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INSTABILITY IN PARALLEL CHANNEL SYSTEM

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ABSTRACT

In this paper, the investigation on the instability in parallel channel system is summarized systematically. This phenomenon in parallel channel system is very typical, interesting and challengeable. The experiment data of a twin-channel system is used as the validation. Two typical methods are adopted to simulate this phenomenon for deciding the instability boundary. One is the integral method, which is based on the model of Clausse and Lahey [1] and developed by Lee and Pan [2] and GUO [3]; the other is the classical system analysis code: Relap5/MOD3.4. In the experiment the influences of inlet resistance, system pressure and nonuniform heating are obtained. The influences of system pressure and inlet resistance can be simulated by both methods. However, there are some differences between the results of two methods. And for the effects of nonuniform heating and asymmetric inlet resistances, which are very popular in the nuclear power system, the results of numerical methods cannot get a good numerical agreement with those of experiment. It should be noticed in the practical engineering design. Finally, the typical "Ledinegg" instability phenomenon may occur in the parallel channel system according to the numerical results. Sometimes it will induce the burnout before the parallel channel instability. Both methods predict the same tendency. And a detailed explanation is given. The slope of the pressure drop–mass flux curve is the key to avoid the flow excursion phenomenon in parallel channel system.

INTRODUCTION

In CHINA more and more cities become the night bright as daytime with consuming more energy. And the carbon emission is the key, which will influence the economic growth profoundly. One solution method by Chinese government is nuclear power. In the next decade, about 40000MW nuclear power plants will be built in the huge country. This big plan absorbed public attention, especially from the viewpoint of nuclear safety. In nuclear power system many safety problems exist, which come from physics, thermal hydraulic, control system et al. Among them the instability in parallel channel system is very typical, interesting and challengeable.

In 1938 Ledinegg studied the pure static instability [4]. The occurrence of multiple solutions and the instability threshold itself could be predicted from the steady state equations governing the process. Boure and Bergles reviewed the two-phase flow instability in 1973 [5] and made a very clear classification. Now in China the textbook still uses it. Classification of density wave instability (DWI) was available by Fukuda [6]. The DWI in low quality absorbed researchers' attention. Now, parallel channel instability gives some interesting behaviours. In present paper, the parallel channel instability will be studied by experiment and theory. DWI and Ledinegg instability will be discussed in greater detail.

EXPERIMENT

The experiment of parallel channel instability was done in the National Key Laboratory of Bubble Physics & Natural circulation, China. Fig.1 shows the test loop, which includes a pump, a preheater, a pressurizer, two parallel vertical heated sections with inlet and riser pipelines and two heat exchangers. The distilled water is used as working fluid which is supplied by the purification system.

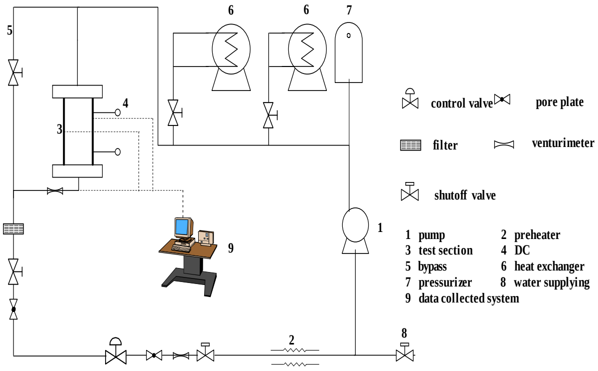


Fig. 1 Flow diagram of the test loop

Based on the results of experiment under different system pressures and different boundary conditions, the boundaries or critical conditions of the parallel channel instability can be obtained, which listed in Figs.2-4, separately. Fig. 2 gives the instability boundaries under different system pressures from 1MPa to 3 MPa. With the pressure increase the boundary moves to the high equilibrium quality region. Fig. 3 shows the effect of inlet resistance. The black points mean two channels have the same inlet conditions. If only one channel's inlet resistance increases, the stability of the system will not vary (from 37:38 to 38:61, the numbers in Fig.3 mean the inlet resistance coefficients). When both of them are increased the system becomes more stable (from 38:61 to 59:60 in Fig. 3). The nonuniform heating is prevalent in real system. Fig. 4 shows the influence of nonuniform heating. The larger power difference between two channels the more instable the system.

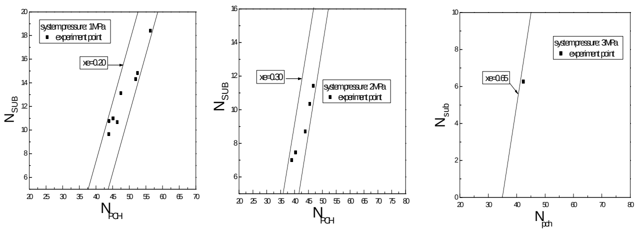
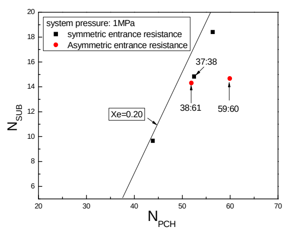


Fig. 2 Instability boundaries under different system pressures



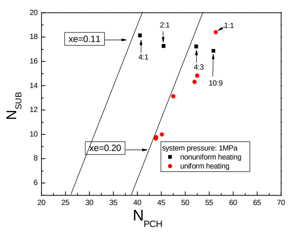


Fig. 3 Influence of asymmetric Fig. 4 Influence of nonuniform heating

INTEGRAL METHOD

The integral method can be used to predict the boundary of parallel system. The basic model came from Lahey [1] and developed by Lee [2] and Guo [3]. The details of the model and the results listed in this section can be found in the above-mentioned papers. Here only introduced briefly. The integral method is based on homogeneous model. The instability boundary looks conservative in low pressure shown in Fig. 5. With the pressure increase the calculation accuracy becomes better. However, the problem exists in the calculation of asymmetric inlet resistances. According to the calculation results even only one channel's inlet resistance increases the system's stability will be enhanced. Fig. 6 shows the influence of nonuniform heating. This result shows the same tendency with the experiment.

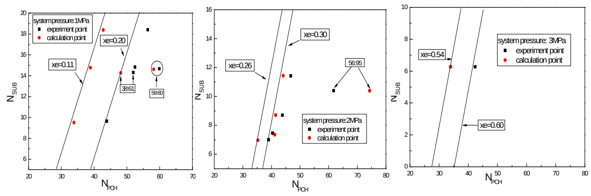


Fig. 5 Instability boundaries under different system pressures

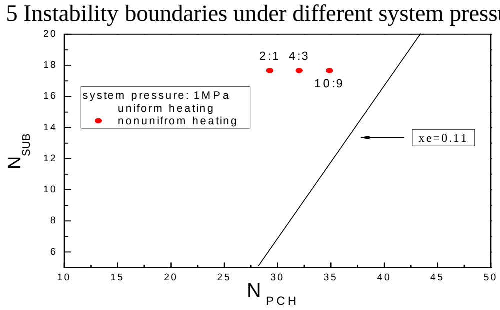


Fig.6 Influence of nonuniform heating

RELAP5

RELAP5/MOD3.4 code has equilibrium and non-equilibrium models. Fig.7 gives the node structure of RELAP5. The details of results can be found in Fig. 8. The equilibrium results are similar to those of integral method, which are conservative. If the researcher uses the non-equilibrium model the results will be unsafe in low pressure system. At present, the results are only for low pressure. In high pressure system the non-equilibrium model maybe better. According to present results, if the pressure is greater than 3 MPa both models are conservative.

Noticeable, the same problem also exists for asymmetric inlet resistances. Neither equilibrium model nor non-equilibrium model can predict the instability critical condition well. The RELAP5 code and integral method code almost have the same tendency. However, both of them do not consist with the experiment.

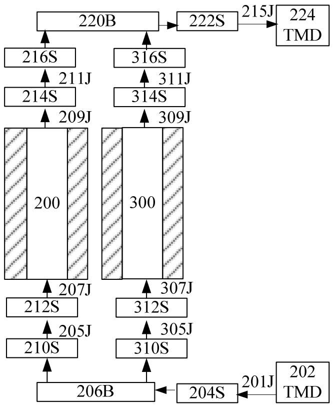


Fig. 7 RELAP5 nodalization

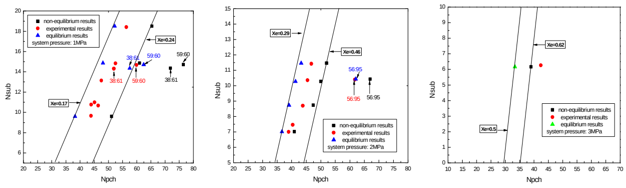


Fig. 8 Instability boundaries under different system pressures

A detailed analysis of nonuniform heating is performed by RELAP5 code. Fig.9 shows the critical power varying with the power ratio. As a whole the larger powers difference the lower total critical heating power. However, the influence is not linear and degressive. When the power ratio is between 0.4 and 0.8 the total critical heating power varies slightly. This conclusion needs more experiment validation.

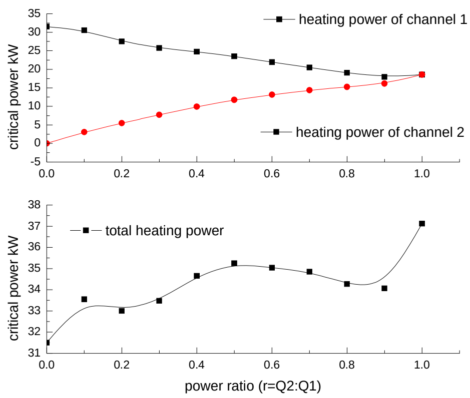


Fig. 9 Effect of nonuniform heating on total heating power

LEDINEGG INSTABILITY ANALYSIS

In parallel channel system the Ledinegg instability analysis is always neglected. Whereas, in such systems this kind of instability maybe exist if the flow resistance characteristic of the channel satisfies some conditions. In this paper, two methods are used to find this kind of instability.

The first is keeping the heating power and decreasing the mass flow rate step by step. Fig. 10 shows the results. When the mass flow rate is smaller than a critical value the mass flow rates of two channels will jump to two new values. The reason can be found in the pressure drop–mass flux curves of two channels. In Fig. 10 when the mass flow rates reach "A" point there are three solutions for one pressure drop. Hence, the mass flow rate of one channel moves to "B" point and the other jumps to "C" point. If the total mass flow rate continues decreasing both mass flow rates will move to "D" point.

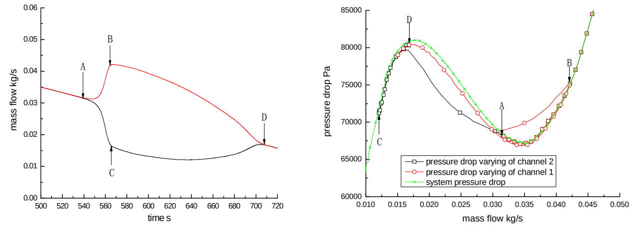


Fig. 10 mass flow rate curves and hydrodynamic curves by method 1

The secondary method is keeping the mass flow rates of two channels and decreasing the heating powers step by step. Fig. 11 gives the details of the process. When the heating power is greater than the threshold value this kind of instability is induced. In Fig. 11 left the pressure drop–mass flux curves for different heating power are drawn. The varying process can be explained by these curves. If the pressure drop–mass flux curve has negative slope region, such as at Q=27kW, "A" point, multi-solution condition exists. If the heating power increases the mass flow rate will moves to "B" point, where the multi-solution condition disappears. Then the Ledinegg instability finish.

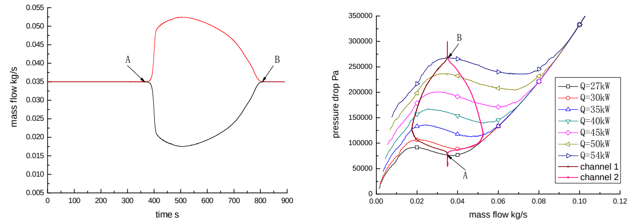


Fig. 11 mass flow rate curves and hydrodynamic curves by method 2

This kind of instability is analyzed by RELAP5 code and integral method code, separately. Very similar results are obtained for the same initial and boundary conditions, which shown in Fig. 12. Although the amplitudes of two codes are different the phenomena are same. The authors point out that all the simulation results are based on very narrow channel. The equivalent diameter is 1mm. In our calculation if the equivalent diameter is larger than 1.5mm the Ledinegg instability in parallel channel system will not occur. That may be why it is very hard to be found in parallel channel system. Obviously, this phenomenon also needs experiment validation.

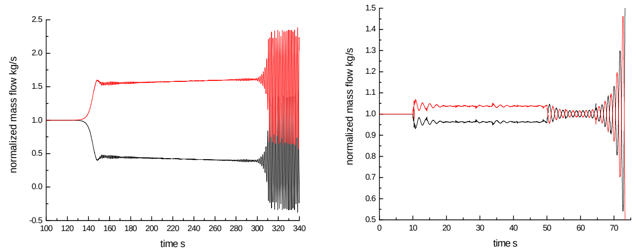


Fig. 12 mass flow rate curves of two channels by RELAP5 code and integral method code

Fig. 13 is drawn according to many calculation data. The heating power range is from 15 to 32.5 kW. At very low power, the negative slope region of pressure drop–mass flux curve is very short. Hence, the Ledinegg instability is nonexistent. With the power increase the length of the negative slope region becomes longer. Hence, multi-solution region exists. This kind of instability will occur. In Fig. 13 line 2 is the initial boundary and line 1 is the end boundary. If the system operates at one point of line 2 the Ledinegg instability will start. And then it stops at one point of line 1.

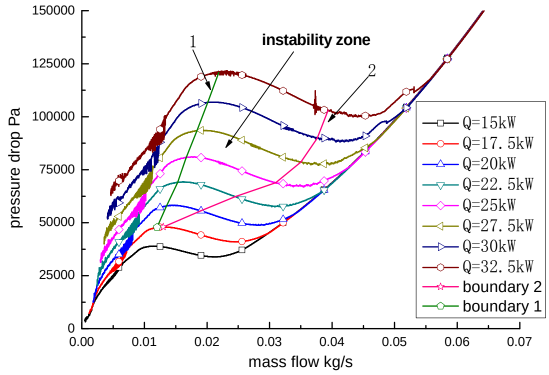


Fig. 13 Ledinegg instability region of parallel channel system

Just like what has been done in the analysis of Ledinegg instability in single channel system the influence of some main parameters can be analyzed by Relap5 code. If one of the system or geometry parameters can change the negative slope region of pressure drop–mass flux curve it has some effect on the Ledinegg instability. In Fig. 14, if the equivalent diameter is smaller than 1.5 mm the negative slope region is very cliffy. In this region the instability is very easy to be induced. Shown in Fig. 15 is the influence of system pressure. Higher system pressure can restrain the negative slope region. Fig. 16 and 17 gives the effect of inlet and outlet resistance. The larger the inlet resistances more stable the system. The larger the outlet resistances more unstable the system. However the influence of inlet subcooling is nonlinear. In Fig.18 with higher inlet subcooling degree the length of negative slope region is shorter, but the slope is larger. If the inlet subcooling degree is smaller the length of negative slope region is longer, but the slope is smaller. Hence, the inlet subcooling degree has double-face effect.

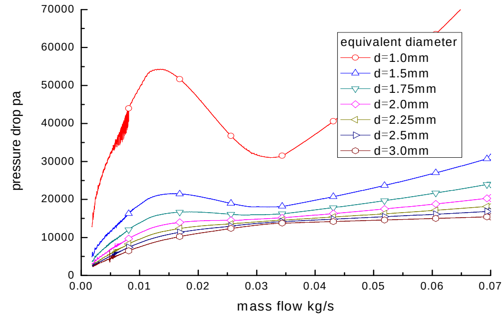


Fig.14 The effect of hydraulic diameter

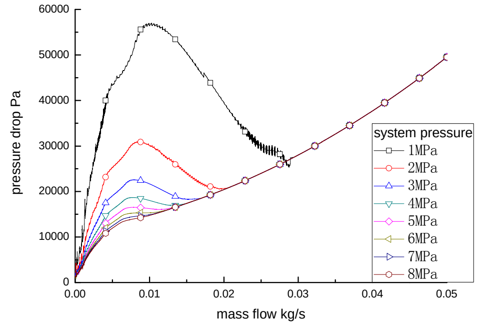


Fig. 15 The effect of pressure

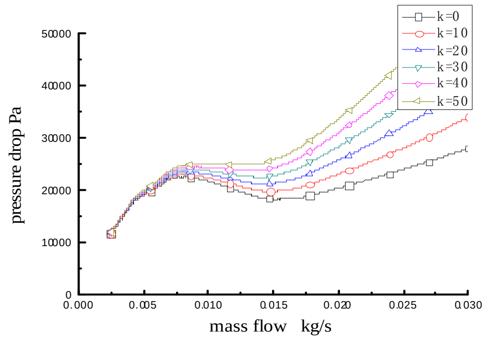


Fig. 16 The effect of inlet resistance

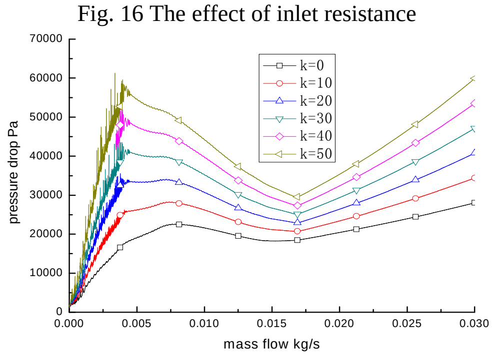


Fig. 17 The effect of outlet resistance

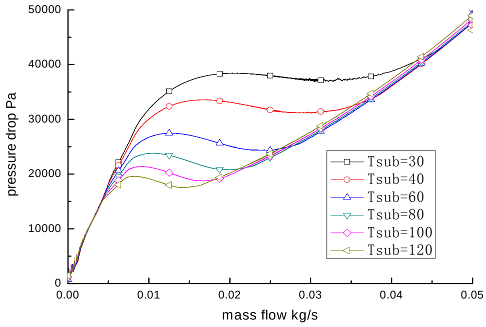


Fig. 18 The effect of inlet subcooling

CONCLUSION AND REMARKS

In this paper the parallel channel instability is studied by experiment and theory. According to the results some conclusions can be drawn in the following.

(1) The codes of integral method and RELAP5 can be used to predict the instability boundary of parallel channel. In low pressure system, the results of integral method and equilibrium model of RELAP5 are conservative;

(2) Both of the code cannot analyze the influence of asymmetric inlet resistances.

Just as what have mentioned in this paper some experiment data is needed for validating the following problems in the future study.

(1) The precise effect of nonuniform heating;

(2)The Ledinegg instability in very narrow parallel channel system.

NOMENCLATURE

Q: heating power (W);

h_{fg}: latent heat of evaporation (Jkg^{-1});

h_f: saturated liquid enthalpy (Jkg^{-1});

h_i: inlet enthalpy;

r: power ratio, Q_2/Q_1;

υ_f: specific volume of saturated liquid;

υ_{fg}: difference in specific volume of saturated liquid and vapor;

W: mass flow rate (kgs^{-2});

Xe: equilibrium quality

$$N_{pch} = \frac{Q}{W}\frac{\upsilon_{fg}}{h_{fg}\upsilon_f}$$: phase change number

$$N_{sub} = \frac{h_f - h_i}{h_{fg}}\frac{\upsilon_{fg}}{\upsilon_f}$$: subcooling number

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