THERMAL PERFORMANCE OF SOLAR THERMAL COLLECTOR USING METAL REINFORCED POLYETHYLENE TUBE

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ABSTRACT

This study aims at finding out thermal properties and performance of a solar thermal collector using a metal reinforced polyethylene tube (MRPT) through an outdoor experiment, which was conducted from August to December 2013. A very thin circular sheet of aluminum was embedded in a black MRPT with a thickness of 2 mm, an inner diameter of 10 mm and a length of 84 m. The experimental equipment consists of a MRPT mounted on a wooden plate, a line pump and a heat storage tank. Heat-carrier fluid temperature and circulation-flow rate were measured to calculate the solar energy extracted from the MRPT as well as meteorological data. Main conclusions drawn from the experiment are (i) the fluid temperature difference between the MRPT inlet and outlet was 4.8°C in summer and 2.9°C in winter on average, (ii) there exists a linear positive relationship between the cumulative extracted energy per unit MRPT length, ΣE_e, and global solar radiation, ΣR_s, over the circulation period within the range ΣE_e [15.8 - 111.9 kJ/m] and ΣR_s [0.4 - 4.8 MJ/m^2].

Keywords: *Solar thermal collector, heat extraction, metal reinforced polyethylene tube, heat-carrier fluid*

1. INTRODUCTION

In Japan, the Ministry of the Environment has adovocated 12 measures towards a low-carbon society, and it has been promoted to use renewable energy sources such as solar energy, small and medium hydropower, wind power and wave power, and to reduce the cost of these renewable energy (Ministry of Environment of Japan, 2015). Especially, development and active use of renewable energy facilities have been promoting in particular after the Great East Japan Earthquake in March 2011. Among the renewable energy facilities, solar water heaters have been commonly used for a long time because of its high energy efficiency and easy installation work. Flat-plate collectors and evacuated-tube collectors are the representative types of solar water heaters. Xu et al. evaluated the environmental load reduction and economic efficiency of a vacuum-tube solar water heater (Xu, 2008). An OM solar roofing system controls air conditioning of builings and houses by using air heated by solar energy extracted under roofs (Architectural Thought Research Institute, 1991). Although these solar collector systems save running costs, there are some concerns regarding market access because of high initial costs and limitations on the system installation (for example, the OM solar roofing system can hardly apply to existing roofs).

China has the highest penetration rate of solar water heaters in the world and the installed capacity accounts for 65% of the entire world (enestudy Co., 2015). Then the United States, Germany, Turkey, Brazil follow China and in these countries the amount of introduction of solar water heaters has been still increased in recent years. However, one of main disadvantages of these thermal collector systems is also high initial costs.

Considering such situation, we have been testing a solar thermal collector (STC) using a metal reinforced polyethylene tube (MRPT) to overcome disadvantages mentioned above (Akao, 2014). The MRPT is black and lightweight, and has a high thermal conductivity to improve the extraction efficiency of solar energy. It was seen that the temperature of heat-carrier fluid in the MRPT sensitively varied in response to changes of air temperature and solar radiation. There are past studies on the performance evaluation or design of solar thermal collectors using a vacuum tube, for example G.L.Morrison et al. (Morrison, 2004), Zhiyong Li et al. (Zhiyong, 2010) and L.M.ayompe et al. (Ayompe, 2011). Hasuike et al. (Hasuike, 2007) proposed a model for heat transfer analysis in pipe array and showed the effects of light incidence angel and pipe pitch on the heat extraction performance of the pipe.

This paper presents the thermal performance of the STC using the MRPT with data obtained from an outdoor experiment from August (summer) to December (winter) 2013.

2. SOLAR THERMAL COLLECTOR SYSTEM

Photo 1 shows the STC system used in the outdoor experiment. The STC consists of a MRPT spirally formed (Sekisui Chemical Co., inside diameter 10 mm, outside diameter 14 mm, thickness 2 mm and length 84 m), a wooden panel for placing the MRPT (plywood, length 900 mm, width 1800 mm and thickness 12 mm), a line pump (Ebara Co., 0.4kW) and a heat storage tank (200L). The MRPT was oriented approximately in the east-west direction, and was tilted to be at nearly right angles to the sun's rays, i.e. at an angle of 30° from horizontal. The weight of the MRPT and wooden panel per unit area is 4.6 and 5.3 kg/m^2, respectively, and the total weight per unit area (9.9kg/m^2) is 1/2 or less of that of conventional solar water heaters (about 20kg/m^2). The temperature of heat-carrier fluid, T_w, rises by absorbing solar energy while heat-carrier fluid circulates in the MRPT.

3. EXPERIMENTAL METHOD

Figure 1 shows an outline of the STC system using the MRPT and a sectional view of the MRPT. An outdoor experiment was conducted from August to December 2013 on the roof of University of Fukui. Table 1 shows measurement items and a thermal image of the STC was sometimes taken during the experiment. Thermo-couples were inserted in the MRPT at different axial direction positions of x = 0 (inlet), 5, 10, 20, 40 and 84 m (outlet) from the inlet to measure the spatial variation of T_w along the MRPT. The top and bottom surface temperatures of the MRPT and aluminium sheet were measured with thermo-couples at the centerline of the MRPT at x = 80.4 m. In addition, short and long wave radiation fluxes (R_s and R_{atm}) were measured by a

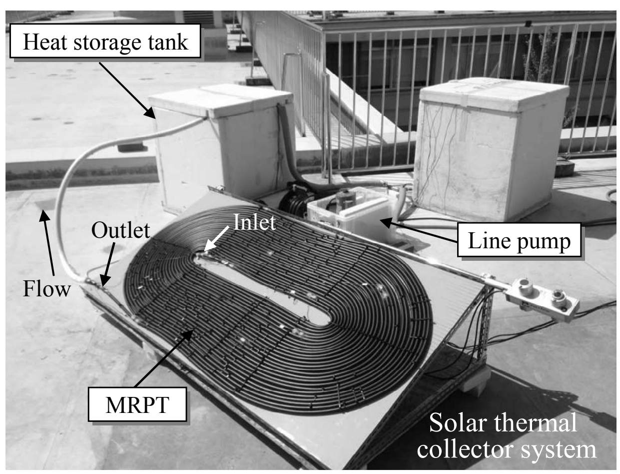

Photo 1: Solar thermal collector system using a metal reinforced polyethylene tube

Table 1: Measurement items

Weather observation	Short and long wave radiation fluxes, Air temperature, Relative humidity, Wind velocity
Experiment	Heat-carrier fluid temperature {x = 0 m (inlet), 5 m, 10 m, 20 m, 40 m, 84 m (outlet)} MRPT temperature {Tube surface(top and bottom), Aluminium sheet (top and bottom) x = 80.4 m} Panel temperature, Heat storage tank temperature, Thermal image

radiation balance meter (Kipp & Zonen Co.) at a height of 2 m above the roof surface. Air temperature and relative humidity near the STC system were measured by a thermo-hygrometer (Kipp & Zonen Co.). Wind velocity was measured by a three cup anemometer at the same height as the radiation balance meter. Another radiation balance meter was placed on the tilted wooden panel to measure R_s and R_{atm}, which incident at right angles to the wooden panel. Ice water provided a constant temperature source at the inlet of the MRPT. The flow rate of the ice water circulation (hereinafter referred to as circulation) was 8.0×10^{-5} m^3/s and the circulation period was about 2 hours. The start time of the circulation changed depending on weather conditions and all data was automatically downloaded to a data logger (Graphtec Co.) at an interval of one minute.

4. EXPERIMENTAL RESULTS

Figure 2 shows the monthly variations of R_s, R_{atm} and T_a averaged over the circulation period. R_s decreased from August (800W/m^2) to December (250W/m^2) except November. The reason of this exception of R_s is that R_s in November was frequently measured under cloudy and sunny days. R_{atm} and T_a also decreased monotonously from August (420W/m^2, 33.5°C) to December (360W/m^2, 10.3°C).

Figures 3 and 4 show the time variations in T_w at $x=0$ (inlet), 40 (middle point) and 84 m (outlet) in August and December, respectively. T_w at $x=0$ and 84 m, i.e. T_{w0} and T_{w84} ranged 40.0 to 43.4°C in August and 19.4 to 20.9°C in December before starting the circulation. On the other hand, T_w at $x=40$ m, T_{w40}, was 56.7°C in August and 23.7°C in December, which was higher than T_{w0} and T_{w84}, regardless of season. As shown in Figure1, the MRPT at the central part of the STC such as x = 40 m is surrounded by the neighboring MRPT (i.e. a high tube density), while both ends of the MRPT have a relatively low tube density. Therefore, the heat loss

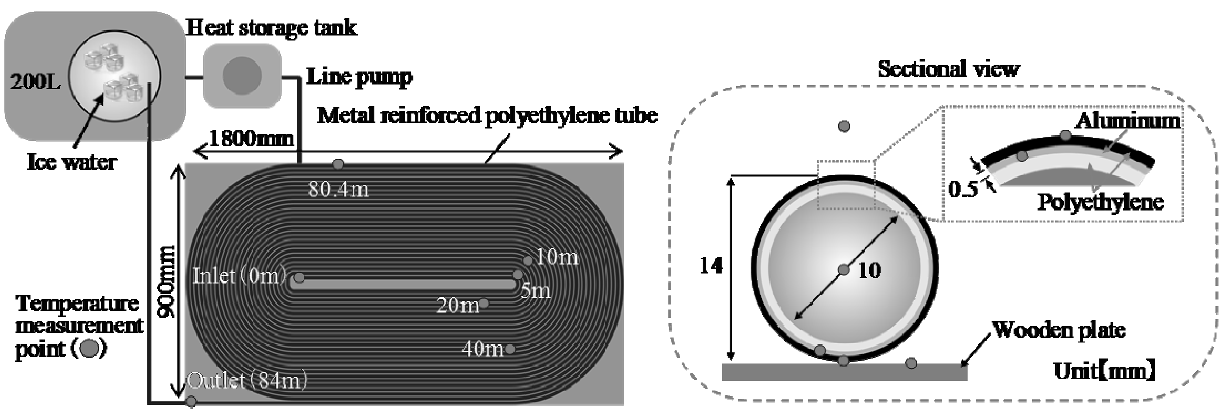

Figure 1: Outline of outdoor experiment of solar thermal collector and sectional view of MRPT

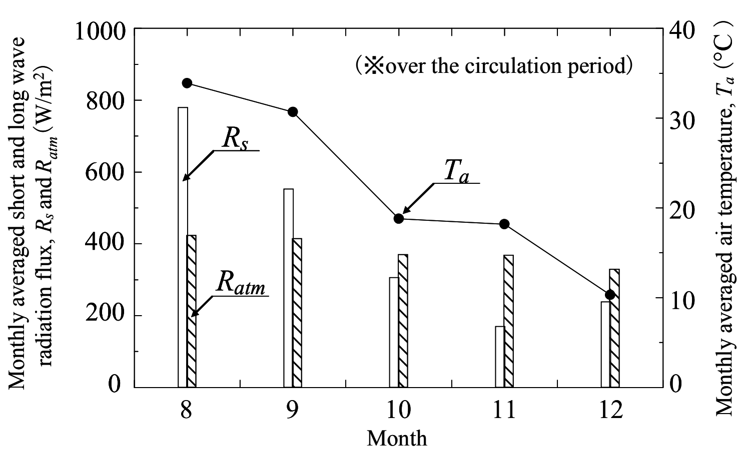

Figure 2: Monthly variations of R_s, R_{atm} and T_a

through the MRPT due to sensible heat (air movement) may cause the difference in T_w ($T_{w40} > T_{w0}$ and $T_{w40} > T_{w84}$). Immeiately after starting the circulation, T_{w0} and T_{w40} decreased rapidly because of an influx of cold fluid from the heat storage tank. On the other hand, a sudden increase of T_{w84} (as shown by an upward arrow in Figures 3 and 4) was observed due to high temperature heat-carrier fluid flowing into the outlet from the central part of the MRPT. After that, T_{w84} decreased in the same state as T_{w0} and T_{w40} did. About 20 minutes later (12:16 to 13:56), the heat-carrier fluid reached thermodynamically equilibrium state. In this state, T_w increased in the order T_{w0}, T_{w40} and T_{w84} due to the absorption of solar energy while the heat-carrier fluid circulated in the MRPT. As a result, the fluid temperature difference between the MRPT inlet and outlet, i.e. (T_{w84} - T_{w0}) ranged 3.1 to 7.3°C (average 4.8°C) in August and 1.7 to 4.3°C (average 2.9°C) in December. After stopping the circulation, T_w remarkably increased again and became steady in about 30 minutes.

Figures 5 and 6 show the spatial variations in T_w in August and December, respectively. Before starting the circulation, T_w at the central part of the STC was higher than that at both edges of the STC or the MRPT. During the circulation, T_w increased in general from the MRPT inlet toward the outlet. However, T_w decreased locally for the section $0 \le x \le 5$ to 10 m. The MRPT crosses tightly the wooden panel at $x = 0$ and the wooden panel temperature, T_{panel}, was about 20.0°C higher than the MRPT temperature, T_{tube}. The heat transfer through the MRPT due to the relation $T_{panel} > T_{tube}$ may caused the increase of T_{w0}, although the wooden panel is thin. As a result, T_{w0} became higher than T_w for $0 \le x \le 5$ to 10 m. After stopping the circulation, T_w increased uniformly over the whole MRPT.

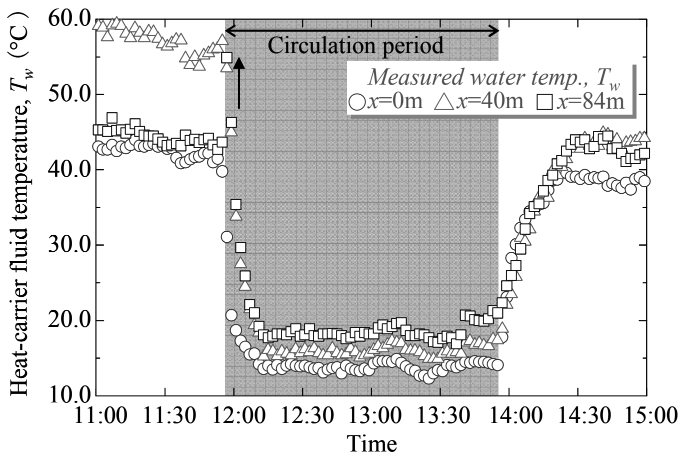

Figure 3: Time variations in heat-carrier fluid temperature in August

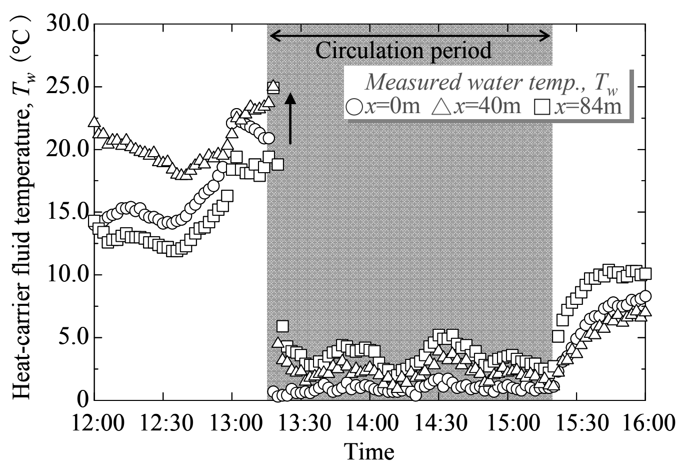

Figure 4: Time variations in heat-carrier fluid temperature in December

Figure 7 shows the relation between the cumulative exracted energy during the circulation period (daily extracted solar energy) per unit MRPT length, ΣE_e, and the global solar radiation integrated over the circulation period, ΣR_s. ΣE_e is calculated by the following equation;

$$\Sigma E_e = \int_0^t Q_w c\left(T_{w84} - T_{w0}\right)/L \qquad (1)$$

where t (s) is circulation time, Q_w (kg/s) is the mass flow rate of heat-carrier fluid, c (kJ/kgK) is the specific heat of heat-carrier fluid and L (m) is the length of the MRPT. Although there are some scattered plots, ΣE_e is in proportion with ΣR_s and is expressed by the following equation;

$$\Sigma E_e = a\Sigma R_s \qquad (2)$$

where a is 26.3. The Value of ΣE_e varied from 15.8 to 111.9 (kJ/m) for the range of ΣR_s [0.4 to 4.8 (MJ/m^2)].

5. CONCLUSIONS

We developed a new solar thermal collector using a metal reinforced polyethylene tube (MRPT). This study aims at finding out thermal performance of the MRPT through an outdoor experiment carried out over five months between August and December 2013. The thermal performance was evaluated by circulating ice water in the MRPT for about two hours.

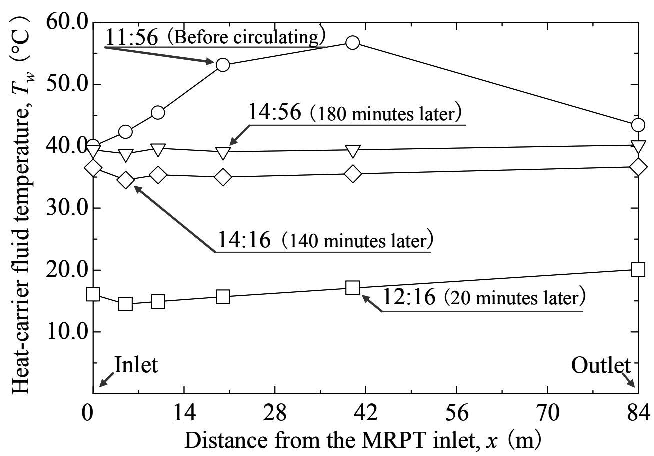

Figure 5: Spatial variations in heat-carrier fluid temperature in axial direction of the MRPT in August

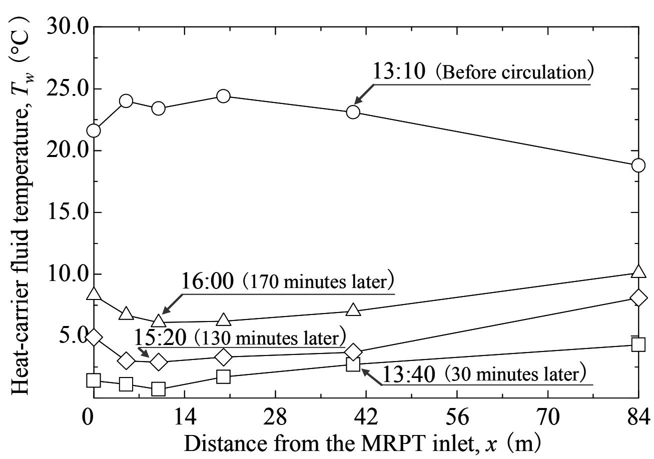

Figure 6: Spatial variations in heat-carrier fluid temperature in axial direction of the MRPT in December

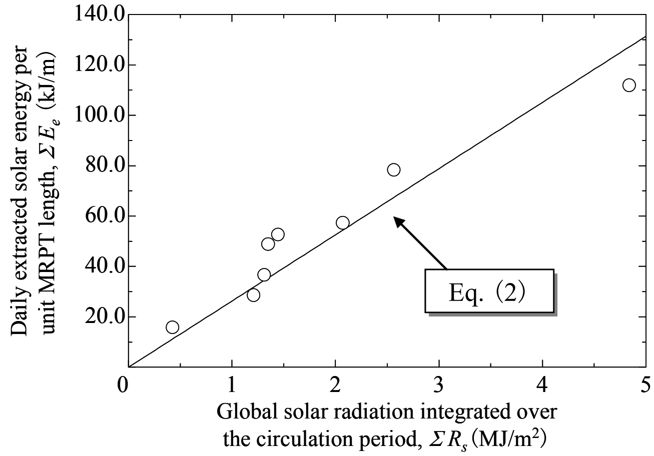

Figure 7: Relation between the cumulative extracted energy during circulation per unit MRPT length and global solar radiation integrated over circulation period

Main conclusions drawn from the present experiment are as follows.

1) It can be confirmed that heat-carrier fluid temperature increased from the MRPT inlet toward the outlet due to the absorption of solar energy while the heat-carrier fluid circulated in the MRPT. The fluid temperature difference between the MRPT inlet and outlet ranged 3.1 to 7.3°C (average 4.8°C) in August and 1.7 to 4.3°C (average 2.9°C) in December.
2) The cumulative extracted energy during the ice water circulation (daily extracted solar energy) increases linearly in proportion to the global solar radiation integrated over the circulation period.

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