Basic Study on Flow Stabilization of Top-heat-type Thermosiphon

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Abstract

A top-heat-type thermosiphon utilizing vapor bubble pumping, which can realize heat transfer without any external electric power, has been extensively studied. However, its application has some problems, one of which is the unstable heat transfer, that is, intermittent circulation flow rate of the working fluid. This occurs under the conditions of less solar radiation during the morning and evening, and has been investigated by conducting a field experiment using a model house. To overcome this problem, a thermosiphon control system has been proposed to realize stable heat transfer, that is, almost constant flow rate of the working fluid. In this study, a method for reducing the buffer chamber pressure is adopted to stabilize the flow rate. The control system comprises a buffer chamber, a solenoid valve, a pressure transducer, a vacuum pump with tank, and an embedded computer. The pressure of the buffer chamber is ratcheted down to avoid violent boiling. In addition, the effectiveness of the system is demonstrated using the indoor experimental apparatus.

Keywords: Renewable energy, Solar thermal, Solar thermosiphon, Top heat type, Low-temperature heat, Control.

1. Introduction

The emission reduction effort of greenhouse effect gases, which cause global warming, is an essential problem for humankind. An effective use of renewable energy is a key challenge for sustainable development. Renewable energy is low-density energy, with a wide distribution globally. Therefore, it is important to find a new way to use the energy. Power generation systems using renewable energy, for example, solar energy, hydraulic power, wind power, geothermal power, and biomass energy, are being intensively studied. In addition, the utilization of photovoltaic energy continues to increase. However, the generated power fluctuates according to the cloud conditions. In addition, a certain amount of thermal energy converted from electric power is utilized in modern society. Thus, we focus on utilizing solar thermal energy, which is affected less by the weather than photovoltaic energy, and a top-heat-type thermosiphon, which enables heat transfer from solar energy collectors on the roof to an accumulator on the ground, which is a heat storage unit, without any external electric power source.

To date, several measures have been adopted to use solar energy for heating water, including using a thermosiphon (Morrison, 2001; Jamar et al., 2016; Jafari et al., 2016). The thermosiphon, which can transfer heat without any external electric power source, is being intensively studied. In this study, we focus on the top-heat-type thermosiphon, which can transfer heat form the top of the system to the bottom. Various top-heat-type thermosiphons have been proposed to date, such as the wick heat pipe type, osmotic heat pipe type, vapor pressure type, and vapor bubble pumping type (Imura and Koito, 2005 (in Japanese)). The wick heat pipe-type thermosiphon requires capillary tubes, while the osmotic pipe type requires semipermeable membranes. Thus, these two types have difficulty increasing the flow rate. Meanwhile, the vapor pressure type requires a complex valve operation (Koito et al., 2006 (in Japanese)). Therefore, the present study focuses on the vapor bubble pumping-type thermosiphon because of the simplicity of its configuration and scalability. This system has been proposed and studied since the 1970s (Hirashima et al., 1993 (in Japanese); Ippohshi et al., 2003). Ito et al. (2007) proposed separating the condenser and reservoir for closer to practical use. Thereafter, the circulation of a working fluid of height 4 m was realized by conducting a field test using a model house (Hagino and Yoshida, 2011; Imada et al., 2013 (in Japanese)). Furthermore, the hydraulic power generation using the flow of a working fluid was studied (Yoshida, et al., 2014), and the drive performance of the working fluid was analyzed (Hagino, et al., 2016 (in Japanese)).

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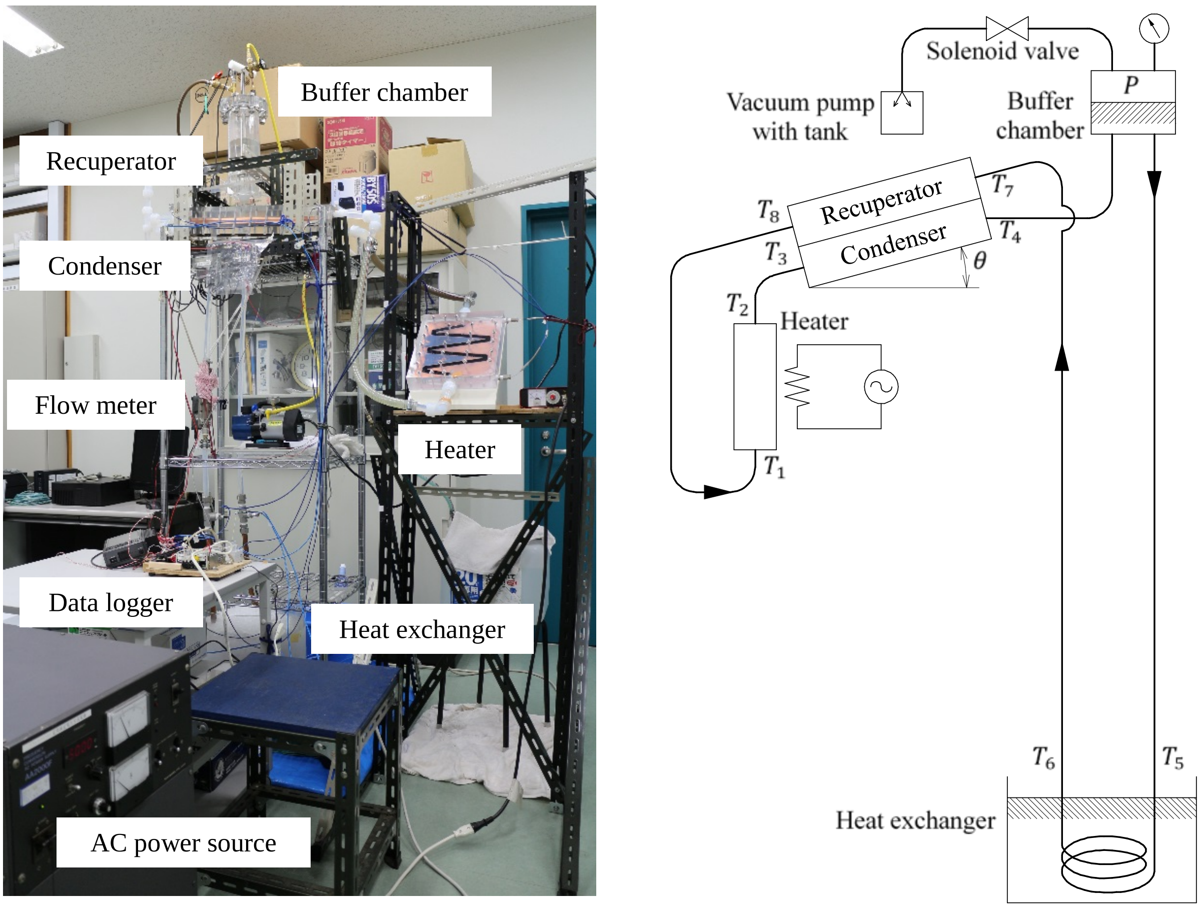
However, the practical use of the thermosiphon still has some problems. One of the problems is unstable heat transfer, that is, intermittent circulation flow rate of the working fluid. This happens under the condition of less solar radiation during morning and evening, and was investigated by conducting a field experiment using a model house (Hagino and Yoshida, 2011). To solve this problem, we propose a control system for the thermosiphon system to realize a stable heat transfer, namely almost constant flow rate of the working fluid, and generate the operation power for the controller from renewable energy such as photovoltaic energy. However, the control of the thermosiphon has been rarely studied (Bratsun et al., 2008). In this study, a method for reducing the buffer chamber pressure is adopted to stabilize the flow rate. The control system comprises a buffer chamber, a solenoid valve, a pressure transducer, a vacuum pump with tank, and an embedded computer, and the pressure of the buffer chamber is ratcheted down to avoid violent boiling. In addition, the effectiveness of the system is demonstrated using indoor experimental apparatus.

2. Experimental apparatus of thermosiphon and the operating principle

A photograph of the thermosiphon experimental apparatus is shown in Fig. 1(a), and the sematic illustration is shown in Fig. 1(b). This apparatus includes a buffer chamber, a recuperator, a condenser, a heater, a heat exchanger, and translucent pipes made of translucent perfluoroalkoxy alkane. Boiled water is used as the working fluid to reduce the amount of gas dissolved in the working fluid. The flow rate of the working fluid; the pressure of the buffer chamber; and the inlet and outlet temperatures of the heater, condenser, recuperator, and heat exchanger are measured and recorded in a multi-channel data logger. One feature of this apparatus is that it observes the boiling of the working fluid in the heater, two-phase flow in the flexible pipe from the heater to the condenser, and disappearance of vapor bubble in the condenser. To achieve this feature, one surface of the heater, condenser, and recuperator is made of a clear acrylic plate, and the translucent flexible heat-resistant pipes between the heater and the condenser.



(a) Photograph **(b) Schematic illustration**

Fig. 1: Experimental apparatus for thermosiphon utilizing vapor bubble pumping

Next, the operating principle of the experimental thermosiphon apparatus is explained. The pressure of the buffer chamber is first decreased using the vacuum pump for decreasing the boiling point of the working fluid. The working fluid is heated by the heater, which is modeled as a solar collector. The two-phase flow of the boiling working fluid moves upward in the pipe to the condenser and drives the entire working fluid. The vapor bubble of the two-phase flow disappears in the condenser by cooled water flowing through the recuperator, in contact with the condenser, and the working fluid flowing through the recuperator is preheated. The heated working fluid flows to the heat exchanger through the buffer chamber. The sensible heat of the working fluid transfers to a water cooled by the ice in the heat exchanger. Then, the cooled working fluid is preheated in the recuperator, and returned to the heater. In this system, the working fluid is circulated and the absorbed heat in the working fluid at the upper side of the system is transferred to the lower side.

3. Intermittent working flow under the condition of insufficient thermal energy input

The intermittent working flow under the condition of insufficient thermal energy input is examined here. Representative results obtained using the experimental apparatus mentioned above are shown in Figs. 2 and 3.

Figure 2 shows the result in the case where the input power of the heater is the simulated amount of solar radiation at the equinoctial point. The maximum input power of the heater is 200 W. The pressure of the buffer chamber in the beginning is about 30 kPa. The change in the input power of the heater is shown in Fig. 2(a), the changes in the temperatures of the heater inlet T_1 (thin line), outlet T_2 (bold line), and the calculated boiling point (broken line) are shown in Fig. 2(b). The changes in the temperatures of the condenser inlet T_3 (thin line) and outlet T_4 (bold line) are shown in Fig. 2(c), the changes in the temperatures of the heat exchanger inlet T_5 (thin line) and outlet T_6 (bold line) are shown in Fig. 2(d), and the changes in the temperatures of the recuperator inlet T_7 (thin line) and outlet T_8 (bold line) are shown in Fig. 2(e). The change in the pressure of the buffer chamber is shown in Fig. 2(f), and the change in the flow rate of the working fluid is shown in Fig. 2(g). The water in the heater starts boiling at about 225 min as the input power increases to about 62% of the maximum power. Next, the working fluid flows intermittently from about 225 min to 255 min, and T_1 fluctuates significantly. Then, the working fluid becomes stable because the temperature distribution of the fluid becomes stable.

Figure 3 shows the result in the case where the input power of the heater is the simulated amount of solar radiation at the equinoctial point and saturated at 64% of the maximum power simulating the cloudy weather. The maximum input power of the heater is 200 W. The pressure of the buffer chamber in the beginning is about 30 kPa. The water in the heater starts boiling at about 220 min as the input power increases to about 62% of the maximum power, and then, the working fluid continues to flow intermittently under the insufficient input power condition. Moreover, the temperatures fluctuate except for the heat exchanger input, because it is made stable by the fluid flowing through the buffer chamber.

For comparison, the result in the case where the maximum input power of the heater is 800 W is shown in Fig. 4. The input power of the heater is the simulated amount of solar radiation at the equinoctial point. The pressure of the buffer chamber in the beginning is about 30 kPa. The scales of vertical axes of Figs. 4(a), (f), and (g) are modified. The water in the heater starts boiling at about 120 min, as the input power increases to about 25% of the maximum power. The working fluid begins and continues to flow stably under the sufficient input power condition. Moreover, the temperatures become stable.

Therefore, in the next chapter, the control system is proposed to stabilize the intermittent flow of the working fluid under the condition of insufficient thermal energy input.

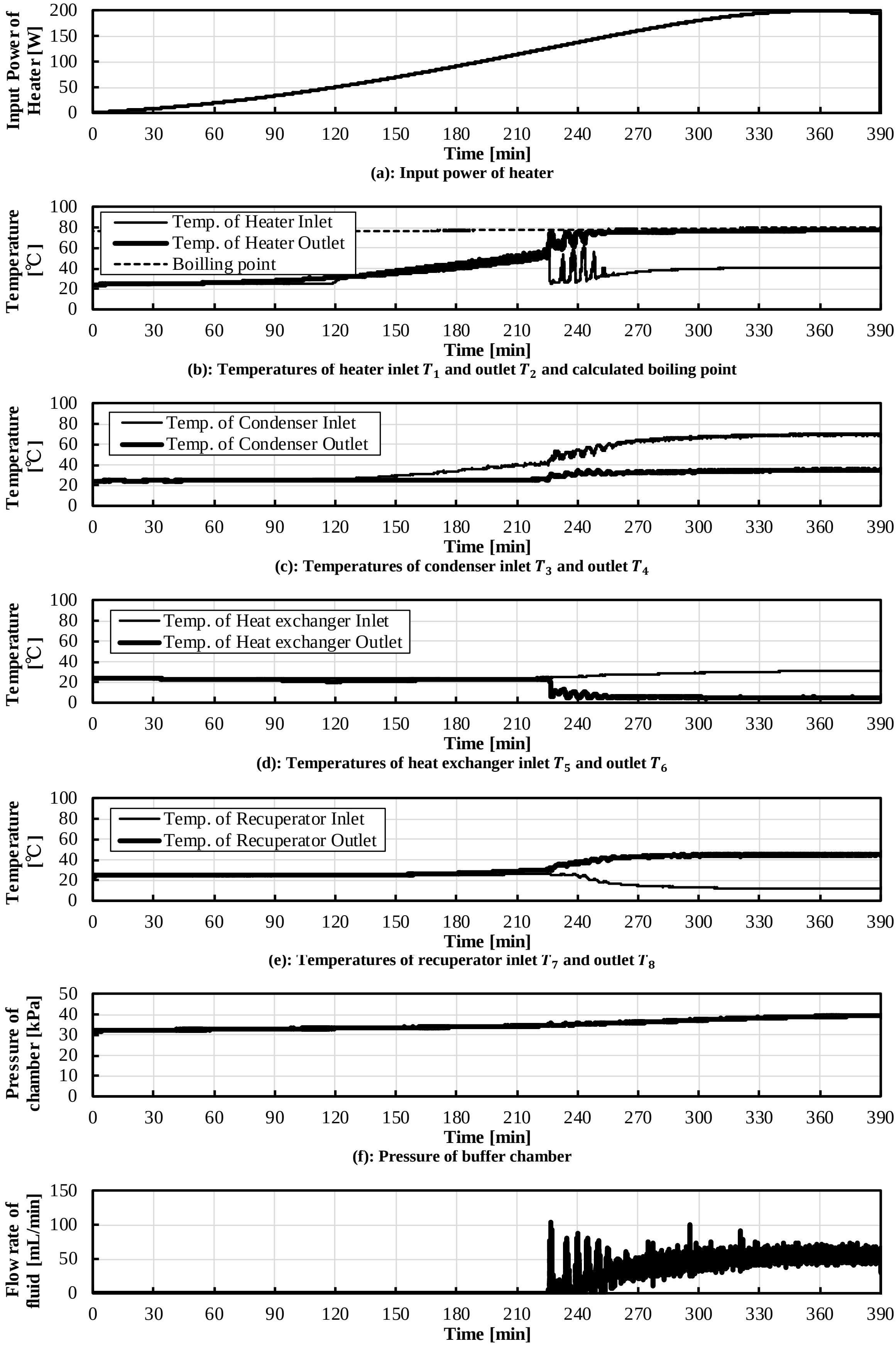


Fig. 2: Experimental result under the condition of insufficient thermal energy input (the input power is the simulated amount of solar radiation at the equinoctial point. The maximum input power is 200 W.)

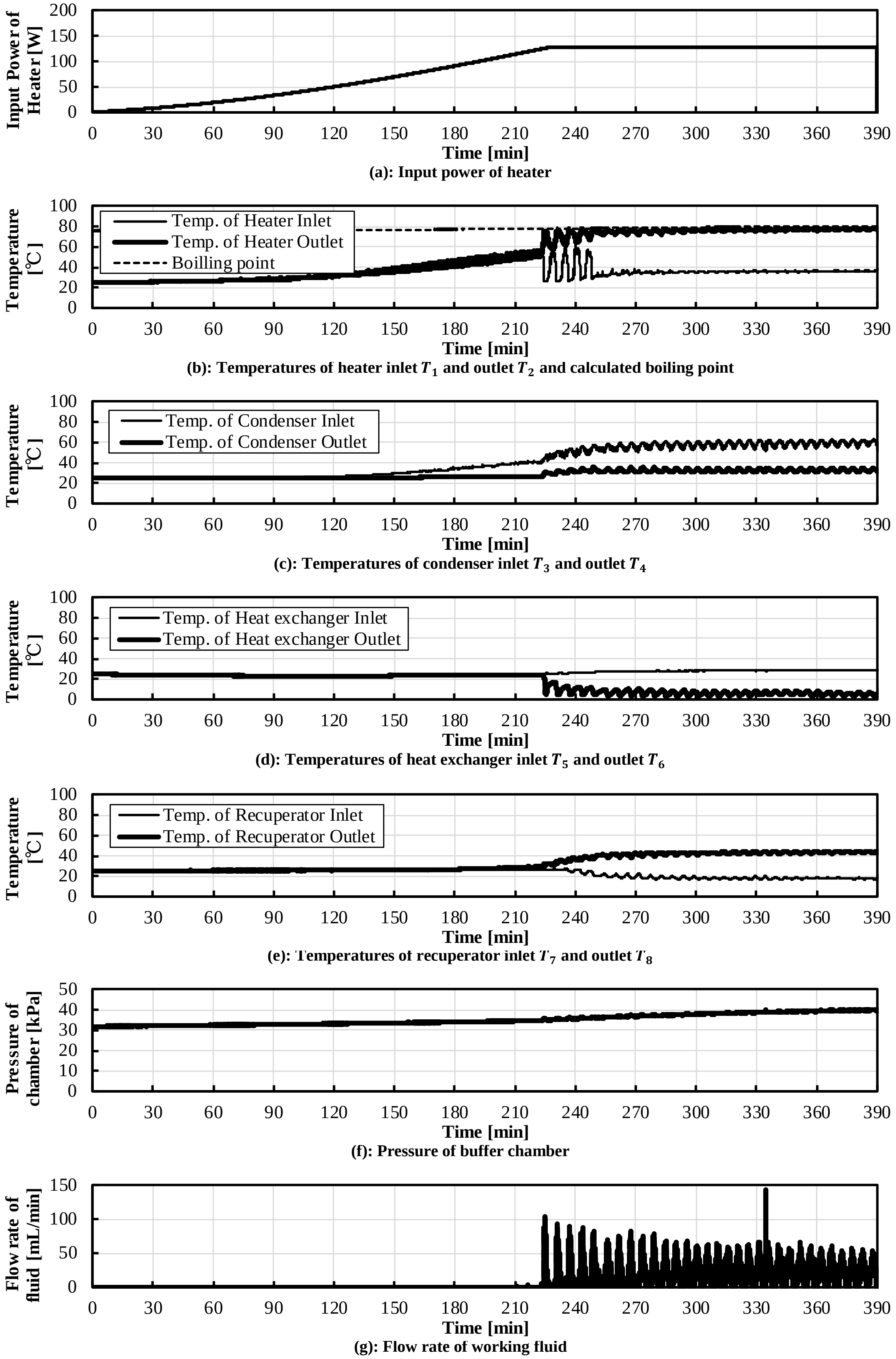
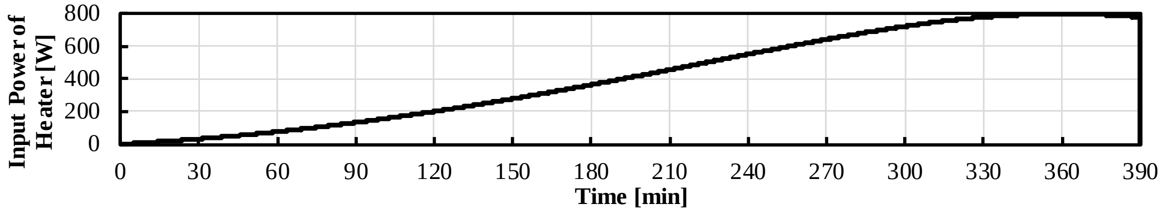
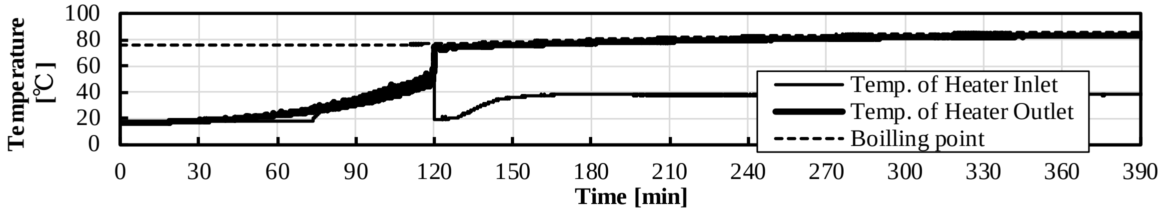


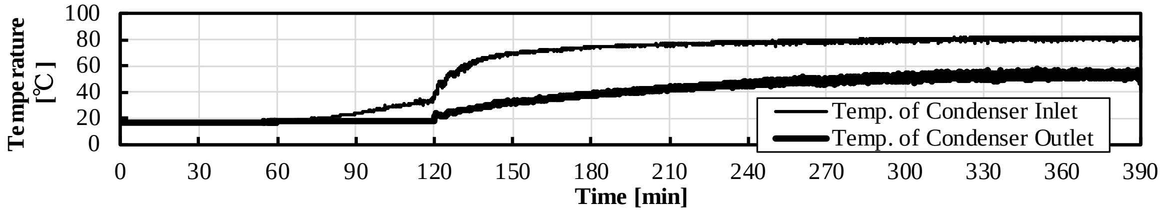
Fig. 3: Experimental result under the condition of insufficient thermal energy input (the input power is the simulated amount of solar radiation at the equinoctial point and saturated at 64% of the maximum power simulating the cloudy weather. The maximum input power is 200 W.)



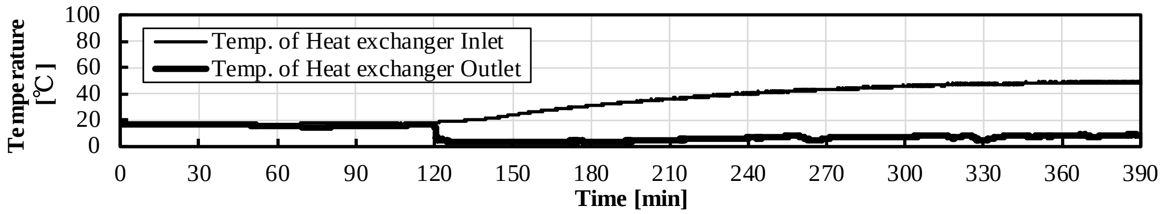
(a): Input power of heater



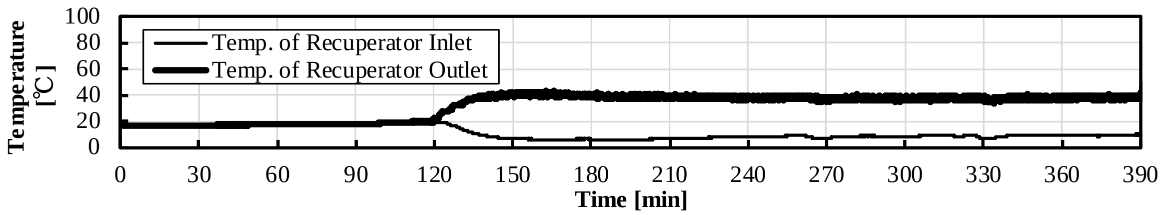
(b): Temperatures of heater inlet T_1 and outlet T_2 and calculated boiling point



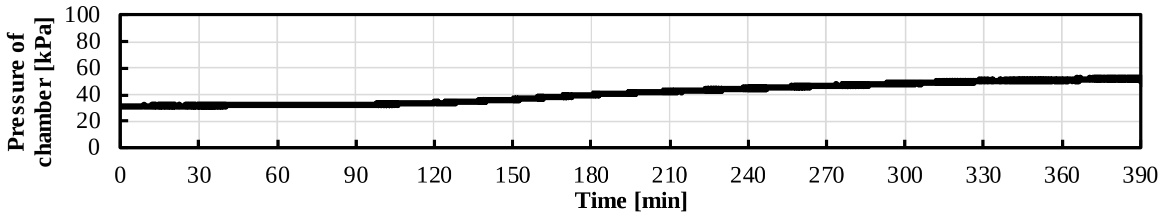
(c): Temperatures of condenser inlet T_3 and outlet T_4



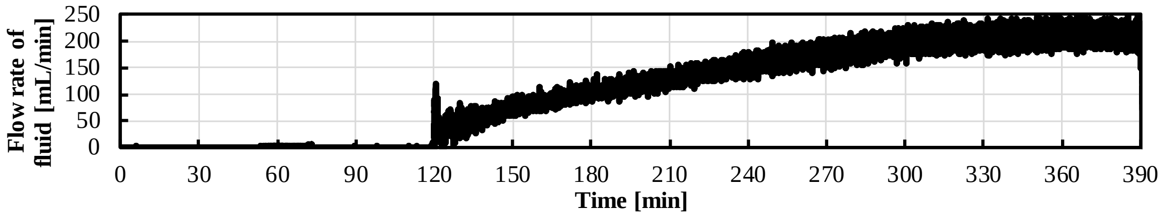
(d): Temperatures of heat exchanger inlet T_5 and outlet T_6



(e): Temperatures of recuperator inlet T_7 and outlet T_8



(f): Pressure of buffer chamber



(g): Flow rate of working fluid

Fig. 4: Experimental result under the condition of sufficient thermal energy input (the input power is the simulated amount of solar radiation at the equinoctial point. The maximum input power is 800 W.)

4. Thermosiphon control system

There are a few control methods available for stabilizing the intermittent circulation flow rate of the working fluid (Bratsun et al., 2008). We focuses on the control method used to adjust the pressure of the buffer chamber. The block diagram of the pressure control system for the thermosiphon is shown in Fig. 5. The control system comprises a solenoid valve, a pressure transducer, a vacuum pump with tank, and an embedded computer. The pressure of the buffer chamber and the flow rate of the working fluid are measured using a pressure gauge and a Coriolis flow meter, respectively. The pressure is ratcheted down slowly to avoid violent boiling.

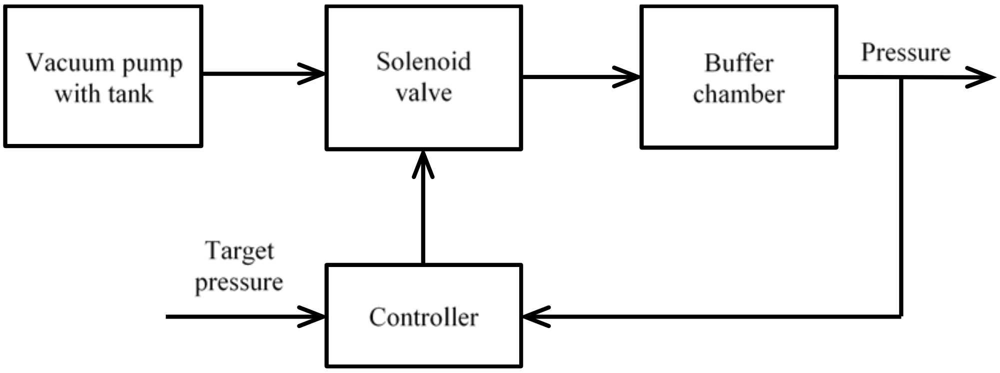


Fig. 5: Block diagram of the pressure control system for thermosiphon utilizing vapor bubble pumping

The working fluid in the heater begins to boil as the fluid is heated. However, the rest of the working fluid is still cold. The boiling fluid flows upward and toward the condenser with the vapor bubbles, and the cold fluid flows into the heater. Under the conditions of small thermal energy input from the heater, the flow of the working fluid stops, although it continues under the condition where enough thermal energy is supplied for boiling the fluid. Therefore, a stable flow rate of the working fluid can be achieved by decreasing the pressure of the buffer chamber to decrease the boiling point of the fluid.

Under this consideration based on the experimental results, we propose the following algorithm.

1. The control algorithm starts from the static condition of the thermosiphon, that is, no flow rate of the working fluid with no thermal energy supply.

2. The flow rate of the working fluid in the first boil is detected.

3. If the flow stops, the solenoid valve is opened for one second every 30 s until the pressure of the buffer chamber gradually decreases to the setting value.

5. Results of control experiment

The effectiveness of the proposed control system is verified by conducting control experiments using the thermosiphon experimental apparatus. Representative results obtained using the experimental apparatus mentioned above are shown in Figs. 6 and 7.

Figure 6 shows the result in the case where the input power of the heater is the simulated amount of solar radiation at the equinoctial point. The maximum input power of the heater is 200 W. The pressure of the buffer chamber in the beginning is about 30 kPa. The pressure of the vacuum tank is adjusted from 15 kPa to 23 kPa by the vacuum pump. The target pressure of the buffer chamber is set to 20 kPa. The water in the heater starts boiling at about 220 min as the input power increases to about 62% of the maximum power. Then, the pressure control system starts opening the solenoid valve for one second every 30 s until the pressure of the buffer chamber gradually decreases to the setting value. The pressure of the buffer chamber reaches the target pressure by opening the solenoid valve 10 times. The intermittent flow of the working fluid decreases in comparison with the result without control shown in Fig. 2. Therefore, the hard boiling of the heater, which degrades the heater, can also be avoided.

Figure 7 shows the result in the case where the input power of the heater is the simulated amount of solar radiation at the equinoctial point and saturated at 64% of the maximum power simulated the cloudy weather. The maximum input power of the heater is 200 W. The pressure of the vacuum tank is adjusted from 15 kPa to 23 kPa by the vacuum pump. The pressure of the buffer chamber in the beginning is about 30 kPa. The water in the heater starts boiling at about 225 min as the input power increases to about 62% of the maximum power. Then, the pressure control system starts opening the solenoid valve for one second every 30 s until the pressure of the buffer chamber gradually decreases to the setting value. The pressure of the buffer chamber reaches the target pressure by opening the solenoid valve six times. The intermittent flow of the working fluid is also decreased in comparison with the result without control shown in Fig. 3.

As a result, the intermittent flow under the condition of a small thermal energy input from the heater can be controlled by decreasing the pressure of the buffer chamber. Then, the effectiveness of the proposed control system can be confirmed using a model experiment.

If the pressure of the buffer chamber is further lowered, more stable circulation of the working fluid can be achieved. However, this requires more energy of the vacuum pump.

Subsequently, the photovoltaic capacity required for the proposed control system is estimated to operate the control system without any external electric power source.

Assumptions:

1. In the pressure control, a vacuum pump of 200 W rated power is operated for about 60 s per day, with an efficiency of 80%. Furthermore, the operation power of the embedded microcomputer and sensors is 5 W in total. Then, on average, an electric energy of 163 MJ is required per year.

2. A photovoltaic cell of 1 kW rated capacity generates electric energy of 1,100 kWh per year, on average, that is, 3.96 GJ per year.

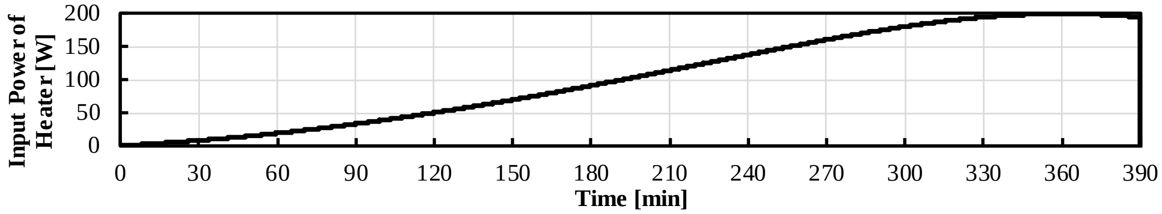
3. The area of a photovoltaic cell of 1 kW rated capacity is 5.19 m^2.

As a result, a photovoltaic cell of 41.2 W rated capacity is required, with an area of 0.214 m^2. Since the capacity and area of the photovoltaic cell are small enough, the feasibility of the proposed control system for the top-heat-type thermosiphon can be confirmed.

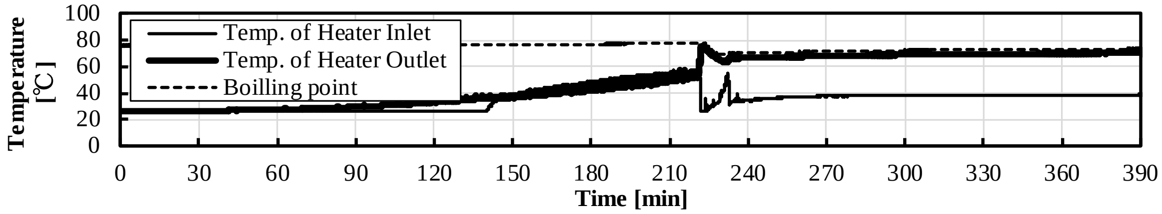
6. Conclusions

This paper focuses on the top-heat-type thermosiphon, which can facilitate heat transfer from solar energy collectors on the roof to an accumulator on the ground, which is the heat storage unit, without any external electric power source for using solar thermal energy. However, this has some problems, one of which is unstable heat transfer, that is, intermittent circulation flow rate of the working fluid. This happens under the condition of less solar radiation during morning and evening. To resolve this problem, a method for reducing the buffer chamber pressure is proposed to stabilize the flow rate of the working fluid. The effectiveness of this system is demonstrated using the indoor experimental apparatus.

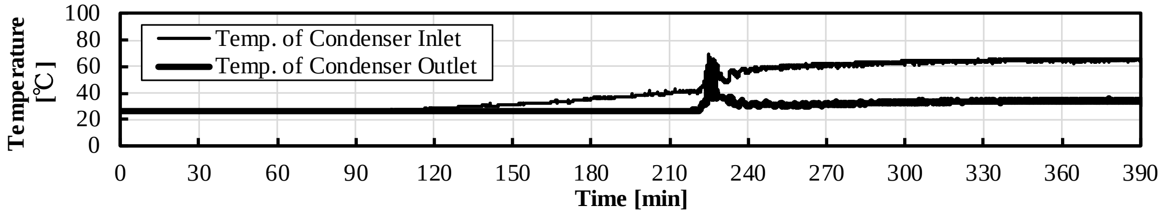
The development of the energy harvesting system for the power of the control system and the field test are future challenges.



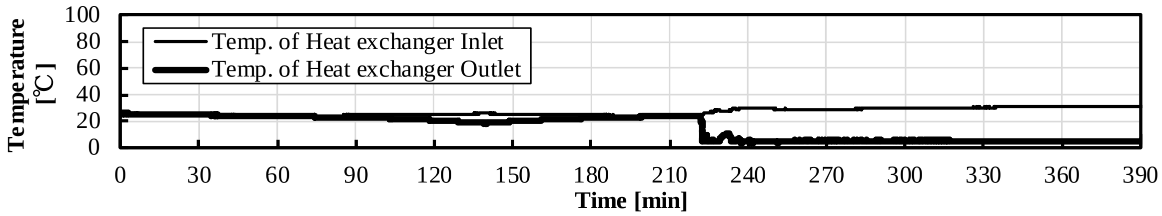
(a): Input power of heater



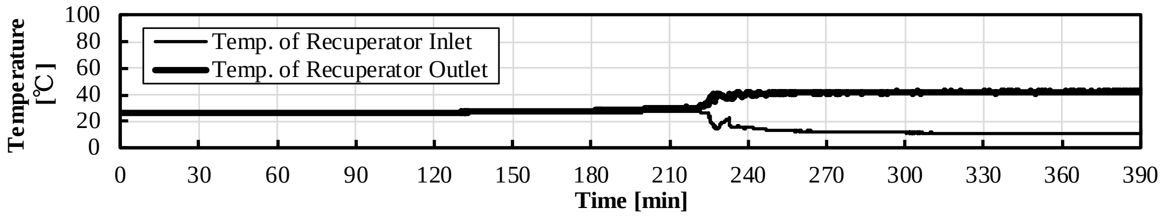
(b): Temperatures of heater inlet T_1 and outlet T_2 and calculated boiling point



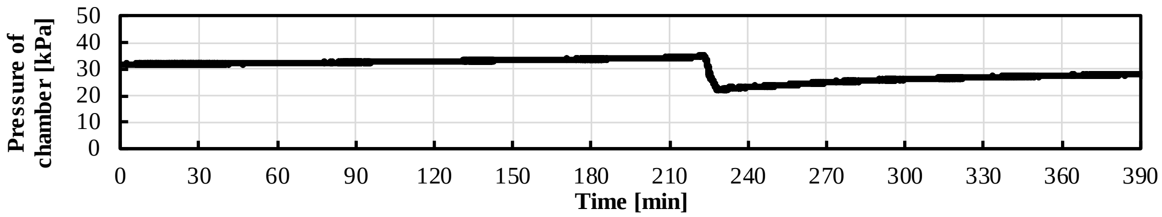
(c): Temperatures of condenser inlet T_3 and outlet T_4



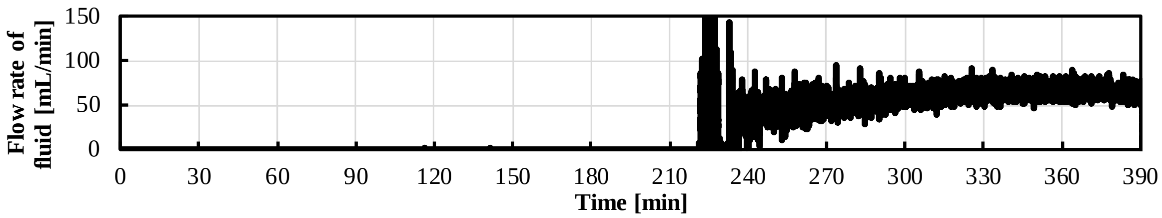
(d): Temperatures of heat exchanger inlet T_5 and outlet T_6



e): Temperatures of recuperator inlet T_7 and outlet T_8

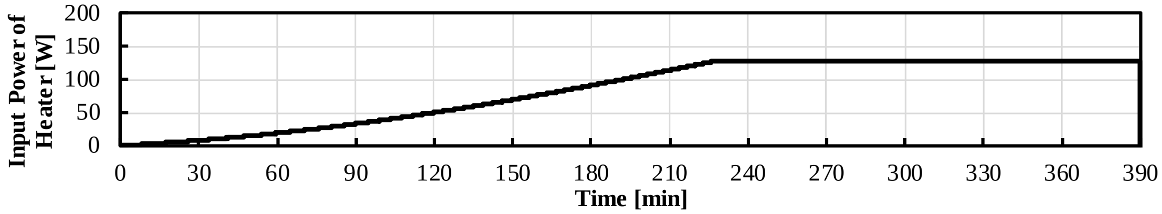


(f): Pressure of buffer chamber

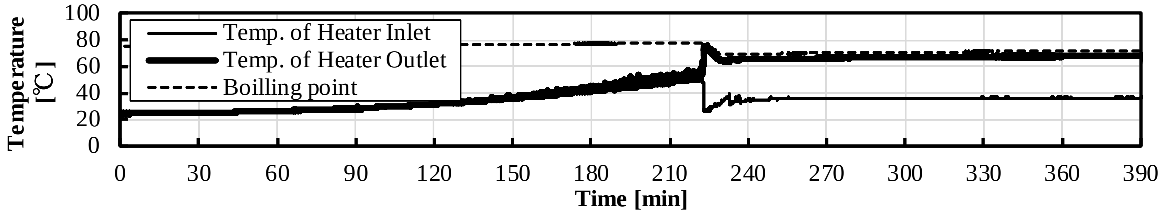


(g): Flow rate of working fluid

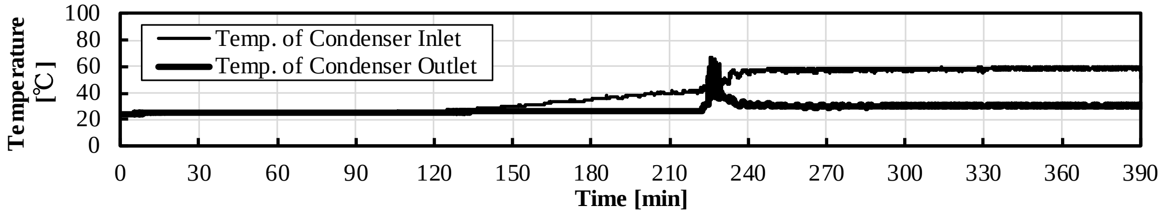
Fig. 6: Result of control experiment under the condition of insufficient thermal energy input (the input power is the simulated amount of solar radiation at the equinoctial point. The maximum input power is 200 W.)



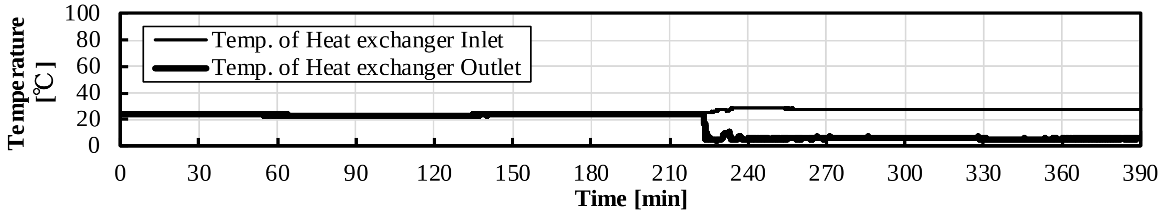
(a): Input power of heater



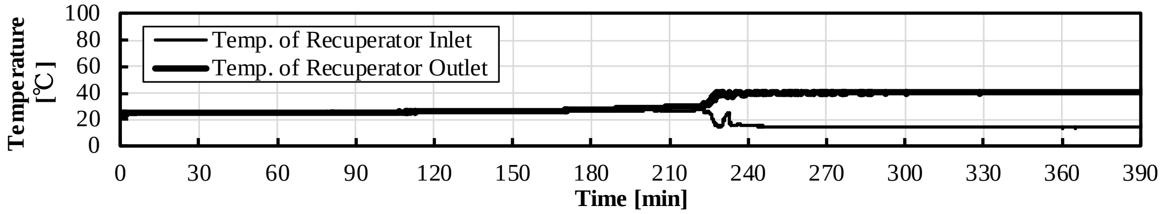
(b): Temperatures of heater inlet T_1 and outlet T_2 and calculated boiling point



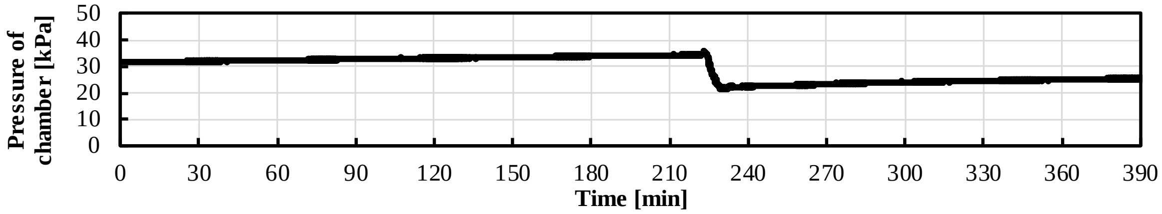
(c): Temperatures of condenser inlet T_3 and outlet T_4



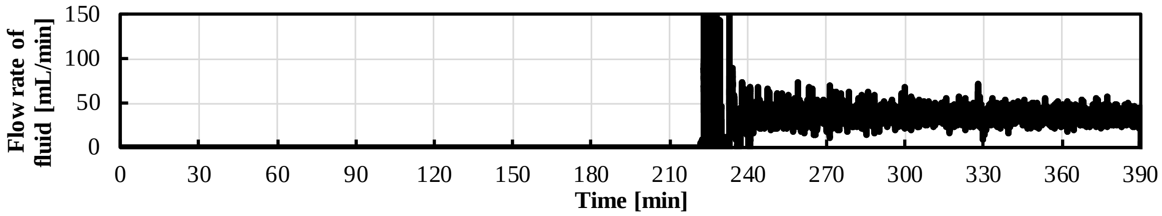
(d): Temperatures of heat exchanger inlet T_5 and outlet T_6



(e): Temperatures of recuperator inlet T_7 and outlet T_8



(f): Pressure of buffer chamber



(g): Flow rate of working fluid

Fig. 7: Result of control experiment under the condition of insufficient thermal energy input (the input power is the simulated amount of solar radiation at the equinoctial point and saturated at 64% of the maximum power simulating the cloudy weather. The maximum input power is 200 W.)

7. References

Bratsun, D.A., Zyuzgin, A.V., Polovinkin, K.V., Putin, G.F., 2008. Active Control of Fluid Equilibrium in a Thermosyphon. Tech. Phys. Lett. 34(8), 650-652.

Hagino, N., Yoshida, H., 2011. PERFORMANCE OF A SELF-CIRCULATING THERMOSYPHON. ASME Power Conference, July 12-14, Denver, Colorado, USA. POWER2011-55358.

Hagino, N., Yoshida, H., Imada, H., 2016. A study of self-circulating thermosiphon (Basic performance). Trans. Japan Soc. Mech. Eng. 82(837), DOI: 10.1299/transjsme.15-00596. (In Japanese)

Hirashima, M., Kimura, K., Utsumi, Y., Kimura, K., Negishi, K, 1993. Experimental Study of Top Heat Mode Thermosyphon (On the Lifting Mechanism of Working Fluid Effects on the Extension of Stable Working Range). Trans. Japan Soc. Refrig. Air Condition. Eng. 10(2), 83-92. (In Japanese)

Imada, H., Hagino, N., Yoshida, H., 2013. Field Experiment of Solar Thermosyphon. Trans. Japan Soc. Mech. Eng. Ser. B. 79(801), 809-813. (In Japanese)

Imura, H., Koito, Y., 2005. Heat Transport Using Top-heat-type Thermosyphons. Trans. Japan Soc. Refrig. Air Condition. Eng. 22(1), 1-12. (In Japanese)

Ippohshi, S., Tabara, S., Motomatu, K., Mutoh, A., Imura, H., 2003. DEVELOPMENT OF A TOP-HEAT-MODEL LOOP THERMOSYPHON. The 6th ASME-JSME Thermal Engineering Joint Conference, March 16-20, Hawaii. TED-AJ03-578.

Ito, S., Tateishi, K., Miura, N, 2007. STUDIES OF A THERMOSYPHON SYSTEM WITH A HEAT SOURCE NEAR THE TOP AND HEAT SINK AT THE BOTTOM. ISES Solar World Congress 2007, September 18-21, Beijing, China. 930-934.

Jafari, D., Franco, A., Filippeschi, S., Marco, P.D., 2016. Two-phase closed thermosyphons: A review of studies and solar applications. Renew. Sust. Energy Rev. 53, 575-593. DOI: 10.1016/j.rser.2015.09.002.

Jamar, A., Majid, Z.A.A., Azmi, W.H., Norhafana, M., Razak, A.A., 2016. A review of water heating system for solar energy applications. Int. Comm. Heat Mass Transfer. 76, 178-187. DOI: 10.1016/j.icheatmasstansfer.2016.05.028.

Koito, Y., Horiuchi, Y., Yamaguchi, T., Imura, H., Torii, S., 2006. Development of a Top-heat-type Heat Transport Loop Utilizing Vapor Pressure. Trans. Japan Soc. Mech. Eng. Ser. B. 72(718), 1574-1581. (In Japanese)

Morrison, G.L., 2001. Solar water heating, in: Gordon, J. (Ed.), Solar energy: the state of the art: ISES position papers, James & James, London, pp. 223-289.

Yoshida, H., Imada, H., Hagino, N, Yada, N., 2014. Hydropower Geberation by Solar Thermosyphon. International Conference on Solar Energy and Buildings (EuroSun 2014), September 16-19, Aix-les-Bains, France. 506-511. DOI: 10.18086/eurosun.2014.16.24.