Development of a Two-Phase Cold Plate

By

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Abstract: A two-phase cold plate using evaporators of grooved double-pipe type has been tested in order to examine its heat transfer and hydrodynamic characteristics under practical operating conditions.

Under uniform heat load, excellent temperature uniformity of the cold plate was obtained. Under uneven heat load, however, the temperature distributions were not uniform, high at an active area and low at an inactive area. It seems to be due to ineffective liquid flow through inactive pipes, which causes liquid shortage at active tubes and over-cooling by sub-cooled liquid at inactive tubes.

Parallel operations with two cold plates were performed successfully demonstrating that the both temperatures were kept at the same level even under different heat loads. In a certain operating condition, individual flow rate of the two cold plates was observed to oscillate symmetrically to each other, while total flow rate was kept constant and no anomalous behavior on heat transfer was induced.

Through the tests, a design approach for the cold plate from the viewpoint of a loop control technology was obtained.

Introduction

Various kinds of two-phase cold plates are currently under development for thermal management systems of future spacecraft [1]. Their evaporative heat transfer manners are basically classified into two categories according to the state of liquid-vapor interfaces, that is, evaporation from liquid films held on wicking structures and forced convective boiling. The evaporation manner is the most important factor determining the loop characteristics and its control technology. With respect to liquid film evaporation, the operation principle under zero gravity environment is clarified theoretically and is proven by many flight experiences of heat pipes.

According to such a consideration as before, we have chosen an arterial heat pipe as an evaporator for two-phase cold plates and have developed a heat pipe of grooved double pipe type. The design concept was verified as a loop heat pipe through tests previously made [2]. Next, it was integrated as a pump assisted heat pipe system and was operated successfully [3]. From the tests, the feasibility of a pump-driven two-phase fluid loop system using liquid film evaporation principle has been confirmed and our research is in a new stage where development effort will be focused on a loop control technology [4].

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This paper describes the test results of a two-phase cold plate consisting of many parallel evaporator pipes including uneven heat load tests and parallel operation tests. Also given are discussions on the heat transfer characteristics and the hydrodynamic behaviors from the viewpoint of loop control technology.

Test Loop Description

Cold Plate Design

The evaporator of grooved double pipe type which are applied to the cold plate

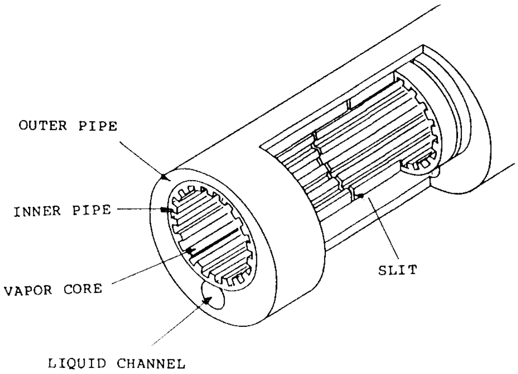


Fig. 1. Grooved Double Pipe Heat Pipe

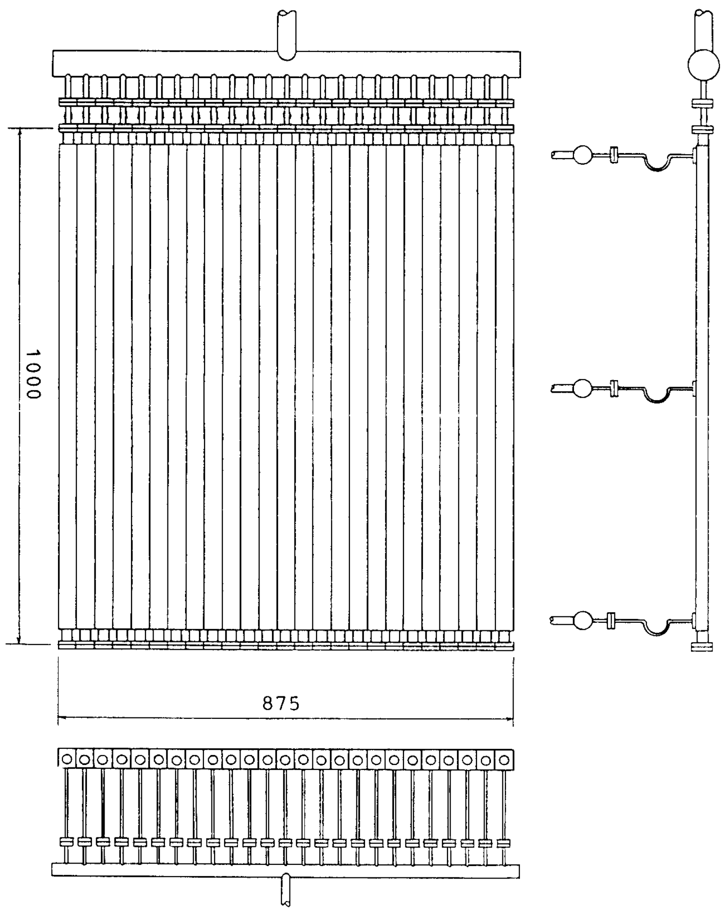


Fig. 2. Cold Plate

have double pipe construction, as shown in Figure 1. The outer pipe contains two axial channels, the inner pipe and the liquid channel. The inner pipe serves as vapor passage and is provided with axial grooves and circumferential slits. These two channels are connected each other through the slits.

The cold plate consists of 25 pipes as shown in Figure 2. Each pipe is provided with one vapor exit at the pipe end and three liquid inlets on the bottom surface. such a design of the liquid inlet is adopted as to attain an axially uniform distribution of the liquid suppply. The top surface is 940 mm long and 875 mm wide, on which electrical film heaters are stuck in order to simulate thermal dissipation of mounting equipments.

Test Loop

The test loop, in which the cold plate is integrated as an evaporator section, is illustrated in Figure 3.

The radiator header as a condenser section is also of grooved double pipe type and consists of 15 pipes. The pipe design is basically the same as that for the cold plate. The vapor is liquified on the grooved surface of the vapor core and the liquid film prevent the vapor flowing into the liquid channel. The latent heat of condensation is transferred to the water jacket clamped on the top surface of the radiator header.

The accumulator is connected to a nitrogen gas cylinder through a control valve so that the accumulator pressure is actively controlled by externally applied gas pressure. By means of the pressure control function, the loop temperature can be set at specified one. In this prosess, thermal conductance from the radiator header to the water jacket is automatically adjusted with a liquid blockage effect as to make a thermal balance between the applied heat and the rejected heat.

The working fluid is Freon R－11.

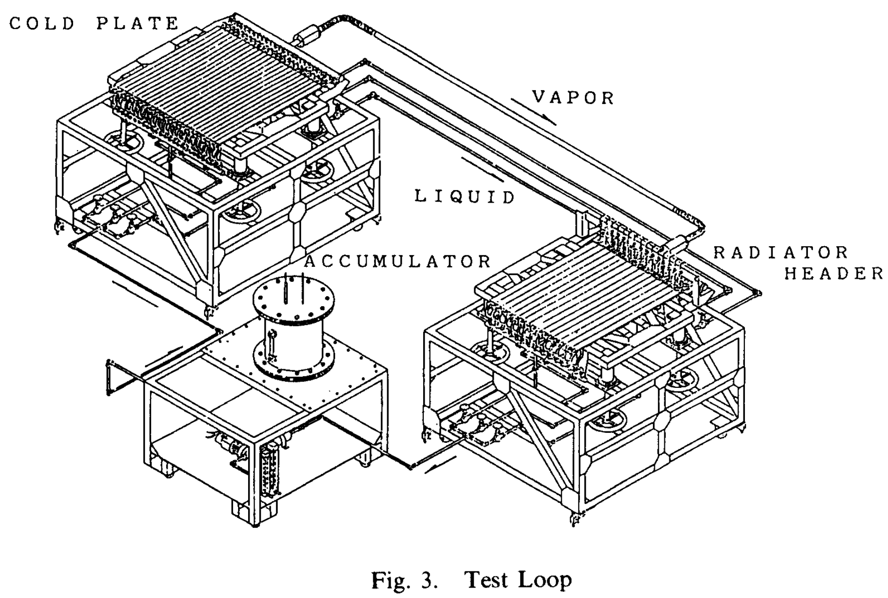


Fig. 3. Test Loop

Heat Transfer Characteristics

Test results are shown in Figure 4, in which the temperature differences between the cold plate and the radiator header are shown as function of the working fluid flow rate. The smallest flow rate for each test series is the lower operation limit and it is nearly equal to the theoretical flow rate. In the sufficient flow rate region, stable operations are obtained but near the theoretical flow rate, a slight rise of the temperature difference is observed.

Typical liquid behaviors observed through a sight glass are illustrated in Figure 5. In the case of the sufficient flow rate, a puddle is formed at the bottom of the vapor core and a liquid film extends towards the top with decreasing its thickness. At the top, local dry-out occurs. As the flow rate decreases, local dry-out propagates and the puddle recedes. Near the theoretical flow rate, no puddle is observed.

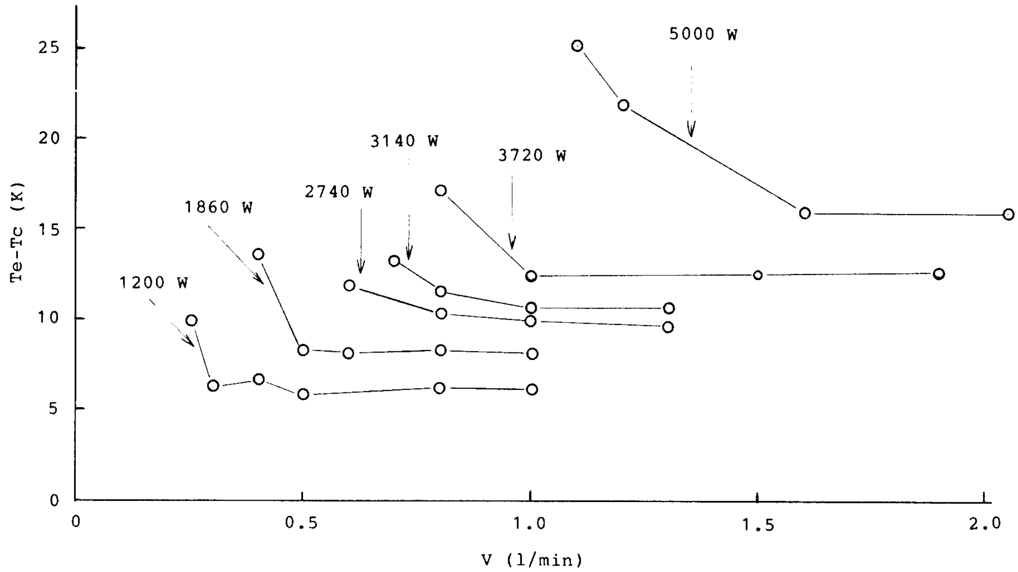


Fig. 4. Heat Tranfer Characteristics

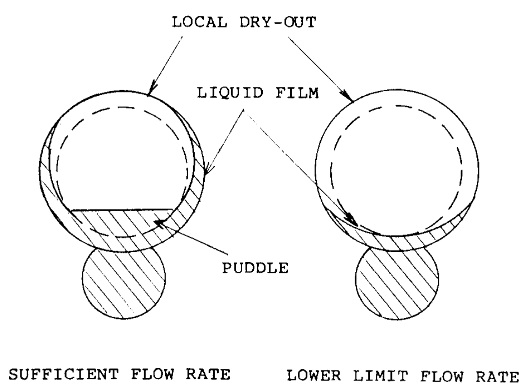
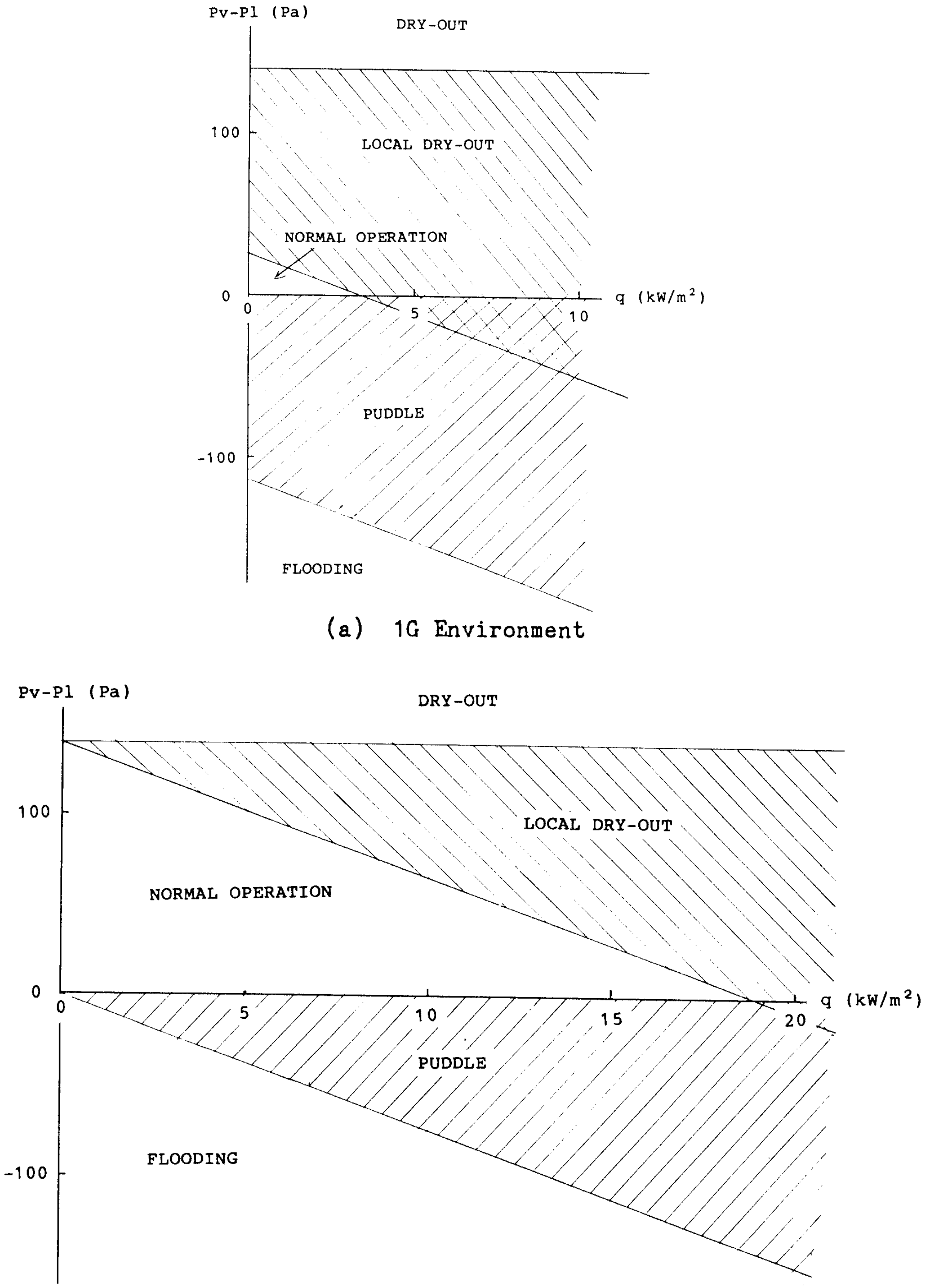


Fig. 5. Liquid Behavior in Evaporator.

These liquid begaviors in the vapor core are determined by the pressure difference between the vapor and the liquid as follows:

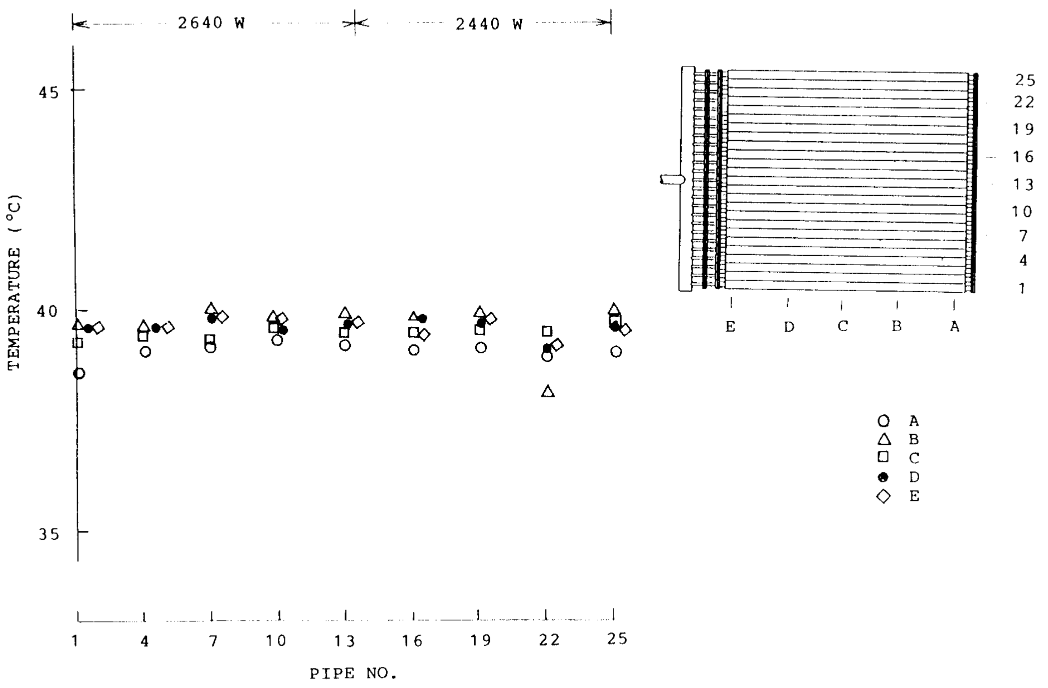
$Pv - Pl > Pcap.\ max$	dry-out
$Pcap.\ max > Pv - Pl > 0$	liquid film
$Pv - Pl < 0$	puddle



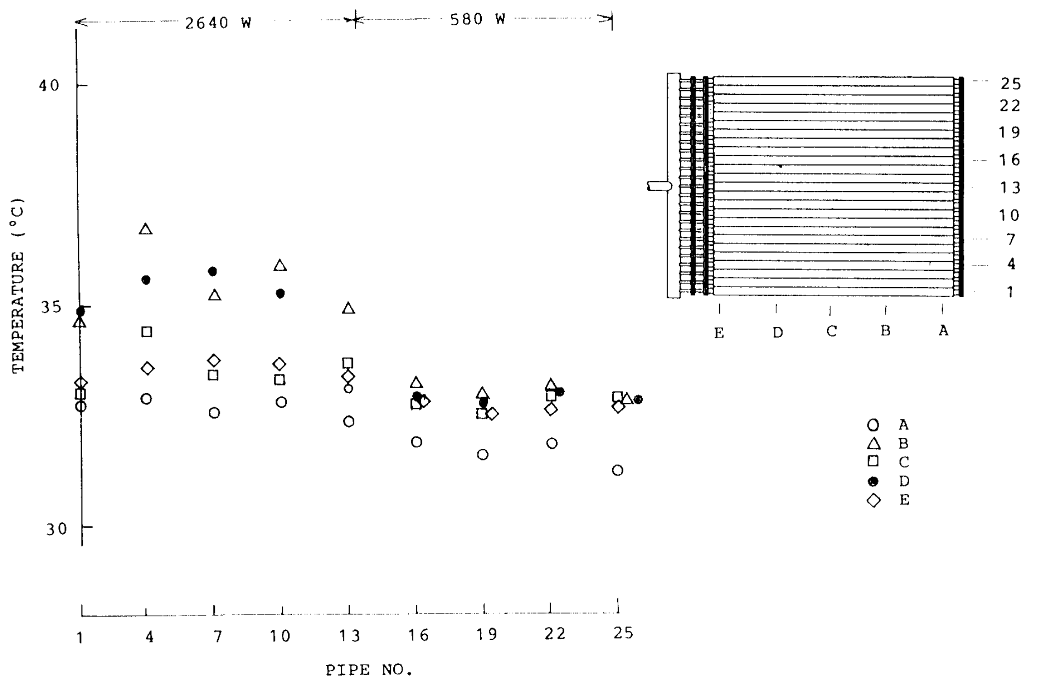
(a) 1G Environment

(b) 0G Environment

Fig. 6. Liquid Behavior Chart

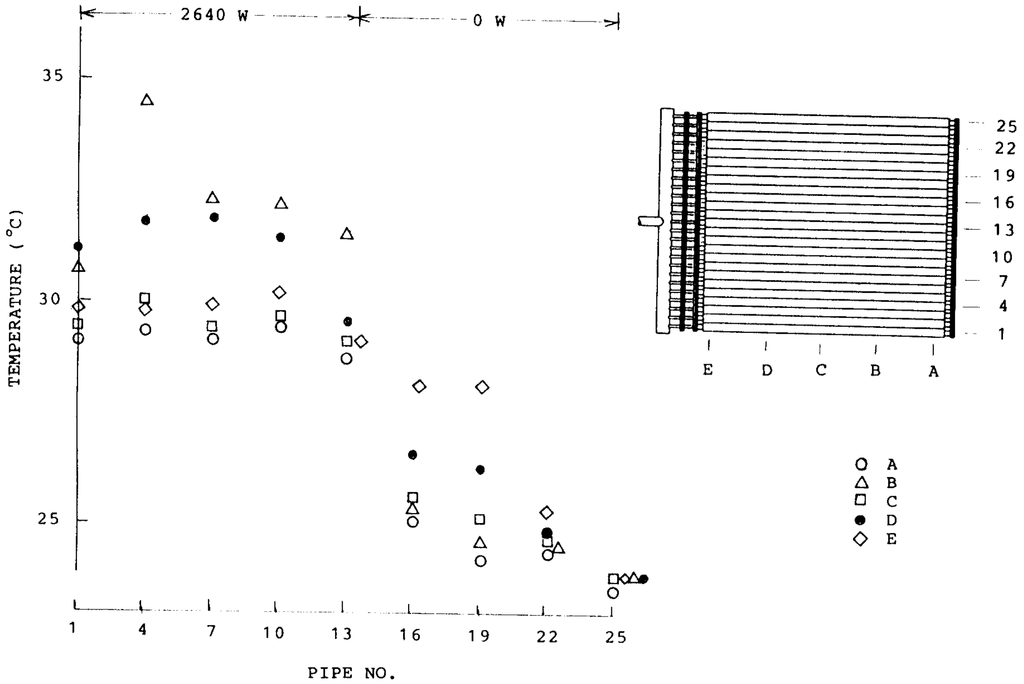


(a)



(b)

Fig. 7. Test Results of Uniform and Uneven Heat Load across the Cold Plate



(c)

Fig. 7 (Continued)

where Pv, Pl and Pcap.max denote the vapor pressure, the liquid pressure and the maximum capillary head, respectively. According to the relationship, the liquid behavior patterns are shown in a chart of pressure difference vs heat flux as shown in Figure 6–(a) and 6–(b). Figure 6–(a) is for the test cold plate under ground test condition. It is seen in the figure that an normal operation region in which liquid films would form on whole grooves is limited in a small heat load range and local dry-out and/or puddle formation would occur in a larger heat load range.

The excess flow rate effect on the liquid behavior pattern is also shown in the figure. Decreading the excess flow rate, the liquid pressure is also decreases. In the chart, the process is expressed as an upward shift of the corresponding point. It predicts that a puddle recession and a local dry-out propagation would arise as the excess flow rate decreases. Thus, the phenomena observed in the test can be explained well by the chart.

The chart for zero gravity environment is shown in Figure 6–(b), in which remarkable extension of normal operation region is predicted. It gives good prospect for practical use in space that stable operation of high heat transfer performance would be obtained even in a high heat load region.

Uneven Heat Load Test

Three examples of temperature profiles measured for different distributions of heat load are shown in Figure 7. In these tests, the heaters are divided into two groups. The first group is for 13 evaporator pipes and its heat load is maintained constant throughout the test. The second group is consist of 12 evaporator pipes and its head load is changed. The flow rate is kept constant for three cases, which is the sufficient flow rate for 5 kW of uniform heat load.

For the uniform heat load, a fairly uniform temperature distribution is obtained and the maximum temperature difference on the plate is only 1.9 °C. For the uneven heat load, however, temperature distributions are not uniform. At an active area of high heat load, the temperature rise is observed. It suggests that local dry-out arises there. To the contrary, the temperature decreases at an inactive area of low or no heat load. The over cooling is due to the sub-cooled liquid flow through the pipes of the area. It is seen from the tests that under an uneven heat load condition, liquid flow through pipes of low heat load occurs and the flow rate increases as the heat load difference becomes larger. This causes the liquid shortage at an active pipe and the increase of the ineffective liquid flow rate through the inactive pipe.

Figure 8 shows the temperature distribution for an uneven heat load, in which heat load varies along the pipes and each pipe is provided with the same heat load. In this case, the same level of temperature uniformity as that of the uniform heat load is obtained. This reveals that the uneven heat load along the cold plate does not cause an uneven temperature distribution so long as the heat load profile across the cold plate is uniform.

The ineffective liquid flow through inactive pipes induces some problems such as a loop efficiency reduction or a flow rate control difficulty. Hence, it is desired to prevent the liquid flow to arise. One approach for this purpose is a utilization of capillary force like a heat pipe. When the capillary force is sufficiently large to

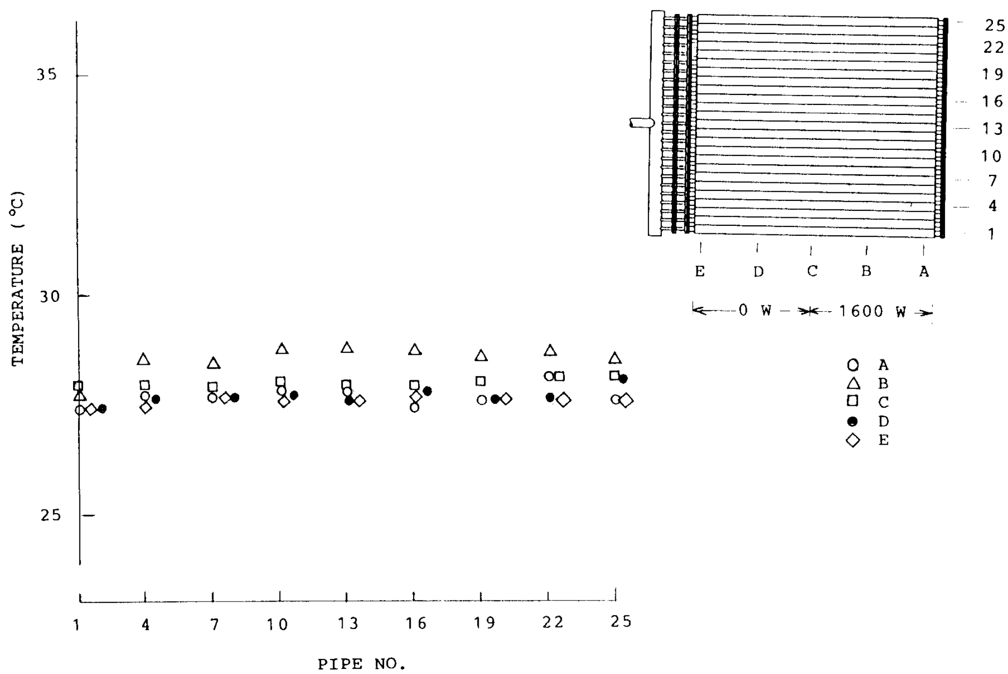


Fig. 8. Test Results of Uneven Heat Load along the Cold Plate

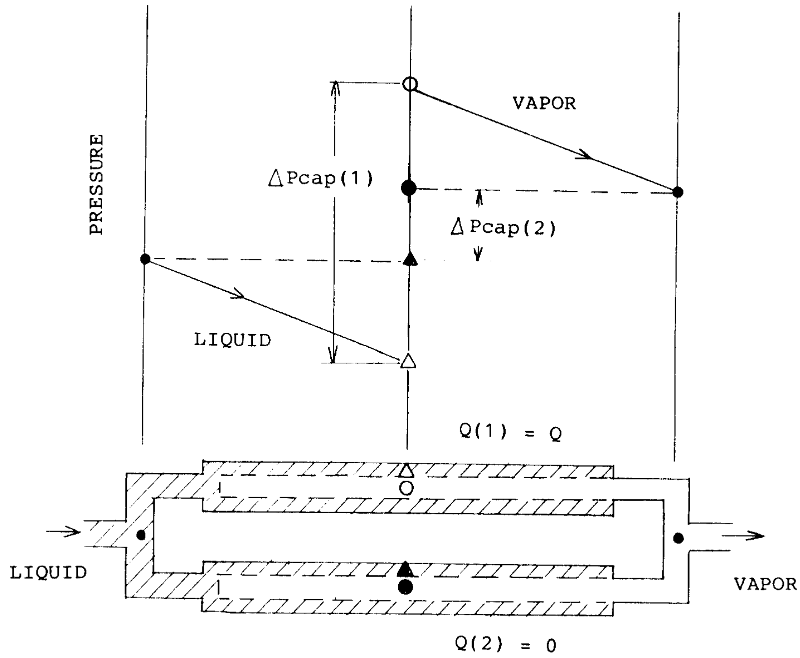


Fig. 9. Desirable Pressure Profile.

provide the pressure loss in active pipes, the exit vapor pressure can be higher than that of inlet liquid pressure as shown in Figure 9. In this case, the liquid would not flow into the vapor core and the liquid surface is at the groove withstanding the vapor pressure under the assist of capillary force as seen in a heat pipe. As described before, under zero gravity environment, such an ideal operating condition would be realized in a relatively wide range of heat load distribution, although it is limited in a very small one under the ground test condition.

Parallel Operation Test

Figure 10 shows a test loop for parallel operation tests. Two cold plates of the same design are arranged in parallel and each cold plate is equipped with a control valve at its liquid inlet pipe. The cold plates are different from that for the previous tests but the evaporator design is the same as shown in Figure 1. The cold plate consists of 19 evaporator tubes and its top surface is 660 mm long and 665 mm wide.

One example of the test result is shown in Figure 11. The cold plates are well controlled at the same temperature even though applied heat loads are different.

Figure 12 shows flow late oscillation observed in a parallel operation test. As shown in the figure, individual inlet flow rate oscillates symmetrically to each other, whereas the total flow rate remains nearly constant. The oscillation occurs under the limited condition that flow rates are near the theoretical one and both of the control valves are opened so as to minimize the flow resistance between the two cold plates via the main liquid line.

The flow rate oscillation seems to be caused by the cyclic vapor ingress into the

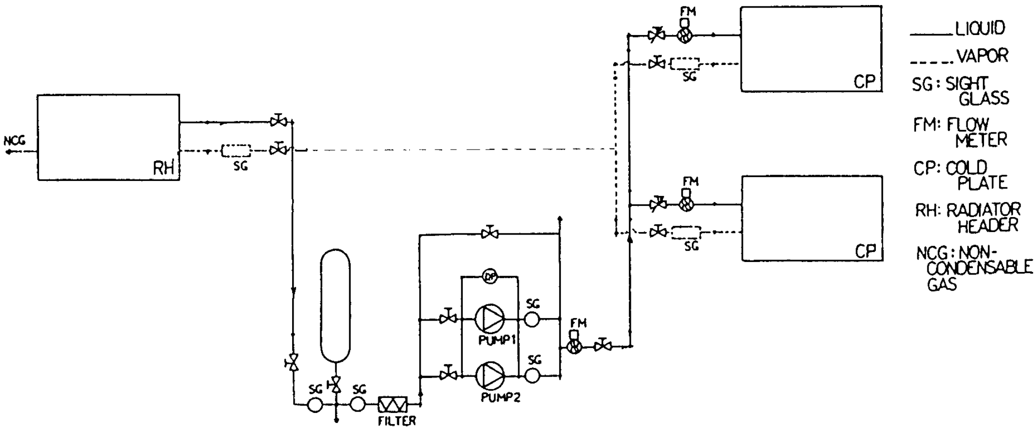


Fig. 10. Schematic Diagram of Parallel Operation Test Loop

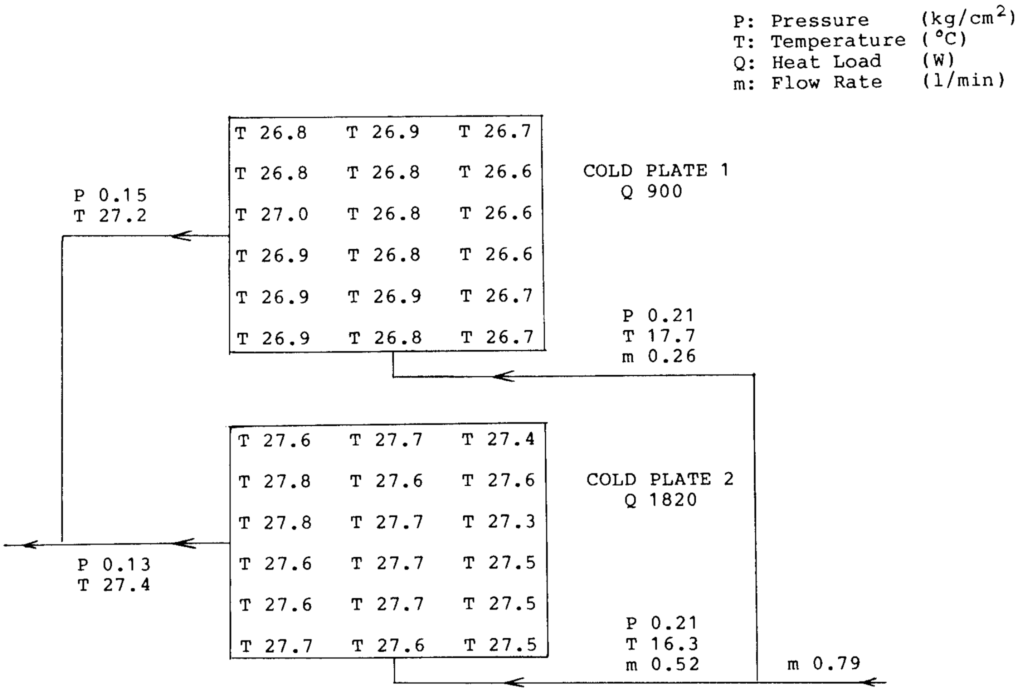


Fig. 11. Test Result of Parallel Operation

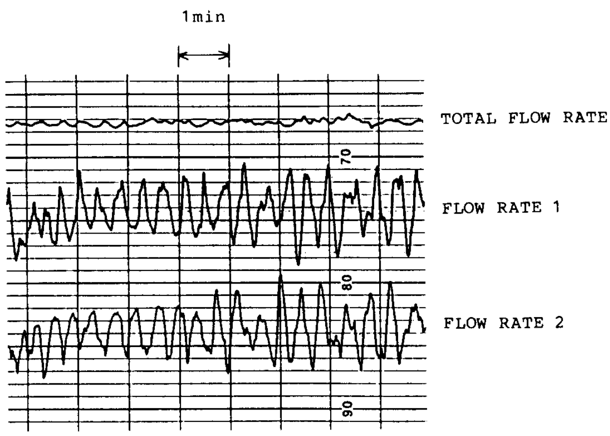


Fig. 12. Flow Rate Oscillation

liquid channel. Although almost all of invaded vapor would be condensed on the subcooled liquid, a certain portion of the vapor could grow as a bubble. In the bubble growth process, ilquid channel pressure would rise from that of the stable state and liquid flow rate would decrease. Over a certain bubble diameter, condensation would exceed the vapor supply from the vapor core and the bubble would turn to shrink. In the shrink process, the bubble would be cut from the vapor core and the liquid channel pressure would decrease in response to the progress of the bubble shrink. The pressure decrease would cause the liquid flow rate increase. The hypothetical oscillation model predicts that the osciillation would not occur so long as the capillary head is sufficiently large as to withstand the vapor ingress into the vapor channel. At present, the oscillation model is not confirmed and further studies would be needed to clarify the precise oscillation mechanism.

Concluding Remarks

A two-phase cold plate using grooved double-pipe evaporators has been tested including tests of uneven heat load conditions and parallel operations.

From these tests, it is revealed that the cold plate is under a delicate pressure balance, where various categories of phenomena can occur according to the balance condition. When the liquid pressure exceeds the vapor pressure, a puddle forms and it causes an ineffective liquid flow through inactive evaporator pipes. Inversely, when the vapor pressure is too much higher than the liquid pressure, local dry-out or a flow rate oscillation occurs, which seems to be induced by vapor ingress into the liquid channel.

These test results suggest the importance of capillary force improvements because the undesirable phenomena described above would be avoided when the capillary force is much larger than the pressure loss in the cold plate.

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