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Buoyancy driven convection of nanofluids in an infinitely long channel under the effect of a magnetic field

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ABSTRACT

In this paper, we have proposed a theoretical analysis to investigate buoyancy driven convection of nanofluids in an infinitely long channel under superimposed magnetic field. We derive closed form analytical solutions for the magnetohydrodynamic flow and temperature field under two distinctive wall boundary conditions. Proceeding further ahead, we also present an analysis for the total entropy generation due to magnetohydrodynamic fluid friction and heat transfer irreversibilities. Utilizing water based Al_2O_3 nanofluids, results are shown for the following range of conditions as $0 \leqslant Ha \leqslant 50$, $0 \leqslant \phi \leqslant 4\%$ and $10^3 \leqslant Gr \leqslant 10^5$. It is revealed that magnetohydrodynamic effect reduces flow strength. Likewise the case of the velocity profiles, magnetic effect reduces the magnitude of temperature distribution. Total entropy generation shows decreasing trend when the volume fraction of the nanofluids is increased. Increasing nanoparticle size results in increasing total entropy generation and the Bejan number.

1. Introduction

The need of a fluid for industrial purposes with higher heat dissipation properties has been in place for a long time. Though water offers advantages over other fluids due to easy availability and properties, use of water is limited by its lower thermal conductivity in comparison to other materials. A new class of heat transfer fluids offering significant improvement in heat transfer performance is nanofluids [1]. Nanofluids is a mixture of a carrier fluid and suspended metallic nanoparticles and is characterised by higher thermal conductivities and high heat transfer coefficients compared to the base fluids. The presence of nanoparticles changes the transport properties of the fluid, which ultimately enhances the heat transfer rate of nanofluids. The possible application area of nanofluids is in advanced cooling systems, micro/nano-electromechanical devices as well as in large scale thermal management systems, *viz.* heat exchangers, evaporators and industrial cooling applications.

Serious attention has been paid over the last few years [2–6] to study the thermal properties and heat transfer characteristics of nanofluids primarily because of the immensely significant technological implications of the use of nanofluids. Several experimental and theoretical studies on the subject have been reported in open literature. Eastman et al. [2] measured the thermal conductivity of nanofluids containing alumina (Al_2O_3), Copper oxide (CuO) and copper (Cu) nanoparticles in different base fluids and observed a significant improvement (~60%) in thermal conductivity as compared to the corresponding base fluids for only 5 vol.% of nanoparticles. Xuan and Li [3] indicated that the suspension of Cu-nanoparticles (2–5% by volume) in transformer oil with the use of oleic acid as dispersant had superior characteristics of conductivity compared to the suspension of Cu particles in water. They concluded that the thermal conductivity of nanofluids is also dependent on the properties of base fluids and the nanoparticles. Xie et al. [4] investigated the effects of the specific surface area (*SSA*) of the dispersed nanoparticles, *pH* value of the suspension, and thermal conductivity of the base fluid on the thermal conductivity of the Al_2O_3 nanofluids. In another study, Das et al. [5] have demonstrated the effect of particle size on the enhancement of thermal conductivity. The effect of volume fraction has been found to be prominent with the lower volumetric fraction of the nanofluids providing better heat transfer. Ding et al. [6] investigated the heat transfer performance of aqueous suspensions of carbon nanotubes (*CNT* nanofluids) and observed a significant enhancement of heat transfer coefficient of the nanofluids.

In recent years, studies on convective heat transfer characteristics of nanofluids have been conducted and reported in literature

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Nomenclature

B	magnetic field
Be	Bejan number
g	acceleration due to gravity
Gr	Grashof number $\left(\frac{\beta_f g H^4 (\Delta T/L)\rho_f^2}{\mu_f^2}\right)$
H	depth of the channel
Ha	Hartmann number $\left(Ha = \sqrt{\frac{B^2 \sigma H^2}{\mu_f}}\right)$
J	local ion current density
k_f	thermal conductivity of the fluid, W/m K
k_s	thermal conductivity of the solid, W/m K
L	length of the domain
p	pressure
t	time
T	temperature
U, V	dimensional velocity components in X and Y directions
u, v	non-dimensional velocity components in x and y directions
X, Y	dimensional coordinates
x, y	non-dimensional coordinates

Greek symbols

σ	electrical conductivity
α_f	thermal diffusivity of a fluid
β	thermal expansion coefficient
β_f	fluid thermal expansion coefficient
β_s	solid thermal expansion coefficient
μ_f	viscosity of a fluid
ρ_f	density of a fluid
ρ_s	density of a solid
θ	non-dimensional temperature,
ϕ	nanoparticle volume fraction
ν_f	kinematic viscosity of the fluid
δ	aspect ratio of the domain (H/L)
ΔT	temperature difference between the lateral ends of the domain

Subscripts

eff	effective
ref	reference
f	fluid
nf	nanofluids
s	solid

[7,8]. In particular, fluid flow and heat transfer in a rectangular or square enclosure filled with nanofluids has been the subject of many studies in the past [9–19]. Khanafer et al. [9] investigated the heat transfer performance of nanofluids in a differentially heated enclosure and found significant increase in heat transfer rate due to the presence of suspended nanoparticles in the fluid. However, in a similar study, Putra et al. [10] found apparently contradictory behaviour of heat transfer deterioration of nanofluids inside a horizontal cylinder. The authors [10] found a systematic deterioration in natural convective heat transfer in their experimental study. Jou and Tzeng [11] also reported heat transfer enhancement using nanofluids in a two-dimensional enclosure and presented an empirical equation between average Nusselt number and particle volume fraction. Tiwari and Das [12] studied the heat transfer augmentation in a lid-driven cavity and analysed the flow processes induced by a nanofluids. Ho et al. [13] conducted studies for natural convection in a square enclosure filled with Al_2O_3–water nanofluids and observed both heat transfer enhancement as well as reduction in heat transfer. In a recent study, Yu et al. [14] presented a numerical analysis of transient buoyancy-driven convective heat transfer of water-based nanofluids in a triangular enclosure. Among the above-mentioned studies, many of the research efforts have been directed towards investigating the effects of thermal conductivity and effective viscosity on natural convection of nanofluids in enclosures under different physical conditions [15–19].

A number of studies have been carried out on the magnetohydrodynamic convection of fluids inside cavities of various aspect ratios and operating conditions [20–29]. Studies pertaining to magnetohydrodynamic convection of nanofluids inside square [30] and rectangular [31] cavities indicated that increasing the magnitude of magnetic field decreases heat transfer and average Nusselt number.

Apart from convection in cavities, some studies are available in the literature on the mixed convection in parallel plate channels. Aung and Worku [32] presented theoretical analysis on the fully developed mixed convection vertical channel. They reported the condition for flow reversal for a critical buoyancy parameter. Recently, Chamkha et al. [33] reported theoretical analysis on the fully developed mixed convection flow of a micropolar fluid in a parallel plate vertical channel with an asymmetric wall temperature distribution. Grosan et al. [34] studied thermophoretic transport of small particles through a fully developed laminar, mixed convection flow in a parallel vertical channel. They observed that particle deposition efficiency is less effective near the hot wall than near the cold wall. In another investigation, Grosan and Pop [35] investigated the effect of thermal radiation on fully developed mixed convection flow in a vertical channel. They found that increase in radiation parameter reduces flow reversal. Owing to the rapid developments in heat transfer enhancement in a spectrum of industrial settings (MEMS, heat exchangers of different geometrical configurations, microtubes, channels, etc.) several research efforts have been directed at elucidating the role of nanofluids through different media [36–44].

To the best of the authors' knowledge, the number of studies reported in the previous literature related to magnetohydrodynamic flow of nanofluids inside a long channel is very limited, and this has motivated the present investigation. Accordingly, in this paper, a theoretical analysis has been undertaken to investigate buoyancy driven convection of nanofluids in an infinitely long channel under superimposed magnetic field. The present problem is extremely significant with wide range of technological (viz. electronic cooling, synthesis of polymeric nanocomposites, nano-structured magnetorheological fluids for semi-active vibration dampers etc.) and biomedical (viz. biostimulators, magnetically driven drugs, micro-total analysis systems-μ *TAS* etc.) applications [45–47]. On the other hand, the study of the effect of an external magnetic field on the flow and heat transfer in a channel or a cavity is significant because of engineering applications such as cooling of nuclear reactors, MHD micropumps, electronic packages, microelectronic devices, and so on [48].

In the present paper, we analyze the effect of a transverse magnetic field on the fully developed, buoyancy driven laminar mixed convective flow of nanofluids in an infinitely long channel using closed form analytical solutions. For the purpose of analysis, water-based nanofluids containing various volume-fractions of aluminum oxide (Al_2O_3) nanoparticles is used. The combined effects of magnetohydrodynamic mixed convection, magnetic effect,