Study of Conversion Efficiency of Tube-type Solar Thermal Collectors

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Abstract

There has been more and more attention to research on design and usage of solar thermal collectors so as to satisfy economic development. Nowadays, the extent of applicability of a tube-type solar thermal collector is an intriguing problem for new engineering design. In this paper, analytical and experimental studies of a multi-tube type solar thermal collector are presented as a tool. Thermodynamic analysis of the thermal collector is derived to describe and evaluate its performance in aspects of energy conversion efficiency. A small-scale rig of a multi-tube type solar thermal collector is made from materials available in market. It is experimentally tested during 9-hr of daytime in real use. It is found that experimental results give a good agreement with the mathematical model of conversion efficiency, which relates to material parameters of the solar thermal collector.

Keywords: solar thermal collector, conversion efficiency, tube-type collector

1. Introduction

Conceptually, a solar thermal collector is intended to absorb radiation from sunlight in order to provide usable heat. This class of solar heating system is widely used in many countries especially with high incidents of sunny climates like Thailand. There are various types of solar thermal collectors. Up to now, flat plate and box-type collectors have been used in household and industrial applications. In conventional designs, a black metal sheet with built in pipes is placed to face toward the sun and it is covered with a transparent plate such as glass, which allows solar energy to pass through, but reduces heat loss from the black metal sheet [1-2]. A heat-transport fluid such as water circulating through pipes is heated up and passed to a storage tank located above a solar thermal collector. High efficiency of this type of collector can be obtained if the solar metal absorber directly faces toward the sun with right altitude angle and azimuth angle all the time [3]. Some improved solar thermal collectors are equipped with automatic sun tracking system [4]. The approaches have been not very attractive to practitioners owing to the high costs of instrumentation and maintenance.

To avoid those limitations, solar thermal collectors are currently built with multiple transparent tubes, which heat up solar absorbers that are made of black-coated metal pipes inside. An advantage of this design over flat-plate type collectors is that the round profiles of the tubes are always perpendicular to the sun's rays and therefore the solar radiation absorbed is approximately constant over the course of a day. This allows them to reach considerably higher temperature [5]. In turn, the tube-type collectors have drawn more and more researchers' attention to obtain the most effective use [6]. In [7], efficiency characteristics of tube-type solar thermal collectors are proposed to investigate performance by using supercritical CO_2 as a working fluid in test studies. Experimental results report an interesting fact that there are variations of the collector efficiency against the ratio of temperature difference between inlet fluid temperature and ambient air temperature, to the solar radiation, under different seasons during the year. Unfortunately, analytical explanations have not explicitly been given in their works or even in other open literature [8]. Understanding this relation might be a significant contribution to the design of the solar thermal collectors. In this study, such a characteristic model of the collector efficiency is determined with the principle of energy balance in section 3. The details of the experimental setup of a multi-tube type solar thermal collector are discussed in section 2. Section 4 yields the experimental verification of the proposed characteristic model. The conclusion is given in section 5.

2. Experimental setup

The schematic diagram of a multi-tube type solar thermal collector is tested in closed circuit under outdoor conditions as shown in Fig. 1.

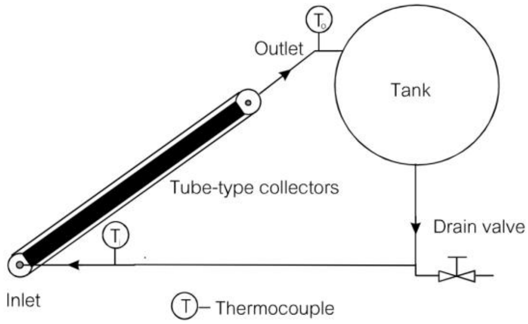

Fig. 1 Schematic diagram of tube-type solar thermal collector.

The upper 50-litre insulated storage tank is used for hot water storage. The water is circulated by a thermal siphon effect through the solar thermal collector by heating up the cool water heading into the storage tank. With a conventional inclined angle of ~10°, the solar thermal collector consists of ten double tubular pipes connected in sequence; the outer tubes are made of transparent UV-resistance acrylic with 20-mm outside diameter and 2-mm thickness while the inner tube is made of black rubber pipe with 15-mm outside diameter and 3-mm thickness. They are selected for low cost and easy assembly. Fig. 2 shows the testing panel of the 1-m long solar thermal collectors. The water temperature at inlet and outlet as well as the ambient temperature and the water temperature in the storage tank are measured by type-K thermocouples. The incident solar radiation is measured with a pyranometer. All measurements from thermocouples and pyranometer are taken by a PC-based data acquisition system with 5-minute sampling time during experiments.

Fig. 2 Testing panel of solar thermal collector.

3. Analysis on conversion efficiency

From upstream to downstream of flow in the solar thermal collector, the useful heat collected along the pipe per unit time can be expressed by:

$$Q = \rho \dot{V} C_p \left(T_o - T_i\right) \quad (1)$$

where ρ is the density of the working fluid (kg/m^3), $\dot{V}$ is the volume flow rate (m^3/s), C_P is the constant pressure specific heat (J/(kgK)), T_o is the temperature at outlet (K), and T_i is the temperature at inlet (K).

The conversion efficiency expresses the fraction of incident heat that is collected by the working fluid to the incident solar radiation [7].

$$\eta = \frac{Q}{IA} \quad (2)$$

where I is the solar radiation on collector tilted surface (W/ m^2), and A is the tilted surface area of the collector (m^2).

It should be noticed from Eq. (2) that there is no explicit description on how the parameters of the solar thermal collector influence the conversion efficiency. By applying the principle of energy balance to the solar thermal collector, one portion of incident radiation from the outer transparent pipe that is transmitted to the black coated pipe, is absorbed to heat up the working fluid. Another portion is lost by the heat transfer back to ambient. The heat transfer in radial direction is considered for simplicity. It should be noted that the heat conduction in the circumferential direction can be neglected owing to a thin-walled tube. The working fluid is lumped in this analysis, e.g., the mean temperature of the working fluid. The convective heat transfer between the thin-wall tube and the working fluid is neglected since the flow rate of the working fluid is significantly low when it is caused by the thermal siphon effect. Fig. 3 illustrates the thermal circuit of the heat transfer in the tube-type solar thermal collector.

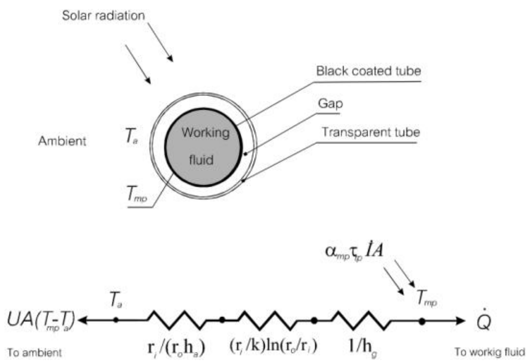

Fig. 3 Thermal circuit of tube-type solar thermal collector.

Hence, the useful heat collected along the pipe can be governed as well by:

$$Q = \alpha_{mp}\left(\tau_{tp} IA\right) - UA(T_{mp} - T_a) \quad (3)$$

where α_{mp} is the absorption factor of the inner black-coated pipe, τ_{tp} is the transmission factor of the outer transparent pipe, U is the overall heat transfer coefficient (W/(m^{2}K)), T_{mp} is the mean surface temperature of the inner black-coated pipe (K), and T_a is the ambient temperature (K). The overall heat transfer coefficient can be related to material properties as:

$$U = \frac{1}{r_i/r_o h_a + (r_i/k)\ln(r_o/r_i) + 1/h_g} \quad (4)$$

where h_a is the convection heat transfer coefficient of the outside air (W/m^2), k is the thermal conductivity of the transparent pipe (W/m), r_o and r_i are respectively, the outer and inner radiuses of the transparent pipe (m), and h_g is the convection heat transfer coefficient between gap (W/m^2).
Now, the conversion efficiency in Eq. (2) can be expressed in terms of parameters of the solar thermal collector as:

$$\eta = \alpha_{mp}\tau_{tp} - U\frac{(T_{mp} - T_a)}{I} \quad (5)$$

In this work, the derivation of Eq. (5) yields contributive enlightenment in design of the solar thermal collector. It can be seen that the optimal design parameters of the solar thermal collector can be obtained by selecting transparent pipe with high radiation transmission and black-coated pipe with high radiation absorption and heat conduction, while the gap should provide high thermal resistance. In this high-level technique, one may use an evacuated gap for insulation of conducted heat loss. Besides, cooling from ambient degrades the conversion efficiency. The high ambient temperature and radiation in daytime causes the tendency of a higher conversion efficiency.

For verification of the characteristic model in Eq. (5) through experimental results, it is not practical to measure directly the temperature of the black-coated pipe. The modification by a factor is proposed in this study to make it more convenient to present the conversion efficiency in terms of a more accessible variable of the working fluid. The factor, called collector efficiency factor F, is the ratio of the actual useful heat collected along pipe in Eq. (3) to the equivalent useful heat, where the heat loss is determined by the temperature difference between the mean temperature of the working fluid and the ambient temperature.

$$F = \frac{Q}{\alpha_{mp}\tau_{tp} IA - UA(T_{mf} - T_a)} \quad (6)$$

where T_{mf} is the mean temperature of the working fluid.

$$T_{mf} = \frac{T_o + T_i}{2} \quad (7)$$

It should be noted that the value of the collector efficiency factor is less than unity.

Applying the definition of the collector efficiency factor in Eq. (6), the conversion efficiency in Eq. (5) can be written as:

$$\eta = F\alpha_{mp}\tau_{tp} - FU\frac{(T_{mf} - T_a)}{I} \quad (8)$$

Now, it can be seen that the conversion efficiency is proportional to the ratio of the temperature difference between the mean temperature of the working fluid and the ambient temperature, to the solar radiation. Experimental results on solar collector testing are to verify the relation of the conversion efficiency in the following section.

4. Results and Discussion

The experiment is run so as to determine the conversion efficiency of the tube-type solar thermal collector. Including the ambient temperature and the incident solar radiation, the water temperatures at inlet and at outlet of the solar thermal collector and the water temperature in the storage tank are measured every 5 minutes, since the thermal response is quite slow in nature. All the measurements are from 8:30 a.m. to 5:30 p.m. Fig. 4(a)-4(e) illustrates the dotted lines of the water temperature at the inlet and at the outlet of the solar thermal collector and the water temperature in storage tank T_w, as well as the ambient temperature and the incident solar radiation.

The solid lines are determined by the least-squared-error method with polynomial interpolation for attaining the best possible estimation of trends. It is observed that all the temperatures, including the water temperature in the storage tank, increase while the incident solar radiation increases. This can be also interpreted that the thermal siphon circulates the hot water from the thermal collector filling up to the storage tank in a loop. When the solar radiation decreases at certain times, the water temperature at the outlet and the air temperature decrease accordingly, while the water temperature at the inlet and the water temperature in the storage tank remain steady, due to heat trapped in the storage tank by insulation. It should be noticed that the highest value of the water temperature is about 38 °C, which is feasible in various medium-temperature applications.

In the calculation of conversion efficiency, the density and the pressure specific heat of the water are 1000 kg/m^3 and 4.186 kJ/(kg.K), respectively. The useful heat collected along the black rubber pipe is to be determined in Eq. (1). However, it should be noted that it is not practical to measure a low flow rate of the water in the thermal collector for calculating the useful heat in Eq. (1). Intuitively, the useful heat collected along the black rubber pipe causes an increase of the internal energy and, in turn, the temperature of the water within the insulated tank increases. Therefore, the difference between the incoming enthalpy of the water and the outgoing enthalpy of the water in Eq. (1) is equal to the rate of change in the internal energy of the water contained within the insulated tank. For calculation of the useful heat, this yields:

$$Q = \rho \dot{V} C_p \left(T_o - T_i\right) = \rho V C_P \dot{T}_w \qquad (9)$$

where $\dot{T}_w$ is the rate of temperature change of the water in the insulated tank and V is the volume of the water contained in the insulated tank.

Now, the derivatives of the water temperature with respect to time can be simply determined by a numerical difference approximation from the plots of the water temperature within the insulated tank against time from Fig. 4(c). It is straightforward to determine the useful heat from Eq. (9) instead of Eq. (1). From Eq. (2), the instantaneous conversion efficiency is calculated. Fig. 4(f) shows the conversion efficiency of the solar thermal collector designed in section 2 against the corresponding ratio of the temperature difference between the mean temperature of the working fluid and the ambient temperature, to the solar radiation. The ratios are obtained from the variation of the sampled data such as the mean temperature of the working fluid T_{mf}, the incident solar radiation of the sunlight I, and the ambient temperature T_a ,during days of experiments. As the plots of the results, the characteristic values of the conversion efficiency, that is $\left(F\alpha_{mp}\tau_{tp}\right)$ and $\left(FU\right)$ in Eq. (8), are obtained to be $0.49\left(<1\right)$ as expected, and –14.01, respectively. Experimental results in Fig. 4(f) are fitted well, in agreement of the characteristic model. With the same procedure, the experiments on the following days are performed to obtain the linear characteristics of conversion efficiency of the tube-type solar thermal collectors. It is observed that the experimental results have a similar tendency of all measurements in Fig. 4 on the first day. Table 1 shows the compared results of best fits to a linear regression in all three successive days of experiments. It can be deduced from Fig. 4(f) that the maximum conversion efficiency takes place when the ratio of the temperature difference between the mean temperature of the working fluid and the ambient temperature, to the incident solar radiation approaches zero. Hence, a high value of the conversion efficiency can be obtained when the incident solar radiation is high (>1000 W/m^2), during working daytime for a given temperature difference between the mean temperature of the working fluid and the ambient temperature.

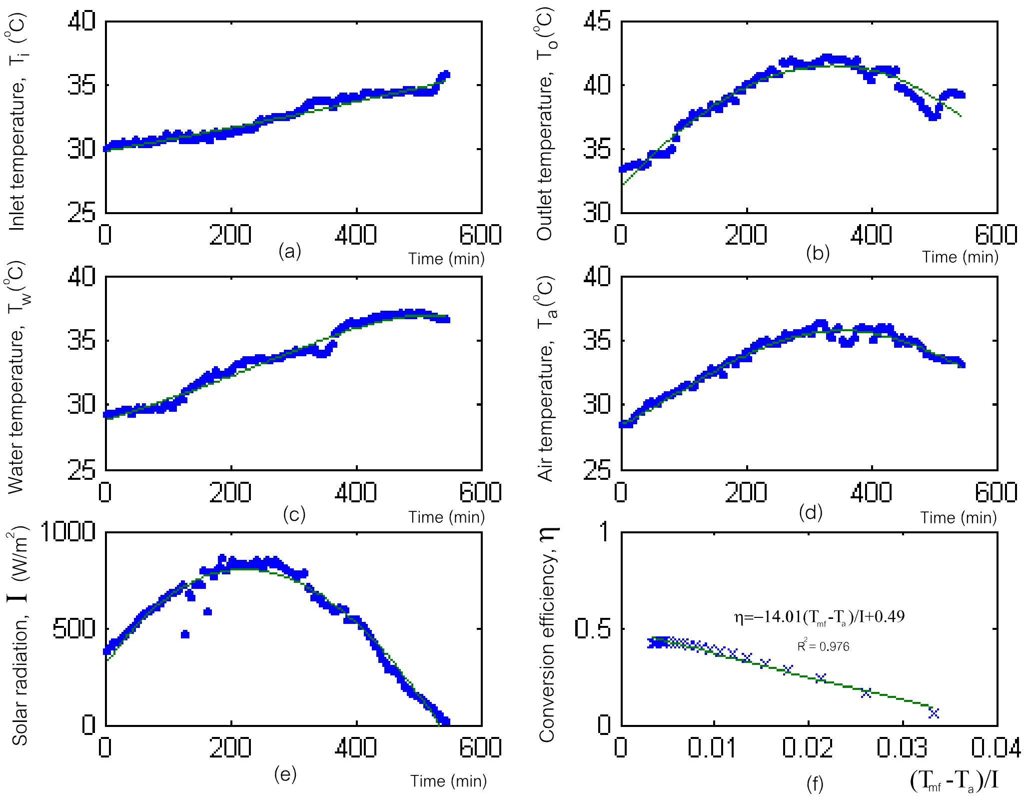

Fig. 4 Plots of temperatures, solar radiation and conversion efficiency.

Table 1. Results of linear regression in three-day experiments.

	Slope	**Intercept**
1st day	-14.01	0.49
2nd day	-15.05	0.54
3rd day	-14.34	0.62
Average value	-14.47	0.55

5. Conclusion

Basically, the main contribution of this work is to present the thermal analysis on conversion efficiency of the tube-type solar thermal collector for engineering design. Furthermore, the solar thermal performance of a real low-cost tube-type collector is evaluated experimentally. The model of the conversion efficiency yields good agreement with experimental results. The results indicate the conversion efficiency is proportional to the ratio of the temperature difference between the mean temperature of the working fluid and the ambient temperature, to the solar radiation. It can be confirmed that material parameters of the solar thermal collectors are coefficient factors of the conversion efficiency. Therefore, in the optimal design on those parameters of the solar thermal collector, a transparent pipe might be selected with high radiation transmission and a black-coated metal pipe can be chosen with high radiation absorption and heat conduction as well as a gap should provide high thermal resistance. It should be noted that other types of solar thermal collectors can be analyzed for parametric characteristics on conversion efficiency by generalizing the concepts of this proposed experimental study for those related works.

6. Acknowledge

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