Study on Flow Distribution Characteristics of Reactor Passive Residual Heat Removal System

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Abstract. During the passive residual heat removal system at the reactor primary loop (PRHRS) operation, the parallel pipeline is formed between the channels of PRHRS heat exchanger (HX) and steam generator (SG), and the later flow is large, which has a bypass effect on the former flow. Based on one-dimensional N-S equation, a theoretical model is established to describe the flow distribution characteristics of this parallel pipeline. To verify the model, the AP1000 PRHRS is taken as an example, and the results calculated by the model are compared with that of RELAP5 numerical simulation, the error of which is no more than 5%. Based on the model, the flow distribution characteristics of the parallel line are analyzed. The results show that, due to the large flow area and small flow resistance, the SG channel flow is much bigger than the HX channel flow after PRHRS is activated. Because this phenomenon has a great effect on the capacity of PRHRS, it’s necessary to be further analyzed.

1. Introduction

The inlet line of the primary side of the passive residual heat removal system (PRHRS) is connected to the hot leg of the primary loop, while the outlet line is connected to the cold leg. Due to this structural design, the parallel pipeline is formed between the channels of PRHRS heat exchanger (HX) and steam generator (SG). As soon as the station blackout accident occurs, the reactor is shut down, and the SG is isolated by lose of feedwater and close of steam isolation valve. Then PRHRS is activated, the reactor decay heat is mainly removal by the natural circulation of PRHRS, while the secondary side and primary side of the SG U-tube reach dynamic thermal equilibrium state, and its heat removal capacity can be ignored [1]. At that time, the natural circulation driving force of the SG branch is very small. However, Wang et al [2] and Yang et al [3] has carried out a numerical simulation on the transient characteristics of PRHRS during the AP1000 station blackout accident (SBO), which showed that when the PRHRS establishes a stable natural circulation flow, the SG channel had a large flow. Yang et al [4] has also carried out numerical simulation on the PRHRS of floating nuclear power plant, and the same result was obtained.

Because of the loss of the main heat sink function after the SG is isolated, the flow of this channel has no effect on the reactor cooling. In addition, the bypass effect of the SG channel will change the resistance characteristics of PRHRS, which may cause its heat removal capacity decrease. For this phenomenon, this paper establishes the flow distribution model by theoretical analysis, and analyzes the
flow distribution characteristics of the PRHRS channel, so as to provide some references for further research on the influence of the SG channel flow on the PRHRS capacity and the improvement of PRHRS design.

2. Establishment of the flow distribution model
For a single-phase one-dimensional incompressible flow, it is assumed that the density and other thermophysical properties follow Bossinseq hypothesis, and the energy dissipation term caused by wall friction and local resistance in the energy equation is ignored, then the field equation can be expressed as:

\[ \frac{\partial W}{\partial x} = 0 \]  

(1)

\[ \frac{\Delta x}{A} \frac{\partial W}{\partial t} = -\Delta p - \Delta p_f - \Delta p_k - \rho_0 \left[ 1 - \beta \left( T - T_0 \right) \right] g \Delta x \cos \theta \]  

(2)

\[ \frac{\partial T}{\partial t} + \frac{W}{\rho A} \frac{\partial T}{\partial x} = \frac{pq}{\rho c_p A} \]  

(3)

Where, \( W = \rho A v \) is the mass flow; \( \Delta p \), \( \Delta p_f \), \( \Delta p_k \) is the static pressure drop, friction pressure drop, and local pressure drop; \( \rho_0 \) and \( T_0 \) is the reference density and temperature; \( \beta \) is the coefficient of thermal expansion; \( q \) is the surface heat flux; \( p \) is the equivalent heat transfer perimeter.

For the fully developed flow, the pressure drop characteristics of the pipeline can be expressed as:

\[ \Delta p_f + \Delta p_k = \lambda \frac{1}{d_e} \frac{\rho v^2}{2} + k \frac{\rho v^2}{2} = \frac{W^{2-b}}{A^{2-a} d_e^{1+b}} \]  

(4)

Where, \( d_e \) is the equivalent hydrodynamic diameter; \( l_e = k d_e / \lambda \), \( \lambda \) and \( k \) are the friction and local resistance coefficient; \( a \) and \( b \) are constants associated with the flow state, used for calculating the friction coefficient, that is

\[ \lambda = \frac{a}{Re^b} \]  

(5)

Where, \( a=0.64, b=1 \), for laminar flow and \( a=0.3164, b=0.25 \), for turbulent flow [5].

Typical passive residual heat removal system configuration is shown in figure 1. The lines in different colors represent the pipe in different operating temperatures, where red represents hot segment, blue represents cold segment, and brown represents that between them. In the figure, the reactor core, SG, PRHRS HX and pipes between them are simplified. The reactor core channel (RC channel, 4-1-2), SG channel (2-3-4) and HX channel (2-5-4) are respectively expressed as Ch1, Ch2 and Ch3, where \( W_i, P_i \) are the flow rate and power of channel \( i \), and \( N_i \) is the total number of pipes, valves, elbows and other parts of channel \( i \). Then

\[ W_i = W_{i1} + W_{i2} \]  

(6)

\[ P_i = c_p W_i \Delta T_i, P_i = P_{i1} + P_{i2} \]  

(7)
During the steady state, when the SG has been isolated and its heat transfer power can be ignored, the residual heat is mainly removed by PRHRS, i.e. \( P_2 = 0, P_1 = P_3 \). Integrate equation (2) along Ch1+Ch2 loop and Ch1+Ch3 loop respectively, then

\[
\frac{W_{1}^{2} g \mu_{1}}{2 \rho_{0}} G_{1} + \frac{W_{2}^{2} g \mu_{2}}{2 \rho_{0}} G_{2} = \rho_{0} g \beta \Delta H_{14} \frac{P_{1}}{c_{p} W_{1}} \]

(8)

\[
\frac{W_{1}^{2} g \mu_{1}}{2 \rho_{0}} G_{1} + \frac{W_{3}^{2} g \mu_{3}}{2 \rho_{0}} G_{3} = \rho_{0} g \beta \left( \Delta H_{14} \frac{P_{1}}{c_{p} W_{1}} + \Delta H_{45} \frac{P_{3}}{c_{p} W_{3}} \right) \]

(9)

Where, \( G_{i} = \sum_{j=1}^{N} G_{i,j} = \sum_{j=1}^{N} \left[ \frac{a(l + l_{j})}{A^{2-i} d^{n-i}} \right] \); \( \Delta H \) is the elevation difference.

The equations (6), (8) and (9) constitute the flow characteristics equations on the primary side of PRHRS during steady state condition. The left side of the equations contains some non-integer power terms of the unknowns, and their solutions can only be approximately obtained by numerical method.

### 3. Verification of the flow distribution model

Taking the AP1000 PRHRS as an example, the model is verified by the numerical calculation results based on RELAP5. First, the structural parameters of the AP1000 plant [6] are substituted into the flow characteristics equations. Suppose that the steady-state decay power is 1%FP, and \( a = 0.3164, b = 0.25 \). After several iterations, the flow distribution is shown in table 1. The flow rate of the SG channel is about 3.8 times of that of the HX channel.

Then, a numerical model of the PRHRS based on RELAP5 is established, and the detailed control volume nodalization and the main initial parameter are given by reference [7]. As shown in table 1, the relative error between the results of the RELAP5 simulation and theoretical calculation is within 5%. Since the physical parameters of water are regarded as a constant value determined by qualitative temperature when the characteristics equations are solved iteratively, while in the RELAP5 calculation they are obtained by the interpolation of individual parameters of each control volume, there is an error between the two methods.

| Table 1. Flow distribution of the analysis and simulation |
|-----------------------------------------------|
| flow distribution model, kg/s | Simulation by RELAP5, kg/s | Relative error |
| W₁ | 282.15 | 285.02 | 1.02% |
| W₂ | 223.4 | 224.39 | 0.44% |
| W₃ | 58.76 | 60.67 | 3.25% |
4. Flow distribution characteristics

Subtract equation (8) from equation (9), and suppose \( b=0.25 \), then get the pressure drop balance equation:

\[
\frac{W_2^{1.75} \mu^{0.25}}{2 \rho_0} G_2 = \frac{W_3^{1.75} \mu^{0.25}}{2 \rho_0} G_3 - \rho g \beta \Delta H_{45} \frac{P_1}{c_p W_3}
\]

(10)

In order to analyze the flow relationship between the HX channel and the SG channel, the primary and secondary analysis of variation trend is carried out on the right side of equation (10). The first term on the right side of equation (10) varies by 1.75 power of \( W_3 \), while the second term varies by one power of \( W_3 \). When \( W_3 \) becomes larger, the first term increases faster than the second term. In other words, when \( W_3 \) is large, the second term on the right side of equation (10) is much smaller than the first term. Therefore, in order to simplify the analysis process, ignore the second term on the right, then

\[
W_2^{1.75} G_2 \sim W_3^{1.75} G_3
\]

(11)

According to the definition of \( G_i \), it is proportional to \( A_i^{-1.75} d_i^{-1.25} \) and \( A_i^{-2.375} \), then

\[
\frac{W_2}{W_3} \sim \left( \frac{A_2}{A_3} \right)^{1.36}
\]

(12)

The above formula shows that the flow ratio of the two channels is proportional to the flow area ratio of 1.36 power. For a typical PRHRS configuration, the flow area of the SG channel, which is a part of primary loop, is usually larger than that of the HX channel. According to equation (4), under the same flow, the flow velocity of the SG channel is lower, and the flow resistance is smaller. Therefore, the SG channel flow is much bigger than the HX channel flow at the same press drop across the parallel line.

5. Conclusion

Aiming at the flow distribution problem of SG and HX channel during the operation of PRHRS at the primary loop, this paper establishes a flow distribution characteristic model, which is verified by the comparison with the results of RELAP5 numerical simulation. Based on this model, the flow relationship between the channels is analyzed.

During the SBO accident, because the SG is isolated, the heat transfer on both sides of the U-tube is weak, and the natural circulation driving force of the SG channel is very small. However, according to the typical PRHRS configuration, the SG channel is a part of the primary loop, and its flow area is usually much larger than that of HX channel. Under the effect of the pressure difference at both ends of the parallel pipe, the SG channel will generate a large flow.

Large bypass flow of the SG channel will change the resistance characteristics and heat transfer effect of the reactor core channel, which will have a significant impact on the operation characteristics and heat removal capacity of PRHRS. It is necessary to carry out further analysis.

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