Heat Transfer Characteristics of Arterial Heat Pipe with Axial Grooves

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Summary: An arterial heat pipe with axial grooves has a three dimensional network of liquid passages and its heat transfer characteristics are significantly influenced by gravity force.

An analytical model for the heat pipe operation under the gravity field has been presented. Calculated results using the model predict a wide range of partial dryout region and it shows a good agreement with experimental results.

Heat transfer characteristics under the zero gravity field are also calculated. It predicts that the maximum heat transport capacity would be higher than that for the gravity field but the range of partial dryout region would be very narrow.

1. INTRODUCTION

A new type of arterial heat pipe with axial groove has been fabricated and tested [1]. The heat pipe consists of separated two channels, one is a liquid channel and the other is a vapor core which is provided with axial grooves.

Comparing with conventional axial groove heat pipes, this heat pipe has relatively complex wick structure and the liquid flow passages form a three dimensional network.

Hence, the heat transfer characteristics of the heat pipe are significantly influenced by the gravity force even under horizontal configuration.

A heat transfer analysis considering gravity effect has been made for monogroove heat pipes [2], but it has been limited to a dry-out initiation point and some features around the dry-out initiation point are left to be further investigated.

In this paper, an analytical model for heat transfer characteristics including dry-out propagation process is presented and analytical results for the arterial heat pipe with axial grooves are compared with experimental results.

2. THEORY OF OPERATION

2.1 Arterial Heat Pipe with Axial Grooves

An arterial heat pipe with axial grooves has double pipe construction, as shown in Figure 1. The outer pipe, provided with two axial channels is a container and an inner pipe is inserted into the larger channel. The inner pipe is provided with axial grooves

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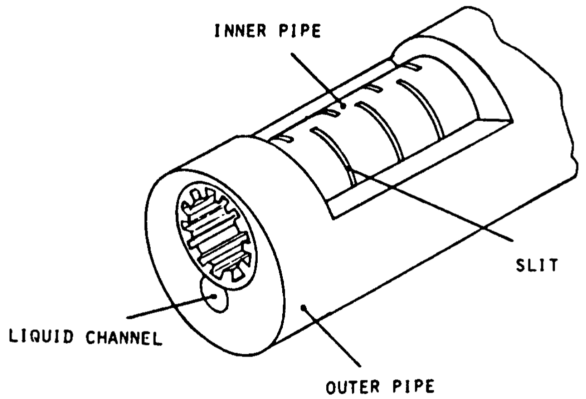

Fig. 1. Heat Pipe Construction.

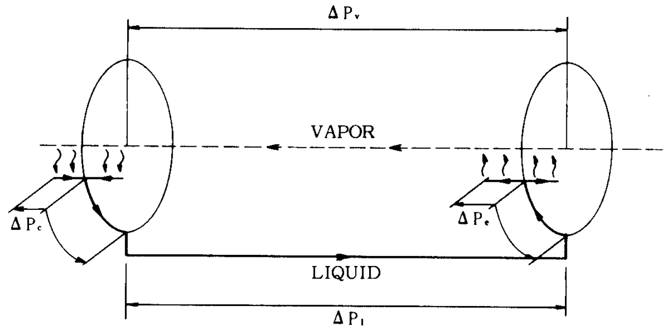

Fig. 2. Fluid Flow and Viscous Losses.

and circumferential slits. Owing to this construction, the heat pipe has two axial channels, a larger one with a grooved wall and a smaller one with a smooth wall. The larger one is a vapor core and a smaller one is a liquid channel. The grooves communicate with the liquid channel through the slits.

2.2 Pressure Balance Relationship

The working fluid flow in the heat pipe is shown in Figure 2 schematically. The flow is characterized by pressure balance relationship between the pumping heads and the pressure losses due to flow resistances. For the flow direction of heat pipe operation, capillary force at the evaporator grooves $\Delta P_{cap\cdot e}$ and gravity force at the condenser $\rho g h_c$ works as pumping heads and capillary force at the condenser grooves $\Delta P_{cap\cdot c}$ and gravity force at the evaporator $\rho g h_e$ have opposit effect. The net pumping head is obtained as a difference between possitive power and opposit power and it balances with pressure losses around the flow loop. The pressure balance relationship is described as follows.

$$\Delta P_{cap\cdot e} - \Delta P_{cap\cdot c} + \rho g h_c - \rho g h e = \Delta P_v + \Delta P_l + \Delta P_e + + \Delta P_c \qquad (1)$$

Where ΔP_v, ΔP_l, ΔP_e and ΔP_c are pressure losses of the vapor transport line, the liqyud return line, the evaporator and the condenser, respectively.

Employing standard viscous loss equations, the pressure loss terms in the above equation are expressed as a function of the working fluid flow rate.

$$\Delta P_i=\frac{32G^2L_i}{R_{e.i}\rho_i A_i^2 D_i}$$

$$\Delta P_i=\frac{0.1582G^2L_i}{R_{e.i}^{1/4}\rho_i A_i^2 D_i} \tag{2}$$

$$R_{e.i}=\frac{GD_i}{\rho_i \nu_i A_i}$$

Where G, D_i, A_i, ρ_i and v_i are the working fluid flow rate, the hydraulic diameter, the area, the fluid density and the kinematic viscosity, respectively and subscript i may be v, l, e or c.

The working fluid flow rate is related to heat load by the following equation.

$$G=\frac{Q}{\lambda} \tag{3}$$

Where Q and λ are the heat load and the latent heat of the working fluid.

The set of the above equation represents relationship between the necessary capillary pumping head and the specified heat load.

Capillary head is limited by the groove geometory and its maximum value is given by the following equation.

$$\Delta P_{\mathrm{cap\cdot max}}=\frac{2\sigma}{w} \tag{4}$$

Where w and σ are the width of the grooves and the surface tension coefficient of the working fluid, respectively.

Heat load for dry-out initiation, which is definition of the maximum heat transport capacity, is obtained by solving the set of equations under the condition that the capillary head at the evaporator top groove becomes its maximum value.

Over the heat load, dry-out propagates. Analysis technique for the dryout propagation process is shown in Figure 3.

3. Experiment

3.1 Experimental Apparatus

An experimental model is illustrated in Figure 4. The model is not a straight heat pipe but a looped heat pipe, which consists of an evaporator, a condenser, a vapor transport line and a liquid return line.

The evaporator and the condenser are arterial heat pipes with axial grooves of 200 mm in length and they are provided with a sight glass on one end individually. Through the sight glass, liquid behavior in a liquid channel and grooves can be observed.

The evaporator has an electrical heater, which supplies specified heat load. In order

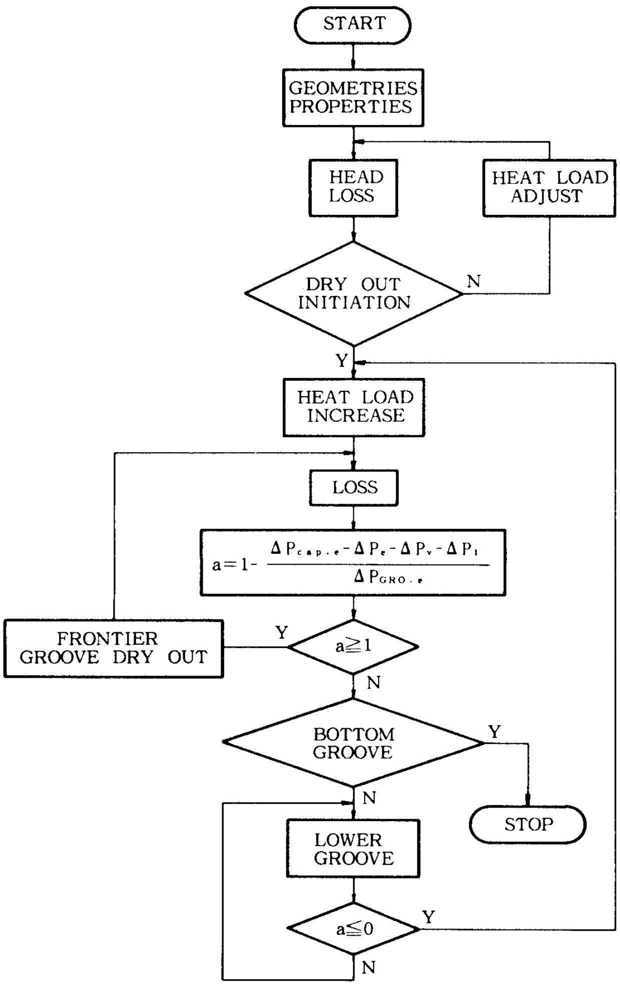

Fig. 3. Flow Chart of Dry Out Analysis.

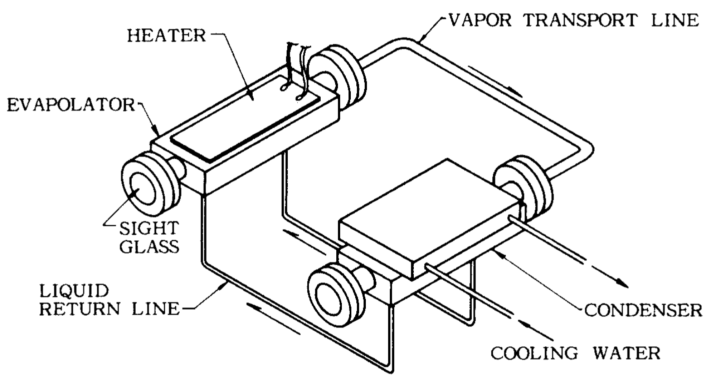

Fig. 4. Experimental Apparatus.

to prevent heat leak to ambient air, the evaporator is thermally insulated. The condenser has a water cooling plate.

The evaporator and the condenser are set horizontal and the liquid channel is directioned downward. This configuration is adopted in order to realize the same liquid distribution as that for the zero gravity field.

Table 1. Specification of the Heat Pipe

Pipe Material	A-6063
Heat Pipe Length	200 mm
Liquid Channel ID	5 mm
Vapor Core ID	8 mm
Groove Width	0.25 mm
Groove Depth	0.5 mm
Groove Number	50
Slit Width	0.25 mm
Slit Pitch	33 mm

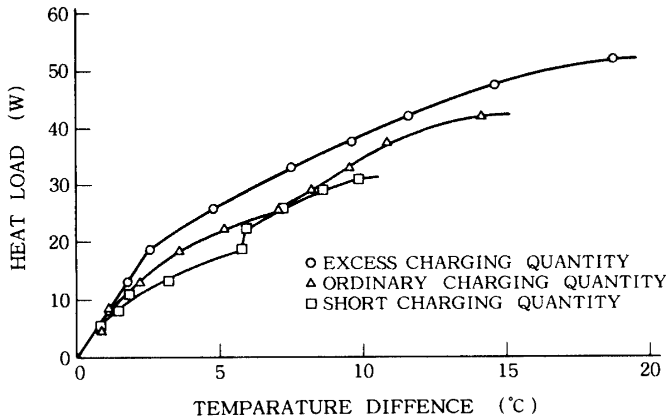

Fig. 5. Experimental Results.

Major specification of the heat pipes are shown in Table 1. Working fluid is Freon R11.

3.2 Experimental Results

Three series of experiments have been carried out, excess, ordinary and short charging quantity of working fluid. In the case of excess charging quantity, a puddle is formed at the bottom of vapor core. Ordinary charging quantity is obtained by purging a little of working fluid from the states of excess charging quantity so as that no puddle is formed and meniscus on the bottom groove is flat when no heat load is applied. For the case of working fluid shortage, again a little quantity of working fluid is purged from the state of ordinary charging quantity.

Experimental results are shown in Figure 5.

The dry-out initiation heat load varies depending on charging quantity. It is supposed that the larger heat load obtained fo excess charging quantity is due to puddle effect and the smaller heat load for short charging quantity is due to opposit cappillary head caused by a concave meniscus on the condenser groove.

Over the dry-out initiation heat load, relatively wide range of partial dryout region is observed. In the region, even though some upper grooves are dried out, the other grooves operate normally and a temperature excursion does not occur.

In the partial dry-out region of a short charging quantity case, an abrupt thermal conductance change is observed. It is caused by boiling occurrence in the evaporator

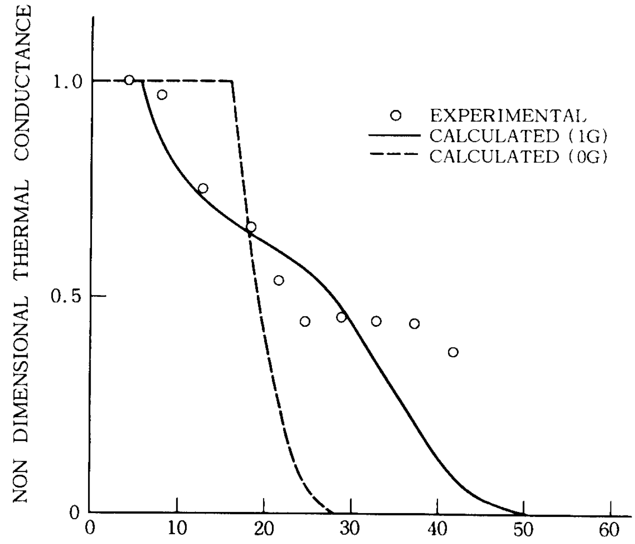

Fig. 6. Heat Transfer Characteristics.

liquid channel. In the other two cases, boilinbg occurrence is also observed but thermal conductance change is not so clear as that for the short charging quantity case.

4. Heat Transfer Characteristics

Figure 6 shows heat transfer characteristics relating to partial dry-out. The vertical axis represents the non-dimentional thermal conductance and the horizontal' axis represents the heat load. Eperimental values in the figure are for the standard case of ordinary charging quantity. Analytical values of a non-dimensional thermal conductance are obtained under the assumption that the thermal conductance is proportional to the effective heat transfer area of the evaporator.

Analytical results show good agreement with experimental results especially in low heat load region. In the high heat load region, the experimental values differ from the analysis result due to boiling occurrence.

In Figure 6, analysis results for the zero gravity field are also shown. In the case for the zero grvity field, a maximum heat transport capacity exceeds that for the gravity field and a partial dry-out range is very narrow.

In a small heat load region, pressure losses due to flow resistance are small comparing with gravity head. In such a state, large curvature of meniscus generated on the condenser grooves provides opposit pumping head to offset gravity head at the condenser under the gravity field. Consequently net pumping head and the maximum heat transport capacity become smaller than that for the zero gravity field.

In a range of partial dry-out, on the contrary, necessary gravity head at the evaporator becomes smaller as dry-out propagates and pressure loss due to flow resistance at the condenser becomes dominant as working fluid flow rate increases. In this state, an operation under the gravity field has an advantage that gravity head at the condenser porovides a necessary head for flow in the condenser. It is the reason why a partial dry-out range for the gravity field is wider than that for non gravity field.

5. CONCLUSION

Heat transfer characteristics for an arterial heat pipe with axial grooves has been discussed especially stressed on a partial dry out phenomenon.

An analytical model based on pressure balance relationship between the pumping head and the pressure drops due to flow resistance has been developed. It has been applied for dry-out initiation point and its propagation process. The analytical results predict a wide range of partial dry-out region, which is a remarkable featue distinguished arterial heat pipes from conventional axial groove heat pipes. The prediction showed good agreement with the experimental results.

REFERENCES

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