A VAPOR-PRESSURE-DRIVEN HEAT PIPE FOR SIDEWARD LONG-DISTANCE HEAT TRANSPORT

Yasushi Koito^{a,*}, Yoshitake Ikemizu^a, Toshio Tomimura^a, Masataka Mochizuki^b

^a Department of Advanced Mechanical Systems, Kumamoto University, Kumamoto-shi, Kumamoto, 860-8555, Japan

^b Thermal Technology Division, Fujikura Ltd., Koto-ku, Tokyo, 135-8512, Japan

ABSTRACT

An experimental study is carried out on a sideward long-distance heat transport utilizing vapor pressure of a working fluid. The present heat pipe is a closed loop, which consists of a heated section (evaporator), a cooled section (condenser), a reservoir, valves and pipes connecting these components. The experimental results confirm that the heat pipe works periodically corresponding to the valve operation, and the heat is transported sideward continuously from the heated section to the cooled section. The vapor-pressure-driven heat pipe is effective for a large-scale thermal management.

Keywords: Special heat pipe, Periodic operation, Large-scale thermal management.

1. INTRODUCTION

A two-phase closed thermosyphon is a typical thermal device for upward heat transport. The bottom of the thermosyphon is an evaporator section while the top is a condenser section. Since the condenser section is located above the evaporator section, the condensate is returned to the evaporator section passively by the force of gravity. The two-phase closed thermosyphon has been widely used in many industrial applications where it is required to transport heat from lower to higher positions.

A two-phase downward heat transport, on the other hand, requires lifting the condensate against the force of gravity. This type of heat pipe is referred to as “anti-gravity heat pipe” or “top-heat-type heat pipe”. For the anti-gravity operation, a capillary force (Maydanik, 2005), an osmotic force (Minning *et al.*, 1978; Minning *et al.*, 1979; Basiulis *et al.*, 1980) and a vapor lift pump (Chisholm, 1974; Hirashima *et al.*, 1993) were used in the past studies. In addition, many studies were carried out on a vapor-pressure-driven anti-gravity heat pipe, where vapor pressure of a working fluid was utilized to lift the condensate against the force of gravity. As regards the vapor-pressure-driven heat pipe, the experimental studies were carried out by Ogushi *et al.* (1986), Hashimoto *et al.* (1995), Kawabata *et al.* (1996), Fantozzi *et al.* (2002, 2004), Kadoguchi *et al.* (2004) and Filippeschi (2006). A mathematical model of the heat pipe was also presented in the paper by Filippeschi (2006) to discuss the operational characteristics. Compared with the others, the vapor-pressure-driven heat pipe is recommended for the anti-gravity heat transport because of its reliability and simplicity. However, it should be noted here that the vapor-pressure-driven heat pipe cannot be applied for the downward long-distance heat transport. This is attributed to the fact that the

vapor pressure required to lift the condensate is increased with the increase in a heat transport height, causing to increase the inner temperature difference and therefore decrease the thermal conductance of the heat pipe.

This paper addresses the use of the vapor pressure of the working fluid for a sideward heat transport over a long distance. The heat transport direction is perpendicular to the gravity. Including a conventional capillary-driven heat pipe, there are many types of heat pipes known today for the sideward heat transport; however, enough data have not been published on the reliability of heat pipes when the heat transport distance is greatly increased. The vapor-pressure-driven sideward heat pipe is therefore presented in this study based on the previous studies mentioned above. The principle of operation of the heat pipe is described in detail, and the experimental results are shown on the operational characteristics.

In recent years, many studies have been carried out on a cooling of data centers (Gondipalli *et al.*, 2009; Karajgikar *et al.*, 2009; Patterson *et al.*, 2009; Mochizuki *et al.*, 2010), where not only a component level but also a system level thermal management is required for thermal engineers. The present study is thus motivated for such a large-scale thermal management.

2. PRINCIPLE OF OPERATION

Figure 1 shows a schematic illustration of the proposed heat pipe. The heat pipe is a closed loop, which consists of a heated section (evaporator section), a cooled section (condenser section), a reservoir, two valves (Valve 1 and Valve 2), a check valve and pipes (vapor line, liquid line etc.) connecting these components. The heated section and the cooled section are the same in height, and the reservoir is slightly higher than them. The check valve is used to prevent a reverse flow.

* Corresponding author. Email: koito@gpo.kumamoto-u.ac.jp

Fig. 1 Schematic illustration of proposed heat pipe

After the air is evacuated inside the heat pipe, the working fluid is charged as shown in the figure. The heat is transported sideward from the heated section to the cooled section according to the principle of operation explained as follows:

- (i) Valve 1 and Valve 2 are initially closed. The heated section receives the heat from the heat source.
- (ii) The liquid inside the heated section vaporizes and the vapor flows sideward through the vapor line to the cooled section, where the heat is discharged into the heat sink. The vapor condenses and the condensate is moreover subcooled in the cooled section. The accumulation of condensate decreases the area for condensation and then increases the vapor pressure inside the cooled section. The vapor pressure thus pushes the condensate through the liquid line to the reservoir, where the cooled liquid is stored.
- (iii) When the heated section becomes empty, Valve 1 and Valve 2 are opened. The vapor inside the heated section flows into the reservoir, and then the cooled liquid stored inside the reservoir flows down to the heated section under the action of gravity.
- (iv) Valve 1 and Valve 2 are closed. The operations of (ii), (iii), (iv) are repeated.

Corresponding to the valve operation, the heat pipe works periodically and transports the heat utilizing the latent heat of evaporation and condensation of the working fluid. It should be noted here that the pressure to push the condensate from the cooled section to the reservoir is ensured even when the heat transport distance (= the distance between the heated section and the cooled section) is very long. This is the advantage of the present heat pipe.

During the heat transport period when Valve 1 and Valve 2 are closed, there exists the following relation between the pressures inside the heated section, P_h , the cooled section, P_c , and the reservoir, P_r .

$$P_r < P_c < P_h \quad (1)$$

The pressure difference between the heated section and the reservoir, $P_h - P_r$, is essentially a driving force to circulate the working fluid inside the heat pipe. The pressure difference between the heated section and the cooled section, $P_h - P_c$, corresponds to a vapor pressure drop due to the friction, while that between the cooled section and the reservoir, $P_c - P_r$, is the sum of the two pressure drops in the liquid line due to the friction and the gravity. It should be pointed out that, in the case of the sideward heat transport, the pressure drop due to the gravity remains unchangeable against the heat transport distance. The pressure drop due to the friction is therefore an important consideration for the sideward long-distance heat transport. The effect of the pressure drop on the operational characteristics of the heat pipe will be discussed in this paper.

3. EXPERIMENTAL APPARATUS AND

PROCEDURE

3.1 Experimental Apparatus

Figure 2 shows an experimental apparatus of the present heat pipe, which mainly consists of a heated section (1.65 L), a cooled section (0.38 L), a reservoir (1.65 L), two valves (Valve 1 and Valve 2), a check valve and pipes (vapor line, liquid line etc.) connecting these components. Both the heated section and the reservoir are made of a stainless steel pipe (inner diameter: 49.5 mm) and clear polycarbonate end caps. The clear resin is used to observe the working fluid inside the heated section and the reservoir. Two copper blocks holding a cartridge heater (maximum 900 W) each are attached as a heat source on the outer surface of the bottom of the heated section. The cooled section is made by coiling a copper tube having the inner diameter of 8.0 mm and the length of 7.37 m. The cooled section is immersed in water in the bath, where the water temperature is controlled by using the unit shown in Fig. 3. The water in the bath is also stirred by a mixing pump. The stainless pipe having the inner diameter of 8.0 mm is used to connect the components. The cooled section is the same height as the heated section, while the reservoir is 400 mm higher than the heated section. The heat pipe is covered with a thermal insulator to reduce any heat loss. After the air is evacuated inside the heat pipe, the working fluid is charged from a fill tube with Valve 1 and Valve 2 open. In the charging process, the working fluid flows through the fill tube, the liquid line and the reservoir, and then it is stored in the heated section. Water is used as the working fluid.

The measuring points of temperatures and pressures are also indicated in Figs. 2 and 3. The liquid temperatures inside the heated section, T_h , the cooled section (outlet: T_c), the reservoir, T_r , the heat exchanger (inlet: $T_{HEX,in}$, outlet: $T_{HEX,out}$), the water bath, T_w , are measured by thermocouples. The pressure transducers are used to measure the vapor pressures inside the heated section, P_h , the vapor line (inlet: $P_{l,in}$, outlet $P_{l,out}$) and the reservoir, P_r . The liquid flow rate, m , inside the heat exchanger of the temperature control unit and the amount of heat input from each heater are measured by a flow meter and two watt meters, respectively.

3.2 Experimental Procedure

Two kinds of experiments termed as (A) and (B) are performed in this study. Experiment (A) is a fundamental study to investigate the operational characteristics of the present heat pipe. Experiment (B), on the other hand, aims at discussing the effect of the pressure drop inside the heat pipe on the operational characteristics. In both experiments, Valve 1 and Valve 2 are operated by hand. However, in a practical system, as described in the previous paper (Imura *et al.*, 2003), it is recommended to use an electromagnetic switching valve and a check valve as Valve 1 and Valve 2, respectively. The former is usually closed by the force of the spring and is opened by the very small amount of the electricity, while the latter allows the fluid flow in one direction only from the reservoir to the heated section.

Fig. 2 Experimental apparatus

Experiment (A) According to the principle of operation, this experiment is performed as follows. After Valve 1 and Valve 2 are closed, the same amount of heat is applied from the two heaters to the heated section, while the cooled section is cooled in the water bath. The water temperature, T_w , is maintained at 20 °C using the temperature control unit shown in Fig. 3. When the heated section becomes empty, Valve 1 and Valve 2 are opened simultaneously. After 90 sec, Valve 1 and Valve 2 are closed simultaneously, and then the same operation is continued. The total heat input from the heaters, Q , and the amount of charged working fluid, V_0 , are changed as $Q = 400, 500, 600$ W and $V_0 = 0, 0.2, 0.4, \dots, 2.0$ L, respectively.

Experiment (B) In this experiment, Valve 3 is added on the vapor line as shown in Fig. 2 to change the pressure drop inside the heat pipe intentionally. Except the operation of this valve, the experimental procedure is essentially the same as that of Experiment (A). This experiment is performed under the conditions of $Q = 400, 500, 600$ W, $V_0 = 1.0$ L and $T_w = 20$ °C.

Fig. 3 Temperature control unit

4. RESULTS AND DISCUSSION

4.1 Experiment (A)

The three kinds of pressure differences, ΔP_I , ΔP_{II} , ΔP_{III} , inside the present heat pipe are defined respectively by the following equations:

$$\Delta P_I = P_h - P_{l,in} \quad (2)$$

$$\Delta P_{II} = P_{l,in} - P_{l,out} \quad (3)$$

$$\Delta P_{III} = P_{l,out} - P_r \quad (4)$$

Figure 4 shows the transient variations of the temperatures, T_h , T_r , T_c , the pressures, P_h , P_r , and the pressure differences, ΔP_I , ΔP_{II} , ΔP_{III} , inside the heat pipe for (a) $Q = 400$ W, $V_0 = 1.0$ L and (b) $Q = 600$ W, $V_0 = 1.0$ L. The open periods of Valve 1 and Valve 2 are also indicated in the figures. Because Valve 1 and Valve 2 are operated simultaneously, the open periods of the two valves are the same. It is confirmed that the temperatures, the pressures and the pressure differences inside the heat pipe vary cyclically corresponding to the valve operation, and the heat is transported sideward continuously from the heated section to the cooled section. Because the air is evacuated

inside the heat pipe, P_h and P_r correspond to the saturated pressures of T_h and T_r , respectively.

After Valve 1 and Valve 2 are closed, T_h and P_h increase for a while and the boiling occurs inside the heated section, which is observed through the clear end caps of the heated section. The generated vapor flows sideward through the vapor line to the cooled section, where the heat is discharged into the heat sink. The vapor condenses and the condensate is moreover subcooled in the cooled section. T_c is almost equal to T_w , implying that the condensate is subcooled sufficiently inside the cooled section. The cooled liquid is pushed to the reservoir by the vapor pressure of the working fluid. Because the vapor inside the reservoir is condensed by the incoming cooled liquid, T_r and P_r decrease gradually during the heat transport period when Valve 1 and Valve 2 are closed. The decreases in T_r and P_r also cause the decreases in T_h and P_h . When the heated section becomes empty, Valve 1 and Valve 2 are opened simultaneously. The vapor inside the heated section flows into the reservoir, and then the cooled liquid stored inside the reservoir flows down to the heated section under the action of gravity. Resulting from this, the differences in temperature and pressure between the heated section and the reservoir are canceled.

The total pressure difference, ΔP_t , inside the heat pipe is expressed as,

Fig. 4 Transient variations of temperatures, pressures and pressure differences; experiment (A)

$$\Delta P_t = \Delta P_I + \Delta P_{II} + \Delta P_{III} = P_h - P_r \quad (5)$$

ΔP_I is also shown in Fig. 4. ΔP_I is essentially a driving force to circulate the working fluid and remains almost constant throughout the heat transport cycle except the period when Valve 1 and Valve 2 are opened. It is found that ΔP_I and ΔP_{II} are both less than 1.0 kPa, implying that the frictional drag is very small between the heated section and the cooled section. ΔP_{III} is the sum of the two pressure drops in the liquid line due to the friction and the gravity. The pressure drop due to the gravity, ΔP_g , is expressed as,

$$\Delta P_g = \rho g H \quad (6)$$

where ρ is the liquid density, g the gravitational acceleration and H the difference in height between the vapor-liquid interfaces inside the cooled section and the reservoir. In this experiment, the value of H cannot be obtained exactly because the vapor-liquid interface is invisible inside the cooled section; but the value of ΔP_g is estimated at 3.9 kPa substituting the difference in height (400 mm) between the heated section and the reservoir for H . It is confirmed that ΔP_g is a primary factor dominating ΔP_I in this experiment. It is also revealed

that the heat transport cycle becomes faster with the increase in Q because of the increase in the evaporation rate of the working fluid inside the heated section.

The amount of the working fluid which circulates inside the heat pipe, V_I , is also measured through the clear end caps of the heated section. Figure 5 shows the relation between V_0 and V_I for $Q = 400, 500, 600 \text{ W}$. For the case where V_0 is small, the working fluid does not circulate inside the heat pipe, and thus there exists a minimum value of V_0 for the heat pipe operation. For the case where V_0 is greater than the minimum value, $V_{0,min}$, V_I increases almost linearly with V_0 and this relation is expressed as,

$$V_I = V_0 - 0.53 \quad (V_{0,min} \leq V_0 \leq V_{0,max}) \quad (7)$$

where $V_{0,max}$ is the maximum value of V_0 , which depends on the inner volume of the heat pipe. $V_{0,max}$ is 2.1 L for the present heat pipe. Equation (7), which is also shown in Fig. 5, implies that about 0.53 L of the working fluid is stagnant inside the heat pipe including the liquid line (0.084 L) and the cooled section (0.38 L).

Figure 6 shows the average temperatures of the heated section, $T_{h,ave}$, and the reservoir, $T_{r,ave}$, during the heat transport period when Valve 1 and Valve 2 are closed. With the increase in V_0 , the amount

Fig. 5 Amount of working fluid which circulates inside heat pipe

of the cooled liquid stored inside the reservoir is increased and the condensation of vapor inside the reservoir is enhanced, resulting in the decrease in $T_{r,ave}$ and $T_{h,ave}$.

Figure 7 shows the relation between the heat input, Φ_{in} , and the heat output, Φ_{out} , of the heat pipe. Φ_{in} and Φ_{out} are expressed respectively as,

$$\Phi_{in} = Q \quad (8)$$

$$\Phi_{out} = \frac{mc \int_{t_{cycle}} (T_{HEX,out} - T_{HEX,in}) dt}{t_{cycle}} \quad (9)$$

where m and c are the mass flow rate and the specific heat respectively of the liquid inside the heat exchanger shown in Fig. 3, and t_{cycle} is the time of one heat transport cycle. It is shown that more than 91 % of the heat is transported from the heated section to the cooled section with the heat loss less than 9.0 %, which confirms the effectiveness of the present heat pipe for the sideward heat transport.

4.2 Experiment (B)

Figure 8 shows the transient variations of the temperatures, T_h , T_r , T_c , the pressures, P_h , P_r , and the pressure differences, ΔP_I , ΔP_{II} , ΔP_{III} , inside the heat pipe for $Q = 500$ W, $V_0 = 1.0$ L having the pressure drops of maximum (a) 0.3 kPa, (b) 5.0 kPa and (c) 10 kPa respectively inside the vapor line. ΔP_{II} corresponds to this pressure drop, which is intentionally made by using Valve 3. The open periods of Valve 1 and

Fig. 6 Average temperatures of heated section and reservoir

Fig. 7 Relation between heat input and heat output

Valve 2 are also indicated in the figures. Regardless of the pressure drop, it is confirmed that the heat pipe works periodically corresponding to the operations of Valve 1 and Valve 2, and the heat is transported sideward continuously from the heated section to the cooled section. However, it is revealed that the pressure drop greatly affects the transient variations of the temperatures and the pressures inside the heat pipe. The temperature and the pressure not only inside the heated section but also inside the reservoir become higher with the increase in the pressure drop in the vapor line. This is due to the increase in

Fig. 8 Transient variations of temperatures, pressures and pressure differences; experiment (B), $Q = 500$ W, $V_0 = 1.0$ L

temperature of the vapor flowing into the reservoir when Valve 1 and Valve 2 are opened. The present heat pipe enables to transport the heat over a long distance. Moreover, in a practical application, the vapor and liquid lines can be bent without any difficulty. However, the pressure drop is an important consideration for the design of the present heat pipe.

5. CONCLUSIONS

For the purpose of the sideward heat transport over a long distance, the vapor-pressure-driven heat pipe is devised and its operational characteristics are experimentally investigated. It is confirmed that the heat pipe works periodically corresponding to the valve operation, and the heat is transported sideward continuously from the heated section to the cooled section. Effect of the amount of the working fluid on the operational characteristics of the heat pipe is also revealed. The circulation of the working fluid inside the heat pipe is ensured even when the heat transport distance is very long. Therefore, the present heat pipe enables to transport the heat over a long distance. Moreover, in a practical application, the vapor and liquid lines can be bent without any difficulty. However, the pressure drop is an important

consideration for the design of the present heat pipe. The vapor-pressure-driven heat pipe is effective for a large-scale thermal management.

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NOMENCLATURE

c	specific heat (J/ kg·K)
g	gravitational acceleration (m/s ²)
H	height (m)
m	mass flow rate (kg/s)
P_c	vapor pressure inside cooled section (kPa)
P_h	vapor pressure inside heated section (kPa)
P_l	vapor pressure inside vapor line (kPa)
P_r	vapor pressure inside reservoir (kPa)
Q	heat input (W)

T_c	liquid temperature inside cooled section (°C)
T_{HEX}	liquid temperature inside heat exchanger (°C)
T_h	liquid temperature inside heated section (°C)
T_r	liquid temperature inside reservoir (°C)
T_w	water temperature (°C)
t_{cycle}	time of one heat transport cycle (s)
V_0	amount of working fluid charged inside heat pipe (L)
V_l	amount of working fluid which circulates inside heat pipe (L)

Greek Symbols

ΔP	pressure difference (kPa)
Φ	heat input, heat output (W)
ρ	density (kg/m ³)

Subscripts

I, II, III	sections of I, II, III
ave	average
g	gravity
in	inlet, input
max	maximum
min	minimum
out	outlet, output
t	total

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