possible. In the mid-1990s, researchers observed experimentally that the increase in thermal conductivity (a property of great importance in terms of increasing the thermal exchange capability) of nanoparticle liquid suspensions is underestimated by the equation proposed by [3]. Thus, interest in using dispersions of nanoparticles has grown rapidly. Masuda et al. [4] found an increase of about 30% in thermal conductivity using a 4.3% volume concentration of alumina particles (Al_2O_3) in water. Choi and Eastman [5] presented a theoretical study of dispersions of nanometric particles in liquids, showing the potential of dispersions in heat exchangers – the authors were the first to call this type of dispersion a nanofluid. Several other authors have reported significant increases in the thermal conductivity of nanofluids ([6–8]), leading to studies on the application of nanofluids in thermal systems. Among these systems, one can highlight those related to convection heat transfer.

Evaluation of the convection coefficients on flows governed by natural convection is often conducted in closed cavities with prescribed thermal boundary conditions. Aiming to analyze the heat exchange capability of nanofluids in natural convection, [9] performed experimentally the natural convection of nanofluids of Al_2O_3 and CuO in water, with volume concentrations of 1% and 4% in an enclosure with a surface maintained at a higher temperature,

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http://dx.doi.org/10.1016/j.mechrescom.2015.03.009
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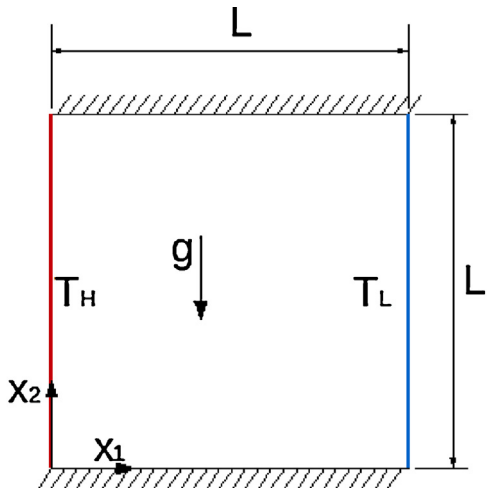

Fig. 1. The problem sketch.

a surface maintained at a lower temperature, and the other surfaces properly insulated. In comparison with the base fluid, they observed that the use of nanofluids led to a degradation of the convection mechanism, with smaller Nusselt numbers for the same Rayleigh number. Khanafer et al. [10] numerically evaluated nanofluids on natural convection in a two-dimensional cavity employing a model for the thermal conductivity of nanofluids, wherein the increased thermal conductivity of nanofluids is dependent on the thermal dispersion, which is related to the size of the nanoparticle, the volume concentration, and the velocity field. The authors used copper nanoparticles, with volume concentrations up to 25% water. The authors noticed that the increased volume concentration of nanoparticles led to a growth in the energy transport due to the random motion of nanoparticles, which intensified the thermal dispersion and consequently the thermal conductivity of the nanofluids, increasing the fluid thermal exchange capability.

Aminossadati and Ghasemi [11] performed numerical simulations of laminar flows of water-based nanofluids in a cavity with a heat sink located on the bottom wall. The authors aimed to evaluate the influence of different Rayleigh numbers, volume concentrations of nanoparticles, and positions and intensities of the heat sink on the natural convection. They considered the nanofluids as a monophase fluid with modified properties, wherein the viscosity and the thermal conductivity were estimated using, respectively, the [12] and [3] models. They simulated the influence of spherical nanoparticles of Cu, Al_2O_3, TiO_2, and Ag, and it was shown that the increasing of the volume concentration led to a reduction of the maximum temperature of the heat sink – an effect more pronounced for smaller Rayleigh numbers, i.e., where the diffusive transport is more representative. Their results for different nanoparticles showed that nanofluids with higher thermal conductivity (Ag and Cu) had higher average Nusselt numbers on the heat sink. Abu-Nada et al. [13] performed numerical simulations of Al_2O_3 and CuO nanofluids based on water in a closed cavity. The nanofluid properties were evaluated as functions of the temperature. The authors observed the increase of the average Nusselt number for lower Rayleigh flows; for high Rayleigh numbers, the increase in the volume concentration led to a reduction of the nanofluid's Nusselt number when compared to the base fluid.

Although there are many results for natural convection inside cavities in the literature, there is no general agreement. In order to investigate the natural convection heat transfer inside a square enclosure, this paper presents water–copper nanofluid simulations performed using the finite volume method and a multi-field Galerkin least-squares finite element methodology, which have as primal variables the velocity, pressure, extra-stress, and temperature fields. The addition of mesh-dependent terms on the flow-governing equations makes it possible for the formulation to successfully capture the buoyancy effects present in the employed modeling, even making use of an equal-order combination of linear Lagrangian finite element interpolations. The thermal boundary conditions employed are assigned temperatures at the sidewalls and insulation at the top and bottom walls – over all walls, the employed velocity boundary condition is $\mathbf{u}=0$. The thermal conductivity was set based on experimental results [14], and the viscosity was estimated by the correlation found at [15]. The mechanical model considers the nanofluid as a single-phase fluid, i.e., there is no slip between the nanoparticles and the base fluid. The heat transfer coefficient was obtained for various Rayleigh numbers and for different volume concentrations of copper nanoparticles in the base fluid – 0.1%, 0.5%, and 1.0%.

Table 1
Physical properties.

Properties	Base fluid	Nanoparticle	Water–copper nanofluid		
	Water	Copper	0.1%	0.5%	1.0%
κ [W/mK]	0.604	401	0.61	0.633	0.663
c_p [J/kgK]	4179.0	383.0	4145.2	4015.1	3863.3
ρ [kg/m^3]	997.1	8954.0	1005.1	1036.9	1076.7
μ [$\times 10^{-3}$ Pa s]	1.0	—	1.0025	1.0127	1.0257

2. Mechanical model

The problem analyzed in this work consisted of the flow of water-based copper nanofluids in a closed two-dimensional square enclosure of length L_c subjected to free convection due to a temperature difference between two walls. The employed boundary conditions for the numerical simulations are thermal insulation on the top and bottom walls, prescribed temperature on the side walls, and no-slip and impermeability over all the cavity walls ($\mathbf{u}=0$), as shown in Fig. 1. In order to ease the numerical approximation, some simplifying hypotheses were considered:

- the nanofluid is a single-phase incompressible Newtonian fluid
- the physical properties are constant
- the nanoparticles and the base fluid are instantaneously in thermal equilibrium
- the fluid exhibits laminar flow
- the buoyancy force term is modeled with the Boussinesq approximation

The numerical values of the thermal conductivity were taken from the work of [16] whereas the viscosity was evaluated with the correlation proposed by [15]. The fluid density is estimated from the principle of mass conservation and the specific heat from the first law of thermodynamics. The physical properties of the nanofluids and the base fluid (water) are shown in Table 1. Therefore, the momentum balance, continuity, and energy equations for the given problem are set as

$$\begin{aligned} &\rho(\partial_t \mathbf{u} + (\nabla \mathbf{u})\mathbf{u}) = -\nabla p + 2\mu \mathrm{div}\ \ \mathbf{D}(\mathbf{u}) + \rho \mathbf{g}\beta(T - T_{ref}) \\ &\mathrm{div}\mathbf{u} = 0 \\ &\rho c_p(\partial_t T + (\nabla T)\mathbf{u}) = \kappa \nabla^2 T, \end{aligned} \tag{1}$$

where $\mathbf{u}$ is the velocity vector, $\mathbf{D}$ the strain rate tensor, p the hydrostatic pressure, $\mathbf{g}$ the gravity vector, ∂_t the time derivative, T the temperature, and T_{ref} a reference temperature; β is the volumetric thermal expansion coefficient; μ, ρ, c_p, and κ are, respectively, the fluid viscosity, density, specific heat, and thermal conductivity. For the nanofluids, μ is calculated with the correlation proposed by

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