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Investigation of heat transfer performance and friction factor of a counter-flow double-pipe heat exchanger using nitrogen-doped, graphene-based nanofluids☆

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ABSTRACT

Nitrogen-doped graphene (NDG) nanofluids are prepared using a two-step method in an aqueous solution of 0.025 wt.% Triton X-100 as a surfactant with various nanosheets at several concentrations (0.01, 0.02, 0.04, 0.06 wt.%). This paper reports results of experiments on thermal conductivity, specific heat capacity, and viscosity of the NDG nanofluids, as well as their convective heat transfer behavior flowing in a double-pipe heat exchanger. To assess the thermal properties, we used various water-based nanofluids as coolants to analyze the total heat transfer coefficient, convective heat transfer coefficient, the percentage of wall temperature reduction, pressure drop, and pumping power in a counter-flow double-pipe heat exchanger. A novel MATLAB code carried out the calculations for Reynolds numbers between 5000 and 15,000 (turbulent flow) and nanosheet weight percentages between 0.00% and 0.06%. An increase in Reynolds number or the percentage of nanomaterial could perhaps enhance the heat transfer of the working fluid. As an example, using 0.06 wt.% nanomaterial in the base fluid led to 15.86% enhancement of the convective heat transfer coefficient in comparison with water. Nonetheless, the penalty in terms of the rise in the pumping power was rather small. For a particular material, increasing Reynolds number or nanomaterial weight percentage would augment pumping power. Power consumption, heat removal, and heat transfer rate were greater for nanofluids than for water in all investigated cases, for a particular pumping power. The average increase in heat transfer coefficient was nearly 16.2%. As a result, choosing NDG/water as the working fluid can improve the performance of double-pipe heat exchangers.

1. Introduction

A variety of heat exchangers has been widely employed in different engineering applications. Examples are double-pipe or plate heat exchangers used in power production and recovery, food processing, chemical industry, and mechanical appliances such as air conditions, refrigerators, and ventilators [1]. Recent efforts have tried to enhance heat transfer performance of heat exchangers. The applied methods mostly comprise creation of turbulent flow [2] and use of fins, twisters, and baffles [3–5]. An obstacle to heat transfer improvement of heat exchangers is the limited thermal properties of conventional coolants. An important factor is the thermal conductivity of the coolant, which motivated Choi and Eastman [6] to introduce nanofluids to it. These fluids are highly conductive, made up of a base fluid and nanoparticles of 1–100 nm in size with superior thermal conductivity compared to base fluids. Hence, the percentage of nanoparticles appears likely to improve the thermal conductivity of the resulted nanofluid [7]. Solid materials of micron size were added to base fluids a few decades ago. The result was the settlement of the particles concluding in clog in the channel, pipes, and heat exchangers [8]. Another undesirable outcome was the accumulation of those abrasive particles, which eventually eroded and corroded the system. Yet, the use of nanofluids with stable particles suspended inside the base fluid decreases all the above consequences [9].

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Nomenclature

A_s	Annular flow area, (m^2)
A	Area, (m)
t	Coolant temperature, (K)
f	Friction factor
fR	Fouling resistance, (m^2 K/W)
Q_{given}	Heat exchange capacity of exchanger, (W)
h	Heat transfer coefficient, (W/m^2 K)
T	Hot fluid temperature, (K)
D_h	Hydraulic diameter, (m)
L	Length of the tube, (m)
LMTD	Logarithmic mean temperature difference
M	Mass flow rate, (kg/s)
NDG	Nitrogen-doped graphene
Nu	Nusselt number
Pr	Prandtl number
P	Pressure, (Pa)
Pp	Pumping power, (W)
Re	Reynolds number
Cp	Specific heat, (J/kg K)
K	Thermal conductivity, (W/m K)
U	Total heat transfer coefficient, (W/m^2 K)
V	Velocity, (m/s)
P	Wetted perimeter, (m)

Greek Symbols

ρ	Density, (kg/m^3)
μ	Dynamic viscosity, (Pa s)
φ	Volume fraction of nanosheets

Subscripts

ave	Average
bf	Base fluid
eq	Equivalent diameter
h	Hot fluid
nf	Nanofluid
1	Inlet flow
np	Nanosheets
2	Outlet flow
W	Wall

Since the invention of Choi and Eastman [6] for the suspension of nanoparticles in a base fluid, many studies have applied nanofluids for heat transfer improvement [10,11]. However, nanofluid-cooled heat exchangers, considering their wide applications, have gotten little attention. The studies are few in both experimental and numerical investigations [12] and sometimes have contradictory results. Duangthongsuk and Wongwises [13] used TiO_2/water nanofluid in a heat exchanger of a horizontal double-tube type to test its hydrothermal properties. Their conclusion was that increase in mass flow rate of either hot fluid or nanofluid, gives rise to the heat transfer coefficient of the nanofluid. This coefficient also increases with the reduction in nanofluid temperature. Convective heat transfer coefficients of two nanofluids were experimentally investigated in two types of heat exchanger by Zamzamian, Oskouie, Doosthoseini, Joneidi, and Pazouki [14]. The nanofluids were comprised of Al_2O_3 and CuO nanoparticles in ethylene glycol as base fluid and examined in double-pipe and plate heat exchangers. It was found that convective heat transfer coefficient of nanofluids increases with the rise in nanofluid temperature. This result conformed to the results of Akhtari, Haghshenasfard, and Talaie [15], but differed from [13]. Huminic and Huminic [16] numerically examined heat transfer properties of CuO/water and TiO_2/water nanofluids in a double-tube helical heat exchanger. The result was that using nanofluids in laminar condition considerably improves the convective heat transfer; and the increment is higher when particle concentration increases. This was similar to the findings of Chandra Sekhara Reddy and Vasudeva Rao [17]. However, Wu, Wang, and Sunden [18] found different results when examined laminar and turbulent flow of nanofluids in a double-pipe helically coiled heat exchanger. They used Al_2O_3/water nanofluid with weight concentration percentage from 0.78 to 7.04 at a fixed flow velocity. Enhancement percentage of heat transfer was insignificant in both flow conditions, ranging between 0.37% and 3.43%.

In another study, Duangthongsuk and Wongwises [19] showed that for nanofluid flow in a horizontal double-pipe heat exchanger, there is an optimum volume fraction of nanoparticle in base fluid, more than that, the thermal conductivity of nanofluid decrease. However, Abbasian Arani and Amani [20] conducted the same experiments. The result was that higher concentration of nanoparticles delivered notably higher Nusselt number and device thermal performance in all the examined Reynolds numbers.

The above literature review reveals the effectiveness of nanofluids as coolants [21], and yet identifies the requirement for supplementary research [22]. The objective of this research is to improve understanding of the effect of nitrogen-doped graphene (NDG) nanofluids concentration on heat transfer and fluid flow in double-pipe heat exchangers. Such research on the NDG nanofluids in heat transfer systems is required for several reasons: (a) no one has yet investigated the NDG nanofluids on the double-pipe heat exchangers, and (b) NDG has a high thermal conductivity and can improve the heat transfer coefficient of the base fluid [23]. The NDG synthesized by heat treatment of graphene in an ammonia solution leads to the preparation of stable nanofluids with desired characteristics, based on the method of Mehrali [23]. The present investigation examines the characteristics of NDG nanosheets and the stability, thermal conductivity, specific heat capacity, and viscosity of NDG nanofluids at several concentrations (0.01, 0.02, 0.04, and 0.06 wt.%) with Triton X-100 as a surfactant.

Finally, we examined various weight fractions of aqueous NDG nanofluids inside a double-pipe heat exchanger to analyze the resulting heat transfer coefficient, pressure drop, wall temperature reduction, and pumping power. A novel MATLAB code solved the governing equations. Findings of the current study may result in the use of the proposed coolant in heating and cooling devices [24].

2. Nanofluids preparation and characterization

2.1. Materials

A simplified Hummers' method synthesized graphene oxide (GO) [25,26]. After that, a hydrothermal process prepared the NDG nanosheets, as follows. A solution of 50 mg GO dispersed in 100 mL of DW and we adjusted pH of the solution to 11, using ammonia solution. Then, we hydrothermally treated the solution in a Teflon-lined autoclave at a temperature of 160 °C for 12 h. After collecting using centrifuge, we washed the obtained black wooly precipitate for several times with DW and finally, dried the NDG samples at 40 °C, under vacuum.

2.2. Analysis methods

A field emission scanning electron microscopy (FESEM-CARL ZEISS-AURIGA 60) observed the microstructure of the NDG. Transmission electron microscopy (TEM) study used a CARL ZEISS-LIBRA120 microscope. An X-ray photoemission spectrometer (PHI-Quantera II) with an Al-Kα ($h\nu = 1486.8$ eV) X-ray source distinguished the bonding of the elements in the NDG. A KD2 pro transient heated needle with 5% accuracy measured the thermal conductivity. An Anton Paar rheometer (Physica MCR 302) measured the viscosity of NDG-based nanofluids. A Cary60 UV–Vis spectrophotometer, Agilent Technologies measured all samples' light transmission between 190 and 1100 nm.