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Optimization of irreversibility and thermal characteristics of a mini heat exchanger operated with a new hybrid nanofluid containing carbon nanotubes decorated with magnetic nanoparticles

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ABSTRACT

A numerical investigation is performed to evaluate the effect of nanoparticle volume concentration and Reynolds number on the heat transfer and entropy generation characteristics of a hybrid nanofluid containing tetramethylammonium hydroxide (TMAH) coated Fe_3O_4 (magnetite) nanoparticles and gum arabic (GA) coated carbon nanotubes (CNTs) flowing inside a counter-flow double-pipe heat exchanger. Variable thermophysical properties are employed such that thermal conductivity is considered dependent on temperature and concentration, while viscosity is dependent on temperature, concentration and shear rate. The results demonstrate that the overall heat transfer coefficient and the entropy generation rate augment with the increase of Reynolds number, CNT concentration and magnetite concentration. In addition to the assessment and analysis of the outcomes, models of the overall heat transfer coefficient and global total entropy generation are developed in terms of the Fe_3O_4 and CNT concentrations and Reynolds number using neural network. Then, genetic algorithm is utilized in combination with compromise programming in order to obtain the optimal cases with maximum heat transfer and minimum total entropy generation. To achieve the minimum total entropy generation along with the maximum heat transfer, applying the nanofluids with great nanoparticle concentrations alongside low Reynolds numbers is suggested.

1. Introduction

Double-pipe heat exchangers are perhaps the simplest heat exchangers used in industries that consist of one pipe inside another. This kind of heat exchanger is extensively used in industry because of its simplicity, ease of manufacturing and compactness. Conventional heat transfer fluids such as water, air, transformer oil, and ethylene glycol (EG) are dominant fluids in industrial cooling and heating but their inherently low thermal conductivity has hampered their application in the cooling or heating of high heat flux devices. In order to overcome this issue, nanofluids seem to be a promising option for researchers. These suspensions are produced by dispersion of solid particles with sizes of 1–100 nm in a base liquid [1]. This term was first proposed by Choi [2] in 1995, and it has since gained in popularity.

The convective heat transfer characteristics of different nanofluids flow in a double-pipe heat exchanger have been experimentally and numerically investigated by various researchers in the recent years. Bahiraei and Hangi [3] applied the two-phase Eulerian-Lagrangian technique to examine the effect of quadrupole magnetic field on the efficacy of aqueous magnetic nanofluid containing Mn-Zn ferrite nanoparticles in a counter-flow double-tube heat exchanger. Their results revealed that an increase in the magnetic field magnitude causes increment of the pressure drop and heat transfer. Sarafraz et al. [4] assessed the heat transfer attributes of CNT-water nanofluid within a double-tube heat exchanger under turbulent and laminar flow conditions. They stated a heat transfer enhancement as much as 44% with respect to that of pure water for the mass concentration of 0.3%. The convective heat transfer of different concentrations of Fe_3O_4-water nanofluid flow in inner tube of a double-tube heat exchanger having return band for turbulent conditions was experimentally studied by Kumar et al. [5]. The maximum heat transfer enhancement was 14.7% for concentration of 0.06%. Shirvan et al. [6] implemented the response surface methodology and two-phase mixture model to conduct the sensitivity analysis for heat transfer of Al_2O_3 nanofluid inside a double-tube heat exchanger. It was concluded that the sensitivity of the mean Nusselt number to concentration is negative whereas to the Reynolds number is positive.

Literature survey shows that the majority of the investigations on the cooling performance of nanofluids are based on the first law of thermodynamics. However, due to the fact that it is impossible to

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Nomenclature

A	internal area of tube (m^2)
b	distance parameter
c_p	specific heat capacity (J/kg K)
D_b	compromised function
k	thermal conductivity (W/mK)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (Pa)
$\dot{Q}$	heat transfer rate (W)
Re	Reynolds number
$\dot{S}'''_{g,f}$	frictional entropy generation rate (W/m^3 K)
$\dot{S}'''_{g,h}$	thermal entropy generation rate (W/m^3 K)
$\dot{S}'''_{g,t}$	total entropy generation rate (W/m^3 K)
$\dot{S}_{g,f}$	global frictional entropy generation rate (W/K)
$\dot{S}_{g,h}$	global thermal entropy generation rate (W/K)
$\dot{S}_{g,t}$	global total entropy generation rate (W/K)
T	temperature (K)
U	overall heat transfer coefficient (W/m^2 K)
V	velocity (m/s)

Greek symbols

α	relative importance of the objective functions in comparison with each other
γ	shear rate (s^{-1})
ρ	density (kg/m^3)
φ	concentration (%)
μ	viscosity (kg/ms)

Subscripts

CNT	carbon nanotube
in	inlet
$LMTD$	logarithmic mean temperature difference
M	magnetite
nf	nanofluid
out	outlet
w	water

convert heat into equivalent amount of work, the quality of thermal energy should be evaluated. The lost work due to irreversible processes can be determined using the second law of thermodynamics. Entropy generation analysis is an effective tool to calculate the irreversibility of energy processes in thermal engineering systems. Moghaddami et al. [7] analytically examined the irreversibilities resulting from heat transfer and friction for Al_2O_3-water and Al_2O_3-ethylene glycol nanofluids within a heated pipe. They found that the rate of average entropy generation intensifies with augmenting nanofluid concentration in the cases that frictional entropy generation is main cause. Bianco et al. [8] numerically investigated friction, thermal and total irreversibilities of Al_2O_3-water nanofluid turbulent flow inside a heated pipe. They reported a descending trend for total irreversibility in terms of concentration for constant Reynolds number approach, whereas the opposite occurred for the constant mass flow rate approach.

Up to now only very few attempts have been made to examine the second law performance of nanofluids in annular spaces. Huminic and Huminic [9] assessed the heat transfer and entropy generation within a helically coiled double-pipe heat exchanger for TiO_2-water and CuO-water nanofluids. The thermal entropy production decreased with increment of volume concentration and the mass flow rate ratio, while the opposite is true for the frictional entropy generation. Farzaneh-Gord et al. [10] investigated the optimum geometry and working conditions of a double-pipe helical heat exchanger via the entropy generation minimization method. To this end, they introduced a dimensionless function for entropy generation number with four dimensionless variables, namely Prandtl number, Dean number, the ratio of helical pipe diameter to the tube diameter, and the duty parameter of heat exchanger. The authors minimized this function to develop expressions for the optimum values of the mentioned factors.

Hybrid nanofluids are novel nanofluids which are prepared by dispersing different types (two or more than two) of nanoparticles in a base fluid, and offer better heat transfer performance and thermophysical properties than convectional heat transfer fluids and nanofluids with single nanoparticles. So far, various hybrid nanofluids such as Fe_3O_4/Ag-EG [11], CNT/CuO [12], CNT/MgO [13], and CNT/TiO_2-water [14] have been prepared and tested by different researchers. The suspensions of CNT/Fe_3O_4 hybrid nanoparticles are one of the most widely studied group of hybrid nanofluids which combine the great thermal conductivity material of CNT and high magnetic material of Fe_3O_4. The hydrothermal attributes of CNT/Fe_3O_4-water hybrid nanofluid flowing within a circular pipe were experimentally evaluated by Sundar et al. [15]. They reported enhancement of Nusselt number about 14.81% and 31.10% for nanofluid with nanoparticle concentration of 0.3% at the Reynolds numbers of 3000 and 22,000, respectively. Shahsavar et al. [16] experimentally investigated the effects of constant and alternating magnetic fields on the convective heat transfer of CNT/Fe_3O_4-water hybrid nanofluid under laminar flow regime condition. Their results revealed that by application of the magnetic field, the convection heat transfer increases and the effect of the constant magnetic field was higher than that of the alternating magnetic field. Harandi et al. [17] carried out experiments to measure the thermal conductivity of CNT/Fe_3O_4-EG hybrid nanofluid as a function of temperature (25–50 °C) and concentration (0–2.3%). It was found that the thermal conductivity ratio augments with increment of the temperature and volume concentration.

Going through the literature, it is noticed that the effects of CNT/Fe_3O_4-water hybrid nanofluids on the first law and second law performances of heat exchangers have not been evaluated so far. Besides, it is revealed that there is a lack of understanding of how the non-Newtonian feature of nanofluids affect the performance of heat exchangers from the viewpoint of the first and the second laws of thermodynamics. The present study aims to investigate the heat transfer and entropy generation characteristics of a non-Newtonian water-based nanofluid containing Fe_3O_4/CNT nanoparticles in a double-pipe counter-flow heat exchanger. Variable thermal conductivity and viscosity are employed for simulating the nanofluid behavior. In addition to the assessment and analysis of the results, genetic algorithm is used in combination with compromise programming in order to determine the optimal cases with maximum heat transfer and minimum entropy generation. To the best knowledge of the authors, this work is the first investigation presenting the behavior of the laminar forced convective heat transfer and entropy generation of CNT/Fe_3O_4-water hybrid nanofluids inside a double-tube heat exchanger.

2. Physical properties of nanofluid

The water-based nanofluid containing TMAH coated magnetite nanoparticles and GA coated CNTs was synthesized and characterized in the author's previous work [18]. In order to synthetize the hybrid nanofluid, different amounts of the separately prepared magnetite-water and CNT-water nanofluids were mixed and the resulting mixture was sonicated for 5 min. The magnetite-water nanofluid was prepared via the method described by Berger et al. [19] and the water-based CNT nanofluid was produced via the technique proposed by Garg et al. [20]. The dispersibility and stability of magnetite and CNT nanoparticles in