Evaluation on cooling performance and reliability of low-height aluminum thermosyphon in high-temperature environment

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Received: 22 April 2019; Revised: 6 June 2019; Accepted: 17 June 2019

Abstract
Information and communication technology (ICT) cooling devices increasingly need to be able to be installed in high-density packaged equipments, especially those exposed to high-temperature environments such as 1U-height servers and packet transport systems (PTS) for telecommunication networks. Therefore, in this study, we have developed a low-height and cost-effective aluminum thermosyphon with a boiling surface that has a porous structure by using a micro-curl skived fin and fluorine-based refrigerant (HFE7000) usable at over 50 °C. This research aimed to evaluate the cooling performance and reliability of this aluminum thermosyphon when exposed to temperatures over 50 °C and to determine an operating limit temperature. Thus, we carried out cooling performance tests of our thermosyphon supplied with hot air up to 100 °C and high-temperature aging tests to examine its corrosiveness in an environment containing aluminum and HFE7000. From these examinations, we concluded the following. (1) The cooling performance at a heat input of 100 W was quite stable with the intake air up to 100 °C without an excessive temperature rise of the boiling surface. (2) Until the intake air was up to 60 °C, in which the plastic deformation of the boiling part did not occur, the thermal resistance of the boiling surface decreased as the increase of the saturated vapor pressure, and the minimum wall superheat of the boiling surface was 1.6 K and the maximum boiling-heat-transfer coefficient was 57 kW/(m²°K). (3) The generation rate of fluorine ions increased as the temperature rose due to the promotion of the hydrolysis reaction between HFE7000 and dissolved water. (4) Under an actual use condition of the thermosyphon, fluorine ions due to the hydrolysis reaction of HFE7000 were barely generated, and aluminum corrosion due to fluorine adsorbed on the aluminum surface barely occurred either. (5) The operating limit temperature of this aluminum thermosyphon was 60 °C from strength constraints.

Keywords: Aluminum thermosyphon, Fluorine-based refrigerant, Boiling-heat-transfer, Micro-curl skived fin, Fluorine ion, Cooling performance, Reliability

1. Introduction

Information and communication technology (ICT) cooling devices increasingly need to be able to be installed inexpensively in high-density packaged equipments such as 1U-height servers and packet transport systems (PTS) for telecommunication networks. Also, these ICT equipments need to have enough environmental resistance to meet customer demands of usage in high-temperature environments around 50 °C. Furthermore, from the viewpoint of cost and weight reduction, even these cooling devices need to be made of aluminum.

As a cooling device, a thermosyphon has attracted attention from the viewpoint of cooling performance and power saving. A thermosyphon is a cooling device that uses boiling and condensing heat-transfer to effectively transport heat generated from elements such as central processing units (CPUs) into a heat sink without using a power source (e.g., pump) (Lamaison et al., 2017). For cooling ICT equipments, thermosyphons have been widely studied so far, especially those
made of copper with water coolant (Toyoda et al., 2012, 2014) (Fujimoto et al., 2014). These studies clarified the effects of the tilt angle and the amount of non-condensable gases dissolved in water coolant on heat-transfer performance (Toyoda et al., 2012, 2014). In these studies, boiling surfaces have a porous structure represented by small interconnected cavities and openings through which these cavities communicate with the surrounding water coolant in order to enhance the boiling-heat-transfer performance (Nakayama et al., 1980a, 1980b, 1982). However, the cooling performance and reliability of aluminum thermosyphons, especially in high-temperature environments, have not been studied so far.

Therefore, in this study, we have developed an aluminum low-height thermosyphon for cooling high-density packaged ICT equipments usable at over 50 °C. We fabricated the prototype of the aluminum thermosyphon with fluorne-based refrigerant (HFE7000) and the boiling surface that has micro cavities formed by a micro-curl skived fin to meet further demands of downsizing for installation in 1U-height servers at low cost. This research aimed to evaluate the cooling performance and reliability of our aluminum thermosyphon when exposed to temperatures over 50 °C and to determine an operating limit temperature. Thus, we carried out cooling performance tests supplied with hot air up to 100 °C and high-temperature aging tests to examine its corrosiveness in an environment containing aluminum and HFE7000.

2. Aluminum thermosyphon and experimental method

Figure 1 and 2 show the prototype of our low-height aluminum thermosyphon and the boiling surface having a porous structure with a micro-curl skived fin. The thermosyphon consists of the boiling part with the boiling surface, the condensing part, and the heat sink (air heat exchanger), which were all made of aluminum (alloy No.1050). All aluminum parts were connected simultaneously by aluminum brazing in a vacuum furnace, and 25 cc of the degassed HFE7000 (C₃F₇OCH₃) was encapsulated into the thermosyphon under reduced pressure. Water coolant is commonly known to generate a non-condensable hydrogen gas by reacting with aluminum, which deteriorates the condensing performance. Thus, considering the environmental load of refrigerant and the boiling point which is relatively close to the environmental temperature, we selected a fluorine-based refrigerant HFE7000 with a boiling point of 34 °C at atmospheric pressure and a latent heat of vaporization of 142 kJ/kg.

By receiving heat from a heat-generating element, such as a CPU, HFE7000 is vaporized on the aluminum boiling surface with the dimensions of 30 mm × 38 mm and the base thickness of 1.3 mm. It is then condensed on the corrugate fin in the condensing part by exchanging heat with intake air at the heat sink also consisting of a corrugate fin which has the same size as that of the condensing part (the corrugate fin thickness and fin gap are 0.2 and 0.8 mm, respectively). Condensed HFE7000 then flows back to the boiling surface due to gravity without the need to use a pump. The micro-curl skived fin of the boiling surface was manufactured inexpensively by continuously cultivating the aluminum base metal and has many micro cavities (400 - 500 μm) to retain vapor bubbles inside the boiling surface and stabilize bubble desorption.

Figure 3 illustrates the experimental apparatus used to evaluate heat-transfer performances in the high-temperature environment. The boiling part of the thermosyphon was set on the copper heater block which has the same size as the boiling surface (30 mm × 38 mm) through the thermal-conductivity grease (3.1 W/(mK)) with a pressing load of 10 kgf, which is a general mounting load of a CPU's heat sink. The controlled intake air with the temperature from 25 to 100 °C and flow rate 0.2 m³/min (flow velocity 1.4 m/s) was supplied to the heat sink through the air duct equipped with the heater to generate warmed intake air, then the exhaust was discharged through the local ventilation system. A heat input to the copper heater block by the DC power supply was set to 100 W, which is a typical heat rate from a CPU and a heat input to the boiling surface was obtained by the temperature gradient inside the copper heater block measured by two thermocouples mounted inside this heater block. In this research, to determine an operating limit temperature of this thermosyphon for cooling CPUs was the main purpose, therefore, we carried out cooling performance tests on 1 heat load condition (100 W).

The main points for measuring temperatures were (i) the back of the boiling part (the center of the groove to insert the thermocouple) as the boiling surface temperature, (ii) the top-plate surface of the boiling part, which is in contact with the vapor; as the saturated vapor temperature, (iii) the intake air to the heat sink, (iv) the exhaust of the heat sink, and (v) the room temperature. Moreover, the internal pressure of the thermosyphon was also measured by preparing another thermosyphon of the same dimensions that had an adapted pressure sensor at the top surface of the boiling part. The pressure sensor was adapted by manual aluminum brazing at the connecting portion of the pressure sensor, as indicated in Fig.3. At this time, the thermal resistance of the boiling surface ($R_{b,sat}$) and the boiling-heat-transfer coefficient ($h_{b,sat}$) at saturated boiling are obtained by
\[ R_{b,sat} = \frac{\Delta T_{sat}}{Q_b} = \frac{T_{b,sat} - T_{v, sat}}{Q_b} \]  

(1)

\[ h_{b,sat} = \frac{1}{R_{b,sat} A_b} = \frac{Q_b}{(T_{b,sat} - T_{v, sat}) A_b} \]  

(2)

where \( Q_b \) is the heat input to the boiling surface, \( \Delta T_{sat} \) is the wall superheat of the boiling surface, \( T_{b,sat} \) is the temperature of the boiling surface at saturated boiling, \( T_{v, sat} \) is the saturated vapor temperature, and \( A_b \) is the area of the boiling surface (=30 mm \( \times \) 38 mm).

The corrosion behavior of the aluminum thermosyphon with HFE7000 is mainly assumed as a pitting corrosion due to fluorine ions (F\(^-\)) generated from a hydrolysis reaction between HFE7000 and dissolved water as follows (Japan Society of Corrosion Engineering Data Handbook: Corrosion Engineering, 1993),

\[ C_3F_7OCH_3 + H_2O \rightarrow C_3F_7OH + CH_3OH \]  

(3)

and

\[ C_3F_7OH + H_2O \rightarrow C_2F_5COOH + 2H^+ + 2F^- \]  

(4)

Therefore, we measured the amount of dissolve water in degassed HFE7000 by the Karl Fischer titration method first. Then, we carried out high-temperature acceleration tests up to 150 °C for 1 month on 2 samples as illustrated in Figure 4. One sample was HFE7000 in the pressure-resistant vessel with an aluminum specimen including the aluminum brazing area cut from our thermosyphon, and the other was only HFE7000 in the vessel without an aluminum specimen. We measured the concentration of fluorine ions (F\(^-\)) in HFE7000 by pure-water-extraction ion-exchange chromatography and analyzed the aluminum surface by using a scanning electron microscope (SEM) and energy dispersive X-ray spectrometry (EDX).

Fig. 1 The prototype of our low-height aluminum thermosyphon. All aluminum parts were connected simultaneously by aluminum brazing in a vacuum furnace, and 25 cc of the degassed HFE7000 was encapsulated into the thermosyphon under reduced pressure.
Fig. 2  The boiling surface with the micro-curl skived fin. The micro-curl skived fin was manufactured inexpensively by continuously cultivating the aluminum base metal and has many micro cavities (400 - 500 μm) to retain vapor bubbles inside the boiling surface and stabilize bubble desorption.

Fig. 3  The experimental apparatus for evaluating heat-transfer performances in high-temperature environments. The boiling part of the thermosyphon was set on the copper heater block which has the same size as the boiling surface (30 mm × 38 mm) through the thermal-conductivity grease. The controlled intake air with the temperature and flow rate was supplied to the heat sink through the air duct equipped with the heater to generate warmed intake air, and then the exhaust was discharged through the local ventilation system. The internal pressure of the thermosyphon was also measured by using the pressure sensor adapted at the top surface of the boiling part.
3. Experimental results

3.1 Cooling performance tests

Figure 5 indicates the boiling surface temperature \( T_b \) and the vapor temperature \( T_v \) when increasing the intake air temperature \( T_i \) from room temperature around 25 °C to 100 °C at a heat input of 104 W (heat flux 91 kW/m\(^2\)) and intake air volume of 0.2 m\(^3\)/min. In each condition (1st to 14th), after both temperatures of the boiling surface and vapor were saturated, we raised up the intake air temperature. Figure 6 compares the measured internal pressure of the thermosyphon with the saturated vapor pressure of HFE7000 \( P_{v,sat} \) obtained experimentally by Tanaka (Tanaka, 2014). The solid line in this figure indicates the saturated vapor pressure calculated by the correlation equation (Eq.(5)) proposed by Tanaka.

\[
\ln \frac{P_{v,sat}}{P_c} = \frac{T_c}{T_{v,sat}} \left\{ A_1 \left( 1 - \frac{T_{v,sat}}{T_c} \right) + A_2 \left( 1 - \frac{T_{v,sat}}{T_c} \right)^{1.5} + A_3 \left( 1 - \frac{T_{v,sat}}{T_c} \right)^{2.5} + A_4 \left( 1 - \frac{T_{v,sat}}{T_c} \right)^{5} \right\} \quad (5)
\]

where \( P_{v,sat} \) is the saturated vapor pressure, \( P_c \) is the critical pressure (=2481 kPa (Sato et al., 1996)) and \( T_c \) is the critical temperature (=437.70 K (Sato et al., 1996)) with coefficients \( A_1 = -8.11725 \), \( A_2 = 2.27890 \), \( A_3 = -3.70789 \) and \( A_4 = -7.24536 \).

As can be seen from Fig.5, both temperatures were quite stable up to the intake air of 100 °C without an excessive temperature rise of the boiling surface. Moreover, the measured internal pressure was almost the same as the saturated vapor pressure (Fig.6). Therefore, it is clear that the boiling and condensing phenomena inside the thermosyphon were maintained stably up to 100 °C. This is considered due to the stable vapor desorption from micro cavities of the boiling surface.

Figure 7 indicates the boiling surface and vapor temperature, the wall superheat of the boiling surface, and the internal pressure when the intake air temperature was room temperature (1st condition in Fig.5). After heat was applied to the boiling part, the temperature difference between the boiling surface and vapor \( T_b - T_v \) increased rapidly up to 10.7 K (point (A) in Fig.7) and then decreased gradually until 5 K (point (B)). Then, at point (C), the internal pressure reached the saturated vapor pressure \( P_{v,sat} \). It is considered that the nucleate boiling started at point (A) and became the state of the saturated nucleate boiling at point (C). At the 1st condition, the rapid temperature rise of the boiling surface at the beginning of the boiling (over-shoot) was 5.7 K. The cause of this over-shoot is considered to be the lack of bubble cores inside micro cavities of the boiling surface caused by the degassing process of HFE7000 before it was encapsulated into the thermosyphon. However, once the nucleate boiling began, this over-shoot was not observed from the 2nd to 14th conditions as shown in Fig.5.
Fig. 5  Temperatures of the boiling surface and vapor as the intake air temperature increased from 25 to 100 °C. Both temperatures were quite stable up to 100 °C without an excessive temperature rise of the boiling surface.

Fig. 6  Comparison of the measured internal pressure of the thermosyphon with the saturated vapor pressure of HFE7000 obtained experimentally by Tanaka (Tanaka, 2014). The solid line indicates the saturated vapor pressure calculated by the correlation equation proposed by Tanaka. The measured internal pressure was almost the same as the saturated vapor pressure. Therefore, it is clear that the boiling and condensing phenomena inside the thermosyphon were maintained stably up to 100 °C.
In Figure 8, red circles indicate the thermal resistance of the boiling surface ($R_{b,\text{sat}}$) obtained by Eq. (1) at a heat input of 105 W (heat flux 92 kW/m$^2$) versus the saturated vapor pressure ($P_{v,\text{sat}}$). The saturated vapor pressure ($P_{v,\text{sat}}$) was calculated by the correlation equation of the saturated vapor pressure of HFE7000 (Eq. (5)) and the measured saturated vapor temperature when the intake air was 34 - 101 °C. Moreover, in order to compare the boiling-heat-transfer performance of this aluminum thermosyphon to that of another thermosyphon, we show the thermal resistance of the boiling surface of the copper thermosyphon with water coolant, which has been conducted by the author in the past (Fujimoto et al., 2014). The boiling surface of the copper thermosyphon has the same size as that of the aluminum thermosyphon (30 mm × 38 mm) and also has a porous structure represented by small cavities and openings as illustrated in Figure 9 to enhance the boiling-heat-transfer performance (Nakayama et al., 1980a, 1980b).

Until the intake air was up to 60 °C, the thermal resistance of the boiling surface decreased as the increase of the saturated vapor pressure. The minimum thermal resistance and wall superheat of the boiling surface were 0.016 K/W and 1.6 K, respectively, and at this time, the boiling-heat-transfer coefficient reached 57 kW/(m$^2$K). Such a cooling performance enhancement is considered to be due to the effect of the micro-curl skived fin mentioned above. From author’s past studies on the copper thermosyphon, the thermal resistance of the boiling surface was 0.042 K/W and the boiling-heat-transfer coefficient was 21 kW/(m$^2$K) (Fujimoto et al., 2014). Therefore, in this research on the aluminum thermosyphon, the higher boiling-heat-transfer performance could be confirmed. This is considered to be caused by the higher saturated vapor pressure of HFE7000 in comparison with that of water coolant.

However, when the intake air was over 70 °C, the thermal resistance of the boiling surface drastically increased. When the intake air is over 70 °C, the saturated vapor pressure exceeds 500 kPa. Thus, this deterioration was considered to be caused by the reduction in the contact area between the boiling surface and the heater block due to the plastic deformation of the boiling part. Figure 10 indicates the appearance image of the deformed boiling surface at the intake air of 80 °C and the visualized contact area between the boiling surface and the heater block when the intake air was 70 - 100 °C. We visualized the contact area by pressing the ink-coated surface of the deformed boiling part to a flat paper. When the intake air was up to around 70 °C, no deformation of the boiling part was observed. However, when the intake air was higher than 70 °C, the contact area was reduced sharply. Hence, it follows that the upper limit of the environmental temperature of this thermosyphon is 60 °C from strength constraints.

Figure 11 indicates the hysteresis characteristics of the boiling surface temperature. By taking into account the deformation of the boiling part when the intake air is over 70 °C, in the range of 30 - 70 °C, we evaluated the boiling surface temperature by conducting cycle tests with temperature raising and lowering processes. We carried out this cycle test continuously three times. In each test, the boiling surface temperature was almost the same without an excessive rise. These
experimental results clarify that our aluminum thermosyphon is a sufficiently useful cooling device in actual use condition, in which the environmental temperature is up to around 50°C.

Fig. 8  Red circles indicate the thermal resistance of the boiling surface obtained by Eq.(1) versus the saturated vapor pressure. The saturated vapor pressure was calculated by the correlation equation of the saturated vapor pressure of HFE7000 (Eq.(5)) and the measured saturated vapor temperature when the intake air was 34 - 101 °C. Until the intake air was up to 60 °C, the thermal resistance of the boiling surface decreased as the increase of the saturated vapor pressure. The minimum thermal resistance of the boiling surface were 0.016 K/W and the boiling-heat-transfer coefficient reached 57 kW/(m²K). However, when the intake air was over 70 °C (over 500 kPa of the saturated vapor pressure), the thermal resistance drastically increased due to the reduction in the contact area between the boiling surface and the heater block caused by the plastic deformation of the boiling part.

Fig. 9  The boiling surface of the copper thermosyphon has a porous structure represented by small interconnected cavities and openings through which these cavities communicate with the surrounding water coolant in order to enhance the boiling-heat-transfer performance (Fujimoto et al., 2014, Nakayama et al., 1980a, 1980b).
Fig. 10  The appearance image of the deformed boiling surface at the intake air of 80 °C and the visualized contact area between the boiling surface and the heater block when the intake air was 70 - 100 °C. When the intake air was up to around 70 °C, the deformation of the boiling part was not observed, but when it was over 70 °C, the contact area was reduced sharply.

Fig. 11  The hysteresis characteristics of the boiling surface temperature. By taking into account the deformation of the boiling part when the intake air is over 70 °C, in the range of 30 - 70 °C, we evaluated the boiling surface temperature by conducting cycle tests with temperature raising and lowering processes. We carried out this cycle test continuously three times. In each test, the boiling surface temperature was almost the same without an excessive rise.
3.2 High-temperature aging tests

Table 1 shows the measurement results for dissolved water in degassed HFE7000 by the Karl Fischer titration method. The amount of dissolved water was 35.7 ppm, which was the average value of 3 measurements on the same HFE7000 sample. Saturated dissolved water of HFE7000 is 60 ppm (at 25 °C), so the moisture saturation defined by the proportion of dissolved water for saturated dissolve water is 59.5 %. This value is close to the critical humidity at which a solid surface begins to adsorb moisture (Japan Society of Corrosion Engineering Data Handbook: Corrosion Engineering, 1993). Thus, a certain degree of water content is considered to be dissolved in HFE7000.

Figure 12 shows the generation rate of fluorine ions (F⁻) in 2 samples of HFE7000 that were exposed to temperatures up to 150 °C for 1 month (one sample was HFE7000 with an aluminum specimen, which is close to the real environment of the aluminum thermosyphon, and the other was only HFE7000 as explained in Fig.4). The green and blue circles indicate the F⁻ generation rates of the HFE7000 sample without and with an aluminum specimen, respectively. As reference data, the red triangles indicate the F⁻ generation rate obtained from an environment containing HFE7000 and an aqueous solution of sodium acetate (CH₃COONa) with an aluminum specimen. We carried out this reference test to reproduce the environment to promote the degradation of HFE7000 and to grasp the temperature dependence on the hydrolysis reaction between HFE7000 and dissolved water.

The generation rate of fluorine ions increased as the environmental temperature rises. This is due to the promotion of the hydrolysis reaction between HFE7000 and dissolved water as described in Eq.(3) and Eq.(4). In conditions without the acceleration of HFE7000 degradation (blue and green circles), the F⁻ generation rate was the order of 10⁻⁷ ppm/hr when the environmental temperature was 100 °C. The F⁻ generation rate was smaller in the sample containing HFE7000 and the aluminum specimen (blue circles) than in containing only HFE7000 (green circles). This is considered to be caused by the adsorption of fluorine ions on the surface of the aluminum specimen. In the actual use condition of the thermosyphon (blue circles), the F⁻ generation rate was 1.4×10⁻⁶ ppm/hr when the environmental temperature was 50 °C. If this thermosyphon is to be used for 10 years continuously at 50 °C, which is an assumed upper limit temperature, the generated amount of fluorine ions calculated by the generation rate 1.4×10⁻⁶ ppm/hr and the enclosed amount of HFE7000 25 cc will be 0.004 mg. This amount is 3×10⁻⁴ % the minimum lethal dose of hydrogen fluoride at oral 1.5 g (Japan Poison Information Center, 2009) and small enough to not affect the human body.

Figure 13 shows SEM and EDX analytical results of the aluminum specimen’s surface after 1-month aging tests at 50, 100, and 150 °C. We analyzed at the aluminum brazing area especially, because the brazing area is assumed to be vulnerable to the pitting corrosion caused by generated fluorine ions. At 150 °C, the quantity of fluorine was 5.94 At %. However, fluorine was very small at 100 °C (0.94 At %) and was not detected at all at 50 °C. Thus, more fluorine was detected on the aluminum surface at higher temperatures. This trend is same as that of the temperature dependence on the generation rate of fluorine ions mentioned above. In regards to the aluminum pitting corrosion, we could not detect any corrosion area on the aluminum specimen’s surface up to 150 °C in the SEM analysis. In Fig.13, detected magnesium, silicon, and iron are components originally included in the aluminum specimen (alloy No.1050).

These aging test results demonstrate that fluorine ions due to the hydrolysis reaction of HFE7000 were barely generated and the aluminum corrosion due to fluorine adsorbed on the aluminum surface barely occurred either under an actual use condition of the thermosyphon.

Table 1  Measurement results for dissolved water in degassed HFE7000 by the Karl Fischer titration method. The amount of dissolved water was 35.7 ppm. Saturated dissolved water of HFE7000 is 60 ppm, so the moisture saturation is 59.5 %. This value is close to the critical humidity at which a solid surface begins to adsorb moisture.

| Sample         | Dissolved water | Moisture saturation (Proportion of dissolved water for saturated dissolved water*) | Critical humidity |
|----------------|----------------|---------------------------------------------------------------------------------|------------------|
| HFE7000 (degassed) | 35.7 ppm       | 60%~70% ( = 35.7 ppm / 60 ppm )                                                 |                  |

* Saturated dissolved water of HFE7000 60 ppm (at 25 °C)
Fig. 12  The generation rate of fluorine ions in HFE7000 samples that were exposed to the high-temperature environment for 1 month. The green and blue circles indicate the F$^-$/generation rates of HFE7000 samples without and with an aluminum specimen, respectively. The red triangles indicate the generation rate of fluorine ions obtained from an environment containing HFE7000 and CH$_3$COONa with an aluminum specimen. The generation rate of fluorine ions increased as the environmental temperature rises. In the actual use condition of the thermosyphon (blue circles), the F$^-$ generation rate was $1.4 \times 10^{-6}$ ppm/hr at 50°C.

Fig. 13  SEM and EDX analytical results for the aluminum specimen's surface after 1-month aging tests at high environmental temperatures. At 150°C, the quantity of fluorine was 5.94 At %. However, fluorine was very small at 100°C (0.94 At %) and was not detected at all at 50°C. Thus, more fluorine was detected on the aluminum surface at higher temperatures. This trend is the same as that of the temperature dependence on the generation rate of fluorine ions.
4. Conclusions

We carried out cooling performance tests of our aluminum thermosyphon supplied with hot air up to 100 °C and high-temperature aging tests to examine its corrosiveness in an environment containing aluminum and HFE7000. From these examinations, we concluded the following.

1. The cooling performance at a heat input of 100 W was quite stable with the supplied air of up to 100 °C without an excessive temperature rise of the boiling surface.
2. Until the intake air was up to 60 °C, in which the plastic deformation of the boiling part did not occur, the thermal resistance of the boiling surface decreased as the increase of the saturated vapor pressure, and the minimum wall superheat of the boiling surface was 1.6 K and the maximum boiling-heat-transfer coefficient was 57 kW/(m²K).
3. When the intake air was over 70 °C (saturated vapor pressure over 500 kPa), the boiling-heat-transfer performance drastically deteriorated due to the reduction in the contact area between the boiling surface and the heater block caused by the plastic deformation of the boiling surface.
4. The generation rate of fluorine ions increased as the environmental temperature rose due to the promotion of the hydrolysis reaction between HFE7000 and dissolved water.
5. Under an actual use condition of the thermosyphon, fluorine ions due to the hydrolysis reaction of HFE7000 were barely generated and the aluminum corrosion due to fluorine adsorbed on the aluminum surface barely occurred either.
6. The operating limit temperature of this aluminum thermosyphon was 60 °C from strength constraints.

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