FLAT PLATE SOLAR WATER HEATER WITH CLOSED-LOOP OSCILLATING HEAT PIPES

by

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The flat plate solar water heater, using the closed-loop oscillating heat pipes, was constructed and investigated. The flat plate collector consisted of 10 pipes of closed-loop oscillating heat pipes and the collector area was 1.5×1 m². Each closed-loop oscillating heat pipes was made of a copper capillary tube with a 1.5 mm inner diameter, a 2.8 mm outer diameter, and had 20 turns. The distilled water was used as the working fluid with a filling ratio of 50% the tube's total internal volume. The evaporator section of the closed-loop oscillating heat pipes was placed on the absorber plate of the collector, and its condenser section was wrapped around the copper tube, in which hot water flowed through. The solar water heater was tested under the solar simulator with halogen lamps generating the uniform artificial solar energy. The irradiation intensity and the water flow rate of the solar water heater were adjusted. It was found that the thermal performance of the solar water heater clearly improved with an increase in the irradiation intensity from 480-1086 W/m². However, the water flow rate in the range of 1.5-3.0 Lpm, had a thermal performance that was slightly different. The thermal efficiency of 0.67 was archived at the high irradiation intensity of 947-1086 W/m². Moreover, the mathematical model to predict the thermal efficiency of the flat plate solar water heater with the closed-loop oscillating heat pipes was obtained.

Key words*: closed-loop oscillating heat pipe, flat plate solar collector, thermal performance*

Introduction

A solar water heater is a well-known piece of technology that utilizes solar energy. The solar energy is absorbed in the form of the thermal energy and is simultaneously transported into hot water by a solar collector. The flat plate collector has less thermal efficiency relative to the evacuated glass tube collector because of its uncontrolled convection and radiation heat loss. However, because of the simplicities of its construction, installation, and inexpensive equipment cost, the thermal performance of the flat plate collector has been continuously developed such that the heat pipe became the effective device for heat transfer. In the majority of previous research, two main types of heat pipe, *i.e.* the two-phase closed thermosyphon [1-4] and the heat pipe with wick structure [5-9], were applied in the flat plate collector. In Thailand, the collector faces south and has an inclination angle of about 18° from a horizontal axis. Since the thermal performance of the thermosyphon was lower when its operational inclination an-

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gle from a horizontal axis was less than 50° [10], an application of the thermosyphon in the collector was improper. The influence of gravity was less in the heat pipe with wick structure, since the working fluid circulation mainly depended on the capillary force that occurred in a wick structure. However, there are several heat transfer limits that probably happened during the capillary-driven heat pipe operation [11], and it is not suitable for large quantity of heat transferring application, especially when the inner diameter of the heat pipe is small. In order to eliminate these problems, the development of the flat plate collector with an application of a closed-loop oscillating heat pipe (CLOHP) was created. A CLOHP, was invented by Akachi [12]. It had several advantages, *i.e.* high thermal performance and high thermal responsibility, simplicity of construction, and flexibility in operational orientation. A CLOHP was made of a small capillary tube without the wick structure. One capillary tube was bent to form the number of meandering turns at the evaporator and condenser parts of the CLOHP and was partially filled with a working fluid. The working fluid inside a CLOHP would arrange itself, alternating the forms of liquid slugs and vapor bubbles throughout the tube length. Its operational principle [12, 13] was the oscillation and circulation of the working fluid, mainly driven by the vapor pressure difference between the evaporator and condenser sections, and the sensible and latent heat transfer of the working fluid. However, the flat plate collector with the CLOHP was rarely investigated, and there was little research done for this topic.

Arab *et al.* [14] developed a thermosyphon solar water heater in which two pipes of CLOHP type were applied at the flat plate solar collector. A CLOHP was used as the auxiliary heat transport device to enhance the rate of heat gain of water in a tank. Because, not only was there the piping system of the natural circulation of hot water, but the capillary tubes of the CLOHP were also embedded in the collector, the design of the flat plate solar collector was complex. The flat plate solar collector in combination with only the CLOHP as the heat transfer device was studied by Abed *et al.* [15], who proposed an application of the CLOHP in the solar desalination system. The cupric CLOHP had a 2 mm inner diameter, a 0.4 m condenser length, a 1 m evaporator length with 24 turns, and it was partially filled with distilled water. The evaporator of the CLOHP was attached to the absorber plate with an area of 0.5×1 m^2. The condenser was attached to the basin floor pan. The absorbed heat was transferred to the saline water by the CLOHP. The efficiency of the solar desalination system improved, and an increase in the production rate of desalinated water was shown. The flat plate solar collector with the CLOHP that was illuminated by the solar simulator was studied by Nguyen *et al.* [16]. Twelve 300 W halogen lamps were used to simulate solar energy and were controlled by a voltage regulator. The CLOHP was made of the copper tube. It had a 2 mm inner diameter, a 0.155 m condenser length, and a 0.245 m evaporator length with eight turns. The evaporator was attached to the absorber plate, and was illuminated by the solar simulator. The condenser was inserted into the cooling jacket, which the cold water was flowing through. The results showed that the working-fluid's filling ratio, and the cooling-water's flow rate, influenced the collector's efficiency. The best performance occurred at working-fluid's filling ratio of 60% with low flow rate of 0.15 Lpm. Recently, the simulation and optimization of the flat plate solar collector with CLOHP was developed by Jalilian *et al.* [17] using neural networks and genetic algorithm. The CLOHP was made of a copper tube with a 2 mm inner diameter, a 4 mm outer diameter and 21 turns and partially filled with the distilled water. An investigation on the effect of optimization variables on the system efficiency indicated that the evaporator length of 1 m and the filling ratio of 57% of total internal tube volume received the maximum system efficiency. The thermal performance of the flat plate collector with four CLOHP improved by using a double vacuum glass cover plate was studied by Gao *et al.* [18]. Each CLOHP was made of a capillary tube with a 3 mm inner diameter, a 5 mm outer diameter and 8 turns. The length of the heating section was 1 m. Distilled water was used as the working fluid, with a liquid filling rate of 50%. The results showed that the heat loss coefficient of the solar collector was reduced by the double vacuum glass cover plate equal to 6.58 while the efficiency of the solar collector increased to 0.74. Furthermore, Jin *et al.* [19] used the transparent CLOHP filled with the solar absorptive nanofluids in a solar collector. The pipe wall of the CLOHP was made of high temperature resistant quartz glass, which can allow almost all the sunlight to pass through. The CLOHP had a 2 mm inner diameter and 6 turns. The results showed that the nanoparticle type, the nanoparticle concentration and the nanofluids filling ratio influenced on the performance of CLOHP. An optimal filling ratio of the nanofluid was 83%. The thermal resistance of the CLOHP reached the minimum when the CLOHP was filled with 3.0 wt.% multi-walled carbon nanotubes (MWCNT) nanofluid. The thermal efficiency of solar collector using the transparent CLOHP filled with the solar absorptive nanofluids increased to 0.92. However, Using distilled water as CLOHP working fluid is still interesting because distilled water has high latent heat of vaporization, high surface tension, non-toxic and cheap [13, 20].

The majority of the research on solar collectors with CLOHP, as previously mentioned, the collector plate consisted of a single CLOHP and the tube arrangement of the CLOHP in the collector plate was only one row. If the heat transfer capability of the CLOHP fails, the solar collector cannot work. The study of flat plate collector with multiple CLOHP is rare and the structural design of the system should be considered. Therefore, the flat plate solar water heater using the CLOHP was practically developed in this research. The new design of the flat plate collector with multiple CLOHP was revealed. The dependencies of variable irradiation intensity and water flow rate on the thermal efficiency of the system were also investigated.

Detail configuration of flat plate solar water heater

The assembly drawing of the flat plate solar water heater is shown in fig. 1. Because the collector area was defined as 1.5×1 m^2, its frame size was 1.7×1.1×0.1 m^3. At the back and lateral sides, the surface was entirely covered by an aluminum sheet in order to reduce the heat loss from the collector. At the bottom, the inside surface area was well insulated by a 25 mm thick layer of ceramic fiber to reduce heat loss from the bottom and then a 1 mm thick zinc sheet painted black (Hi-Temp Silicone Acrylic Aerosol Spray) was placed on the insulator and operated as an absorber plate. The ten CLOHP were attached to the absorber plate. Although the solar collector performance should be higher with more number of CLOHP, since the number of CLOHP is dictated by solar panel dimensions, only ten CLOHP can be contained in the solar collector. Finally, the 5 mm thick sheet of clear glass was covered at the top of collector. The thickness of glass sheet affects the transmission and absorption of solar radiation. A thin glass sheet has high transmissivity but it is easy to break.

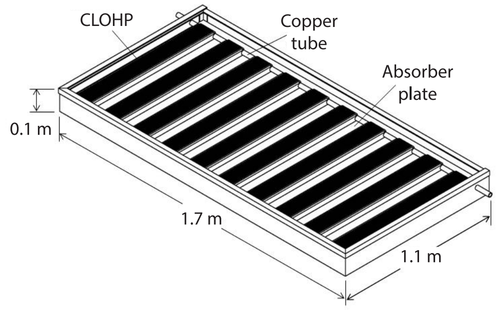

Figure 1. Detail configuration of flat plate solar water heater with CLOHP

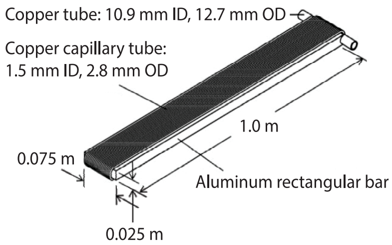

Figure 2. Detail configuration of each CLOHP

The detail configuration of each CLOHP is presented in fig. 2. Its dimensions were consistent with the previous research results as previously mentioned [15, 17, 18]. It was made of a copper capillary tube with a 1.5 mm inner diameter, a 2.8 mm outer diameter and was filled with the distilled water at a filling ratio of 50% the total internal tube volume. This filling ratio is appropriate for a CLOHP that operates at horizontal orientation and has the short effective length between the evaporator and condenser sections [13, 20]. The copper capillary tube was wrapped around a rectangular aluminum bar and a copper tube to form 20 meandering turns. This number of turns was higher than the critical value, and the CLOHP can work horizontally and nearby [20]. As in Thailand, the inclination angle of the flat plate collector is small, about 18° from a horizontal axis as shown in fig. 3, therefore, ensuring that all CLOHP in the system can transfer heat. In fig. 2, the evaporator part was located at the aluminum bar and had a length of 1.0 m. The condenser part, located at the copper tube, had length equal to the copper tube diameter of 12.7 mm. The length of adiabatic section is negligible. The capillary tube of the evaporator part and the rectangular bar were painted black.

Experimental set-up and procedure

Figure 3 shows the experimental set-up. It consisted of a flat plate solar water heater with CLOHP, a solar simulator, a voltage regulator, a pyranometer, a data recorder, and a flow meter. The collector was tested under the solar simulator using fifteen 1000 W halogen lamps, which was modified from previous research [16], to generate the uniform artificial solar energy. The irradiation was absorbed by the absorber plate and, simultaneously, heat was transferred by the CLOHP from the evaporator part to the condenser part. Then heat was moved to the tap water with the temperature of 28-33 °C that flowed into the copper tube wrapped by the condenser part. During the experiment, the irradiation intensity of the solar simulator was adjusted, via the voltage regulator, and measured by the pyranometer (KIPP&ZONEN, SP Lite 2). The temperatures of the evaporator parts, the absorber plate, the glass cover, the ambient air, and the water temperature inside the copper tube at the inlet and exit of the plate were measured with *K*-type thermocouples. All temperatures were recorded with a data recorder (Agilent, 34972A with ±0.5 °C accuracy). The rate of water flowing through the copper tube in an opened-loop circuit was measured with a float meter (Uni-Pure, 1-7 Lpm with ±0.1 Lpm accuracy). All experimental data were kept after reaching a steady-state or approximately 30 minutes after the start of the test. Moreover, the experiment was repeated three times for the given conditions.

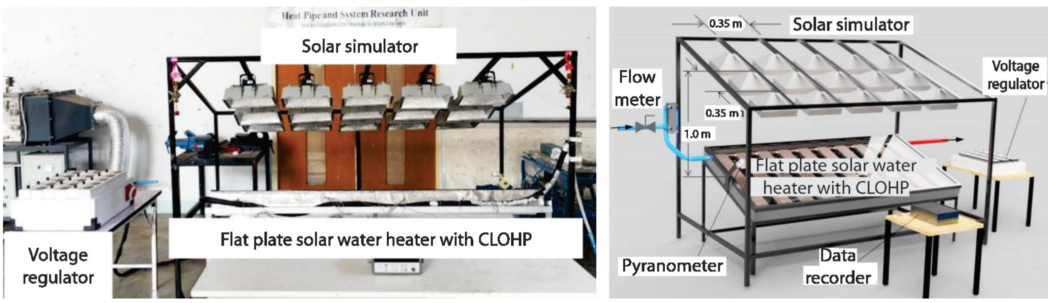

Figure 3. Real equipment apparatus and details of experimental set-up

In order to analyze the thermal performance of a solar water heater, the rate of heat gain of water, q, was calculated:

$$q = \dot{m}_{\mathrm{w}} c_{p,\mathrm{w}} \left(T_{\mathrm{w,o}} - T_{\mathrm{w,i}} \right) \tag{1}$$

The specific heat of water, $c_{p,\mathrm{w}}$ = 4.187 kJ/kgK. The thermal efficiency, η, was also calculated:

$$\eta = \frac{\dot{m}_{\mathrm{w}} c_{p,\mathrm{w}} \left(T_{\mathrm{w,o}} - T_{\mathrm{w,i}} \right)}{IA} \tag{2}$$

The collector area A = 1.5 m^2. Furthermore, the mathematical model to predict the thermal efficiency of the flat plate solar water heater with the CLOHP was evaluated [21]:

$$\eta = F_R \left(\tau\alpha \right) - F_R U_L \frac{T_{\mathrm{e}} - T_{\mathrm{a}}}{I} \tag{3}$$

The air temperature, T_{a}, during the experiment was about 35-38 °C. The measurement error of the recording instruments was also considered.

Results and discussion

In order to investigate the thermal performance, the variable experimental data was the water flow rate of 1.5-3.0 Lpm and the irradiation intensity of 480-1086 W/m^2. These rated values are consistent with ASHRAE standard and actual use in Thailand.

Thermal performances

Figure 4 shows the dependencies of the irradiation intensity, I, and the water flow rate on the heat gain rate of water, q. At the minimum irradiation intensity of 480 W/m^2, the heat rates for all the flow rates were similar, around 300-350 W. When the irradiation intensity increased from 480-1086 W/m^2, the heat gain rates of water increased for all flow rates of water. However, for the irradiation intensity range of 625-1086 W/m^2, the heat transfer rate for the flow rate of 1.5 Lpm was clearly low, relative for other flow rates, while the rates of heat transfer were slightly different by about 5% for the flow rates of 2, 2.5, and 3 Lpm. The maximum heat gain rates of water for all water flow rates, always appeared at the highest irradiation intensity of 1086 W/m^2. The values were about 900 W for 1.5 Lpm and 1100 W for 2-3 Lpm.

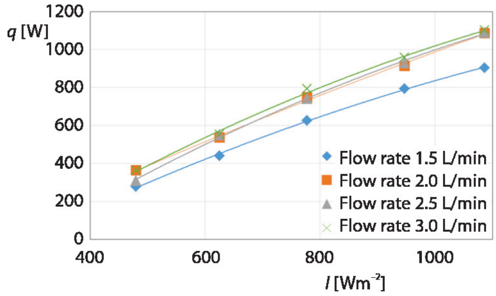

Figure 4. Effects of irradiation intensity and water flow rate on the heat gain rate of water

This was because at the high intensity the solar energy was absorbed intensely and the evaporator temperature of the CLOHP was also high. The saturation vapor pressure difference between the evaporator and condenser sections increased, which enhanced the fluid motion in the CLOHP and the heat transfer rate [20]. Because ASHRAE standard 93-77 [21] stated that the optimum water flow rate in the collector should be 0.02 kg/m^{2}s or 2 Lpm used in this experiment. Therefore, the coefficient associated with forced convective heat transfer from the inner surface of the copper tube to the water will be high. For flow rates of 2.5 and 3 Lpm, although the heat transfer coefficient is higher. But the mass-flow rate is also increasing. Since the heat transfer process is single-phase, the temperature difference of hot water is reduced. Therefore, the rate of heat transfer is almost the same as at 2 Lpm. This result encouraged the previous

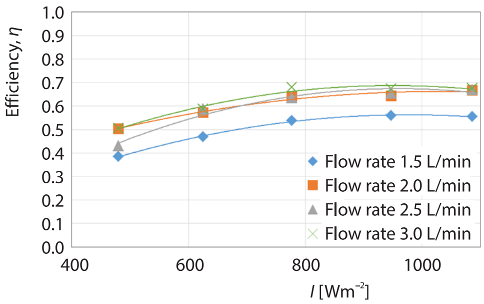

Figure 5. Effects of irradiation intensity and water flow rate on the thermal efficiency

research [16], at which the dependency of thermal performance on irradiation intensity was not clear. Because the working fluid and geometry of the CLOHP used in their research differed to that applied in this research, the optimum operating temperature range of the CLOHP, which corresponded to the irradiation intensity, will also differ [13, 20].

Figure 5 shows the thermal efficiency of the solar water heater, η. For all water flow rates, when the irradiation intensity increased from 480 W/m^2 to 777 W/m^2, the efficiencies gradually improved, thereafter they were nearly constant at the irradiation intensity of 947-1086 W/m^2. At high irradiation intensity, the thermal efficiency for the flow rate of 1.5 Lpm was relatively low, about 0.55, while for the other flow rates, the efficiencies were the same. The maximum thermal efficiency of the solar water heater occurred at the irradiation intensity of 947-1086 W/m^2, the water flow rate range of 2-3 Lpm, and its value was 0.67. This is almost equal to the value of previous work [18]. In this study because a single clear glass sheet covers the top of the collector, the top heat loss of the collector cannot be controlled but almost all the sun's rays will pass easily. Moreover, ten CLOHP with the proper tube arrangement in the collector plate can work well. The efficiency of the flat plate solar water heater developed in our present study satisfies and correlates with the efficiency of the more expensive heat pipe system. The cost of the flat plate solar water heater developed in this work was approximately 900 $.

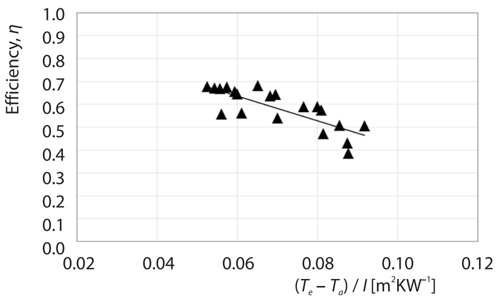

Figure 6. Relationship between the η and $(T_e - T_a)/I$

Mathematical model

The mathematical model of thermal efficiency of the flat plate solar water heater with the CLOHP was analyzed as presented in fig. 6. This picture showed the relationship between the η and $(T_e - T_a)/I$. The model was carried out by applying the least-square linear regression method with the reliable data sets, *i.e.*, the measurement error of the heat transfer rate was less than 20%:

$$\eta = 0.96 - 5.43\frac{T_e - T_a}{I} \tag{4}$$

The coefficient of determination, R^2, of math model is 0.73. This equation corresponded to eq. (3). The transmission and absorption capability of the collector $F_R(\tau\alpha) = 0.96$, and it also represented the ideal maximum thermal efficiency, *i.e.*, there is almost no heat loss from the system ($T_e \to T_a$) or the solar intensity is almost infinite ($I \to \infty$). The heat loss $F_R(\tau\alpha) = 5.43$. The heat loss coefficient of the collector evaluated in this research was slightly lower than previous work [18] as previously mentioned, while the transmission and absorption capability of the collector was very high. This may have been a result of the new design of the flat plate solar collector with multiple CLOHP that could be set up with a large number of CLOHP, so the large amount of absorbed heat could be rapidly transferred to water, and the heat loss of the plate would be reduced.

Conclusion

The new compact design of a flat plate solar water heater with multiple CLOHP was revealed and investigated under the solar simulator. The dependencies of variable irradiation intensity and water flow rate on its thermal efficiency were studied, and had found that the maximum thermal efficiency of the solar water heater occurred at the irradiation intensity of 947-1086 W/m^2, the water flow rate of 2-3 Lpm, and was about 0.67. The mathematical model to predict its thermal efficiency was also carried out. The efficiency of the flat plate solar water heater developed in our present study satisfies and correlates with the efficiency of the more expensive heat pipe system.

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Nomenclature

A – area, [m^2]
c_p – specific heat, [kJkg^{-1}K^{-1}]
F_R – heat removal factor
I – irradiation intensity, [Wm^{-2}]
$\dot{m}$ – mass-flow rate, [kgs^{-1}]
q – heat transfer rate, [W]
T – temperature, [°C]
U_L – overall heat loss coefficient, [Wm^{-2}K^{-1}]

Greek letters

α – absorptivity, [–]
η – thermal efficiency, [–]
τ – transmissivity, [–]

Subscripts

a – ambient air
e – evaporator
i – inlet
o – outlet
w – water

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