Heat Transfer Rate of Looped Type Heat Pipes Using Water and Nak as Working Fluid under Liquid Phase Flow

By

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1. Introduction

As shown in Fig. 1, the looped type heat pipe used in this study is consisted of a riser tube and a downcomer, in which a suitable amount of working fluid selected according to the useful temperature is filled.

Heat is transfered from the heating section in the lower part of the riser tube to the cooling section in the upper part of the downcomer.

Driving force for the circulation of the working fluid is given by one of the following three modes according to the flow in the riser tube, that is, 1) liquid phase flow, 2) two phase flow and 3) gas phase flow.

The heat transefer rate of the looped type heat pipe employing sodium, potassium, mercury, water, etc., as working fluid are calculated according to the following assuption and the result is shown in Fig. 2.

(1) The sectional area of each tube is 2 cm^2 and the height of each Fig. 2 tube is 7 m as shown in Fig. 1.

(2) In the radial direction of the tube, temperature, pressure, and velocity are constant, liquid phase and gas phase are saturated equilibrium states, thermodynamical properties of these phase are constant.

(3) Enthalpy, kinetic energy and potential energy in the fluid are increased by the quantity of heat added from the external, but the absolute values of kinetic energy and potential energy are very small and can be neglected, then the increase in the enthalpy of fluid is considered.

(4) The friction coefficient of the tube is 0.03 for the homogeneous phase flow.

(5) The enthalpy of the liquid in the liquid phase flow is independent on pressure, and is considered to be the same as that of liquid which is under the state of

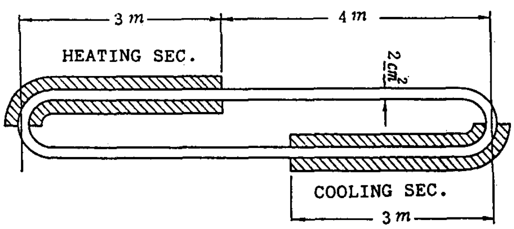

Fig. 1. The fundamental structure of the looped type heat pipe.

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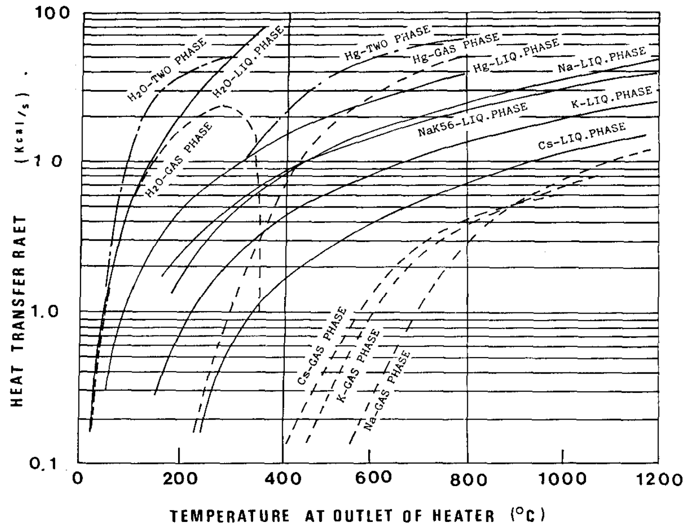


Fig. 2. The calculated heat transfer rate of the looped type that pipe.

saturated equilibrium with vapor at all the temperatures.

As shown in Fig. 2, the looped type heat pipe is suitable for the large amount of heat transfer. An typical heat pipe is used as the element for heat transfer to assemble, for instance, heat recovery unit. On the other hand, the looped type heat pipe can act as the element for the heat transfer, but mostly is used itself as a heat recovery unit.

The purpose of this research is to develop the looped type heat pipes employing working fluids of various kinds and in this report, the authers described the experimental results on the heat transfer rate in case that the flow in the riser tube is liquid phase flow.

In this study, two looped type heat pipes employing water and Nak as working fluid were designed and tested.

2. Tested looped type heat pipes

2.1 Fundamental construction

The looped type heat pipes used in our experiments had some different design details each other according to the applied working fluid. These different details were tube diameter, length of riser tube and downcomer, electric heater capacity, structures of cooler and expansion tank. The tested looped type heat pipes had the fundamental constructions as shown in Fig. 3.

2.1.1 NaK-looped type heat pipe

As shown in Fig. 3, NaK-looped type heat pipe consisted of a riser tube 1, a heater 2, a cooler 3, a downcomer 4 and an expansion tank 5. The container was made of SUS 316 stainless steel tube with the inner diameter 16.7 mm, and the length of vertically set riser tube and the downcomer each were 1000 mm.

In order to heat NaK directly, an electric heater was mounted at the lower part of the riser tube. The electric heater was internal heating type and consisted of

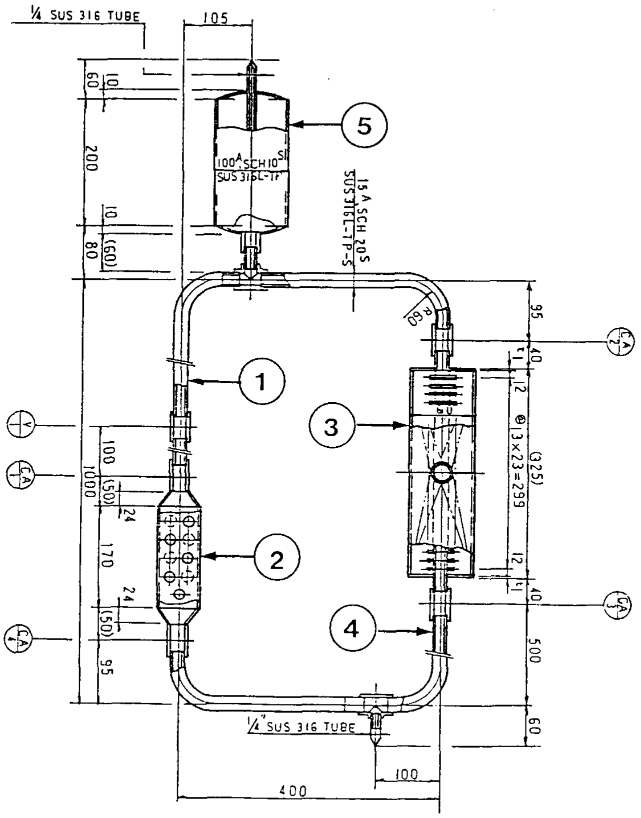


Fig. 3. Schematic diagram of looped type heat pipe employing NaK as working fluid.

nine sets of cartridge-heater (650 W/200 V/set). The inlet of the heating section was situated at 145 mm from the center line of the lower connector. The length of the flow pass in the heater was 170 mm. The cooler was placed at the upper part of the downcomer to remove heat by cooling air and the length of the flow pass in the cooler was 325 mm. The inlet of the cooling section was situated at 135 mm from the upper end of the downcomer.

An expansion tank was mounted at the upper part of the riser tube in order to absorb pressure fluctuation owing to the thermal expansion of the working fluid in the flow pass and to circulate the working fluid smoothly.

NaK used in our experiment was what is called NaK 45, and it was composed of sodium 55 wt% and potassium 45 wt%. The enclosed weight of NaK was 2.15 kg and the highest liquid level of the working fluid reached to about one-fifth of the height of the expansion tank.

The flow pass of high temperature side, the flow pass of low temperature side, the heater and the cooler of the looped type heat pipe were covered with 150 mm thick heat insulating materials.

2.1.2. Water-looped type heat pipe

The container was made of copper tube, and the length of the riser tube and the downcomer respectively was 1320 mm. The heater was the internal heating type, and consisted of twelve sets of cartridge-heaters (ϕ16×160 mm, 640 W/set).

The cooler was shell-and-tube type heat exchanger and its dimention was 200 mm in the direction of flow pass, 400 mm in width and 100 mm in depth. The heat transfer surface consisted of heating tube with 15 mm diameter and aluminum plate-fin with 0.6 mm in thickness. The heat exchanger area is 3.6 m^2 and the working fluid flowes on the outside of the tube, and the cooling water flowes on the inside of the tube.

Each part of the water-looped type heat pipe were covered fully with insulating material. In order to detect the heat loss from the insulating material surface of the heater case, four heat flux meters were installed on it.

2.2 Summary of the expriments

In our experiments, the heat transfer rates of the looped type heat pipes were measured on conditions that NaK temperature range at the outlet of the heater was 350~520°C, and for water temperature range was 30~100°C.

The heat transfer rates were determined from the net electric power supplied to the electric heater. Therefore the net heat inputs were obtained as the quantity of heat deducted the quantity of the said heat loss from the heater input measured by the integrating wattmeter. The temperatures inside the circular flow pass of NaK were measured by the sheath type cromel-arumel thermocouples with diameter 3.2 mm. The CHEN type void meter sensers for sodium were inserted at the outlet of the heating section to monitoring the growth of the void. The heads of the sheath type thermocouples and the void meter were placed on the center line of the flow pass. For these reasons, the positions of the above mentioned heads were confirmed by the *X*-ray photograph.

The positions of the temperature measurements are shown in Fig. 3 by the signs CA/n, where n indicates 1–4. And the position of the void meter is shown in Fig. 3 by the sign $V/1$.

The temperature measurement for the water-looped type heat pipe were carried out at the outlet and the inlet of the heating section and cooling section for circulating water, and at the outlet and the inlet of the cooler for cooling water with the copper-constantan thermocouple, and also the quantity of the cooling water was measured.

2.3 Physical properties of NaK 45

The physical properties of NaK 45 vary with the mixing ratio of sodium and potassium. The specific heat C_{PNaL} (kcal/kg°C) of NaK 45 used in this study is calculated by the following equations (1) and (2)

$$\left.\begin{aligned} C_{PNa}&=0.34324-1.3868\times10^{-4}t+1.1044\times10^{-7}t \\ C_{PK}&=0.2004-0.8777\times10^{-4}t+1.097\times10^{-7}t \end{aligned}\right\} \quad (1)$$

$$C_{PNaK}=X_{Na}C_{PNa}+X_{K}C_{PK} \quad (2)$$

Where t: temperature (°C), C_{PNa}: specific heat of sodium (kcal/kg°C), C_{PK}: specific heat of potassium (kcal/kg°C), X_{Na}: weight ratio of sodium (=0.55), X_K: weight ratio of potassium (=0.45).

The specific weight of *NaK* (kg/m^3) is calculated by the following equation (3) using the table of physical properties for sodium and potassium.

$$V_{NaK}=N_{Na}V_{Na}+N_K V_K \tag{3}$$

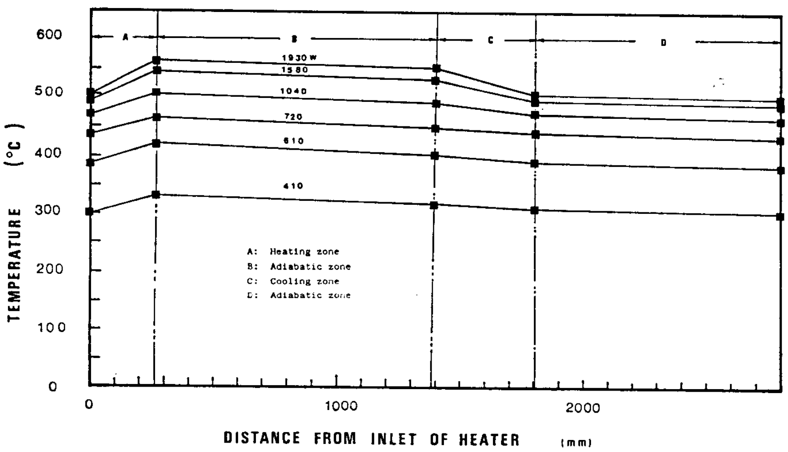
Where V_{NaK}: specific volume of NaK (m^3/kg), V_K: specific volume of sodium (m^3/kg), V_K: specific volume of potassium (m^3/kg), N_{Na}: molar fraction of sodium, N_K: molar fraction of potassium.

The coefficient of kinematic viscosity of *NaK* (m^2/s) is obtained from the table of physical properties.

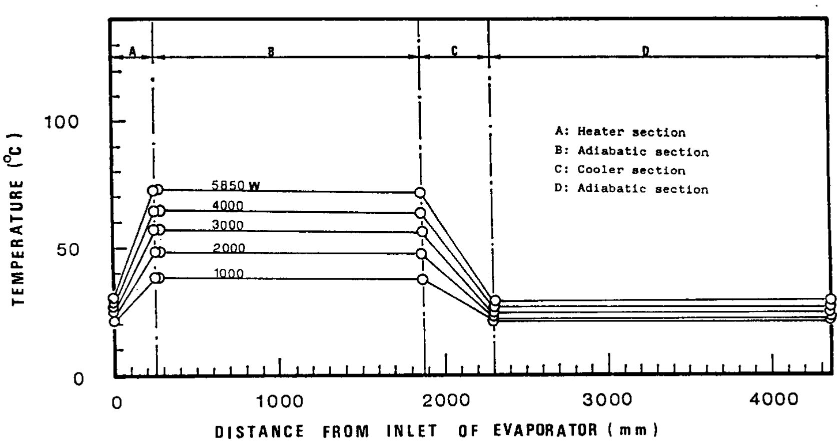
3. Results and discussion

Some examples of temperature profile are shown in Fig. 4. Fig. 4 (a) refers to NaK-looped heat pipe, and Fig. 4 (b) to water.

In the temperature profile of NaK-looped type heat pipe, temperature drops caused by the heat loss are observed at the high temperature side flow pass from the outlet of the heating section to the inlet of the cooling section, and at the low



(a) NaK.



(b) Water.

Fig. 4. Temperature profile of looped type heat pipe.

temperature side flow pass from the outlet of the cooling section to the inlet of heating section. For example, in case of heat input 1930 W, temperature drops of 9.5°C at the high temperature side and of 4.7°C at the low temperature side flow pass could be found. The heat loss corresponding with this temperature drop at the high temperature side flow pass is equivalent to about 16% of heat input, about 8% for the low temperature side and 76% of total heat input is removed by the cooler. The heat loss for the low temperature side acts effectively to circulate the working fluid, but the heat loss for the high temperature side brings the decrease in the quantities of circulation flow and of heat removed.

It is very difficulty to prevent the heat loss on the surface of the high temperature side flow pass with the increase of operating temperature. The increase in the heat loss is unavoidable problem to the looped type heat pipe for the medium or high temperature region.

Against this, in the case of the water-looped type heat pipe, the heat loss of the high and the low temperature sides are very small, so the temperature drops caused by the heat loss can be almost negligible.

The flow mode in the tube of both looped type heat pipes within this experimental conditions can be considered as liquid phase flow, so using the calculation model shown in Fig. 5, the heat transfer rate of the both looped type heat pipes are calculated. In this calculation model, the looped flow pass of working fluid is divided into four flow passes, namely the flow pass of the heating section (L1), the high temperature section (L2) the cooling section (L3) and the low temperature section (L4). Furthermore the riser tube and the downcomer, both vertically placed, are divided into three sections respectively as shown in Fig. 5. The length

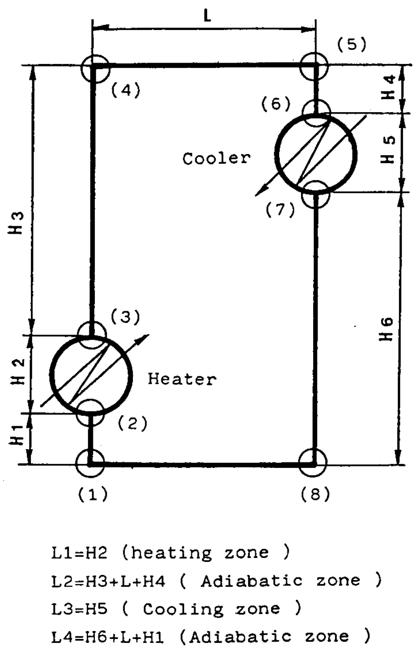


Fig. 5. Calculation model.

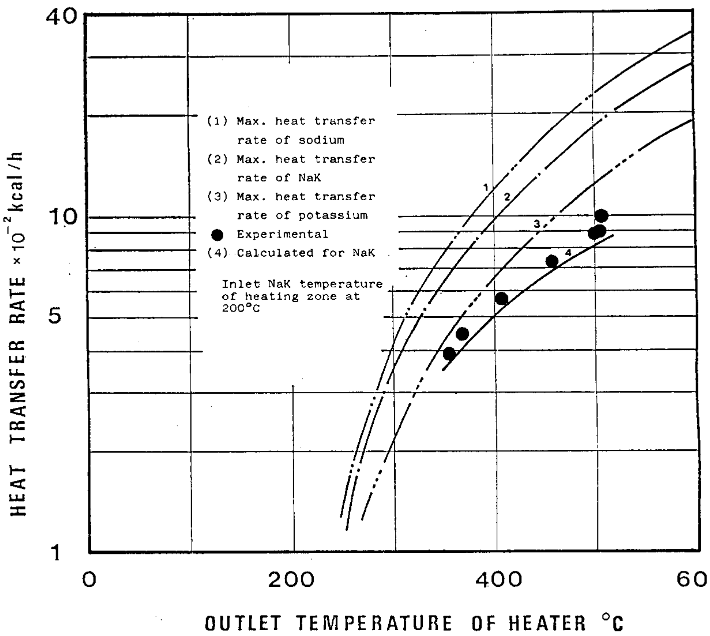


Fig. 6. Hea. transfer rate for looped type heat pipe employing NaK as working fluid.

of the every section is indicated by the signs H1, H2 and H3 for the riser tube, and H4, H5, and H6 for the downcomer.

Therefore, when the working fluid flow under liquid phase, the fundamental equation to calculate the mean velocity of the flow is given by the following equation (4).

$$(H4\gamma_4+H5\gamma_5+H6\gamma_6)-(H1\gamma_1+H_2\gamma_2+H3\gamma_3)=\Delta P_{\text{Loss}} \qquad (4)$$

Where γ_i (i=1, 2, ... 6): mean specific weight of the working fluid for the divided section respectively (kg/m^3), ΔP_{Loss}: total pressure loss by the circular flow pass (kg/m^2).

ΔP_{Loss} can be calculated by equation (5) as the summation of the pressure loss caused by the pipe friction of the flowpass, and the local pressure loss of the sections shown in Fig. 5 by the sign ○.

$$\Delta P_{\text{Loss}}=\sum_{i=1}^{4}\Delta P_i+\sum_{R=1}^{8}\Delta P_R \qquad (5)$$

If we difine U_1 as the mean flow velocity in the heating section, U_2 as the mean flow velocity in the high temperature region, U_3 as the mean flow velocity in the cooling section and U_4 as the mean flow velocity in the low temperature region, we can obtain the relations of equation (6) by the equation of continuity.

$$U_1=C_1U_2, \quad U_3=C_3U_2, \quad U_4=C_4U_2 \qquad (6)$$

Where C_i (i=1, 3, 4): value determined by the sectional area, specific weight and so on.

Using the relation of equations (4), (5), (6) and discriminating between laminar flow and turbulent flow in each flow pass, the mean flow velocity U_2 in the high temperature side flow pass satisfying equation (4) can be calculated by the repeating method.

The quantity of the circular flow is given by the following equation (7) using the mean flow velocity U_2 in the high temperature side flow pass, and the heat transfer rate Q_c is given by the following equation (8).

$$G=A_2\gamma_2U\ (\text{kg}/h) \qquad (7)$$

$$Q=C_PG(t_{\text{out}}-t_{\text{in}})\ (\text{kcal/h}) \qquad (8)$$

Where A_2: the sectional area of the high temperature side flow pass (m^2), C_P: the mean specific heat of working fluid in the high temperature side (kcal/kg°C), t_{out}: the temperature of working fluid at the outlet of heating section (°C), t_{in}: the temperature of working fluid at the inlet of the heating section (°C).

The maximum heat transfer rate as shown in Fig. 6 were calculated by equation (8) to three kinds of the working fluid, that is, sodium, NaK 45 and potassium respectively. In Fig. 6, the calculated results are shown by the numerical signs (1) for sodium, (2) for NaK 45 and (3) for potassium. In addition, the calculations were done on the assumption that there are not the heat loss at both the high and the low temperature sides, and that the temperature of each working fluid at the inlet of the heating section is 200°C constant.

But, in practice, owing to the presence of the heat loss mentioned above and the restriction of cooling capacity, as compared with the maximum heat transfer rate, the heat transfer rate was smaller. The heat transfer rates for NaK 45 are shown likewise in Fig. 6 by the real line with the numerical sign (4), and the sign ● respectively. The real line (4) represents the calculated values by equation (8) using the actual temperatures and the sings ● represent the actual heat transfer rates.

Although the calculated values are smaller about 10% than the actual values, the calculated values are in the safety side. But when the flow mode in the looped tube is the liquid phase flow, the heat transfer rate of the looped type heat pipe can be estimated by equation (8). The calculated results by the similar method for the heat transfer rate of the water-looped type heat pipe under liquid phase flow is shown in Fig. 7. The calculated values are generally smaller than the actual value, and the difference between the calculated values and the actual values is large, when the flow velocities in the high temperature side flow pass and the low temperature side flow pass are both small and are the laminar flows. On the contrary, the difference becomes small in case of the turbulent flow in the high temperature side flow pass.

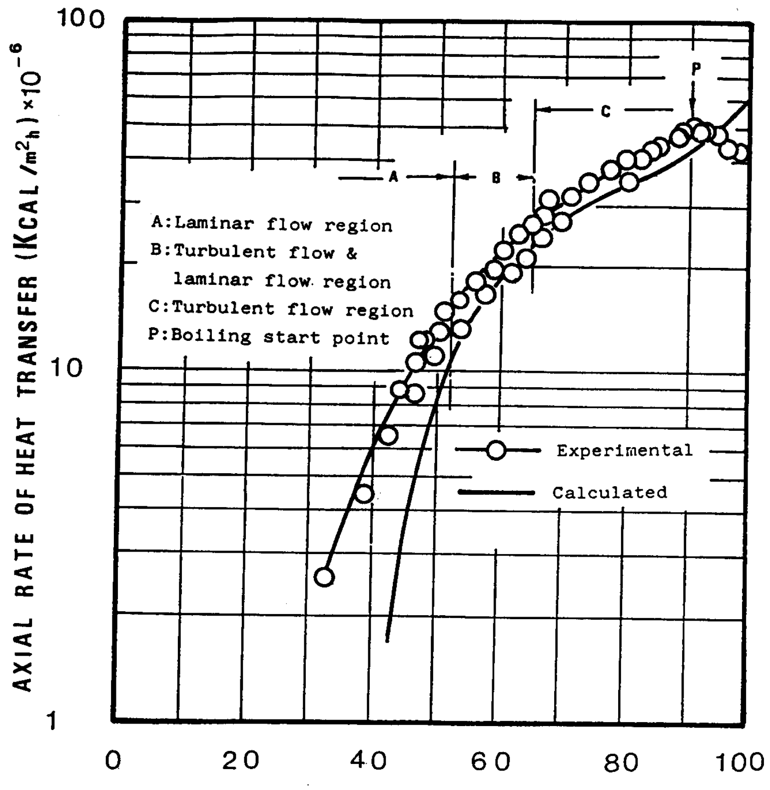


Fig. 7. Heat transfer rate for looped type heat pipe employing water as working fluid.

In practice, the heat transfer rate is very small under the temperature condition that produces the laminar flow, so such temperature condition is unfit to use. For that reason, when we have no need of consideration for such temperature range, equation (8) is available for the looped type heat pipe using water as the working fluid.

Moreover, when water is used as working fluid, there are three combinations of the flow, that is, the laminar flow in both flow passes, the turbulent flow in the high temperature side flow pass and the laminar flow in the low temperature side flow pass, the turbulent flow in both flow passes. But, in the case of liquid metals, the flow is the turbulent flow.

4. Conclusion

The summary of the experimental results is shown below.

(1) The heat transfer rate of the looped type heat pipe under liquid phase flow can be estimated by equation (8).

(2) In the looped type heat pipe for high temperature side flow range, it is difficult to decrease heat loss in the high temperature side flow pass, so the looped type heat pipe presented here is useful for the low temperature range.

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