Main coolant pump resistance influence on single phase water reverse flow in the inverted U-tubes under natural circulation

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Abstract Based on nuclear power plant (NPP) best-estimate transient analysis with RELAP5 / MOD3 code, the reactor point kinetics model in RELAP5 / MOD3 code is replaced by the two-group, 3-D space and time dependent neutron kinetic model, and two-fluid model is replaced by drift flux model. A coupled three-dimensional physics and thermal-hydrodynamics model is used to develop its corresponding computing code, thus simulating natural circulation of single-phase flow for the PWR. In this paper, we report the forward and reverse flow distribution in the inverted U-tubes of the steam generator（SG）under some typical operating conditions in the natural circulation case, and analyze the influence of main coolant pump resistance on the forward and reverse flow distribution. The calculation results show that, the pressure drop between SG inlet and outlet plenum decreases, and the SG inlet and outlet mass flow decrease with an increased main coolant pump resistance, but net mass flux of reverse flow in inverted U-tubes, and the ratio of mass flow in all reverse flow tubes to that of main coolant pipeline increase, meanwhile, the secondary steam load is invariable in this process.

Key words Steam generator, Natural circulation, Reverse flow, Main coolant pump resistance

1 Introduction

Natural circulation, a sort of circular flow, only depends on driving force of the density difference between cool and hot fluid in a closed system. Natural circulation can improve reactor passive safety effectively, the capacity and price ratio of integrated reactor, and reduce the reactor core flow maldistribution[1], thus playing an important role in design and operation of new generation reactor.

At present, overseas research results on natural circulation of civilian nuclear installations and marine nuclear power plant have been obtained, such as HSBWR (Japan), SBWR (the USA), VK-50 (Russia), Dodeward (Holland). All the nuclear reactor power outputs depend on natural circulation.

Some domestic researches on characteristic of natural circulation have now been reported. Zhang Y *et al.* [2] and Lu C *et al.*[3] (Nuclear Power Research and Design Institute, China), Yang R C *et al.*[4–6] (Tsinghua University, China), and Zhang D *et al.* [7–9] (Navel University of Engineering, China) conducted in-depth research single phase water reverse flow in the inverted U-tubes of SG under the natural circulation condition, and verified their analysis results by experiments.

In this paper, based on the modeling with RELAP5/MOD3 code, the reactor point kinetics model in the RELAP5/MOD3 code is replaced by the two groups, the 3D space and time dependent neutron kinetic models, and the two-fluid model is replaced by drift flux model. A coupled three-dimensional physics and thermal-hydrodynamics model is used to develop its corresponding computing code. The summary research results on the transient process characteristic of the forced circulation to the natural circulation are conducted by experiments.

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2 System Brief Introduction

2.1 Nodalization of Inverted U-tubes of SG

The PWR nuclear power plant belongs to a typical two loops PWR design with the capacity of natural circulation. As shown in Fig.1, The SG has the identical length of inverted U-tubes straight segment, inner and outer diameter, and component material. The U-tubes are divided into 16 sorts by their bending segment lengths. The length ratio of the longest U-tube to the shortest one is about 1.42, and the amount ratio of the shortest U-tube to the longest one is about 3.43.

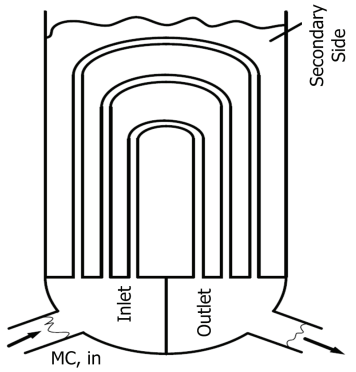

Fig.1 Structure of inverted U-tubes of SG.

2.2 Establishment of Natural Circulation

The plant natural circulation is established by transforming forced circulation into natural circulation. In their transition process, the main coolant pumps of two loops stop successively, and the mass flow drops quickly. The initial reactor power reduces due to reactivity feedback, and then rises because of auto rod withdrawal constantly. The reactor temperature difference between their inlet and outlet increases, also the reactor mass flow increases gradually. The auto rod movement stops when average coolant temperature reaches the rated operation. As reactor power and natural circulation mass flow tend to a steady state, the natural circulation is established, the secondary steam load is also invariable in this process.

3 Calculation and Validation

3.1 Node Nodalization

When the RELAP5/MOD3.3 code is used to model the U-tubes of the SG, the lumped nodalization is usually used, as shown in Fig.2. All the U-tubes are divided by lumped parameter under the conditions of the inside and outside U-tubes, and the SG pressure drop of inlet to outlet is invariable. The traditional node nodalization method is suitable to simulate forced circulation cooling, but cannot simulate the forward and reverse flow in some inverted U-tubes under the natural circulation condition. For our new method, the U-tubes are divided into 16 sorts according to their lengths. Each sort is divided into 10 nodes connected with flow path, and primary side of each SG is divided into 162 nodes (Fig.3). Nodalization of reactor core and pipelines and secondary side of SG in our new method are the same as those of the traditional method[10,11]. Flow resistance calculation model of main coolant pump under the natural circulation is referred to Ref.[11].

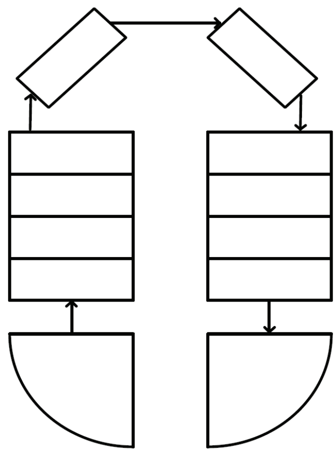

Fig.2 Nodalization of the inverted U-tubes with traditional method.

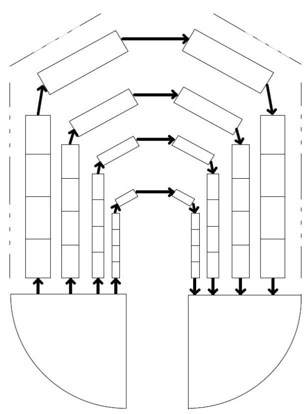

Fig.3 Nodalization of the inverted U-tubes with new method.

3.2 Analysis Conditions and Results

The operation conditions of typical natural circulation for the PWR nuclear power plant are simulated, and all the main parameters are not dimensional. Six different main coolant pump resistance coefficients are defined as 1.00, 1.24, 1.48, 1.71, 1.95, and 2.19, respectively. The positive mass flow in the inverted U-tubes, which is the same direction to forced circulation, is the sum of forward flow; and the negative mass flow in the inverted U-tubes, which is opposite direction to the forced circulation, is the sum of reverse flow. The total net mass flow in the pipeline is the sum of positive and negative mass flow in the inverted U-tubes of SG. When ration of main coolant pump (MCP) resistance coefficients is 1.00, all SG steam pressures correspond to their MCP resistance coefficients and inlet flows are defined as 1; and the reverse flow as –1. For our new method, ratios of mass flow in the U-tubes of16 sorts and main pipelines under the six sorts of MCP resistance coefficients in the natural circulation case are listed in Table 1.

Table 1 Ratio of mass flow in different length inverted U-tubes and net flux in main pipeline under MCP resistance 1.00–2.19

Parameter	Ratio of inverted U-tube length to shortest	Ratio of mass flow in different length inverted U-tubes to net mass flow in main pipeline under different MCP resistance coefficients / %					
		1.00	1.24	1.48	1.71	1.95	2.19
Value	1.00	–13.91	–14.78	–15.94	–16.39	–17.08	–17.40
	1.03	–15.25	–16.18	–17.41	–17.88	–18.63	–18.94
	1.06	–14.96	–15.86	–17.07	–17.53	–18.26	–18.56
	1.08	14.07	14.29	14.58	14.69	14.79	14.83
	1.11	13.79	14.02	14.33	14.45	14.60	14.66
	1.14	13.88	14.13	14.45	14.58	14.78	14.86
	1.17	13.53	13.78	14.11	14.24	14.45	14.54
	1.20	12.95	13.19	13.52	13.64	13.86	13.94
	1.22	12.76	13.01	13.33	13.46	13.67	13.76
	1.25	12.14	12.38	12.69	12.82	13.02	13.11
	1.28	11.50	11.73	12.03	12.16	12.35	12.43
	1.31	10.44	10.65	10.93	11.04	11.21	11.30
	1.34	9.58	9.78	10.04	10.13	10.30	10.38
	1.36	8.31	8.48	8.71	8.79	8.93	9.00
	1.39	7.04	7.19	7.37	7.44	7.57	7.63
	1.42	4.13	4.21	4.32	4.36	4.43	4.47

For the new method, six sorts of the MCP resistance coefficients are calculated in the transition process of forced to natural circulation. On MCP resistance, the SG reverse flow with is shown in Fig.4. Its reverse flow fraction is shown in Fig.5; its inlet flow in primary side is shown in Fig.6; the pressure drop between SG inlet and outlet is shown in Fig.7; the SG steam pressure is shown in Fig.8; and the temperature difference between SG inlet and reactor outlet is shown in Fig.9.

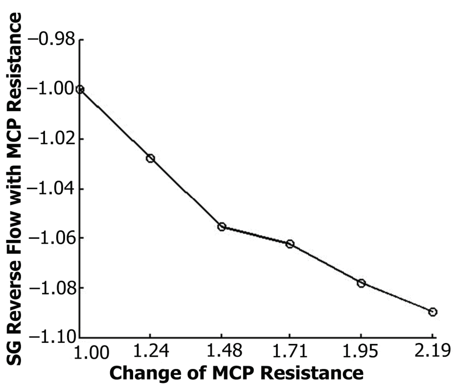

Fig.4 SG reverse flow with MCP resistance.

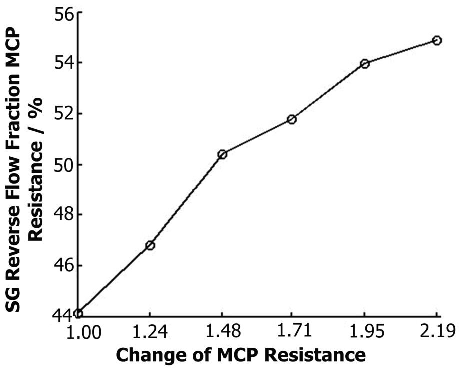

Fig.5 SG reverse flow fraction with MCP resistance.

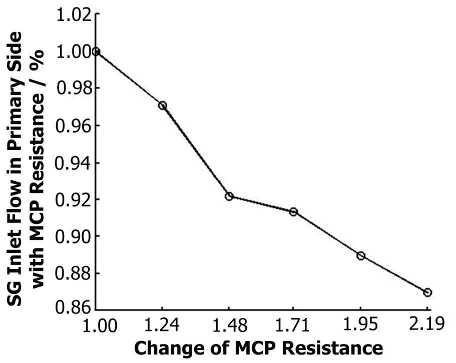

Fig.6 SG inlet flow in primary side with MCP resistance.

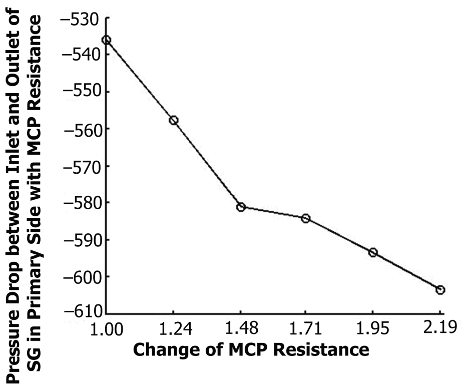

Fig.7 Pressure drop between inlet and outlet of SG in primary side.

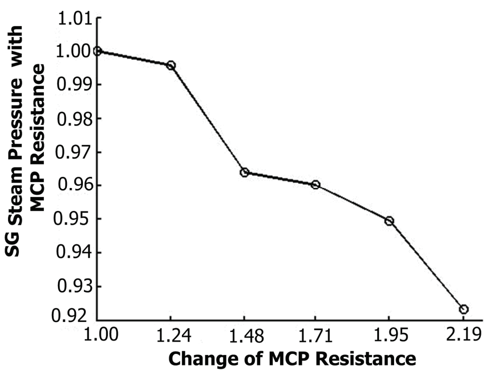

Fig.8 The SG steam pressure with MCP resistance.

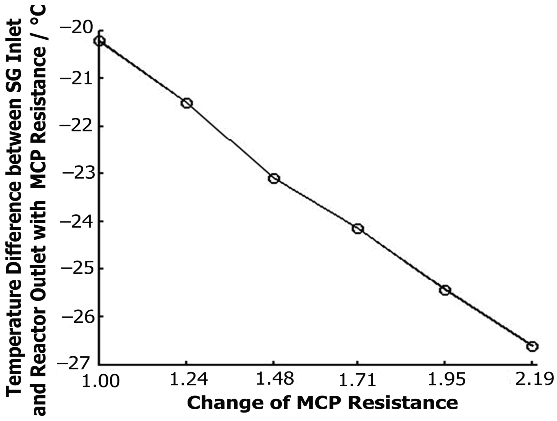

Fig.9 Temperature difference between SG inlet and reactor outlet with MCP resistance.

To consider the tube gravitational pressure drops in the transition process of the forced to natural circulation, several pipelines of the first, the second, the third, and the 16th sort tubes were used to be analyzed, as shown in Figs.(10)–(13).

3.3 Results Analysis

Analysis results are shown in Table 1 and Figs.(1)–(4).

Dividing the inverted U-tubes of SG, the traditional lumped parameter method cannot simulate the forward and reverse flow distribution in inverted U-tubes, thus not calculating natural circulation flow accurately. But, the reverse flow in some inverted U-tubes of SG can be quantitatively simulated by our new method (Table 1).

Table1 shows that all the reverse flow occurs in the shorter inverted U-tubes of first three sorts under the six different MCP resistance coefficients. The negative reverse flow decreases with increasing pump resistance, that is, absolute value increased (Fig.4). The ratio of reverse flow in inverted U-tubes to net mass flow in main pipeline increases with the MCP resistance coefficient (Fig.5).

The SG inlet flow in primary side of the nuclear power plant decreases gradually with increasing MCP resistance in the transition of the forced circulation to the natural circulation (Fig.6), decreasing the pressure drop between the SG inlet and the outlet plenum (Fig.7) and the SG secondary pressure (Fig.8).

The SG inlet temperature in primary side is the same as the reactor core outlet temperature under the forced circulation. In the transition of the forced to natural circulation, especially reverse flow in parallel connection inverted U-tube, the coolant with quite low temperature reflows from the SG outlet to its inlet. Because the coolant temperature drops sharply, the SG inlet temperature in primary side is lower than that of its outlet, the temperature difference is up to 20–27°C and increases with MCP resistance. The gravitational pressure drop in the reverse flow inverted U-tubes is less than 20 Pa, as shown in Fig.s(10)–(12), and is negative in the forward flow inverted U-tubes (Fig.13). So the gravitational pressure head, which increases with MCP resistance, is higher in long tubes than in short ones.

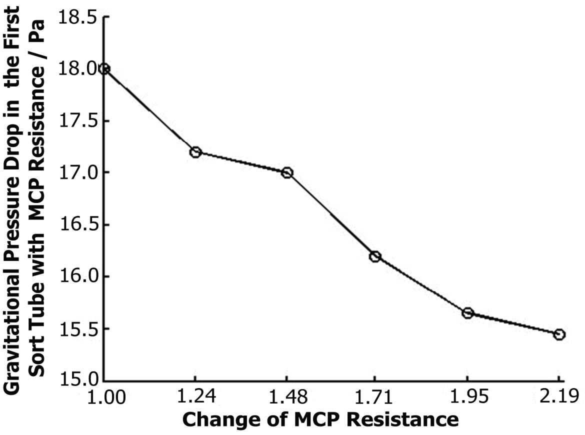

Fig.10 Gravitational pressure drop in the first sort tube with MCP resistance.

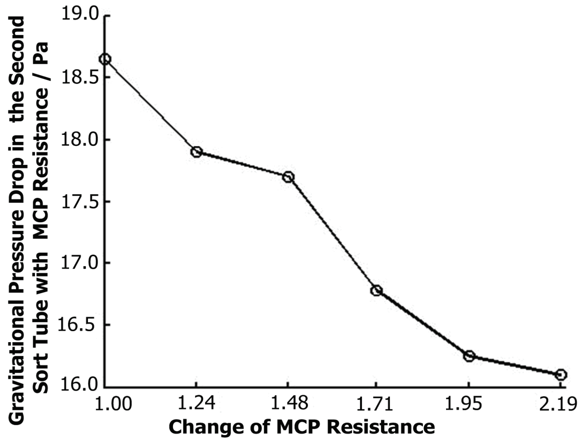

Fig.11 Gravitational pressure drop in the second sort tube with MCP resistance.

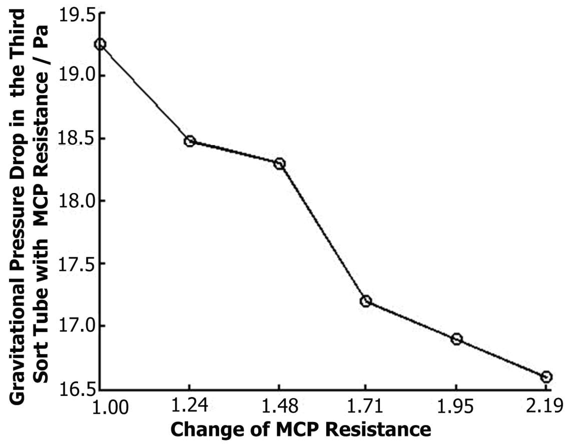

Fig.12 Gravitational pressure drop in the third sort tube with MCP resistance.

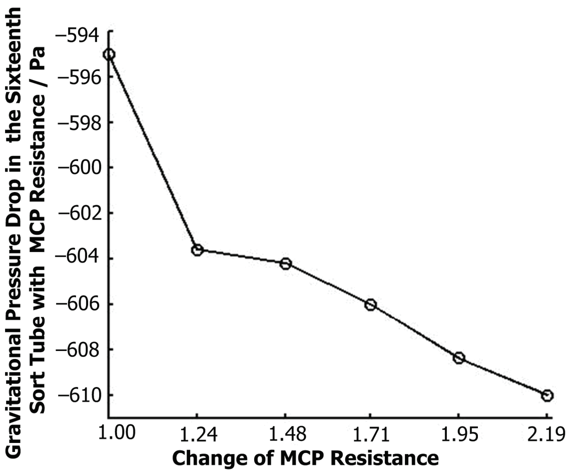

Fig.13 Gravitational pressure drop in the sixteenth sort tube with MCP resistance.

4 Conclusions

We calculate the reverse flow characteristic of inverted U-tubes under natural circulation of main coolant pump resistance coefficients.

Dividing the inverted U-tubes of SG, the traditional lumped parameter method cannot simulate the forward and reverse flow distribution, but the reverse flow characteristic of inverted U-tubes can be simulated by our new method.

The SG inlet flow in primary side and its steam pressure, and the negative pressure drop between the SG inlet and outlet decrease with increasing main coolant pump resistance, providing the driving force for reverse flow in inverted U-tubes. The gravitational pressure head is higher in long tubes than in short ones, that is, the gravitational pressure head in short tubes is insufficient, this may be the reason that reverse flow occurs in short tubes.

The increased main coolant pump resistance results in the decreased pressure drop between SG inlet and outlet plenum in primary side, and the net reverse flow in first three sorts increases. In the main pipeline, the net mass flow decreases with increasing MCP resistance, the flow ratios of the net reverse to the net mass in main pipeline increase with main coolant pump resistance.

The reverse flow in inverted U-tubes increases in the transition of the forced circulation to natural circulation with increasing main coolant pump resistance, namely, the more coolant with low temperature reflows from the SG outlet to its inlet. Further, the overall coolant temperature drops, and temperature difference between SG inlet and its outlet continue to increase. Considering the temperature effect on density, the gravitational pressure drop in short inverted U-tubes increases, thus limiting the sustained growth of reverse flow to a certain extent and ensuring the stability of systemic mass flow under the steam load.

The reverse flow in the inverted U-tubes reduces the mass flow in the primary coolant circuit under the natural circulation. The net mass flow in main pipeline decreases with increasing main coolant pump resistance, and reduces the mass flow of the natural circulation.

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