Study on Flow Instability in Natural Cycle Parallel Channel Based on RELAP5

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Abstract: The natural circulation was widely adopted in the design of new and advance reactors due to its passive nature. Given the facts that the instabilities in a natural circulation system with multi-channel structure showed great complexity and threatened the safety of the plant, the phenomena of instabilities presented in a natural circulation system with 4 parallel heated channels was simulated and analyzed by using RELAP5 code. The results showed that there were 3 different types of instabilities dominated by subcooled boiling, flashing and saturated boiling respectively and the mechanisms were interpreted.

1. Introduction
The experience of several nuclear accidents in the world shows that relying only on the subjective judgment of the operator and the function of the active system has certain risks to the safety of the reactor. For this reason, passive systems such as natural circulation have been widely used in the design of new nuclear reactors. However, compared with forced circulation, two-phase flow instability is more likely to occur under natural circulation. Therefore, the flow instability in the natural circulation system has been studied extensively. For example, Xu [1] explored the stability boundary and instability type in a simple single-channel natural cycle experimental loop. Su [2] conducted an in-depth study on the two-phase natural circulation density wave instability through experiments. S. Kakac and B. Bon [3] classified the two-phase flow instability phenomenon in the boiling channel in detail and explained the corresponding mechanism. Fukuda [4] divides density wave oscillation (DWO) into two categories for the instability under low power and high-power conditions. Furuya [5] systematically analyzed the difference between flash instability and other two-phase instability, such as geyser instability, density wave instability, and popular transition instability. For natural cycle multi-parallel channel systems, Chato [6] studied the initial state of the metastable region in a three-channel system. Fukuda and Hasegawa [7] studied the instability of two-phase flow and its oscillation form in multiple channels. Vikas Jain [8] used PCL device to study the first and second types of density wave instability in two-phase natural circulation system under low pressure conditions, which provided a reference for further understanding of two-phase flow instability in multi-parallel channel system. D 'Auria [9] discussed the ability of the RELAP5 program to predict natural circulation instabilities in the simulation of natural circulation instabilities using system analysis programs. Amit Mangal, Vikas Jain and A.K. Nayak [10] evaluated the suitability of the RELAP5 program by using the HPNCL device and the PCL device in the literature [8]. It is shown that the flow instability of natural circulation can be correctly simulated by using the system analysis program in a certain range.
In this paper, the system analysis program Relap5 was used to construct a multi-parallel channel natural circulation system, and the behavior characteristics of the system were simulated and analyzed. The characteristics and classification of the flow instability phenomenon in the parallel channel were determined, and the mechanism of its generation was analyzed.

2. Analyzed objects and models

In this paper, the PCL experimental device designed in Reference [8] is selected as the research object, and its geometric structure is shown in Figure 1. The heating section of the experimental device is composed of four parallel channels. The pressure in the system is maintained by the steam drum. The operation mode of the system is the whole natural circulation mode.

![Schematic diagram of PCL experimental device](image)

Fig. 1 Schematic diagram of PCL experimental device

Taking the experimental device shown in Figure 1 as the prototype, this paper builds the corresponding Relap5 node model and is shown in Figure 2. The drum part is composed of 104Branch, 106branch and 180P voltage regulator space. The inlet underheat of the system is controlled by the water temperature on the secondary side of condenser. The system pressure is 0.9 MPa.
3. Analysis and Result

When the system pressure is 0.9MPa, the inlet temperature of the heating section is kept at 438.15K, and the corresponding inlet underheat is about 26.4K. The transient process of the natural circulation system and the corresponding flow instability boundary are studied by gradually increasing the heating power of the heating section. With the increase of heating power, the circulating flow rate in the natural system gradually increases from the initial zero state. As the heating power increases, the system begins to fluctuate at low frequency, as shown in Fig. 3. This phenomenon is similar to the results given in literature [11]. It can be seen that the change rule of the cavitation share at the exit of the heating section was observed when the natural cycle was established and developed to the unstable stage in figure 4. The results show that the cavitation share at the exit of the heating section was 0.03

Table 1 lists the geometric parameters of the PCL device and the node partitioning mode in the corresponding RELAP5 model

| Number | assembly unit | length/m | diameter/m | Node number |
|--------|---------------|----------|------------|-------------|
| 1      | Heating       | 3        | 0.03       | 50          |
| 2      | Adiabatic ascent | 8        | 0.08       | 64          |
| 3      | Collecting ascent | 0.95     | 0.252      | 19          |
| 4      | Cooling       | 1.6      | 0.08       | 10          |
| 5      | Descent       | 7.4      | 0.05       | 20          |
| 6      | Condenser     | 0.75     | 0.08       | 10          |
| 7      | Horizontal two phase | 0.5      | 0.05       | 10          |
| 8      | Voltage space | 1.5      | 0.8        | 6           |
during the oscillation process. The bubble share of flash time and space is not more than 0.06, indicating that the low-frequency flow pulsation occurs in the natural circulation system. The system is mainly controlled by subcooled boiling with low gas content and condensation and flash evaporation in the ascending stage. The temperature evolutions at typical positions in the heating section and the rising section in the same process are shown in figure 5. The results show that the temperature of the fluid is still slightly lower than the saturation temperature when boiling occurs in the heating section. It is further proved that the instability of two-phase flow under this condition is dominated by subcooled boiling. When underheated boiling occurs in the natural circulation system, bubbles appear near the wall of the heating section, which reduces the fluid density in the heating section. Under the condition of nearly constant fluid density in the descent section, the driving pressure head of natural circulation increases, thus increasing the flow rate. As the bubbles continue to enter the rising section and flash occurs near the exit of the rising section, the driving pressure head further increased and the flow continues to increase. With the increase of flow rate, the main temperature and wall temperature decrease, and the under-heat boiling cannot be maintained. The two phases gradually turn into single phase, and the driving pressure head of the natural circulation system decreases, and the natural circulation flow decreases. Under the condition of constant heating power, the decrease of flow rate will promote the under-heat boiling phenomenon to appear again, thus forming the periodic flow oscillation phenomenon.

![Fig. 3 System flow oscillation when the heating power is 12kW](image)

![Fig. 4 Evolution law of cavitation share at different positions of the system when the heating power is 12kW](image)
Under the premise of maintaining the same other conditions, the heating power of the heating section is continued to increase to 14kW, and the system begins to show the phenomenon of short-period pulsation. The flow rate variation curve of each channel is shown in Fig. 6. The results show that the flow fluctuation in the four channels presents two different oscillation states. Among them, the channel with 12X and 13X as a group has a larger flow amplitude and is in a different phase fluctuation. 14X and 15X are another group, and the amplitude of flow fluctuation is small, and its phase also shows a certain degree of difference, there is a lag in the phase. In the process of flow oscillation, the flow reversal phenomenon even appears. The change rule of fluid temperature when the flow oscillation occurs in the system under the heating power of 14kW is shown in figure 7. The results show that the supercooled boiling and saturated boiling coexist in the heating section during the oscillation period.
Fig. 7 Liquid phase temperature changes at typical positions of each channel in the system when the heating power is 12kW

On this basis, the fluid temperature at the inlet of the heating section of the natural circulation system was increased to 448.15K, and the corresponding underheat at the inlet was about 5.4K. When the heating power was increased to 20kW, the flow of the natural circulation system was changed as shown in Fig. 8. The results show that the total flow of the natural circulation system is generally stable with only a small fluctuation under this condition. However, the flow rate changes in each channel are more complex, showing that the fluid in one channel is in the reverse flow state, while the other three channels are generally in the forward flow. At the same time, in the three forward flow channels, there is a 120° phase difference of coupling oscillation phenomenon. This indicates that there are self-circulation and inter-tube pulsation phenomena in the system between the four channels. Due to the low degree of undercooling at the entrance of the heating section, the boiling phenomenon in the system at this time is mainly controlled by saturation boiling. Fig. 9 shows the cavitation share at each typical position in the heating section and rising section of a channel under corresponding working conditions.
As the heating power of the heating section is further increased, such as the heating power in the system is raised to 35kW, the system gradually returns to the state of stable two-phase flow. During this process, the change curve of the mass flow in a channel is shown in Figure 10. It is shown that with the increase of boiling in the two-phase section, the cavitation share increases, the driving force of the system increases, the difference and mutual disturbance in the parallel channels in the natural circulation system are suppressed, and the system restores to stability.
4. Conclusion

In this paper, the PCL experimental device was used as the prototype, and the system analysis program RELAP5 was used to simulate and analyze the two-phase flow instability in a natural circulation system with four parallel channels. Through this study, the following conclusions were obtained:

1) In a four-channel low-pressure natural circulation system, the key physical phenomena controlling the flow instability included supercooling boiling in the heating section, flash boiling in the rising section, and saturation boiling in the heating section.

2) In the low-frequency oscillation region, the main factors controlling the flow instability in the natural circulation system were supercooled boiling and flash.

3) In the four-channel natural circulation system, there may be in-pipe self-circulation and inter-pipe pulsation with complex phase difference, which was different from the common two-channel system.

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