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EXERGY ANALYSIS OF GRAPHENE-BASED NANOFLUIDS IN A COMPACT HEAT EXCHANGER

Ferhat KILINÇ* and Cihan Zeki UYGUN**
Sivas Cumhuriyet University, Faculty of Engineering, Department of Mechanical Engineering
58140, Sivas, TURKEY
*fkilinc@cumhuriyet.edu.tr, ORCID: 0000-0003-2707-6438
**cihanzekiuygun@gmail.com, ORCID: 0000-0002-1319-1948

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Abstract: In this study, the exergy analysis of graphene-based nanofluids in a compact heat exchanger is examined. In experiments using distilled water as the base fluid, graphene nano-ribbon and graphene oxide nanofluids were used at 0.01% and 0.02% of the volume concentrations. The experiments were carried out at 36, 40, and 44 °C fluid inlet temperatures and 0.6, 0.7, 0.8, and 0.9 m^3/h mass flow rates. As a result of the calculations made for all temperature and flow rates, it was found that the exergy efficiency values of 0.01% by volume GO nanofluid were higher than the exergy efficiency of the other nanofluids used. Also, the exergy destruction values calculated for %0.01 GO were lower than the value of exergy destruction calculated for other nanofluids. It was concluded that the exergy efficiencies of nanofluids increased with the increase of the fluid flow rates and the inlet temperature of the heat exchanger. When the exergy efficiencies were compared according to the nanofluid concentrations, it was found that the exergy efficiencies decreased with the increase of the fluid concentration. It was examined that the exergy destruction values also increases with the increase of nanofluid flow rates, as well as exergy efficiency. When the exergy destructions were compared to the nanofluid concentrations, it was concluded that the exergy destructions increased with the increase of the nanofluid concentration. It was determined that the amount of increase in exergy destruction of GO nanofluid was higher than that of GNR.
Keywords: Exergy, Second law analysis, Nanofluid, Heat exchanger, Improving heat transfer, Graphene.

KOMPAKT BİR ISI DEĞİŞTİRİCİSİNDE GRAFEN BAZLI NANO AKIŞKANLARIN EKSERJİ ANALİZİ

Özet: Bu çalışmada, kompakt bir ısı değiştiricide grafen bazlı nanoakışkanların ekserji analizi incelenmiştir. Taban akışkan olarak saf su kullanılarak yapılan deneylerde, hacim konsantrasyonlarının %0.01 ve %0.02'sinde grafen nano-ribon ve grafen oksit nanoakışkanlar kullanılmıştır. Deneyler 36, 40 ve 44 °C akışkan giriş sıcaklıklarında, 0.6, 0.7, 0.8 ve 0.9 m^3/h kütlesel debilerde gerçekleştirilmiştir. Tüm sıcaklık ve debi değerleri için yapılan hesaplamalar sonucunda hacimce %0.01 GO nanoakışkanının ekserji verimi değerlerinin kullanılan diğer nanoakışkanların ekserji verimlerinden daha yüksek olduğu bulunmuştur. Ayrıca %0.01 GO için hesaplanan ekserji yıkım değerleri, diğer nanoakışkanlar için hesaplanan ekserji yıkım değerinden daha düşüktür. Nanoakışkanların ekserji verimlerinin, akışkan debilerinin ve ısı değiştiricinin giriş sıcaklığının artmasıyla arttığı sonucuna varılmıştır. Nanoakışkan konsantrasyonlarına göre ekserji verimleri karşılaştırıldığında, akışkan konsantrasyonunun artmasıyla ekserji verimlerinin azaldığı sonucu bulunmuştur. Nanoakışkan akış hızlarının artması ve ekserji veriminin artmasıyla ekserji yıkım değerlerinin de arttığı sonucu elde edilmiştir. Nanoakışkan konsantrasyonları ile ekserji yıkımları karşılaştırıldığında, nanoakışkan konsantrasyonunun artmasıyla ekserji yıkımlarının arttığı sonucuna varılmıştır. GO nanoakışkanın ekserji yıkımındaki artış miktarının GNR'den daha fazla olduğu belirlenmiştir.
Anahtar Kelimeler: Ekserji, İkinci yasa analizi, Nanoakışkan, Isı değiştiricisi, Isı transferi iyileştirilmesi, Grafen.

NOMENCLATURE

T	Temperature
Ex	Exergy
S	Entropy
h	Enthalpy
η	Second law efficiency
φ	Volume fraction

INTRODUCTION

More effective and efficient use of energy is considered as an alternative energy source. In this context, heat exchangers used in all areas of the industry have created remarkable literature in terms of the energy economy in the studies aimed at improving heat transfer. Heat exchangers are the most important components of heating and cooling systems. Many researchers have done a lot of research to improve heat exchangers' design and operation. Any changes that are made in its design and operation affect the entire system. In this context, the radiators used in vehicle cooling systems are a type of compact heat exchanger and are the main component of the cooling system. In many industrial areas, the studies such as energy efficiency, minimizing energy consumption, optimizing the parts planned to be produced are carried out. While saving energy with these studies, the required performance criteria should also be met. Due to the low thermal properties of conventional fluids, nanofluids have been used in many systems in recent years. Nanofluids with different types, concentrations, and thermal properties have been used numerically and experimentally in many studies in the literature. In almost all of these studies, it was obtained that the use of metallic nanofluids increased the heat transfer (Pantzali *et al.*, 2009; Vajjha *et al.*, 2010; Fard *et al.*, 2011; Peyghambarzadeh *et al.*, 2011; Hung *et al.*, 2012; Pandey *et al.*, 2012; Javadi *et al.*, 2013; Khairul *et al.*, 2014). Also, the effects of several parameters were examined including nanoparticle size, shape, material composition, and acidity (Lomascolo *et al.*, 2015). Graphene particle-based nanofluids have been better properties such as high thermal conductivity, low density, low corrosion, low pumping power, and more stability compared to metallic particle-based nanofluids (Baby and Ramaprabhu, 2011; Sadeghinezhad *et al.*, 2016). In different studies using graphene-based nanofluids reported that thermal conductivity significantly increased up to 86% for 5.0 vol. % graphene dispersion (Yu *et al.*, 2011) and exhibited 47.5% thermal conductivity enhancement at 0.25 wt.% concentration (Hajjar *et al.*, 2014).

Many studies have been investigated the use of nanofluids in different types of heat exchangers. Vajjha *et al.* (2010) numerically investigated heat transfer enhancement of two different nanofluids (Al_2O_3 and CuO) in a flat tube car radiator. The average heat transfer coefficient increased by 94% for the 10% Al_2O_3 and 89% for 6% CuO nanofluids at the Reynolds number of 2000. Hung *et al.* (2012), experimentally investigated the suitability of the alumina nanofluid (Al_2O_3/water) for heat dissipation in the air-cooled heat exchanger. They reported that the highest heat transfer increase was 40% at the highest mass fraction (1.5%). Kılınç *et al.* (2020), experimentally investigated the cooling performance of a vehicle radiator by using graphene-based nano-fluids. They reported that the average enhancement of the overall heat transfer coefficient was 26.08% for 0.02 vol.% of GO and 20.64% for 0.02 vol.% concentrations of GNR/water nano-fluids. Karabulut *et al.* (2020), numerically and experimentally investigated the convection heat transfer coefficient of a graphene-based nanofluid along a circular copper tube under a turbulent flow regime. They reported that the heat transfer coefficient increment is about 48% for 350 W, heat flux at 0.02 vol.% concentration. The exergy analysis tells us how much is the usable work potential of the system or process. Also, exergy is key to the understanding of the thermodynamic behavior of energy systems. In recent most, studies were examined to exergy analysis of heat exchangers. Pandey and Nema (2012), were experimentally investigated the heat transfer, frictional losses, and exergy loss in a counter flow corrugated plate heat exchanger by using nanofluids. Esfahani and Languri (2017), were studied the benefits of using graphene oxide nanofluids, regarding their thermal performances in a shell-and-tube heat exchanger. The study was concluded that the increase in the concentration of graphene oxide particles resulted in higher viscosity and aggregate size in nanofluids at room temperature. There are more examples to analyze energy and exergy using nanofluids on various heat exchangers (Khaleduzzaman *et al.*, 2014; Sun *et al.*, 2016; İpek *et al.*, 2017; Singh and Sarkar, 2018; Wang *et al.*, 2018; Bahiraei *et al.*, 2018).

It is generally accepted that two types of losses occur in a heat exchanger: losses due to temperature difference and losses due to frictional losses caused by pressure drop. Both losses can be quantified at once with total entropy generation and to achieve an ideal heat exchanger design, the total entropy generation must be minimized. The second law of thermodynamics is a modern approach for the optimization of a thermal system and the entropy generation is used as the parameter for evaluating the efficiency of the system (Ahammed *et al.*, 2016).

Exergy analysis; is a useful analysis method in order to use the energy and resources efficiently, since it accurately determines the size, shape and location of energy losses. It is also a technique that uses the principles of conservation of mass and energy, together with the second law of thermodynamics, for the analysis, design, and development of energy and other systems (Dinçer and Rosen, 2012). An energy system's efficiency can be improved by using exergy analysis as a tool for design, evaluation, improvement, and optimization. It helps us to understand how thermodynamics phenomena affect effective processes, to compare the importance of different factors, and to determine how to improve the process most effectively (Maddah *et al.*, 2017). The first and second laws of thermodynamics are used to analyze a system's thermal properties. The combined use of both laws is necessary to obtain information about the performance and optimization of the system. To have a good understanding of a heat exchanger's thermal performance, exergy analysis or second law analysis is crucial (Esfahani and Languri, 2017). The analysis of exergy provides insight into the irreversibilities of the system and allows a comprehensive assessment of all the critical aspects of energy use (Rosen, 2002).

The graphene structure, an allotrope of carbon, is two-dimensional on one plane and has an atomic thickness (Singh *et al.*, 2012). Due to its remarkable mechanical, thermal, and electrical properties, graphene attracts the attention of many researchers (Novoselov *et al.*, 2005).

In addition, the hydrophilic nature of graphene makes it superior in terms of many disadvantages seen in metal-based nanofluids. The literature confirms that nanofluids improved heat transfer properties. However, the effects of these improvements in terms of radiator design and exergy analysis have not been evaluated sufficiently. Additionally, a very limited number of studies have been published on graphene-based nanofluids and their performance characteristics in a vehicle radiator (compact heat exchanger).

As a result, different studies have been carried out in the literature that nanofluids improve heat transfer. Although there are studies involving nanofluids and exergy analysis in heat exchangers, most of them are conducted with metal-based nanofluids. The use of graphene-based nanofluids in heat exchangers is less common and is much more limited in terms of exergy analysis. With this study, it is aimed to increase the number of experimental studies on graphene-based nanofluids (known as graphene oxide and graphene nanoribbons) applications in compact heat exchanger systems and to close the consistency and comparability gaps in the literature and based on the authors' knowledge, there is no such research in the corresponding literature. Also with the exergy analysis, it is aimed to reveal what needs to be improved, as well as see the irreversible effects of nanofluids on the system.

MATERIAL AND METHOD

Experimental Setup

The actual photo and schematic diagram of the experimental setup are shown below (Fig. 1) used in this study which includes a reservoir tank, a heater, a centrifugal pump, flow lines, a flow meter, an adjustable forced fan, an airflow channel, thermocouples for temperature measurement, a datalogger and a compact heat exchanger (vehicle radiator). Distilled water and nanofluid are used as internal fluid and air is used as external fluid at the heat exchanger. Inlet and outlet temperatures of the distilled water, nanofluids, and air were measured by using J and K-type thermocouples. The nanofluids are heated by a controllable electrical resistance.

The nanofluids are pumped into the tubes of the compact heat exchanger at various rates (0.6-0.9 m^3/h) using variable frequency drive equipment. The compact heat exchanger which is used in experiments has a stadium-shaped cross-section and consists of 36 horizontal tubes. The fins and tubes are made from aluminum. The system is cooled by air using a fan. The airflow channel and the fan are placed in a rectangular duct and directed to the radiator. An electric heater (2500 W) is used to heat the heating tank made of stainless steel. The circulation pump is equipped with a frequency converter, which allows it to function from 0 to + 110°C, and has a maximum pumping capacity of 2.7 m^3h^{-1}. A flow meter that is capable of withstanding 80°C temperature, with the precision of 0.01 L/min (with ±2% accuracy) is used to measure flow rates. Two K-type and two J-type thermocouples are used to record the inlet and outlet temperatures of the cooling air and fluids, respectively, using a datalogger. Additionally, 7 J-type thermocouples are used to record the surface temperatures of the compact heat exchanger. Nanofluids were synthesized at the Nanotechnology Research Center of Sivas Cumhuriyet University. Nanofluids were prepared by using graphene as a nanoparticle and distilled water as a base fluid.

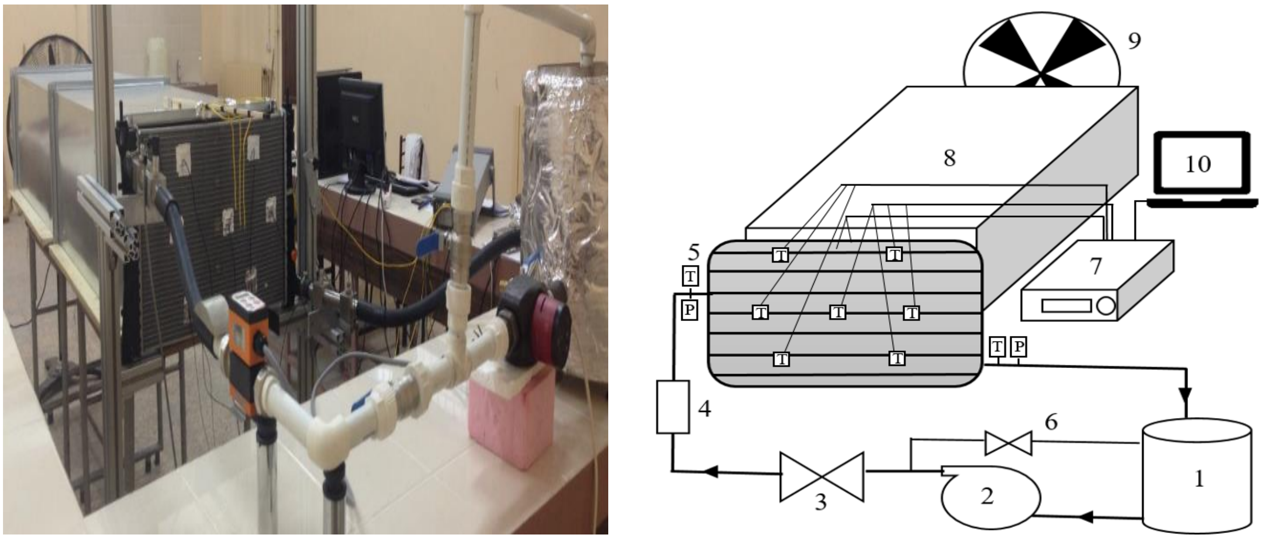

Figure 1. Actual and schematic view of the experimental system (1-storage tank 2-circulation pump 3-ball valve 4-flow meter 5-compact heat exchanger 6-recycle line 7-data logger 8-air flow channel 9-fan 10-computer)

Calculation Method

The schematic view of the compact heat exchanger used in this study is shown in Figure 2, where the red and blue lines show hot and cold fluids, respectively (Çalışkan and Hepbaşlı, 2013).

The calculations are based on the assumption of one-dimensional, steady-state heat conduction at the base of the aluminum channels and is expressed as follows: fluids and air are assumed to have constant properties, heat rejected by fluids will be fully absorbed by air and

all processes are assumed to be steady-state. Also, based on the assumption that nanoparticles are dispersed within the base fluid.

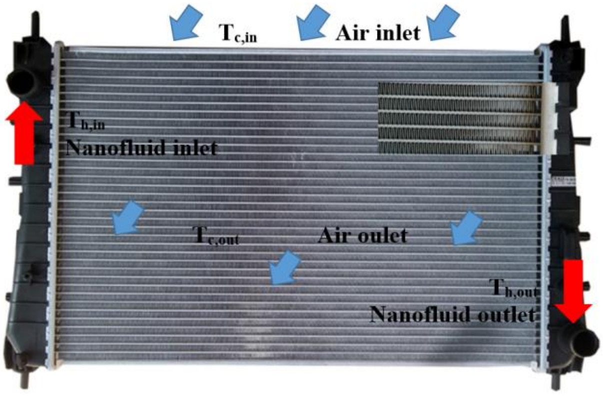

Figure 2. Diagram and detailed tube/fin view of the compact heat exchanger used in the present study

The exergy balance of the heat exchanger is written as follows.

$$(\dot{E}x_{h,in}+\dot{E}x_{c,in})-(\dot{E}x_{h,out}+\dot{E}x_{c,out})=\dot{E}x_{dest} \quad (1)$$

where "$\dot{E}x_{h,in}$" ve "$\dot{E}x_{h,out}$" are the exergy input and output for the hot fluids and "$\dot{E}x_{c,in}$" ve "$\dot{E}x_{c,out}$" are the exergy input and output for the cold fluids. "$\dot{E}x_{dest}$" is the exergy destruction.

Exergy flow of the fluid "$\dot{E}x_f$" is written as follows:

$$\dot{E}x_f=\dot{m}_f[(h_f-h_o)-T_0(s_f-s_o)= \dot{m}_f C_{p,f}[(T_f-T_0)-T_0 \ln\left(\frac{T_f}{T_0}\right)] \quad (2)$$

where "$\dot{m}_f$" is the mass flow of fluid, "T_f" is the fluid temperature, "$C_{p,f}$" is the specific heat capacity of fluid, "h_f" is the enthalpy of fluid at fluid temperature, "s_f" is the entropy of fluid at fluid temperature, "T_0" is the dead state temperature, "h_o" is the enthalpy of fluid at dead state temperature, "s_o" is the entropy of fluid at dead state temperature. The above equation is more clearly expressed as follows.

$$\dot{E}x_{h,in}=\dot{m}_{h,in}C_{p,h}[(T_{h,in}-T_0)-T_0 \ln\left(\frac{T_{h,in}}{T_0}\right)] \quad (3)$$

$$\dot{E}x_{h,out}=\dot{m}_{h,out}C_{p,h}[(T_{h,out}-T_0)-T_0 \ln\left(\frac{T_{h,out}}{T_0}\right)] \quad (4)$$

$$\dot{E}x_{c,in}=\dot{m}_{c,in}C_{p,c}[(T_{c,in}-T_0)-T_0 \ln\left(\frac{T_{c,in}}{T_0}\right)] \quad (5)$$

$$\dot{E}x_{c,out}=\dot{m}_{c,out}C_{p,c}[(T_{c,out}-T_0)-T_0 \ln\left(\frac{T_{c,out}}{T_0}\right)] \quad (6)$$

where "in", "out", "c", ve "h" subscripts are meant that input, output, cold and hot, respectively.

The exergy destruction current "$\dot{E}x_{dest}$" of the heat exchanger can be found as follows:

$$\dot{E}x_{dest}=\dot{S}_{gen}T_o \quad (7)$$

Where "$\dot{S}_{gen}$" is the entropy generation.

There are different ways to calculate exergy efficiency in the literature. According to Hepbaşlı (2008), the most commonly used equation is as follows:

$$\eta_{II}=[(\dot{E}x_{h,out}+\dot{E}x_{c,out})/(\dot{E}x_{h,in}+\dot{E}x_{c,in})]*100 \quad (8)$$

where "η_{II}" refers to the second law efficiency.
The correlations of nanofluids to be used for exergy analysis can be calculated as follows:

$$c_{nf}=\varphi c_p+(1-\varphi)c_{bf} \quad (9)$$

where c_p is the specific heat of nanofluids, ρ is the density of nanofluids, and φ is the volume fraction of nanoparticles. Also, nf, p, and bf refer to nanofluid, particle, and base fluid, respectively (Pak and Cho, 1998).

The density of the nanofluids can be calculated as follows (Khanafer and Vafai, 2011):

$$\rho_{nf}=(1-\varphi_p)\rho_{bf}+\varphi_p\rho_p \quad (10)$$

Also, $\varphi_p=V_p/(V_p+V_{bf})$ is the volumetric concentration of nanoparticles.

Uncertainty analysis

Uncertainty analysis is important in terms of the precision of the measured results and the accuracy of the results obtained. To obtain the uncertainty values the following equation was used (Holman, 2001);

$$w_R=\left[\left(\frac{\partial R}{\partial x_1}w_1\right)^2+\left(\frac{\partial R}{\partial x_2}w_2\right)^2+\ldots+\left(\frac{\partial R}{\partial x_n}w_n\right)^2\right]^{1/2} \quad (11)$$

where R is a function of independent variables ($x_{1,2,n}$) and resulting from the experimental study. $w_{R,1,2,n}$ can be taken as the uncertainties in the independent variables. According to the uncertainty analysis, the values estimated as ±2.65% for flow rate, ±0.5% for temperature, ±0.65% for circulating pump power input and ±1.25% for heating tank power input.

RESULTS AND DISCUSSION

In the calculations of this study, the data from a previous experimental study were used (Kılınç, 2015). In the experiments, five different fluids as water, graphene oxide (0.01 and 0.02 vol.%) and graphene nanoribbon (0.01 and 0.02 vol.%), three different inlet temperatures (36, 40, and 44 °C), and four different mass flow rates for each temperature (0.6, 0.7, 0.8 and 0.9 m^3/h) were used.

Besides, ambient air was used to cool as the fluid passed through the radiator, and it was sent to the radiator with the help of a fan, at a constant flow rate of 0.45 m^3/h. The inlet/outlet temperatures of the water and nanofluids, the surface temperature of the radiator, and the outlet temperature of the air passing through the radiator were measured in the experiments. During the experiments, changes in the ambient air are affected by the calculations. The sudden jumps and decreases in different flow transitions are directly proportional to the ambient temperature which is measured and used in the calculations in the graphics below. Since the dataset obtained as a result of calculations are close to each other, exergy efficiencies and exergy destructions have been calculated as two significant steps after the comma (Uygun, 2019).

In Figures 3 and 4, the heat transfer coefficients for water-based nanofluid containing graphene nanoparticles at different concentrations and different inlet temperatures are compared with pure water. The heat transfer coefficients of both GO and GNR nanofluids increased with increasing flow rate, inlet temperature and particle volume concentration. Numerous studies have emphasized the importance of this situation in terms of energy analysis (1st law efficiency) and it provides the basis for the second law efficency (Vajjha *et al.*, 2010; Peyghambarzadeh *et al.*, 2011; Kılınç *et al.*, 2020).

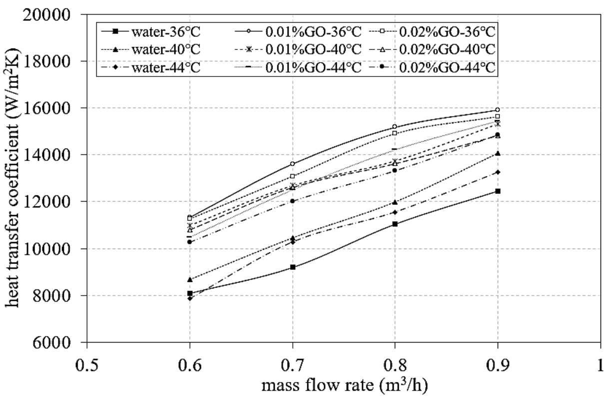

Figure 3. Comparison of heat transfer coefficients for water/GO nanofluids

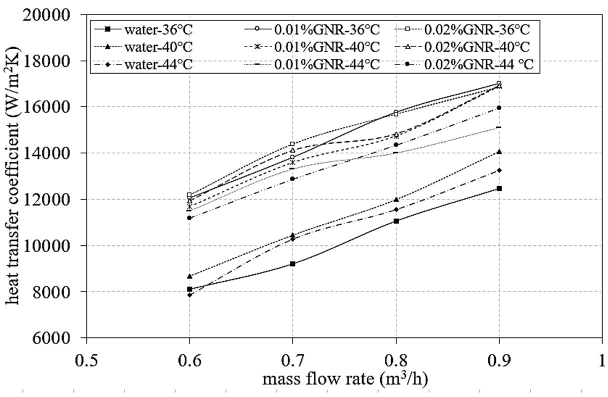

Figure 4. Comparison of heat transfer coefficients for water/GNR nanofluids

Exergy efficiency calculated for different temperatures (36ºC, 40 ºC, and 44ºC) from the data obtained after the experiments is given comparatively in Figure 5. As a result of the calculations made for a temperature of 44 ℃ and a flow rate of 0.9 m^3/h, the exergy efficiency for water was found to be 95.18%, while the exergy efficiency value for 0.01% GO was 94.93%. At the same temperature and flow rate values, the exergy efficiency was calculated as 92.40% for 0.01% GNR, 91.25% for 0.02% GNR, and 90.10% for 0.02% GO.

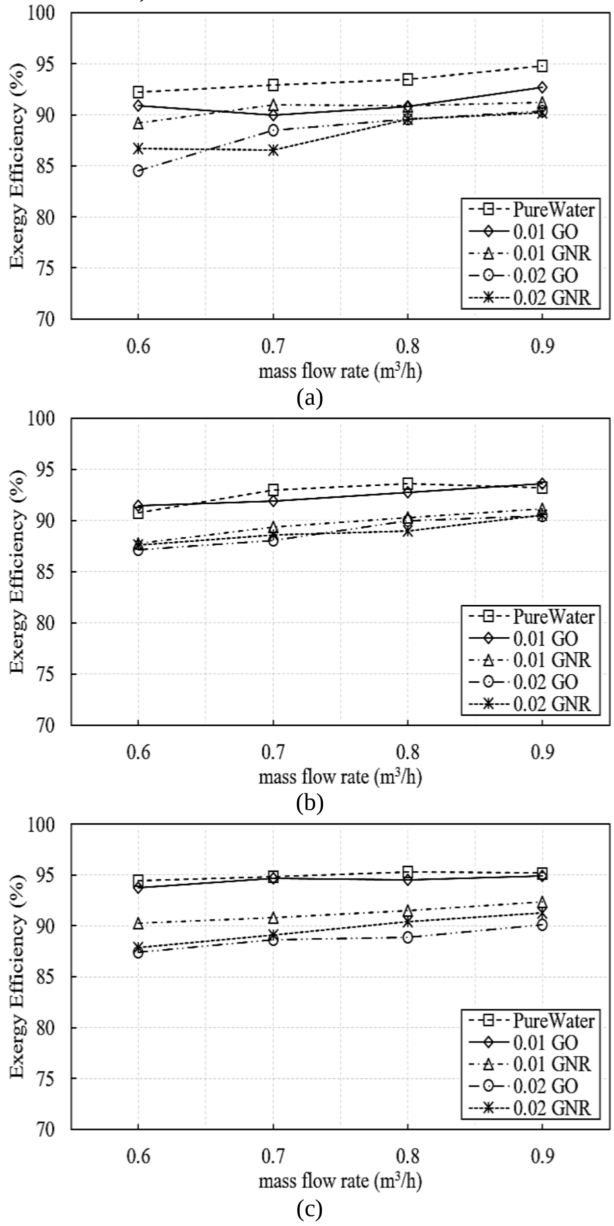

Figure 5. Comparison of exergy efficiencies for all nanofluids at a) 36 ºC b) 40 ºC c) 44 ºC

According to Figure 5(a), it has been obtained that the water exergy efficiency is higher in all flow rates compared to other nanofluids and the highest exergy value has been calculated as 94.79% (Khaleduzzaman *et al.*, 2014). The value of exergy efficiency closest to water was calculated for 0.01% GO and 92.79% for 0.9 m^3/h fluid flow. The lowest exergy efficiency was calculated as 84.57% for 0.02% GO at 0.6 m^3/h flow rate and 36℃ temperature. According to Figure 5(b), the highest exergy efficiency was obtained as 93.63% at a flow rate of 0.9 m^3/h for 0.01% GO. The lowest exergy efficiency was calculated as 87.14% at a flow rate of 0.6 m^3/h for 0.02% GO. Exergy efficiencies of water and 0.01% GO were higher compared to other fluids when the fluid temperature was 40℃. In Figure 5(c), a comparison of exergy efficiencies for four different flow rates of nanofluids at 44 °C is given. Exergy efficiencies for water and 0.01% GO were calculated very close to each other. The highest exergy efficiency for water was calculated as 95.19% at a flow rate of 0.9 m^3/h. For 0.01% GO, the exergy efficiency calculated at the same flow rate was 94.93%. The lowest exergy efficiency was calculated as 87.37% again for 0.02% GO at 0.6 m^3/h flow rate.

The comparison of exergy destruction for four different flow rates of nanofluids at different temperature are given in Figure 6.

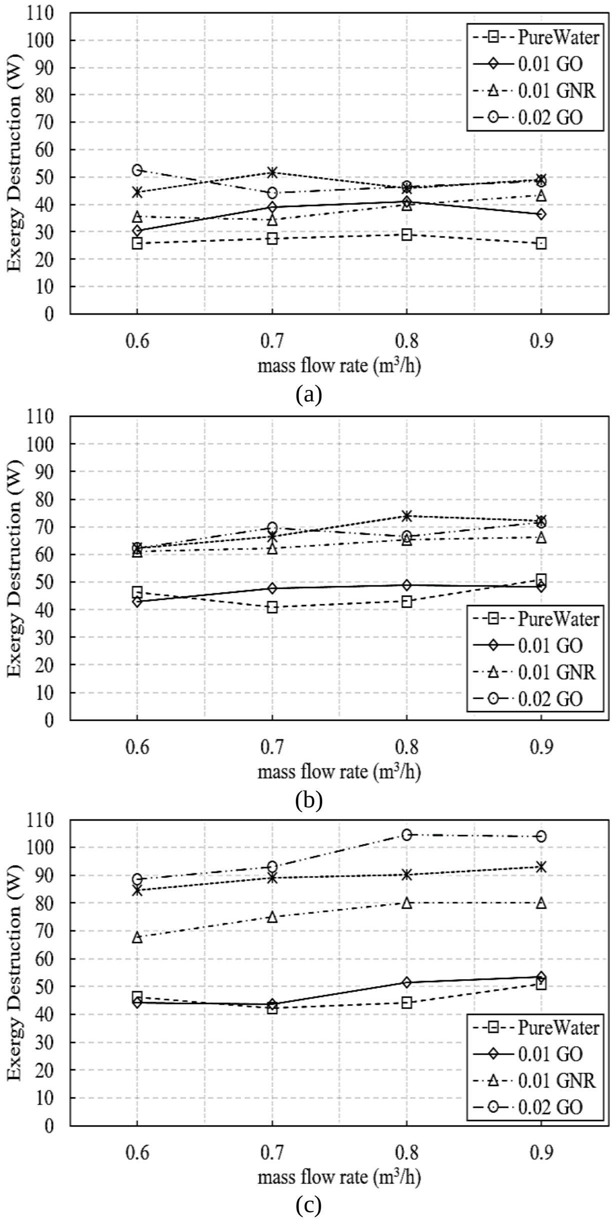

Figure 6. Comparison of exergy destruction for all nanofluids at a) 36 ºC b) 40 ºC c) 44 ºC

According to Figure 6 (a), the highest exergy destruction was 52.42 W for 0.02% GO nanofluid at a flow rate of 0.6 m^3/h. The second highest exergy destruction was calculated as 51.77 W for 0.02% GNR nanofluid at 0.7 m^3/h flow rate. The lowest exergy destruction was 25.77 W for water at a flow rate of 0.6 m^3/h. The lowest exergy destruction value was 30.41 W for 0.01% GO at 0.6 m^3/h when compared to each nanofluid at a given temperature. Figure 6(b) shows the changes of exergy destruction of nanofluids at different flow rates at 40 °C. According to obtained data, the lowest exergy destructions were obtained for water at 0.7 m^3/h flow and 0.01% GO nanofluid at 0.6 m^3/h flow and these values were calculated as 40.84 W and 42.80 W, respectively. Exergy destruction values are close to each other such as exergy efficiency values for water and 0.01% GO nanofluid at 40 °C, and the highest exergy destruction difference is 6.86 W. The highest exergy destruction value is 73.93 W which was obtained at a flow rate of 0.8 m^3/h for 0.02% GNR nanofluid (Figure 6(b)). According to Figure 6(c), the lowest exergy destructions obtained at 44 °C fluid inlet temperature were calculated as 42.43 W for water and 43.73 W for 0.01% GO at 0.7 m^3/h. The highest exergy destructions were calculated for 0.02% GO as 104.42 W at 0.8 m^3/h and 104.01 W at 0.9 m^3/h. It has been observed that the exergy destruction values calculated when the fluid inlet temperature is 44 °C are higher than the exergy destruction values calculated for 36 °C and 40 °C fluid inlet temperatures. On the other hand, exergy destruction values for water and 0.01% GO was observed as a result of the calculations concerning the exergy values calculated for water at 40 °C and 0.01% GO oxide.

The graphs of exergy efficiency for water and all nanofluids (0.01% GO, 0.01% GNR, 0.02% GO, 0.02% GNR) are given in Figure 7, comparatively for all flow rates at 36, 40, and 44 °C temperatures.

According to Figure (7), the graphs of exergy efficiency for water and all nanofluids (0.01% GO, 0.01% GNR, 0.02% GO, 0.02% GNR) are given comparatively for all flow rates at 36, 40, and 44 °C temperatures. The highest exergy efficiency among all nanofluids and all temperature values for a flow rate of 0.6 m^3/h is 94.48% and 93.73% for water and 0.01% GO at 44 °C, respectively. The lowest exergy efficiency which is 84.57% is obtained for 36 °C temperature and 0.02% GO nanofluid. The highest exergy efficiency among all nanofluids and all temperature values for a flow rate of 0.7 m^3/h is 94.85% and 94.68% for water and 0.01% GO at 44 °C, respectively (Khaleduzzaman *et al.*, 2014). The lowest exergy efficiency is obtained for 36 °C temperature and 0.02% GNR nanofluid, and the exergy efficiency is 86.57%. The highest exergy efficiency among all nanofluids and all temperature values for a flow of 0.8 m^3/h is 95.29% and 94.53% for water and 0.01% GO at 44 °C, respectively. The highest exergy efficiency among all nanofluids and all temperature values for 0.9 m^3/h flow is 95.19% and 94.93% for water and 0.01% GO at 44 °C, respectively. The calculated exergy efficiency values for 0.01% GO nanofluid were the highest at 6.33% compared to other nanofluids, and water's exergy efficiency was generally between 1% and 2% higher than 0.01% GO compared to water (Gamal *et al.*, 2021). The graphs of comparative exergy destructions for water and all nanofluids are given in Figure 8.

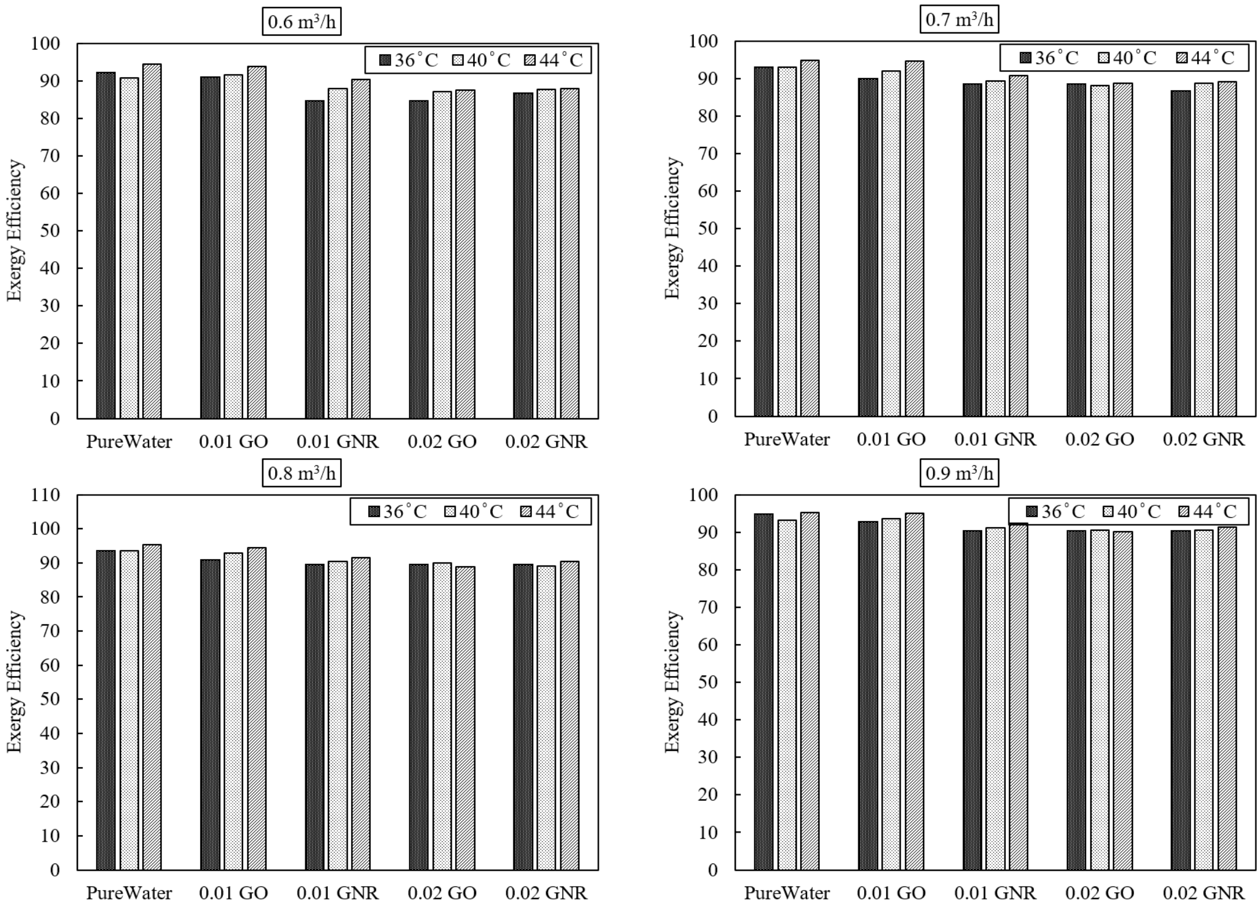

Figure 7. Comparison of the exergy efficiency of water and nanofluids at different temperatures for all flow rates

According to Figure 8, the highest exergy destruction value for a flow of 0.8 m^3/h among all temperature values and nanofluids is 88.63 W for 0.02% GO at 44 °C. The lowest exergy destruction values are at 36 °C for water and 0.01% GO, which are 25.77 W and 30.41 W respectively. For the flow rate of 0.7 m^3/h, the lowest exergy destruction value of 36 °C water and 0.01% GNR were obtained, which are 27.58 W and 34.56 W respectively. The highest exergy destruction was calculated as 92.98 W for 44 °C temperature and 0.02% GO nanofluid. Also, the exergy destruction value at 44 °C calculated for 0.01% GO nanofluid is 43.73 W and the exergy destruction value at 40 °C is 47.70 W.

As seen in Figure 8, the highest exergy destruction was calculated as 104.42 W at 44 °C for 0.02% GO nanofluid. Among exergy destructions calculated for the flow rate of 0.8 m^3/h, water has a lower exergy destruction value than nanofluids at all temperature values. The nanofluid with the lowest exergy destruction value at 40 °C and 44 °C is 0.01% GO. The nanofluid with the lowest exergy destruction value for 36 °C is 0.01% GNR. The highest exergy destruction value for the flow rate of 0.8 m^3/h was obtained as 104.01 W at 44 °C for 0.02% GO. It is seen that the nanofluid with the lowest exergy destruction is 0.01% GO. It has been observed that 0.01% GO has lower exergy destruction at all temperatures and flow rates compared to other nanofluids.

In Table 1, the exergetic analysis results are shown for all fluids at 36, 40 and 44 ºC. Exergy destruction and exergy efficiency values are summarized in tabular form for a better understanding of the graphs. In addition, entropy generation values are also given. Exergy destruction in a heat exchanger is dependent on the heat exchanger's dead state and its inlet and outlet temperatures. Improvement of these parameters will increase the exergy efficiency of the system by reducing the exergy destruction of the heat exchanger.

In many studies under the heading of exergy analysis, changes in exergy destruction and exergy efficiency have been evaluated in terms of flow rate, inlet temperature, and particle concentration parameters. The positive and negative results obtained as a result of the changes in these parameters are attributed to some factors that occur with the use of nanofluids. Increasing the nanoparticle concentration provides higher thermal conductivity and increases the heat transfer coefficient. In addition, increasing the nanoparticle concentration increases the viscosity and friction losses. It has been stated that this situation provides an increase in the second law efficiency (Gamal *et al.*, 2021). Similarly, it has been reported that the increase in flow rate and particle loading increases the heat transfer coefficient, and an improvement in exergy efficiency is observed with the resulting particle migration, molecular level layering of the liquid at liquid particle interface and hydrodynamic effect of Brownian motion of nanoparticles (Khairul *et al.*, 2014; Ahammed *et al.*, 2016)

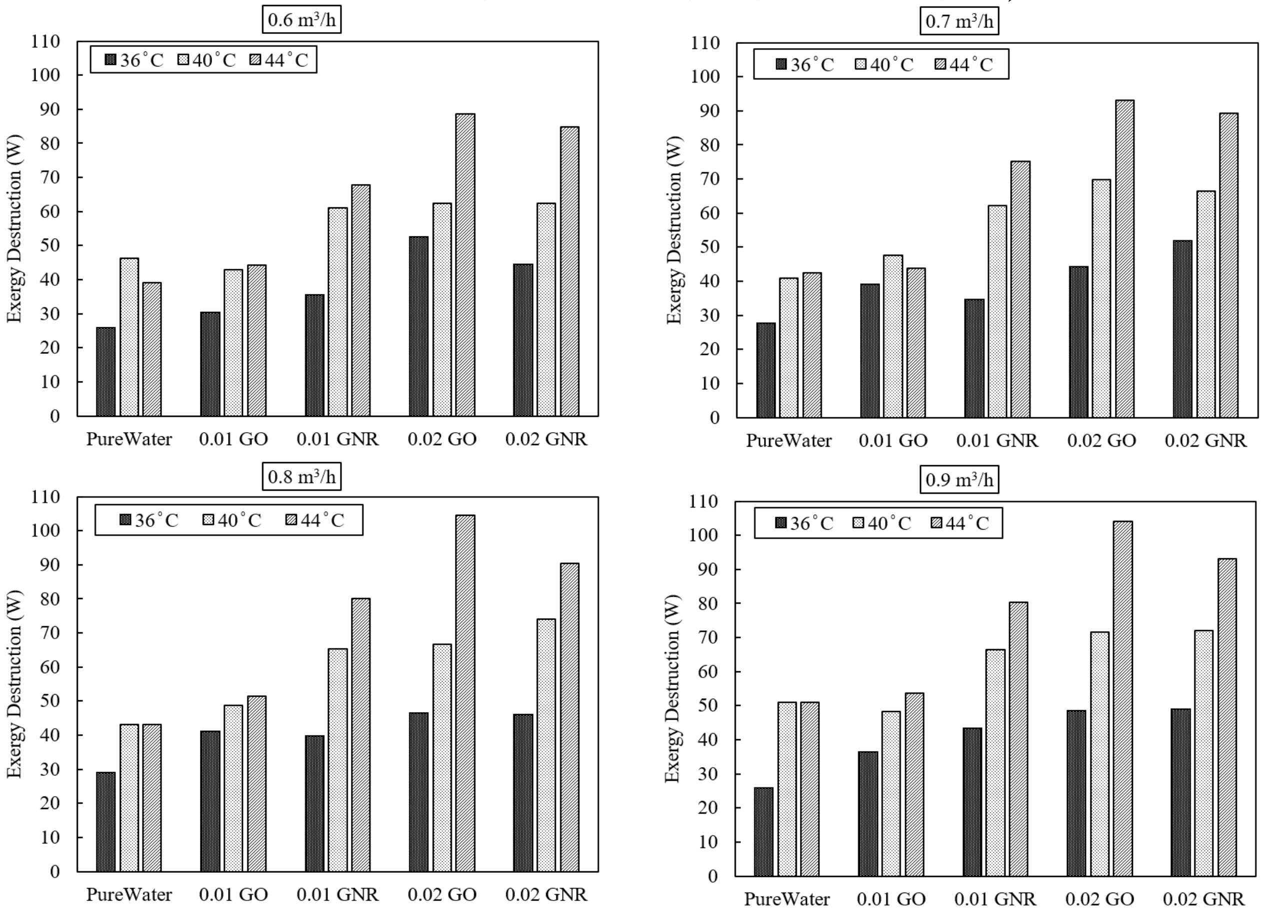

Figure 8. Comparison of the exergy destruction of water and nanofluids at different temperatures for all flow rates

Table 1. Exergetic analysis results for all fluids at 36, 40 and 44 °C

Fluid	$\dot{m}_{fluid}$ *(m^3/h)*	*36 °C*	$\dot{E}x_{dest}$ *(W)*	$\dot{S}_{gen}$ *(W/K)*	η_{II} *(%)*	*40 °C*	$\dot{E}x_{dest}$ *(W)*	$\dot{S}_{gen}$ *(W/K)*	η_{II} *(%)*	*44 °C*	$\dot{E}x_{dest}$ *(W)*	$\dot{S}_{gen}$ *(W/K)*	η_{II} *(%)*
water	**0.6**		25.77	0.088	92.24		46.23	0.158	90.78		39.07	0.134	94.48
	0.7		27.58	0.094	92.89		40.84	0.140	93.00		42.43	0.145	94.85
	0.8		29.04	0.099	93.45		43.04	0.147	93.62		44.37	0.152	95.29
	0.9		25.94	0.089	94.79		50.99	0.175	93.25		50.98	0.175	95.19
0.01% GO	**0.6**		30.41	0.104	90.91		42.80	0.147	91.48		44.30	0.152	93.73
	0.7		39.15	0.134	89.98		47.70	0.163	91.91		43.73	0.150	94.69
	0.8		41.06	0.141	90.84		48.78	0.167	92.78		51.45	0.176	94.53
	0.9		36.48	0.125	92.73		48.33	0.166	93.63		53.57	0.183	94.93
0.02% GO	**0.6**		52.42	0.180	84.57		62.34	0.213	87.15		88.63	0.304	87.37
	0.7		44.24	0.152	88.49		69.76	0.239	88.06		92.98	0.318	88.63
	0.8		46.58	0.160	89.56		66.57	0.228	90.01		104.42	0.358	88.84
	0.9		48.43	0.166	90.38		71.58	0.245	90.49		104.01	0.356	90.10
0.01% GNR	**0.6**		35.54	0.122	89.16		60.98	0.209	87.79		67.72	0.232	90.28
	0.7		34.56	0.118	91.00		62.25	0.213	89.37		75.13	0.257	90.81
	0.8		39.83	0.136	90.87		65.27	0.224	90.28		80.03	0.274	91.49
	0.9		43.23	0.148	91.22		66.32	0.227	91.18		80.24	0.275	92.40
0.02% GNR	**0.6**		44.49	0.152	86.67		62.28	0.213	87.60		84.75	0.290	87.88
	0.7		51.77	0.177	86.57		66.50	0.228	88.60		89.16	0.305	89.13
	0.8		45.94	0.157	89.60		73.93	0.253	88.98		90.29	0.309	90.44
	0.9		48.99	0.168	90.24		72.11	0.247	90.53		93.04	0.319	91.25

When the increase in exergy loss is examined for the inlet temperature, it is concluded that the temperature difference between the hot and cold fluids increases the exergy loss, which is due to the finite temperature difference, and this is the main reason for the exergy loss in the heat exchangers (Dizaji *et al.*, 2017). As the fluid flow rate increases, it increases fluid disruption and destroys the flow boundary layer. Additionally, graphene nanoparticles in nanofluids are subjected to Brownian forces for irregular Brownian diffusion and thermal diffusion. Micro-convection occurs between nanoparticles and the base fluid, energy is transferred from the nanoparticles to the base fluid, the boundary layer is sharply disrupted, disturbance is heightened, and heat transfer is enhanced (Wang *et al.*, 2020).

CONCLUSION

In this study, the exergy analysis of graphene-based nanofluids in a compact heat exchanger is examined. Exergy efficiency and exergy destruction values were calculated comparatively for distilled water and nanofluids. The results of the calculations can be summarized as follows:

It was concluded that the exergy efficiencies of nanofluids increased with the increase of the fluid flow rates and inlet temperature to the heat exchanger (Bahiraei and Mazaheri, 2021; Khairul *et al.*, 2014; Saleh and Sundar, 2021; Gamal *et al.*, 2021; Sadighi *et al.*, 2016; Ahammed *et al.*, 2016). The increase in the number of Nusselt resulted in an increase in heat transfer and an increase in the exergy efficiency of the nanofluid. Enhanced exergy efficiency results from changes in entropy generation of the fluid and irreversibility rates in the system (Saleh and Sundar, 2021).

When the exergy destruction and entropy generation were compared to the nanoparticle concentrations, it was concluded that the exergy destructions increased with the increase of the nanoparticle concentration. It can be explained by the limited heat transfer temperature difference, the fluid viscosity flow resistance, Brownian motion, particle migration, etc. (Wang *et al.*, 2020; Pandya *et al.*, 2020).

It was concluded that the exergy destruction and entropy generation of nanofluids increased with the increase of the flow rates (Bahiraei and Mazaheri, 2021). However, it showed an increasing and decreasing trend by oscillating in some conditions. It was determined that the amount of increase in exergy destruction of GO nanofluid was higher than that of GNR. Graphene nanofluid's lower concentration enhances heat transfer more than fluid viscosity's effect on performance (Wang *et al.*, 2020).

When the exergy destruction values are compared with the fluid temperatures, it was found that the exergy destruction values increase with the increase of fluid inlet temperatures (Pandya *et al.*, 2020; Esfahani and Languri, 2017; Sadighi *et al.*, 2016).

In this study, it was concluded that the positive effect of the nanofluids prevails to the adverse effects and fluid flow rate, inlet temperature and particle concentration play an important role in heat exchanger efficiency This shows that the use of the nanofluid is a valuable method to reduce the total irreversibility of the heat exchanger.

As a result, it has been determined that the exergy efficiency of 0.01% GO nanofluid is better and the amount of exergy destruction is less compared to 0.02% GO nanofluid. The calculated values were found to be comparable to previous studies in the literature (Khaleduzzaman *et al.*, 2014; Gamal *et al.*, 2021; Jils and Jesseela, 2021). Considering that the flow structure of nanofluids will cause irreversibilities and entropy generation, the nanoparticles in the fluid will cause a turbulent flow structure, these values are quite remarkable. Finally, further work is required to investigate the effects of the economic efficiency of nanofluids and the use of hybrid nanofluids.

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