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Solar Water Heater of Absorption Type using Natural Black Rock

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Abstract. This work studies the novel solar water heater using natural black rocks as the absorption material. The objective of this study is to compare the thermal performance of solar water heater between using black rocks and black copper pipes. Both options were tested at the same parameters such as 0.8 m^2 collector area, angle tilted 19º and 30 litters of water tank volume. The experimental results showed that the maximum mean temperatures of solar water heater of absorption type using natural black rock system and black copper pipes system were 54.3 ºC and 50.7 ºC, respectively. In addition, the efficiencies of the water heater of absorption type using natural black rock system and black copper pipes system were 44.6% and 33.5%, respectively. Therefore, the water heater of absorption type using natural black rock system is another option used in the household sector to reduce the energy consumption of the country.

1. Introduction

Nowadays, the fossil fuels are the major resources of energy to drive in many sections all around the world, especially in industrialized and developing countries. As the population continues to grow, the limited amount of fossil fuels begins to diminish. To solve this situation, one of the potential solutions is to enhance by using the renewable energy resources. Solar energy has been known as a potential renewable energy. According to use directly and indirectly from the sun, solar energy applications will increase significantly such as photovoltaics, solar drying process [1], solar absorption refrigeration [2], and solar desalination [3,9], as well as solar water heater. To get abundant, clean, and free energy from sun, solar water heater is the simple and economic way to turn solar radiation into thermal energy. In the research, the present of a solar water heater in dwelling is significantly higher in rural areas than the cities because of utility area and it can reduce the annual energy bill by ten percent for the average homeowner [4]. Because the desired hot water heater temperature is usually under 60 °C, there are many advantages of the hot water heater system such as easy to install, having a low payback period, and reducing the electricity consumption, as well as emitting negligible greenhouse gases [5]. In past few decades, the flat plate collector normally had been used to rise the water temperature and the maximum was around 50°C [6,7]. In order to improve the thermal performance of solar water heater system, the tubular collectors had been presented to enhance solar energy storage, space area saving, and decrease the fabrication cost. The system increased the water temperature up to 62°C [8]. Additionally, the concentric tube was also conducted to reduce the heating space and appropriate for typical household water usage [5,9]. However, all these absorption materials still have been made by metal or inorganic product. To be environmentally friendly, the black colored sand collector was investigated in the passive solar water heater to be the simple and low-cost compact solar water heater [11]. In the reseach, the results showed that the collector absorbed as gray material and the temperature could be reached about 90 °C. However, the solar water heater is not only limited application for the human living standard, it also can be enhanced in the aquaculture field. To illustrate, the warm water fish has been affected by the temperature in winter months. The fish weight loss occurs due to the metabolism of fish and it is directly correlated to water temperature [12]. Additionally, if the solar water heater is applied in the winter season, the fish farming has been to increase profitability and sustainability. Moreover, the economic and environmental life cycle assessments of solar water heaters had been applied to aquaculture to show the optimal operating of solar water heater for aquaculture [13]. Consequently, it will be a good choice of solar water heater, if the collector includes having a large thermal storage capacity per unit volume, a suitable operating temperature range, long life, simple, inexpensive, and natural material, as well as hygiene. The current study, the natural black rocks as the solar collector has been proposed for the solar water heater. In the experiment, the thermal performance of the system has been investigated by comparing between the natural rocks and tubular copper collector. Furthermore, other parameters such as absorptivity, emissivity, and heat capacity of collector influenced the system were also analysed.

2. Experimental setup and procedure

The experiment was carried out to investigate the thermal performance of the solar water heater. It was conducted by testing both the tubular copper absorber (Type I) and natural rocks absorber (Type II) with a specific solar collector set. Type I was made of copper tube with 0.64 cm of outside diameter and 100 cm of length. The tube was sprayed solar selective coating and closely arranged one by one. Type II was made of natural black rocks with 0.7 cm of average diameter and the amounts of rock were 6496 pieces. Similarly, system was designed in a rectangle shape of dimension 76x100 cm and 18 cm thickness and there are 3 parts of the system which are the covers, absorber, and storage tank as shown the schematic diagram in figure 1. The cover components, the double transparent glasses of thickness 5 mm each with the 3 cm airy distance between them had been used for keeping maximum amount of incident radiation. Absorber was installed on keeper plate that was attached to the down glass. The steel box was used to house all the parts of the collector. Additionally, the collector had been submerged in the storage tank. The water was allowed to flow through collector's space between the absorber and bottom surface by natural convection mechanism. In order to maintain the heat gain, the outer storage tank had been well insulated with 3 cm thickness of glass wool. The setting systems were tilted 19^{o} (local latitude). The experiment was operated from 8.00 am to 5.00 pm. According to the temperature data, the locations were set using thermocouple type K and connected to the data logger as shown in the figure 1. In addition, the extra thermocouples were installed to measure the temperature distribution in system and ambient temperature.

Nomenclature

Q_o = optical losses (W)
Q_l = heat loss (W)
Q_{st} = heat absorber storage (W)
Q_u = useful heat (W)
$Q_{collector}$ = heat collector storage (W)
t_a = ambient temperature (K)
$t_{c1,1}$ = upper cover1 temperature (K)
$t_{c1,2}$ = lower cover1 temperature (K)
$t_{2,1}$ = upper cover2 temperature (K)
$t_{2,2}$ = lower cover2 temperature (K)
t_{ab} = absorber temperature (K)
t_w = wall temperature (K)
$h_{conv,c1-a}$ = convection heat transfer coefficient between cover1 and ambient (W/(m^2 K))
U_T= total heat loss coefficient (W/(m^2 K))
Nu= dimensionless Nusselt number
Gr= dimensionless Grashof number
Pr= dimensionless Prandtl number
Ra=dimensionless Rayleigh number
v = kinematic viscosity (m^2/s)
a = thermal diffusivity (m^2/s)
g= gravitational acceleration
I_r = solar irradiation (W/m^2)
A= collector area (m^2)
c_p= water specific heat (kJ/(kg K))
s =Stefan–Boltzmann constant (W/(m^2 K^4))
e_I = emissivity of absorber type I
e_{II} = emissivity of absorber type II

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$h_{conv,c1-c2}$ = convection heat transfer coefficient between cover1 and cover 2 (W/(m^2 K))
$h_{conv,c2-ab}$ = convection heat transfer coefficient between cover2 and absorber (W/(m^2 K))
$h_{conv,ab-w}$ = convection heat transfer coefficient between absorber and wall (W/(m^2 K))
$h_{r,c1-a}$ = radiation heat transfer coefficient between covers 1 and ambient (W/(m^2 K))
$h_{r,c1-c2}$ = radiation heat transfer coefficient between cover1 and cover 2 (W/(m^2 K))
$h_{r,c2-ab}$ = radiation heat transfer coefficient between cover2 and absorber (W/(m^2 K))
$h_{r,ab-w}$ = radiation heat transfer coefficient between absorber and absorber (W/(m^2 K))

h = efficiency
b = tilt angle of water heating system
b =volumetric coefficient
L = characteristic length (m)
K_e = the extinction coefficient
l_g = the glass thickness (m)

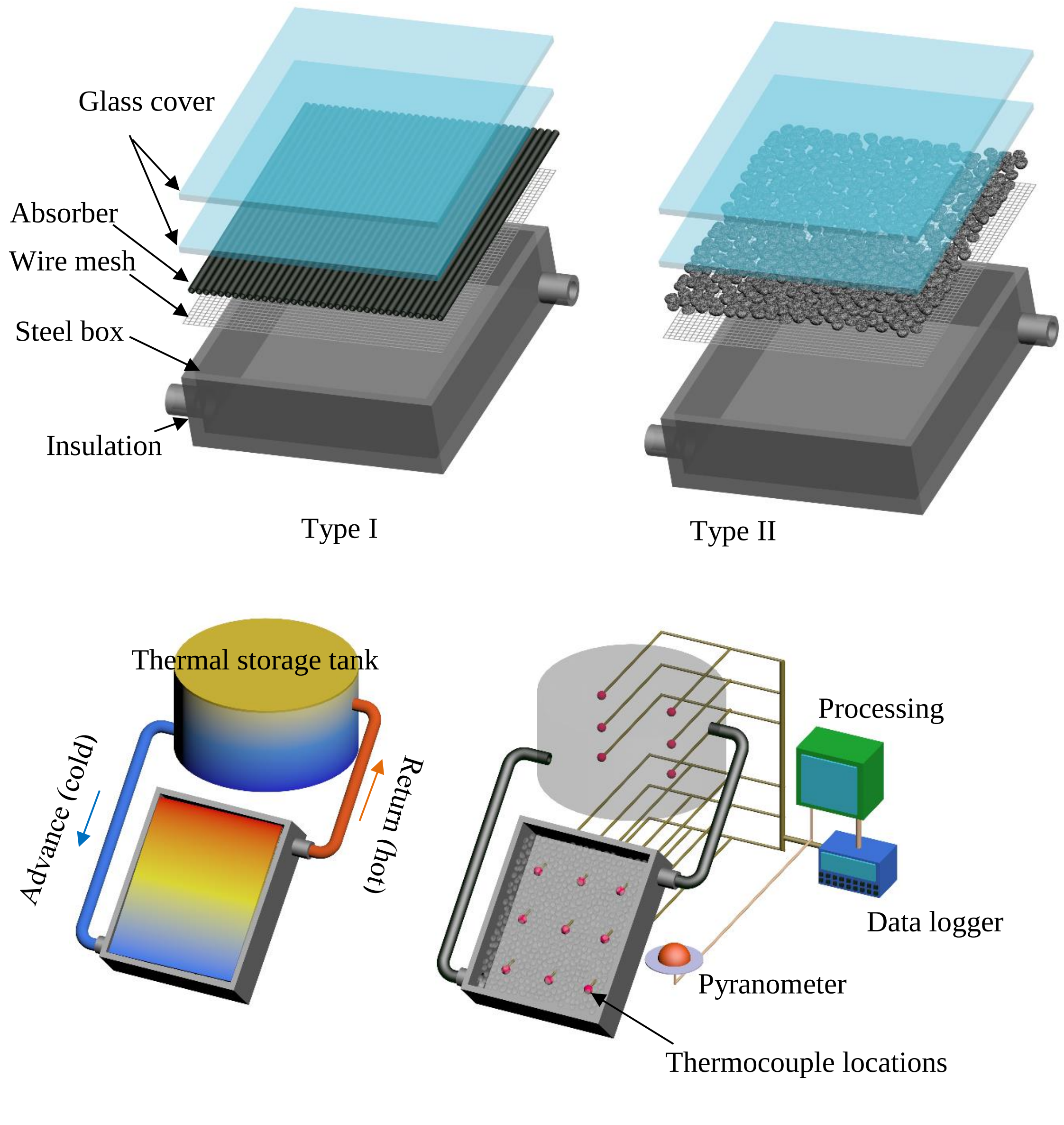

Figure 1 Schematic of solar water heater

3. Theoretical model

According to heat transfer phenomena of solar water heater, as shown on figure 2, when solar radiation incident passes through the transparent cover, the solar radiation has been converted in to heat at the absorbing surface which is transferred to a heat transfer fluid. Normally, the black colored collector is used to increase the solar radiation absorption. To achieve the maximum heat gain, the collector material has been investigated to increase the thermal performance of solar water heater such as black rock and copper tube collector.

The thermal network of the system has been shown in the figure 2. To illustrate, it begins with the solar radiation in surrounding at ambient temperature (t_a) on the upper transparent glass cover at $cover_1$ temperature ($t_{c1,1}$) and the conduction heat transfer at the upper cover increases temperature ($t_{c1,2}$) at the lower surface. When the solar radiation goes through the air gab of double glasses, it raises the $cover_2$ temperature ($t_{c2,1}$). The same conduction as the upper glass, there is the lower surface temperature ($t_{c2,2}$). At the absorber, the collector absorbs the solar radiation at absorber temperature (t_{ab}) and converts into heat transferring to the water. Last step, the heat gain of water losses through the wall surface at wall temperature (t_w). Consequently, the thermal energy from the top to the bottom of the system can be expressed in equivalent thermal network for solar collector as in figure 2.

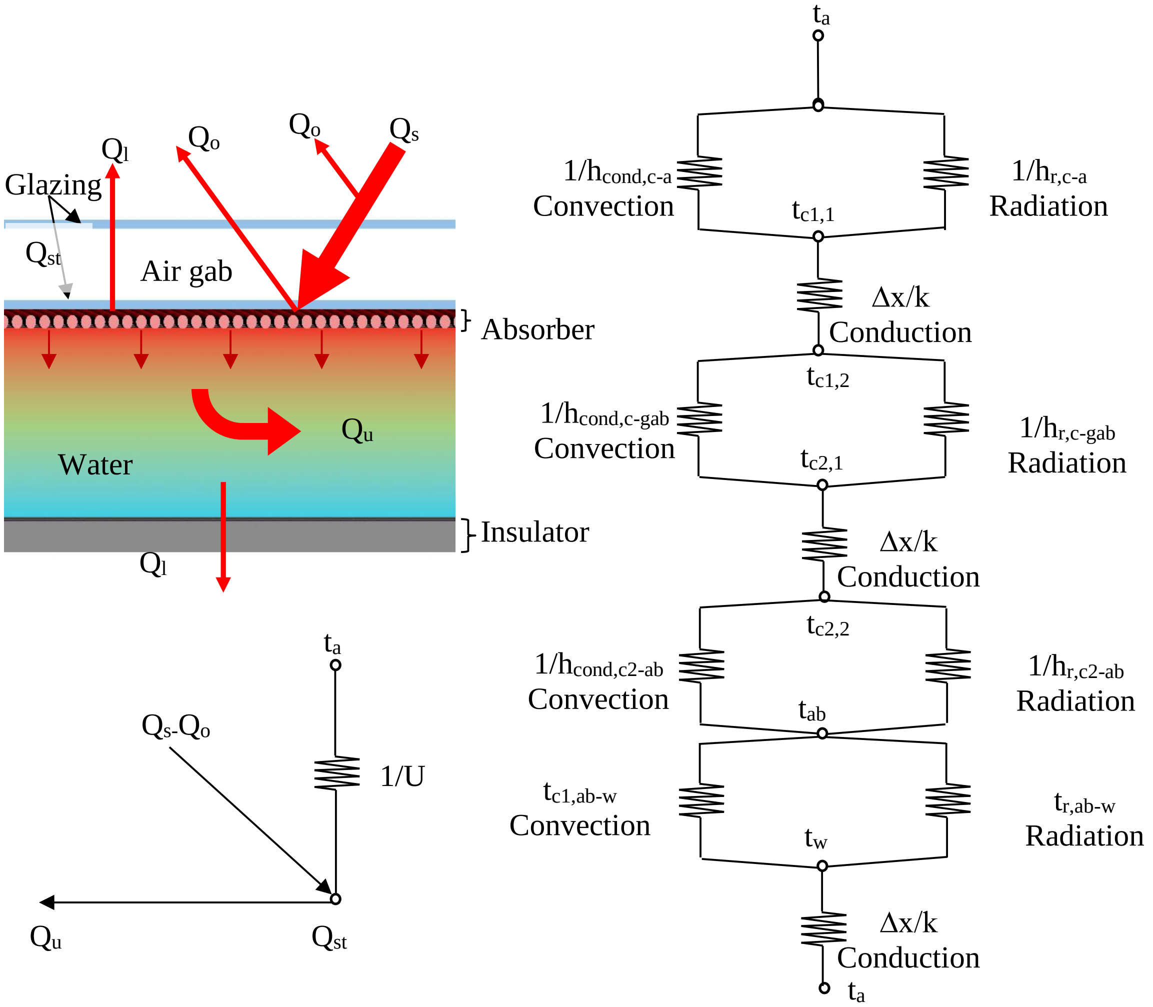

Figure 2 Heat transfer scheme and thermal network of the system

Energy balance of absorber

When the absorber receives the solar radiation, the total energy (Q_s) of the system can be presented in the energy reflection (Q_o) from the cover, energy loss (Q_l) from the system, energy storage (Q_{st}) in the absorber, and energy useful (Q_u) of warm water. The energy balance of the system can be expressed as shown.

$$Q_s = Q_o + Q_l + Q_{st} + Q_u \tag{1}$$

The collector transmittance (τ) equation is defined as the following [14]:

$$\tau = \frac{I_{transmitted}}{I_{incident}} = \exp\left(-\frac{K_e l_g}{\cos\theta_2}\right) \tag{2}$$

where θ_1 is the incidence index and θ_2 is the refraction angle after transmiting from the glass cover 1. The linked together them as follows:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{3}$$

where n is the index of refraction.

$$Q_u = Q_s - Q_s\tau \tag{4}$$

In order to obtain the efficiency of system (η), one can use the following equation as

$$\eta = \frac{\sum Q_{collector}}{A\sum I_r} \tag{5}$$

where I_r is the daily incoming radiation recorded by pyranometer (the both beam and diffuse intensity).

Furthermore, $\sum Q_{collector}$ is the summation of daily absorbed energy by the water into the storage tank and heat gain of absorber from solar radiation is calculated as the following.

$$\sum Q_{collector} = \sum Q_u + \sum Q_{st} \tag{6}$$

The heat gain ($Q_{collector}$) also can be calculated from energy useful (Q_u) of warm water and energy storage (Q_{st}) using $\sum Q = mc_p\Delta t$ where Δt is the difference of the inside collector at mean temperatures, from the beginning up to the end of the test. In addition, mean temperature is determined at 15 points by sum of terms that calculated from ratio of temperature and volume at a single point.

Balance equations of constant-flow process are used. The heat loss transfer rate of the collector can be expressed as:

$$q_T = U_T\left(t_{ab} - t_a\right) \tag{7}$$

The rate of relative heat transfer between i toward j is given as:

$$q_{i\rightarrow j} = h_{c,ij}(t_j - t_i) \tag{8}$$

The radiative heat transfer coefficient between i toward j is given as:

$$h_{r,i\rightarrow j} = \frac{\sigma\left(t_j^2 + t_i^2\right)\left(t_j + t_i\right)}{\frac{1}{\varepsilon_i} + \frac{1}{\varepsilon_j} - 1} \tag{9}$$

The conductive heat transfer coefficient between i toward j is given as:

$$h_{cond,i\rightarrow j} = \frac{\Delta x_{ij}}{k} \tag{10}$$

The convective heat transfer coefficient (air gab) between i toward j is given as:

$$h_{conv,ij} = \frac{Nuk}{L_{ij}} \tag{11}$$

Furthermore, when Nusselt number is a function of Grashof and Prandtl number, the heat transfer coefficient in natural convection shows as the following.

$$Nu = f\left(Gr, \mathrm{Pr}\right) \tag{12}$$

Where the Grashof number (*Gr*) is the dimensionless as the following equation.

$$Gr = \frac{\beta g L^3 \Delta t}{v^2} \tag{13}$$

$$\mathrm{Pr} = \frac{v}{\alpha} \tag{14}$$

The Rayleigh number is a function of Grashof number and Prandtl number as shown.

$$Ra = Gr.\mathrm{Pr} \tag{15}$$

In convection model, heat in the system transfers by natural convection. Therefore, Nu is the dimensionless, Nusselt number, $k(W/m \cdot K)$ is the thermal conductivity of air between double glasses and L is the distance between two covers. Nusselt number obtains as [14]:

$$Nu = 1 + 1.44\left[1 - \frac{1708(\sin 1.8\beta)^{1.6}}{Ra\cos\beta}\right]\left[1 - \frac{1708}{Ra\cos\beta}\right]^{+} - \left[\left(\frac{Ra\cos\beta}{5830}\right)^{1/3} - 1\right]^{+} \tag{16}$$

According to the thermal network of the system and the equations from (1) to (16) , the simulation model has been established for analyze of heat transfer at individual part of collector and evaluate the performance of absorbers based on the system efficiency by input the experimental data.

4. Results and discussion

In this section, the results of experimental and numerical data have been presented for solar water heater of type I and type II. To illustrate, the thermal performance of both systems has been compared indicating in water temperature, system efficiency and utility heat in the system as the following.

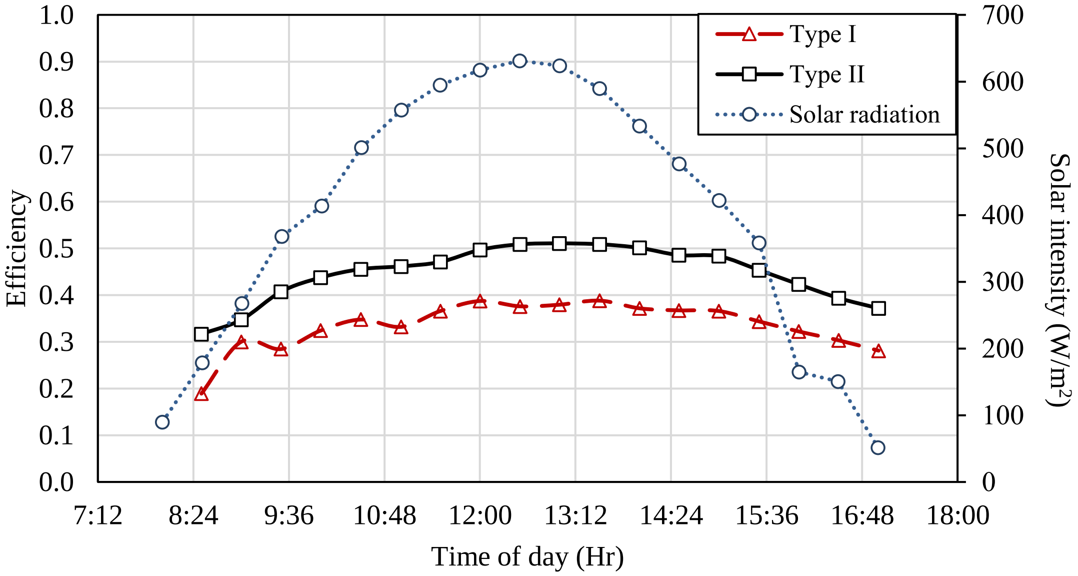

Figure 3 The hourly efficiency for natural rock and copper pipe absorber

The solar radiation is one of parameters that indicates the performance of the system. As shown in Figure 3, the system efficiency increases in the morning and reaches the maximum at the highest daily radiation. After that, when the solar radiation continuously decreases, the efficiency also slow down decreases depended on the solar radiation. In addition, as we expected, the experimental results show that system efficiency of type II absorber exceeds type I absorber, mean system efficiency of type II absorber is higher than mean system efficiency of type I about 10 % because of the significantly higher heat capacity of the natural rock indicating the higher thermal performance of the system.

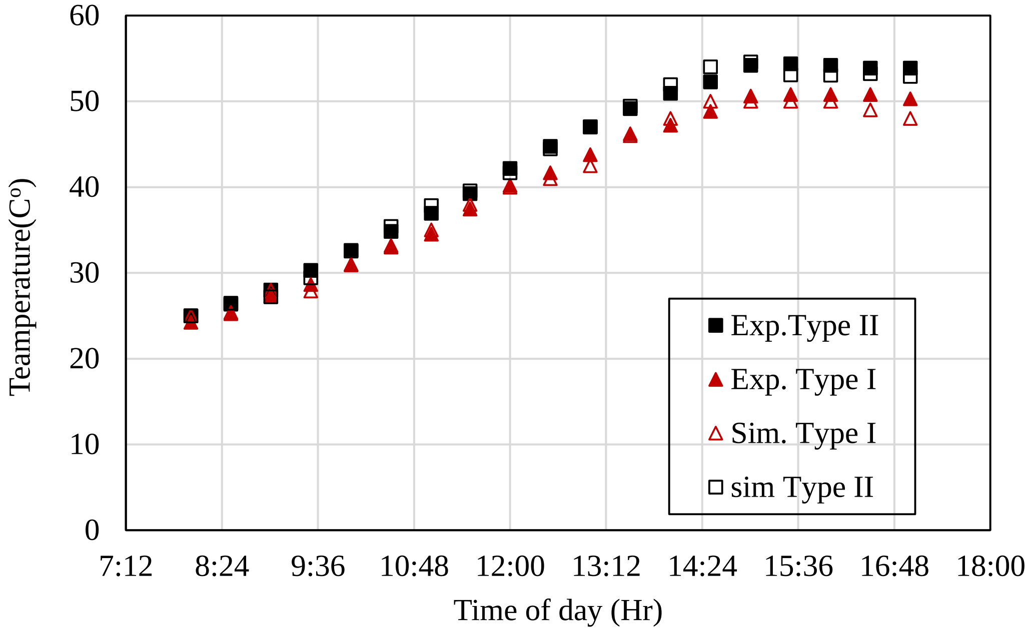

Figure 4 Temperature variation of mean water temperature along the local time

To support this reason, we plotted variation of temperature along the local time. As shown in Figure 4, the experimental results show that the mean water temperature is continuously increased in the morning and it significantly increases in the afternoon because of influenced solar radiation and ambient temperature for both absorbers. The water temperature of natural rock collector is higher than copper tube collector because the heat capacity rate of rock is much higher than copper and the heat capacity rate can be effective in the afternoon, as we can see the water temperature difference. Therefore, the more absorber has heat capacity rate the higher system gets heat gain. Moreover, comparison between mean temperatures of water obtained from the simulation and experimental data, experimental data is compared with the simulation results. There is well agreement; the standard deviation of error temperatures was 0.74. Especially, at the maximum temperature value, the simulation accurately provides performance prediction. Consequently, the simulation can be employed as implementation for further consideration of system efficiency in this study.

Figure 5 shows the simulation results, the efficiency system based on absorber temperature. As you have seen, efficiency difference between Type I and type II is about 2%. It is effect of absorber emissivity on thermal loss ($e_I = 0.3, e_{II} = 0.85$) resulting the available heat in type I more than type II. However, the higher we use absorber emissivity, the more absorption ability is obtained. In this study, the efficiency of type II exceeds type I by average 11.14% and it is much more than emissivity effect to thermal loss. Thus, the heat useful for the type II is more than type I. Furthermore, the total resistance of the type II is much lower than type I.

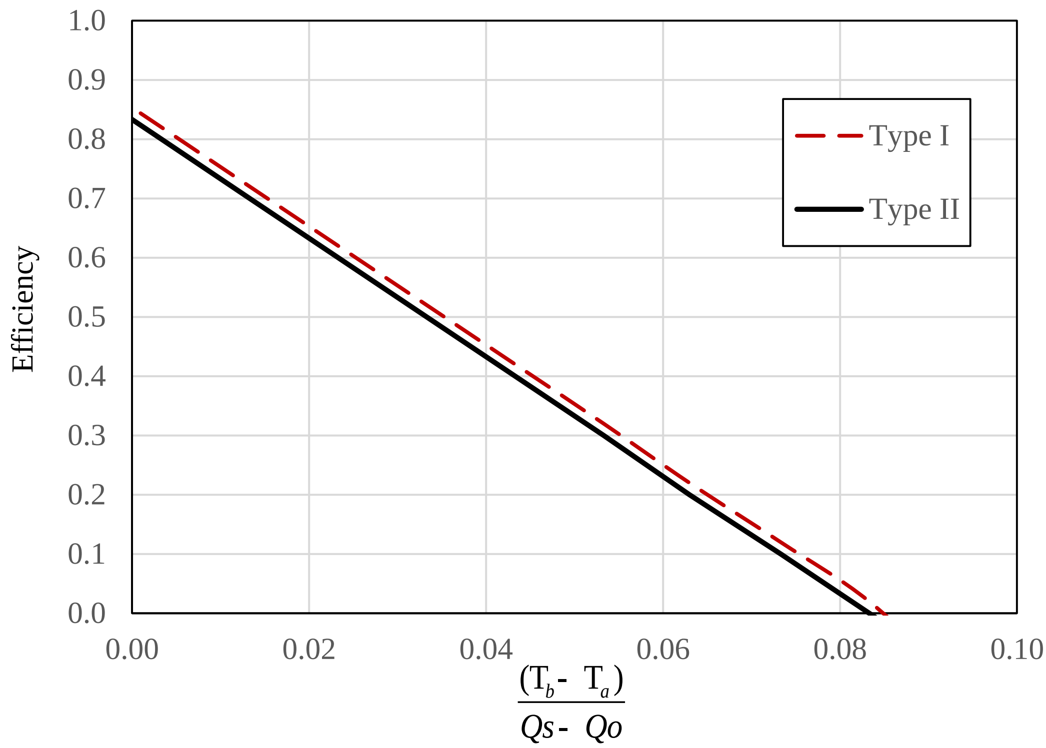

Figure 5 Efficiency curve of type I and type II absorber based on absorber temperature

5. Conclusions

The novel solar water heater using natural black rock collector is proposed in this paper. The idea of the proposed system is based on utilizing the high heat capacity of natural rock to implement the solar water heater. Such natural material leads to long life, simple, inexpensive, as well as hygiene. The thermal performance of new proposed model was experimentally investigated and analyzed experimentally by comparing with the conventional solar water heater, copper tube collector. The obtained results illustrated that the thermal performance of natural black rock collector exceed the copper tube collector by average 11.1%. Additionally, the system increased the water temperature up to 54°C, with a performance instantaneous efficiency that reached to average 44.6% which was very satisfactory. Ultimately, the proposed solar water heater system introduces an efficient practical solution utilizing solar energy for the human living standard as well as the aquaculture to reduce the energy consumption of the country.

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