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The variations of heat transfer and slip velocity of FMWNT-water nano-fluid along the micro-channel in the lack and presence of a magnetic field

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HIGHLIGHTS

- The effects of Ha, Re, slip coefficient and nano-particles volume fraction were investigated.
- The stronger magnetic field leaded to less maximum of U at horizontal centerline and greater fluid velocity near the walls.
- Magnetic field affected severely the slip velocity along the walls of micro-channel.

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ABSTRACT

Simulation of forced convection of FMWNT-water (functionalized multi-walled carbon nano-tubes) nano-fluid in a micro-channel under a magnetic field in slip flow regime is performed. The micro-channel wall is divided into two portions. The micro-channel entrance is insulated while the rest of length of the micro-channel has constant temperature (T_C). Moreover, the micro-channel domain is exposed to a magnetic field with constant strength of B_0. High temperature nano-fluid (T_H) enters the micro-channel and exposed to its cold walls. Slip velocity boundary condition along the walls of the micro-channel is considered. Governing equations are numerically solved using FORTRAN computer code based on the SIMPLE algorithm. Results are presented as the velocity, temperature, and Nusselt number profiles. Greater Reynolds number, Hartmann number, and volume fraction related to more heat transfer rate; however, the effects of Ha and ϕ are more noteworthy at higher Re.

1. Introduction

In recent decades, study on different methods to enhance the heat transfer of fluids has attracted the attention of researchers. In this way, a new generation of fluids, called nano-fluids, with great potential in industrial application was considered as a result of the distribution of nanoparticles in a common liquid [1–5].

Common heat transfer fluids including water, oil and ethylene glycol generally have low thermal conductivity, while solid nanoparticles have high thermal conductivity. Hence, dispersion of nanoparticles in the base fluid can lead to increase its thermal conductivity. Therefore, nano-fluids could be considered an option for improving the heat transfer rate [6–10]. Enhancement of heat transfer coefficient of nano-fluids is subject to many factors. For example, heat transfer coefficient can be increased by changing the flow geometry, boundary conditions or enhancement of thermal conductivity of the fluid [11]. Numerous studies on heat transfer in different geometric shapes and the effects of external factors on the heat transfer have been performed. In this regard, Tahir and Mital [12] investigated the heat transfer in channels with a circular cross section. Heat transfer in channels with different geometry has been reported in the literature [13,14].

Cooling systems are the main concerns of thermal and electronic systems. In these circumstances, the use of improved and optimal cooling systems is inevitable. Tullius et al. [15] examined the effect of micro-channel geometry and fluid type on the cooling rate from micro-channels. The most common fluids used in micro-channels were air and water, which have low thermal conductivity.

Low heat transfer rate in micro-channels containing water or air led to use of various methods such as increasing the heat transfer surface, while this method increase the size of systems. Therefore, to overcome this problem, a new and effective cooling is required and nano-fluids were introduced as a new approach in this field [16].

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In order to study the heat transfer in micro-channels, different models were studied [17–19]. The effects of micro-channel geometry, Reynolds number and nanoparticles volume fraction on the thermal performance of micro-channels have also been investigated. In general, it seems that using new nano-fluid shows a better performance against the heat load generated by small electronic devices [20–26].

Surface effects in micro-scale have dramatic impact than that in macro-scale. For example, no-slip condition commonly used for the macro-scale, in micro-channels is not true; consequently, slip condition should be used along the walls. Moreover, for micro and nano scales, specific methods such as Lattice-Boltzmann method or molecular dynamics, which are based on particles, should be used [27–31]. Raisi et al. [32] investigated numerically the heat transfer in micro-channels by assuming existence or lack of slip velocity. They also reported the effect of nano-fluids on heat transfer rate in micro-channel in the presence of slip velocity. To this day, much researches assuming slip velocity have been presented in the field of heat transfer in micro-channel containing nano-fluids with different boundary conditions such as constant temperature or constant flux, which quickly slip boundary condition have also been studied [33–37].

In recent years, the flow and heat transfer in different sections of macro-scales exposed to a magnetic field have attracted the attention of the researchers [38–44]. In this case, the magnetic field leads to produce a force, called the Lorentz force, which affects the fluid flow [45–48]. Aminossadati et al. [49] studied the effects of magnetic field on a micro-channel under constant heat flux, while the slip velocity along the walls of the micro-channel was neglected.

However, a review of previous researches [53,54] showed that regarding the study of flow and heat transfer in micro-channels under the magnetic field, thes lip velocity as a boundary condition has been ignored. Up to now, there is no comprehensive research on the Simultaneous effects of the magnetic field, slip velocity boundary condition, forced convection on the flow and heat transfer in micro-channels. In this study, all of these conditions are considered simultaneously and efforts were also made to simulate the effects of magnetic field on the slip velocity of molecules adjacent wall. Moreover, in this study water-based nano-fluid containing functionalized multi-walled carbon nanotubes (FMWNT) is used as the working fluid.

2. Problem statement

Simulation of forced convection of FMWNT-water (functionalized multi-walled carbon nano-tubes suspended in water) nano-fluid in a two dimensional micro-channel under a magnetic field for slip flow regime is performed.

Single-walled carbon nanotubes (SWNTs) and multi-walled carbon nanotubes (MWNTs) are similar in certain respects but they also have striking differences. SWNTs structure is a cylindrical tube including six-membered carbon rings similar to graphite. They consist of a hollow cylinder of carbon ~1 nm (in present work for one cylinder) in diameter, up to 1000 times as long as it is wide. Analogously MWNTs include several tubes layers (concentric tubes) of graphene in concentric cylinders. The interlayer distance in multi-walled nanotubes is close to the distance between graphene layers in graphite, approximately 3.4 Å. The number of these concentric walls may vary from 6 to 25 or more. The diameter of MWNTs may be 30 nm (used at present article) when compared to 0.7–2.0 nm for typical SWNTs. The unique properties of carbon nanotubes enable a wide range of novel applications and improvements in the performance of existing ones. However, one can functionalize the nanotubes to enhance both the strength and dispersibility of composites.

The supposed micro-channel aspect ratio is 30; hence the fully developed condition is achieved at outlet. As shown in Fig. 1, the

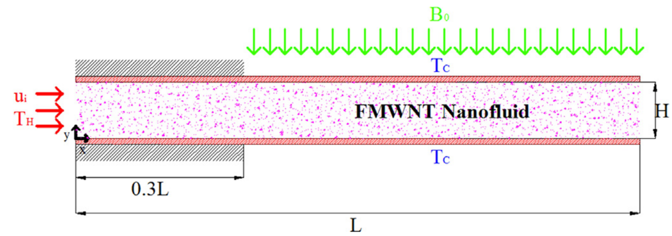

Fig. 1. The schematic configuration of the micro-channel.

Table 1
Empirical data for thermo-physical properties of the FMWNT nanofluid [50].

wt% FMWNT/water	ρ (kg/m³)	k (W/mK)	μ (Pas)
0	995.8	0.62	7.65×10^{-4}
0.12%	1003	0.68	7.80×10^{-4}
0.25%	1008	0.75	7.95×10^{-4}

micro-channel wall is divided into two portions. The micro-channel entrance ($X=0.3L$) is insulated while the rest of length of the micro-channel has constant temperature (T_C). This configuration leads to approach the hydrodynamic fully developed condition. Moreover, the micro-channel domain is exposed to a magnetic field with constant strength of B_0. Slip velocity boundary condition along the walls of the micro-channel is considered. High temperature nano-fluid (T_H) enters the micro-channel and exposed to its cold walls. Finally, it leaves the micro-channel from the other side. The empirical data for thermo-physical properties of the FMWNT-water nano-fluid are presented in Table 1.

With regard to consider thevery low weight fraction of nanotubes, nano-fluid is assumed as a Newtonian fluid. Reynolds number (Re) commonly is low in a micro-channel duo to express a real physical condition (Re=20 and 200). Moreover, in order to investigate the slip velocity boundary condition different values of slip coefficient such as $B=0.005$ and $B=0.05$ are assumed. Based on Table 1, three different values of weight fractions of FMWNTs are applied. Earlier investigations showed that the Hartman numbers greater than 40 have no significant effect on the flow and heat transfer; thus, a reasonable range of Hartmann number is found lower than 40. It should be noted that the nanofluid is incompressible and homogeneous mixture.

3. Mathematical formulation

The two-dimensional Navier–Stokes equations (continuity, momentum and energy) with regard to the effect of a magnetic field strength (B_0) are as follows:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\vartheta\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\frac{\sigma B_0^2}{\rho} \tag{2}$$

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

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

σ indicates the electrical conductivity of the nano-fluid and is equal to 4.99×10^{-2} (S/cm).