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Experimental investigation on the heat transfer performance of evacuated tube solar collector using CuO nanofluid and water†

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Abstract

The efficiency of an evacuated tube solar collector was experimentally measured and analyzed according to the size of CuO nanoparticle and the concentration of the CuO nanofluid. In addition, the efficiency of the evacuated tube solar collector using CuO nanofluid as a working fluid was compared with that when water was used. As a result, the efficiency of the evacuated tube solar collector improved as the concentration of the CuO nanofluid increased at low concentration. Further, the efficiency of the evacuated tube solar collector was higher at a mass flux rate of 598 kg/s·m^2 than at 420 kg/s·m^2. The highest efficiency of the solar collector with 40 nm-CuO nanofluid was 69.1 %, an improvement of 2.0 % compared to 80 nm-CuO nanofluid. The most optimal concentration of the 40 nm-CuO nanofluid was 0.5 vol% and an improvement of thermal efficiency was 7.2 % compared to water. In addition, at this concentration, the efficiency improved by 4.4 %, 2.3 % and 0.3 % compared to that at concentrations of 0.1 vol%, 0.3 vol% and 0.7 vol%, respectively. The use of CuO nanofluid in the evacuated tube solar collector can improve the efficiency and can maintain the high efficiency for wide operating conditions compared to water.

Keywords: Evacuated tube solar collector; Nanofluid; Thermal efficiency; CuO (copper oxide); Heat loss parameter

1. Introduction

The use of fossil fuels to make energy has been a steady increase in the world, the amount of which accounts for 86 % of the global energy usage in 2017. Further, the use of fossil fuels is expected to reach approximately 80 % in 2035. The use of these fossil fuels has had a serious impact on global warming owing to the emission of several greenhouse gases such as CO_2 and SO_2. Therefore, many countries in the world signed the Paris Climate Agreement in 2015 in order to reduce greenhouse gas emissions. Accordingly, the signatories have agreed to submit a greenhouse gas reduction target every five years until 2020 and are making an effort to achieve this target. In this situation, it is necessary to develop renewable energy technologies to solve the greenhouse gas reduction and environmental pollution problem simultaneously.

Renewable energy solutions are widely distributed throughout the world, including solar thermal, geothermal, biomass, marine energy, solar energy, and hydro energy. Solar energy converters, one of these diverse renewable energy technologies, absorb solar energy from the sun and change it into thermal energy to heat water or generate electricity to provide it to consumers [1, 2]. The most prevalent method for harvesting solar radiation from the sun is to utilize a solar collector. Generally, solar collectors can be divided into those using a flat-plate, evacuated tube, or parabolic type in terms of their shape or construction and can operate at low, medium, or high temperatures depending on the required temperature range. There are several types of solar collectors. The flat-plate and evacuated tube solar collectors are typical examples. In the evacuated tube solar collector, the absorption plate is placed under vacuum inside a glass tube to minimize the heat loss owing to convection. Thus, the evacuated tube solar collector has the advantage that it can maintain high heat collecting efficiency at a higher temperature than the flat-plate collector. In addition, the evacuated tube collector is lightweight with the benefit of easy installation because the installation area can be reduced by 30 % compared to that of the flat-plate solar collector. However, the energy efficiency of the solar collector remains less than optimal when the installation cost is taken into consideration. Therefore, many studies has been performed in order to improve the efficiency of various solar collectors.

The use of nanofluids, obtained by adding nanoparticles into the base working fluid to increase the efficiency of the

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solar collector system, is considered one of the best ways to solve the aforementioned problems. This approach has attracted much attention from researchers. The nanofluid is a mixture of solid particles with a diameter ranging from 1 to 100 nm and is used in the solar collector as working fluid. Chiam et al. [3] reviewed existing nanofluid studies to investigate the variation in thermal conductivity and viscosity according to the concentration and temperature of an Al_2O_3 nanofluid. They reported, as the concentration of Al_2O_3 nanofluid increased, the thermal conductivity and viscosity increased and the thermal conductivity increased but the viscosity decreased with an increase of temperature. In addition, the maximum improvement in thermal conductivity of the Al_2O_3 nanofluid was 12.8 % at 1.0 vol%. Sundar et al. [4] carried out an experiment on the thermal conductivity of Al_2O_3 and CuO nanofluid, and they reported that an increase in thermal conductivity was observed when the concentration and temperature increased. In addition, they reported that the thermal conductivity of CuO nanofluid was higher than that of Al_2O_3 nanofluid at the same concentration. Moreover, from many previous studies on thermal conductivity, the thermal conductivity is known to increase as the temperature and concentration of nanofluid increase [5-7].

Based on these findings, a number of studies about the best ways to improve the efficiency of a solar collector using various nanofluids have been conducted. In the studies on the application of nanofluids in a flat-plate solar collector, Noghrehabadi et al. [8] reported that the efficiency of a solar collector using a SiO_2/water nanofluid improved by 3.8 % compared to that using only water. He et al. [9] used Cu/water nanofluid in a flat-plate type solar collector, and they presented the efficiency of the solar collector using Cu/water (Cu:25 nm, 0.1 wt%) improved by 23.8 % compared to water and the efficiency of the solar collector at a concentration of 0.2 wt% was lower than that at 0.1 wt%. Verma et al. [10] studied the thermal performance of a flat-plate solar collector using SiO_2, TiO_2, Al_2O_3, CuO, graphene, and multi-wall carbon nanotube (MWCNT) nanofluids as the working fluid. When the MWCNT nanofluid was used as the working fluid, the energy and exergy improved by 29.3 % and 23.5 %, respectively, compared to water. In addition, Moghadam et al. [11] reported that the efficiency of the flat-plate solar collector increased by 16.7 % when the concentration of the CuO nanofluid was 0.4 vol%. Further, Said et al. [12, 13] carried out an experimental study on the performance of the flat-plate solar collector using TiO_2 and Al_2O_3 nanofluid and they showed that the efficiency of energy and exergy increased by 76.6 % and 16.9 %, respectively, when the mass flow rate of the nanofluid was 0.5 kg/min and the concentration of the TiO_2 nanofluid was 0.1 %.

Yousefi et al. [14] investigated the efficiency of a flat-plate solar collector depending on the pH variation of the MWCNT nanofluid. The test results showed that the efficiency was maximum at a pH of 9.5 and was an improvement of 61.6 % compared to water. Faizal et al. [15] carried out an energy and economic analysis when metal oxide nanoparticles were used in a flat-plate solar collector, and they reported that CuO nanofluid had the highest thermal efficiency compared to other nanofluids. In addition, they reported that it was possible to reduce the area of the solar collector when metallic oxide nanoparticles were used as working fluid. Besides, Liu et al. [16, 17] designed a special open thermosyphon device which was for high-temperature evacuated tubular solar collector using pure water and CuO/water nanofluids as the working fluid. Substituting CuO/water nanofluid instead of water as the working fluid can considerably increase the thermal efficiency of the evaporator.

In a review of studies on the efficiency of evacuated tube solar collectors, Rybar et al. [18] measured the thermal power of an evacuated tube and other types of solar collectors. They reported an improvement in the performance and thermal power of evacuated tube solar collectors compared to those of other existing other solar collectors. Ghaderian and Sidik et al. [19] carried out an experimental study on the performance of an evacuated tube solar collector and they reported that the total average energy efficiency of the solar collector for water and Al_2O_3 nanofluid was 22.85 % and 58.65 %, respectively, at a mass flow rate of 60 l/h. Mahendran et al. [20] determined the maximum efficiency of a solar collector as 73 % and 53 % for using TiO_2 nanofluid and water, respectively. The efficiency of the solar collector could increase by approximately 20 % because of using TiO_2 nanofluid instead of water. Sabiha et al. [21] reported the experimental results when a single wall carbon nanotube nanofluid was used in an evacuated tube solar collector. They also showed that the efficiency of the solar collector increased by 93.4 % at a concentration of 0.2 vol% and mass flow rate of 0.025 kg/s. In addition, Kim et al. [22-24] carried out an experimental and theoretical study on the efficiency of an evacuated tube solar collector using various nanofluid and they found that the efficiency of evacuated tube solar collectors increased as the size of the Al_2O_3 nanoparticles decreased and the concentration of Al_2O_3 nanofluid increased. Ersöz et al. [25] measured the efficiency and exergy of an evacuated tube solar collector by using various working fluids and achieved the best efficiency with the solar collector when a mixture of chloroform and acetone was used as the working fluid. Hussain et al. [26] reported that the use of nanofluids (Ag: 30 nm, ZrO_2: 50 nm) could improve the thermal performance of an evacuated tube solar collector compared to that when using water.

Previous studies have reported that the use of a nanofluid improves the performance of a solar collector by 5 %-71 % compared to the use of water as the working fluid. However, existing research results are noted for a shortage of objective and quantitative data on the performance improvement of solar collector used in conjunction with nanofluids. In addition, very few experimental studies of the performance of evacuated tube solar collectors are available in open literature and their performance improvement was assessed in various ways depending on the experimental method. In particular, experi-

Fig. 1. Photograph of experimental setup.

mental studies on evacuated tube solar collectors using CuO nanofluid are insufficiently detailed despite the high conductivity of CuO nanofluid. Therefore, this work studied about the efficiency of the evacuated tube solar collector by using experimental method in order to determine the effect of the size of CuO nanoparticles, concentration of the CuO nanofluid, and mass flux rate of the working fluid on the performance of the solar collector. In addition, the thermal efficiency of the evacuated tube solar collector when CuO nanofluid was used was compared to that when water was used.

2. Experimental setup and procedure

2.1 Experimental setup and test method

Fig. 1 shows an image of the test setup used in this study, and detailed specifications of the evacuated tube solar collector used in the experiment are provided in Table 1. In this study, the efficiency test of the evacuated tube solar collector using water and CuO nanofluid was carried out under the same operating condition at the same time for the purpose of comparison. Fig. 2 shows a schematic of the experimental setup. Working fluid from a storage tank enters the solar collector via the pump. The working fluid discharged from the solar collector flows into a storage tank with a capacity of 100 L and is repeatedly circulated through the system. To compare the performance of solar collector using water and nanofluid, two solar collectors with the same specification were installed at the same place and the experiment was performed at the same time. Besides, the solar collector was operated for 30 minutes before the experiment to reduce the irreversibility of experimental results. In order to evaluate the performance of solar collector, it is necessary to know amount of solar radiation and heat gain of working fluid by measuring of performance variables. A mass flow meter was installed at the exit of the solar collector to measure the mass flow rate of the working fluid. T-type thermocouples, with an operating range of -200 °C to 300 °C and a reading accuracy of ±1.0 °C, were installed to measure both the temperature of the working fluid at the inlet and outlet of the solar collector and ambient temperature simultaneously. The solar radiation was measured using a QMS solar radiation sensor with a solar radiance

Table 1. Specifications of the U-tube solar collector.

Parameter	U-tube solar collector
Collector length (mm)	1445
Collector width (mm)	1640
Gross area (m^2)	2.37
Weight (kg)	51.5
Riser tube material	Copper
Inner diameter of pipes (mm)	10
Outer diameter of pipes (mm)	15
Absorptivity of absorber coating	0.95

Table 2. Experimental conditions.

Item	Condition
Nanoparticle	Copper oxide (CuO)
Stabilizer addition	Arabic gum
Nanoparticle size (nm)	40 / 80
Nanoparticle concentration (vol%)	0.1 / 0.3 / 0.5 / 0.7
Mass flux rate (kg/s·m^2)	420 / 598
Experimental time	AM 10:00 ~ PM 17:00

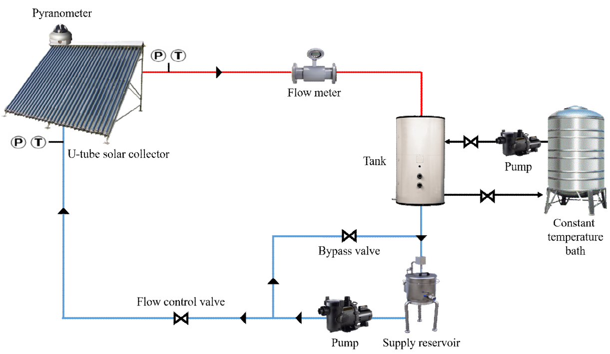


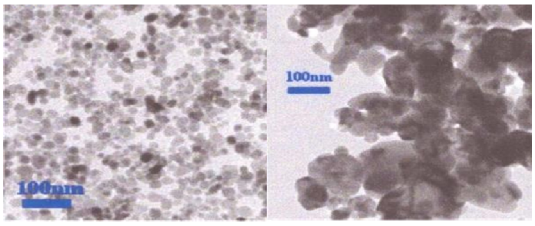
Fig. 2. Schematics of U-tube solar collector system.

measuring range from 0 to 2000 W/m^2 and with an accuracy of ±2 %. The equipment was installed to analyze the performance of the solar collector, and the information of system was collected by using a data acquisition system.

The evacuated tube solar collector was installed at an angle of 45° in Gwang-ju (Latitude: 35°, longitude: 126°), South Korea. The experiment was performed from 10:00 am to 5:00 pm for five months (November 2016 to March 2017). Table 2 presents the experimental conditions used in this study. The CuO nanoparticle size was either 40 nm or 80 nm, the concentrations of the CuO nanofluid were 0.1 vol%, 0.3 vol%, 0.5 vol% and 0.7 vol%, and the mass flux rate of the working fluid was varied by using either 420 kg/s·m^2 or 598 kg/s·m^2, respectively.

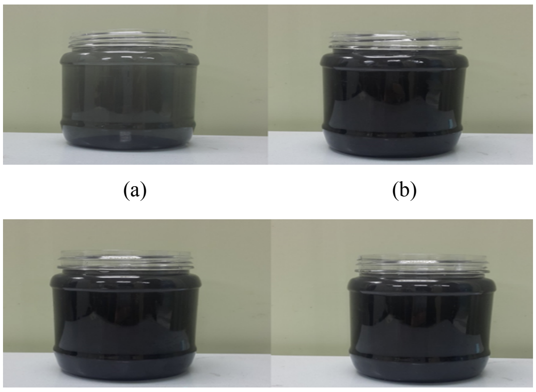
2.2 Preparation of nanofluid

A uniform dispersion of the CuO nanofluid for use in the evacuated tube solar collector was obtained by manufacturing



(a) (b)

Fig. 3. Transmission electron microscope(TEM) photograph of CuO nanoparticle: (a) CuO nanoparticle size = 40 nm; (b) CuO nanoparticle size = 80 nm.



(a) (b)

(c) (d)

Fig. 4. Comparative image of CuO nanofluid sample with different concentration: (a) 0.1 vol%; (b) 0.3 vol%; (c) 0.5 vol%; (d) 0.7 vol%.

the CuO nanofluid using a two-step method. First, a suspension of CuO nanoparticles in water was mixed for 3 hours with Arabic gum (dispersion stabilizer). After the CuO nanofluid was mixed thoroughly, it was agitated for 7 hours in an ultrasonic oscillation apparatus (SHT 750S, power-750 W, Frequency-19.97 kHz, Inc. Sonictopia).

Fig. 3 shows the transmission electron microscope (TEM) photograph of the CuO nanoparticles used in this study. The CuO nanoparticles have a globular shape and are mostly uniform in size. Fig. 4 shows photographs of the CuO nanofluids 7 days after mixing. After observing the CuO nanofluid for 7 days, the dispersion stability was ascertained by visual inspection. As the concentration of the CuO nanofluid increases, the color of the fluid becomes black.

2.3 Efficiency calculation of solar collector

To calculate the useful heat in the solar collector, the inlet and outlet temperatures of the working fluid in the solar collector, and the mass flow rate of the working fluid were used. The useful heat in the solar collector was calculate by using Eq. (1).

$$Q_u = \dot{m}c_p(T_o - T_i) = A_c F_R[G(\tau\alpha) - U_L(T_i - T_a)] . \quad (1)$$

The efficiency of the solar collector is obtained using the density and specific heat of the CuO nanofluid. The density of the CuO nanofluid was calculated by Eq. (2).

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_n . \quad (2)$$

The specific heat and thermal conductivity of the CuO nanofluid was calculated by Eqs. (3) and (4).

$$c_{p(nf)} = \frac{(1-\varphi)\rho_{bf}c_{p(bf)} + \varphi\rho_n c_{p(n)}}{(1-\varphi)\rho_{bf} + \varphi\rho_n} \quad (3)$$

$$k_{nf} = \frac{k_n + 2k_{bf} + 2\varphi(k_n - k_{bf})}{k_n + 2k_{bf} - \varphi(k_n - k_{bf})}k_{bf} . \quad (4)$$

By using properties of nanofluid, the efficiency of the U-tube solar collector was calculated using Eqs. (5) and (6).

$$\eta = \frac{Q_u}{A_c G} = \frac{\dot{m}c_p(T_o - T_i)}{A_c G} \quad (5)$$

$$\eta = F_R(\tau\alpha) - F_R U_L \frac{(T_i - T_a)}{G} \quad (6)$$

where $F_R(\tau\alpha)$ is the absorbed energy in the absorbing plate as the heat gain parameter, and $F_R U_L$ signifies the heat loss on the outside of the solar collector as the heat loss parameter.

In this study, uncertainties in the experimental value of the efficiency of the solar collector occurred because of errors in the measurements of the mass flow meter, thermocouples, and pyranometer. Uncertainties in the solar collector were calculated using Eq. (7) from Moffat et al. [27].

$$\frac{\delta\eta}{\eta} = \left[\left(\frac{\delta\dot{m}}{\dot{m}}\right)^2 + \left(\frac{\delta(T_o - T_i)}{T_o - T_i}\right)^2 + \left(\frac{\delta G}{G}\right)^2\right]^{0.5} . \quad (7)$$

In the experimental data of this study, because of the uncertainties in the U-tube solar collector caused by using Eq. (7), the maximum and average uncertainties were approximately 3.03 % and 1.44 %, respectively.

3. Results and discussion

In order to analyze the efficiency of solar collector according to the operating temperature and concentration of CuO nanofluid, the thermal conductivity of CuO nanofluid was investigated firstly. Fig. 5 shows the thermal conductivity ratio dependence of CuO nanofluid concentration and operating temperature at the nanoparticle size of 40 nm. Where, k_{nf} is the thermal conductivity of CuO nanofluid and k_{bf} is the thermal conductivity of basic fluid(water). In case the CuO nanofluid concentration was 0.1 vol%, as the temperature of nanofluid increased from 10 °C to 50 °C, the thermal conductivity ratio increased by 1.3 % at the nanoparticle size of 40 nm. In case the CuO nanofluid concentration was 0.7 vol%, that increased

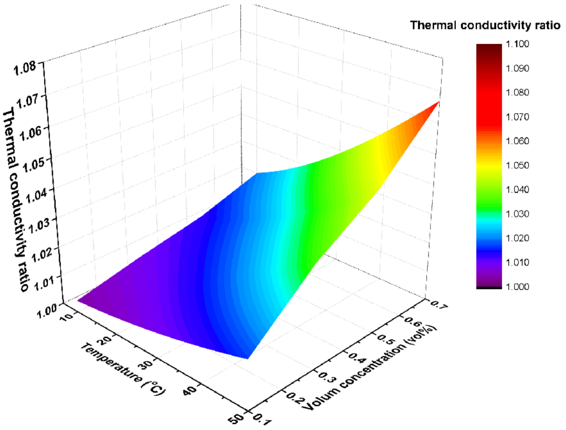


Fig. 5. Thermal conductivity ratio as a function of temperature for different nanofluid concentration at the nanoparticle size of 40 nm.

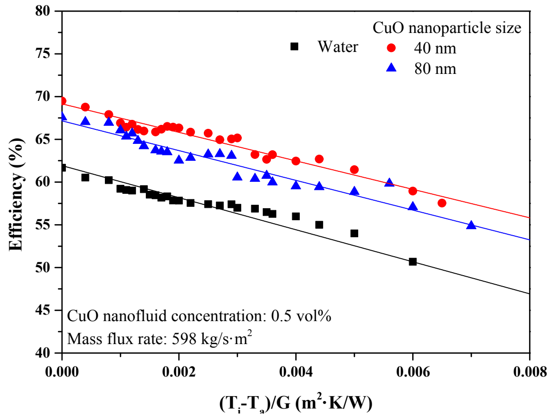


Fig. 6. Variation of thermal efficiency of the evacuated tube solar collector for different nanofluid size (CuO nanofluid concentration = 0.5 vol%, Mass flux rate = 598 kg/s· m^2).

by 4.6 % as the temperature of nanofluid increased from 10 °C to 50 °C. As the concentration of CuO nanofluid increased from 0.1 vol% to 0.7 vol% at an operating temperature of 10 °C and 50 °C, the thermal conductivity ratio of CuO nanofluid increased by 1.57 % and 4.67 %, respectively. As shown in Fig. 5, it was found the thermal conductivity of CuO nanofluid increased linearly with an increase of operating temperature and nonlinearly with an increase of concentration.

This study involved an experimental investigation of the thermal efficiency of an evacuated tube solar collector using CuO nanofluid as a function of the CuO nanoparticle size and concentration of the CuO nanofluid. Besides, the results were compared to that obtained using water. The effect of the size of the CuO nanoparticles in CuO nanofluid on the thermal efficiency of the solar collector was investigated by analyzing the thermal performance of the solar collector according to the size of the CuO nanoparticles, firstly. The thermal performance of the solar collector can be evaluated with heat loss parameter($(T_i-T_a)/G$) because the thermal performance is seriously affected by the change in the heat loss parameter. In addition, the solar collector can have maximum efficiency at $T_i = T_a$ and the efficiency decreases as the heat loss factor increases. Fig. 6 shows the efficiency of the evacuated tube solar collector using CuO nanofluid depending on the nanoparticle size when the mass flux rate and concentration of the CuO nanofluid were 598 kg/s·m^2 and 0.5 vol%, respectively. Under all operating conditions, the evacuated tube solar collector using CuO nanofluid with a nanoparticle size of 40 nm, which is relatively small, showed higher efficiency. The maximum efficiency of the solar collector using 40 nm-CuO nanofluid was 69.1 %, which was 2.0 % higher than that using 80 nm–CuO nanofluid at the same operating condition. Generally, the thermal conductivity increases as the nanoparticle size decreases because Brownian motion between particles causes nanoparticles to be more active; therefore, the heat transfer performance increases. Based on this phenomenon, the thermal efficiency of the evacuated tube solar collector using 40 nm-CuO nanofluid was higher than that using 80 nm–CuO nanofluid. When the CuO nanofluid with nanoparticle sizes of 40 nm and 80 nm was used as the working fluid, the maximum efficiency of the evacuated tube solar collector was increased by 7.2 % and 5.2 %, respectively, compared to that using water as the working fluid.

Table 3 presents the characteristic parameters in relation to the efficiency of the evacuated tube solar collector when 0.5 vol%-CuO nanofluid with different nanoparticle sizes andwater was used as the working fluid. As the heat gain parameter ($F_R(\tau\alpha)$) increases, the thermal energy transfer and absorption heat in the solar collector increases, thus the maximum efficiency increases. Besides, the smaller the heat loss parameter (F_RU_L) means the less the heat loss to the outside of solar collector. Thus, the high thermal efficiency can be maintained for wide operating conditions when the solar collector has a small heat loss parameter. That is, a high-efficiency solar collector has a high heat gain parameter and a small heat loss parameter. The experimental results showed that the heat gain parameter ($F_R(\tau\alpha)$) of the evacuated tube solar collector using 0.5 vol%-CuO nanofluid was 0.671 and 0.691 for nanoparticle sizes of 80 nm and 40 nm, respectively. Under the same conditions, the heat loss parameter (F_RU_L) was 16.66 and 17.39, respectively. The heat gain parameter ($F_R(\tau\alpha)$) of the evacuated tube solar collector using CuO nanofluid with a nanoparticle size of 40 nm was about 2.0 % higher than for a particle size of 80 nm; however, the heat loss parameter(F_RU_L) was about 4.4 % lower. It was confirmed that the use of CuO nanofluid with a nanoparticle size of 40 nm as a working fluid increased the thermal energy transfer and absorption heat, with less external heat loss compared to that of 80 nm. Previous studies found that the smaller nanoparticles could improve the heat transfer and thermal conductivity of working fluid, thus the thermal performance of the solar collector could improve. In an analysis of the efficiency of the flat-plate solar collector using Al_2O_3 nanofluid, it could be checked a smaller nanoparticle size resulted in higher thermal conductivity and higher efficiency [23].

Table 3. Parameters of efficiency in the U-tube solar collector depending on CuO nanoparticle size.

Working fluid (condition)	$F_R(\tau\alpha)$	F_RU_L	R^2
Water	0.619	18.75	0.916
CuO nanofluid (40 nm, 0.5 vol%)	0.691	16.66	0.969
CuO nanofluid (80 nm, 0.5 vol%)	0.671	17.39	0.947

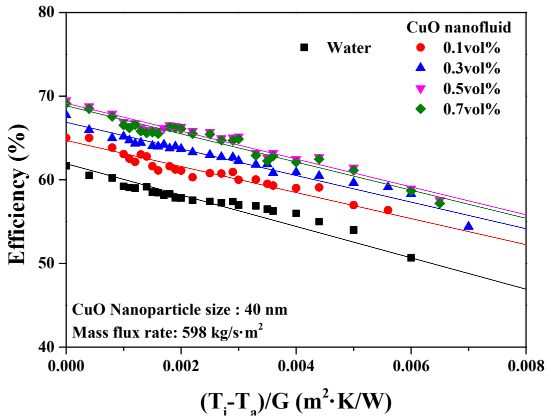


Fig. 7. Variation of efficiency of evacuated tube solar collector for different nanofluid concentration (CuO nanoparticle size = 40 nm, Mass flux rate = 598 kg/s· m^2).

Fig. 7 shows the variation in the efficiency of the evacuated tube solar collector depending on the concentration of CuO nanofluid when the mass flux rate of the working fluid and CuO nanoparticle size was 598 kg/s·m^2 and 40 nm, respectively. When CuO nanofluid was applied into the evacuated tube solar collector, it can be seen that the efficiency greatly improved compared to that using water. In particular, when the concentration of CuO nanofluid was 0.5 vol%, the highest efficiency was presented, namely 69.1 %, which was about 7.2 % higher than that using water. In addition, CuO nanofluid with a concentration of 0.5 vol% showed an efficiency improvement of 4.4 %, 2.3 % and 0.3 %, respectively, as compared to that of 0.1 vol%, 0.3 vol% and 0.7 vol%. When the concentration of CuO nanofluid was 0.7 vol%, the thermal conductivity of the nanofluid increased compared to that at a concentration of 0.5 vol%. However, the efficiency of evacuated tube solar collector was almost similar. This means that various factors affecting to the efficiency of the solar collector including the thermal conductivity of the nanoparticle. It was concluded that the heat transfer performance did not significantly increase for a high concentration of CuO nanofluid because of the increase of the boundary layer on the wall surface, which was mainly owing to an increase of accumulation (low dispersion stability) and viscosity of the CuO nanofluid at high concentrations. In the previous study [10, 11], the efficiency of solar collector was increased by 16.7 % and 12.7 % at the concentrations of CuO nanofluid of 0.4 vol% and 0.75 vol%, respectively, compared to that when the water used. In this study, it was increased about 7.2 %. The efficiency improvement of this study was a little small compared to that of

Table 4. Parameters of efficiency in the U-tube solar collector depending on CuO nanofluid concentration.

Working fluid (condition)	$F_R(\tau\alpha)$	F_RU_L	R^2
Water	0.619	18.75	0.916
CuO nanofluid (40 nm, 0.1 vol%)	0.647	15.56	0.955
CuO nanofluid (40 nm, 0.3 vol%)	0.668	15.89	0.966
CuO nanofluid (40 nm, 0.5 vol%)	0.691	16.66	0.969
CuO nanofluid (40 nm, 0.7 vol%)	0.688	16.82	0.964

previous results. This is maybe due to the difference and characteristics of solar collector as well as the difference of the mass flux rate of CuO nanofluid. Besides, the previous results were obtained in the flat-plate solar collector but the evacuated tube solar collector was used in this study.

Table 4 provides the calculated performance parameters in relation to the efficiency of the evacuated tube solar collector using linear equations according to the volume concentration of CuO nanofluid with a nanoparticle size of 40 nm. For the 0.5 vol%-CuO nanofluid, the heat gain parameter ($F_R(\tau\alpha)$) had a maximum value of 0.691 and the heat loss parameter (F_RU_L) was 16.66. However, the heat gain and heat loss parameters were 0.688 and 16.82, respectively, at a concentration of 0.7 vol%. As the experimental results of this study, it was confirmed that the best concentration of CuO nanofluid in the evacuated tube solar collector was 0.5 vol%. When the water was applied to the evacuated tube solar collector as a working fluid, the heat gain parameter ($F_R(\tau\alpha)$) of the solar collector was 0.619, which was the lowest, and the heat loss parameter (F_RU_L) was 18.75, which was the highest. As a result, compared to using water, the evacuated tube solar collector using CuO nanofluid can have a higher performance and maintain higher efficiency for a wide operating range.

Fig. 8 shows the efficiency of the solar collector depending on the mass flux rate of the working fluid (CuO nanofluid or water). In the case of CuO nanofluid, the concentration was 0.5 vol% with a nanoparticle size of 40 nm, which had the highest efficiency as the working fluid. In case the 0.5 vol%-CuO nanofluid was applied into the evacuated tube solar collector, the maximum efficiency was 69.1 % at a mass flux rate of 598 kg/s·m^2, and the efficiency was increased by 1.9 % compared to that at a mass flux rate of 420 kg/s·m^2. The maximum efficiency of the evacuated tube solar collector using water was 61.9 % at a mass flux rate of 598 kg/s·m^2, i.e., it was about 2.5 % higher than that at 420 kg/s·m^2. The efficiency of the evacuated tube solar collector could be maintained at a relatively higher level when CuO nanofluid was used as the working fluid regardless of the mass flux rate of CuO nanofluid. In addition, the increase in thermal efficiency according to the mass flux rate of the CuO nanofluid decreased compared to that of water. When both water and CuO nanofluid were applied into the evacuated tube solar collector, the efficiency of 598 kg/s·m^2 was higher than that of 420 kg/s·m^2. This is because the heat transfer rate increases be-

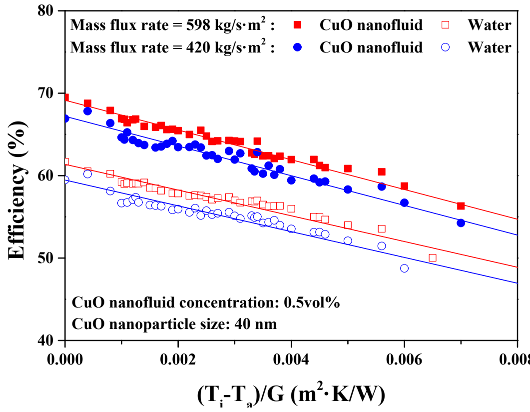


Fig. 8. Variation of efficiency of evacuated tube solar collector for different mass flux rate (CuO nanoparticle size = 40 nm, nanofluid concentration = 0.5 vol%).

cause of the rise in the temperature difference between the CuO nanofluid and the solar collector plate with increasing the mass flux rate of the working fluid in the solar collector. Thus, the efficiency of the solar collector may increase when the mass flux rate of the CuO nanofluid increases. However, the outlet temperature of the evacuated tube solar collector is reduced in relative terms. In this study, the efficiency of an evacuated tube solar collector was experimentally investigated according to the size of the CuO nanoparticles, the concentration of the CuO nanofluid, and the mass flux rate of the working fluid. The experimental results presented that the thermal efficiency of the solar collector using CuO nanofluid with a relatively small nanoparticle size was higher than that using a larger size one. The maximum efficiency of the CuO nanofluid with a CuO nanoparticle size of 40 nm was 69.1 % when the concentration of the CuO nanofluid and mass flux rate of working fluid was 0.5 vol% and 598 kg/s·m^2, respectively. Moreover, the aforementioned efficiency was about 2.0 % higher than for 80 nm. The thermal efficiency of the evacuated tube solar collector with CuO nanofluid was much higher than that with water. In particular, when the concentration of the CuO nanofluid was 0.5 vol%, the efficiency was the highest, i.e., 7.2 % higher than when using water. Besides, the use of 0.5 vol%-CuO nanofluid in the solar collector increased the efficiency by 4.4 %, 2.3 % and 0.3 %, respectively, compared to that using CuO nanofluid in concentrations of 0.1 vol%, 0.3 vol% and 0.7 vol%. The thermal efficiency of the evacuated tube solar collector using CuO nanofluid increased by 1.9 % as the mass flux rate of the CuO nanofluid increased from 420 kg/s·m^2 to 598 kg/s·m^2. In addition, an increase of the CuO nanofluid flow rate brought a higher efficiency of the solar collector, while it brought a decrease of discharge temperature at the outlet of solar collector.

Fig. 9 shows the efficiency comparison of solar collector with existing research results of previous study. There are only few studies on the efficiency of evacuated tube solar collector using nanofluid, in particular, for CuO nanofluid. The detailed experimental conditions in each study are presented in Table 5.

Table 5. Specific conditions of previous study for comparison the efficiency of solar collector.

Reference	Solar collector	Working fluid	Size	Concentration	$F_R(\tau\alpha)$	F_RU_L
This study	Evacuated tube	CuO	40 nm	0.5 vol%	0.691	16.66
Ersöz et al. [25]	Evacuated tube	Chloroform	-	-	0.736	27.12
Ghaderian et al. [28]	Evacuated tube	CuO	40 nm	0.06 vol%	0.549	2.52
He et al. [9]	Flat-plate	Cu	25 nm	0.1 wt%	0.821	78.02

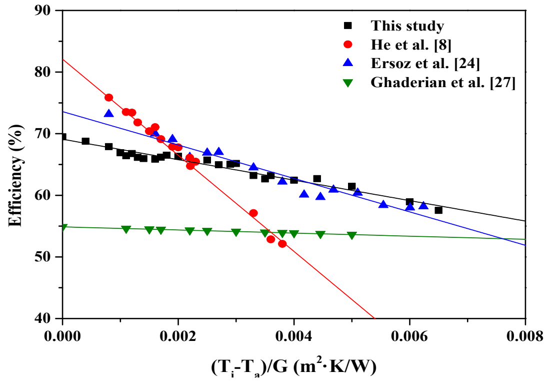


Fig. 9. Efficiency comparison with existing research results.

The evacuated solar collector was used in the experimental of this study, Ersöz et al. [25] and Ghaderian et al. [28]. Otherwise the flat-plate solar collector was used in the experiment of He et al. [9]. Ersöz et al. [25] used Chloroform as working fluid and the maximum efficiency of the solar collector was 73.6 %. Ghaderian et al. [28] used 40 nm-0.06 vol% CuO nanofluid and the maximum efficiency was 54.9 %. He et al. [9] performed the experiment by using 25 nm-0.1 wt% Cu nanofluid and the maximum efficiency was 82.1 %. The highest efficiency of solar collector among existed study using the evacuated tube solar collector was presented by Ersöz et al. [25]. Besides the heat loss parameter(F_RU_L) of the evacuated tube solar collector was in the ranges of 2.5-27.1 and the heat loss parameter(F_RU_L) of the flat-plate solar collector was 78 which was significantly high. As shown in Fig. 9, the slope of efficiency increases sharply as the heat loss coefficient increases. In the evacuated tube solar collector, since the absorber is placed inside the vacuum glass tube and there is rare convection heat loss, it is confirmed that the efficiency of evacuated tube solar collector is higher under high temperature than that of the flat-plate solar collector.

4. Conclusion

In this study, the efficiency of an evacuated tube solar collector was experimentally investigated according to the size of the CuO nanoparticles, the concentration of the CuO nanofluid, and the mass flux rate of the CuO nanofluid. In addition, the thermal efficiency of the evacuated tube solar collector using CuO nanofluid was compared to that using water. As a result, the use of CuO nanofluid in the evacuated tube solar collector caused the efficiency increase about 7.2 % compared to that when water was used. The result of this study presented the efficiency of the solar collector using CuO nanofluid with a relatively small nanoparticle size was higher than that using a nanofluid with a larger particle size. The maximum efficiency of the evacuated tube solar collector using the CuO nanofluid with a nanoparticle size of 40 nm was 69.1 % when the concentration of the CuO nanofluid was 0.5 vol% and its mass flux rate was 598 kg/s·m^2. This was approximately 2.0 % higher than the efficiency of the CuO nanofluid with a particle size of 80 nm.

The efficiency of the evacuated tube solar collector using CuO nanofluid improved as the concentration of the CuO nanofluid increased at low concentrations, but an optimal concentration was found as the concentration level was increased. The most effective concentration of the CuO nanofluid was 0.5 vol% in this study, and the maximum efficiency of the evacuated tube solar collector with 0.5 vol% increased by 4.4 %, 2.3 % and 0.3 %, respectively, compared to that with 0.1 vol%, 0.3 vol% and 0.7 vol%. As the mass flux rate of the CuO nanofluid increased from 420 to 598 kg/s·m^2, the efficiency of the solar collector increased by 1.9 %. In addition, an increase in the CuO nanofluid in the system led to decrease in efficiency compared to that of water. Overall, the use of CuO nanofluid as the working fluid in the evacuated tube solar collector can be expected to improve the performance by over 7.2 % compared to water.

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Nomenclature

A_c : Surface area of solar collector, (m^2)
c_p : Specific heat capacity, (J/kg·K)
F_R : Heat removal factor
G : Solar radiation, (W/m^2)
Q_u : Useful heat, (W)
T : Temperature, (K or °C)
U_L : Overall loss coefficient, (W/m^2·K)

Greek symbols

η : Efficiency
φ : Volume concentration of nanoparticles
ρ : Density
$\tau\alpha$: Effective penetration absorption rate

Subscripts

a : Ambient
bf : Base fluid
f : Fluid
i : Inlet
n : Nanoparticle
nf : Nanofluid
np : Nanoparticle
o : Outlet

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