Forced-Convective Boiling in Small Diameter Tube

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Summary: A straight bare tube type evaporator was tested in order to evaluate its feasibility on space applications. Two categories of flow regime were observed during the test. One flow regime indicated a high pressure loss and a slight temperature decrease along the flow direction, and the test results showed a fairly good agreement with the analytical results obtained using a nucleate boiling model. Whereas, the other flow regime showed a contrasting feature of low pressure loss and abrupt temperature rise along the flow direction. In this case also the results obtained on the basis of the analytical model of film boiling showed a fairly good agreement with the experimental results of heat transfer characteristics.

1. INTRODUCTION

Two categories of vaporization for the two phase fluid loop system are currently being studied by many scientists. One is surface evaporation. The heat transfer mechanism in this system is basically the same as that in heat pipes. In this case, phase change occurs on the thin liquid film held at the pipe inner wall, and hence, liquid and vapor get separated. The monogroove cold plate developed by Edelstein, et al. [*1*, *2*] and the faced plate heat pipe, which is studied analytically by Hwangbo and McEver [*3*] are included in this category. The other is forced-convective boiling. In this case, the quality of the liquid vapor mixture which flows through the evaporator and condenser of this system changes with the flow. Fowle [*4*] fabricated and tested an experimental model of a forced-convective evaporation system using a straight bare tube of 12 mm inner diameter and demonstrated that its heat transport capacity is about one thousand times greater than the existing heat pipes. However, in this type of evaporator, there is a very high possibility of facing the problem regarding the detaching of liquid from the heated wall under reduced gravity environment.

Since the gravity effect is proportional to the characteristic length, the reduced gravity effect may occur very easily in a small diameter pipe of horizontal configuration. From this view-point, evaporator test using a small diameter pipe of 2.4 mm inner diameter has been carried out. The test results are presented in this paper.

2. TEST RESULTS

The schematic diagram of the experimental apparatus for the evaporation process is

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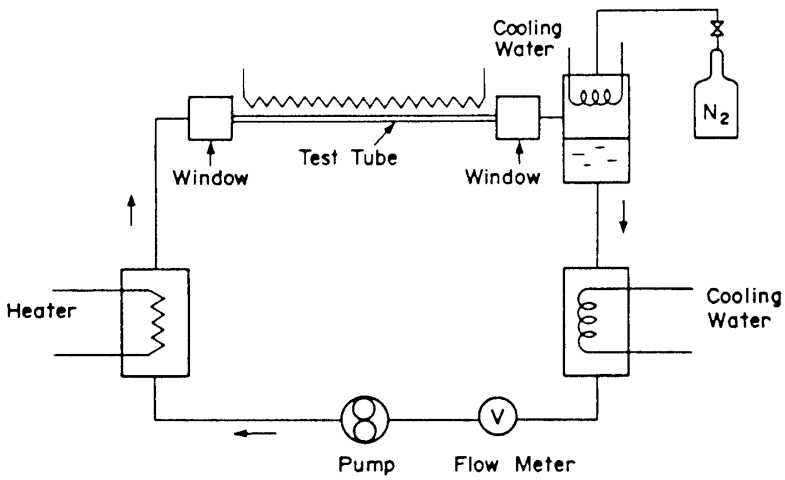

Fig. 1. Experimental apparatus of forced-convective boiling.

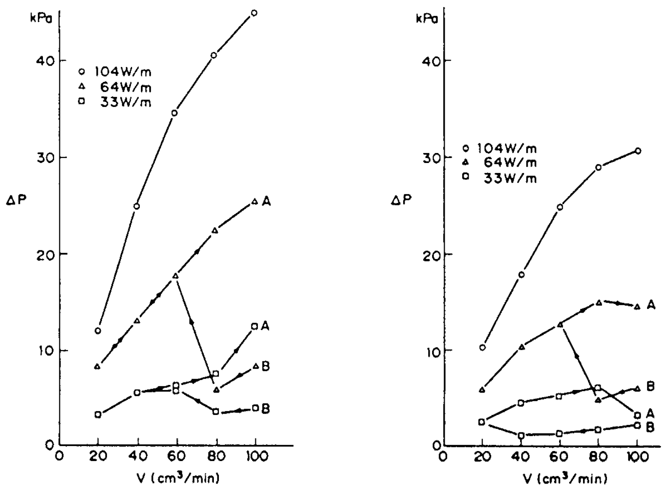

Fig. 2. Pressure loss of evaporator.

shown in Fig. 1. The evaporator is a stainless steel tube of 2.4 mm inner diameter. Heat load is applied by electric heating. The working fluid is Freon R-11. The pressure of the accumulator at the test tube outlet is controlled at specified one by adjusting control valve to the nitrogen gas cylinder and the inlet liquid temperature is controlled nearly at the saturated one by the heater in the accumulator at the inlet side.

Representative experimental results are shown in Fig. 2, in which pressure losses are shown as function of the working fluid flow rate. The arrow symbols on the curves for the 64 W/m and 33 W/m test cases shows the direction of the flow rate change. In the two test cases of lower heat loads, two flow patterns in which pressure losses are different are observed for the same fluid flow rate. As seen in the figure, the manner of flow rate change determines which flow pattern will occur. The flow pattern of the higher pressure loss appears when the flow rate is changed from lower to higher and the flow pattern for the lower pressure loss is observed in a inverse case. Hereafter, the former is called flow pattern A and the latter flow pattern B, for convenience.

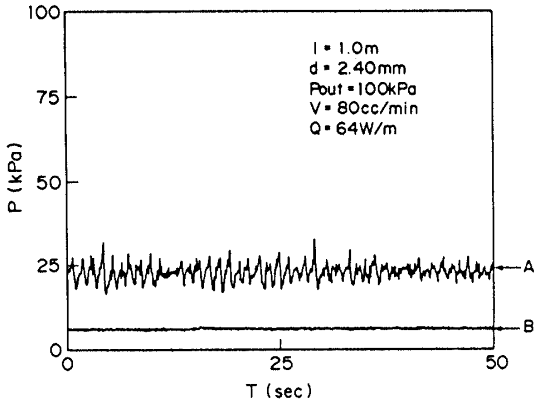

Fig. 3. Evaporator pressure.

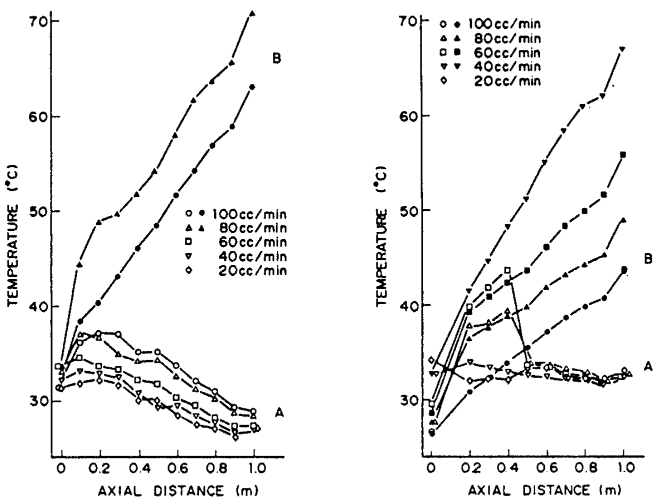

Fig. 4. Temperature profile along evaporator.

Pressure fluctuation observed in flow pattern A and B is shown in Fig. 3. The feature of pressure losses and pressure fluctuations suggests the nucleate boiling occurrence in the flow pattern A and the surface evaporation occurrence in the flow pattern B.

The temperature profiles along the evaporator also shows drastically different characteristics according to the flow patterns. Typical examples of the temperature profiles are shown in Fig. 4. The evaporator temperature for the flow pattern A decreases along the flow direction and its variation is relatively small. On the other hand, the evaporator temperature for the flow pattern B rises sharply along the flow direction. In some cases, temperature profiles changes from that for the flow pattern A to that for the flow pattern B at a point along the way. It suggests that the flow pattern transition takes place at the point.

Each testing condition was held over ten minutes and no unstable phenomenon such as periodic flow pattern transition or the movements of the transition point were observed within the test range.

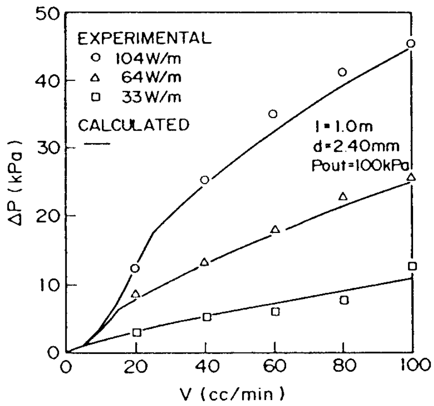

Fig. 5. Pressure loss for flow pattern A.

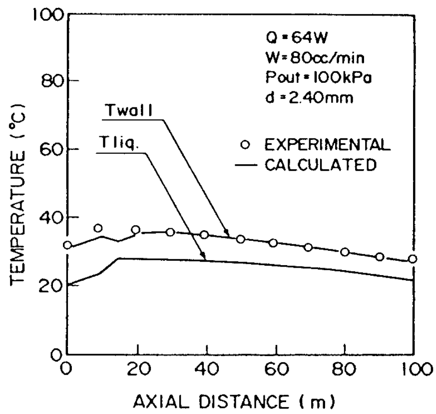

Fig. 6. Temperature profile for flow pattern A.

3. Discussion

The flow pattern A can be simulated using the homogeneous model, in which the mean kinematic viscosity weighted by the volume fraction is used. The calculated pressure profiles using this model agree well with the experimental results as shown in Fig. 5. The liquid temperature is determined for the given pressure profile under the assumption that the liquid is at saturated state in the two phase mixture region. The calculated evaporator temperature shows good agreement with experimental results as shown in Fig. 6. In this test case, the liquid at the inlet is at subcooled state and it reaches to the saturated state at 0.15 m from the inlet. In the subcooled region, liquid temperature rises along the flow direction. In the two phase mixture region, liquid temperature decreases along the flow direction according to the pressure decrease due to flow resistance. Thus, the homogeneous model explains well the characteristics of the flow pattern A.

A simplified model for the flow pattern B is shown in Fig. 7. The liquid rod is suspended by the vapor film. The flow pattern is called rod flow or inverted annular flow. From the heat transfer viewpoint, this is categorized as film boiling. Such phenomena can occur when large heat flux is applied even in one-G field.

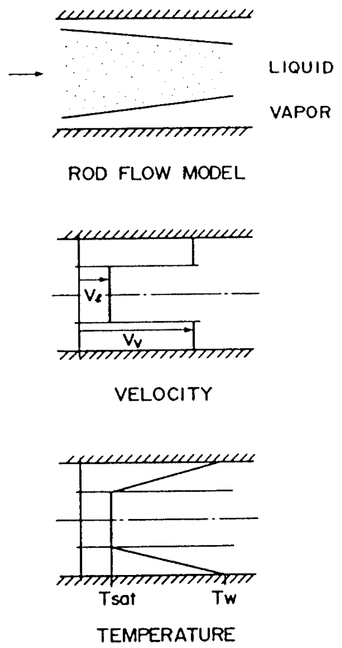

Fig. 7. Rod flow model.

Corresponding velocity profile and temperature profile are simplified is the same figure. Liquid fiows racreaseing its flow rate due to evaporation as:

$$\pi v_1^2 \zeta_e v_e = G - \frac{2\pi V_0 q}{\lambda} z \tag{1}$$

where r_1, r_0, Z, q and λ denote the liquid rod radius, the evaporator inner radius, the axial length, the heat flux defined for the evaporator inner surface and the latent heat, respectively.

Now, by assuming that the liquid velocity does not change along the flow direction, the following equation is obtained.

$$v_e = \frac{G}{\pi r_0^2 \rho_e} \tag{2}$$

Substitution of Eq. (2) into Eq. (1) leads to the liquid rod expression as a function of the axial length.

$$\left(\frac{r_1}{r_0}\right)^2 = 1 - \frac{2\pi r_0 q z}{G\lambda} \tag{3}$$

where the second term of right side represents the quality x.

$$x = \frac{2\pi r_0 q z}{G\lambda} \tag{4}$$

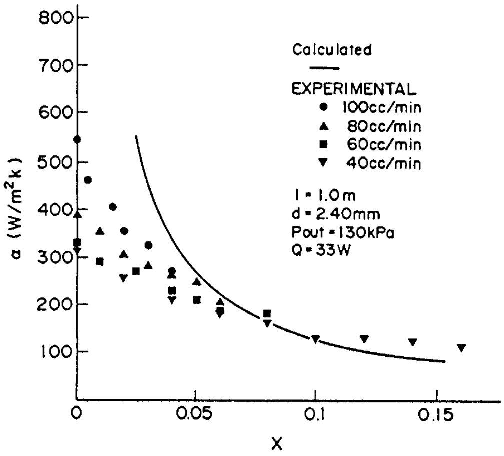

Fig. 8. Evaporative heat transfer coefficient.

Then, Eq. (3) results in the following expression:

$$\left(\frac{r_1}{r_0}\right)^2 = 1 - x \tag{5}$$

Now attention is turned to the vapor film. Regarding the vapor film, r_1 and r_0 represent the inner and outer radiuses, respectively, and Eq. [5] provides the radius ratio. Then the heat transfer coefficient for the heat flow through the vapor film is readily obtained neglecting the convection effect:

$$\alpha = \frac{2k_v}{r_0 ln\left(\frac{1}{1-x}\right)} \tag{6}$$

where kv is the vapor thermal conductivity. The calculated results are shown in Fig. 8 compared with the experimental results. although the analytical model is extremely simplified, it shows relatively good agreement with the experimental results. In the small quality region, calculated results deviate from the experimental results. The deviation is caused by the thermal resistance in the liquid rod which is neglected in the present analytical model.

This analysis reveals that the abrupt temperature rise of the evaporator is caused by the vapor film growth along the flow direction.

4. Conclusion

Preliminary test of the bare tube type evaporator using forced-convective boiling have been carried out. The test revealed that two categories of flow regime are generally observed under the same flow rate and line pressure condition within a certain test range. One of the flow regime indicated abrupt temperature rise along the flow direction. In this case, analytical results based on film boiling model showed good agreement with this heat transfer characteristics.

From the viewpoint of space applications, further investigations in connection with the film boiling occurrence condition including reduced gravity effect are needed.

5. Acknowledgement

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References

[*1*] Edelstein, F. and Brown, R., "Initial Testing of a Two-Phase Thermal Loop", AIAA Paper 86–1296, June 1986.

[*2*] Edelstein, F., Brown, R., and Koubek, K., "Design and Test of a Two-Phase thermal Loop", AIAA Paper 86–1296, June 1986.

[*3*] Hwangbo, H. and McEver, W. S., "High thermal capacity Cold Plate/Hot Plate", AIAA Paper 85–0921, June 1985.

[*4*] Fowle, A. A., "A Pumped Two-Phase Flow Heat Transport system for Orbiting Instrument Payloads", AIAA Paper 81–1075, June 1981.