International Journal of Heat and Mass Transfer 68 (2014) 94–109

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effect of magnetic field on laminar convective heat transfer of magnetite nanofluids

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ARTICLE INFO

Article history:
Received 13 March 2013
Received in revised form 24 July 2013
Accepted 5 September 2013
Available online 3 October 2013

Keywords:
Magnetite nanofluid
Thermal conductivity
Convective heat transfer coefficient
Laminar flow
Magnetic field
Aggregation

ABSTRACT

The effect of an external magnetic field on the convective heat transfer and pressure drop of magnetite nanofluids under laminar flow regime conditions ($Re < 830$) is investigated. Specifically, the influence of magnetic field strength and uniformity on the convective heat transfer coefficient is examined through experiments and supporting simulations of the magnetic flux density distribution and magnetic force acting on nanoparticles. The data show that large enhancement in the local heat transfer coefficient can be achieved by increasing the magnetic field strength and gradient. The convective heat transfer enhancement becomes more pronounced at higher Reynolds numbers, with a four-fold enhancement (i.e., relative to the case with no magnetic field) obtained at $Re = 745$ and magnetic field gradient of 32.5 mT/mm. The effect of the magnetic field on the pressure drop is not as significant. The pressure drop increases only by up to 7.5% when magnetic field intensity of 430 mT and gradients between 8.6 and 32.5 mT/mm are applied. Based on the simulation results of magnetic field and magnetic force distribution, the mechanisms for heat transfer enhancement are postulated to be accumulation of particles near the magnets (leading to higher thermal conductivity locally), and formation of aggregates acting enhancing momentum and energy transfer in the flow.

1. Introduction

Magnetite nanofluids are engineered colloidal suspension of magnetite nanoparticles in a basefluid, designed to be used in heat transfer applications such as cooling systems of microdevices [1]. Recent studies have shown significant enhancement in the thermal conductivity of magnetite nanofluids when magnetic fields are applied [2]. The main mechanism responsible for such enhancements is believed to be particle alignment in the direction of the applied magnetic field, parallel to the temperature gradient [2]. The alignment is assumed to reduce thermal resistance for heat transfer, due to increasing the thermal conductivity of magnetite nanofluids.

Remarkable heat transfer enhancements have been also reported under forced convection conditions. Motozawa et al. [1] examined the effect of uniform magnetic fields on heat transfer coefficient of magnetite nanofluid in laminar flow regime experimentally. They demonstrated that increasing the magnetic field intensity, locally increases the heat transfer coefficient by up to 20%. Similarly, Lajevardi et al. [3] reported an enhancement in heat transfer performance of magnetite nanofluid due to an increase in the concentration of magnetite nanoparticles when a uniform magnetic field was applied perpendicular to the flow. The observed enhancement was attributed to increased aggregation at higher solid volume fractions. Conversely, the investigation of Li and Xuan [4] on the effect of external magnetic field strength and its orientation on heat transfer characteristics of magnetite nanofluid flow around a fine wire showed enhancements only in presence of a magnetic field gradient. The Kelvin forced-induced particle migration was considered to be responsible for the observed enhancement. Li and Xuan [4] data however indicated that the heat transfer coefficient can be reduced when a uniform magnetic field perpendicular to the flow was applied. It is believed that the experimental setup used by Li and Xuan [4] may have contributed to the reported inconsistencies.

The aim of this study is to gain an insight into the effect of magnetic field on the laminar convective heat transfer of magnetite nanofluids using a systematic experimental approach. Specifically the effects of magnetic field uniformity, gradient, and strength as well as magnets configuration, in terms of the number and arrangement of magnets, on the convective heat transfer of

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.09.011

Nomenclature

Variables

B	magnetic flux density
B_r	remnant magnetic flux density
c_p	specific heat capacity
D	diameter
f	friction factor
F	force
h	convective heat transfer coefficient
H	magnetic field
k	thermal conductivity
k_w	temperature-dependent thermal conductivity of stainless steel
L	length
Nu	Nusselt number
Pr	Prandtl number
Q	thermal power
q''	heat flux based on thermal power
r	radius
Re	Reynolds number
T	temperature
V	velocity
z	vertical distance from the entrance

Greek symbols

μ	dynamic viscosity
μ_0	permeability of free space
μ_r	relative permeability
υ	kinematic viscosity
ρ	density
ϕ	particle volume fraction
χ_i	magnetic susceptibility

Subscript and superscript

b	bulk
f	fluid (liquid)
i	inside
M	magnetic
nf	nanofluid
o	outside
p	particle (solid)
w	wall

magnetite nanofluid in the laminar flow regime are examined. The experimental findings combined with the simulation results for magnetic flux density and magnetic force acting on nanoparticles, are then used to explain the potential driving mechanisms for the observed enhancements under given conditions.

2. Experimental method

2.1. Apparatus

A schematic diagram of the experimental setup used in this study is shown in Fig. 1. The experimental setup was a closed loop

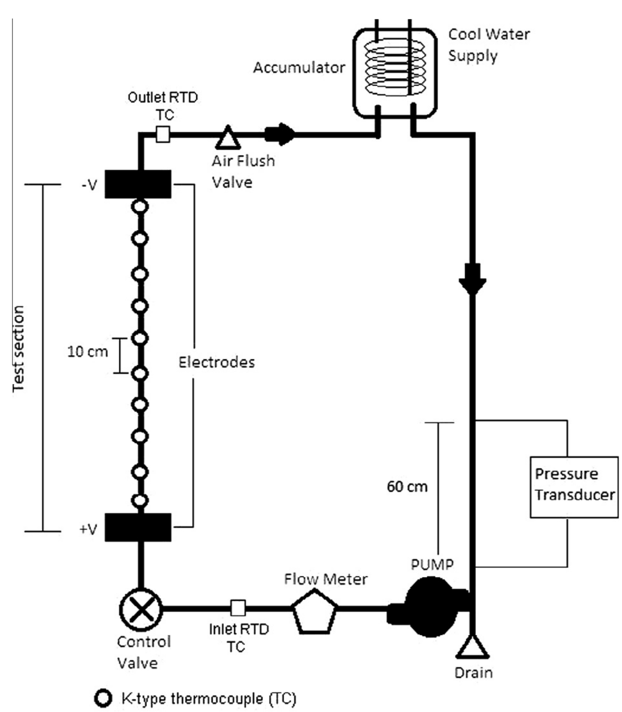

Fig. 1. A schematic diagram of the closed loop convective laminar flow system.

Table 1
NdFeB, grade N42 permanent magnet specifications.

Maximum operating Temperature	80 °C
Surface field	333.2 mT
Residual flux density (B_{rmax})	1320 mT
Maximum energy product (B_{Hmax})	42 MGOe

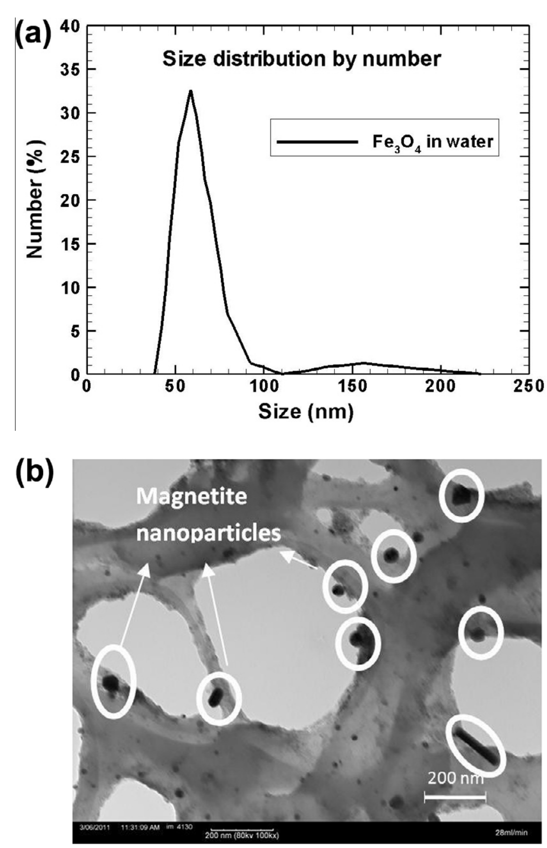

Fig. 2. Particle size distribution of magnetite nanoparticles using (a) DLS, (b) TEM.