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Experimental study of single walled carbon nanotube / water nanofluid effect on a two-phase closed thermosyphon performance

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Abstract: Thermosyphons are one of the most efficient heat exchanger apparatus that are used extensively in different industries. One of the most common uses of this device is energy recovery, which is essential due to the energy crisis. Several parameters, such as geometric dimensions, type of working fluid, type of thermosyphon’s body, affect a thermosyphon efficiency. In this experiment, the effect of type and concentration of single-walled carbon nanotube nanofluid (SWCNT / Water) on heat transfer efficiency in a two-phase closed thermosyphon (TPCT) has been investigated. For this purpose, a system with a two-phase closed thermosyphon was initially constructed. Then SWCNT / water nanofluids at 0.2, 0.5 and 1 % weight concentration were used as a working fluid in the thermosyphon system. The results of current experiments showed that the addition of nanofluid with any weight concentration and the increase of input power increases the performance of the system. Also, the heat resistance of TPCT reduced when the level of SWCNT and input power increased. So, for prepared nanofluid’s samples, minimum thermal resistance obtained at 1 wt. % SWCNT and 120 W. Also, the Nusselt number increased with raising the input power and decreased with increasing the concentration. In all experiments, all prepared nanofluid samples have significantly better thermal performance in comparison with pure water.

Keywords: energy recovery, swcnt / water-based nanofluid, efficiency, thermal resistance, TPCT.

INTRODUCTION

Apparatuses like heat pipes are one of the most utilized tools ever known. It can be noted that this system can be transmitted the large quantities of heat at a slight temperature difference in small cross-section at relatively long distances, between the hot and cold source, without need to external power, quickly. Perhaps, for this reason, the heat pipe is reminisced to as a superconductor.

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By investigating nanofluids, it has been shown that these materials, which are a stable and homogenized suspension consist of a base fluid and additional nanoparticles as an additive, lead to notable enhancement in the thermal performance of this kind of heat exchangers\textsuperscript{1-4}. Also, the studies showed that compared to fluids without nanoparticles, nanofluids have higher thermal conductivity significantly\textsuperscript{5-9}. Kang et al.\textsuperscript{6} assayed a nanofluid containing diamond nanoparticles in ethylene glycol as a base fluid. Their result showed improvement of thermal conductivity up to 70\% for nanofluid 1\% UDD in Ethylene glycol compare to the base fluid. Also, Godson et al.\textsuperscript{7} have demonstrated that Ag / water-based nanofluid leads to enhancement of 80\% at 0.9 vol\% in thermal conductivity compared to pure water. Zeinali Heris et al.\textsuperscript{9-11} investigated the addition of CuO / water-based and Al\textsubscript{2}O\textsubscript{3} / water-based nanofluid effects on convective heat transfer via a roundish tube. Their results led to this fact that by increasing the nanofluids density, the heat transfer coefficient improves accordingly; hence the Al\textsubscript{2}O\textsubscript{3} / water-based nanofluids showed better enhancement rather than CuO / water-based solutions. Noie et al.\textsuperscript{12} in Ferdowsi Engineering University of Mashhad investigated that heat transfer improvement in a thermosyphon using an Al\textsubscript{2}O\textsubscript{3} / water-based nanofluid. They investigated the thermal efficiency of a thermosyphon in various volume Concentrations of nanofluid. The results showed that increasing the nanofluid concentration to 3\% by volume concentration would increase the thermal efficiency to 14.7\% in comparison with pure water. According to Kang et al.\textsuperscript{13} results, compared to pure water, the thermal proficiency of Ag / water-based nanofluid in a heat pipe was comparatively higher. Thermal resistance decreased 10–80\% compared to DI-water at an input power of 30–60 W. Also, Jia et al.\textsuperscript{14} studied the heat transfer performance of SiO\textsubscript{2} / water-based nanofluids at various concentrations on the pulsating heat pipes (PHP), which showed that high concentrations of SiO\textsubscript{2} / water reduced the PHP efficiency compared to pure water. That was because of the increase of thermal resistance and evaporator section temperature at high SiO\textsubscript{2} / water nanofluid concentration. The results of Xu et al.\textsuperscript{15} showed that hybrid nanofluid 25\% Al\textsubscript{2}O\textsubscript{3} + 75\% TiO\textsubscript{2} / water-based and the single nanofluid TiO\textsubscript{2} / water-based exhibit better thermal performance than deionized water in a TPCT. Another study by Das et al.\textsuperscript{16} is performed to characterize the thermal performance of water-based TiO\textsubscript{2} nanofluid with ethylene glycol as a surfactant, and their results noticed that use of nanofluid improve thermal proficiency of circular finned thermosyphon about 20.12\% for 0.30 vol\% TiO\textsubscript{2} nanofluid compared to deionized water as a working fluid.

One of the essential categories of material properties is its thermal properties. The thermal properties of carbon nanotubes are significantly important in various fields of technology, particularly due to the high thermal...
conductivity of diamond and graphite and the similarities between them. Scientists are interested in studying these properties and found some results in terms of the thermal conductivity of carbon nanotubes in their experimental studies. It has been predicted that carbon nanotubes have higher thermal conductivity than graphite and diamond at room temperature. So, it is necessary to study the carbon nanotubes' performance on the thermal efficiency of thermosyphons because of their thermal properties. Liu et al. confirmed the thermal performance improvement and thermal resistance reduction by using CNT / water-based suspension in a weight concentration of 2% and an operating pressure of 7.4 kPa. Their research showed a 150% enhancement in heat transfer compared to water at optimal pressure and concentration. The results of experiments by Choi and Eastman showed that MWCNT / water-based nanofluid can increase thermal conductivity more than base fluid. Also, Choi et al. determined the effective thermal conductivity in the oil suspensions of MWCNT. They reported that the measured conductivity enhancements for a 1.0 vol% nanotubes / oil-based suspension are noticeably greater than those predicted by theoretical models and are about 160%. Shanbedi et al. research on multiwalled carbon nanotubes also suggested thermal efficiency of MWCNT / water-based suspension increase, and the Nusselt number and thermal resistance of the thermosyphon diminish by increasing the density of nanofluid, which led to the increase of the conduction heat transfer by these nanoparticles.

Single-walled carbon nanotubes (SWCNT) are one of the most important types of carbon nanotubes, and the properties vary considerably with different types of SWCNTs. Also, Pettes and Shi results showed the thermal conductivity of CNTs' dependency on the number of walls, and the thermal conductivity of CNTs decreases with an increase in the number of walls, accordingly. Also, this is attributed to the increasing number of walls and the decrease in the concentration of CNTs consequently. Despite the advantages of CNTs, some factors such as poor solubility and instability of aqueous and organic suspensions of CNTs, difficulty in working with them due to their extremely small size, relatively expensive the current CNTs production processes, and confined understanding of how CNTs work has limited their applications. The current work intends to investigate the effects of (SWCNT) addition to water as the operating fluid in a two-phase closed thermosyphon, on the Nusselt number, thermal resistance, thermal efficiency, vacuum pressure drop, and evaporator mean temperature. Considering the desirability of the results of experiments and research, the possibility of increasing the efficiency of thermosyphons and preventing the waste of energy in thermal engineering applications will be more than ever possible.
EXPERIMENTAL

In these experiments, single-walled carbon nanotubes with a purity of over 95%, a length of 5-30 microns, an internal diameter of 0.9-2 nm, and an outer diameter of 1-3 nm were used to prepare nanofluid that purchased from VCN Materials Co. Ltd. One of the difficulties of carbon nanotubes is their stability in polar fluids. Arabic gum was used as a surfactant to stabilize the carbon nanotube suspension in water. Arabic gum stabilizes carbon nanotubes in polar solvents such as water, due to the creation of non-covalent bondings. So, according to reports in the publications22,23, in this current study, Arabic gum (AG) was used at a concentration of 0.5% by weight. Then SWCNT / water nanofluid containing AG was prepared at concentrations of 0.2, 0.5 and 1% by weight. In order to prepare these concentrations of nanofluid the balance (AND model GF-1000) with an accuracy of 0.001 gr was used. Finally, for further uniformity of suspension, a sonicator (bath type, operating frequency, and power source of the sonicator are 43 kHz and AC 100-120 V / AC 220-240 V 50/60 Hz, respectively) was used for 5 hours. Substances and their weight fractions for prepared nanofluid samples are given in Table 1.

Table 1. Substance and weight fraction in different samples of nanofluid

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Content of nanoparticle % in nanofluid, wt</th>
<th>Substance for prepare nanofluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>SWCNT with purity of 95 %</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>+ 0.5 wt.% Arabic gum</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Due to the stability of prepared suspension and the absence of sediment formation in the samples, tests were performed about several days after the preparation of nanofluids. Also, to evaluate the stability of the nanofluid, Transmission Electron Microscopy (TEM) analysis was provided by the nanofluid manufacturer. After several days from the preparation of the nanofluid until the test, no sediment was observed in the samples. Figure 1 represents the TEM image of SWCNT / water nanofluid.

![TEM image of SWCNT/water sample](image)

Fig. 1. TEM images of SWCNT/water sample.

The TPCT set up used in this study is schematically depicted in Figure 2a, and the constructed apparatus is pictured in Figure 2b. The Primary part of this system is fabricated by
a 20×450 mm copper tube with a wall thickness of 1 mm, including the evaporator, adiabatic, and the condenser sections, which are 160, 90, and 200 mm in length, respectively, as per illustrated in figure 1a. Also, the diameter of the casing used in the condenser section is 40 mm. At the outer surface of the copper tube, precisely in the evaporator and condenser sections, four thermocouples (ARVAN model TG-4) were installed to study the process of temperature change in the TPCT system. These K-type thermocouples were posited at a distance of 5, 10, 15, and 35 cm from the end of the evaporator section, respectively, and were able to measure temperatures in the range of -200 to 1350 °C. Also, to observe the temperature changes of the cooling water in the condenser section, two thermometers (CEM DT-131) with an accuracy of 0.1 °C with a temperature range from 0 to 100 °C were used before the inlet and after the outlet of the condenser part. The cooling water flow rate was controlled and monitored by a flowmeter (Rotameter LZE-15) with an accuracy of 5 L hr⁻¹ in the outlet of the condenser at 15 L hr⁻¹. Also, a vacuum pump (Hamer 2RS-5 VE 2100) that makes a vacuum near -85 kPa was used to exhaust the non-condensate gases before testing from the thermosyphon and a pressure gauge to measure the TPCT vacuum pressure. Also, an electrical element with the power of 1000 watts was used to heat the evaporator section. This electrical element was metal and fitted series with an ammeter (AKB DT-9205A) with an accuracy of 0.01 A and power supply (Variac TDGC2-1KVA) in the circuit. The apparatus was insulated by 2 cm of fiberglass to prevent heat dissipation while considering the thermocouples are adequately protected. Because by contacting the electrical element with these parts, the registered temperatures are unrealistic and higher than expected.

The experimental method is as follows: first, to remove non-condensable gases such as air, the thermosyphon is vacuumed about -85 kPa by a vacuum pump. The operating fluid of deionized water, with or without the nanoparticles, is then charged into the thermosyphon. In these experiments, a constant filling ratio (FR) of 60 % was used in the system. This ratio is
defined as the volume of fluid to the total volume of the evaporator section fraction. The experiment started up with a 30 W input power initially following up to 30, 45, 60, 90, and finally 120 Watts afterward with different SWCNT nanofluid concentrations of 0.2, 0.5, and 1.0 wt% accordingly.

**Data Processing**

The heat transfer rate from the condenser section can be determined as equation (1) \(^{11,23}\):

\[
Q_{\text{out}} = \dot{m}C_p(T_{\text{out}} - T_{\text{in}}) \tag{1}
\]

where the variables of \(\dot{m}\), \(C_p\), \(T_{\text{in}}\), and \(T_{\text{out}}\) indicate the mass flow rate of cooling water, the specific heat of cooling water, inlet temperature, and outlet temperature of the cooling, respectively. The total heat transfer alongside the evaporator section by the electrical element is expressed as follows\(^{12,24}\):

\[
Q_{\text{in}} = VI \tag{2}
\]

In the above equation, \(V\) is defined as voltage, and \(I\) is defined as electric current of power supply for various input powers.

Also, an equation is defined to estimate the thermal efficiency of thermosyphon as the following form\(^{12}\):

\[
\eta = \frac{Q_{\text{out}}}{Q_{\text{in}}} \tag{3}
\]

Also, the Nusselt number for a TPCT could be defined as follows\(^{25,26}\):

\[
Nu = \frac{Q_{\text{net, conv}}}{Q_{\text{net, cond}}} \tag{4}
\]

In which \(Q_{\text{net, conv}}\) indicates the net convective heat transfer amount and \(Q_{\text{net, cond}}\) indicates the net conductive heat transfer amount. The amount of the net convective heat transfer will be obtained by equation (1), while the net conductive heat transfer amount is determined using the equation\(^{25}\):

\[
Q_{\text{net, cond}} = \pi r^2 K_{nf} \frac{\Delta T}{L} \tag{5}
\]

In this equation, \(r\) defined as the radius, and \(L\) described as the length of TPCT. Also, \(K_{nf}\) is the thermal conductivity coefficient of the nanofluid, and \(\Delta T\) is the temperature difference between the condenser and the evaporator section. Therefore, according to these definitions, the Nusselt number of TPCT is calculated from the following equation:

\[
Nu = \frac{\dot{m}C_p(T_{\text{out}} - T_{\text{in}})}{\pi r^2 K_{nf} \frac{\Delta T}{L}} \tag{6}
\]

The Nusselt number of the thermosyphon can be derived by the above equation (6). In this equation, only \(K_{nf}\) is unknown. Various models are presented for the estimation of the nanofluid thermal conductivity. However, all of these models are valid only for compounds containing spherical or oval-shaped particles with a small axis ratio. While carbon nanotubes can be considered as oval-shaped nanoparticles with large axial ratios. Also, existing models
cannot explain the CNT spatial distribution effect on the coefficient of thermal conductivity. Accordingly, Xue\textsuperscript{27} presented an equation based on the Maxwell model to calculate the thermal conductivity of CNT containing nanofluids, including the effect of a large axis ratio and spatial distribution of carbon nanotubes. Therefore, Xue's equation is defined to estimate the thermal conductivity coefficient:

\[ K_{nf} = \frac{(1 - \nu) + 2\nu\alpha \ln(\gamma)}{(1 - \nu) + 2\nu\beta \ln(\gamma)} K_{bf} \]  
(7)

where

\[ \alpha = \frac{K_{CNT}}{K_{CNT} - K_{bf}}, \beta = \frac{K_{bf}}{K_{CNT} - K_{bf}}, \gamma = \frac{K_{bf} + K_{CNT}}{2K_{bf}} \]

The parameter \( \nu \) describes the nanotubes volume fraction of a nanofluid in the above equation. Therefore, considering the volume fraction of carbon nanotubes used in this study are 0.095, 0.238 and 0.476 for nanofluid with Concentration of 0.2, 0.5 and 1 \% by weight, respectively. Also, \( K_{nf}, K_{df}, \) and \( K_{CNT} \) are the thermal conductivity amount of pure water, nanofluid, and carbon nanotubes, respectively.

The thermal resistance (\( R_{th} \)) for the TPCT is obtained from the following equation\textsuperscript{18,28}:

\[ R_{th} = \frac{T_e - T_c}{Q} \]
(8)

In this equation, \( T_e \) and \( T_c \) are defined as the evaporator and condenser section temperatures, respectively, and \( Q \) indicates the amount of the heat transferred from the condenser section.

In this study, the uncertainty could be estimated by Holman correlation as follows\textsuperscript{39}:

\[ \text{Max } E_\eta = \pm \left\{ \left( E_{Q_{in}} \right)^2 + \left( -E_{Q_{in}} \right)^2 \right\}^{0.5} \]  
(9)

\[ \text{Max } E_{Q_{out}} = \pm \left\{ \left( E_i \right)^2 + \left( E_r \right)^2 + \left( E_{T_{in} - T_{in}} \right)^2 \right\}^{0.5} \]  
(10)

\[ \text{Max } E_{Q_{in}} = \pm \left\{ \left( E_\nu \right)^2 + \left( E_r \right)^2 \right\}^{0.5} \]  
(11)

Since the maximum precision of voltmeter, ammeter and thermometer is 1 V, 0.01 A, and 0.1 °C, respectively, the maximum uncertainties in thermal efficiency obtained 3.5 %.

RESULTS AND DISCUSSION

This section observes the thermal efficiency results of the two-phase closed thermosyphon (TPCT) from current experience. The factors of Thermal efficiency, thermal resistance, and the Nusselt number will be investigated in different operating conditions, as the essential factors affecting the thermal performance of a closed thermosyphon. The effect of parameters such as sample type and nanofluid concentration in various input power on the thermal performance of the two-phase closed thermosyphon (TPCT) is investigated, and the respective diagrams with
complete discussion are given. Also, the temperature distribution on the external surface of the core cylinder of the TPCT, which can be a good indication of the thermal resistance, and the vacuum pressure drop in the thermosyphon, will be discussed.

In this research, experiment operations were carried out at 30, 45, 60, 90 and 120 W input powers in accordance with three weight (volume) concentrations of SWCNT/water suspension (nanofluid) of 0.2 % (0.095 %), 0.5 % (0.238 %), and 1 % (0.476 %) CNT concentrations. A 3D and linear diagram for the variability of thermal efficiency with an input power at a different weight fraction of nanoparticles for five diverse input power used in this study plotted in Figure 3. This figure shows that the thermal efficiency increases due to the input power and weight fraction of nanoparticles increase. This enhancement of thermal efficiency depends on the heat transfer behavior of the nanostructure. Nanoparticles, with their Brownian motion, resulting in a noticeable rise in the rate of the heat transfer between the fluid and nanotube wall11. Therefore, as the nanofluid weight fraction increases, the TPCT thermal efficiency increases as well, because of the addition of nanostructure into the base fluid enhances the particle collisions in the TPCT. As shown in figure 3, the thermal efficiency in the lower concentrations is significantly increased, but at higher concentrations, it is less. For example, in the range of 30 to 45 W for input power along with the concentration amount of 0.2 wt%, the thermal efficiency of TPCT was increased by about 10%. According to figure 3, it is observed that the nanofluid sample with a concentration of 1 wt% of SWCNT obtained the highest efficiencies in all input powers, and maximum efficiency was reported for an input power of 120 W about 89 %. In this study, for an input power of 120.75 W (Voltage = 75 V, I = 1.61 A) and concentration of 1 wt%, the temperature of the inlet ($T_{in}$) and outlet ($T_{out}$) cooling water obtained 19 and 25.1 °C, respectively. According to Eq. (1) and the mass flow rate of cooling water (0.00415 kg s⁻¹), $Q_{out}$ obtained about 107.09 W. By substituting the values of $Q_{out}$ and $Q_{in}$ in Eq. (3), the thermal efficiency of thermosyphon was obtained about 0.89.

Fig. 3. The TPCT thermal efficiency versus input power and concentration of nanofluid
The dimensionless Nusselt number in a thermosyphon represents the ratio of the heat transferred through the displacement to the heat transferred through the conduction, which is obtained from Eq. (6). In this study, the variation of the Nusselt number in different concentrations of carbon nanotubes and various input power is shown in Figure 4.

Fig. 4. The thermosyphon Nusselt number versus input power and concentration of nanofluid

According to this figure, the Nusselt number decreases with the increasing concentration of carbon nanotubes in the nanofluid. For example, nanofluid with 0.2 wt.% of CNT, the Nusselt number at 30 W is about 145.19, while in the concentration of 0.5 and 1.0 wt.% of CNT, these values are about 70.22 and 30.26 at the same input power, respectively. According to Eq. (7) with increasing concentration of carbon nanotubes, the coefficient of thermal conductivity for the nanofluid (\(K_{nf}\)) increases and considering the definition of the Nusselt number in Eq. (6) by increasing the denominator, the Nusselt number decreases consequently, which represents the increase in heat transfer through the conduction mechanism.

By an increase in the input power, the thermal resistance of the TPCT decreases, whereas, according to Eq. (8), the thermal resistance has an inverse relation to power. However, the reduction of thermal resistance at lower power is more than a higher power. Also, by increasing the concentration of SWCNT in the nanofluid, the resistance against the thermal proficiency of the thermosyphon is reduced. For example, at the input power of 30 W, the highest and the lowest thermal resistance are related to water (2.34 °CW\(^{-1}\)) and nanofluid 1.0 wt.% of CNT (1.71 °CW\(^{-1}\)), respectively. In this study, at the input power of 30.24 W (Voltage = 36 V, I = 0.84 A), the average evaporator temperature, condenser temperature, and temperature difference of condenser section obtained about 62.9 °C, 21.8 °C, and 1 °C for water and 61.2 °C, 22.3 °C and 1.3 °C for nanofluid 1.0 wt.%, respectively. The variation of thermal resistance against the input power of the TPCT is plotted in Figure 5.
The bubble formation at the liquid-solid interface of the TCPT is considered as the primary cause of the thermal resistance. The larger size of these bubbles leads to creating higher amounts of thermal resistance, which interferes with the heat transfer from the solid surface to the fluid. In the presence of nanoparticles dispersed in the fluid, the vapor bubbles will explode at the first formation moments. Therefore, much smaller vapor bubbles shall be expected for a fluid containing suspended nanoparticles rather than a fluid that does not contain any nanoparticles, which reduces the thermal resistance of TPCT consequently.

Figure 6 shows the variations in the vacuum pressure drop of operating fluid for each test. It is observed that with increasing nanofluid concentration, the vacuum pressure drop also increases. Because at higher pressure, the boiling point of the fluid is even higher, and the thermal proficiency of thermosyphon is reduced. In this study, the maximum vacuum pressure drop was obtained for a SWCNT concentration of 1 wt.%. Although the nanofluid has the highest thermal efficiency, it also has the most top vacuum pressure drop.

The evaporator section average temperature against various input power with various concentrations of SWCNT is plotted in Figure 7. According to the results of experiments, expect the power of 90 and 120 W as the density of nanofluid risen, the evaporator section average temperature was decreased too. For example, at an input power of 45 W, the evaporator section average temperature for water, nanofluid 0.2, 0.5, and 1 wt.% obtained about 63.9, 63.8, 63.7, and 62.9 °C, respectively. According to equation 8, thermal resistance is related to the variations of temperature between the evaporator and condenser section directly. Hence, by reduction of the average temperature of the evaporator section, the temperature difference between the evaporator and condenser section decreases evidently, which represents thermal resistance reduction in TPCT. The thermal resistance of the thermosyphon core surface, the evaporation and condensation process thermal...
resistances, and the two-phased flow resistance alongside the length of the TPCT shall form the overall thermal resistance of a thermosyphon totally in-between the evaporation core and the condenser section\textsuperscript{20}. The surface properties of the thermosyphon interior surfaces, such as wettability and roughness, effect on bubbles formation and, consequently, on thermal resistance in the evaporator and condenser section. Using nanofluids, by increasing thermal conductivity and density of the liquid and decreasing the diameter of the released bubbles, leads to reduce thermal resistance and temperature in the evaporator section\textsuperscript{12,24,29,30}. On the other hand, the reason of increasing temperature in the evaporator section at high input power (90 and 120 W) and low concentrations (0.2 and 0.5 wt.%) can be related to an increase in the number of bubbles at high input power and the inability of the nanofluid to explode these bubbles at low concentrations.

Fig. 7. The average temperature distribution of the evaporator section of TPCT versus input power and concentration of nanofluid

\textit{A Comparison between the Performance of MWCNT & SWCNT in TPCT}

The research carried out on the performance of MWCNT / water nanofluid as the operating fluid in a TPCT\textsuperscript{20} indicates that at the concentration of 1 wt.% (\(R = 0.43\)) and 90 W input power, which has the highest thermal efficiency, thermal resistance (in condenser section) decreased to about 12.24 % compared to the water as a base fluid (\(R = 0.49\)). While this reduction for SWCNT / water nanofluid at a concentration of 1 wt.% (\(R = 0.52\)) and the same input power compared to water (\(R = 0.63\)) is about 17.46 %. Also, improvement in the thermosyphon thermal efficiency at an input power of 90 W is about 12.19 % after applying MWCNT / water nanofluid at a concentration of 1 wt.% (\(\eta = 0.8944\)) compare to pure water (\(\eta = 0.7972\)). While this improvement in thermal efficiency for SWCNT / water nanofluid at a concentration of 1 wt.% (\(\eta = 0.88\)) and the same input power is about 15.78 % compared to water (\(\eta = 0.76\)). Also,
to achieve steady-state condition and thermal efficiency of 89 % needs about 5200 seconds by using MWCNT / water nanofluid, while this amount of time for SWCNT / water nanofluid to achieve to this thermal efficiency is about 2215 seconds.

**CONCLUSIONS**

In this research, the experiments were carried out with a TPCT initiated by input powers of 30, 45, 60, 90, and 120 W along with SWCNT concentrations of 0.2, 0.5, and 1.0 wt.% in the operating nanofluid. The purpose of the current research was to explore the effect of SWCNT nanoparticles addition in addition to the operating fluid of a TPCT on the thermal efficiency and its leading parameters such as vacuum pressure drops, the average temperature of the TCPT evaporator, Nusselt number, and the thermal resistance of the apparatus. In this section, the most relevant results of this research are mentioned. The results show that SWCNT / water nanofluids at all concentrations lead to improve the thermal proficiency of a TPCT. By increasing the density of nanofluid and electrical power, the TCPT thermal efficiency also increases, which the improvement in thermal efficiency is more significant in lower input power. Also, by increasing the concentration of SWCNT in the operating nanofluid, the Nusselt number of TPCT decreases, which, alongside input power increase, will lead to a reduction in the thermal resistance. The minimum thermal resistance will occur at a concentration of 1 wt.%. Also, by condensing the nanofluid, the vacuum pressure drop in the TPCT increases. Also, by increasing the concentration of nanofluids at all amounts of input power, the evaporator section average temperature is reduced (except 90 and 120 W at a concentration of 0.2 and 0.5 wt.%), which it can be confirmed thermal resistance reduction at the evaporator section. Also, with comparing the performance of the MWCNT / water and SWCNT / water nanofluids on a TPCT, it is observed that SWCNT nanofluid has higher thermal efficiency and leads to more reduction in thermal resistance at a TPCT.

**NOMENCLATURE**

- $C_p$: water specific heat, J kg$^{-1}$ K$^{-1}$
- $I$: current, A
- $K_b$: base fluid thermal conductivity, W m$^{-1}$ K$^{-1}$
- $K_{CNT}$: carbon nanotube thermal conductivity, W m$^{-1}$ K$^{-1}$
- $K_{nf}$: nanofluid thermal conductivity, W m$^{-1}$ K$^{-1}$
- $L$: length of evaporator section, m
- $m$: water mass per unit time, kg s$^{-1}$
- $Nu$: Nusselt number
- $Q_{in}$: input heat transfer by evaporation, W
- $Q_{net}$: net conductive heat transfer, W
- $Q_{out}$: output heat transfer by condensation, W
- $r$: radius, m
- $R_{th}$: thermal resistance, K W$^{-1}$ or °C W$^{-1}$
- $T_e$: evaporator temp, °C
- $T_c$: condenser temp, °C
- $T_i$: inlet temp of cooling water, K
- $T_o$: outlet temp of cooling water, K
- $\Delta T$: temperature difference ($T_e$-$T_c$), °C
- $\eta$: efficiency of two-phase closed thermosyphon
- $\nu$: volume concentration (%)
ИЗВОД

ЕКСПЕРИМЕНТАЛНО ИСПИТИВАЊЕ УГЉЕНИЧНИХ НАНОЦЕВИ СА ЈЕДНОСТРУКИМ ЗИДОМ / ЕФЕКАТ ВОДЕНОГ НАНОФЛУИДА НА ПЕРФОРМАНСЕ ДВОФАЗНОГ ЗАТВОРЕНОГ ТЕРМОСИФОНА

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Термосифони су медију најефикаснијим апаратима за размену топлоте који се користе у различитим индустријама. Једна од најчешћих употреба ових уређаја је ре-генерација енергије, што је изузетно битно, с обзиром на енергетску кризу. Неколико пар метара, као што су геометријске димензије, тип радног флуида, тип тела термосифона, утиче на ефикасност термосифона. У овом експерименту испитиван је утицај типа и концентрације воденог нанофлуида са угљеничним наноцевима са једно-струким зидом (енгл. single-walled carbon nanotube nanofluid – SWCNT) на ефикасност преноса топлоте у двофазном затвореном термосифону (енгл. two-phase closed thermo-syphon –TPCT). За ову сврху, најпре је конструисан двофазни затворени термосифон. Затим су водени SWCTN нанофлуиди са тежинским концентрацијама 0.2, 0.5 и 1 % коришћени као радни флуид у термосифонском систему. Резултати експеримената су показали да додатак нанофлуида било које концентрације и повећање улазне снаге побољшавају перформансе система. Такође , топлотни отпор TPCT опада са повећањем нивоа SWCNT и улазне снаге. Тако , за припремљене узорке нанофлуида, најмања вредност топлотног отпора је добијена за 1 % SWCNT и 120 W. Такође , Нуселтов број расте са повећањем улазне снаге и смањује се са повећањем концентрације. У свим експериментима, сви припремљени узорци нанофлуида су имали значајно боље топлотне перформансе у поређењу са чистом водом.

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