PAPER ID: 1200
DOI: 10.18462/iir.gl.2020.1200

Solar heat recovery system using CO_2 as working fluid

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ABSTRACT

This article proposes a solar water heater system induced by natural convective flow using supercritical CO_2 as a working fluid. The proposed solar water heater can produce thermal energy as hot water from solar thermal energy without any electric power consumption. In order to investigate the characteristics of the system, the dynamic characteristics and heat transfer property of the supercritical CO_2 flow are measured when the inclination angles of the solar collector are changed. The current results indicate that the circulation of CO_2 flow in this solar heater system can be easily induced by natural convection even if the solar collector angles are changed from 30° to vertical against gravity direction. The heat recovery efficiencies of this system are 86.5%, 68.5%, and 58.8% at the collector inclination angles of 30°, 60°, and 90°, respectively.

Keywords: Carbon Dioxide, Water Heater, Natural Circulation, Solar Radiation, Solar Heat Recovery.

1. INTRODUCTION

Utilization of renewable energy has been attracting much attention for decades due to the global warming issue, the energy depletion, and the air pollution problem. For the spread of renewable energy, it is important to improve energy generation efficiency and effective use of land. Land with higher population density has higher energy demands, which limits the land that can be used effectively. Among environmentally friendly renewable energy systems, the amount of solar energy is rather large comparing other renewable energies, which has been studied intensively for an effective utilization in practical situation. Also, since the amount of energy that used to supply hot water in our society is large, the solar water heater has been used and studied extensively in the past time and has been put to practical use for many years. However, most of the solar water heaters in the market use water as a working fluid, which has low specific heat capacity and result in low efficiency. In contrast, CO_2 has higher specific heat capacity, which is stable at an ordinary temperature, and also be classified as nontoxicity, non-flammability working fluid. In addition, CO_2 has zero Ozone Depletion Potential, and low Global Warming Potential compared with many other Fluorocarbons. Also, solar thermal energy can be efficiently recovered into other energies (Zhang et al., 2007; Zhang et al., 2008). Based on the motivations, a new solar water heater using supercritical CO_2 has been proposed (Yamaguchi et al., 2010). In the present study, natural circulation model of heat recovery system using supercritical CO_2 was developed, as well as the thermal properties and flow behaviours were experimentally investigated. It is highly expected that the system provides a possibility to circulate CO_2 without any mechanical pumps with the high heat recovery efficiency achieved. In the practical applications, most of solar water heaters in Japan were installed at a collector inclination angle about 30° without site latitude and local climatic conditions. Therefore, the present study is focused on investigating the system characteristics under three conditions (30°, 60°, and 90°) of collector inclination angle by measuring flow property and heat-transfer property of supercritical CO_2.

2. EXPERIMENTS

In the solar heat recovery system, CO_2 absorbs solar thermal energy in an evacuated solar collector and is driven by the buoyancy force generated by the phase change of CO_2 from the liquid state to the supercritical state.

2.1. Experimental set-up

The experimental set-up is illustrated in Figure 1. The system can be divided into two loops that are CO_2 heat collection loop and water heat recovery loop, which are coupled by a heat exchanger. The system consists of the following components: evacuated solar collectors, pyrheliometer, valves 1 and 2, heat exchanger, gear pump, flow meters, and data analysis apparatus. The evacuated solar collectors (detail description in Ref. Yamaguchi et al. (2010)) have a maximum allowable working pressure of 12 MPa. The selective absorption membrane is covered inside of the solar collector, so that the solar radiation energy can be efficiently absorbed inside the collector. The selective absorption membrane coating on collector tubes has an absorption ratio of 92.7% and an emissivity of 1.93% at the temperature 100 ^{o}C, which is possible to absorb solar radiation effectively until the selective absorption membrane reaches 250 ^{o}C. U-tube is installed inside the selective absorption membrane, and CO_2 flow inside the U-tube. Aluminium fins are installed around the U-tube to increase the heat transfer area inside the collector. The installation area of the solar collector of the system is 1.97 m^2. In the initial state before the start of the experiment, liquid CO_2 at a pressure of 6 MPa and a temperature of 20 ^{o}C is enclosed in the CO_2 heat collection loop of the system. In the system operation, the solar collector collects solar heat, which increases the CO_2 temperature and pressure in the collector. At that time, when the pressure of CO_2 exceeds 7.38 MPa and the temperature exceeds 304.3 K, the CO_2 becomes supercritical state. In the heat exchanger, CO_2 changes from the supercritical state to liquid state by exchanging heat with cooling water. Due to the density difference between supercritical CO_2 in the collector and liquid CO_2 in the heat exchanger, a natural convection flow of CO_2 is induced. In the water heat recovery loop, a gear pump (with a maximum flow rate of 2.4 L/min and a rated power consumption of 45 W, MDG-M2S6B100, Iwaki co. Ltd) is used to power the water flow. The cooling water driven by the pump is turned into hot wall by exchanging heat with supercritical CO_2 in the heat exchanger. The heat exchanger has a double-tube structure and the heat exchanger are is about 1 m^2. CO_2 flows inside the inner tube and transfers heat to the water in the outer tube. The diameters of the inner and outer tubes are 12.7 and 34 mm, respectively. The mass flow meter (Coriolis type, CA003, Oval co. Ltd.) installed in the CO_2 heat collection loop is measured the CO_2 mass flow in the measurement range of 0–70 kg/h with an accuracy of ±0.2%. Another one (Coriolis type, CR004, Oval co. Ltd.) installed in the water heat recovery loop is measured the water mass flow in the measurement range of 0–160 kg/h with an accuracy of ±0.2%. The solar radiation is measured by a pyrheliometer (LP-PYRA03DB, Filed Pro cp. Ltd.) in the measurement range of 0–2 kW/m^2 with an accuracy of ±0.2%. The pyrheliometer is set at a horizontal place.

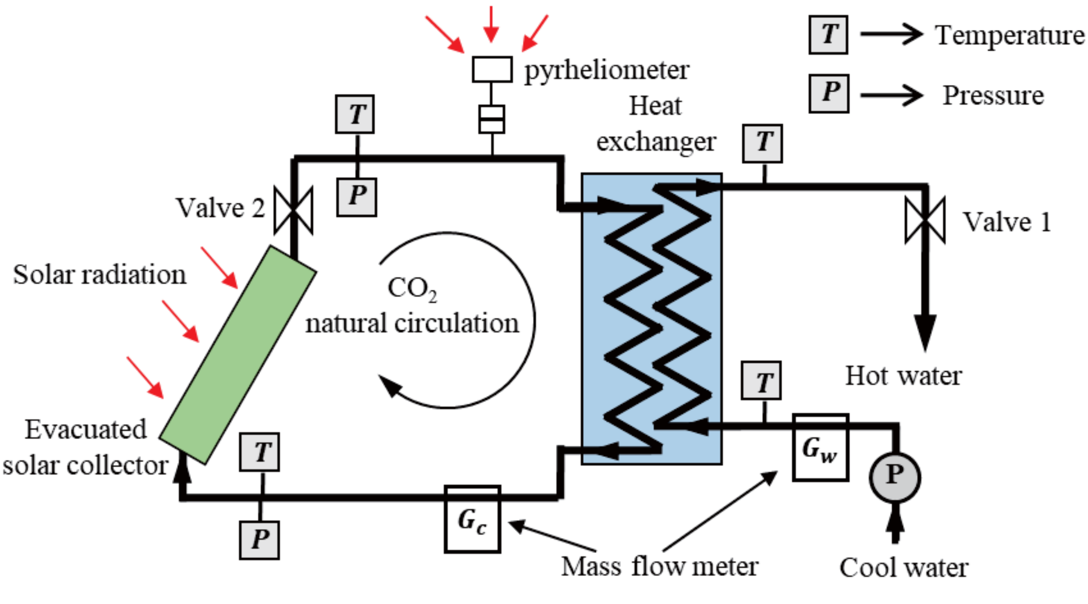

Figure 1: Schematic diagram of experimental set-up

Figure 2 is a schematic diagram showing how to change the tilt angle of the solar collector. As shown in figure 2, the inclination angle can be changed around the header tube at the bottom of the collector. In this system, only the inclination angle of the solar collector, which is the heating unit, is changed, and the heat exchanger and the pipe unit connecting each component are not affected by the angle change. The tilt angle of the collector can be arbitrary changed between 30 and 90^{o} with respect to the horizontal plane. The solar collector is faced toward the south direction. Experiments were carried out for some days selected from March to October in 2015. At the start of the experiment, the collector is moved to any location where solar heat can be collected, while tap water flows into the

http://dx.doi.org/10.18462/iir.gl.2020.1200

heat exchanger. The pressure and temperature in the system were measured by K-type thermocouples (with the accuracy of ±0.1 ºC) and pressure transmitters (with the accuracy of ±0.2%). The specific measured quantity in the experiment include the following: CO_2 pressure and temperature in the inlet and outlet of the solar collector, water temperature in the inlet and outlet of the heat exchanger, CO_2 mass flow rate in the outlet of the heat exchanger, water flow rate in the inlet of the heat exchanger, and solar radiation intensity. Each measurement data are taken into a computer via a data loggers with sampling rate of 10 s.

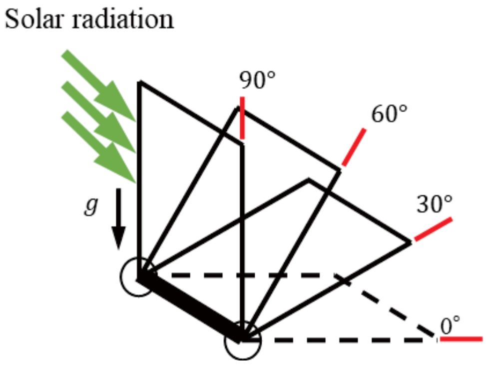

Figure 2: Schematic diagram showing how to change the tilt angle of the solar collector.

2.2. Evaluation

In order to evaluate the system performance of the proposed solar water heater system, the evaluated parameters are defined as shown below. The solar radiation energy power J is defined as follows

$$J = AI \quad \text{Eq. (1)}$$

where $A = 1.5$ m^2 is the effective area of the solar collector and I is the solar radiation intensity. The solar radiation quantity Q_J can be given by

$$Q_J = \int_t AIdt \quad \text{Eq. (2)}$$

The collected heat energy power of the solar collector Q_C can be given by

$$Q_C = G_C\left(h_{C2} - h_{C1}\right) \quad \text{Eq. (3)}$$

where G_C is the mass flow rate of CO_2 inside the solar collector and h_{C1} and h_{C2} are the CO_2 enthalpy values at the inlet and outlet of the solar collector, respectively. The enthalpy values are referred from PROPATH V13.1. The recovered heat power of water Q_W is defined by

$$Q_W = G_W C_p\left(T_{W2} - T_{W1}\right) \quad \text{Eq. (4)}$$

where G_W is the mass flow rate of water inside the heat exchanger, T_{W1} and T_{W2} are the water temperature at the inlet and outlet of the heat exchanger, respectively. Cp is the specific heat capacity coefficient of water. The heat collection efficiency η_c and the heat recovery efficiency η_w are determined based on the obtained heat quantities by the ratios, which are given as

$$\eta_C = \frac{\int_t Q_C dt}{Q_J} \quad \text{Eq. (5)}$$

$$\eta_W = \frac{\int_t Q_W td}{Q_J} \quad \text{Eq. (6)}$$

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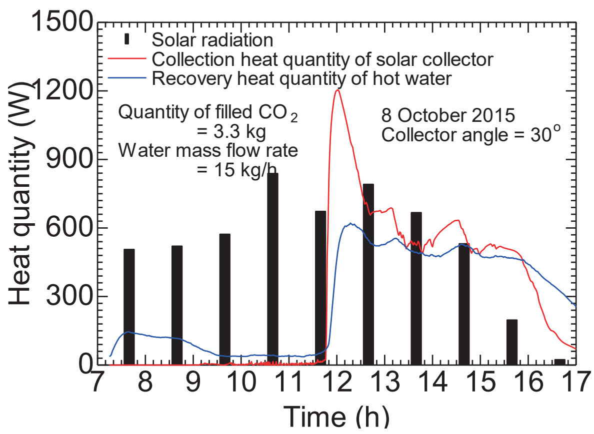
3. RESULTS AND DISCUSSION

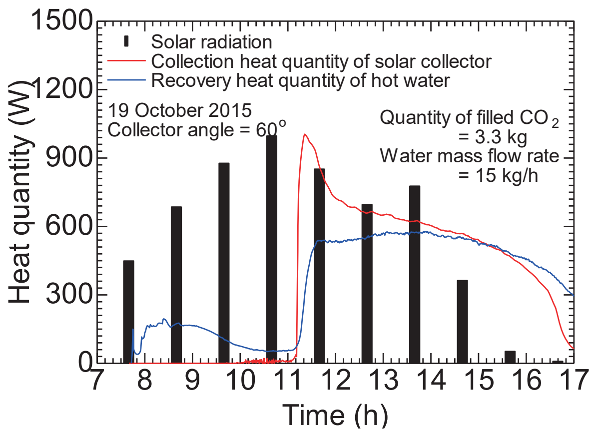
In order to evaluate the effect of the tilt angle of the solar collector, the performance of this system was carried out in Spring, Summer, and Autumn seasons (April–November, 2015) of Kyoto, Japan (34º47’58.1”N, 135º46’04.6”E). In the characteristic experiment, the quantity of hot water, the temperature of which is above 40ºC, is considered to evaluate the output of this system. Radiation time are defined as hours with direct solar radiation of 0.12 kW/m^2 or more.

Table 1 Conditions and results of three representative days in autumn.

Date	Collector angle (degree)	Average temperature (ºC)	Highest temperature (ºC)	Radiation time (h)	Average solar radiation (W)	Thermal collection efficiency (%)
8 October	30	16.9	24.2	7.4	532	53.6
19 October	60	17.0	26.1	10.5	592	58.1
7 October	90	17.0	25.0	10.9	528	46.0



(a)



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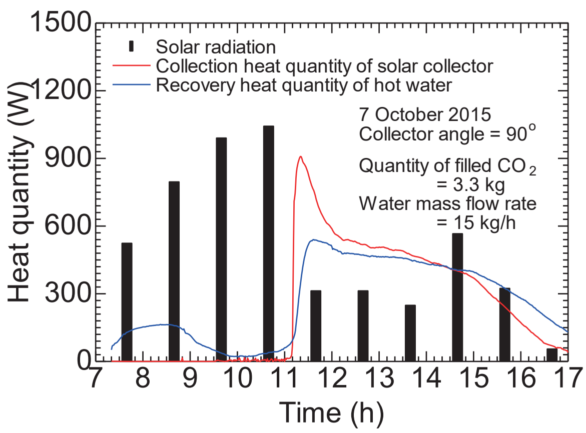

(c)

Figure 3. Solar radiation, heat quantity collected by the solar collector, and the hot water in the three representative days: (a) solar installation angle of 30º (8 October), (b) solar installation angle of 60º (19 October), and (c) solar installation angle of 90º (7 October)

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Table 1 shows the measurement results of three representative days in autumn of 2015. The average solar radiations in the three experiments are almost same value as 560 W ±5.7%. The radiation time on 8 October was reduced compared to other conditions due to cloudy weather. The heat collection efficiency by the solar collector at the installation collector angle of 90° was lower than the heat collection efficiency at the other installation angles. On the other hand, even if the installation angle is 90 degrees, it is possible to collect sufficient solar energy. Figure 3(a), (b), and (c) shows the hourly results of solar radiation, heat quantity collected by the CO_2 fluid in the solar collector, and heat quantity recovered by hot water in the three representative days from 7:00 to 17:00. As shown in Figure 3, this system begins collecting heat between 11:00 and 12:00, 4 h after the start of the experiment. This is because it takes time until CO_2, which was in a liquid state at the start of the experiment, is heated in the collector to be in a gas-liquid two-phase state and buoyancy convection is induced. In the time required for the CO_2 preheating process, there is no difference in the amount of heat collection depending on the collector angle. The amount of heat collection becomes maximum about one hour later than the time when solar radiation becomes maximum. After that, the amount of heat collected decreases with the decrease in solar radiation. In either case as shown in Figure 3, heat recovery is performed between 7:00 and 10:00 before heat collection by CO_2, since the heat stored in the heat exchanger by outside air is taken away by cool water. Heat recovery by hot water is started about 20 minutes later from solar heat collection by the solar collector. After 16:00, when solar radiation hardly occurs, the amount of heat recovered is higher than the amount of heat collected. This is because the CO_2 circulation speed is very slow, and a time lag occurs between the temperature change of CO_2 in the collector and the temperature change of water in the heat exchanger. Although there is a difference between the amount of heat collection and the amount of heat recovery, it is clear that a sufficient amount of heat can be recovered at any collector installation angle.

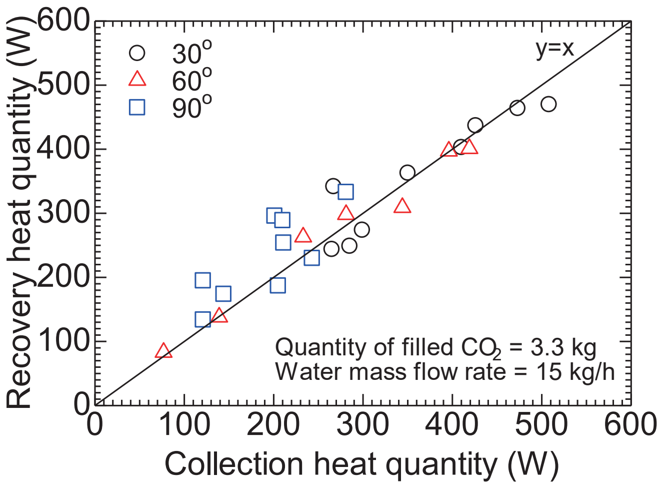

Figure 4: Collection heat quantity of solar collector v.s. recovery heat quantity of heat exchanger with different collector angles.

In order to clarify the difference in the heat recovery efficiency due to the difference in the collector angle, Figure 4 shows the average daily heat collection amount and the heat recovery amount at each collector angles. At any of the collector angles, when the amount of heat collection increases, the heat recovery effect also increases, and there is no difference in the increasing tendency. Here, the reason why the heat recovery amount exceeds the heat collection amount is that there is a large time lag between the heat collection by CO_2 and the heat recovery by water. As described above, after 15:00 when sufficient solar radiation cannot be obtained as shown in Figure 3, the heat recovery amount exceeds the heat collection amount. This is because, the mass flow rate of CO_2 sharply decreases when the solar radiation decreases. Since the CO_2 filling amount is 3.3 kg, a time lag of about 20 minutes occurs even at a CO_2 mass flow rate of 10 kg/h, and the time lag increases as the CO_2 mass flow rate decreases.

The maximum heat recovery efficiencies η_w of this system achieve 86.5%, 68.5%, and 58.8% at the collector inclination angles of 30°, 60° and 90°, respectively. This system can supply hot water efficiently even at an installation angle of 90 degrees, and it is possible to design system performance from solar radiation regardless of the installation angle. In addition, by introducing a heating booster for the purpose of promoting the initial flow of CO_2, it is thought that it is possible to supply hot water more effectively, and this can be said to be a future issue.

http://dx.doi.org/10.18462/iir.gl.2020.1200

4. CONCLUSIONS

In the present work, the dynamic characteristics and system efficiency of the solar heat recovery system using CO_2 are evaluated when the inclination angles of the solar collector are changed. The performance parameters such as the heat collection efficiency, heat recovery efficiency by this heater system are presented and analysed in detail. The current results indicate that the circulation of supercritical CO_2 flow in this solar heater system can be easily induced by natural convection even if the solar collector angles are changed from 30° to vertical against gravity direction. The heat recovery efficiencies of this system are 86.5%, 68.5%, and 58.8% at the collector inclination angles of 30°, 60° and 90°, respectively.

ACKNOWLEDGEMENTS

This publication has been funded by HighEFF - Centre for an Energy Efficient and Competitive Industry for the Future. The authors gratefully acknowledge the financial support from the Research Council of Norway and user partners of HighEFF (Centre for Environment-friendly Energy Research, 257632/E20).

NOMENCLATURE

A	effective area of the solar collector (m^2)	G_C	mass flow rate of CO_2 (kg/s)
G_W	mass flow rate of water (kg/s)	h	enthalpy (kJ/kg)
I	solar radiation intensity (W/m^2)	J	solar radiation power (W)
Q_C	collected heat energy power of the solar collector (W)	Q_J	solar radiation quantity (W)
η_C	heat collection efficiency (-)	η_W	heat recovery efficiency (-)

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http://dx.doi.org/10.18462/iir.gl.2020.1200