Thermal Analysis Of Graphene Based Nanofluids For Energy System And Economic Feasibility

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1 Thermal analysis of Graphene Based Nanofluids for Energy System and 2 Economic Feasibility

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Abstract

Thermal and economic evaluation using covalent functionalized Graphene Nanoplatelets (CF-GNPs) were performed inside a heated-pipe under turbulent conditions. The current nanofluids were produced from CF-GNPs added and distilled water in different mass percentages such as 0.025, 0.05, 0.075 and 0.1 wt.%. The thermal system was under the condition of fully-developed turbulent flow in the range of $6,401 \leq Re \leq 11,907$ and heated up to $11,205 \text{ W/m}^2$. The characterization and morphological properties were done through different examinations and techniques such as zeta potential, nanoparticle sizer, Field Emission Scanning Electron Microscopy (FE-SEM), and Field Emission Transmission Electron Microscope (FE-TEM). Moreover, the economic performance was evaluated to estimate the price-operation of the current thermal system. The heat exchanger size reduced by 16.10%, 21.92%, 25.37% and 29.35% for 0.025 wt.%, 0.05 wt.%, 0.075 wt.% and 0.1 wt.%, respectively. Furthermore, the required power for base fluid was 422W then reduced to 354W, 326W, 315W and 298W for 0.025 wt.%, 0.05 wt.%, 0.075 wt.% and 0.1 wt.%, respectively.

Keywords: Graphene Nanoplatelets; economic analysis; energy saving; cost; Thermophysical Properties; Thermal analysis; Turbulent flow; Economic analysis.

1. Introduction

1.1 Research background and motivation

The essential demand for high-performance heat transfer fluids in a variety of applications and industries, particularly in the energy and electrical sectors, has motivated a lot of research¹. Heat transfer efficiency is low in many engineering applications due to the usage of low-conductive fluids such as water-based and oil-based fluids. As a result, researchers are seeking for an alternate mechanism to replace these traditional fluids to improve thermal transfer efficiency. “Nanofluids” are solid nanoparticles (NPs) suspended in base fluids in a long-stable and homogeneous approach^{2, 3, 4}. Nanofluids have previously been shown to improve heat transfer efficiency in a variety of engineering applications, including heat exchangers, heating/cooling systems, and solar panel appliances^{5,6}. As a result, new conductive fluids containing various nanoparticles have been developed such as metal oxides (Al_2O_3 , ZnO , CuO , SiO_2 , and TiO_2)^{7, 8, 9}, and carbon-based nanofluids (MWCNTs, GO, and GNPs)^{10, 11, 12}.

1.2 Adopted literature review on nanofluids-based heated pipe

The varied features of graphene have attracted a lot of research interest^{13, 14}. Graphene is a carbon allotrope composed of a single layer of hexagonally organised carbon atoms that are sp^2 bonded¹⁵. Exfoliated graphene nanoplatelets (GNPs) are a new type of graphite nanoparticle made up of microscopic flakes of graphene that are around 1-15 nm thick and with sizes ranging from sub-micrometres to 100 micrometres¹⁶. GNPs are a fantastic nanomaterial from an economic standpoint because they can be manufactured at a minimal cost¹⁷. Graphene nanoplatelets, on the other hand, have a problem with solubility in solution because they prefer to collect under the influence of strong Van der Waals forces^{18, 19}. Different techniques and tactics for chemically functionalizing the surface of GNPs have been developed in order to address the issue of solubility²⁰.

The graphene surface can be changed using two basic strategies: covalent functionalization (rapid insertion of functional groups on the graphite surface) and strong attachment of surfactants to increase dispersion (non-covalent functionalization) ^{21, 22}. The non-covalent approach is used to create polar-polar linkages by coating the graphene surface with surfactants or polymers that act as stabilisers to prevent GNPs from solidifying in homogenous liquids ²³. The presence of stabilisers is inconvenient since it can contaminate GNPs and lower their value ²⁴. Covalent functionalization, on the other hand, necessitates binding with hydrophilic functional groups such as carbonyl, hydroxyl, carboxyl, sulfhydryl, amino, and phosphate groups ²⁵. Furthermore, altering the graphene structure appears to be a viable option for increasing its solubility in solvents and polymers ²⁶. To date, toxic substances such as high-risk acids have been used in chemical oxidation-reduction reactions to functionalize GNPs.

Functionalized GNPs have been developed by some researchers and used as fluids in heat exchangers and different thermal applications. The forced convective turbulence of GNPs-H₂O nanofluid in a fully developed flow inside a horizontal smooth heat exchanger has been investigated experimentally and numerically for varied mass fractions and heat flux intensities ²⁷. Using a 0.1 wt.-%-GNPs-H₂O nanofluid with three heating rates (8231, 10,351 and 12,320 W/m²), the average Nusselt number (Nu_{avg}) enhanced by 75%, 79%, and 83%, respectively. The use of PGGNP-H₂O nanofluid for heat transfer and fluid flow enhancement has been investigated experimentally ²⁸. The circular pipe was heated with various heat flux intensities (i.e., 23,870 and 18,565 W/m²) and turbulent flow in the range of $3,900 \leq Re \leq 11,700$. The study reported a significant improvement of about 119% and 84% in the heat transfer parameter with 23,870 and 18,565 W/m², respectively. Yarmand et al. ²⁹ developed a GNPs-H₂O nanofluid to test the effects of long-term stability on the hydrodynamic and heat transport parameters inside a heated pipe. The heat transfer parameters showed improvements of about

19.68 and 26.5%, in terms of heat transfer coefficient and Nusselt number, respectively, for 0.1wt.-%-GNPs-H₂O. Sadri et al.³⁰ developed stable and environmentally compatible CGNPs-H₂O nanofluids with three different mass fractions as heat transfer working fluids. The average Nusselt number and heat transfer coefficient were improved by 18.69% and 37.54%, respectively using 0.1wt.-% nanofluid with Re = 15,927. Recently, transitional flow of graphene-H₂O nanofluid was tested experimentally in a heated pipe³¹. The transition initiated at a Reynolds number of 2475 for H₂O, while it initiates at 2315 for the nanofluid with 0.2wt.-%. The maximum heat transfer enhancement is observed as 36% for a Reynolds number of 3950.

1.3 Research objectives

Many academics were drawn to the significant demand for developing methods to enhance the heat transfer rate in cooling systems. After two decades of study on this phenomenon, it is time to see if nanofluids have met heat transfer researchers' predictions and created a significant shift in heat transfer. Following the findings of the literature analysis, a deeper knowledge of the thermal-price performance of employing covalently functionalized Graphene Nanoplatelets (CF-GNPs) for convective heat transfer research is necessary. As a result, the goal of this research is to investigate the thermal enhancement and CF-GNPs-H₂O nanofluid flow under fully developed turbulent conditions. The thermophysical and surface modifications properties of the synthesised CF-GNPs were investigated at various conditions. Economic and thermal analysis were performed such as heat exchanger size reduction, energy savings and the total cost of thermal system operation.

2 Methodology

2.1 Materials and Functionalization Approach

The raw materials of GNPs in the specifications of 2 µm, SSA = 750 m²/g and 98%-purity were purchased abroad from (XG Sciences, Lansing, MI, USA). Also, the primary chemicals such

as Nitric acid (HNO_3 ; 65%) and Sulfuric acid (H_2SO_4 ; 95-97%) were purchased locally from (Sigma-Aldrich Co., Selangor, Malaysia).

In the first process, the raw materials GNPs were dispersed in the functionalization medium containing HNO_3 (67%) and H_2SO_4 (98%) at a mixing ratio of 1:3³². Then, the sample was transferred into H_2SO_4 with mild shaking. One gram of the pristine GNPs (P-GNPs) was added into a flask with 250 mL containing the oxidation agent before being placed in an iced bath. Then, few drops of Nitric acid were added to the mixture, and the solution was magnetic stirred at room temperature for 30 min. Then, ultrasonication bath was applied for 3 hrs to the black product. Also, further reflux for 30 mins was performed at the room temperature. Washing process was applied at the speed of 6000 rpm for 15 min before using the dryer at 80°C for 24 hours using DW until the value of pH reached 5. In the last step, four different mass fractions were prepared such as 0.025, 0.05, 0.075, and 0.1 wt.% as heat transfer working fluids in the current investigations.

2.2. Experimental Measurements

The addition of CF-GNPs nanoparticles to the base fluid (DW) increase/decrease the thermal-physical properties (thermal conductivity, viscosity, density, and specific) of nanofluids. The new values of nanofluids thermal-physical properties show implications on the heat transfer and fluid flow in the thermal applications. In this regard, The device (KD-2 pro, Decagon, USA) was used to measure the base fluid and nanofluids thermal conductivity in the temperatures range of 0-60°C with an average accuracy of 5%³³. The device measurements were validated with the published data of DW. The dynamic viscosity of DW and GNPs-DW nanofluids were measured by using the device of (Rheometer, Physica, MCR 301, Anton Paar, Austria). Also, the specific heat capacity and density of DW and GNPs-DW were assessed using (DSC 8000, Perkin Elmer, USA) and (Mettler Toledo, DE-40 with the accuracy of $\pm 2\%$

and $\pm 10^{-4}$ g/cm³, respectively. The average errors between the measurements and published data were 3.3%, 4.45%, 3.13%, and 2.46%, for thermal conductivity, dynamic viscosity, density, and specific heat respectively. Lastly, the produced nanoparticles/nanofluids were characterized to test the morphological properties (size and shape) using two different tools such as Field Emission Transmission Electron Microscopy (FE-TEM, JEM-2100F) and Field Emission Scanning Electron Microscopy (FE-SEM, Zeiss Supra 55VP). Meanwhile, the long-term stability was measured through the device of (Anton Paar, Litesizer 500, Austria).

Figure (1) displays the schematic drawing of the experimental setup used in the current study. In general, the heating system includes the heated-pipe (test section) with different measuring and controlling tools, a data logger device, and a chiller compartment. The heat transfer fluid (sample) was pumped using a magnetic drive pump (Cole-ParmerTM) at 0-10 L/m flow rate from a stainless-steel jacket tank (12-L capacity). The desired flow rate for both base fluid and nanofluids was controlled by (Burkert Flow Meter, Type SE32). Meanwhile, the pressure inlet and pressure outlet along the heated- pipe test sections were measured by Differential Pressure Transmitter (PX154-025DI, OMEGA) with an accuracy of $\pm 0.75\%$.

The test section is a square heated-pipe (the dimensions; length = 1.4-m, inner width = 10-mm, outer width = 12.8-mm). The heating source is a 900 W flexible tape heater (OMEGA, USA) with an adjustable transformer. Also, the insulation is applied by thick glass wool to reduce the heat loss to the environment. Five T-type thermocouples from OMEGA were installed to measure the surface temperature with an uncertainty of $\pm 0.1^{\circ}\text{C}$. Moreover, two RTD-sensors (PT-100) with an uncertainty of $\pm 0.1^{\circ}\text{C}$ were inserted into the inlet and outlet flow to measure the bulk temperature. The working fluids container was attached to a chiller (DAIHAN-brand, WCR-P30) to maintain the desired input temperature at 30°C .

2.3. Data Reduction and Uncertainties

Firstly, the water run was performed for calibration reasons before proceeding with the CF-GNPs-DW nanofluids. The data was collected from the setup after the steady-state condition was reached such as inlet, outlet and heated surface temperatures. Table (1) shows the adopted methodologies in the current study to determine the main parameters to evaluate the thermal performance and nanofluids flow.

Here, $T_w = \frac{\sum T}{5}$ (T_w = the average temperature of the heated-wall surface), P = the wetted perimeter, $T_b = \frac{T_o - T_i}{2}$, $D_h = \frac{4A_c}{P}$, A_c = the cross-sectional area ³⁴.

The maximum error between the heat supplied to the system ($P = V \times I$) and the heat gained by the working fluid ($Q = \dot{m}C_p[T_o - T_i]$) was $\pm 7.2\%$, which acknowledges a minor percentage of heat loss to the room ambience.

Here are some of the Nusselt number correlations that are currently available:

The single-phase fluids formula of Petukhov ³⁵ was modified by Gnielinski ³⁶ :

$$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{0.5}(Pr^{2/3} - 1)} \left[1 + \left(\frac{d}{L}\right)^{2/3}\right] \left(\frac{Pr_m}{Pr_w}\right)^{0.11} \quad (7)$$

Here, the Gnielinski equation is only applicable in the ranges of $3000 < Re < 5 \times 10^6$ and $0.5 < Pr < 2000$. Pr_m & Pr_w refer to Prandtl number at bulk and wall temperatures, respectively.

According to Eq. (8), the friction factor for a fully developed turbulent flow was determined depending on Re-number by applying the Colebrook formula as follows: ³⁷

$$\frac{1}{\sqrt{f}} = -2.0 \log\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \quad (8)$$

Meanwhile, the turbulent flow formula of Petukhov is shown in Eq. (9)

$$Nu = \frac{\left(\frac{f}{8}\right)RePr}{1.07 + 12.7\left(\frac{f}{8}\right)^{0.5}(Pr^{2/3} - 1)} \quad (9)$$

Here, Petukhov formula is valid for $0.5 < Pr < 2000$ and $3000 < Re < 5 \times 10^6$. Also, the Blasius and Petukhov correlations were employed to verify the water run test results³⁸.

$$\text{Petukhov}^{35} \quad f = (0.79 \ln(Re) - 1.64)^{-2} \quad (10)$$

$$\text{Blasius}^{39} \quad f = \frac{0.316}{Re^{0.25}} \quad (11)$$

For more evaluation, the thermal performance index (PI) is determined to describe the desired output enhancement (heat transfer performance) over the unwanted output enhancement (pumping power) of CF-GNPs-H₂O nanofluids⁴⁰:

$$PI = \frac{h_{nf}/h_{bf}}{\Delta P_{nf}/\Delta P_{bf}} = \frac{R_h}{R_{\Delta P}} \quad (12)$$

where, (R_h) and ($R_{\Delta P}$) indicate the ratio of heat transfer enhancement (nanofluid/DW) to the pressure loss increments (nanofluids/DW). When the performance index (PI) is more than 1, it means that the CF-GNPs-DW nanofluids can be effectively used in the square heated-pipe instead of the distilled water as HTFs. At the same time, when the $PI < 1$, then the CF-GNPs nanofluid is not a proper replacement. Table (2) shows the range and accuracies of instruments and fluid flow properties. While Table (3)⁴¹ identified the uncertainties of all the values discussed.

3 Results and Discussion

3.1 Characterization and Thermophysical Properties

Figs. (2-3) show the morphologies of P-GNPs and CF-GNPs via HR-TEM and FE-SEM examinations. As shown in Fig. (2-a), P-GNPs was composed of smooth surfaces, transparent structures, and dual sheets with intact edges. The attachments of the carboxyl group (COOH) on the surfaces and edges of the GNPs during the acid-based functionalization process caused the occurrence of a slight blur effect with wrinkles and crumpled on the sheets. The presence of defective folded flakes and rough edges as seen in Fig. (2-b) points towards a successful

reaction between the GNPs-COOH and the acid solution molecules. The wrinkles on the surface of GNPs are visible in HR-TEM pictures due to their inherent stability in 2D structures. These lines were stronger after the sonication-assisted chemical reactions than the previous wrinkling or surface roughness. Another observation from the FE-SEM micro-images for the CF-GNPs results in graphene nanoplatelets' fractured sheets is shown in Fig. 3(a-b). The energy-dispersive X-ray (EDX)-based spectra of the CF-GNPs is shown in Fig 3(c-d), with four elements (C, O, Si, and S) detected. The high carbon percentage (92.59%) indicates the success of the chemical reaction, and the presence of oxygen (7.33%) refers to the use of Oxidizing acid. Furthermore, the silicon and sulphur contents were 0.04% and 0.04%, respectively.

The produced CF-GNPs nanofluids' zeta potential and particle size distributions are illustrated in Fig. 4 (a-b), where Fig. 5(a) shows the determined zeta-potential and polydispersity index (PDI) of CF-GNPs-H₂O nanofluid at pH-7. The zeta potential must be as high as possible (+/-) to achieve a natural intra-particles repulsive force, as this would assure the existence of electrostatic repulsive forces between the CF-GNPs nanoparticles. The experiments showed that the CF-GNPs exhibited a negative charge of -39.4 mV at 25°C within 1 hr sonication period. The average size distribution of nanomaterials was determined using the dynamic light scattering (DLS) technique. The average particle size was calculated to be 447.3 nm (Fig 5(b)), while the DLS results revealed that the particle size scale ranged from 51.6-121.6 nm with a low PDI of 0.306, indicating a consistent and uniform particle size distribution.

The thermal-physical properties for DW and CF-GNPs-DW nanofluids are presented in Fig. (5) versus the temperature and nanoparticles mass fractions. The collected data of thermal conductivity were validated with National Institute of Standards and Technology (NIST) database ⁴², and the maximum error was < 2% only. The result in Fig.(5-a), showed

that the effective thermal conductivity of CF-GNPs nano-samples was significantly higher relative to DW. Furthermore, any rise in the temperature of the produced nanofluids improved the thermal conductivity due to Brownian motion of CF-GNPs when suspended in DW. The biggest increase in thermal conductivity was 31.6% for 0.1wt. % at 50°C.

Fig. (5-b) presents the effective dynamic viscosity of base fluid and nanofluids at shear rate = 200 1/s, and temperature in the range of 20 - 60°C. The dynamic viscosity of the CF-GNPs nanofluids increased slightly due to the low CF-GNPs% in the DW. Low mass fractions were used to improve the thermal conductivity of the nanofluids and minimise a dramatic increase in dynamic viscosity, which would necessitate more pumping power, which would be undesirable in real-world thermal applications. Also, the dynamic viscosity of CF-GNP nanofluids and DW was seen to decrease as temperature increased due to the loss of intermolecular forces.^{43,44}

The density of CF-GNPs-DW nanofluids and DW were measured with a temperature range of 20-50°C (Fig. 5c). A significant decrease in the density of the nanofluids as the temperature increases. Additionally, the density of CF-GNPs-DW nanosuspensions increased insignificantly with increases in the mass fraction. The reported rise in the density of CF-GNPs-DW was due to the higher density of solid NPs than that of the base fluid. A slight increase of 0.236% was observed in the density of the nanofluid at 0.1wt.%-CF-GNPs and 20°C. Moreover, an increase in the fluid temperature from 20 to 50°C reduced the density by approximately 1.1%, demonstrating a critical role of temperature.

Fig. (5-d) exhibits the collected data for specific heat capacity for base fluid and nanofluids. It was discovered that increasing the temperature of the sample had no influence on the specific heat. These findings are consistent with prior publications' particular heat curves⁴⁵. The addition of CF-GNPs percentage in DW also resulted in a small drop (0.88-1.38 %) in

the specific heat of the nano coolants. This was related to the fact that CF-GNPs had a lower specific heat than the base fluid.

3.2 Distilled water a working fluid

Figure 6(a-c) show the measured and collected data from Eqs. (7-9) for the heat transfer enhancements parameters (average Nusselt number and average heat transfer coefficient). The results of heat transfer parameters from the measurements and empirical correlations were in good agreement during the water-run. The deviation between the experimental testing and Petukhov equation was less than 8%. According to Cengel ⁴⁶, Gnielinski formula considers one of the most reliable comparisons for estimating the Nusselt number (Nu) inside the heated-pipe. Figs 6(b and d) depict the relative errors between the Nu number and average heat transfer coefficients between the experimental and theoretical parts during the water-run. The values of Darcy friction factor during the water-run were validated with two famous formulas of Blasius and Petukhov ⁴⁷. Blasius formula (see Eq. 11) can be considered the basic formula for estimating Darcy friction factor due to its wide range applications in the smooth heated-pipes. The experimental and theoretical values of pressure loss and friction factor of the heated-pipe were compared as shown in Fig. 6(e-g). As the same time, Fig. 6(f-h) reports the relative error between the measured and theoretical data for pressure drop and friction factor.

3.3 Heat Transfer Properties of CF-GNPs Nanofluids

The current results for the heat transfer enhancements are compared with the previous reports using the carbon based nanofluids as HTFs inside the heated-pipes as shown in Table (4) ⁴⁸. As earlier stated, the researchers avoid using surfactants in carbon based nanofluids productions due to degradation at low-temperature ⁴⁹, and must be added in very specific amount. The ionic and non-ionic polymers showed influences on hydrodynamic efficiency of colloidal nano-dispersion by trying to separate nanoparticles in the high mass fraction percentages. As previous recommendations, the current nanomaterials were synthesized/prepared with no

surfactant's addition as the goal of the research is to explain why manufactured nanofluids are used to increase heat transport and fluid flow qualities in a heated square pipe.

Fig. 7(a) presents heat transfer coefficients of the forced convective using CF-GNPs-DW nanofluids at different inlet flow (Reynolds numbers) with four different samples. The heat transfer coefficient describes the rate of convective heat transfer between the fluids' surface heated-wall and the working fluid medium. The heat transfer coefficients can be enhanced due to several factors, such as the Brownian forces of the CF-GNPs in the base fluid, thermal diffusion, and thermophoresis⁵⁰. Higher fluid velocity was induced by the thermal boundary layers, which increased the thermal resistance between the fluid stream and the inner wall surface temperature, improving thermal conductivity and heat transfer. The current study revealed that, using 0.1wt.-%-CF-GNPs-DW enhanced the heat transfer coefficient up to 44%, meanwhile using 0.025wt.-%-CF-GNPs-DW enhanced it to 33.3% at a constant heat flux of 11,205 W/m².

The Nusselt number (Nu) is the ratio between the convective rate to the conductive rate of the developed nanomaterials as HTFs. Fig. (7-b) shows the measuring values of average Nu number as a function of Re number at constant wall heat flux. The presented values of average Nu for CF-GNPs-DW nanofluids exhibited superb increases. The highest improvement in Nu was observed at 0.1 wt.-%- CF-GNPs-H₂O, $q'' = 11,205 \text{ W/m}^2$, $Re = 11,907$ with 35.1% relative to DW. The reported increase in Nu values was a result to the reduction in the circulation temperature due to the increase in the HTFs-thermal conductivity, which produced a decrease in the difference between the bulk fluid temperature and the surface heated-wall temperature.

3.4 Hydrodynamic Properties of CF-GNPs Nanofluids

The friction factor and pressure loss results of CF-GNPs nanofluid were determined at different weight concentrations and Reynolds number. Figure 8 (a-b) shows the difference in the friction factor and pressure drop at four nanofluids samples. Meanwhile, Fig. (8) suggested a minor

increment with an increase in the mass percentage regardless of the small instability in the tested data at different Re. The highest rise in the pressure drop of (20.8%) and friction factor of (3.85%) was observed under the testing conditions of 0.1 wt.%- CF-GNPs-H₂O, $\nu = 0.833$ m/s.

3.5 Economic and thermal analysis

The primary objective of this article is to compare the efficiency of nanofluids to their cost. The expense of manufacturing nanoparticles is well known. On the other hand, in addition to the expense of nanoparticles, the production of nanofluids is expensive. The price of basic fluid is regarded insignificant in the pricing of nanofluids. The Mouromtseff criterion⁵¹ is one of the criteria for the efficiency of nanofluids with turbulent flow that is widely utilised in research. This criterion considers four properties of nanofluids in terms of performance and efficiency under turbulent flow circumstances, namely density, thermal conductivity, specific heat capacity, and viscosity. The Mouromtseff criteria is depicted in Equation (13). In Fig. (9), Mouromtseff criterion for different mass fractions and inlet temperatures are given. The Mouromtseff criteria shows that the efficiency of CF-GNPs in different mass percentages is higher than 1. The efficiency of CF-GNPs nanofluids increases as mass percentages are increased. This means that, using CF-GNPs nanofluids will save energy.

$$MO = \left(\frac{\rho_{nf}}{\rho_{bf}}\right)^{0.8} \times \left(\frac{k_{nf}}{k_{bf}}\right)^{0.67} \times \left(\frac{Cp_{nf}}{Cp_{bf}}\right)^{0.33} \times \left(\frac{\mu_{nf}}{\mu_{bf}}\right)^{0.47} \quad (13)$$

Figure (10) shows the difference in weight concentrations of particular Re and varied CF-GNPs in the Performance Index (PI). The average PI of the tested concentrations of CF-GNPs-DW was observed to be > 1 , addressing the stability of the synthesized samples for proper use in the thermal applications. Increases in the weight concentrations of CF-GNPs caused more increase in the average PI (positive parameter) than the increase in pressure loss (negative parameter). The PI of CF-GNPs-DW increases as the Reynolds number and mass

fractions are increased. The maximum increase of 2.13 was observed in the thermal efficiency of 0.1 wt.%-CF-GNPs-DW at $Re = 11,907$, and $q'' = 11,205 \text{ W/m}^2$.

Before starting, it should be remembered that for the use of cooling fluids in various cooling equipment, it is feasible to accept fully developed flow, since fluid has a very turbulent flow in many industrial applications, such as in heat exchangers. Second, numerous researches on the heat transfer coefficient of nanofluids show that it is even less efficient than turbulent flow.

To get a better understanding of the performance of nanofluids in relation to their cost, the size reduction of heat exchangers is assessed using thermal efficiency values as shown in Fig (11). As shown below, the heat exchanger size reduced by 16.10%, 21.92%, 25.37% and 29.35% for 0.025wt.%, 0.05wt.%, 0.075wt.% and 0.1wt.%, respectively. In economics and engineering, using heat exchanger with less size and efficient more than the conventional base fluids will reduce the total cost of production and manufacturing. Based on the reduced size of heat exchanger, the energy savings are calculated and presented in Fig. (12). The required power for base fluid was 422W then reduced to 354W, 326W, 315W and 298W for 0.025wt.%, 0.05wt.%, 0.075wt.% and 0.1wt.%, respectively. Furthermore, Fig. (13) depicts the entire cost of manufacturing and production of the present thermal system, as well as maintenance and yearly interest. The total cost of the baseline prototype was USD12,020, Nanomaterials and Chemicals were USD 2765 (23% of the capital cost), Manufacturing was USD 240 (2 % of the capital cost), Transportation was USD 361 (3% of the capital cost), System use was USD 8360 (72.3% of the capital cost), Maintenance was USD 240 (2% of the capital cost), and Annual interest was USD 240. (2% of the capital cost).

4 Conclusions

The nanomaterials of CF-GNPs were produced using a covalent functionalization approach as HTFs inside a square heated-pipe. The developed nanomaterials were characterized using

different tools and the thermal-physical were measured in order achieve the current goal of the study. Thermal and economic assessments were carried out to evaluate the current heat exchange system. The following conclusions were drawn from the study's findings:

- i. The functionalized graphene nanoplatelets (CF-GNPs) were characterized by different techniques such as Zeta potential, Particle size distributions, HR-TEM, SEM, and EDX to examine the stability and morphological properties.
- ii. The prepared samples' thermophysical properties demonstrated significant operating performance in heated-pipe, with the most considerable improvement in thermal conductivity being 31.6% at 50°C and 0.1wt.%.
- iii. The highest increments in the average Nusselt number and average heat transfer coefficient were 35.1% and 44.4%, respectively, using 0.1wt.-%CF-GNPs-DW.
- iv. In comparison to the base fluid, the friction factor and nanofluid pressure loss increased by 3.85% and 20.8%, respectively.
- v. The prepared nanofluid showed PI, performance evaluation criterion and Mouromtseff criteria of more than 1, which further increased with the nanoparticles' higher mass content.
- vi. The heat exchanger size reduced by 16.10%, 21.92%, 25.37% and 29.35% for 0.025wt.%, 0.05wt.%, 0.075wt.% and 0.1wt.%, respectively.
- vii. The required power for base fluid was 422W then reduced to 354W, 326W, 315W and 298W for 0.025wt.%, 0.05wt.%, 0.075wt.% and 0.1wt.%, respectively.
- viii. The total cost of the baseline prototype was USD12,020, Nanomaterials and Chemicals were USD 2765, Manufacturing was USD 240, Transportation was USD 361, System use was USD 8360, Maintenance was USD 240, and Annual interest was USD 240.

Conflict of interest: The authors declare no conflict of interest.

392 **Authors contributions**

393 Reem Sabah Mohammad: Conceptualization, modeling, data analysis, validation,
394 investigation, writing up.

395 Mohammed Suleman Aldlemy: Visualization, data analysis, validation, investigation, writing
396 up.

397 Mayadah W. Falah: Visualization, data analysis, validation, investigation, writing up.

398 Raad Z Homod: Visualization, data analysis, validation, investigation, writing up.

399 Zaher Mundher Yaseen: Conceptualization, project leader, supervision, visualization, data
400 analysis, validation, investigation, writing up.

401 **Data availability:** The data used for the current research is presented in the manuscript itself.

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Figures

Figure 1

Drawing diagram for the forced convective heat transfer in turbulent flow.

(a)

(b)

Figure 2

HR-TEM microscopy at different magnifications (a) pristine GNPs, (b) CF-GNPs.

Figure 3

SEM and EDX analysis of the CF-GNPs nanoparticles; (a-b) SEM at 1 μm, (c) EDX mapping analysis, (d) EDX elemental analysis.

Figure 4

(a) Zeta potential values of CF-GNPs nanofluids, (b) Particle size distributions for CF-GNPs at 25°C.

■ NIST ■ DW ■ 0.025 wt% ■ 0.05 wt% ■ 0.075 wt% ■ 0.1 wt%

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Figure 5

Thermal-physical properties of CF-GNPs versus mass fraction and temperature; (a) Thermal conductivity, (b) Dynamic viscosity, (c) Density, (d) Specific heat capacity.

Figure 6

Validation and verification for water run; (a) Heat transfer coefficients, (b) Relative errors between measurements and equations, (c) Average Nusselt number, (d) Relative errors between measurements and equations, (e) Darcy Friction factor, (f) Relative errors between measurements equations, (g) Pressure drop, (h) Relative errors between measurements and equations.

Figure 7

Heat transfer coefficients and Average Nusselt number of CF-GNPs nanofluids at various mass fractions against Reynolds number (a) Heat transfer coefficients, (b) Average Nusselt number.

Figure 8

Fluid flow properties of CF-GNPs nanofluids at various mass fractions versus Reynolds number (a) Friction factor, (b) Pressure drop.

Figure 9

Mouromtseff criterion of base fluid and CF-GNPs nanofluids in different mass percentages at different inlet temperatures.

Figure 10

PI of CF-GNPs nanofluids as a functions of various mass fractions and versus Reynolds number.

Figure 11

Heat exchanger size reduction of different mass percentages at different inlet temperatures.

Figure 12

Energy savings for different mass percentages at different inlet temperatures.

Figure 13

Total Cost of the current thermal system running.

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