Field experiment on flow stabilization of working fluid in a top-heat-type thermosyphon

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Abstract. To address the problem of global warming, increasing efforts are being made to use renewable sources of energy, such as solar energy, wind energy, and geothermal energy. However, the effective use remains a major challenge for its sustainable development. In this study, we used a top-heat-type thermosyphon to heat water using solar energy and transport the low-density hot water from the source to the sink (high to low elevation) without an external power source. The transported hot water can be used for cooking, bathing, underfloor heating, and heating homes and buildings, and warming cold springs. However, a disadvantage of top-heat-type thermosyphon is the intermittent flow of the circulating working fluid under low solar radiation. To address this issue, the authors proposed and developed a control system to stabilize the intermittent flow and prevent equipment damage and failure due to the sudden boiling of water. Field experiments were conducted to assess the practicability of the developed controller. The results showed that the controller efficiently converted the intermittent flow of working fluid to continuous flow by reducing the pressure in the buffer chamber and thus lowering the boiling point of the working fluid in the header of the solar collector.

1. Introduction

Increasing efforts are being made to reduce the emission of greenhouse gases to address the critical issue of global warming. These strategies include the use of renewable energy, such as solar energy, hydraulic power, wind power, geothermal power, and biomass energy, which are low-density energy sources with a wide global distribution. However, the effective use of renewable energy remains a key challenge for its sustainable development; thus, it is important to determine new ways to utilize renewable energy. A mainstream application of renewable energy is photovoltaic power generation, which conveniently converts solar energy into electricity. A certain amount of the generated power could be used as low-temperature heat, such as water heating. Solar energy can be used more effectively to produce hot water using solar collectors with a conversion efficiency of 40–50%, compared to producing hot water using the electric power generated by photovoltaic panels with a conversion efficiency of 15–20%.

To date, several measures have been adopted to utilize solar energy for heating water, including the use of a thermosyphon. Morrison [1], Jamar et al. [2], and Jafari et al. [3] have reviewed the applications of solar energy. In addition, there have been extensive studies on top-heat-type thermosyphons, which can transfer heat from high to low elevations without any external electric power source. The transported
hot water can be used for cooking, bathing, underfloor heating, and heating homes and buildings, and warming cold springs. Several types of top-heat-type thermosyphons have been proposed. Imura and Koito [4] reviewed the studies conducted on heat transfer using four types of top-heat type thermosyphons, namely loop heat pipe using a wick, vapor-lift pumping loop thermosyphon including two-phase flow top-heat thermosyphon, osmotic heat pipe, and vapor pressure anti-gravity thermosyphon including loop thermosyphon with a switching chamber. In addition, they discussed the improvements made in thermosyphons and the challenges faced. The loop heat pipe using a wick requires capillary tubes and the osmotic heat pipe requires semipermeable membranes, which hinder the increase in flow rate. The vapor pressure anti-gravity thermosyphon and the loop thermosyphon with a switching chamber have a complicated structure. Therefore, in this study, a vapor bubble pumping type thermosyphon, which circulates the working fluid using buoyancy forces of vapor bubbles generated by solar energy, was investigated for simplicity and scalability. This type thermosyphon is an improved version of two-phase flow top-heat thermosyphon.

Since the 1970s, there have been several studies on vapor bubble pumping type thermosyphons. Among these, Hirashima et al. [5] and Ippohshi et al. [6] have conducted early research on this type of thermosyphon. In these studies, the prototypes were manufactured and the heat transfer characteristics were experimentally investigated. Ito et al. [7] improved the condenser, and Yoshida et al. [8–11] continued the research of Ito et al., demonstrating the installation of a thermosyphon in a prefabricated full-scale model house to circulate working fluid with a height difference of 4 m and generate electricity using a small-scale power generator. These studies revealed some of the problems associated with this type of thermosyphon. One of the issues is the intermittent flow of the working fluid under low solar radiation in the morning and evening [10]. This intermittent flow causes sudden boiling of water in the header of the solar collector, resulting in equipment failure and shortened service life. In addition, studies on stabilizing the flow of circulating fluid in thermosyphons are limited [12–13]. Thus, a control system is needed to stabilize the flow rate of the working fluid. Therefore, we focused on a top-heat-type thermosyphon to utilize solar energy to heat water and transport low-density hot water from the top to the bottom of the thermosyphon without an external power source. Further, to solve the issue of the intermittent flow of the circulating working fluid in the thermosyphon, the authors proposed a control system to stabilize intermittent flow by reducing the buffer chamber pressure to lower the boiling point of the working fluid in the header of the solar collector. The effectiveness of the controller was validated using indoor models [14]. In this study, field experiments were conducted to evaluate the effectiveness of the control system by assessing its ability to change the flow of the working fluid from intermittent to continuous. In addition, the feasibility of the thermosyphon system with the controller was confirmed.

2. Operating principle of the top-heat-type thermosyphon

Figure 1 shows a schematic of the top-heat-type thermosyphon used in this study. The thermosyphon system consists of a solar collector, condenser, buffer chamber, heat exchanger, recuperator, and pipes. The vacuum pump decreases the pressure of the buffer chamber to lower the boiling point of the working fluid heated at the header of the solar collector. This results in buoyancy force-mediated upward flow of the boiling water with vapor bubbles along the pipes to the condenser, thereby driving the flow of the working fluid. The vapor bubbles in the two-phase flow disappear in the condenser upon cooling using the cold working fluid flowing through the recuperator, which is in contact with the condenser. The working fluid flows to the heat exchanger through the buffer chamber, and the thermal energy stored in the working fluid, that is, sensible heat, is transferred to water, cooled by the ice in the heat exchanger. The cooled working fluid is then preheated at the recuperator and returned to the header of the solar collector. Therefore, the collected thermal energy at the upper side of the system is transferred to the lower side without external power. Under a theoretical steady-state condition, all thermal energy obtained at the solar collector is transferred to the cooled water in the heat exchanger with no heat dissipation. Meanwhile, the latent heat and some
amount of sensible heat in the working fluid circulate in the solar collector, condenser, and recuperator only.

3. Field experimental facility of the top-heat-type thermosyphon

Figure 2 shows a photograph of the field experimental facility of the top-heat-type thermosyphon used in the study.

The flow rate of the working fluid was measured by a Coriolis flow meter FD-SS02A produced by KEYENCE Co. The pressure in the buffer chamber was measured by a pressure sensor AP10S (-100–100 kPa) produced by KEYENCE Co. The inlet and outlet temperatures of the solar collector, heat exchanger, condenser, and recuperator, and ambient air temperature were measured by a type K thermocouple. The amount of solar radiation perpendicular to the solar collector was measured with a pyranometer MS-602 produced by EKO Instruments Co. Ltd. The measured data were recorded using a multi-channel data logger system GL220 produced by Graphite Co.

In this facility, one surface of the condenser and recuperator was made of a clear acrylic plate. Translucent flexible heat-resistant pipes were used from the condenser to the recuperator to observe the bubbles, especially their disappearance in the condenser. The working fluid used in the system was boiled tap water cooled to ambient air temperature to reduce the amount of dissolved air.

4. Intermittent flow of the working fluid

Figure 3 shows the measurement results of the thermosyphon without flow control, that is, atmospheric pressure exists in the buffer chamber on a sunny day.

From figure 3, it can be seen that the working fluid clearly exhibits a continuous flow because of sufficient thermal energy obtained from solar radiation on a sunny day. Under these conditions, the temperature of the working fluid in the header of the solar collector reaches its boiling point.

Figure 4 shows the results without flow control, that is, atmospheric pressure exists in the buffer chamber on a sunny day with occasional thin clouds.
Figure 3. Measurement results of the thermosyphon without control on a sunny day, in which the working fluid exhibits a continuous flow.

Figure 4. Measurement result of the thermosyphon without flow control on a sunny day with occasional thin clouds, in which the working fluid exhibits an intermittent flow.
Figure 4 shows that the working fluid exhibited an intermittent flow as it did not obtain sufficient thermal energy from the solar radiation on a sunny day with occasional thin clouds. Under this condition, the temperature of the working fluid at the condenser inlet fluctuates. Nonetheless, the temperature of the working fluid in the header of the solar collector reaches its boiling point. The insufficient latent heat absorbed by the working fluid results in discontinuous boiling under a limited amount of solar radiation. To convert the intermittent flow of the working fluid into a continuous flow, the pressure in the buffer chamber was reduced. The experimental results with the manual pressure control of the buffer chamber on a sunny day with occasional thin clouds are shown in figure 5.

As the amount of solar radiation increases, the working fluid exhibits an intermittent flow starting at approximately 120 min. The flow of the working fluid then changes to a continuous flow by slowly reducing the pressure in the buffer chamber at 168.9 min to prevent excess boiling. Therefore, these results confirm the effectiveness of the proposed method by changing the pressure of the buffer chamber to lower the boiling point of the working fluid.
5. Stabilizing the intermittent flow of the working fluid

A control system consisting of a solenoid valve, pressure transducer, vacuum pump with a tank, and embedded computer was subsequently employed to stabilize the intermittent flow of the working fluid. An algorithm encoded in a microcontroller board Arduino Uno was implemented to decrease the pressure in the buffer chamber to -80 kPa when the flow rate of the working fluid was above 30 mL/min and below 10 mL/min and this change was repeated three times within 18 min. The experimental results using the control system on a fairly sunny day are shown in figure 6. In this system, the pressure in the buffer chamber decreased from the beginning to promote a continuous flow of the working fluid.

As the amount of solar radiation increased, the working fluid exhibited an intermittent flow at 77.15 min. The controller detected the intermittent flow of the working fluid and reduced the pressure in the buffer chamber. Subsequently, the intermittent flow changed to a continuous flow at 83.65 min. After a while, the continuous flow reverted to intermittent flow at 90.35 min because of the increase in the boiling point with a slow increase in the pressure in the buffer chamber due to a small air leak. Subsequently, the controller detected the intermittent flow and reduced the pressure in the buffer chamber. The interval of the changes in the intermittent flow depends on the amount of solar radiation received. The controller stopped working at 230 min and the intermittent flow of the working fluid

![Figure 6](image-url)
continued thereafter. Therefore, these results confirm the feasibility of the thermosyphon with the controller.

Figure 7 shows the experimental result with the control system on a sunny day with the target pressure in the buffer chamber set to -75 kPa.

Figure 7. Experimental result of the thermosyphon with a pressure control system that set the buffer chamber pressure to -75 kPa on a sunny day, exhibiting the conversion of the intermittent flow of the working fluid to a continuous flow.

Even if the pressure reached its target value at 37.45 min, the working fluid continued to exhibit an intermittent flow until 80.45 min due to its boiling point, which was higher than that in the case with higher target pressure, as depicted in figure 6. Subsequently, the flow of the working fluid was converted to a continuous flow at 80.45 min as the amount of solar radiation increased until sufficient latent heat was obtained for continuous boiling. Although the pressure increased, the continuous flow was maintained due to a large amount of solar radiation received after 130 min. Therefore, the target pressure in the buffer chamber should be set according to the capacity of the thermosyphon system.

6. Considerations
The aim of this study was to assess the practicability of the proposed controller by conducting field experiments. The experimental equipment, i.e., thermosyphon, consisted of translucent flexible heat-resistant pipes to observe air bubbles instead of heat insulation. Although the temperature difference
between the condenser outlet and the heat exchanger inlet is large, it does not affect the heat transfer performance and the control performance. In contrast, the temperatures of the condenser inlet and the header outlet of the solar collector are almost the same because of the insulated pipes between them, which affect the circulation of the working fluid.

The decrease in the temperature in the condenser is attributed to the transfer of latent heat and sensible heat to the recuperator. The transferred heat contributes to evaporation at the header. Therefore, the energy wastage is prevented and the effective transport of hot water from the top (source) to the bottom (sink) is ensured, when the pipes are insulated perfectly.

The flow of working fluid in the thermosyphon is greatly affected by the amount of solar radiation received. Small amounts of solar radiation do not cause a flow, whereas a large amount of solar radiation causes a continuous flow. Intermittent flow occurs when the amount of solar radiation received is insufficient to allow a continuous flow of the working fluid. It is not possible to conduct all field experiments under the same weather conditions and thus the amount of solar radiation received differs in each experimental result. In this paper, the experimental results showing intermittent flow were presented to assess the practicability of the proposed controller.

Even if the amount of solar radiation changes rapidly, the flow rate of working fluid does not change significantly unlike the amount of power generation of photovoltaic panels, because of the large time constant of the thermosyphon. The rapid changes are not cause of the intermittent flow.

The reason for intermittent flow is related to the solar input. When the amount of solar radiation received is large, the working fluid, which is cold water preheated in the recuperator moves to the header and is continuously boiled, resulting in its continuous flow. However, when the amount of solar radiation received is less, the inflowing cold water cannot be boiled continuously and the flow stops. Upon boiling, the water in the header flows out; the preheated cold water flows into the header and boiling stops. This process is repeated, resulting in the intermittent flow of the working fluid. Therefore, the occurrence of intermittent flow is related to the capacity of the solar collector and the volume of the header with respect to the amount of solar radiation.

7. Conclusions
In this study, we evaluated the ability of a top-heat-type thermosyphon to effectively use solar energy and its feasibility of the thermosyphon with a control system to stabilize the flow of the working fluid. Particularly, we studied the intermittent flow of the circulating working fluid in this type of thermosyphon under low solar radiation as this can damage the equipment due to the sudden boiling of water. The practicability of the proposed controller system was assessed by conducting field experiments, in which the intermittent flow of the working fluid was converted to a continuous flow by reducing the pressure in the buffer chamber due to lower the boiling point of the working fluid in the header of the solar collector after three pulsations of the flow rate of working fluid was detected. In addition, the results highlighted the significance of setting an appropriate target pressure of the controller. In this experimental facility, the target pressure was set to -80 kPa, and it should be set according to the capacity of the thermosyphon system. After all, the top-heat-type thermosyphon with the controller effectively uses solar energy to heat water that can be used for cooking, bathing, underfloor heating, and heating homes and buildings, and warming cold springs.

In the future, we will focus on harnessing solar energy using thermosyphons equipped with controllers without using an external power source.

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