Evaluation and Improvement of Thermal Energy of Heat Exchangers with SWCNT, GQD Nanoparticles and PCM (RT82)

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Mohammadreza Hasandust Rostami[1], Gholamhassan Najafi[1,*], Ali Motevalli[2], Nor Azwadi Che Sidik[3], Muhammad Arif Harun[3]

[1] Department of Mechanics of Biosystems Engineering Tarbiat Modares University, Tehran, Iran
[2] Department of Mechanics of Biosystem Engineering, Sari Agricultural Sciences and Natural Resources University, Sari, Iran
[3] Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia

ARTICLE INFO	ABSTRACT
	Today, due to the reduction of energy resources in the world and its pollutants, energy storage methods and increase the thermal efficiency of various systems are very important. In this research, the thermal efficiency and energy storage of two heat exchangers have been investigated in series using phase change materials (RT82) and single wall carbon nanotubes (SWCNT) and graphene quantum dot nanoparticles (GQD) In this research, two heat exchangers have been used in combination. The first heat exchanger was in charge of storing thermal energy and the second heat exchanger was in charge of heat exchange. The reason for this is to improve the heat exchange of the main exchanger (shell and tube) by using heat storage in the secondary exchanger, which has not been addressed in previous research. The results of this study showed that using two heat exchangers in series, the thermal efficiency of the system has increased. Also, the heat energy storage of the double tube heat exchanger was obtained using phase change materials in the single-walled carbon nanotube composition of about 3000 W. The average thermal efficiency of the two heat exchangers as the series has increased by 52%. In general, the effect of the two heat exchangers on each other was investigated in series with two approaches (energy storage and energy conversion) using fin and nanoparticles, which obtained convincing results.

1. Introduction

Today, much attention has been paid to the development and improvement of suitable options for fossil fuels because due to concern about pollution and conventional energy sources. Among renewable and sustainable energies, the solar and wind energies play a more prominent and

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* *Corresponding author.*
E-mail address: g.najafi@modares.ac.ir

attractive role in researchers. Due to the nature of their operation, thermal energy storage systems have many applications, especially in the air conditioning and solar energy systems [1-3]. However, solar energy, like other options, such as wind, geothermal and hydropower, suffers from an inherent source of interruption. Therefore, energy storage systems with dual characteristics are doubly important. The properties of this energy storage systems should be including high storage density, high thermal conductivity and high stability of materials used to better efficiency and safety this system. The phase change materials (PCM) based on high latent heat have been determined as a suitable approach. The main disadvantage in these materials is their low thermal conductivity, which makes the process of melting and solidification of these materials difficult. Solutions have been devised to solve this problem which heat transfer rate from the fluid to the phase change material increases such as nanoparticles, metal fins, metal foams and heat tubes [4-14]. The use of nanoparticles has expanded in recent years. Khodadadi and Hosseinizadeh [15] conducted an experimental study on the heat transfer rate of heat exchanger that their experiment indicated the heat transfer rate have been increased by adding the nanoparticles to the phase change material (PCM). There were two reasons for this enhancement: the decrease of latent heat fusion of phase change material and augmentation of thermal conductivity of this material.

Many studies such as Fan and Khodadadi [16], Wu *et al.*, [17], Ho and Gao [18], and Dhaidan *et al.*, [19] have been performed on the improvement of thermal properties of phase change material by using the various nanoparticles as an effective method. However, some studied have shown that adding the nanofluid to the base fluid has negative effect on the thermal characteristics of working fluid. Mohamad [20] investigated an empirical study on the heat transfer rate and other thermal properties of a fluid in the presence of nanoparticles and indicated a slight improvement in fluid thermal properties if physics is assumed to be a simple problem. Also, he showed that by adding the nanoparticles to the working fluid, viscosity and density of working fluid and sedimentation of the particles dispersed in the nanofluid increase which reduce the convection heat transfer. Also, many studies have been investigated on the enhancement of thermal properties of different heat exchangers as increase energy efficiency and storage energy. Al-Abidi *et al.*, [21] conducted a study on the temperature and mass flow rate of water as working fluid on the thermal properties of heat exchanger and phase change material (PCM) in the triplex tube heat exchanger that results obtained from this study showed both two parameters increased the thermal characteristics of phase change material but the effect of temperature was greater than the other parameter. Mahdi and Nsofor [23] have conducted a study on the melting and solidification of phase change material by using three parameters which include fins, nanoparticles, and combination of fins and nanoparticles. The results obtained from this study showed that the use of two parameters increased melting and solidifications of phase change material, but the effect of using fins was greater than the nanoparticles. Joybari *et al.*, [24] investigated the melting and solidification of phase change material with a new combination of fins in the triplex tube heat exchanger. This new design of fins increased significantly charging of phase change material compared to systems that have conventional fins and nanoparticles. Enhancement the heat transfer rate in charging and discharging of the energy storage and conversion systems have been studies in the most researchers to improve of thermal conductivity of phase change material but in a few numbers of studies dealt to simultaneous charging and discharging of phase change materials. Joybari *et al.*, [25] performed an experimental study on the simultaneous charging and discharging of phase change materials in the triplex tube heat exchanger. This research investigated the impression of natural convection on the heat transfer. The results gained from study have been shown that increment melting of the phase change material leads to increasing upward motion of natural convection heat transfer that cause enhancement the heat transfer rate. In another study Joybari *et al.*, [25] conducted an experimental study on the enhancement of heat transfer rate

under condition the simultaneous charging and discharging of phase change material that with using the fins that results showed the use of fins will provide the best system performance for convective heat transfer. Also, other researches have been done in this field by using the metal nanoparticles and fins in the various heat exchanger which results obtained showed the thermal characteristics of the heat exchanger were generally increased.

There has also been other research on the use of nanoparticles in improving the heat transfer rate of fluids, which has addressed various aspects of the effects of nanoparticles [40-45].

According to previous research, most research has focused on the use of various nanofluids in improving the thermal properties of thermal energy conversion and storage systems. But in this research, a new method to increase the thermal efficiency of thermal systems is presented. In this research, to increase the heat efficiency of heat exchangers, a combination of two heat exchangers has been used in series. The first exchanger is responsible for storing thermal energy using phase change materials and the second exchanger (main exchanger) is responsible for cooling the working fluid. In fact, by adding a heat exchanger that stores thermal energy along with the main heat exchanger (shell and tube), in addition to significantly improving the temperature of the cooling system, it caused the use of phase change material the amount of heat lost throughout the system absorb using phase change materials and significantly prevent energy wastage [47,48]. In this research, two heat exchangers (shell and tube and double tube heat exchanger) have serially placed in the systems that double tube heat exchanger was used as energy storage system and shell and tube heat exchanger was used as energy transfer system which have not been investigated yet. Thus, the main goal of this research was to evaluate the effect of using two heat exchangers in series on the heat transfer and storage characteristics of this system.

2. Methodology
2.1 Definition of Shell and Tube and Double Tube Heat Exchangers

Designed heat exchangers in this research include a shell and finned tube heat exchanger which possess 21 tubes with fin blade tubes and other is a double tube heat exchanger which is a thermal energy storage system. The length and diameter of the shell and tube heat exchanger are 400 mm and 150 mm respectively and also, both parameters to double tube heat exchanger are 500 mm and 100 mm respectively. Figure 1 represents the schematic of the shell and tube and double tube heat exchangers that it should be noted hot fluid flows from center of the double tube heat exchanger and exits from center of the shell and tube heat exchanger whereas cold fluid enters from circumference and flows to out from perimeter of the shell and tube heat exchanger and phase change material (PCM) embedded in the external tube of the double tube heat exchanger as well as used nanofluid in heat exchanger (SWCNT and GQD) at the various volume concentration flows inside the tubes.
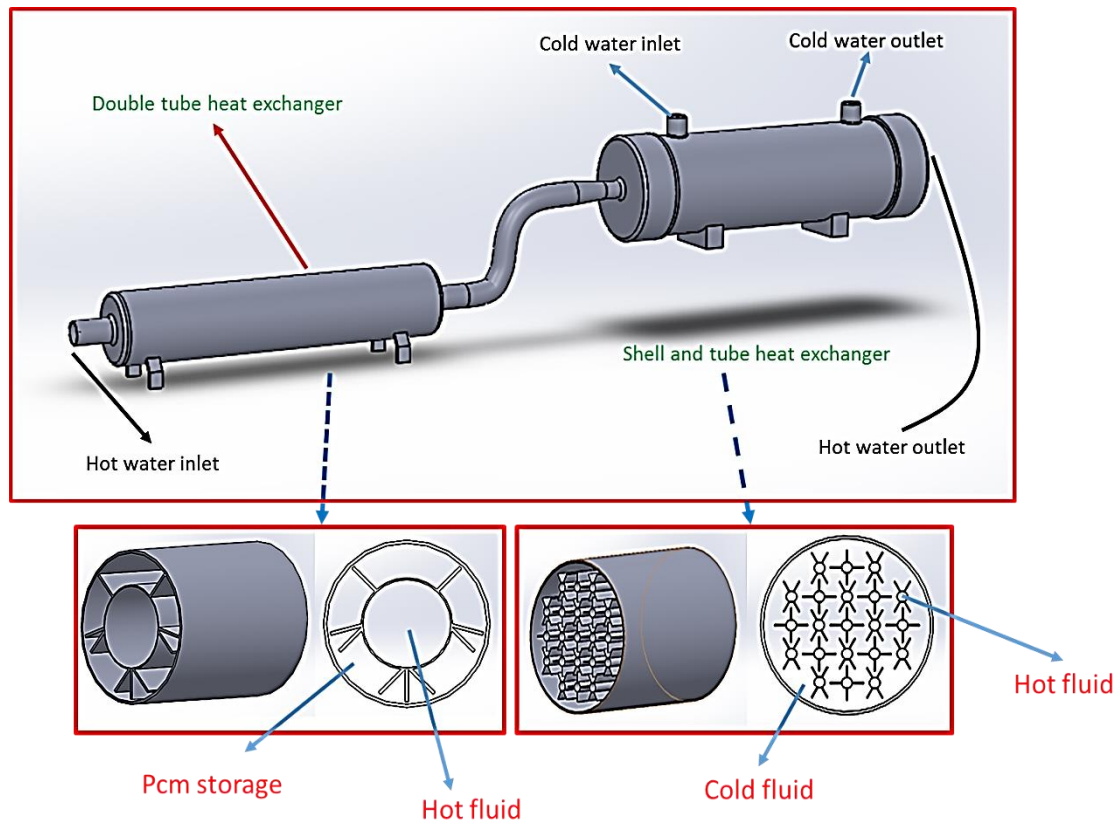
Fig. 1. Schematic of constructed system in this research

Also, Table 1 shows the geometry characteristics of double tube and shell and tube heat exchanger as following

Table 1
Geometry characteristics of designed heat exchanger in this research

Parameters	Shell and tube quantity	Double tube quantity
Shell inside diameter (outer tube)	150 mm	50 mm
Shell thickness (outer tube)	2 mm	2 mm
Shell length (outer tube)	400 mm	500 mm
Number of baffles	-	-
Number of tubes	21	1
Tubes length	400 mm	500 mm
Tubes arrangement pattern	Square	-
Tubes thickness (inner tube)	1 mm	1 mm
Tubes outside diameter (inner tube)	10 mm	28 mm
Fins length	400 mm	500 mm
Fins thickness	1 mm	1 mm
Fins width	10 mm	10 mm
Fins angle1	60 deg	-
Fins angle2	90 deg	-

2.2 Experimental Setup

The experiments are conducted on the apparatus in the heat transfer exchange process of shell and tube heat exchanger and double tube heat exchanger that contains a stainless steel shell (outer tubes) and copper tubes in shell and tube heat exchanger (inner tubes), tow screw pumps in order to create pumping force for tow flow rates (cold flow and hot flow), nanofluid cooling system, a

heating tank (20 L), four type-k thermocouples with ± 0.1% accuracy, temperature data logger, tow flow meters (rotameters) with ± 2% precision , electrical heater, reservoir tank for reciprocal flow of cold fluid and electronic thermostat with precision about by ± 0.3% . In this experiment there were two flow loops (water flow loop and nanofluid flow loop) which the nanofluid flows through the 21 tubes of shell and tube heat exchanger with 10mm outside diameter, 9mm inside diameter, 1mm thickness, 400mm length and 4 fins on the outside diameter of the tubes that it includes two angles of positioning the fins (45 degrees and 90 degrees) and one tube of double tube heat exchanger with 28 mm diameter and cold water flow passes inside the shell with 152mm outside diameter, 150mm inside diameter, 2mm thickness and 400mm length that didn't use of the baffle inside the shell and tube heat exchanger also phase change material (PCM) embedded in the outer tube of the double tube heat exchanger that contact with fin blades at the outer section of inner tube. Figure 2 shows the constructed and block diagram of heat exchanger in the test conditions.
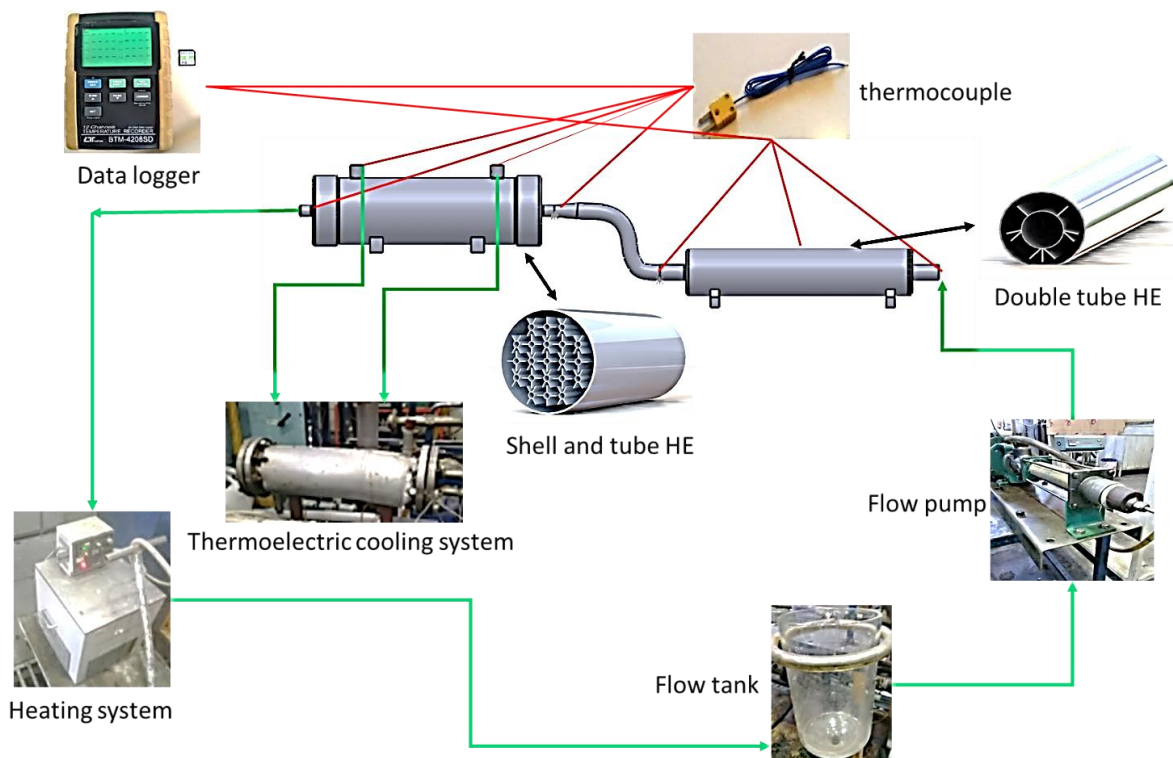

Fig. 2. Block diagram of energy conversion and storage system

For decreasing of heat losses of heat exchanger at the time of testing be used thermal inhibitor (glass wool) and also for prevent of experimentally errors, two flow meters (rotameters) were calibrated by measuring specified volume of the discharged fluid into the gradient container over the taken time. seven type-k thermocouples (PT100) were placed in the inlet and outlet shell and tube of heat exchanger and double tube heat exchanger for recording the temperatures and launch to the temperature data logger. In this research, are used two nanoparticles of Single-walled carbon nanotube (SWCNT) and Graphene quantum dot (GQD) at volume concentrations equal to 1%, 3% and 5% that flow in the central section and 21 tubes of shell and tube heat exchanger and one tube of double tube heat exchanger so that when the temperature of the hot fluid (nanofluid) reaches over the 353 K by electric heater the nanofluid flows from heating tank to the fabricated thermal processing and as well as the base fluid or pure water passes through shell section of heat exchanger and eventually when the temperature changes of the two sides of the inlet and outlet of the heat

exchangers approximately to be constant thus amount of temperatures record the data logger until desirable calculation of thermal properties be done.

2.3 Nanofluid Preparation

In general, there are two different methods for producing nanofluids: the single-stage method and the two-stage method. In the one-step method, along with the production of nanoparticles, the dispersion function of nanoparticles inside the base liquid is performed, which is the compaction of solid body vapor particles in low pressure vapor of the base liquids in the vacuum chamber. This method is suitable for the production of nanofluids including metal particles with high thermal conductivity. The most important advantage of single-stage is better control over the size and distribution of particle size on the other hand, because the disadvantages of this method are the lack of production of nanofluids in a wide range, high cost and low fluid vapor pressure. Also, in this method, some reactants remain in the produced nanofluid, which are difficult to remove due to the stability of the suspension system and their concentration in liquids. In the two-step method, the nanoparticles or nanotubes are first synthesized using a chemical vapor deposition (CVD) in a neutral gas atmosphere as a dry powder, and in the second stage, they are dispersed in the base liquid. To do this, techniques such as magnetic cutting machines, ultrasonic cutting machines, homogeneous cutting mixtures or surfactants can be used to form nanoparticle clusters (shrinkage) and minimize the dispersion of nanoparticles in the fluid. Minimize. The two-step method is more suitable for some cases, such as metal oxide into the deionized water. This method has many economic advantages, one of the advantages of which is the production of the ability of nanofluids in the industrial range, but their most important weakness is the accumulation and stability of nanofluids that must be solved. Surfactants are commonly used to improve the hydrophobic surface of CNTs to increase the stability of nanofluids or nanotubes, making them more stable. However, it should be noted that high surfactant levels reduce the thermal conductivity of nanofluids. In this study, a two-step method has been used to prepare and disperse two nanofluids (SWCNT and GQD). To do this, in the first two nanoparticles with different concentrations of volume (1, 3 and 5%), we disperse the base liquid (water) and then each sample (SWCNT with N-Methylpyrrolidone (NMP) Surfactant and GQD without Surfactant) is be kept. The ultrasonic homogenizer chamber was cooled for 45 to 60 minutes at room temperature and finally the solutions were cooled to ambient temperature. The phase change material (PCM RT82) used in this research that the solidification and melting temperature this material equal to 350 K and 358 K, respectively. An SEM image (scanning electron microscope) and some nanofluid properties and thermophysical characteristics of PCM RT82 are shown in Figure 3 and Table 2, respectively.
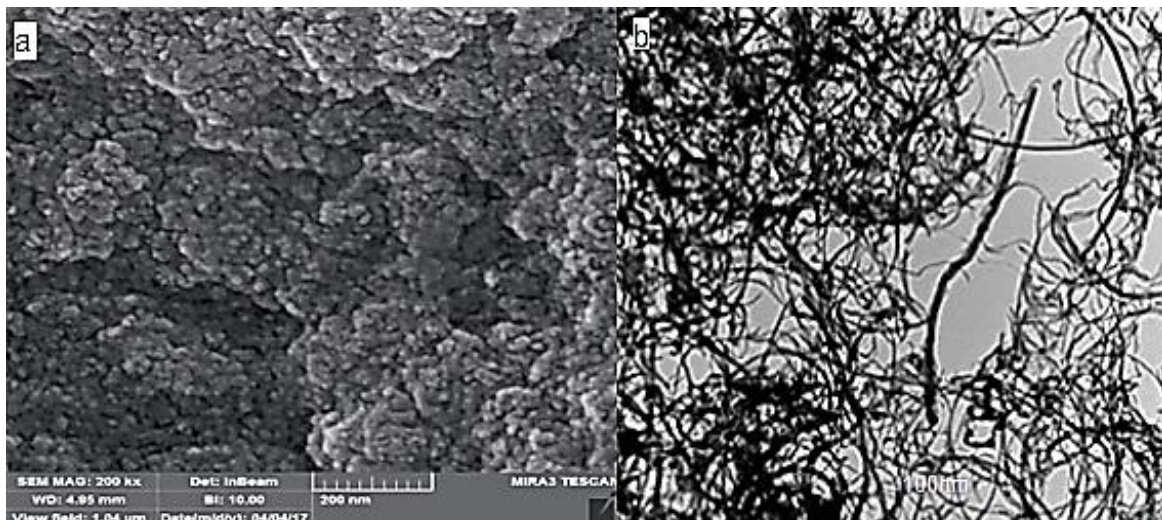
Fig. 3. SEM images of (a) Graphene quantum dot and (b) SWCNT nanofluids

Table 2
Thermophysical characteristics of nanofluids and PCM RT82

Properties	RT82	SWCNT	GQD
ρ (kg/m^3)	770	2600	400
C_p (j/kgK)	2000	425	643
k(W/mK)	0.2	6600	3000
μ (Ns/m^2)	0.03499	-	-
Γ (kj/kg)	176	-	-
T_s (k)	350	-	-
T_l (k)	358	-	-
β (1/k)	0.001	-	-

2.4 Data Processing

For calculation of heat transfer equation and thermophysical properties of materials and two heat exchangers in this study were used from following equations. Thermal efficiency (ε) and NTU index that is number of transfer units have been determined from the below equations [26-29].

$$\varepsilon = f\ (\text{NTU}, \underbrace{C_{\min} / C_{\max}}_{C_r}) \tag{1}$$

$$\varepsilon_{parallel-flow} = \frac{1 - exp[-NTU(1+C_r)]}{1+C_r}$$
$$\varepsilon_{counter-flow} = \frac{1 - exp[-NTU(1+C_r)]}{1+C_r\,exp[\,NTU(1-C_r)]} \tag{2}$$

So that

$$NTU = \frac{UA}{C_{\min}} \tag{3}$$

and

$$C_r = \frac{C_{min}}{C_{max}} = \frac{(\dot{m}c_p)_{min}}{(\dot{m}c_p)_{max}} \quad (4)$$

As regards in current research amount flow rate of hot fluid lesser than cold fluid, thus $c_{min} = c_{p,h}$ so that $c_{p,h}$ is specific heat capacity of hot working fluid in the shell and finned tube heat exchanger.

Also, the following equations were used to obtained thermophysical characteristics of nanofluid and nano-enhanced PCM [30-34].

$$\frac{k_{nf}}{k_{bf}} = \frac{k_{np} + 2k_{bf} + 2\varphi(k_{np} - k_{bf})}{k_{np} + 2k_{bf} - \varphi(k_{np} - k_{bf})} \quad (5)$$

$$\rho_{nf} = (1 - \varphi)\rho_{bf} + \varphi\rho_{np} \quad (6)$$

$$Cp_{nf} = \frac{(1-\varphi)\rho.Cp_{bf} + \varphi Cp_{np}}{\rho_{nf}} \quad (7)$$

$$\mu_{nf} = (1 + 2.5\varphi)\mu_{bf} \quad (8)$$

where $\rho, C_p, k, \mu, \varphi$ represent density, heat capacity, thermal conductivity, viscosity and volume fraction of nanofluids and nano-enhanced PCM, respectively. Also, the subscript np, bf, nf are nanoparticle, base fluid and nanofluid, respectively.

Melting heat (ΔH) of PCM was calculated based on latent heat (Γ), i.e.:

$$\Delta H = \lambda \Gamma \quad (9)$$

where λ is PCM liquid fraction that dependent to temperature by:

$$\begin{aligned} &\lambda = 0 \; if \; T \leq T_s \\ &\lambda = 1 \; if \; T \geq T_l \\ &\lambda = (T - T_s / T_l - T_s) \; if \; T_s \leq T \leq T_l \end{aligned} \quad (10)$$

where T_s, T_l are solidification temperature and melting temperature of PCM, respectively.

3. Results and Discussion

In this study, thermal properties of desired shell and tube heat exchanger and double tube heat exchanger such as thermal efficiency and stored thermal energy by using the two nanoparticles (SWCNT and Graphene quantum dots) and RT82 PCM are examined so that hot fluid that included nanofluids, flows at the inside tubes of two heat exchangers and cold working fluid that involved pure water moves at the shell section. It should be noted that Reynolds number in the shell side was considered constant and equal to 850 whilst it was variable from 850 to 10000 at the inside tube section. Inlet temperature of inlets was equal to 353 K and 293 K for the tube and shell sections,

respectively. Two nanoparticles SWCNT and Graphene quantum dots with different volume concentration $w = 1\%, 3\%, 5\%$ in the tubes of two heat exchanger and $w = 1\%, 2\%, 3\%$ in combination with PCM with various Reynolds number was applied in this study.

3.1 Thermal Efficiency of Shell and Tube Heat Exchanger

Figure 4 shows the thermal performance of the shell and tube heat exchanger versus the Reynolds number at the different conditions of volume concentration of nanofluid, mass flow rate and effect of fin blades that obtained results indicated that addition nanofluid with fin blade tubes increases the effectiveness. The mean enhancement in effectiveness of heat exchanger with variation concentration SWCNT and GQD nanofluid and using the fin blades are about over of 100% and 85% respectively. Because the use of finned tubes increases the contact area between the hot liquid and the cold liquid, which increases the heat transfer and convective heat transfer, this is due to the increase in the gradient temperature in the heat exchanger [35]. In general, adding nanoparticles to the base liquid increases the effect of nanoparticles by up to 1%, as it increases the internal heat transfer as well as the total heat transfer and ultimately increases the NTU according to Eq. (3). Increase the effectiveness according to the Eq. (1). On the other hand, in general, by increasing the concentration of nanoparticles from 1% to 5%, the efficiency of the heat exchanger decreases because the specific heat capacity of the nanofluids decreases and then according to the Eq. (4) parameter of C_r decreases and eventually with regarding to the Eq. (1) the thermal efficiency of heat exchanger decreases.
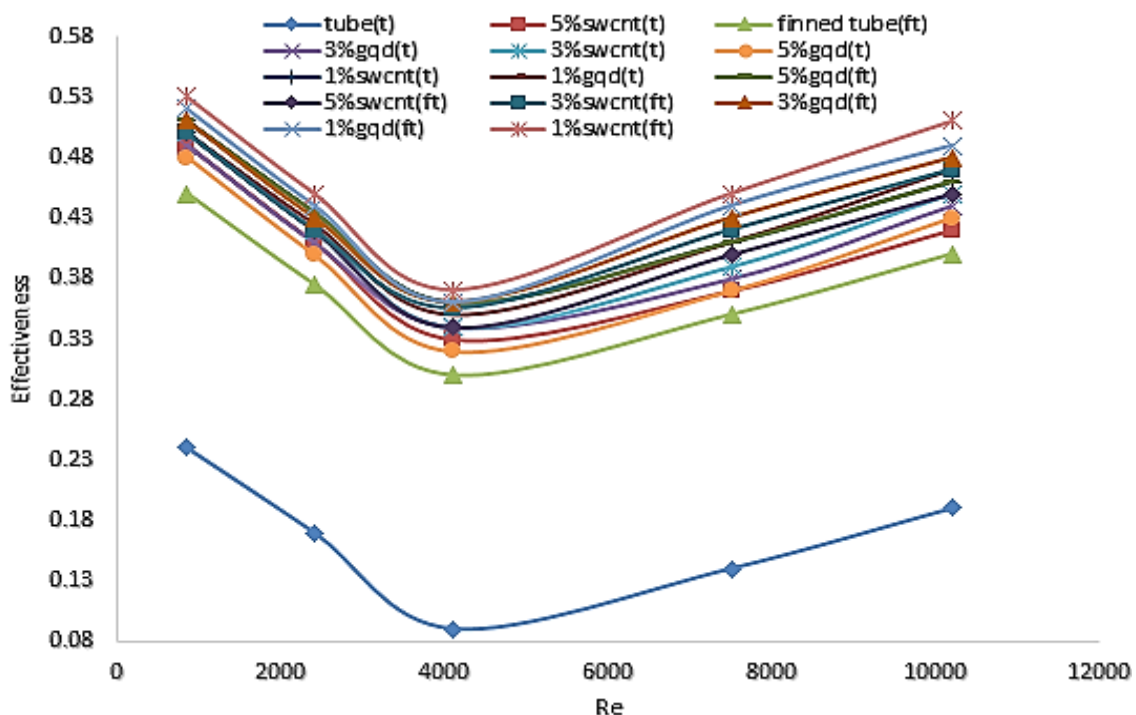

Fig. 4. Thermal efficiency of shell and tube heat exchanger at the different conditions of nanofluid versus Reynolds number

As shown in Figure 4, the effectiveness of the heat exchanger decreases with increasing the Reynolds number and then increases because as the Reynolds number increases from 800 to 4200, the residence time of the hot liquids in the heat exchanger decreases and time of heat exchange two currents at the both section of heat exchanger decreases whereas with increment the amount of Reynolds number from 4200 to 10000 and enters to the turbulence range, the thermal efficiency is increased that it is because turbulence eddy viscosity and turbulence kinetic energy have been augmented which those reduced thickness of boundary layer that consequently, improved effectiveness of heat exchanger. Also, the few of charts are generally decremented which due of increase of volume concentration of nanoparticles up to 5% that decrease of C_r and then effectiveness [38,39].

3.2 Thermal Efficiency of Double Tube Heat Exchanger

Figure 5 shows the changes in this parameter. According to the results, the thermal efficiency of the double tube heat exchanger with 1% nanofluid single-walled carbon nanotubes in the flow inside the pipe and also 3% single-walled carbon nanotube nanoparticles in combination with the RT82 PCM the highest growth rate is reflected in the thermal efficiency of heat exchanger using nanoparticles at 60%, because by using this combination, the rate of thermal conductivity of the working fluid inside the pipe is effectively increased so that the conduction and convection heat transfer coefficient are in an optimal equilibrium also by further increasing the volume fraction of single-walled carbon nanotubes in combination with the RT82 PCM, the thermal conductivity of the phase change material increases, so it melts faster and increases the storage of thermal energy inside the double tube heat exchanger and also increases the thermal efficiency in the shell and tube heat exchanger. Also, by increasing the volume fraction of nanoparticles in the nanofluid inside the tube, the heat efficiency of the heat exchanger is reduced, which is due to the increase in the pressure drop of the heat exchanger and also the decrease in the convection heat transfer coefficient compared to the conduction heat transfer coefficient [36,38,46].
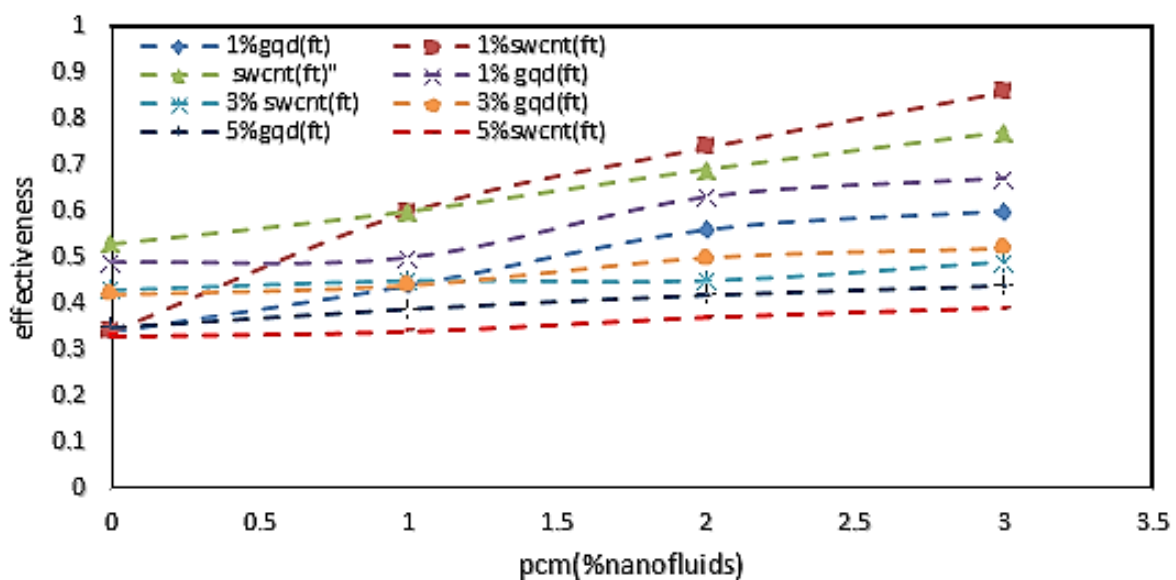

Fig. 5. Effectiveness of double tube heat exchanger with nano-enhanced PCM

3.3 Average Thermal Efficiency of Two Heat Exchanger

Figure 6 shows the process of comparing thermal efficiency in different conditions. According to the calculation of the average thermal efficiency of two heat exchangers, the highest combined thermal efficiency was obtained per 1% of nanoparticle (SWCNT) with 1% of nanoparticles (SWCNT) combined with phase change material (RT82) with shell and tube heat exchanger about 52%. This is because by using a double tube heat exchanger in series with the shell and tube heat exchanger during the heat exchange process, part of the heat from the hot fluid is given to the phase change material (RT82), and this thermal energy in the RT82 PCM is stored. Also, by using this method, the working fluid temperature decreases more and enters the shell and tube heat exchanger with a lower thermal temperature, and considering that the thermal efficiency of the shell and tube heat exchanger is directly related to the difference between the inlet and outlet temperature to the heat exchanger. Therefore, the thermal conductivity of the shell and tube heat exchanger increases, which this augmentation by using a volume fraction of 1% of single-walled carbon nanotubes in combination with the base fluid and also with the phase change material due to the high thermal conductivity of SWCNT nanoparticle [38,39].
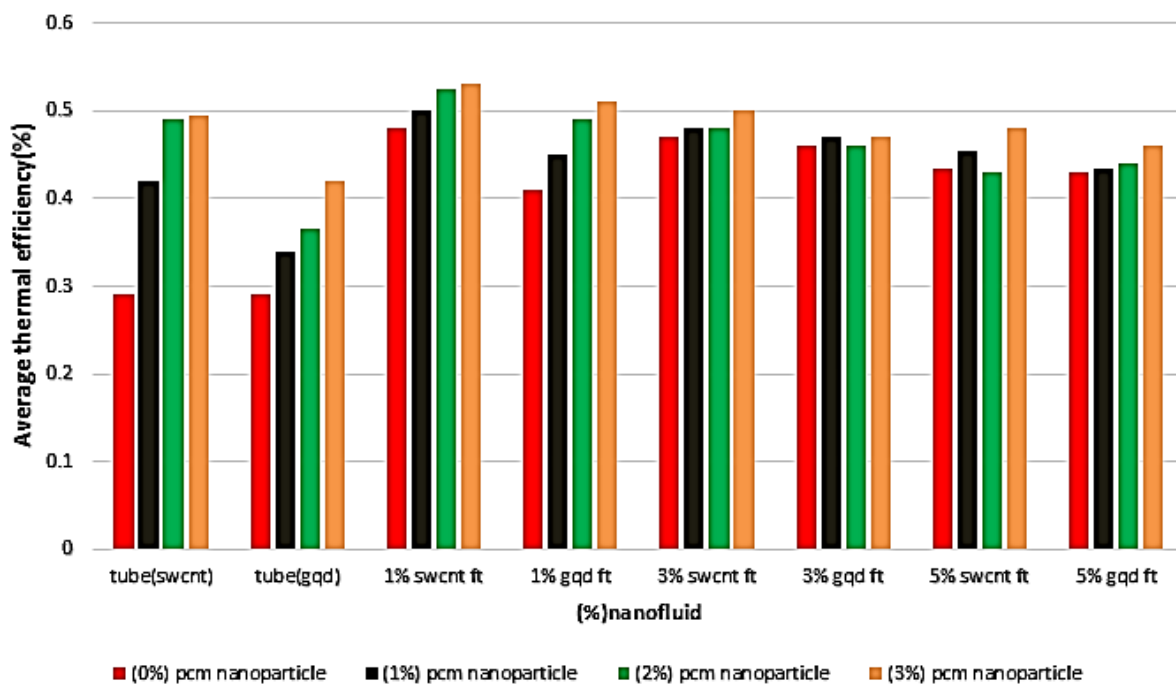

Fig. 6. Average thermal efficiency of two heat exchangers with various volume concentration of nanoparticles and RT82 PCM

3.4 Stored Thermal Energy in System

Using a double tube heat exchanger and using a phase change material (RT82 PCM) around the flow-carrying pipe, a certain amount of fluid thermal energy melts the phase change material. This has two advantages, considering to the phase change materials have high latent heat, thus melting this materials addition to lowering the final temperature of the fluid in the tube and increasing the heat efficiency of the heat exchanger also save thermal energy in the phase change material that reduces the heat dissipation in the shell and tube heat exchanger. As a result, all the thermal energy stored in the phase change material is equal to part of the energy wasted in the heat exchanger of the shell and tube heat exchanger. Therefore, according to these interpretations, the amount of

thermal energy stored in the phase change material is obtained from Figure 7. The use of phase change material with nanoparticles cause melting this material more rapidly, resulting in time and cost savings. Therefore, as soon as the phase change material reaches complete melting, it will be possible to recover the required energy from the system in a shorter time. On the other hand, the high-volume fraction of nanoparticles in the phase change material cause the suppression of natural convection heat transfer by the high thermal conductivity coefficient the composition of nanoparticles and phase change material, which prolongs the melting time of the phase change material [35-38]. It can be seen in Figure 7, that the maximum stored thermal energy is obtained by using 3% SWCNT nanoparticles in combination with RT82 PCM about 3000 W.
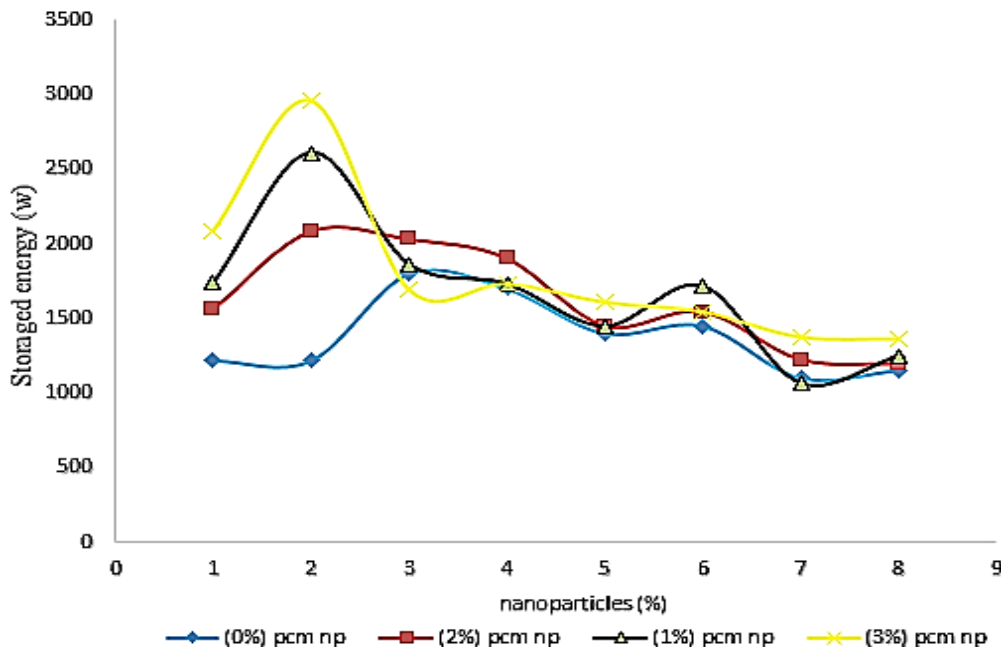

Fig. 7. Stored thermal energy in this system with PCM and nanoparticles

4. Conclusions

In the present study, thermal efficiency and storage energy of double tube and shell and tube heat exchangers by using the RT82 PCM and SWCNT and GQD nanoparticles have been investigated and following results were obtained.

- The maximum stored thermal energy is obtained by using 3% SWCNT nanoparticles in combination with RT82 PCM about 3000 W.
- The highest combined thermal efficiency was obtained per 1% of nanoparticle (SWCNT) with 1% of nanoparticles (SWCNT) combined with phase change material (RT82) with shell and tube heat exchanger about 52%.
- The mean enhancement in effectiveness of heat exchanger with variation concentration SWCNT and GQD nanofluid and using the fin blades are about over of 100% and 85% respectively.
- The thermal efficiency of the double tube heat exchanger with 1% nanofluid single-walled carbon nanotubes in the flow inside the pipe and also 3% single-walled carbon nanotube nanoparticles in combination with the RT82 PCM the highest growth rate is reflected in the thermal efficiency of heat exchanger using nanoparticles at 60%.

Acknowledgement

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