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Research paper

Thermosiphon loop thermal collector for low-temperature waste heat recovery

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HIGHLIGHTS

- The new thermosiphon loop thermal collector is proposed for the waste heat recovery.
- Using water as working fluid enabled to transport heat as hot as 150 °C.
- The effective thermal conductivity of this apparatus is 200 times as high as copper.
- This apparatus maintains preferable performance when inclined to horizontal setting.

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ABSTRACT

This paper describes the thermal collector type loop thermosiphon for low-temperature waste heat recovery. Water is used as the working fluid for heat transport at temperatures 100 °C and higher. The loop thermosiphon comprises of a thermal receiver, a condenser, and riser and downcomer tubes. The thermal receiver is made of a cupper plate brazed by meandering heat transfer tube. This receiver collects the thermal radiation from the electric heater at the heat transfer area of 1000 cm^2 (40 cm × 25 cm), and transports the heat by vaporization of water to the condenser having heat transfer area of 62 cm^2. In the no inclination mode, the thermosiphon is upright so that the thermal receiver and the condenser are placed vertically. In this mode, the effective thermal conductivity exceeds 60 kW/(m K) when the thermal receiver temperature was higher than 125 °C for the water filling ratio $\alpha = 30–70\%$. Although the effective thermal conductivity is deteriorated for the higher filling ratio $\alpha = 80\%$ and 90%, the effects from the filling ratio are tiny for $\alpha = 30–70\%$. The experimental tests were also made for the negatively inclined mode where the inlet and exit ports of the receiver were directed downward and for the positively inclined modes where they were directed upward. The tests revealed that the negative inclination almost halted the heat transport. However, the tests also indicated that the positive inclination showed the performance comparable to the no inclination mode for the cases up to the inclination angle 90°.

1. Introduction

There is an increasing concern about reducing fossil fuel consumption. This concern arises from the diminishing energy resources and increasing carbon dioxide levels in the atmosphere. Therefore, it is becoming more important to utilize low-temperature waste heat, which is now mostly unused. Fig. 1 shows the statistics from Japan in 2011 [1]. The figure reveals that a large amount of waste heat was exhausted at temperatures below 200 °C. The annual waste heat between 100 °C and 200 °C is 282 peta (10^{15}) calories, which is 9.1% of the crude oil consumption there. The recovery of low-temperature waste heat is important for slashing fossil fuel consumption. Heat transfer devices are expected to be developed for waste heat recovery. A device with no external means of power is desirable because of the low density of the waste heat.

Loop-style thermosiphons have been emerging as transportation devices. These have been applied for the removal of high-density thermal loads. Their apparent thermal conductivity exceeds 200 times that of copper [2,3]. Academic papers were published on a thermosiphon loop for electronics cooling [4–10]. Previous papers used isobutene, pentane, and nitrogen as thermal media,

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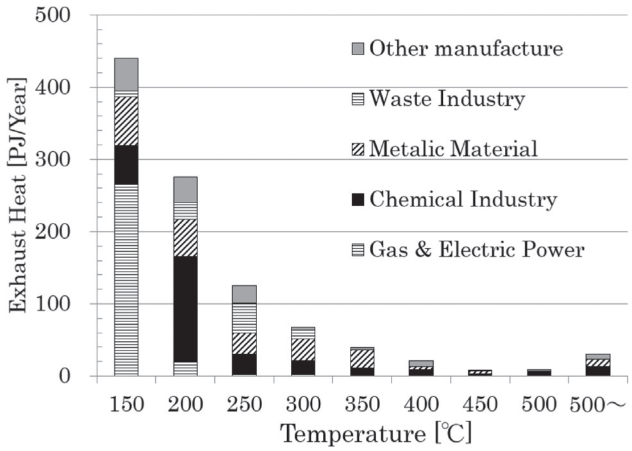

Fig. 1. Exhaust heat in Japan, 2011.

setting temperatures at about 50 °C [4–10]. More recently, Khodabandeh experimentally examined a radio base station cooling loop that was filled with isobutene [11]. Dube et al. performed experiments on the effects of a noncondensable gas on loop thermosiphon heat exchangers with water as the working fluid [12]. Khodabandeh and Furberg [13] visualized the bubbly flow of R134a by using an evaporator with a polycarbonate window [13]. Sarno et al. [14] tested the passive cooling system of an R141 loop for in-flight entertainment avionics. Samba et al. [15] performed transient and steady-state analyses of an n-pentane thermosiphon loop for cooling outdoor telecommunication equipment. Zimmermann and Melo experimented on a carbon dioxide thermosiphon loop for a Stirling cooler [16]. Li et al. [17] performed a visualization experiment of an insert-type closed loop water thermosiphon for solar water heaters. Zhang et al. [18] proposed the integration of a mechanical refrigeration system and thermosiphon for the free cooling of data centers. Xie et al. [19] investigated a dual compensation chamber loop heat pipe subjected to an acceleration field for high-power and high-heat-flux electronic devices in aircraft and spacecraft.

Increasing numbers of academic papers have recently been written on the thermosiphon loop. Most of these papers intended to contribute to electronics cooling and they treated refrigerants as the working fluid [4–11,13–16,18,19]. These papers set the working temperatures at levels from 0 °C to 50 °C, which are not high enough for waste heat transport. Few papers [12,17] used water as the working fluid, setting a temperature as high as 100 °C. However, there are only limited cases of experiments for working temperatures higher than 100 °C. There are still many unknown points concerning how a thermosiphon loop works and what phenomena occur under high-temperature conditions.

The group at Niigata University [2] developed a water thermosiphon loop for waste heat recovery. The evaporator, consisting of three layers of copper blocks, was designed to resist the high saturation pressure of water. This thermosiphon loop of water works for high-temperature conditions in which the condenser wall temperature was increased beyond 150 °C. This is because critical temperature of water is 374 °C and phase change occurs for the temperatures under the critical temperature. This paper extends the previous study [2] to consider the thermal-collector-type thermosiphon loop with water. The heat transfer area of the evaporator was enlarged by using a meandering pipe attached to a copper plate. Series of experiments were conducted for this thermal collector loop to reveal circulation flow stability and heat transfer characteristics.

2. Experimental method

Fig. 2 shows a photograph and line drawing of the thermal collector thermosiphon loop. This apparatus comprises a thermal receiver plate, condenser, riser, and downcomer. The thermal receiver plate is made of copper. The riser and downcomer are bent stainless steel tubes. The thermal receiver is heated from the bottom surface by an infrared lamp heater. The condenser is cooled by a stream of coolant water. The working fluid is designed to circulate in the thermosiphon loop by natural convection. This can be confirmed by the temperature distribution, as will be discussed later. The heat transfer area of the receiver plate is 1000 cm^2 (40 cm × 25 cm). That of the condenser wall is 62 cm^2 ($\pi \times 0.8$ cm × 25 cm). The low-density heat flux of the waste heat is thus intended to be increased at the condenser by shrinking the heat transfer area. The ratio of receiver plate to condenser wall area is 1000:62 = 16.2:1.

As shown in Fig. 3, the thermal receiver plate is soldered to a meandering copper tube. This tube is made by pressing a round tube (φ = 8.0 mm, thickness = 5 mm) until it has an oval cross section with a height of 5 mm and width of 10 mm. The tube was pressed so that it has a larger surface to contact the plate in order to reduce thermal resistance. The condenser is an annulus with a copper center pipe and aluminum alloy shell, as indicated in Fig. 3. The preliminary experiment revealed that the coolant water was boiled in the copper pipe and exited the condenser as a bubbly stream. This was not suitable for the determination of recovered heat because the difficulty of obtaining quality measurements. The copper condenser pipe was thus covered by a stainless steel jacket with a thickness of 6.0 mm to increase the thermal resistance. This could prevent the coolant water from boiling and allow the recovered heat to be calculated on the basis of the temperature difference between the inlet and exit of the condenser cooling side. The thermosiphon loop is insulated by foam insulation on the riser and downcomer, and by sheet insulation on the thermal receiver and condenser. The temperature distribution is measured using thermocouples set on the thermal receiver and tube joints, as illustrated in Fig. 2. The recovered heat was obtained from the temperature difference and flow rate of the coolant water.

Table 1 summarizes the experimental conditions. The water filling ratio is defined as the ratio of the mass of filled water to the mass that can fill the entire volume of the loop $V_{max} = 105$ mL, $\alpha = m/m_{\max}$. Measurements were performed for the case where the thermosiphon loop was mounted at an inclination angle of 0° and the case where the loop was inclined from –45 to 90°. The definition of the mounting angle is as shown in Fig. 4. The thermosiphon loop with no inclination was tested with a water filling ratio that changed from 0.3 to 0.9, whereas the inclined loop was tested with the water filling ratio fixed at 0.3. The thermal load was regulated by changing the input voltage to the infrared lamp heater from 50 V to 100 V. Heat radiation occurred from the infrared lamp to the thermal receiver. Since the absorption rate of radiation at the thermal receiver plate is not very clear in the experiment, its temperature was used to represent the experimental condition. This temperature was set at 80–200 °C for the non-inclined thermosiphon loop and at 70–170 °C for the inclined loop. Temperature is measured by thermocouples at seven positions indicated in Fig. 2. Pressure is measured at positions 4 and 5 indicated in Fig. 2. The pressure sensor is a strain gauge type pressure transmitter, KM31, produced by Nagano Keiki.