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Experimental investigation on the efficiency of flat-plate solar collectors with nanofluids

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A B S T R A C T

In this study, $Cu-H_2O$ nanofluids with different mass fraction and size were prepared through two-step method. Its thermal conductivities and the effect of $Cu-H_2O$ nanofluids on the efficiency of a flat-plate solar collector was investigated experimentally. Meanwhile, the water temperature, heat gain of the flat-plate solar water heater and the frictional resistance coefficient of working fluid were also investigated. The mass flow rate of medium was 140 L/h. The experimental results show that the thermal conductivities can be enhanced observably. The efficiency of solar collector was enhanced by 23.83% with using $Cu-H_2O$ nanofluids (25 nm, 0.1 wt%) as the absorbing medium. The efficiency of $Cu-H_2O$ nanofluids (25 nm, 0.2 wt%) is lower than that of $Cu-H_2O$ nanofluids (25 nm, 0.1 wt%). With the nanoparticle size increasing, the efficiency of solar collector decreased. The highest temperature and highest heat gain of water in the nanofluid (25 nm, 0.1 wt%) tank can be increased up to 12.24% and 24.52% compared with water tank, respectively. The increment rate of the frictional resistance coefficient is less than 1% in the whole working temperature area. From the results, it can be indicated that the $Cu-H_2O$ nanofluids is suitable for enhancing the efficiency of flat-plate solar collector.

1. Introduction

Solar thermal energy is by far the largest exploitable resource. It is a very convenient source of heating. It can be used free of charge, and does not need to be transported [1–3]. The critical problem for solar thermal utilization is how to improve the efficiency of the solar collector. It can be performed with optimizing the structure of collector or developing a new type of working medium. Currently, water as a medium in solar thermal energy system is used widely. But the thermal conductivity of water is not high.

With the development of nanotechnology, an innovative heat transfer fluid arise. Nanofluids, a relatively new class of fluids which consist of a base fluid with nano-sized particles (1–100 nm) suspended within them [4]. These particles are generally metals or metal oxides. Nanofluids have been considered as a new-type heat transfer fluid because of their enhanced thermal conductivities [5–7]. Recently some researchers have put forward to use the nanofluid as the working fluid for the solar collectors.

Tyagi et al. [8] have investigated theoretically the feasibility of using a nonconcentrating direct absorption solar collector (DAC) and compared its performance with that of a conventional flat-plate collector. The $Al-H_2O$ nanofluid was used as the absorbing medium. They concluded that the absorption of incident radiation of nanofluids by more than nine times over that of pure water and the efficiency of a DAC using nanofluid as the working fluid is up to 10% higher than that of a flat-plate collector. Otanicar et al. [9] performed the experiments of photothermal properties for nanofluids made from a variety of nanoparticles (carbon nanotubes, graphite, and silver). They presented an efficiency improvement up to 5% in solar thermal collectors by utilizing the nanofluids as the absorption medium. Taylor et al. [10] have studied the nanofluid optical property characterization. In Taylor's research, the nanofluids that mixed water and graphite, aluminum, copper, silver, titanium dioxide nanoparticles were used as the absorbing medium. According to the results of Taylor's study, over 95% of incoming sunlight can be absorbed with the nanoparticle volume fractions less than 1×10^{-5}. Sani et al. [11,12] have investigated the optical and thermal properties of Single Wall Carbon Nanohorns (SWCNHs) in view of their use as direct sunlight absorbers in solar thermal

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Nomenclature

Q	heat gain of fluids (W)
m	mass flow rate (kg/s)
C_p	heat capacity (J/kg K)
t_o	outlet fluid temperature (°C)
t_i	inlet fluid temperature(°C)
t_a	environment temperature(°C)
A_c	surface area of solar collector(m^2)
F_R	heat removal factor
G	solar radiation(W/m^2)
U_L	overall loss coefficient of solar collector (W/m^2 K)
Greek letters	
ϕ	volume fraction (%)
$\tau\alpha$	absorptance-transmittance product
η_i	instantaneous collector efficiency
Abbreviations	
n	nanofluid
p	particle
b	base fluid

devices. The experimental results indicated that the nanoSWCNHs has considerably higher sunlight absorption. Han et al. [13] investigated the photothermal properties, optical properties, rheological behaviors, and thermal conductivities of the carbon black aqueous nanofluids. The experiments showed that nanofluids had better solar energy adsorption properties. Yousefi et al. [14–16] performed the experiments of efficiency of a flat-plate solar collector with Al_2O_3–H_2O and MWCNT-H_2O nanofluids as the working fluid respectively. The results show that the efficiency of solar collector can be enhanced by 28.3% with 0.2 wt% Al_2O_3 nanofluid than that of pure water. The dose of surfactants in MWCNT-H_2O nanofluids can affect the efficiency of solar collector. The more differences between the pH of nanofluids and pH of isoelectric point cause the more enhancement in the efficiency of collector. Mao et al. [17] performed the experiments of efficiency of a direct absorption solar collectors used carbon-coated copper water-based nanofluids. The results show that the efficiency of solar collector is reach to 74.69%. Mu et al. [18] investigated the radiative properties and the thermal performance of direct solar absorbers using SiO_2, TiO_2 and ZrC aqueous solution. The results show that the solar absorbance of ZrC–H_2O nanofluids is superior to that of SiO_2–H_2O and TiO_2–H_2O nanofluids. Mercatelli et al. [19] investigated the absorption and scattering properties of nanofluids consisting in aqueous and glycol suspensions with single-wall carbon nanohorns. The results show that SWCNHs-based nanofluids have considerably higher sunlight absorption ability with respect to the pure base fluids. The fraction of the power stored in SWCNHs-water nanofluids is higher than that of SWCNHs-glycol nanofluids with the same volume fraction. Later Mercatelli et al. [20]studied the spectral scattering albedo of SWCNHs, the results indicate that the scattering albedo of SWCNHs was not higher than 5% for red and NIR wavelengths. Kameya et al. [21] investigated the radiation absorption characteristics of a Ni nanoparticle suspension. They concluded that the absorption coefficient of the nanoparticle suspension is much higher than that of the base liquid for visible to near-infrared wavelengths. Lee et al. [22] used gold-nanoshell (GNS) nanoparticles with different SiO_2 core sizes and Au coating thicknesses mixed in water to make a GNS-blended nanofluid. It can significantly enhance the solar collector efficiency up to 70% with 0.05% particle volume fraction. Ladjevardi et al. [23] investigated the applications of nanofluids in direct absorptions of solar radiation in volumetric solar collector. The results show that by using graphite nanofluids (0.000025 vol%) can absorb more than 50% of incident irradiation energy, and just about 0.0045 $/L increase in cost. Nathan Hordy et al. [24] investigated the optical characterization of the MWCNTs nanofluids, the results show that are highly absorbing over the majority of the solar spectrum, allowing for about 100% solar energy absorption.

As mentioned above studies, there are only a few research committed to the conventional solar collectors. The main purpose of this study is to discuss the feasibility for nanofluids apply to flat-plate solar collector. In this experiment, Cu–H_2O nanofluids were prepared, and its thermal conductivities with different nanoparticle mass fraction and size were tested. The optimum concentration of nanofluids was chosed as the working fluids. The efficiency of flat-plate solar collectors with nanofluids under various particle size and mass fraction were investigated.

2. Experimental setup

2.1. Preparation of nanofluids

The Cu–H_2O nanofluids was prepared through two-step method (Cu nanoparticle, the average diameter is about 25 nm and 50 nm, supplied by Shanghai ChaoWei Nanotechnology Co. Ltd., China; the base fluid is deionized water). A certain amount of nanopowders were blended with deionized water, and some dispersing agents (SDBS) were added, then adjusted the pH value of nanofluids to 8 by HCl and NaOH in analytical grade. The suspension were stirred 30 min by magnetic stirring apparatus and oscillated 40 min through ultrasonic oscillation apparatus at 90 W (KQ2200DE, Kunshan of Jiangsu Equipment Company, China).

The particle size was measured by Scanning Electron Microscope (Nova NanoSEM 430), as shown in Fig. 1 and Fig. 2. There are a few larger particles, which are likely aggregates of the smaller ones, but the whole distribution of the particles is relatively well-

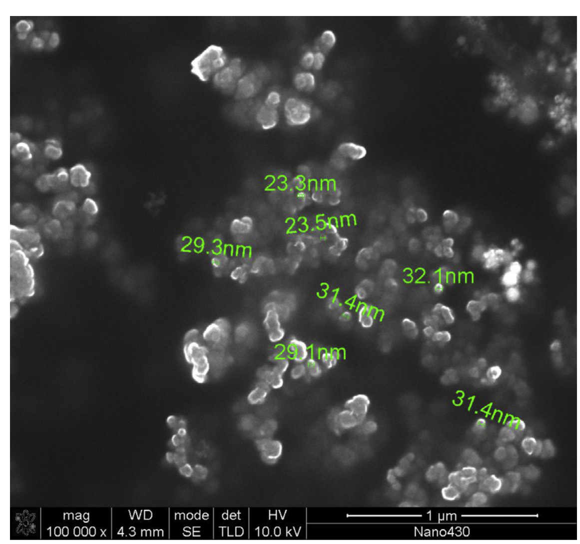


Fig. 1. SEM micrograph of Cu nanoparticles (the average diameter of Cu nanoparticles is about 25 nm).

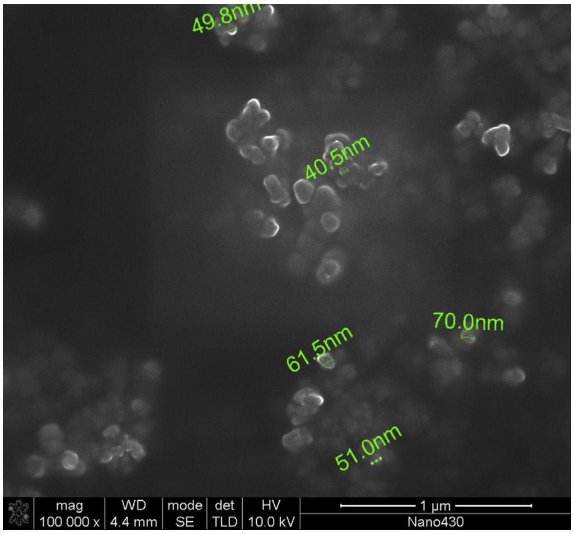


Fig. 2. SEM micrograph of Cu nanoparticles (the average diameter of Cu nanoparticles is about 50 nm).

dispersed. The particles are basically spherical or near spherical, the mean diameter is about 25 nm and 50 nm.

2.2. Solar thermal energy experimental apparatus

The experimental apparatus is shown in Fig. 3. In order to compare the efficiency of nanofluids with water in the same conditions, two same solar collectors were adopted. As can be seen from Fig. 3, the title angle of this flat-plate solar collector is 45°, and this experimental investigation was performed at Shunde Polytechnic, Guangdong, China(latitude is 22°40′ N and longitude is 113°1′ E). The area of solar collector is 2 m^2 and collector plates made of 8 parallel strips (copper pipe, inside diameter 8 mm).

The schematic diagram of the solar collector system is shown in Fig. 4. The two solar water heater systems have a tank for absorbing the heat energy, respectively. The capacity of the tank is about 100 Lit. In the nanofluids solar cycle, one heat exchanger was used inside the tank. So the nanofluids can transmit the heat load of the solar cycle to the water. While in the water solar cycle system, the tank has no heat exchanger. Two glass rotameters were used to measure the mass flow rate of working fluid in the solar system. Two thermocouples (Type K) were used to measure the fluid

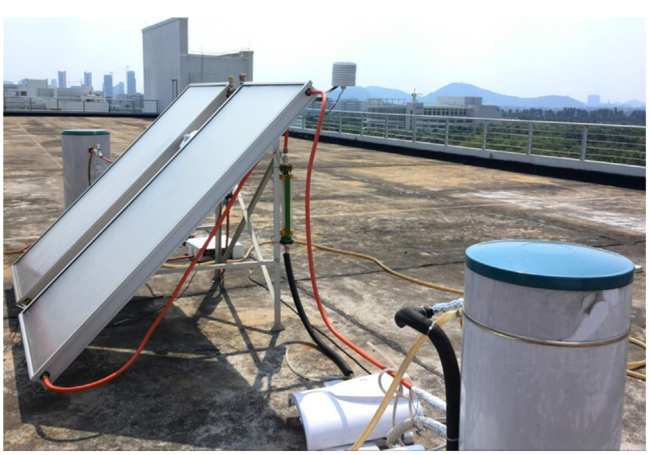
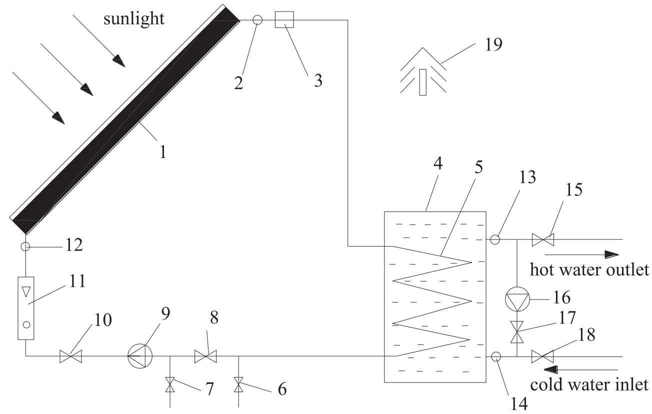


Fig. 3. The experimental apparatus.



1-flat plate collector; 2、12、13、14-thermocouple; 3-vent valve; 4-water tank;

5-heat exchanger; 6、7、8、10、15、17、18-valve; 11-flowmeter; 9、16-water pump;

19- platinum resistance thermometer

Fig. 4. Schematic diagram of solar thermal energy measuring system.

temperatures in the inlet and outlet of solar collector. The test precision of thermocouples is ±0.2 °C, and they were calibrated by a precision thermometer. All thermocouples were connected to the data acquisition system Agilent 34970A. The interval time of data acquisition is 20 s. The air temperature was measured by a platinum resistance thermometer with a cover for solar radiation protection. The total solar radiation was recorded by a TBQ-2 solar meter which using a calibrated reference solar meter with a valid calibration certificate. The platinum resistance thermometer and solar meter were connected to the solar data logger system.

2.3. Experimental method

The thermal performance of the flat-plate collectors were evaluated by the ASHRAE Standard 86-93. The collecting efficiency, water temperature and heat gain were compared in the same solar irradiation. The tests have performed from 9:00 to 16:00. The volume flow rate of woking fluids is 140 L/h. The heat gain of fluids can be calculated using Eq. (1). The heat gain of fluids can also be expressed in terms of the energy absorbed by the absorber and the energy lost from the absorber as given by Eq. (2) [25].

$$Q = mC_p(t_o - t_i) \tag{1}$$

$$Q = A_cF_R[(G(\tau\alpha) - U_L(t_i - t_a)] \tag{2}$$

where Q is the heat gain of fluids, W; m is the mass flow rate, kg/s; C_p is the heat capacity of water or nanofluid, J/(kg K); t_o is the outlet fluid temperature, °C; t_i is the inlet fluid temperature, °C; t_a is the environment temperature, °C; A_c is the surface area of solar collector, m^2; F_R is the heat removal factor; G is the solar radiation, W/m^2; $\tau\alpha$ is the absorptance-transmittance product; U_L is the overall loss coefficient of solar collector,W/(m^2 K);

The heat capacity of nanofluids can be calculated by Eq. (3) [26].

$$C_{p,n} = C_{p,p}\varphi + C_{p,b}(1 - \varphi) \tag{3}$$

where $C_{p,n}$, $C_{p,p}$, $C_{p,b}$ is the heat capacity of nanofluids, nanoparticle and base fluid, respectively, J/(Kg K); φ is the volume fraction of Cu nanoparticle; The heat capacity of Cu and water is 390 J/(kg K) and 4182 J/(kg K), respectively.

The instantaneous collector efficiency, η_i, can be given by Eq. (4) or Eq. (5) [25].

$$\eta_i = \frac{Q}{A_c G} = \frac{mC_p(t_o - t_i)}{A_c G} \tag{4}$$

$$\eta_i = F_R(\tau\alpha) - F_R U_L \frac{t_i - t_a}{G} \tag{5}$$

3. Results and discussion

3.1. Thermal conductivity

In order to investigate the effect of mass fraction and nanoparticle size on the enhancement of the thermal conductivity. The thermal conductivity of Cu–H_2O nanofluids with five different mass fraction (0.01 wt%, 0.02 wt%, 0.04 wt%, 0.1 wt%, 0.2 wt%) and different nanopaticle size were measured by HotDisk instrument. Fig. 5 shows the enhanced thermal conductivity as a function of mass fraction of Cu suspended into deionized water. k_n and k_b stand for the thermal conductivity of the nanofluids and deionized water, respectively. The data indicates that the thermal conductivity of nanofluid increases nonlinearly with mass fraction of the nanoparticles. The enhancement rate is more and more slowly with the mass fraction increases.

When the mass fraction is 0.01 wt% and 0.1 wt%, thermal conductivity is increased up to 17.01% and 23.58% at 70 °C, respectively. It indicates that the nanoparticle concentration has a major influence on thermal conductivity.

Fig. 6 shows the enhanced thermal conductivity as a function of nanoparticle size of Cu(0.1 wt%). As can be seen from the data, the thermal conductivity of 25 nm Cu–H_2O nanofluids is larger than that of 50 nm Cu–H_2O nanofluids. There are two possible explanations to this phenomenon. On the one hand, in the same mass fraction, the quantity of small particle is more than that of large particle. It lead to the former has a larger interfacial area between liquid and particles. Hence, the heat transfer is turned to more quick and high efficiency. On the other hand, due to the small size effect of nanoparticles, the nanoparticles in suspension will random walk. The micro movement of nanoparticles makes the microconvection phenomena exists between particles and liquid. This kind of microconvection enhances the energy transfer process between the particles and liquid, which increased the thermal conductivity of nanofluids. Most important of all, in the particle movement also with the migration of energy at the same time. This part of the energy transfer is closely related to the movement intensity of the particles. The scale of the particle is smaller, the greater the intensity of micromotion, the more frequently the nanoparticles move. It will lead to the nanofluids internal energy transfer rate faster, which make the thermal conductivity of nanofluids greater.

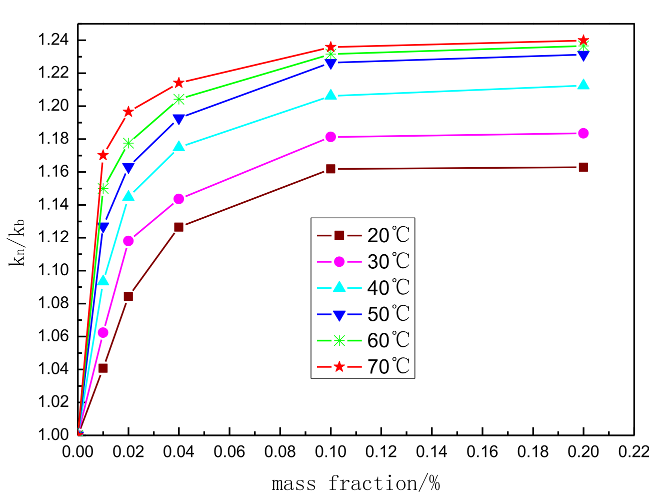


Fig. 5. Thermal conductivity ratio (k_n/k_b) as a function of temperature at different mass fraction of Cu(Cu:25 nm).

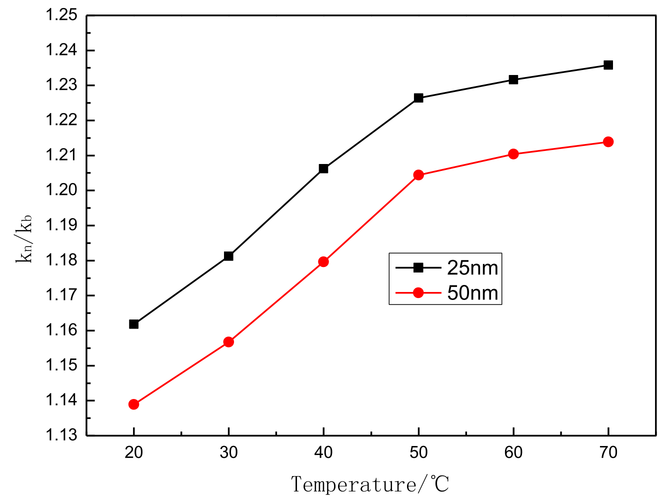


Fig. 6. Thermal conductivity ratio (k_n/k_b) as a function of particle size at different temperature (mass fraction is 0.1%).

3.2. Heat collecting efficiency

3.2.1. The effect of mass fraction

In order to study the performance of nanofluids as the working fluids in the solar collector system, each experiment was performed four times and the good datas were chosed to analyze. Fig 7 shows an example of typical recorded data for water and nanofluids (Cu:25 nm, 0.1 wt%) at 140 L/h in one of the test days. The inlet fluid temperature is almost remain unchanged, the outlet fluid temperature is the critical parameter. As can be seen from Fig. 7, before

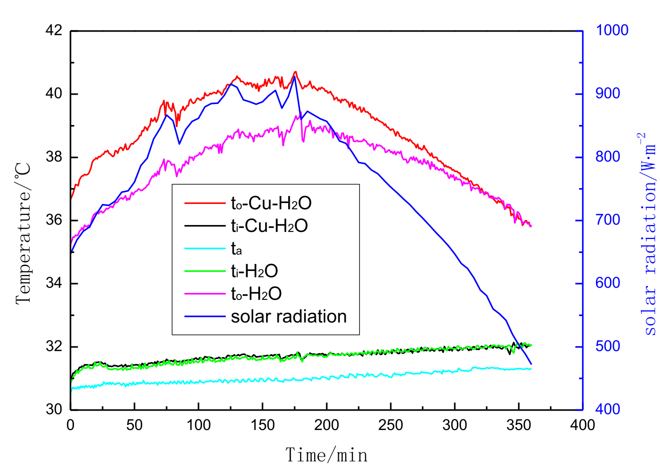


Fig. 7. Temperature curve of Cu–H_2O and water (Cu:25 nm, 0.1 wt%, t_a is the ambient air temperature).

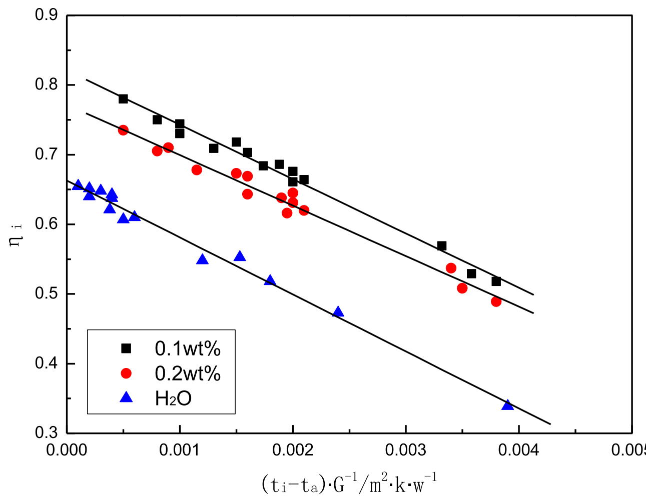


Fig. 8. The efficiency of the flat-plate solar collector with Cu–H_2O nanofluids and water as the absorbing medium (Cu:25 nm).

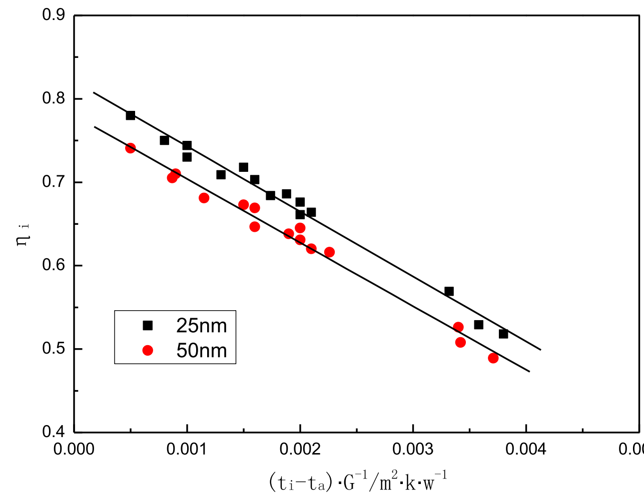


Fig. 9. The efficiency of the flat-plate solar collector with Cu–H_2O nanofluids as the absorbing medium (0.1 wt%,Cu:25 nm, 50 nm).

180 min (12:00), the outlet temperature of nanofliuds is higher than that of water. With the solar radiation decline (12:00–15:00), the temperature difference of the outlet between nanofluids and water is reduce gradually. In the end, the outlet temperature of nanofliuds and water is almost equal. There is a possible explanation to this phenomenon. During the high solar radiation, the heat loss is very little compared with the solar thermal energy absorbed by the fluids. The temperature of nanofluids enhanced faster than that of water because of the superior heat transfer performance. But in the process of solar radiation rapid decline, the heat loss can not be ignored. The heat loss of nanofluids is more than that of water. Hence, the outlet temperature of nanofluids is more and more close to the outlet temperature of water.

Fig. 8 shows the effect of mass fraction of nanofluids on the efficiency of solar collector. As shown in Fig. 8 the efficiency of flat-plate solar collector with Cu nanofluid is higher than that of water. The maximum efficiency ($t_i = t_a$) of flat-plate solar collector with 0.1 wt% Cu–H_2O nanofluid is increased up to 23.83% compared with tap water. But with the mass fraction increasing, the efficiency declined instead. For example, the maximum efficiency at 0.2 wt% is decreased up to 5.97% compared with 0.1 wt% Cu–H_2O nanofluid. There are two possible explanations to this result. On the one hand, according to previous works [27], nanoparticles in base fluid at higher concentration tend to be agglomerated and the stability of homogenous solutions will be reduced. On the other hand, the viscosity of nanofluids is enhanced with the mass fraction increasing. It lead to the boundary layer thickness increasing. Hence, the heat transfer rate reduces. The experimental data are fitted with linear equations to provide the characteristic parameters of the flat-plate solar collector in order to compare the effect of different mass fraction. The specific fitting parameters are shown in Table 1.

3.2.2. The effect of nanoparticle size

As shown in the previous section, the nanoparticle size is a very important factor on the thermal conductivity. Therefore, the effect of nanoparticle size on the efficiency of solar collector is also investigated. The two kinds of nanofluids are prepared with 25 nm and 50 nm at 0.1 wt% of Cu nanoparticle. The efficiency of the flat-plate solar collector for the nanofluids with 25 nm and 50 nm Cu nanoparticle versus the reduced temperature parameters, $(t_i–t_a)/G$, is shown in Fig. 9. The maximum instantaneous efficiency for 25 nm and 50 nm Cu nanoparticle are 0.821 and 0.780, respectively. The performance of solar collector with small nanoparticle is superior to that of large nanoparticle. This phenomenon is in accordance with the literature [28]. The nanoparticle size is smaller the thermal conductivity of nanofluids is higher. The higher thermal conductivity of working fluids lead to the faster heat transfer, and enhanced the efficiency of flat-plate solar collectors. $F_R(\tau\alpha)$ and F_RU_L values of solar collector for the two kinds of nanoparticle size nanofluids are presented in Table 2.

Table 1
Fitting parameters of collection efficiency curves for Cu–H_2O and water.

Working fluid	$F_R(\tau\alpha)$	F_RU_L	R^2
Cu–H_2O(25 nm, 0.1 wt%)	0.821	78.021	0.986
Cu–H_2O(25 nm, 0.2 wt%)	0.772	72.506	0.979
H_2O	0.663	81.831	0.988

3.3. Temperature and heat gain of water in the tank

The temperature curves of water in the two tanks are shown in Fig. 10. As can be seen from the data, the water temperature in system the nanofluids as working fluid increases more quickly than that of system water as working fluid. Before 300 min (about 14:00), the water temperature rises faster. With the solar radiation decline, the water temperature increased more and more slowly. In the end, it reaches the maximum value. The highest temperature of water in Cu–H_2O nanofluid (Cu:25 nm, 0.1 wt%) system is increased up to 12.24% compared with water system. Fig. 11 shows the heat gain of water in the tank. The maximum heat gain of water in Cu–H_2O nanofluid (Cu:25 nm, 0.1 wt%) system is increased up to 24.52% compared with water system.

3.4. The frictional resistance coefficient

The viscosity of base fluid will increase dues to the nanoparticles suspend into water. Hence, the frictional resistance coefficients of

Table 2
Fitting parameters of collection efficiency curves for Cu–H_2O (Cu:25 nm, 50 nm).

Working fluid	$F_R(\tau\alpha)$	F_RU_L	R^2
Cu–H_2O(25 nm, 0.1 wt%)	0.821	78.021	0.986
Cu–H_2O(50 nm, 0.1 wt%)	0.780	76.325	0.985

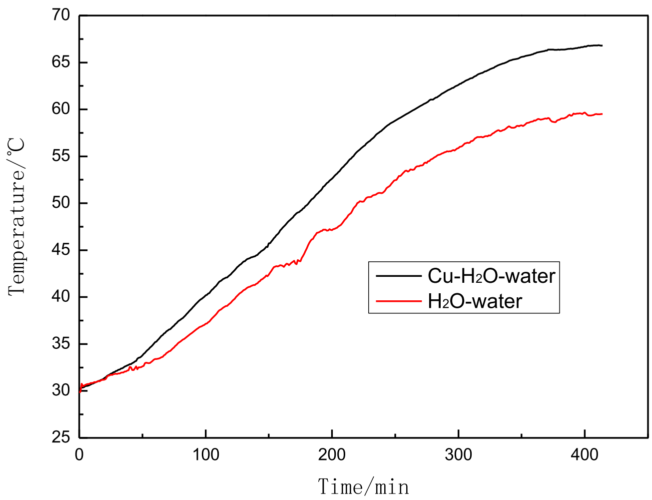


Fig. 10. Temperature curve of water in the tank of the flat-plate solar water heater (Cu:25 nm, 0.1 wt%).

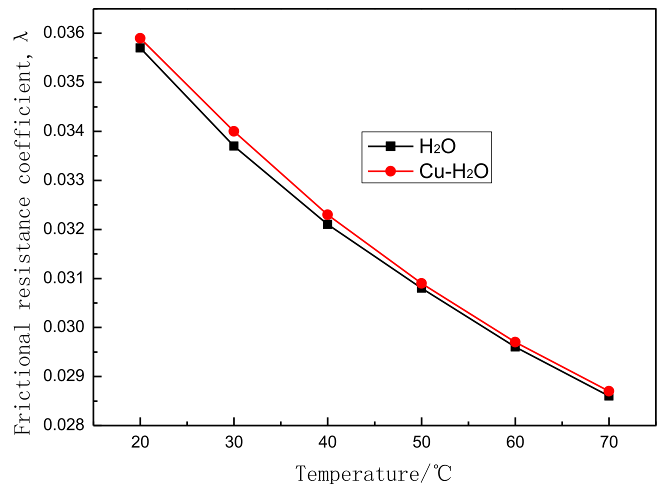


Fig. 12. The frictional resistance coefficient with different temperature (Cu:25 nm, 0.1 wt%).

nanofluids flowing in the tube are necessary calculated. In this experiment, the viscosity of nanofluids (Cu:25 nm, 0.1 wt%) was measured by viscometer (Brookfield-DV2T). The Reynolds number of fluid in the tube is $4000 < Re < 10^5$, which belongs to the turbulent. The frictional resistance coefficient can be calculated by Eq. (6) [29].

$$\lambda = 0.3164 \Big/ \mathrm{Re}^{0.25} \tag{6}$$

Fig. 12 shows the frictional resistance coefficient of water and Cu–H_2O nanofluids (Cu:25 nm, 0.1 wt%) with different temperature. It can be seen from Fig. 12, the increment rate of the frictional resistance coefficient is less than 1% in the whole working temperature area. It indicates that the nanofluids has a little effect on the pump power, it is suitable for solar thermal energy systems.

3.5. Analysis of uncertainty

The uncertainty of temperature data is decided by the precision of thermocouples (in our experiments, the precision of thermocouples is ±0.2 °C). In Eq. (4), the instantaneous collector efficiency is a function of mass flow rate, heat capacity, temperature, surface area of solar collector and solar radiation. The uncertainty of instantaneous collector efficiency can express with the formula recommended by Moffat [30]. The precision of TBQ-2 solar meter is ±2%.

$$\frac{\delta\eta_i}{\eta_i} = \left[\left(\frac{\delta m}{m}\right)^2 + \left(\frac{\delta C_p}{C_p}\right)^2 + \left(\frac{\delta(t_o - t_i)}{t_o - t_i}\right)^2 + \left(\frac{\delta A_c}{A_c}\right)^2 + \left(\frac{\delta G}{G}\right)^2\right]^{0.5} \tag{7}$$

$\delta m/m \leq 1.5\%$, $\delta C_p/C_p \leq 0.1\%$, $\delta(t_o - t_i)/t_o - t_i \leq \left[(\delta t_o/t_o)^2 + (\delta t_i/t_i)^2\right]^{0.5}$ $= \left[(0.2/34)^2 + (0.2/30)^2\right]^{0.5} = 0.89\%$, $\delta A_c/A_c \leq 0.12\%$, $\delta G/G \leq 2\%$, and $\delta\eta_i/\eta_i \leq 2.66\%$.

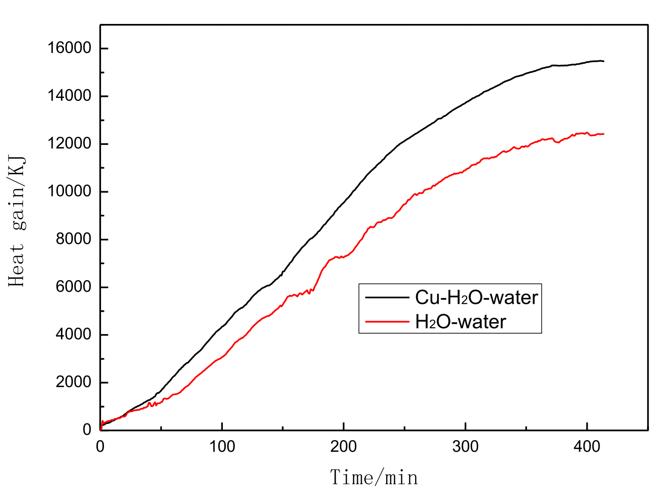


Fig. 11. Heat gain curve of water in the tank of the flat-plate solar water heater (Cu:25 nm, 0.1 wt%).

4. Conclusions

Adding nanoparticle to pure water can increase the thermal conductivity of water. The heat transfer performance is changed. The efficiency of Cu–H_2O nanofluids with different mass fraction as the working fluid in the flat-plate solar collectors were investigated. The experimental results show that their collecting efficiencys are all superior to that of water. The efficiency of Cu–H_2O nanofluids (Cu:25 nm, 0.1 wt%) is increase up to 23.83%. when the mass fraction gets to 0.2 wt%, the efficiency of Cu–H_2O nanofluids is less than that of Cu–H_2O nanofluids (0.1 wt%). It illustrates that the nanoparticle concentration can not be too much. Nanoparticle size also has a major effect on the efficiency of flat-plate solar collectors with nanofluids. In allusion to the temperature and heat gain of water in the water tank, the highest temperature and highest heat gain of water in the nanofluid (25 nm, 0.1 wt%) tank can increased up to 12.24% and 24.52% compared with that of water tank, respectively. On the other hand, the frictional resistance coefficient of nanofluids has a slight increase compared to water. In the compatibility aspect, nanofluids has no corrosion on stainless steel and silicone rubber but has a little corrosion on brass [31]. The corrosion problem can be solved by adding some corrosion inhibitor. In conclusion, the solar energy absorbing experiments show that Cu–H_2O nanofluids have good absorption ability for solar energy, and can effectively enhance the efficiency of flat-plate solar collectors. Thus, Cu–H_2O nanofluids can be hopeful to apply in solar thermal energy system.

Acknowledgements

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