The Flow Instability Analysis for Steam Generator for China Experimental Fast Reactor (CEFR)

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Abstract. Steam generator plays an important role in nuclear power plant, especially in a fast reactor. As a barrier to separate the high temperature sodium and high pressure water/steam, it is important to make sure the safety of the steam generator. For this purpose, it is necessary to guarantee that there is no flow instability happened in the tubes of the steam generator. In order to ensure that the steam generator is stable in all conditions, this paper uses the method of Khabenskii to calculate the minimum inlet resistance coefficient to prevent flow instability in China Experimental Fast Reactor (CEFR) steam generator. The needed inlet resistance coefficient calculated is 1001.2. In addition, this paper analysis the effect of mass flow rate, pressure, subcooling and thermal power on flow instability in steam generator of CEFR. The result demonstrates that the increase of flow rate, pressure and subcooling and the decrease of thermal power will stabilize the flow instability in CEFR steam generator.

1. Introduction

CEFR steam generator is a straight tube, once-through steam generator. Hot sodium flows in the shell side and transfer heat to the water that flows in the tube side. The feedwater gets heated, evaporated and superheated and finally becomes the required superheated steam. The high temperature sodium and high pressure water are separated by the steam generator. Therefore, the steam generator has an important significance to the stability and safety of fast reactor power plant.

In steam generator, the density wave oscillations (DWO) are probably the most common type of instability. The DWO was induced by the delay and feedback effects in relationship between mass flow rate, density and pressure drop [1]. In Fukuda’s researches, two typical types of DWO was observed in experiments: one is governed by gravitational pressure drop and another one by frictional pressure drop[2,3]. Saha studied the effects of the pressure, inlet subcooling, inlet and outlet orifice, and mass velocity on oscillation, and presented a correlation using the dimensionless subcooling number and phase change number to predict the instability margin [4]. Su used the drift model to analyze the influences of mass flow rate, pressure, inlet subcooling, heat flux and exit quality on DWO, and obtained the result that if the pressure, mass flow rate and heat flux increase, the system will tend to be stable[5]. Based on their study, Su developed a code NTDCC, the predictions were in good agreement with the experimental results [6]. Guo studied the behavior of two-phase flow instability of a twin-channel system, and obtained the result that increasing the inlet resistance coefficient and system pressure can make the system stable [7]. DWO will cause heat transfer crisis, structural vibration and system control...
problems [8]. In order to ensure the system operation and safety, CEFR steam generator must be stabilized by orificing the flow at the inlet of the tubes at the expense of pumping power [9].

The minimum inlet throttle resistance to prevent flow instability in steam generator tubes was determined on the basis of CEFR steam generator experimental data using the method proposed by Khabenskii. Meanwhile, the effect of system parameters such as feedwater flow rate, pressure, inlet subcooling and thermal power on flow instability were analyzed. The results can support subsequent design and operation of steam generator for large scale fast reactor.

2. Approach

Khabenskii method [10] to analyze flow instability in parallel channels is induced based on the analysis of effect parameters of flow instability by using the conservation equations for the mass, momentum and energy of single phase and two-phase fluid. The calculation result of this method had been compared with experimental data, and the difference between calculation and experiment was approximately 20%.

In the Khabenskii method, flow instability is evaluated by the critical mass velocity. When the actual mass velocity in the tubes is higher than the critical mass velocity, the flow is stable. The critical mass velocity is calculated by the following equation:

\[
\left( \rho w \right)_{bo} = 4.63 \times 10^{-3} \left( \rho w \right)_{op} \frac{\bar{q} L}{d_{equ}}
\]

Where \( \bar{q} \) is the average heat flux on the pipe surface, MW/m²; \( d_{equ} \) is the equivalent hydraulic diameter of pipe, m; \( L \) is heated length of pipe, m; \( \left( \rho w \right)_{op} \) is the critical mass velocity, kg/(m²·s).

\( \left( \rho w \right)_{op} \) is the function of inlet throttle resistance coefficient \( \xi \), insufficient enthalpy of the entrance \( \Delta \text{i}_{\text{in}} \) and pressure. It can be calculated by the following equation:

\[
\left( \rho w \right)_{op} = \left( \rho w \right)_{o} K_p
\]

Where \( \left( \rho w \right)_{s} \) is the critical mass velocity under the pressure of 10MPa with specific tube length, diameter and heat flux, kg/(m²·s); \( K_p \) is the correction factor, and the value can be obtained by Fig.1. The resistance coefficient \( \xi \) in Fig.1 can be defined by following equation:

\[
\xi = \xi_{\text{in}} - \xi_{\text{out}}
\]

For vertical tube, the critical mass velocity can be calculated:

\[
\left( \rho w \right)_{bo} = C \left( \rho w \right)_{bo}
\]

Where \( C \) is the correction factor obtained from Fig.2 according to the inlet subcooling degree and pressure.
Figure 1. Critical mass velocity of horizontal tube

Figure 2. Correction factor for calculating critical mass velocity in a vertical tube

3. Analysis of instability in CEFR steam generator

Utilizing Khabenskii method to determine the minimum inlet resistance coefficient to prevent flow instability in CEFR steam generator under startup conditions. Table 1 shows the data of startup conditions of CEFR steam generator.

| Reactor Power/% | 9.45 | 26.5 | 26.5 | 40  | 50  |
|-----------------|------|------|------|-----|-----|
| Feedwater flow rate/% | 11.0 | 28.1 | 29.2 | 40.9 | 50.7 |
| Evaporator outlet sodium temperature/℃ | 282.0 | 282.0 | 310.0 | 310.0 | 310.0 |
| Vapor pressure/MPa | 7.0 | 7.0 | 14.0 | 14.0 | 14.0 |
| Feedwater temperature/℃ | 190 | 190 | 190 | 190 | 190 |
| Evaporator outlet steam temperature/℃ | 313.3 | 368.6 | 378.8 | 422.4 | 418.1 |
| Superheater outlet steam temperature/℃ | ----- | 378.6 | 405.6 | 455.2 | 464.9 |

Notes: In reactor power of 9.45%, steam does not enter the superheater because that steam superheat degree in evaporator outlet does not reach 30℃.
According to the data in Table 1, the minimum inlet resistance coefficients to prevent flow instability calculated by using Khabenskii method are shown in Table 2. In 9.45% full power (FP) condition, the superheater did not work so that the equivalent outlet coefficient of evaporator could not be calculated. In 26.5%FP, 7.0MPa pressure condition, the needed inlet resistance coefficient of evaporator to prevent flow instability is the biggest among the conditions in the Table 1. In conditions of 14MPa pressure, the resistance coefficients obtained from Fig.1 are all zero. Therefore, the calculated inlet resistance coefficients in conditions of 14MPa pressure are equal to the equivalent outlet resistance coefficients of the evaporator. Thus, the needed inlet resistance coefficient for CEFR steam generator to prevent flow instability is approximately 1001.2.

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| Feedwater temperature/℃ | 190 | 190 | 190 | 190 | 190 |
| Evaporator outlet steam temperature/℃ | 313.3 | 368.6 | 378.8 | 422.4 | 418.1 |
| Superheater outlet steam temperature/℃ | ------ | 378.6 | 405.6 | 455.2 | 464.9 |
| Resistance coefficient in Fig.1 | 415 | 523 | 0 | 0 | 0 |
| Equivalent outlet resistance coefficient | 0 | 478.2 | 211.0 | 239.2 | 232.9 |

4. Effect parameters analysis

4.1. Effect of flow rate
In the condition of constant power, feedwater temperature and system pressure, the increasing of feedwater flow rate would lengthen the subcooled section and reduce the void fraction. Therefore, the ratio of the two-phase friction pressure drop and the acceleration pressure drop to the total pressure drop is reduced. Thus, the flow state turns to be stable. Based on 26.5% full power condition, using the method of Khabenskii, the minimum inlet resistance coefficients to prevent flow instability under different water flow rate were obtained. Fig.3 shows the minimum inlet resistance coefficient to prevent flow instability varies with the feedwater flow rate. With the increase of the feedwater flow rate, the minimum inlet resistance coefficient to prevent flow instability decreases. Therefore, increasing feedwater flow rate can make the flow be stable.

Figure 3. Relationship between minimum inlet resistance coefficient and feedwater flow rate

(a) 7MPa pressure and 28.1% water flow rate (b) 14MPa pressure and 29.2% water flow rate
4.2. Effect of pressure
In the condition of fixed power, feedwater temperature and water flow rate, the increasing of pressure would decrease the void fraction. Therefore, the ratio of the two-phase friction pressure drop and the acceleration pressure drop to the total pressure drop is reduced. Thus, the flow state turns to be stable. This effect is similar to the effect of increasing the feedwater flow rate. Based on 26.5% full power condition, the minimum inlet resistance coefficients to prevent flow instability under different system pressure were obtained using Khabenskii method. Fig.4 shows the minimum inlet resistance coefficient to prevent flow instability varies with the pressure. The pressure increased, the density difference between water and vapor reduced, the flow tends to be stable.

![Figure 4. Relationship between minimum inlet resistance coefficient and pressure](image)

4.3. Effect of subcooling
In order to obtain the effect of subcooling on flow instability, the system pressure, the water mass flow, and the thermal power are temporarily frozen. The remaining free parameters are the feedwater temperature. Using the method of Khabenskii to calculate the minimum inlet resistance coefficient under different feedwater temperature and the relationship shown in Fig.5. With the decreasing of feedwater temperature, the subcooling increases, and the resistance decreases. An increase in feedwater temperature with a fixed water flow rate, thermal power and system pressure will be likely to result in unstable working conditions. Therefore, the smallest inlet resistance coefficient should increase to prevent the flow instability.

From Fig.1, the relationship between resistance coefficient and insufficient enthalpy of the entrance can be obtained and the relationship is shown in Fig.6. With the increase of insufficient enthalpy of the entrance, the resistance coefficient decreases. In the given insufficient enthalpy of the entrance, the resistance coefficient declines with the increase of the critical mass velocity.

![Figure 5. Relationship between minimum inlet resistance coefficient and feedwater temperature](image)
4.4. Effect of thermal power

In order to obtain the effect of thermal power on flow instability, the system pressure, water mass flow, and subcooling are temporarily frozen. The remaining free parameters are the thermal power. Using the method of Khabenskii to calculate the minimum inlet resistance coefficient under different thermal power and the relationship shown in Fig. 7. With the increasing of thermal power, the resistance increases. An increase in thermal power with stationary water flow rate, feedwater temperature and system pressure will be likely to result in unstable working conditions. Therefore, the minimum inlet resistance coefficient should increase to prevent the flow instability.

5. Conclusion

Using Khabenskii method to calculate the minimum inlet resistance coefficient to prevent flow instability in CEFR steam generator. In all calculated conditions, the needed resistance coefficient in 26.5% thermal power, 7MPa pressure condition is the greatest, and the value is about 1001.2.

Using Khabenskii method to analyze the effect of mass flow rate, pressure, subcooling and thermal power on flow instability in CEFR steam generator. The results show that the increase of flow rate, pressure and subcooling and the decrease of thermal power will stabilize the flow instability in CEFR steam generator.

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