



# Exergy analysis of a shell-and-tube heat exchanger using graphene oxide nanofluids



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## ABSTRACT

Nanofluids are the new-generation heat transfer fluids largely used in heat exchangers for thermal energy transport applications. In this paper, graphene oxide was prepared in-house and used for nanofluid development and characterization. The graphene oxide was prepared by oxidizing purified natural flake graphite via the modified Hummers method. The morphology and structure of fabricated graphene oxide were characterized using X-ray diffraction analysis (XRD) and a scanning electron microscope (SEM). The graphene oxide nanofluids were prepared at 0.01 and 0.1 wt.% concentrations. The particle size and zeta potential of nanofluids were measured using the dynamic light scattering (DLS) technique. The rheological behaviors of nanofluids were investigated at 25 and 40 °C at different shear rates (10–100 1/s). Thermal conductivity of nanofluids was measured using the transient hot wire method at 25 and 40 °C. Exergy analysis showed that increasing the graphene oxide concentration from 0.01 wt.% to 0.1 wt.% resulted in 8.7% and 18.9% thermal conductivity enhancement at 25 and 40 °C, respectively. Furthermore, the thermal performance of graphene oxide nanoparticles in a shell-and-tube heat exchanger was studied experimentally. The effect of nanofluid concentration, flow rates, temperature inlet and flow regime on the system's exergy loss was studied experimentally. The results showed that using graphene oxide nanofluids as the hot fluid resulted in less exergy loss in the shell-and-tube heat exchanger under both laminar and turbulent conditions. Comparing the exergy loss of graphene oxide nanofluids to distilled (DI) water showed that DI water caused 22% and 109% higher exergy loss than in laminar conditions.

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## 1. Introduction

The conventional process fluids such as water, oil, and ethylene glycol with low thermal conductivity cannot satisfy the required high-intensity heat transfer in many different industries including transportation, microelectronics, aerospace, and manufacturing. The main factor limiting the heat transport capability for the abovementioned conventional fluids is their low thermal conductivity. One promising method to overcome this limitation is using the power of small-size particles. When added to a base fluid, particles in micrometer or nanometer sizes show unique and enhanced properties when compared to their base fluids. These enhanced fluids can have significant applications in various fields such as power generation [1] and pharmaceuticals [2] and in environmental processes [3,4]. Based on the aforementioned concept, nanofluids (NFs) are defined as the mixture of nanometer-sized

solid particles, fibers, rods, or tubes and base fluids [5]. NFs exhibit two main advantages over the solid/liquid suspensions: (1) higher specific surface area resulting in more heat transfer surface between particles and fluids and (2) higher dispersion and stability with enhanced particles' Brownian motion [5].

Preparation of NFs is the key step in using nanoparticles to improve fluid thermal conductivity. Several factors including nanoparticle size, shape, material composition, volume concentration, and acidity affect the thermal conductivity of NFs [6]. Among the different types of metallic-particle NFs (such as Cu, Al, Fe, Au, and Ag) and oxidized form particle NFs ( $\text{Al}_2\text{O}_3$ , CuO,  $\text{Fe}_3\text{O}_4$ ,  $\text{TiO}_2$ ) [7], graphene-based particles received notable attention due to their large intrinsic thermal conductivity and low density compared to metals or metal oxides nanoparticles [8]. Yu et al. [9] developed the ethylene glycol-based NFs containing graphene nanosheets that showed up to an 86% thermal conductivity increment. The advantages of graphene nanoparticles can be listed as high thermal conductivity, ease of synthesis, long suspension time (meaning more stable), large surface area-to-volume ratio, low

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### Nomenclature

C	heat capacity (kW/K)	Z	height (m)
E	exergy loss (J)	$\psi$	availability
e	dimensionless exergy loss		
g	gravitational conversion factor (kg m/N s <sup>2</sup> )	<i>Subscripts</i>	
m	mass flow rate (kg/s)	c	cold fluid
p	pressure (Pa)	e	environment condition
Re	Reynolds number	h	hot fluid
S	specific entropy (kJ/kg k)	in	inlet
T	temperature (K)	out	outlet
u	velocity (m/s)		

erosion and corrosion, and low demand for pumping power [10]. Hajjar et al. [11] reported that graphene oxide NFs at different concentrations showed substantially higher thermal conductivities than the base fluid. They reported that the thermal conductivity enhancement depended strongly on the concentration of graphene oxide where NFs with 0.25 wt.% concentration exhibited 47.5% thermal conductivity enhancement at 40 °C.

Heat exchangers are one of the most commonly used pieces of equipment in various engineering processes such as the chemical industry, food industry, power generation, and air conditioning. Because of high energy costs and low energy sources, there are many efforts to enhance heat exchangers' efficiency. The effectiveness of heat transfer is significantly affected by the convective heat transfer coefficient, which is a function of a number of thermo-physical properties of the fluid, such as thermal conductivity and viscosity [12]. Farajollahi et al. [13] used  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>/water and TiO<sub>2</sub>/water NFs in a shell-and-tube heat exchanger under turbulent conditions and indicated that addition of nanoparticles to the base fluid enhances the heat transfer performance, which results in a larger heat transfer coefficient than that of the base fluid at the same Peclet number. They further reported that  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>/water NFs showed better heat transfer behavior at higher volume concentration, but TiO<sub>2</sub>/water NFs showed better heat transfer behavior at lower concentrations. Lotfi et al. [14] performed the experimental test using a multi-walled carbon nanotube, with enhanced hydrophilicity and stability, in water NFs in a horizontal shell-and-tube heat exchanger and reported that heat transfer is enhanced in the presence of multi-walled nanotubes in comparison to the base fluid.

Exergy can be defined as the maximum useful work that can be achieved from the reversible system in a specific environment [15]. The use of exergy analysis or second law analysis is very important in developing a good understanding of the thermodynamic behavior of a heat exchanger's thermal performance. Exergy analysis is a method that uses the conservation of mass and energy principles together with the second law of thermodynamics for the design and analysis of energy systems [16]. Exergy analysis can show whether or not it is possible to reduce inefficiencies in energy systems through better design [17]. Khairul et al. [18] analyzed the exergy loss of a corrugated plate heat exchanger using CuO/water NFs and reported that CuO/water NFs reduce the exergy destruction by 24%, 16.25% and 8% for 1.5 vol.%, 1.0 vol.% and 0.5 vol.% of nanoparticles, respectively, compared to water. Therefore, averages of 34%, 22% and 12% enhanced exergetic heat transfer effectiveness are found for 1.5 vol.%, 1.0 vol.% and 0.5 vol.% of nanoparticles compared to water, respectively.

According to the provided literature review, there still remains a lack of fundamental understanding on how rheological properties, particle size distribution of NFs, and thermo-chemical characteristics of NFs developed in-house affect exergy analysis and

performance when NFs flow through heat exchangers. In this study, graphene oxide particles were first fabricated chemically and then characterized. Second, the graphene oxide NFs were prepared at 0.01 and 0.1 wt.% concentration, and thermal conductivity and rheological behavior of each sample were measured at 20 and 40 °C temperatures. Finally, the exergy performance of a shell-and-tube heat exchanger using graphene oxide NFs was studied experimentally.

## 2. Experiments

### 2.1. Graphene oxide fabrication and characterizations

Graphene oxide was prepared from graphite powder based on the modified Hummers methods [19]. Briefly, 2.5 g of graphite powder (Bay Carbon, Inc., Bay City, Michigan, USA) was treated with 57 ml of concentrated sulfuric acid in an ice bath to prevent the overheating. Sodium nitrate (1.75 g) (Fisher Scientific, Pittsburgh, PA, USA) was added slowly to the mentioned solution and mixed for 1 h. Then, 7.5 g of potassium permanganate was added to the solution and stirred for 12 h. The resulting solution was diluted by adding 1250 ml of DI water under vigorous stirring. Hydrogen peroxide (12.5 ml, 30%) (Fisher Scientific, Pittsburgh, PA, USA) was added to the solution and stirred for 2 h to make sure the potassium permanganate reaction was complete. The final mixture was washed with 57 ml of concentrated hydrochloric acid and 5 L of DI water, respectively. Finally, the mixture was filtered and the graphene oxide cake was collected and dried for 12 h at 40 °C. In general, the mixture of sulfuric acid, hydrochloric acid, and potassium permanganate oxidize the natural graphite powders in the water-based solution. During this process, bonding of hydroxyl, carbonyl and epoxy groups to the graphite structure and insertion of H<sub>2</sub>O and ions into the graphene layer result in an interlayer spacing increment [20–22].

Graphene oxide NFs were prepared by dispersing different masses of graphene oxide in DI water. Graphene oxide in amounts of 0.01 and 0.1 was dispersed in an appropriate mass of DI water and stirred for 5 h. Then, graphene oxide NF colloidal solutions were sonicated at 130 W and 42 kHz using an ultrasonication instrument (Branson Ultrasonics, Danbury, CT, USA) for 1 h.

Morphological characterization of fabricated graphene oxide was examined by an environmental scanning electron microscope (ESEM), FEI Quanta 200, 149 FEI Company, Hillsboro, OR, USA. The crystal structure of graphene oxide was investigated by an X-ray diffractometer (XRD), Rigaku Ultima IV X-ray Diffractometer, Kikago, Texas, USA. Data was collected from 5° to 80° at a scan rate of 3°/min.

Thermal conductivity of 0.01% and 0.1% (wt.%) graphene oxide NF was measured based on the hot-wire technique using a KD2

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