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Experimental investigation of the flow and heat transfer of magnetic nanofluid in a vertical tube in the presence of magnetic quadrupole field

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ABSTRACT

In this paper, the effects of applying magnetic field on hydrodynamics and heat transfer of Fe_3O_4/water magnetic nanofluid flowing inside a vertical tube have been studied experimentally. The applied magnetic field was resulted from quadrupole magnets located at different axial positions along the tube length. The variations of the local heat transfer coefficient and also the pressure drop of the ferrofluid flow along the length of the tube by applying the magnetic quadrupole field have been investigated for different Reynolds numbers.

The obtained experimental results show maximum enhancements of 23.4%, 37.9% and 48.9% in the local heat transfer coefficient for the magnetic nanofluid with 2 vol% Fe_3O_4 in the presence of the quadrupole magnets located at three different axial installation positions for the Reynolds number of 580 and the relative increase in total pressure drop by applying the magnetic field is about 1% for Re = 580. The increase of the heat transfer coefficient is due to the radial magnetic force toward the heated wall generated by magnetic quadrupole field acting over the ferrofluid flowing inside the tube so that the velocity of the ferrofluid in the vicinity of the heated wall is increased. It is also observed that the enhancement of heat transfer coefficient by applying magnetic quadrupole is decreased with increasing the Reynolds number.

1. Introduction

Ferrofluid is a magnetic fluid which is composed of magnetic nanoparticles (such as iron, nickel, cobalt and their oxides, etc.) with the size in the range of 5–15 nm dispersed in the base fluid [1]. The magnetic nanofluids are recommended as the working fluid for engineering applications. Although magnetic nanoparticles have relatively low thermal conductivity rather than metallic and metallic oxide nanoparticles, their controllability by magnetic field makes them ideal to be used in different types of heat exchange equipment, heat transfer enhancement for cooling of high powers, heat pipes [2], thermosyphons [3], microgravity applications [4], heat exchangers [5], magnetically-driven heat transport device [6] and miniature electronic devices [1].

There is a few experimental investigation in the literature about the flow and heat transfer behavior of magnetic nanofluids in the presence of magnetic field. Wrobel et al. [7] studied the thermos-magnetic convective flow of paramagnetic fluid in vertical annular enclosures both experimentally and numerically. They found that external magnetic field is able to control magnetic convection of paramagnetic fluid. Lajavardi et al. [8] studied heat transfer of laminar flows of ferrofluid in presence of magnetic field. They stated that water-Fe_3O_4 nanofluids cannot increase heat transfer of laminar flow regime in absence of magnetic field but by increasing magnetic field strength, the heat transfer coefficient is increased.

Sundar et al. [9] also studied the convective heat transfer of Fe_3O_4 ferrofluid for turbulent flow in a circular tube in the absence of magnetic field experimentally and their results showed that the heat transfer coefficient is enhanced by 30.96% for the volume fraction of 0.6% in comparison with water flow at similar operating conditions. Ghofrani et al. [10] investigated forced convective heat transfer of a

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Nomenclature

c_p	specific heat capacity (J kg^{-1} K^{-1})
d	tube diameter (m)
h	heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number, hd/k
Pr	Prandtl number, $\frac{\mu c_p}{k}$
Re	Reynolds Number, $\frac{4\dot{m}}{\pi d\mu}$
ΔP	pressure drop (Pa)
$\ddot{q}$	heat flux (W/m^2)
T	temperature (°C)
z	axial distance
u	velocity (m/s)

Greek symbols

ρ	density (kg/m^3)
μ	dynamic viscosity (Pa.s)

Subscripts

z	axial direction
i	inner
o	outer

ferrofluid flowing inside a copper tube under constant and alternating magnetic fields. They found that applying a constant magnetic field has low enhancement in the heat transfer. The numerical study of Aminfar et al. [11] showed that applying magnetic field increases the Nusselt number and friction factor in a vertical rectangular duct. Sheikhnejad et al. [12] studied heat transfer enhancement by ferrofluid as a coolant in different linear magnetic field distributions. They found that with constant magnetic field energy, the one with lower gradient and higher intensity will result in the best choice for heat transfer enhancement as well as energy saving that maximizes the effectiveness value. Hayat et al. [13] studied the three dimensional magnetohydrodynamics flow of viscoelastic nanofluid in the presence of nonlinear thermal radiation and they found that the thermal boundary layer thickness is an increasing function of radiative effect. Hayat et al. [14] also presented an analytical solution for magnetohydrodynamic nanofluid flow induced by a stretching sheet with heat generation/absorption and they found that the temperature distribution has a direct relationship with Biot number and magnetic parameter. They also studied the three dimensional boundary layer flow of nanofluid under magnetic field effects [15] and their results showed that the effect of Brownian motion and thermophoresis parameters on the nanoparticles concentration distribution are quite opposite. The convective heat transfer and hydrodynamic behavior of magnetic nanofluids under the effects of an alternating magnetic field were investigated by Goharkhan et al. [16]. Their results showed that the convective heat transfer coefficient is proportional to the Reynolds number and volume fraction of the nanoparticles.

In this study, the effects of applying magnetic quadrupole field on the convective heat transfer characteristics and also on the pressure drop of the Fe_3O_4/water magnetic nanofluid flow through a vertical tube in different Reynolds numbers will be studied experimentally. Different axial installation positions of the quadrupole magnets along the tube length will be examined and the variations of local heat transfer coefficient of the laminar convective flow of the magnetic nanofluid in the presence of magnetic field will be compared with no magnetic field case.

2. Experimental setup

2.1. Test rig

An experimental setup was used to measure the heat transfer coefficients of the upward Fe_3O_4/water nanofluid flow in a vertical tube in the presence of magnetic quadrupole field. The schematic diagrams of the experimental setup at Royal Institute of Technology (KTH) is shown in Fig. 1.

The test rig included a gear pump (MCP-Z, Ismatec, Switzerland) with maximum flow rate of 3840 ml/min and a Coriolis mass flow meter (CMFS015 with 2700 transmitter, Micromotion, Netherlands) with accuracy of 0.1% for the mass flow rate between 167 and 5500 g/min. A cooling jacket has been used in order to cool down the working fluid and adjust the temperature at the inlet of the test section including

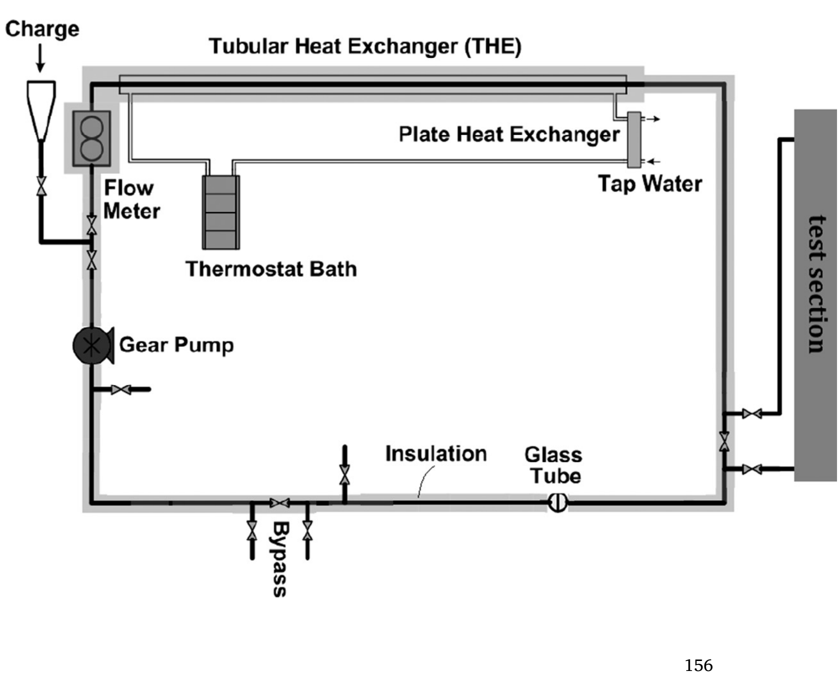

Fig. 1. Experimental setup for measuring heat transfer coefficient of magnetic nanofluid.