Theoretical Analysis of Type-I Flow Instability of Natural Circulation

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ABSTRACT: Fukuda and Kobori proposed three types of Leginegg instabilities and five types of density wave instabilities, according to different mechanisms of density wave instabilities. The instability dominated by gravity pressure drop is classified as Type-I flow instability. The instability dominated by friction pressure drop is classified as Type-II flow instability. And the instability dominated by accelerated pressure drop is classified as Type-III flow instability. In present work, the Type-I flow instability between rectangular parallel channels of natural circulation was studied theoretically. Models including two-phase flow instability, natural circulation system components were established in combination based on the homogeneous model. A computational program was written. The program was validated with experiments, and the results matched well with the experiment data. The marginal stability boundary (MSB) maps under different parameters were obtained by using nondimensional numbers \(N_{sub}\) and \(N_{pch}\). The influence of different kinds of pressure drop, inlet subcooling temperature of heating channels of type-I flow instability were analyzed separately. And the phenomena were explained from mechanism and the change of void fraction. The results show that the induce of inlet subcooling temperature enhances the stability of system. With the increase in system pressure, the system stability of natural circulation is enhanced.

1. INTRODUCTION

Flow instability analysis has become one of the necessary contents in reactor safety analysis. Flow instability refers to flow oscillation of equal or variable amplitude and flow drift of zero frequency, which is the most common phenomenon in circulation system \(^1\). In the past 70 years, with the extensive application of high-power boilers and boiling water reactors after the 1960s, a large number of researchers have done a lot of research on the flow instability of two-phase systems \(^2\)\(^-\)\(^3\). In the two-phase system, the common dynamic instability are: density wave instability, acoustic wave instability, thermal oscillation, pressure drop oscillation, condensation oscillation and pulsation between parallel channels\(^4\)\(^-\)\(^5\). In 1979, Fukuda and Kobori \(^6\) proposed three kinds of Leginegg instability and five kinds of density wave instability according to different mechanisms of density wave instability. The instability dominated by gravity pressure drop is classified as the first kind of density wave instability. The instability dominated by friction pressure drop is classified as the second kind of density wave instability. And the instability dominated by acceleration pressure drop is classified as the third kind of density wave instability. The first kind of density wave instability occurs in a vertical upward passage with an ascending section at a low vapor content. The first kind of density
wave instability usually occurs in natural circulation system, which is very important for nuclear reactor safety analysis. The second kind of density wave instability mechanism is that the velocity of flow disturbance in single-phase region is different from that in two-phase region. The change of flow rate and cavitation in the two-phase region will lead to the change of pressure drop. Because the flow rate and cavitation propagate slowly in the two-phase region. The outlet of the two-phase region has a certain delay compared with the inlet of the channel. The pressure drop in the two-phase region and the pressure drop in the single-phase region oscillate in different phases. The mechanism of the third type of density wave instability is the interaction of inertia, accelerating pressure drop and propagation delay, which is rarely reported in the literature. This classification method of density wave instability is adopted by subsequent researchers.

2. MODELING AND VALIDATION

2.1. NATURAL CIRCULATION MODEL
The layout of natural circulation circuit is shown in Figure 1. For the special equipment in natural circulation system, including parallel channel heating section, heat exchanger, pressurizer and loop pipe, it is necessary to model them separately.

![Figure 1 Natural circulation structure](image)

2.2. MATHEMATICAL MODEL
The mathematical model in this work is shown in reference [7].

2.3. VALIDATION
In order to verify the correctness of the program in the steady-state experiment of natural circulation under static conditions, the calculation results obtained by the program are compared with the existing steady-state conditions. For the natural circulation loop, the working condition range is 12 MPa. The inlet temperature is 89 ~ 109 °C. The flow rate is 101 ~ 233 kg·h⁻¹. Figure 1 shows the structure diagram of the experimental circuit and the label of each structure pipeline section.
Figure 2 validation of inlet and outlet temperature of heating section and heat exchanger

Figure 3 validation of natural circulation flowrate

Figure 2 shows the comparison between the calculated and experimental values of the temperature values of each main position in the natural circulation system. The inlet temperature, outlet temperature and the temperature after heat exchanger cooling are selected for comparison. It can be concluded from the figure that the calculated temperature is in good agreement with the experimental value. The accuracy of temperature calculation depends on the calculation of natural circulation flow and heat balance. Figure 3 shows the comparison between the calculated and experimental values of natural circulation flow, and the flow error is less than 5%.

In addition to the verification of flow and temperature, the verification process of natural circulation also needs to compare the pressure drop of each part of the circuit. The accurate calculation of the distribution of driving force and resistance throughout the circuit is ensured. And the pressure drop of each section is ensured to be closed. In Figure 1, the four pressure drop measurement points of the natural circulation experimental circuit in the static steady-state test are marked, which are the pressure drop of heating section, 102 section, 104 section and 106 section respectively, and the experimental values of the four pressure drop are obtained.
Figure 4 validation of heating section pressure

Figure 5 validation of 102 pressure

Figure 6 validation of 104 pressure
Figures 4 to 7 show the comparison between the calculated and experimental values of pressure drop in each section of natural circulation circuit. The loop of natural circulation system is divided into four parts: heating section, rising condensing section, falling section and horizontal section. The calculated pressure drop values of each section are within ± 10% compared with the experimental values.

3. STATIC CONDITION RESULTS AND ANALYSIS
Under the condition of low pressure, the natural circulation flow rate will fluctuate to a certain extent when it just enters the two-phase region in the process of power increase. With the increase of heating power, the fluctuation disappears, as shown in Figure 8.

The structure diagram of natural circulation circuit is shown in Figure 1. The length of the pipe is indicated in the drawing. The range of calculation parameters is shown in Table 1.

| Parameter                   | Range      |
|-----------------------------|------------|
| Pressure (MPa)              | 0.6-3      |
| Inlet subcooling (°C)       | 130-170    |
3.1. INFLUENCE OF INLET SUBCOOLING

Figure 9 shows the variation of natural circulation flow rate with power up process under different inlet subcooling conditions. The calculation parameter is pressure 0.6 MPa, and other thermal parameters remain unchanged.

![Figure 9 variation of loop flow rate with power under different inlet subcooling conditions](image)

It can be seen in Figure 9 that with the decrease of inlet subcooling, the fluctuation amplitude of the loop gradually decreases and the fluctuation time shortens. With the decrease of inlet subcooling, the first kind of density wave instability will occur in advance due to the increase of outlet gas holdup at the same heating power.

Fig. 10 shows the beginning and ending boundary of the first kind of density wave instability under different undercooling conditions.

![Figure 10 boundary of Type-I of density wave instability](image)

In Fig. 10, it can be seen that the boundary between the beginning and end of the first kind of density wave type flow instability is basically linear parallel to the equilibrium gas holdup line of Xe = 0. When the first kind of density wave type flow instability occurs, the gas holdup at the outlet of the heating section is less than 0.01. Similar to figure 9, with the decrease of inlet subcooling, the distance between the start point and the end point of the first type of density wave instability decreases until it disappears, and the instability region gradually decreases. This is due to the decrease of inlet subcooling. At the same power and flow rate, the proportion of friction pressure drop increases and the proportion of gravity pressure drop decreases with the increase of length of two-phase section. The
effect of pressure drop fluctuation caused by void fraction is reduced, which is beneficial to the stability of the system. Therefore, with the decrease of inlet subcooling, the natural circulation loop tends to be stable.

3.2. INFLUENCE OF SYSTEM PRESSURE
In order to study the influence of system pressure on the flow instability of the first type of density wave, the variation of natural circulation flow with power up process at 0.6 MPa, 1.5 MPa, 2 MPa and 3 MPa was calculated, as shown in Fig. 13. The calculated parameter inlet subcooling is 140 ℃, and other thermal parameters remain unchanged.
Figure 11 variation of natural circulation flow rate with power under different pressures

It can be seen from Figure 11 that when the pressure is 0.6 MPa and 1.5 MPa, the flow rate of natural circulation system fluctuates obviously at low steam content. With the increase of pressure, the power range of the first type of density wave instability becomes smaller, and the amplitude of fluctuation also decreases. When the pressure is 2 MPa, the fluctuation of natural circulation system flow is not obvious, and it disappears quickly. When the pressure increases to 3 MPa, the first type of density wave instability does not occur in the natural circulation system, and the natural circulation system tends to be stable.

4. CONCLUSIONS
In this paper, the first kind of density wave instability in natural circulation system is studied theoretically. The natural circulation loop was built. The mathematical and physical model of flow instability behavior under the condition of dynamic self-feedback was established, and the instability behavior analysis software was developed. The accuracy of the program is verified by comparing with the experimental results. At the same time, the influence of different thermal parameters on the first kind of density wave instability is studied, and the mechanism of the first kind of density wave instability is explained. The results and conclusions are as follows:

The influence of different system pressure, inlet subcooling and other thermal parameters on the first kind of density wave instability is analyzed, and the first kind of density wave instability boundary is obtained. With the decrease of inlet subcooling, the natural circulation loop tends to be
stable. The increase of system pressure is conducive to the stability of natural circulation loop.

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