Journal of Magnetism and Magnetic Materials ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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

Numerical study of magnetic field effect on nano-fluid forced convection in a channel

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ARTICLE INFO

Article history:
Received 14 December 2013
Received in revised form
2 June 2014

Keywords:
Numerical study
Forced convection
Magnetohydrodynamics
Nano-fluid
Channel

ABSTRACT

In this study heat transfer and fluid flow analysis in a straight channel utilizing nano-fluid is numerically studied, while flow field is under magnetic field. Usage of nano-particles in base fluid and also applying magnetic field transverse to fluid velocity are two ways recommended in this paper to enhance heat exchange in straight duct. The fluid temperature at the channel inlet (T_{in}) is taken less than that of the walls (T_w). With assuming thermal equilibrium state of both the fluid phase and nano-particles and ignoring the slip velocity between the phases, single phase approach is used for modeling of nano-fluid. The governing equations are numerically solved in the domain by the control volume approach based on the SIMPLE technique. Numerical studies are performed over a range of Reynolds number, nano-fluid volume fraction and Hartmann number. The influence of these parameters is investigated on the local and average Nusselt numbers. Computations show excellent agreement with the literature. From this study, it is concluded that heat transfer in channels can enhance up to 75% due to the presence of nano-particles and magnetic field in channels. In industrial applications for cooling or heating purposes, the recommended ways in this paper, can provide helpful guidelines to the manufacturers to enhance efficiencies without heat exchanger area increase.

1. Introduction

FORCED convection in a channel is one of the most important subjects in many technological applications like high performance boilers, chemical catalytic reactors, solar collectors, power plants and cooling systems. Management of heat transfer for its enhancement or reduction in these systems is an essential task from an energy saving perspective [1–3].

Many researchers considered Nanotechnology as the most important driving force for the major industrial revolution of this century. The low thermal conductivity of conventional fluids such as air, water, oil, and ethylene glycol mixture is considered as the primary obstacle to enhance the performance of heat exchangers. Addition of nano-particles to the pure fluid, the so called “Nano-fluid”, can improve the thermal conductivity of the mixture. The nano-fluids make larger thermal conductivity compared to the pure fluids [4].

Choi [5] is the first who used the term nano-fluids to refer to the fluids with suspended nano-particles. Several researches [6–8] have indicated that with low (1–5% by volume) nano-particle concentrations, the thermal conductivity can be increased by about 20%. Xuan et al. [8] experimentally obtained thermal conductivity of copper-water nano-fluid up to 7.5% of solid volume fraction. Several researchers [9–14] have investigated heat transfer enhancement with nano-fluid.

Some authors have studied numerical studies on forced convection using nano-fluids. Xuan and Li [15] have experimentally investigated the heat transfer and flow field of copper–water nano-fluid flowing through a tube. They have conducted their study for a range of *Re* (10,000 to 25,000) and ϕ(0.3 to 2%). Yang et al. [16] have investigated experimentally the convective heat transfer of graphite in oil nano-fluid for laminar flow in a horizontal tube heat exchanger. Santra et al. [17] shows the heat transfer due to laminar flow of copper-water nano-fluid through two-dimensional channel with constant temperature walls. They conclude that the rate of heat transfer increases with the increase in flow Reynolds number as well as the increase in solid volume fraction of the nano-fluid.

Recently in a forced convection problem, we computed the heat transfer enhancement and hydrodynamics of the flow field in a wavy channel with nano-fluids [18]. In this study we investigated the effect of wave-amplitudes and wave-numbers on local and average Nusselt numbers, and skin friction. There, we concluded that the heat transfer can enhance up to 50%. In another study we

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http://dx.doi.org/10.1016/j.jmmm.2014.08.001
0304-8853/© 2014 Published by Elsevier B.V.

repeated similar problem in channel with partially blocks installed in bottom wall of the channel [19].

The other way for enhancement of convective heat transfer is to usage of magnetic field. The study of an electrically conducting fluid in engineering applications is of considerable interest, especially in metallurgical and metal working processes or in separation of molten metals from nonmetallic inclusions by the application of a magnetic field. In that case the fluid experiences a Lorentz force. This in turn affects the rate of heat and mass transfer.

Natural convection flow in the presence of a magnetic field in enclosure heated from one side and cooled from the other side was considered by Ece et al. [20] and Jue [21]. Krakov and Nikiforov [22] and Grosan et al. [23] investigated on magnetic field in cavity filled with porous medium. Pirmohammadi et al. [24–27] have simulated magneto-convection inside a tilted enclosure at different applications.

Some papers have investigated natural convection in cavity with presence of both nano-fluid and magnetic field. Mahmoudi et al. [28] have studied natural convection for a two-dimensional triangular enclosure with partially heated from below and cold inclined wall filled with nano-fluid in presence of magnetic field. Ghasemi et al. [29] examined the natural convection in an enclosure that is filled with a water-Al_2O_3 nano-fluid and is influenced by a magnetic field. Nemati et al. [30] applied the Lattice Boltzmann Method to investigate the effect of CuO nano-particles on natural convection with magnetohydrodynamic (MHD) flow in a square cavity.

But few papers have studied the effect of magnetic field and nano-fluid in forced convective heat transfer. As example, Aminossadati et al. [31] examined the laminar forced convection of a water–Al_2O_3 nano-fluid flowing through a horizontal micro-channel. Altan et al. [32] have investigated the presence of Fe_3O_4 magnetite particles on thermal conductivity enhancements both in water and in heptanes. Upon measuring thermal conductivity under externally applied magnetic field, they showed experimentally that thermal conductivity can be further increased even at low concentrations and low magnetic field strengths in both fluids.

Both nano-fluid and magnetic field are useful ways to enhance forced convective heat transfer between the hot wall and core flow. So a comprehensive model has been performed to study convective heat transfer in a channel with nano-fluid and magnetic field for enhancement of heat exchange between fluid and hot wall. Nano-particles are considered copper here. The fluid temperature at the channel inlet (T_{in}) is taken less than that of the walls (T_w). The effects of the Reynolds number, the volume fraction of nano-particles and Hartmann number on Nusselt number are investigated in the present study.

2. Basic equations

Consider a two-dimensional straight channel as shown in Fig. 1 with the opening height 2H and length L which the nano-fluid

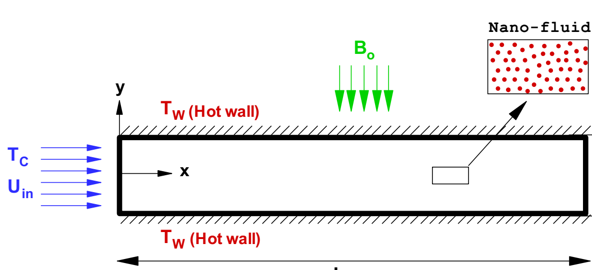

Fig. 1. Schematic diagram of the duct studied here.

flows. Magnetic field is transverse to fluid velocity. The nano-fluid in the duct is taken to be Newtonian, incompressible, and laminar. The nano-particles are assumed to have a uniform shape and size. Moreover, it is assumed that both the fluid phase and nano-particles are in thermal equilibrium state and they are significantly small in size so the slip velocity between the phases is ignored. Based on these assumptions, single phase approach was used for modeling of nano-fluid. Single-phase approach as well as two-phase approach is a common method for simulation of convection heat transfer with nano-fluid. Many authors used single-phase approach for numerical modeling of natural/forced/mixed convection in different geometries and various applications [28–32]. The temperature of the horizontal walls T_w are taken such that $T_w > T_{in}$; where T_{in} is the fluid temperature at the inlet plane. The governing equations in both dimensional and non-dimensional forms are given as follows:

2.1. Dimensional form of the governing equations

The continuity, momentum, and energy equations can be expressed, respectively, as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x}+\upsilon_{nf}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\frac{\sigma_{nf}B_0^2}{\rho_{nf}}u \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y}+\upsilon_{nf}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

where

$$\upsilon_{nf}=\frac{\mu_{nf}}{\rho_{nf}} \tag{5}$$

$$\alpha_{nf}=\frac{k_{nf}}{(\rho\ c_p)_{nf}} \tag{6}$$

where u and v are the velocity components along x- and y- axes, p is pressure and T is the fluid temperature. B_0 is the magnitude of magnetic field and σ is the electrical conductivity. Introducing the nano-fluid volume fraction (ϕ), the thermo-physical properties of the nano-fluid, namely the density and heat capacity, have been calculated from nano-particle and the pure fluid properties at the ambient temperature as follows. Thermo-physical properties of the pure fluid (water) and nano-particles (copper here) have been considered in Ref. [18]. The dynamic viscosity of the nano-fluid can be estimated by Brinkman [33]:

$$\mu_{nf}=\frac{\mu_f}{(1-\phi)^{2.5}} \tag{7}$$

The effective density, heat capacity and electrical conductivity of the nano-fluid at the reference temperature (T_{in}) are determined from:

$$\rho_{nf}=(1-\phi)\rho_f+\phi\rho_s \tag{8}$$

$$(\rho c_p)_{nf}=(1-\phi)(\rho c_p)_f+\phi(\rho c_p)_s \tag{9}$$

$$\sigma_{nf}=(1-\phi)\sigma_f+\phi\sigma_s \tag{10}$$

The effective thermal conductivity of the fluid can be determined by Maxwell–Garnett's (MG model). For the two-component