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Temperature-Controllable Oscillating Heat Pipe

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Experiments are conducted to investigate whether an oscillating heat pipe with a liquid reservoir can serve as a thermal control device in space. The oscillating heat pipe consists of a stainless steel capillary tube (inner and outer diameters of 0.8 mm and 1 mm, respectively), which meanders between a heating section and a cooling section 15 times in each direction (30 times in total). A 50 mL reservoir is connected to the oscillating heat pipe via another capillary tube. The 1,1,1,2-tetrafluoroethane (HFC-134a) is used as the working fluid. The heat input to the heating section is increased from 0 and 70 W, in 10 W increments. When the oscillating heat pipe is set horizontally, the temperature of the heating section remains at about the reservoir temperature of 40°C for three orientations of the reservoir with respect to gravity: vertical, horizontal, and vertically inverted. In the top-heating mode, the temperature of the heating section also remains at about the reservoir temperature. The oscillating heat pipe with a liquid reservoir is confirmed to operate as a variable conductance heat pipe, and its operating temperature can be controlled to almost be the liquid reservoir temperature for each investigated orientation of the reservoir. The oscillating heat pipe with a liquid reservoir is confirmed not to lose its temperature control function in gravity; thus, the operating temperature can be controlled by regulating the liquid reservoir temperature, not only on the ground but also in space.

Nomenclature

H	=	vertical interval
P_H	=	hydrostatic pressure
P_{OV}	=	inner pressure of heating section
P_{RL}	=	liquid pressure inside liquid reservoir
P_{RV}	=	vapor pressure inside liquid reservoir
r_O	=	inner radius of capillary tube of oscillating heat pipe
r_R	=	inner radius of liquid reservoir
ϑ	=	meniscus contact angle
ρ	=	density of working fluid
σ	=	surface tension

I. Introduction

THERMAL control technologies are increasingly required that can achieve tight thermal control with minimal use of spacecraft resources. A variable conductance heat pipe [1] and a loop heat pipe [2] have been used for that purpose. In those devices, the temperature of the heating section or conductance between the heating section and the cooling section (radiator) is regulated by controlling their reservoir temperature.

An oscillating heat pipe (OHP), also known as a pulsating heat pipe (PHP) or a loop-type heat pipe, was invented by Akachi et al. in the 1990s [3–5]. It consists of a meandering capillary tube that does not need an internal wick. The capillary tube goes back and forth many times between a heating section and a cooling section. The working principle of an OHP is described in detail in the literatures [3–5]. OHP operation relies on the oscillation and/or circulation of vapor plugs and liquid slugs in the capillary tube. Vapor bubbles are generated and grow in the heating portion (evaporator), and they collapse in the heat-radiating portion (condenser). The generation and collapse of vapor bubbles pump the liquid slugs, thus causing pressure and temperature fluctuations. As a consequence of thermo-hydrodynamic coupling of pressure and temperature fluctuations with the void fraction, the entrapped liquid slugs and vapor bubbles undergo complex translational oscillatory movement. This leads to transfer of both sensible heat and latent heat. As recently reviewed by Zhang and Faghri [6], fundamental experimental and theoretical research into OHPs has been conducted over the years. A closed-loop OHP has generally better heat transfer performance than an open-loop OHP [7]. Miyazaki et al. proposed a closed-loop OHP with check valves inserted in straight tubes to improve the operating limit of OHP [8]. Charoensawan et al. demonstrated that performance is improved by increasing the diameter of tubes and the number of turns [9]. Khandekar et al. investigated operational regimes of OHPs with different filling ratios and working fluids, observing maximum heat transfer performance at filling ratios of about 25–55% and 35–60% when ethanol and R-123 were used as working fluid, respectively [10]. Lin et al. also investigated the optimal filling ratio of an FC-72 OHP, which was found to be 50%; they also found that a filling ratio of 32% would cause dryout, even at low heat input of 200 W [11]. It was confirmed that PHP is capable of operating satisfactorily under reduced gravity of $0.02g$ by the parabolic flight test performed by Gu et al. [12].

Research has also been carried out in order to understand the physical phenomena of OHPs. Hosoda et al. investigated the propagation of vapor plugs in a meandering closed-loop heat transfer device, experimentally and numerically [13]. They observed that, for two vapor plugs located separately at adjacent turns, in a regular flow pattern, one starts to shrink when the other starts to grow [13]. Khandekar et al. performed flow visualization experiments and concluded that capillary slug flow and semiannular/annular flow depend on heat input and inclination angle [14]. Wilson et al. observed flow patterns in water and nanofluid OHPs using neutron radiography [15]. They found that fluid oscillation is random and intermittent at low heat input around 50 W and that a steady flow pattern appeared upon increasing the heat input to 300 W [15]. A wave equation of pressure oscillation in an OHP was derived based on an analytical model of self-excited oscillation by Miyazaki and Akachi [16]. Shafii

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et al. determined the latent heat transfer coefficient by solving for the thin film evaporation and condensation [17].

Since an internal wick structure is not needed in the capillary tube, the main advantages of OHPs are 1) lower cost due to simple fabrication, 2) lower sensitivity to orientation than a conventional heat pipe (e.g., OHPs can be operated in top-heating mode) [18,19], and 3) adjustability of shape and design for satisfying application requirements.

One useful type of OHPs is a variable conductance OHP (VC-OHP); however, few studies on variable conductance have been carried out to date. Akachi [3] proposed a type of VC-OHP in which a noncondensable gas is used along with the working fluid: a tank filled with noncondensable gas is connected to the OHP, and the amount of the noncondensable gas in the OHP capillary pipe is controlled by regulating the temperature within the tank; thereby, the thermal conductance of the OHP is changed. However, no experimental results have been reported for VC-OHPs. Bsibsi et al. [20] proposed a heat-switch OHP with a liquid reservoir in order to solve the problem with startup when oscillation of the working fluid is stopped. This problem arises after long, cold periods, because the liquid concentrates on the cold side while the vapor concentrates on the hot side, thus hindering the translational oscillatory movement of the working fluid. To initiate movement of the working liquid/vapor during startup, Bsibsi et al. proposed heating the reservoir to expand the liquid therein. They use the reservoir, not for temperature control, but rather to address the startup problem.

A VC-OHP connected to a temperature-controlled liquid reservoir is proposed in the present paper. It is shown that the operating temperature (i.e., the conductance of the VC-OHP) can be controlled by the temperature of the liquid reservoir and that the operation temperature is almost the liquid reservoir temperature. Since the liquid reservoir is thermally isolated from the OHP, a VC-OHP enables the operating temperature to remain constant with low power use while the heat input increases. To demonstrate that a VC-OHP can operate in both gravity and microgravity, we also show that the variable conductance property is maintained for various orientations of the liquid reservoir and the OHP with respect to gravity.

II. Experimental Setup

The test specimen consists of an OHP and a liquid reservoir. The reservoir is connected to the OHP via a polytetrafluoroethylene (PTFE) tube with an inner diameter of 1 mm and a length of 600 mm. The OHP is a closed-loop type: a stainless steel capillary tubes with inner and outer diameters of 0.8 and 1 mm, respectively, meanders between a heating section and a cooling section 15 times in each direction (30 times in total), with both terminals interconnected. Fifteen check valves are inserted between the two sections, at every other line, to direct the flow from the cooling section to the heating section. The working fluid circulates in one direction, and more working fluid is transported as liquid phase than as vapor per unit volume flow rate. The check valves are installed in the tubes of the adiabatic section close to the heating section where liquid slugs flow from the cooling section to the heating section so that the liquid slugs are steadily supplied to the heating section. Figure 1 shows the OHP apparatus. The upper panel shows a top view, and the lower panel shows a lateral view. At the heating section and the cooling section, the tube is set in grooves in the aluminum plates and joined by diffusion bonding. The plates of both the heating and cooling sections are 100 by 100 mm, and 3 mm in thickness. A 100 by 70 mm sheet heater is attached to the heating section plate. The heating section plate and the heater are pinched between two pieces of phenolic resin insulation by C clamps. An aluminum block, in which the 10°C coolant flows, is attached to the cooling section, and the aluminum block and the cooling section are pinched by C clamps. The whole system, except the liquid reservoir and the PTFE tube, is covered with rock wool insulation. The liquid reservoir is a stainless steel tank with volume capacity of 50 mL, around which a silicone rubber heater is wound for temperature control. The liquid reservoir is covered with elastomeric foam insulation. For temperature measurements, thermocouples are attached on the liquid reservoir, as well as to the OHP. The silicone rubber heater and the thermocouple (T_E in Fig. 1) are connected to an ac temperature controller. The heater is turned on or off by the temperature controller to keep the temperature T_E constant. There is a valve located on each side of the reservoir: the top valve and the bottom value. The liquid line bifurcates downstream of the bottom valve. A valve is located on each of the bifurcated lines: the filling valve and the evacuating valve. The OHP is connected to the filling valve via the aforementioned 600-mm-long PTFE tube. The 1,1,1,2-tetrafluoroethane (HFC-134a) is used as a working fluid. The liquid inventory is 50 mL. The method of filling the reservoir with HFC-134a is as follows:

1) The liquid reservoir is evacuated, filled with liquid HFC-134a, and then closed by the top and bottom valves.

2) The PTFE tube from the OHP is connected to the filling valve.

3) Air is evacuated from the OHP, the PTFE tube, and the line downstream of the bottom valve, from the evacuating valve.

4) The evacuating valve is closed, and the bottom valve is opened. After the bottom valve is opened, a liquid-vapor distribution is established in the OHP, as well as in the liquid reservoir. The liquid-vapor distribution depends on environmental factors (e.g., ambient temperature).

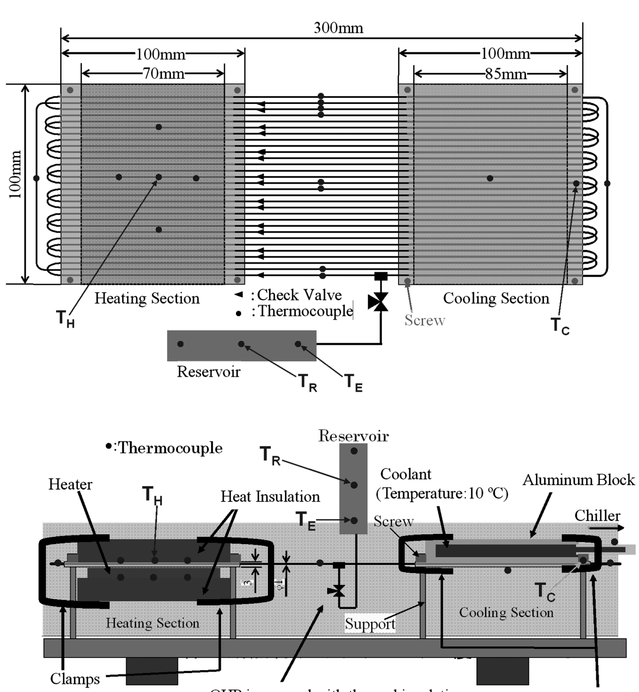

Fig. 1 Schematic of OHP.

III. Experimental Conditions

Table 1 shows the experimental conditions. The OHP is set horizontally or vertically; in the latter case, we test operation in the top heat mode, with the upper heating section and the lower cooling section. The liquid reservoir is set in three ways: horizontally, vertically (i.e., the PTFE tube is placed at the reservoir's bottom), and vertically inverted (i.e., the PTFE tube is placed at the reservoir top). The OHP without the reservoir (i.e., a fixed conductance OHP) is also tested. The coolant temperature is set to 10°C in all experiments. The heat input to the heating section is increased from 0 to 70 W, in 10 W increments. The OHP dries out when the heater dissipated 60 W in the case of the vertically inverted liquid reservoir. The liquid reservoir temperature is kept 40°C.

IV. Experimental Results

A. Horizontal Oscillating Heat Pipe

Figure 2 shows the test result for the horizontal OHP without the reservoir. The temperatures of the heating section and the cool

Table 1 Experimental conditions

	Reservoir orientation					
	No Reservoir		Vertical		Horizontal	Vertically inverted
OHP orientation	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Horizontal
Reservoir temperature, °C	——	——	40	40	40	40
Heat input, W	10, 20, 30, 40, 50, 60, 70		10, 20, 30, 40, 50, 60, 70		10, 20, 30, 40, 50, 60, 70	10, 20, 30, 40, 50, 60
Coolant temperature, °C	10	10	10	10	10	10

section are measured at the locations T_H and T_C, shown in Fig. 1. The temperatures of both the heating section and the cooling section rise as the heat input is increased. The OHP without the reservoir is shown to be a fixed conductance OHP. The error bars in the figure indicate the amount of heat leak from the heating section to the surroundings. Note that the net amount of heat transferred by the OHP is the difference between the heat input and the heat leak. This also applies to the remaining results. The experimental configuration is also shown in the figure.

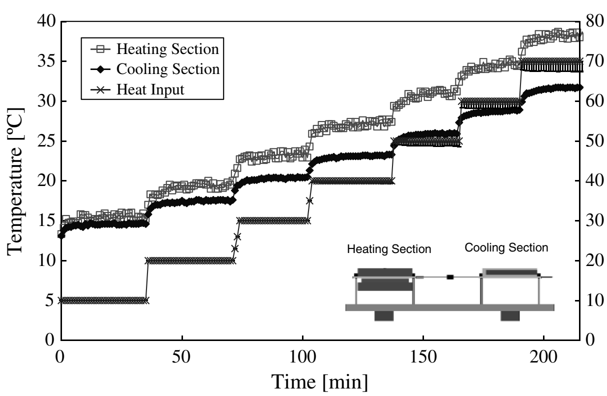

Fig. 2 Experimental results for horizontal OHP without reservoir.

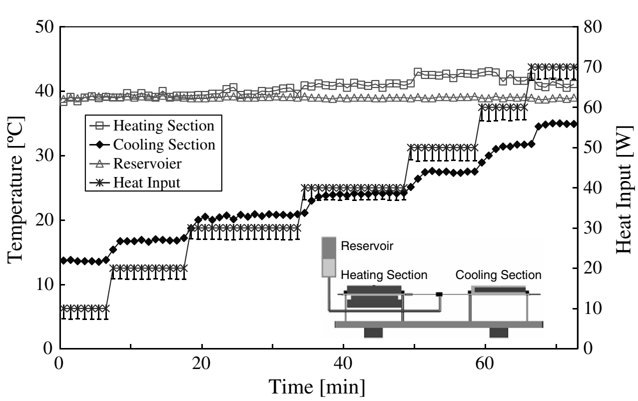

Fig. 3 Experimental results for horizontal OHP with vertical reservoir.

Figure 3 shows the test result for the horizontal OHP with the vertical liquid reservoir. The heating section temperature rises slightly as the heat input is increased, and the temperature increase with increasing heat input is much smaller in comparison with the results shown in Fig. 2. The OHP of this condition operates as a VC-OHP. The heating section temperature is maintained at about 40°C, which is the temperature of the liquid reservoir. The saturated vapor pressure of the liquid reservoir regulates the operating temperature of the OHP and , therefore, the conductance of the OHP. The liquid reservoir is in a two-phase state when its temperature is kept at 40°C. As the heat load increases, excessive vapor builds in the OHP and displaces the liquid from the OHP into the liquid reservoir. The amount of vapor in the cooling section increases, and the excess working fluid is stored in the liquid reservoir, as shown in Fig. 4. The heat rejection area in the cooling section is set such that, as the conductance between the heating section and the cooling section varies, the temperature of the heating section remains unchanged. Since the pressure in the OHP is roughly the saturated vapor pressure in the heating section and is regulated by the saturated vapor pressure in the liquid reservoir, the heating section temperature is about the same as the liquid reservoir temperature. The heating section temperature is slightly higher than that of the liquid reservoir because of hydrostatic pressure and surface tension.

The hydrostatic pressure is given by

$$P_H = \rho \cdot H \tag{1}$$

where H is the vertical interval, and ρ is the density of the fluid. The height difference in the fluid level between the OHP and the liquid reservoir is 0.7 m if the PTFE tube between them is filled with the fluid, as shown in Fig. 5. The density of the liquid HFC-134a at 40°C under 1 MPa is 1155 kg/m^3. Thus, the hydrostatic pressure is 0.008 MPa. According to the saturated vapor pressure curve of HFC-134a, the temperature increase caused by hydrostatic pressure of 0.008 MPa is only 0.04°C.

The inner pressure of the OHP heating section P_{OV} (see Fig. 5) is higher than the liquid pressure inside the reservoir P_{RL} because of surface tension σ in the OHP tube:

$$P_{\mathrm{OV}} = P_{\mathrm{RL}} + \frac{2\sigma \cdot \cos\theta}{r_O} \tag{2}$$

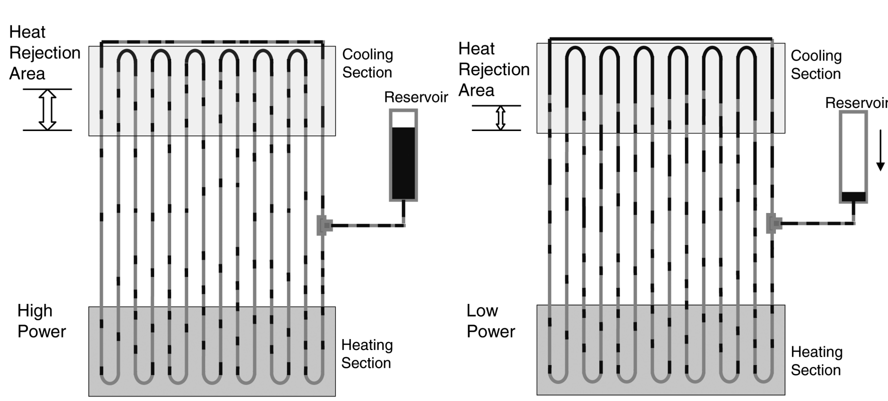

Fig. 4 Theory of VC-OHP.

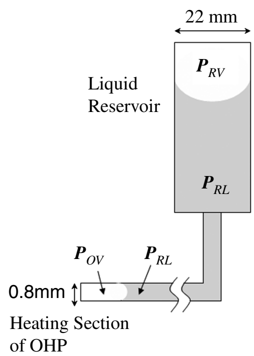

Fig. 5 Pressure increase caused by surface tension in case of horizontal OHP with vertical reservoir.

where θ is the meniscus contact angle, and r_O is the inner radius of the OHP capillary tube.

The vapor pressure inside the reservoir P_{RV} is also higher than P_{RL} due to the surface tension σ in the liquid reservoir:

$$P_{\mathrm{RV}} = P_{\mathrm{RL}} + \frac{2\sigma \cdot \cos\theta}{r_R} \tag{3}$$

Here, r_R is the inner radius of the reservoir.

From Eqs. (2) and (3), the difference between P_{OV} and P_{RV} is

$$P_{\mathrm{OV}} - P_{\mathrm{RV}} = \frac{2\sigma \cdot \cos\theta}{r_O r_R}(r_R - r_O) \tag{4}$$

For $r_R = 11$ mm, $r_O = 0.4$ mm, and $\sigma = 0.0079$ N/m^2, the maximum pressure difference is 38 Pa when $\cos\theta$ is one. According to the saturated vapor pressure curve of HFC-134a, the temperature increase caused by this pressure increase of 38 Pa is only 1.9×10^{-3}°C.

Considering only hydrostatic pressure and surface tension is insufficient for explaining the temperature difference between the liquid reservoir and the heating section. Furthermore, research such as flow visualization and pressure measurement in the OHP liquid reservoir should be conducted.

Figure 6 shows the result for the horizontal OHP with the horizontal liquid reservoir. The heating section temperature remains at about the liquid reservoir temperature of 40°C, similar to the results shown in Fig. 3. The working fluid in the liquid reservoir is supplied to the OHP in either the vapor or liquid states without the aid of gravity. The heating section temperature is slightly higher than that of the liquid reservoir. This slightly higher temperature is thought to be attributable to the hydrostatic pressure and the pressure increase caused by surface tension. The level of the working fluid in the liquid reservoir is higher than its outlet (Fig. 7), because the liquid volume of the total working fluid is more than 10 times the internal volume of the OHP and the PTFE tube. The calculated temperature differences between the heating section and the liquid reservoir, due to hydrostatic pressure and the pressure increase caused by surface tension, are 0.35°C and 2.0×10^{-3}°C, respectively. Again, these factors cannot explain the measured temperature difference; thus, further research is necessary.

Figure 8 shows the results for the horizontal OHP with the vertically inverted liquid reservoir. Even in this case, the temperature controlling function of the liquid reservoir is not lost, even though the working fluid is supplied to the OHP in the vapor state from the liquid reservoir. The heating section temperature remains at about the liquid reservoir temperature. It is assumed that the PTFE tube and the OHP between the liquid reservoir and the heating section are filled with the vapor, as shown in Fig. 9. The hydrostatic pressure is low and can be ignored. The inner pressure of the heating section P_{OV} is equal P_{RV}. No vapor flows under the equilibrium condition:

$$P_{\mathrm{OV}} = P_{\mathrm{RV}} \tag{5}$$

Therefore, the heating section temperature is equal to the liquid reservoir temperature. The heating section temperature shown in Fig. 8 is lower than the liquid reservoir temperature, while the heating section temperatures in Figs. 3 and 6 are higher than the liquid

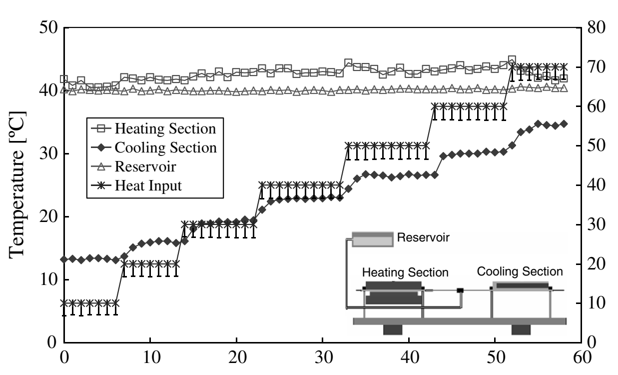

Fig. 6 Experimental results for horizontal OHP with horizontal reservoir.

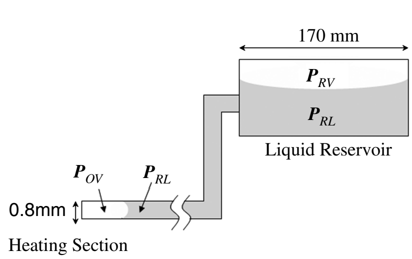

Fig. 7 Pressure increase caused by surface tension in case of horizontal OHP with horizontal reservoir.

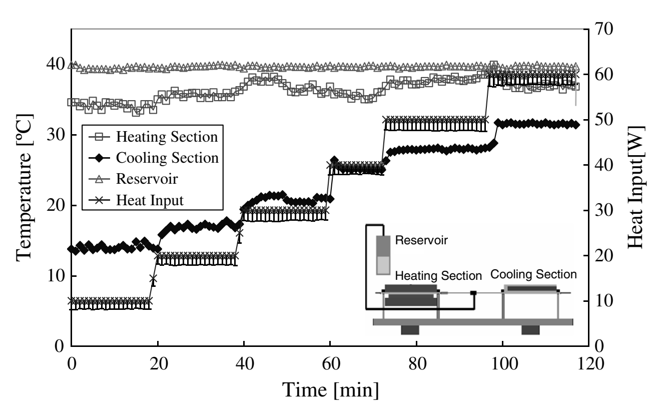

Fig. 8 Experimental results of horizontal OHP with vertically inverted reservoir.

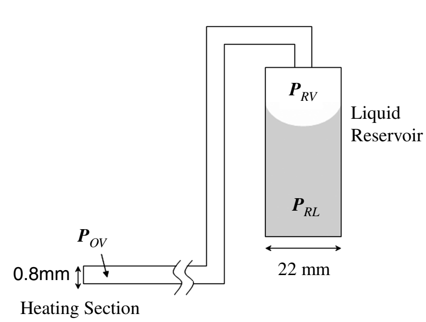

Fig. 9 Pressure increase caused by surface tension in case of horizontal OHP with vertically inverted reservoir.

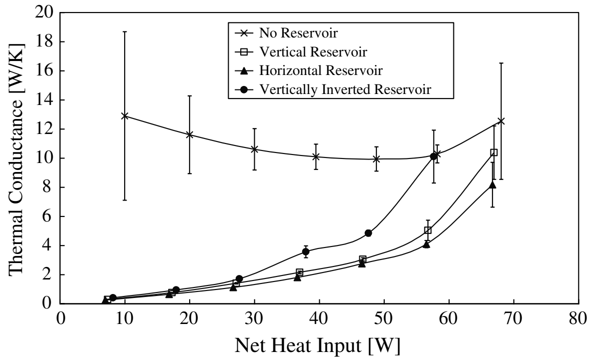

Fig. 10 Thermal conductance (horizontal OHP).

reservoir temperature. We cannot explain these results at the present, and further research and experiments are necessary.

Figure 10 shows the thermal conductance in each direction of the liquid reservoir. They are calculated from the preceding results. The thermal conductance is defined here as the value obtained by dividing the net heat input by the temperature difference between the heating section (i.e., at T_H) and the cooling section (i.e., at T_C). The uncertainty in the conductance is shown as error bars. We evaluated the uncertainties of the measured temperatures. The thermal conductance of the OHP without the liquid reservoir is almost constant and varies only 2 W/K when heat input is increased from 10 to 70 W; it operates as a fixed conductance heat pipe. The liquid/vapor ratio of the OHP without reservoir, and therefore the heat transfer area in the cooling section, are almost unchanged with increasing heat input. Therefore, the temperature difference between the heating section and the cooling section increases as the heat input is increased. On the other hand, the thermal conductance of the OHPs with a liquid reservoir increases more than 8 W/K as the heat input is increased, regardless of the orientation of the reservoir; in other words, they operate as VC-OHPs. The operating temperature remains constant, even though the heat input is increased, because it is controlled by the saturation temperature of the liquid reservoir. The liquid/vapor ratio in the OHP, and therefore the heat transfer area in the cooling section, change such that the pressures in the OHP and the liquid reservoir are in balance; that is, the heating section temperature is nearly the liquid reservoir temperature. Thus, this OHP with a liquid reservoir exhibits variable conductance. These results suggest that the temperature of the heating section can be controlled by regulating the liquid reservoir temperature, not only on the ground but also in space.

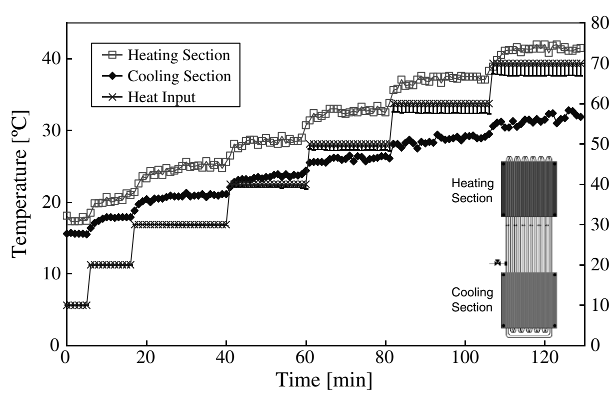

Fig. 11 Experimental results for vertical OHP without reservoir.

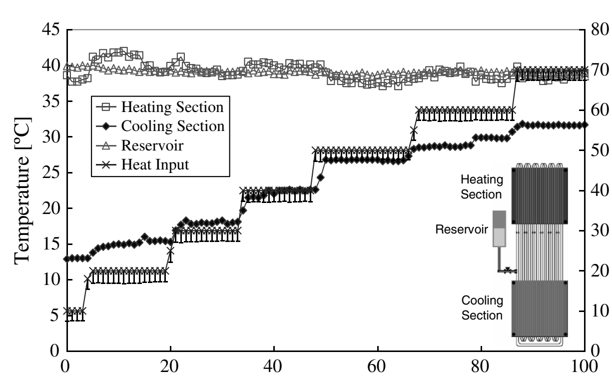

Fig. 12 Experimental results for vertical OHP with vertical reservoir.

B. Vertical Oscillating Heat Pipe

Figure 11 shows the test result for the vertical OHP without the reservoir. The heat generated in the heating section is transported by OHP even if it is set vertically (i.e., in top-heating mode), because the pumping force caused by pressure fluctuation in the working fluid is sufficiently higher than the gravity force. Both temperatures of the heating section and the cooling section rise with increasing heat input. The vertical OHP without the reservoir is shown to be a fixed conductance OHP.

Figure 12 shows the results for the vertical OHP with the vertical liquid reservoir. The heating section temperature remains at about the liquid reservoir temperature of 40°C, similar to the results shown in Figs. 3 and 6. The heating section temperature of the OHP is controlled by regulating the liquid reservoir temperature, even when the OHP is set vertically. The temperature difference between the heating section and the liquid reservoir is less than that shown in Fig. 3. The hydrostatic pressure is less because the heating section is at the same height as the liquid reservoir (Fig. 13). The pressure increase caused by surface tension is estimated to be 3.3×10^{-4}. Therefore, the temperature difference between the heating section and the liquid reservoir is less than that shown in Fig. 3.

Figure 14 shows the thermal conductance of the vertical OHP, with and without the liquid reservoir. The thermal conductance of the OHP without the liquid reservoir is almost constant; it operates as a fixed conductance heat pipe. The thermal conductance of the OHP with the liquid reservoir, on the other hand, increases with increasing heat input; it operates as a VC-OHP. The results demonstrate that OHP is a useful thermal device for heat transfer and temperature control, even in top-heating mode on the ground.

Figure 15 shows the thermal conductance of the horizontal OHP and the vertical OHP, with and without the vertical reservoir. The thermal conductance of the vertical OHP without the liquid reservoir is at least 3 W/K less than that of the horizontal OHP without the liquid reservoir. The difference in the thermal conductance of the vertical OHP with the liquid reservoir and that of the horizontal OHP with the liquid reservoir is only 1 W/K or less. The thermal conductance of the OHP with the liquid reservoir is clearly independent of gravity. The conductance of horizontal OHP without the liquid reservoir is higher than that of the vertical OHP without the liquid reservoir. The liquid column is accumulated in the cooling section because of the effect of gravity, and the effective flow rate is reduced when the OHP is set vertically (i.e., in top-heating mode). As a result, the conductance of the vertical OHP decreases. The inner pressure of the OHP with a liquid reservoir is controlled by the saturation

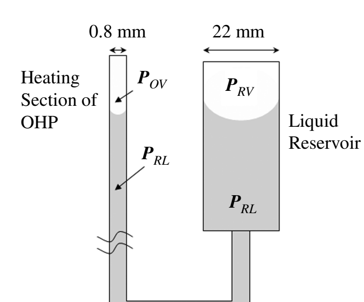

Fig. 13 Pressure increase caused by surface tension in case of vertical OHP with vertical reservoir.

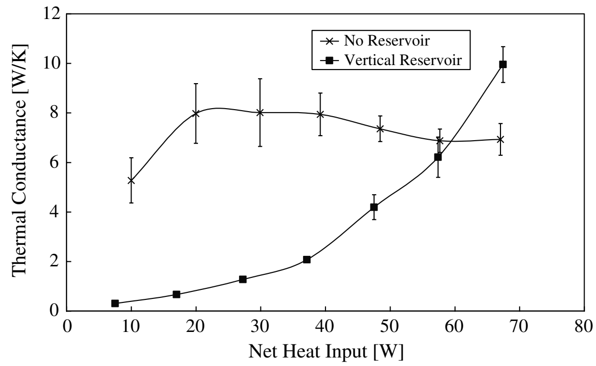

Fig. 14 Thermal conductance (vertical OHP).

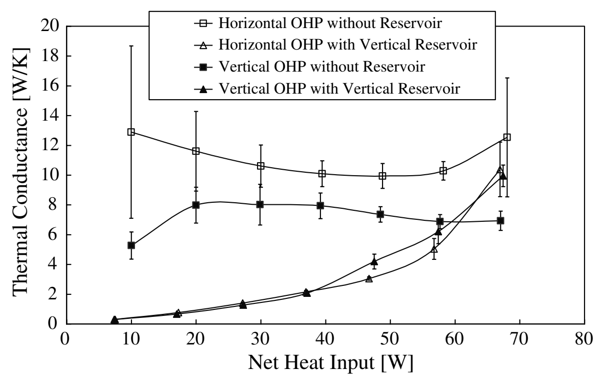

Fig. 15 Comparison of thermal conductance.

temperature of the liquid reservoir. Therefore, the conductance is almost same, even if the OHP is set vertically.

Figures 16 and 17 show the thermal resistance of OHPs. Figure 16 shows the thermal resistances of the horizontal OHP and vertical OHP without liquid reservoir. These same trends were reported by Miyazaki et al. [8], who measured thermal resistances of a closed-loop OHP with three check valves and without a liquid reservoir. They used HFC-134a as the working fluid. The thermal resistance is almost constant, and it is higher in top-heating mode than in the horizontal mode. Figure 17 shows the thermal resistances of the horizontal OHP. The thermal resistance of the OHP with reservoir decreases and approaches the thermal resistance of the OHP without reservoir with increasing heat input, while the thermal resistance of the OHP is almost constant. The variable conductance behavior of the OHP with the liquid reservoir is clear.

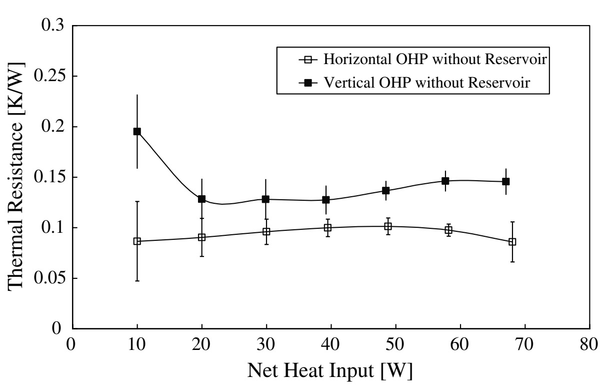

Fig. 16 Thermal resistance of OHPs without reservoir.

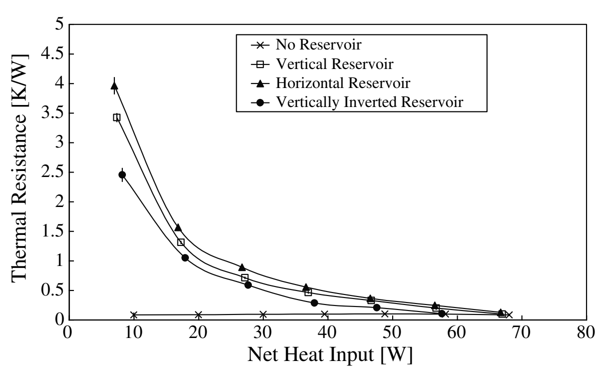

Fig. 17 Thermal resistance of horizontal OHP.

V. Conclusions

A temperature-controllable OHP with a liquid reservoir in experiments has been investigated. The temperature of the heating section is controlled by, and remains almost equal to, the temperature of the liquid reservoir. Even when the heat input was changed, the temperature of the heating section remained within 5°C of 40°C when the temperature of the liquid reservoir was set to 40°C. The thermal conductance of the OHP with the liquid reservoir varied more than 8 W/K, regardless of the orientation of the reservoir, while that of the OHP without the liquid reservoir varied only 2 W/K when heat input was increased from 10 to 70 W. The OHP with a liquid reservoir was found to operate as a VC-OHP, whereas the OHP without a reservoir was a fixed conductance heat pipe. The variable conductance property was observed for all investigated orientations of the reservoir: vertical, horizontal, and vertically inverted. The OHP worked even in top-heating mode. The OHP with the vertical liquid reservoir operated as a VC-OHP, even when the OHP was set vertically and heated on the top.

The effects of gravity on the thermal conductance of the OHP with the liquid reservoir were small. The difference of the thermal conductance of the horizontal OHP and that of the top-heating vertical OHP was less than 1 W/K for the OHP with the liquid reservoir, while that for the OHP without the liquid reservoir was more than 3 W/K. The results suggest that the temperature of the heating section can be controlled by regulating the temperature of the liquid reservoir, not only on the ground but also in space. In future work, continuing study of VC-OHPs is planned through both experiments and analysis.

Acknowledgments

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