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Research Paper

Experimental study on heat transfer augmentation of graphene based ferrofluids in presence of magnetic field

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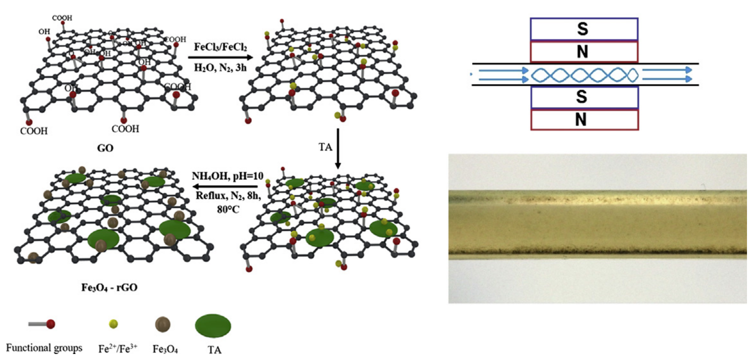
HIGHLIGHTS

- Synthesizing graphene based ferrofluids with high colloidal stability.
- Investigation of thermo-physical and magnetic properties.
- Investigation of the forced convective heat transfer in presence of magnetic field.
- The local convective heat transfer was enhanced up to 82%.

GRAPHICAL ABSTRACT



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ABSTRACT

The effect of a permanent magnetic field on the heat transfer characteristics of hybrid graphene-magnetite nanofluids (hybrid nanofluid) under forced laminar flow was experimentally investigated. For this purpose, a reduced graphene oxide-Fe_3O_4 was synthesized by using two-dimensional (2D) graphene oxide, iron salts and tannic acid as the reductant and stabilizer. Graphene sheets acted as the supporting materials to enhance the stability and thermal properties of magnetite nanoparticles. The thermo-physical and magnetic properties of this hybrid nanofluid have been widely characterized and it shows that the thermal conductivity increased up to 11%. The hybrid nanofluid behaves as a Newtonian fluid with liquid like behavior with superparamagnetic properties as was evident from its magnetic saturation value at 45.9 emu/g. Moreover, the experimental heat-transfer results indicated that the heat transfer enhancement of the hybrid nanofluid compared to the control fluid (distilled water) was negligible when no magnetic field was applied. Additionally, the convective heat transfer was significantly improved under the influence of a magnetic field with a maximum enhancement of 82% in terms of the convective heat transfer properties of the hybrid nanofluid.

1. Introduction

Recently, advances in materials science have developed with a breathtaking speed for the good of mankind and its living

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Nomenclature

Abbreviations

B	magnetic flux density
c_p	specific heat capacity at constant pressure, J/kg K
d	tube diameter, m
f	friction factor
h	convective heat transfer coefficient, W/m^2 K
H	magnetic field
I	electrical current, A
k	thermal conductivity, W/m K
l	liter
L	tube length, m
Nu	Nusselt number
P	pressure, Pa
q''	heat flux, W/m^2
Re	Reynolds number
T	temperature, K
V	voltage
v	mean velocity, m/s
x	axial distance, m

Greek symbols

η	thermal efficiency index
μ	viscosity, Pa s
μ_o	permeability of free space
μ_r	relative permeability
ρ	density, kg/m^3
X_i	magnetic susceptibility

Acronyms

DW	distilled water
FESEM	Field Emission Scanning Electron Microscopy
FT-IR	Fourier transform-infrared
GO	graphene oxide
rGO	reduced graphene oxide
SAED	selected area (electron) diffraction
TEM	transmission electron microscopy
UV–vis	UV–vis spectrophotograph
VSM	vibrating sample magnetometer
wt%	weight percentage
XPS	X-ray photoemission spectromet
XRD	X-ray diffraction

Subscripts

avg	average
b	bulk
bf	base fluid
fl	frictional
i	inner
in	inlet
m	mean
nf	nanofluid
np	nanoparticle
o	outer
out	outlet
r	remnant
Th	thermal
w	wall

conditions. Specifically, advanced nanomaterials such a 2D graphene sheets have been recognized as a formidable future technology for the current century [1]. Graphene oxide (GO) is among the most extensively studied graphene-based nanomaterials and have found wide applications in composite materials for heat transfer applications [2–8]. Especially, over the years nanomagnetic materials with special properties have progressively replaced other less advanced materials in numerous applications [9,10]. For instance, ferromagnetic materials including iron or cobalt, or ferrimagnetic materials including magnetite (Fe_3O_4) has shown great promise as magnetic nanofillers in applications such as heat transfer [11,12], biomaterials [13,14], optical and imaging [15,16] and water purification [17,18]. Among them, Fe_3O_4 nanoparticles have been the most promising because of their low toxicity and good biocompatibility [19,20]. Nanofluids, a new class of working fluids, have due to their excellent thermophysical properties found use in various heat transfer applications [21–23]. Even still, the application range of magnetite nanofluids are even more impressive ranging from biomedicine to lubricating rotary shafts as well as numerous industrial applications [24,25]. Therefore, research into magnetic nanofluids is called upon to advance their hitherto unmatched portfolio of properties [26]. To this end and for reasons discussed above, it's anticipated that the functionalization of GO with Fe_3O_4 nanoparticles (Fe_3O_4-GO) could hold vast potential in the field of nanofluids because of their large saturation magnetization value and heat transfer capability. There are two significant advantages of such hybrid magnetic nanofluids according to previous research works: (a) a well-controlled morphology and size distribution of the Fe_3O_4 nanoparticle in the hybrid magnetic nanofluid, (b) controlled decoration of Fe_3O_4 nanoparticle on the edge of GO nanosheets with the basal plane of the GO nanosheet via $\pi - \pi$ stacking [27].

Although thermal conductivity of hybrid magnetic nanofluids in the presence or absence of magnetic field, has been the subject of many past studies, relatively little effort has been focused on the convective heat transfer of magnetic nanofluids. Indeed, it has been proven that the thermal conductivity of magnetic nanofluids increases under applied oscillating and constant magnetic field [19,20]. Magnetic nanofluid have therefore recently come to the attention of the heat transfer community in recent years. More importantly, there is a need for an effective control of the heat transfer rate, as this system property has many industrial applications in new technologies such as smart cooling devices [28,29]. Logically, if the existence of particles is the reason for enhancement in heat transfer, one way of achieving heat transfer enhancement coupled with adequate control is having the ability to manipulate particles in the base fluid [30]. The properties and characteristics of normal magnetic fluids have been widely researched and tested in a wide variety of applications [31].

Azizian et al. [12] worked on the effect of Fe_3O_4 on the laminar convective heat transfer and found that the local heat transfer coefficient of nanofluids can be enhanced by 300% under constant magnetic field. Lajvardi et al. [11] investigated the local heat transfer coefficients for three different magnetic fields under the thermal developing region. They have found that the use of magnetic particles dispersed in distilled water (DW) cannot enhance the convective heat transfer in the absence of magnetic field. Yarahmadi et al. [9] worked on the Fe_3O_4 nanofluid under oscillating and constant magnetic field with different magnetic field arrangements. They have found that the local convective heat transfer coefficient enhanced by 19.8% with *Re* = 465 and concentration of 5%. Goharkhah et al. [10] studied on the influence of an oscillating magnetic field on laminar convective heat transfer and found that the heat transfer coefficient increased up to 16.4% in the absence of a mag-