Technical note

Experimental observation of flow instability in a semi-closed two-phase natural circulation loop

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Abstract

In this experimental study, the flow instabilities within a semi-closed two-phase natural circulation loop were examined, with an emphasis placed on the role of the expansion-tank-line resistance. Six different modes of loopwise natural circulation were identified: the single-phase natural circulation, periodic two-phase natural circulation with a nonboiling period between the cycles, two-phase continuous circulation (stable circulation), and three other modes of the two-phase natural circulation characterized by different ranges of the cyclic period. The results were also shown in the instability map in the plane of the heat flux and the heater-inlet subcooling. When the frictional resistance at the expansion-tank line becomes larger, the circulation becomes stable, especially at the high heat-flux and high inlet-subcooling conditions, and, as a whole, the stable operation region becomes larger in the instability map. Similarly, the longer expansion-tank line stabilizes the system. However, unlike the analytical prediction, the excursive instability was not identified with the semi-closed loop due to the flow restriction at the expansion-tank line. © 2000 Elsevier Science S.A. All rights reserved.

1. Introduction

In natural circulation loops, the flow is induced by the density difference of the fluid between the riser and the downcomer. Understanding of the two-phase natural circulation behavior is very important in analyzing the hypothetical loss of coolant accident in nuclear power plants. In addition, there are many systems adopting the concept of the two-phase natural circulation, such as thermosyphon reboilers, waste heat recovery systems, solar power heating systems, and geothermal power plants. In many cases, the phase-change two-phase systems tend to be unstable since the heat input/removal induces a large volumetric change by the boiling and condensation. Various types of thermo-hydraulic instabilities and flow oscillations occur depending on the heat input/re-

Basically, the two-phase natural circulation loops can be classified into three different types, namely open, semi-closed, and closed types, depending on their features (Lee and Lee, 1991). Among them, the semi-closed loop can be characterized by the following aspects. First, the flow behavior such as the velocity and enthalpy fluctuations at the heater exit propagates along the loop and, in turn, directly affects that at the heater inlet. Second, the time-averaged system pressure remains constant, since the excess amount of the fluid due to volume expansion by boiling is flowing out to the expansion tank where the constant-pressure head is maintained; however, the instantaneous pressure is not being fixed because of the inertia (i.e. length) of the liquid column within the expansion-tank line and the frictional resistance there.

Relatively few studies have been performed on the flow behavior in semi-closed loops, such as by Ramos et al. (1985), Chen and Chang (1988), Lee and Ishii (1988, 1990a,b), Lee and Lee (1991), Knaani and Zvirin (1993), Tanimoto et al. (1998), Lee and Kim (1999). Among these, Lee and Kim (1999) predicted the stable operation condition using the homogeneous two-phase model and the perturbation technique with linearization, as shown in Fig. 1; there, they identified the significance of the role of the expansion-tank-line length \(L_p\) in flow instability. According to their analysis, the stable region becomes wider at the lower subcooling, but narrows down as the inlet subcooling increases, and such a trend is more pronounced with the shorter pipeline to the expansion tank. In general, the flow becomes stabilized with the longer expansion-tank line. Also, the excursive instability was anticipated. Following the analytical work by Lee and Kim (1999), in the present study, the flow instabilities in semi-closed two-phase natural circulation loops were examined experimentally. The effects of the restrictions at the heater inlet and outlet were confirmed to be the same as those with the open loop; the flow becomes unstable with increase in the exit restriction and/or with decrease in the inlet restriction. Therefore, in this paper, an emphasis is placed on the role of the flow restriction at the expansion-tank line that connects the expansion tank and the loop.

2. Experiment

The experimental loop basically consists of the heater and the condenser sections, and the expansion tank with the tubes connected between them, as in Fig. 2. The diameters of the tubes including the heater and the condenser sections are all the same (11.1 mm i.d. and 12.7 mm o.d.). Also, to simulate the tube friction, the friction control valves were installed at the heater inlet and outlet, and at the expansion-tank line, respectively. Here, the pressure loss coefficients \(K_i\), \(K_o\) and \(K_e\) are

![Fig. 1. Effect of the expansion-tank-line length at the semi-closed loop (Lee and Kim, 1999).](image-url)
defined as the pressure drops across the valves divided by the dynamic pressures at the tubes upstream based on the liquid flow, respectively. For flow visualization, the riser and the downcomer sections have a transparent portion (sight glass), respectively. Void fraction was deduced from the pressure drop across the transparent section at the riser, assuming that the frictional pressure drop corresponding to that section is negligibly small compared with the gravitational pressure drop. The pressure at the free surface of the liquid in the expansion tank was maintained to be in an atmospheric condition, and the pressure at the top of the loop was measured to represent the system pressure. The heater section is made of the stainless steel (SUS 316) with which the direct electric-resistance heating is available. Teflon unions were used at the both ends of the heater section for electric insulation. The heater power input was calculated from the measured values of the current and the voltage applied to the heater section. The condenser section was spirally wound to ensure a sufficient length (15 m in the present case) for cooling, and submerged in a large reservoir through which the cooling water was flowing. The temperatures at the inlet and the outlet of the heater section were measured using the J-type thermocouples. Also, the liquid velo-
ities at the heater inlet and at the expansion-tank line were measured with the calibrated orifices. The error ranges for the measurements are listed in Table 1.

Prior to each test run, the noncondensable gas (air) was eliminated through the air-vent and the loop was completely filled with water. When the test starts, the length of the expansion-tank line and the openings of the valves ($K_i$, $K_o$, and $K_e$) were set to predetermined values with the air-vent valve closed. The temperature of the cooling water within the reservoir was maintained to be constant during each test run. After that, the circulation behavior within the loop was examined and the measurements were performed for each value of the heater power. The duration of each data acquisition was 2 min.

3. Results and discussion

3.1. General flow behavior

Fig. 3 shows the typical experimental results with the heater power input ($q^*$), and the valve frictions at the inlet and the outlet of the heater section ($K_i$, $K_o$) and at the expansion-tank line ($K_e$) taken as the parameters.

The figure contains six different measures of the natural circulation. They are the velocity at the expansion-tank line (positive when the liquid is flowing out from the loop), the circulation velocity at the heater inlet, the void fraction at the riser, the temperatures at the heater inlet and outlet, and the pressure at the top of the loop. Six different modes of loopwise natural circulation were identified as follows:

A very stable, single-phase natural circulation occurs at the low heat flux condition, even though the expansion-tank-line restriction is small (Fig. 3(a)). This operating range becomes larger with the lower loopwise flow restrictions ($K_i$ and $K_o$) since the circulation velocity is large enough to convey the heat from the heater section to the cooling section with the single-phase natural circulation mode. When the heat flux is raised, the boiling occurs and the two-phase flow oscillations with a period of the temporal single-phase circulation within a cycle are observed (Fig. 3(b)). At the beginning of the cycle, the single-phase natural circulation is continued for a while. Then, the boiling occurs abruptly and the large void is formed within the heater section, and a substantial amount of liquid is pushed out in both directions of the heater section; thus, the reverse flow is detected at the heater inlet at this moment. This reverse flow is followed by the sharp rise of the loop pressure, and the excess amount of the liquid by the void formation is flowing out to the expansion tank. At the same time, the two-phase flow is established within the riser, and the heater outlet temperature reaches the saturation condition. Once the two-phase natural circulation is established, the loopwise velocity becomes very large and the vapor condenses in the condenser section rather rapidly. After that, the loop pressure drops subsequently and, this time, the liquid flows back into the loop from the expansion tank. Accordingly, the liquid temperature drops below the saturation condition, and the two-phase natural circulation is terminated. Finally, the single-phase mode is resumed and the whole cycle repeats regularly. This mode is denoted as periodic circulation (A) and is considered the combination of geysering and flashing. This mode resembles periodic circulation (A) of Kyung and Lee (1994) except for one thing; in their work, instead of the occurrence of the temporal single-phase natural circulation, an incubation period existed within a cycle. In the works of Aritomi et al. (1992), Jiang

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Full scale</th>
<th>Error ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heater inlet velocity (cm/s)</td>
<td>±70</td>
<td>±0.5</td>
</tr>
<tr>
<td>Expansion-tank-line velocity (cm/s)</td>
<td>±150</td>
<td>±2.5</td>
</tr>
<tr>
<td>Electric current input (A)</td>
<td>0–400</td>
<td>0–8</td>
</tr>
<tr>
<td>Voltage input (V)</td>
<td>0–40</td>
<td>0–0.4</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>0–150</td>
<td>±0.1</td>
</tr>
<tr>
<td>Heater inlet subcooling (°C)</td>
<td>10–85</td>
<td>±0.5</td>
</tr>
<tr>
<td>Loop pressure (cmH₂O)</td>
<td>±1000</td>
<td>±1</td>
</tr>
<tr>
<td>Pressure for void (mmH₂O)</td>
<td>1500</td>
<td>±5</td>
</tr>
</tbody>
</table>
et al. (1995), the basic phenomena of geysering and flashing were also discussed in detail.

If the heat flux is raised further with the higher valve-friction at the expansion-tank line \((K_e)\), a stable two-phase continuous circulation mode occurs (Fig. 3(c)). This is the most desirable circulation mode. The loop pressure is somewhat higher than the atmospheric pressure due to the hydro-
Fig. 4. Effect of the frictional resistance at the expansion-tank line on the flow instability ($K_i = 371$, $K_o = 10.3$, expansion-tank-line length = 3.5 m).

When the heater power input is increased from the condition of Fig. 3(c), another periodic circulation appears as shown in Fig. 3(d). In this mode, the flow oscillates with continuous boiling in the riser. The period of oscillations in this mode is shorter than that of periodic circulation (A). Kyung and Lee (1994) reported the similar type of flow oscillations and denoted it as periodic circulation (B). This mode is considered to be the density wave oscillations. Here, the system pressure fluctuates along with the changes of the riser void and the loopwise velocity. This happens because, with the high valve friction $K_v$, the excess amount of the fluid due to the volume expansion by boiling cannot pass through the expansion-tank line easily.

Periodic circulation (C) in Fig. 3(e) resembles periodic circulation (B) since it occurs also with continuous boiling within the riser. However, it has much shorter period compared with periodic circulation (B). This mode is considered to be the manometric oscillation that has been reported by Lee and Ishii (1988, 1990a,b).

This time, when the frictional resistance at the expansion-tank line is decreased from Fig. 3(d) with somewhat smaller heat flux, the flow oscillates with the larger amplitude and the longer period, as in Fig. 3(f). This mode is denoted as periodic circulation (D) and considered to be the pressure drop oscillations. Unlike periodic circulation (B), the variations of the system pressure and the heater-inlet velocity in this mode are out of phase. The physics of the pressure drop oscillations are well described in the work by Kakac and Liu (1991). As already stated, the role of the expansion tank is to avoid the change of the system pressure by allowing the excess or deficient amount of the fluid to flow in or out due to the volume expansion or contraction by boiling or condensation. However, in reality, the expansion tank can only maintain the time-averaged pressure to a constant value. In other words, the instantaneous pressure varies because the fluid cannot move readily due to the inertia of the fluid.
in the expansion-tank line and the frictional resistance there. Accordingly, the pressure drop oscillations occur.

3.2. Effects of the frictional resistance and the liquid inertia at the expansion-tank line

Figs. 4 and 5 show the effects of the frictional resistance ($K_f$) and the liquid inertia at the expansion-tank line on the flow instability shown in the plane of the heat flux and the heater-inlet subcooling. In these figures, the regions of the stable two-phase natural circulation and periodic circulations (A)–(D) are shown along with the region of the single-phase natural circulation. The stable operation region increases with the increase of the frictional resistance at the expansion-tank line, as shown in Fig. 4. Similarly, the stable operation region increases with the larger liquid inertia (i.e. with the longer expansion-tank line), as in Fig. 5. That is because, with the higher frictional resistance and/or with the larger liquid inertia, the liquid column in the expansion-tank line hardly reacts to the flow perturbation generated within the loop by boiling and condensation. The boundary locations between periodic circulation (A) and the continuous circulation, and between periodic circulation (B) and the continuous circulation do not change basically. The effect of the flow restriction (i.e. the frictional resistance and the liquid inertia) at the expansion-tank line on the flow stability is consistent with the analytical result by Lee and Kim (1999) as in Fig. 1 qualitatively. With the low frictional resistance at the expansion-tank line (Fig. 4(a)), the pressure drop oscillations (periodic circulation (D)) appear outside the upper right-hand boundary of the stable region. At the higher heat flux and inlet-subcooling condition, the heat is transferred to the fluid more rapidly; thus, the system is more likely to be in a nonequilibrium state, which is one of the main causes of the flow instability. Moreover, if the liquid in the expansion-tank line is susceptible to the sources of disturbances within the loop, the pressure drop oscillations will occur. However, with the increase of the frictional resistance, the region of the pressure drop oscillations is gradually replaced by the stable operation mode (the continuous two-phase natural circulation) and the manometric oscillation mode (Fig. 4(b)), and eventually disappeared with the region of the manometric oscillation mode left at the small part of the upper right-hand corner of the map (Fig. 4(c)). A similar result is obtained with different expansion-tank-line length; with the longer expansion-tank-line length, the region of the stable operation mode is expanded as in Fig. 5.

Finally, a series of experiments have been performed to check if the excursive instability occurs...
with the semi-closed loop as predicted by Lee and Kim (1999). The excursive instability occurs when there are more than two operating states (i.e. different circulation rates) for a given heat flux condition. In such a situation, the fluid inventory within the loop varies corresponding to the operating state. According to the analysis by Lee and Kim (1999), the excursive instability region is expected to occur at the high-subcooling/high-heat-flux condition, as indicated by the dashed line in Fig. 4, and the location of the region is unaffected by the flow restriction at the expansion-tank line. However, in reality, the excursive instability was not identified in the present experiment. This is again believed to be due to the frictional resistance and the liquid inertia at the expansion-tank line. With very high frictional resistance at the expansion-tank line as in Fig. 4(c), the fluid inventory within the loop cannot change instantaneously and the circulation rate cannot vary from one state to another easily; thus, the flow excursion is suppressed and the circulation becomes stabilized. On the other hand, when the expansion-tank line resistance is set to a small value, one can imagine that the liquid in the expansion-tank line can move freely and, accordingly, the fluid inventory in the loop may vary rather easily. However, even in this case, due to the liquid inertia within the expansion-tank line, the flow is subject to the pressure drop instability as shown in Fig. 4(a),(b). It does not conflict with the experimental result with the open loop by Kyung and Lee (1994) where the excursive instability was detected. There, instead of having an expansion-tank (and the tube connected to the loop), the open loop has a large condenser section and the amount of the liquid within the loop can change without any restriction. From this viewpoint, with the semi-closed loop, the excursive instability may be detected only by minimizing both the frictional resistance and the liquid inertia at the expansion-tank line.

4. Conclusion

In the present study, the flow instabilities within a semi-closed two-phase natural circulation loop have been examined. A focus is placed on the effect of the flow resistance at the expansion-tank line on the flow instability through a series of experiments. Six different circulation modes were identified and their flow behaviors were described in detail. Those are also indicated in the instability map with the heat flux and the subcooling at the heater inlet taken as its axes.

The system is stabilized by increasing the flow resistance (by increasing either the frictional resistance or the liquid inertia at the expansion-tank line), especially at the high heat-flux and the high inlet-subcooling conditions. The region of the pressure-drop oscillations shrinks down with the increase of the frictional resistance at the expansion-tank line; instead, the manometric oscillations appear at the upper right-hand corner of the instability map. Excursive instability was not identified with the semi-closed loop due to the frictional resistance and the liquid inertia at the expansion-tank line.

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References


