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Heat transfer and entropy generation analysis of hybrid graphene/Fe_3O_4 ferro-nanofluid flow under the influence of a magnetic field

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ABSTRACT

The heat transfer characteristics and entropy generation rate of hybrid graphene-magnetite nanofluids under forced laminar flow that subjected to the permanent magnetic fields were investigated. For this purpose, a nano-scale reduced graphene oxide-Fe_3O_4 hybrid was synthesized by using graphene oxide, iron salts and tannic acid as the reductant and stabilizer. The thermophysical and magnetic properties of the hybrid nanofluid have been widely characterized and thermal conductivity has shown an enhancement of 11%. The experimental results indicated that the heat transfer enhancement of hybrid magnetite nanofluid compared to the case of distilled was negligible when no magnetic field was applied. Additionally, the heat transfer characteristics have been improved significantly under magnetic field. The outcome of the analysis shows that the total entropy generation rate was reduced up to 41% compared to distilled water. It appears that these magnetic hybrid nanofluids can function as good alternative fluids in the magnetic thermal engineering systems.

1. Introduction

The investigation of the forced convective heat transfer has been attracted in many research works due to its practical relevance in turbo-machinery, heat exchangers, air conditioning systems, refrigeration and chemical reactors [1–3]. More inventive and efficient cooling technologies and fluids are now required to support this technological development [4,5]. Nanofluids, as a new class of working fluids, are a challenge for thermal fluid sciences that provided by nanotechnology. Due to their excellent thermophysical properties, nanofluids find many applications in the heat transfer enhancement [6–8]. The magnetic materials as a new class of nanoscience materials, have been used in the part of daily life since ancient eras [9–12]. Nanomagnetic materials with special properties are progressively replacing by the other material in the specific applications. Therefore, the researchers need to understand their properties at the fundamental level [10,13]. The magnetic particles can be either ferromagnetic materials including iron or cobalt, or ferromagnetic materials including magnetite (Fe_3O_4). Among them, Fe_3O_4 nanoparticles have been paying much attention because of their low toxicity and good biocompatibility [14–17]. However, the research has shown that the functionalization graphene oxide with Fe_3O_4 nanoparticles (Fe_3O_4-GO) holds vast potential in nanofluid because of their large saturation magnetization value and heat transfer capability. Graphene based materials such as graphene oxide (GO) have shown wide applications in composite materials and heat transfer applications [18–29]. A number of studies have been carried out on heat transfer properties of magnetic nanofluid and it was found that heat transfer characteristics under magnetic field are in general better than those of base fluids. Table 1 is summarized some recent work on convective heat transfer of magnetic nanofluids.

Even though, the performance of any thermal management systems such as heat exchangers can be evaluated by the other thermodynamic performance analysis, including entropy generation rates [32–34]. The heat transfer improvement is a non-monotonic parameter and maximizing of this ratio does not really show the improvement of thermodynamic performance due to irreversibilities involved. Therefore, these irreversibilities work can be measured by entropy generation rates of a heat transfer system [35]. The irreversibility analysis of different systems was investigated by several researchers [35–37] and they have shown that this is a powerful tool to decide which process or installation

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Table 1
Recent development on magnetic nanofluid as a heat transfer fluid.

Investigators	Types of magnetic fields	Observations
Azizian et al. [4]	Constant magnetic field	The local heat transfer coefficient of nanofluids enhanced by 300%.
Goharkhah et al. [10]	Oscillating and constant magnetic field	The heat transfer coefficients were enhanced by 24.9% and 37.3% under constant and alternating magnetic field, respectively.
Yarahmadi et al. [9]	Constant magnetic field with different magnetic field arrangements	The local convective heat transfer coefficient enhanced by 19.8% with $Re = 465$ and concentration of 5%.
Ghofrani et al. [30]	Alternating magnetic field	A maximum of 27.6% enhancement in the convection heat transfer was observed.
Lajvardi et al. [31]	Constant magnetic field	The use of magnetic particles dispersed in distilled water (DW) cannot enhance the convective heat transfer in the absence of magnetic field.

Table 2
Details of experimental heat transfer setup, which mimics the heat exchangers in industrial applications.

Parameters	Details
Test section	
Total length	2000 mm
Heating length	1404 mm
Inner diameter	4.5 mm
Outer diameter	6.5 mm
Entrance length	596 mm (L≈0.05ReD)
Heating method	Heated directly by a DC power supply (KEYSIGHT Technologies).
Temperature measurement	
Inlet and outlet temperatures (T_{in} and T_{out})	K-type thermocouple (Omega, ±0.1 °C accuracy).
Outer wall temperatures (T_w)	K-type thermocouples (Omega, ±0.1 °C accuracy), which is fixed at the outer surface of the tube at distances of 830, 1064, 1298, 1532, 1766 mm from the entrance of test section.
Pressure drop measurement	Pressure Meter, Digitron, ±0.15% accuracy.
Flow rate measurement	Flow sensors (OMEGA, ±3% accuracy).
Pump	Peristaltic pump (longer pump).
Data acquisition system	Graphtec (midi logger gl220).
Data sampling rate	Every 1 s for 1000 s after the system reaching steady-state condition.
Cooling unit	Refrigerated circulating bath (Thermo Haake, Karlsruhe, Germany).
Nanofluid tank	2-L capacity jacketed beaker.
Insulator	A thick ceramic fiber cloth and calcium silicate bar is installed around test section.
Heat loss	<5% at inlet temperature of 30 °C.

is more efficient. The irreversibility analysis (entropy generation rate) is the measurement of entropy that created by the irreversibilities such thermal and the frictional loss [1].

This research work has presented a synthesize method for a hybrid reduced graphene oxide (rGO)-Fe_3O_4 nanofluid with TA (tannic acid) as the reductant and stabilizer. The stability, thermal conductivity and viscosity of magnetic nanofluid have been tested at several conditions. Based on the literatures overview, the energy management is analyzed by studying the entropy generations due to fluid frictional loss and heat transfer as the proportions of the irreversibilities works. The aim of the present study is to analyze entropy generation and the advantage or disadvantage of rGO-Fe_3O_4 nanofluids over base fluids in the laminar flow regime will be investigated thoroughly.

2. Experimental method and process

2.1. Materials

Graphite flakes were purchased from Ashbury, Inc. Hydrochloric acid (HCl, 37%), Sulfuric acid (H_2SO_4, 98%), potassium permanganate ($KMnO_4$, 99.9%) and hydrogen peroxide (H_2O_2, 30%) were purchased from Merck Chemicals. Tannic acid (TA), $FeCl_2 \cdot 4H_2O$ and $FeCl_3 \cdot 6H_2O$ were purchased from Sigma-Aldrich.

2.2. Material preparation

Water soluble graphene oxide (GO) that used in this experiment was synthesized by a simplified Hummers' method [38,39]. For the hybrid magnetic nanofluid preparation, 50 mg of GO was mixed with 100 mL distilled water (DW) and then placed in a three-neck round flask. 1.3 g of $FeCl_3 \cdot 6H_2O$ and 475 mg of $FeCl_2 \cdot 4H_2O$ predissolved in 20 mL DW were added into the flask, which was continuously stirred and purged with high-purity N_2 (Nitrogen gas) for 3 h. After addition of tannic acid, pH of mixture was adjusted to 10 using ammonia solution. Then, the mixture was heated up to 80 °C and refluxed in a nitrogen atmosphere for 8 h. Subsequently, the hybrid rGO-Fe_3O_4 was collected after washing with DW for several times. The blackish precipitates were added into the beaker and homogenized by stirring and the concentrations of magnetic nanofluid were maintained at 0.5 wt%.

2.3. Characterization method

Transmission electron microscopy (TEM) measurements were conducted on a CARL ZEISS-LIBRA120 microscope. X-ray diffraction (XRD)

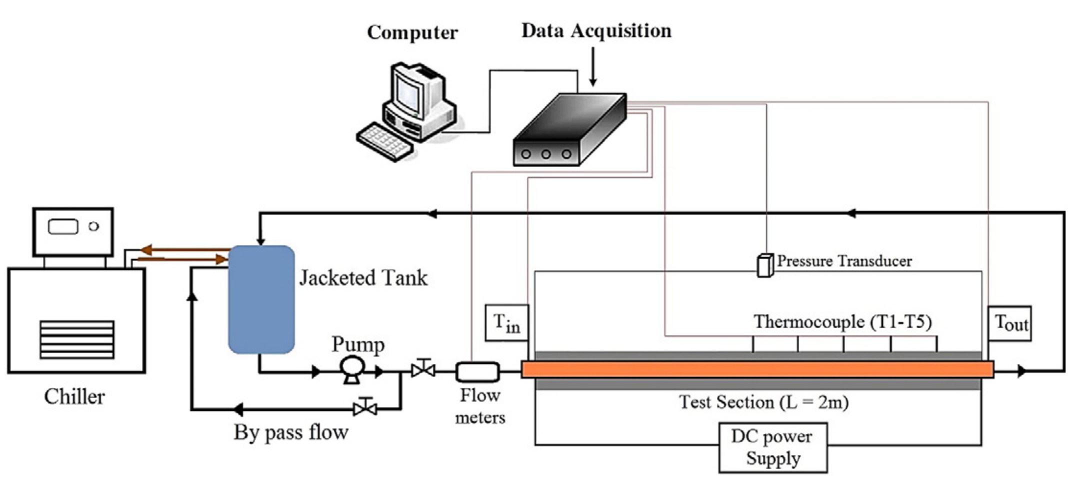

Fig. 1. Schematic of the convective heat transfer loop.