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ARTICLE

Analysis of Reverse Flow in Inverted U-Tubes of Steam Generator under Natural Circulation Condition

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In this paper, we report on the analysis of reverse flow in inverted U-tubes of a steam generator under natural circulation condition. The mechanism of reverse flow in inverted U-tubes of the steam generator with natural circulation is graphically analyzed by using the full-range characteristic curve of parallel U-tubes. The mathematical model and numerical calculation method for analyzing the reverse flow in inverted U-tubes of the steam generator with natural circulation have been developed. The reverse flow in an inverted U-tube steam generator of a simulated pressurized water reactor with natural circulation is analyzed. Through the calculation, the mass flow rates of normal and reverse flows in individual U-tubes are obtained. The predicted sharp drop of the fluid temperature in the inlet plenum of the steam generator due to reverse flow agrees very well with the experimental data. This indicates that the developed mathematical model and solution method can be used to correctly predict the reverse flow in the inverted U-tubes of the steam generator with natural circulation. The obtained results also show that in the analysis of natural circulation flow in the primary circuit, the reverse flow in the inverted U-tubes of the steam generator must be taken into account.

KEYWORDS: steam generator, inverted U-tube, natural circulation, reverse flow, analysis

I. Introduction

Natural circulation has been widely used in thermal equipment of many industries. It is of great use for the safety of light water reactors. Natural circulation can be used to release the residual heat within the reactor during reactor accidents and events. It can also be considered as a major method of circulation cooling during the normal operation of a pressurized water reactor (PWR). Until now, a number of papers, among these, by Schulz *et al.*,[1] Loomis *et al.*,[2] Stumpf *et al.*,[3] Koizumi *et al.*,[4] Kukita *et al.*,[5] Sanders,[6] Kukita and Tasaka,[7] Annunziato,[8] Lee *et al.*,[9] and Wang *et al.*[10] have reported the experimental studies on simulated PWRs to investigate natural circulation cooling during postulated PWR accidents, such as small-break loss-of-coolant accidents, loss-of-feed-water transients and operational transients. Their experimental results indicate that during single-phase liquid natural circulation on the primary side, reverse flow occurred in some inverted U-tubes of steam generators (SGs). When reverse flow occurred, the following phenomena were observed: (1) The pressure difference between the inlet and outlet of the U-tubes was negative (the pressure at the inlet plenum of steam generators was lower than that at the outlet plenum, refer to **Fig. 1**). (2) Reverse flow occurred in the long U-tubes. (3) The primary-side fluid temperature on both the upflow and downflow sides of the long tubes in which reverse flow occurred was uniform and in equilibrium with the secondary-side fluid temperature. (4) There was a sharp drop in fluid temperature from the hot leg to the U-tube inlet in the inlet plenum of steam generators. These phenomena were explained by the researchers mentioned above as follows. During natural circulation, because of the global density differences between the upflow and downflow sides of the U-tubes, *i.e.*, lower densities on the upflow side and higher densities on the downflow side, the outlet plenum pressure was larger than the inlet plenum pressure, which could drive the reverse flow in some U-tubes. Because of the longer flow path, there was less flow in the long U-tubes. Thus, the fluid in these long tubes rapidly cooled to the secondary-side temperature. Owing to the uniform fluid temperature distribution along the long U-tubes, the gravitational head in the long U-tubes tended to be zero. Since all U-tubes in a steam generator were connected in parallel into the same inlet and outlet plenums, the same pressure difference existed in all the U-tubes. By the action of the positive pressure difference between the outlet and inlet plenums, the fluid moved from the outlet plenum to the inlet plenum through the long U-tubes. When reverse flow occurred, the cold fluid flowed back from the outlet plenum to the inlet plenum and mixed with the hot fluid from the hot leg, which caused the sharp drop in fluid temperature in the inlet plenum of steam generators.

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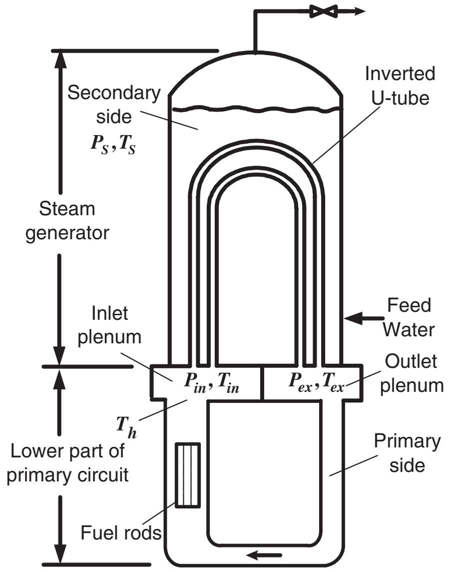

Fig. 1 Simplified schematic of PWR with natural circulation

Reverse flow can decrease both the global effective gravitational head and the net forward flow area on the primary side of steam generators, and thus, the natural circulation flow rate in the systems is lower than that predicted without reverse flow in the U-tubes. Therefore, it is of great significance to develop a theoretical approach of predicting the reverse flow in the inverted U-tubes of steam generators under natural circulation conditions for the safety analysis of PWR.

Concerning the theoretical analysis of reverse flow in the inverted U-tubes of steam generators in PWR under natural circulation condition, Sanders[6] regarded the reverse flow as a kind of flow instability. To study this instability, a one-dimensional flow model was used to describe the flow behavior in the U-tubes. A perturbation technique was used to linearize the conservation equations of the flow. The linearized equations were solved analytically to obtain the solution for a given flow. Though the analysis results showed that stability could be attained if in some tubes the water flowed backward, it was hard to use this theory to exactly predict the reverse flow in the parallel U-tubes. Annunziato[8] considered the reverse flow as the Ledinegg instability[11] and used the steady-state momentum equation of single-phase liquid flow in individual U-tubes to analyze the occurrence of primary fluid flow excursion during primary-side natural circulation. This approach was not able to predict the reverse flow in the parallel U-tubes. Jeong *et al.*[12] also considered the reverse flow in the U-tubes as the flow excursion instability. They still used a one-dimensional flow model to describe the flow behavior in the U-tubes of steam generators of PWR under natural circulation condition. They used the linear perturbation technique to obtain the solution of the mathematical model and analyze the flow excursion in U-tubes under certain flow condition. It was shown from the analysis results that flow excursion could exist in the U-tubes under certain low-flow conditions, but this theory could not be used to predict the reverse flow in multiple U-tubes. Loomis *et al.*[2] used the computer code RELAP5 with a one-dimensional flow model to analyze the reverse flow in the U-tubes during single-phase water natural circulation. Because all the U-tubes were lumped together in this computer code, and nonuniform fluid flow distributions including the reverse flow could not be simulated, the calculation results showed that compared with the experimental data, the total loop flow rates were overpredicted. Schulz *et al.*[1] and Stumpf *et al.*[3] all used the computer code TRAC to simulate the flow behavior in the U-tubes of steam generators during primary-side single-phase liquid natural circulation. In the analysis with TRAC, a single U-tube SG model, in which all the U-tubes were lumped into a single equivalent U-tube with one-dimensional flow, and a three-U-tube SG model, in which all the U-tubes were represented by short, medium and long U-tubes, were used. The comparisons of the analysis results with the experimental data showed that the one-dimensional, single U-tube SG model was unable to simulate the flow behavior properly and the calculated primary loop mass flow rates were too large. Their three U-tube SG model was able to predict the reverse flow in the long U-tube, but the three-U-tube SG model overpredicted the reverse flow rate and the temperature drop of the fluid in the inlet plenum of the steam generators. The differences between the calculated and measured values were explained by Schulz *et al.*[1] and Stumpf *et al.*[3] in part by the impossibility of calculating the complex flow behavior within the 141 full-size U-tubes of nine different lengths by using only a three-U-tube SG nodalization system, and in part by not taking into account the heat transfer in the SG plenum across the plenum divider plate and the tubesheet into the secondary fluid.

In this paper, we report on the analysis of reverse flow in inverted U-tubes of steam generators of PWR under natural circulation condition. The mechanism of single-phase liquid reverse flow in the parallel U-tubes during natural circulation is graphically analyzed by using the full-range characteristic curve of U-tubes to provide the basis for the analysis of reverse flow in the U-tubes. The mathematical model for simulating the reverse flow in the U-tubes and the corresponding calculation technique are developed. The calculated results are compared with the experimental data to verify the accuracy of the predictions.

II. Mechanism of Reverse Flow in Inverted U-Tubes

A simplified schematic of PWR with an inverted U-tube steam generator is shown in Fig. 1. As shown in the experiments mentioned above, when the primary system of PWR simulators operates under steady-state single-phase liquid natural circulation condition with reverse flow in the U-tubes, the static pressures in both the primary and secondary sides, the secondary fluid temperature, the temperatures of both the fluid from the hot leg to the inlet plenum and the fluid from the outlet plenum to the cold leg, and the net primary circuit mass flow rate are all given and remain constant. In this study, the reverse flow occurring in the parallel U-tubes is considered to be a steady-state flow mode just as the normal flow in the U-tubes. Therefore, the mechanism of

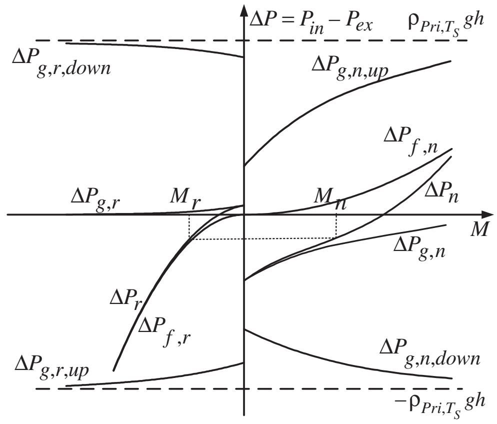

Fig. 2 Full-range characteristic curve of U-tubes for single-phase water natural circulation

reverse flow, which simultaneously exists with the normal flow in the parallel U-tubes, can be graphically analyzed by using the full-range characteristic curve of U-tubes as shown in **Fig. 2** for a U-tube SG as illustrated in Fig. 1 and the given steady-state operating conditions mentioned above. In Fig. 2, the abscissa indicates the mass flow rate in the U-tubes and the ordinate indicates the pressure difference between the inlet and outlet of the U-tubes. The mass flow rate of normal flow is positive and that of reverse flow is negative. The positive pressure difference means the pressure in the inlet plenum is higher than that in the outlet plenum. If the pressure in the inlet plenum is lower than that in the outlet plenum, the pressure difference is negative. It should be pointed out that Fig. 2 can be used to analyze the normal and reverse flows in both individual U-tubes and those connected in parallel as described later. First, the characteristic curve of normal flow in the U-tubes is plotted in Fig. 2. It is easy to draw the curve of frictional pressure drop including the pressure drop due to the local resistance of normal flow in the U-tubes, $\Delta P_{f,n}$, in the first quadrant of Fig. 2. Since the mass flow rate of normal flow in the U-tubes is equal to the net primary circuit flow rate plus the reverse flow rate, both the normal flow rate and the frictional pressure drop of normal flow increase with an increase in reverse flow rate. Because the gravitational pressure drops of normal flow on the upflow side from the inlet to the top of the U-bend and the downflow side from the top of the U-bend to the outlet of the U-tubes are respectively positive and negative, the gravitational pressure drop of normal flow on the upflow side of the U-tubes, $\Delta P_{g,n,up}$, is plotted in the first quadrant of Fig. 2 and the gravitational pressure drop of normal flow on the downflow side of the U-tubes, $\Delta P_{g,n,down}$, is plotted in the fourth quadrant of Fig. 2. As mentioned above, the normal flow consists of the net primary circuit flow from the hot leg with high temperature and the reverse flow from the outlet plenum with low temperature. It is obvious that for the given mass flow rate and fluid temperature of the net primary circuit flow, the normal flow rate increases, while the fluid temperature of normal flow decreases and the fluid density of normal flow increases with the reverse flow rate increasing and the reverse flow mixing with the flow from the hot leg; both the absolute values of the gravitational pressure drops of normal flow on the upflow and downflow sides of the U-tubes increase; the gravitational pressure drops gradually approximate to the static pressure drops, $\rho_{pri,Ts}gh$ and $-\rho_{pri,Ts}gh$, respectively, which are evaluated with the primary-side fluid temperature of normal flow equal to the secondary fluid temperature. Because the temperatures of both the fluid from the hot leg to the inlet plenum and the fluid from the outlet plenum to the cold leg are all given and remain constant, the fluid temperature of normal flow at the inlet of U-tubes is higher than that at the top of U-bend and the fluid temperature at the top of U-bend is higher than that at the outlet of U-tubes even while assuming the normal flow rate to be zero. Consequently, the absolute value of $\Delta P_{g,n,down}$ is not the same as $\Delta P_{g,n,up}$ if the mass flow rate of normal flow becomes zero. The total gravity pressure drop between the inlet and outlet of the U-tubes with normal flow is the algebraic sum of the gravity pressure drops on the upflow and downflow sides of the U-tubes. It is negative, as plotted in the fourth quadrant of Fig. 2. Since the absolute value of $\Delta P_{g,n,down}$ is not the same as $\Delta P_{g,n,up}$ while assuming the normal flow rate to be zero, the total gravity pressure drop in the U-tubes with normal flow $\Delta P_{g,n}$ is not equal to zero at zero normal flow rate. It is possible to neglect the acceleration pressure drop of fluid flow in the U-tubes because compared with the frictional pressure drop in the tubes, it is small enough. By adding up the frictional pressure drop and the total gravity pressure drop of normal flow in the U-tubes, the total pressure drop of normal flow in the U-tubes, $\Delta P_n = P_{in} - P_{ex}$, is obtained. It can be found from Fig. 2 that at certain low positive flow rates, the gravity head outweighs the frictional pressure drop in the U-tubes and the static pressure in the outlet plenum is higher than that in the inlet plenum. This means that when a PWR with an inverted U-tube steam generator operates under natural circulation conditions, it can be considered to be regular that in a certain primary-side low flow range, the pressure difference between the inlet and outlet plenums of the steam generator is negative. However, the negative pressure difference between the inlet and outlet plenums can induce reverse flow in other parallel U-tubes.

Now the characteristic curve of reverse flow in the U-tubes can be constructed in Fig. 2. The curve of frictional pressure drop of reverse flow in the U-tubes, $\Delta P_{f,r}$, is located in the third quadrant of Fig. 2. The gravitational pressure drops of reverse flow on the upflow side of the U-tubes from the outlet plenum to the top of the U-bend and the downflow side of the U-tubes from the top of the U-bend to the inlet plenum are negative and positive, respectively. The gravitational pressure drops of reverse flow on the upflow and downflow sides of the U-tubes, $\Delta P_{g,r,up}$ and $\Delta P_{g,r,down}$, are respectively plotted in the third and second quadrants of Fig. 2. Because for a wide reverse flow range the fluid temperature of reverse flow is not in equilibrium with the secondary-side fluid temperature and is still somewhat higher than that of secondary-side flow, the absolute values of $\Delta P_{g,r,up}$ and $\Delta P_{g,r,down}$ are smaller than the static pressure drop $\rho_{pri,Ts}gh$. However, since the reverse flow fluid temperature is almost in equilibrium with the secondary-side fluid temperature, the gravitational pressure drops of reverse flow on the upflow and downflow sides of the U-tubes rapidly approximate to the static pressure drops $-\rho_{pri,Ts}gh$ and $\rho_{pri,Ts}gh$, respectively. Since the fluid temperature at the inlet of U-tubes with reverse flow is given and remains constant and the fluid temperature at the outlet of U-tubes with reverse flow can be considered to be equal to the secondary fluid temperature, for the same reason as the estimation of $\Delta P_{g,n,up}$ and $\Delta P_{g,n,down}$, the absolute value of $\Delta P_{g,r,up}$ is not the same as $\Delta P_{g,r,down}$ while assuming the reverse flow rate to be zero. The total gravity pressure drop between the inlet and outlet of the U-tubes with reverse flow is the algebraic sum of the gravity pressure drops on the upflow and downflow sides of the U-tubes. It is positive but rapidly approximates to zero, as plotted in the second quadrant of Fig. 2. For the same reason as the evaluation of $\Delta P_{g,n}$, the total gravity pressure drop in the U-tubes with reverse flow $\Delta P_{g,r}$ is not equal to zero under the condition of reverse flow rate becoming zero. It is also possible to neglect the acceleration pressure drop of reverse flow in the U-tubes. By adding up the frictional pressure and total gravity pressure drops of reverse flow in the U-tubes, the total pressure drop of reverse flow in the U-tubes, $\Delta P_r = P_{in} - P_{ex}$, is plotted. As indicated in Fig. 2, the total gravity pressure drop of reverse flow is very small and the total pressure drop of reverse flow in the U-tubes is almost equal to the frictional pressure drop. It can be found from Fig. 2 that at a certain negative pressure difference between the inlet and outlet plenums, normal and reverse flows can simultaneously exist in the parallel U-tubes. The total mass flow rate of normal flow minus that of reverse flow becomes the net primary circuit mass flow rate. It can be pointed out that in order to draw Fig. 2 to analyze the mechanism of reverse flow, if the mass flow rates of normal and reverse flows in the U-tubes of SG are assumed to be zero, due to the influence of the gravity pressure drops of normal and reverse flows in the U-tubes, the total pressure drops of normal and reverse flows in the U-tubes, ΔP_n and ΔP_r, are not continuous or connected with each other under the condition of the mass flow rate becoming zero. However, for a U-tube SG as shown in Fig. 1 and the given steady-state operating conditions described above, a net primary circuit flow exists in the system of PWR. Because the normal flow rate is the net primary circuit flow rate plus reverse flow rate, the normal flow rate must be greater than zero. On the other hand, according to the analysis results described above, reverse flow indeed occurs in the U-tubes of SG and the reverse flow rate must also be greater than zero. This means that for a real U-tube SG operating under the given steady-state operating conditions described above, the mass flow rates of normal and reverse flows cannot exactly become zero.

Based on the analysis mentioned above, it can be further analyzed whether reverse flow may preferentially occur in shorter or longer U-tubes for a given natural circulation condition. Considering that the total pressure drop of reverse flow in the U-tubes is almost equal to the frictional pressure drop, the frictional pressure drop of reverse flow can be taken as the total pressure drop of reverse flow in the U-tubes. Referring to the frictional pressure drop of normal flow in the U-tubes as shown in **Fig. 3** and neglecting the influence of fluid density on the frictional pressure drop of both normal and reverse flows, the total pressure drop of reverse flow in the U-tubes with the same length as the U-tubes of normal flow, ΔP_{r0}, can be plotted. The curve of ΔP_{r0} and the curve of the frictional pressure drop of normal flow, $\Delta P_{f,n}$ are symmetrical near the origin of the coordinate, as shown in Fig. 3. The curves of the total pressure drop of reverse flow in the U-tubes with their lengths being shorter and longer than those of the U-tubes of normal flow, ΔP_{r1} and ΔP_{r2}, are respectively located on the left and right sides of the ΔP_{r0} curve, because for the same reverse flow rate, the total pressure drops in the shorter and longer U-tubes are respectively less and greater than those in the U-tubes with the same length as the U-tubes of normal flow. It is clear that when normal and reverse flows simultaneously exist in parallel U-tubes under natural circulation condition, the pressure difference between the inlet and outlet plenums of steam generator should be negative. In addition, the total mass flow rate of normal flow in the U-tubes must be greater than that of reverse flow in the U-tubes because the total mass flow rate of normal flow in the U-tubes is the net primary circuit flow rate plus the total reverse flow rate. It can be found from Fig. 3 that to meet these conditions of occurrence of reverse flow in the parallel U-tubes, reverse flow should preferentially occur in longer U-tubes. Feng and Yang[13] experimentally studied the flow behavior in vertical tubes of a steam boiler connected in parallel. They found that according to the results of pretest calculation, some tubes would simultaneously confirm the conditions for normal and reverse flows to take place; thus, in practice, the tube operating with reverse flow could only be determined from its history. This means that if the tube flowed in the backward direction at the start-up of the boiler, it would flow in the backward direction, otherwise, in the forward direction.

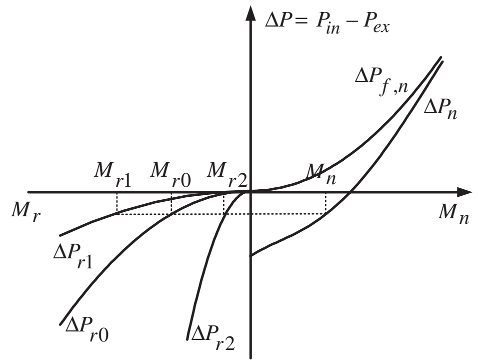

Fig. 3 Preferential occurrence of reverse flow in longer U-tubes

Based on Fig. 2, the mathematical model can be established to predict the flow behavior including reverse flow in inverted U-tubes of steam generators under natural circulation condition.

III. Mathematical Model and Solution Method

In fact, to establish the mathematical model for predicting the flow behavior in inverted U-tubes of steam generators under natural circulation condition is to formulate the model for describing the full-range characteristic curve of U-tubes for given boundary conditions of steam generators, as shown in Fig. 2. Since there are a great number of U-tubes with different geometries in a steam generator and normal and reverse flows can take place in a variety of U-tubes, in order to predict in which U-tubes and at what mass flow rates normal and reverse flows occur in individual U-tubes of the steam generator, it is first necessary to establish the mathematical model for describing the characteristic curves of normal and reverse flows in individual U-tubes. Based on the characteristic curves of normal and reverse flows in individual U-tubes, the characteristic curves of normal and reverse flows in parallel U-tubes can then be obtained. The solution can be found from the full-range characteristic curves of normal and reverse flows in parallel U-tubes on the same coordinate for the given boundary conditions of the steam generator, as illustrated in Fig. 2. In practice, all the solution procedures are performed by numerical calculation.

Concerning the boundary conditions of the steam generator for the analysis of reverse flow in the U-tubes, as shown in Fig. 1, when the primary circuit of a PWR operates under steady-state single-phase liquid natural circulation condition, the static pressures in both the primary and secondary sides, the secondary fluid temperature, the core heating power and the temperature of the fluid from the outlet plenum to the cold leg are all known. This study focuses on the analysis of reverse flow in the U-tubes of a steam generator. To perform the analysis of reverse flow in the U-tubes of a steam generator, the net primary circuit mass flow rate, the pressure difference between the inlet and outlet plenums, and the temperature of the fluid in the hot leg must also be known as the boundary conditions of the steam generator. In fact, if the mathematical model for predicting the reverse flow in the U-tubes of a steam generator is developed, by simultaneously calculating the flow behavior in the whole primary circuit consisting of the steam generator and other parts of the primary circuit as indicated in Fig. 1, the net primary circuit mass flow rate, the pressure difference between the inlet and outlet plenums and the fluid temperature in the hot leg for the given PWR can be all determined to provide the boundary conditions of the steam generator considered.

1. Normal Flow in Individual U-Tubes

To obtain the characteristic curves of normal and reverse flows in individual U-tubes, the number of U-tubes with reverse flow and the distribution of U-tubes with reverse flow in the steam generator should first be assumed. Correspondingly, the number and distribution of U-tubes in which fluid flows in the normal direction are determined. Further assuming the total mass flow rate of reverse flow in U-tubes, M_r, and knowing the net primary circuit mass flow rate M_c, the total mass flow rate of normal flow in U-tubes, M_n, is given by

$$M_n = M_r + M_c. \tag{1}$$

Referring to the total mass flow rate of normal flow, giving a series of normal flow rates for each U-tube to calculate the corresponding total pressure drops between the

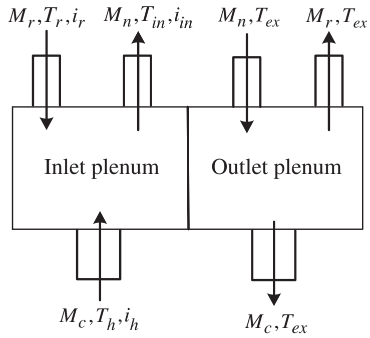

Fig. 4 Mass and energy balances of water in inlet plenum

inlet and outlet of this tube by using the following steady-state momentum equation, the characteristic curve of normal flow in each U-tube is obtained.

$$\Delta P = P_{in} - P_{ex} = \Delta P_g + \Delta P_f \tag{2}$$

In Eq. (2), the acceleration term has been neglected. The total gravitational pressure drop and the frictional pressure drop including the pressure drop due to the local resistance of normal flow in the U-tube, ΔP_g and ΔP_f, in Eq. (2) are calculated by

$$\Delta P_g = \int_{in}^{top} \rho(h) g dh - \int_{top}^{ex} \rho(h) g dh, \tag{3}$$

$$\Delta P_f = \int_{in}^{ex} \frac{\lambda}{d_i} \frac{G^2}{2\rho(l)} dl + \xi_{in} \frac{G^2}{2\rho(l_{in})} + \xi_{ex} \frac{G^2}{2\rho(l_{ex})} + \xi_{bend} \frac{G^2}{2\rho(l_{bend})}, \tag{4}$$

where ξ_{in}, ξ_{ex}, and ξ_{bend} are the coefficient of local resistance of the inlet of the U-tube, the exit of the U-tube, and the U-bend, respectively.

In order to use Eqs. (2)–(4) to calculate the pressure drops, the enthalpy of the fluid at the inlet of the U-tube and the fluid temperature distribution properties along each U-tube, such as the fluid temperature at the top of the U-bend, should be determined. Assuming that the reverse flow of water mixes totally with the flow from the hot leg in the SG inlet plenum, the enthalpy of the fluid at the inlet of the U-tube, i_{in}, is calculated by the equation of energy balance of water in the inlet plenum as

$$M_n i_{in} = M_r i_r + M_c i_h, \tag{5}$$

where i_r and i_h indicate the enthalpy of the fluid at the outlet of the U-tubes with reverse flow and the enthalpy of the fluid from the hot leg, respectively, as shown in **Fig. 4**. As mentioned above, the enthalpy of the fluid at the outlet, i_r, can be evaluated with the temperature of the fluid at the outlet of the U-tubes with reverse flow being equal to the secondary fluid temperature. The fluid temperature distribution along each U-tube can be evaluated by heat transfer through the tube. The heat quantity transferred from the primary water to the secondary fluid through each U-tube is given by

$$Q = \int_H K \Delta T dH. \tag{6}$$

The heat quantity Q in Eq. (6) can be determined by the heat balance of the fluid in the U-tube as

$$Q = M(i_{in} - i_{ex}), \tag{7}$$

where M is the mass flow rate in this U-tube and i_{ex} is the known enthalpy of the fluid at the outlet of the U-tube. The overall heat transfer coefficient K in Eq. (6) is determined as

$$K = \frac{1}{\frac{1}{\alpha_i}\frac{d_o}{d_i} + \frac{d_o}{2k_w}\ln\frac{d_o}{d_i} + \frac{1}{\alpha_o}}. \tag{8}$$

The convective heat transfer coefficient inside the U-tube, α_i, can be calculated from the correlation suggested by Kays and Perkins,[14)] and the correlation of Gnielinski[15)] for different primary side flow Reynolds numbers as

$$Nu_i = 3.656 \quad \text{for} \quad Re_i < 2300, \tag{9}$$

$$Nu_i = \frac{(Re_i - 1000)\cdot Pr \cdot \frac{f}{2}}{1.0 + 12.7(Pr^{\frac{2}{3}} - 1)\cdot\left(\frac{f}{2}\right)^{0.5}}$$

$$\text{for} \quad 2300 \le Re_i \le 5 \times 10^6, \tag{10}$$

where $f = (1.58 \ln Re_i - 3.28)^{-2}$. In Eqs. (8)–(10), the fluid properties, such as density and thermal conductivity, are given as functions of fluid temperature. Assuming that saturated boiling occurs at the outer surface of the U-tube, the boiling heat transfer coefficient at the outer surface of the U-tube, α_o, in Eq. (8) can be computed from the relationship suggested by Feng *et al.*[16)] as

$$\alpha_o = 0.1046 \frac{P_s^{0.314} q_o^{0.7}}{[\sigma_s g(\rho_{f,s} - \rho_{g,s})]^{0.157}}, \tag{11}$$

where q_o is the heat flux at the outer surface of the U-tube. In Eq. (11), the fluid properties are evaluated at the saturation temperature of secondary fluid.

For the assumed total mass flow rate of normal flow and the U-tubes with normal flow, giving a series of mass flow rates, the characteristic curve of normal flow in each U-tube, just like that shown in Fig. 2 if the mass flow rate in Fig. 2 is referred to as that in each U-tube, can be calculated by using the equations described above.

2. Reverse Flow in Individual U-Tubes

The mathematical model and calculation method for obtaining the characteristic curve of reverse flow in individual U-tubes are almost the same as those of normal flow in individual U-tubes except the following two respects. Reverse flow occurs in the U-tubes with water flowing from the outlet plenum to the inlet plenum. In addition, as mentioned previously, because the fluid temperature in the U-tubes with reverse flow becomes uniform and in equilibrium with the secondary-side fluid temperature, the fluid temperature at the outlet of the U-tubes with reverse flow is taken as the secondary-side fluid temperature. Similarly, for the assumed total mss flow rate of reverse flow and the U-tubes with reverse flow, giving a series of mass flow rates, the characteristic curve of reverse flow in each U-tube, just like that shown in Fig. 2, if the mass flow rate in Fig. 2 is regarded as that in each U-tube, can be obtained.

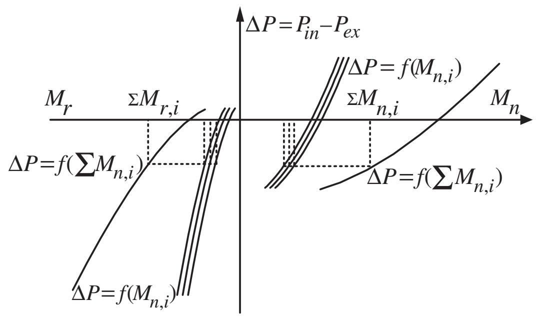

Fig. 5 Method of obtaining the characteristic curve of U-tubes connected in parallel

3. Normal and Reverse Flows in U-Tubes Connected in Parallel

Since all the U-tubes of the steam generator are connected to the same inlet and outlet plenums, they experience the same pressure drop between the inlet and outlet plenums. The characteristic curves of the U-tubes connected in parallel with normal and reverse flows can be determined as the resultant characteristic curves of normal and reverse flows in individual U-tubes, to sum up the flow quantities of the individual U-tubes in parallel at the same pressure difference, as shown in **Fig. 5**.

The solutions of the total mass flow rates of normal and reverse flows, the mass flow rate in each U-tube, the tubes in which normal and reverse flows occur, and their distribution in the steam generator can be found from the characteristic curves of the U-tubes connected in parallel with normal and reverse flows for the given net primary circuit mass flow rate and the known pressure difference between the inlet and outlet plenums, as illustrated in Fig. 2. This means that, if both the calculated pressure drops between the inlet and outlet of the parallel U-tubes with normal and reverse flows are equal to the known pressure difference between the inlet and outlet plenums for the assumed total mass flow rates of normal and reverse flows under the given boundary conditions of the steam generator, the assumed total mass flow rates of normal and reverse flows are just the solutions, as indicated in Fig. 2. After the total mass flow rates of normal and reverse flows are obtained, the mass flow rates of normal and reverse flows in each U-tube can be determined once again from the characteristic curves of the U-tubes, as illustrated in Fig. 5, to distribute the obtained total mass flow rates to individual U-tubes at the same pressure difference between the inlet and outlet plenums on the characteristic curves of the parallel and individual U-tubes.

The solution procedure is as follows.

(1) For the given boundary conditions of the steam generator considered, assume the number of U-tubes with reverse flow and select the longer U-tubes as those in which reverse flow occurs. The number of U-tubes with normal flow and their distribution in the steam generator are correspondingly determined.

(2) Assume the total mass flow rate of reverse flow in the parallel U-tubes. The total mass flow rate of normal flow in the U-tubes is then obtained.

(3) Referring to the total mass flow rate of normal flow in the U-tubes, giving a series of mass flow rates for each U-tube with normal flow, calculate the characteristic curve of normal flow in each U-tube, just like that shown in Fig. 2.

(4) Determine the characteristic curve of normal flow in the U-tubes connected in parallel from the resultant characteristic curves of the individual U-tubes with normal flow, as shown in Fig. 5. Then using the assumed total mass flow rate of normal flow in the U-tubes, obtain the pressure drop between the inlet and outlet of the U-tubes with normal flow from the characteristic curve of normal flow in the U-tubes connected in parallel, as illustrated in Fig. 2.

(5) Compare the pressure drop between the inlet and outlet of the parallel U-tubes with normal flow obtained from step (4) with the known pressure difference between the inlet and outlet plenums. If they are equal, go to the next step, otherwise, return to step (2).

(6) Referring to the total mass flow rate of reverse flow in the U-tubes, giving a series of mass flow rates for each U-tube with reverse flow, calculate the characteristic curve of reverse flow in each U-tube, just like that shown in Fig. 2.

(7) Determine the characteristic curve of reverse flow in the U-tubes connected in parallel from the resultant characteristic curves of the individual U-tubes with reverse flow, as shown in Fig. 5. Then using the assumed total mass flow rate of reverse flow in the U-tubes, determine the pressure drop between the inlet and outlet of the U-tubes with reverse flow from the characteristic curve of reverse flow in the U-tubes connected in parallel, as illustrated in Fig. 2.

(8) Compare the pressure drop between the inlet and outlet of the parallel U-tubes with reverse flow obtained from step (7) with the known pressure difference between the inlet and outlet plenums. If they are equal, go to the next step, otherwise, return to step (1).

(9) Calculate the mass flow rates of normal and reverse flows in the individual U-tubes from the characteristic curves of the U-tubes, to distribute the obtained total mass flow rates of normal and reverse flows to the individual U-tubes at the same pressure difference between the inlet and outlet plenums on the characteristic curves of the parallel and individual U-tubes, as illustrated in Fig. 5.

IV. Calculation Results and Comparison with Experimental Data

The mathematical model and the solution method described above have been used to analyze the reverse flow in an inverted U-tube steam generator of a PWR simulator operated under natural circulation condition. The schematic of the steam generator, as well as the test loop, is just like that shown in Fig. 1, as reported by Wang *et al.*[10] The steam generator contains 47 inverted U-tubes having nine different heights and thirteen different lengths. In the steady-state single-phase liquid natural circulation experiments carried out on this test loop, the static pressures in both the primary and secondary sides, the core heating power, the net primary circuit mass flow rate, the secondary fluid temperature, the temperatures of both the fluids from the hot leg to the inlet plenum and from the outlet plenum to the cold leg, the pressure difference between the inlet and outlet plenums, that is, the pressure drop between the inlet and outlet of the U-tubes, were all measured. The evidence of the occurrence of reverse flow in the U-tubes, such as the sharp drop of fluid temperature from the hot leg to the inlet of the U-tubes in the inlet plenum of the steam generator, was observed in the experiments.

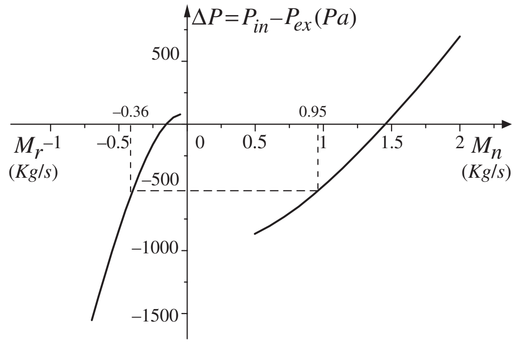

Fig. 6 Calculated natural circulation flow rates in U-tubes

A typical calculated result for the reverse flow behavior in the parallel U-tubes of the steam generator operated under natural circulation condition is shown in **Fig. 6**. In this case, the static pressures in the primary and secondary sides are 13 and 1.90 MPa, respectively. The net primary circuit mass flow rate is 0.59 kg/s. The temperatures of the fluids from the hot leg to the inlet plenum and from the outlet plenum to the cold leg are 567.9 and 488.2 K, respectively. The pressure difference between the inlet and outlet plenums of the steam generator is −510 Pa. These data were all measured from the experiment. It can be found from Fig. 6 that when the net primary circuit mass flow rate is 0.59 kg/s and the pressure difference between the inlet and outlet plenums of the steam generator is −510 Pa, the calculated total mass flow rate in the U-tubes with normal flow is 0.95 kg/s, and the total mass flow rate in the U-tubes with reverse flow is 0.36 kg/s. The calculation results show that at this time reverse flow occurs in 11 long U-tubes. The mass flow rates in each U-tube with normal flow and in each U-tube with reverse flow are all obtained from the calculation results. Because reverse flow mixes with the hot leg flow in the inlet plenum, the fluid temperature in the inlet plenum drops to 32.6 K from the fluid temperature in the hot leg, which agrees very well with the experimental data of 35.5 K. The temperature drop of the primary-side fluid in the inlet plenum due to heat transfer in the SG plenum across the plenum divider plate and the tubesheet into the secondary fluid has been evaluated. It is found that the temperature drop in the inlet plenum due to heat transfer in the plenum is less than 1 K, which can be neglected. This indicates that the mathematical model and the solution method developed in this study can be used to correctly predict the reverse flow in the inverted U-tubes of the steam generator with natural circulation.

In order to investigate the influence of reverse flow in the inverted U-tubes on the natural circulation flow in the primary circuit of the loop, by assuming that the fluid flow in all the U-tubes of the steam generator was in the normal direction, the mass flow rate of natural circulation in the whole primary circuit of the test loop was evaluated. The calculation results show that for the same system operating conditions as those given in the analysis to obtain Fig. 6, the positive pressure difference between the outlet and inlet plenums is 1455 Pa, which is much greater than that obtained from the experiment. The mass flow rate in the primary circuit reaches 0.75 kg/s, which is 27% higher than the experimentally obtained net mass flow rate in the primary circuit with reverse flow existing in the steam generator, 0.59 kg/s. This indicates that in the analysis of natural circulation characteristics in the inverted U-tubes of the steam generator, reverse flow occurring in the U-tubes must be taken into consideration. If a one-dimensional flow model without reverse flow existing in the U-tubes or a one-U-tube steam generator model with all the U-tubes being lumped into one equivalent tube is used for the calculation of natural circulation flow in the parallel U-tubes, the overall loop mass flow rate will significantly be overpredicted.

V. Conclusion

Experimental investigations available show that reverse flow could occur in some inverted U-tubes of steam generators under natural circulation conditions, which would greatly reduce the overall mass flow rate in the primary circuit of PWR. In this study, the analysis of reverse flow in inverted U-tubes of steam generators operated under natural circulation condition is performed. The mechanism of single-phase liquid reverse flow in the parallel U-tubes during natural circulation is graphically analyzed by using the full-range characteristic curve of U-tubes. The mathematical model and the solution technique for simulating the natural circulation reverse flow behavior in the U-tubes connected in parallel are developed. The reverse flow in the inverted U-tube steam generator of a PWR simulator with natural circulation is analyzed. The analysis results show that reverse flow indeed occurs in some inverted U-tubes of the steam generator. Through the calculation, the distribution of the U-tubes with reverse flow in the steam generator and the mass flow rates of normal and reverse flows in the U-tubes are obtained. The predicted sharp drop of the fluid temperature from the hot leg to the U-tube inlet in the inlet plenum of the steam generator due to reverse flow agrees very well with the experimental data. This indicates that the mathematical model and the solution method developed can be used to correctly predict the reverse flow occurring in the inverted U-tubes of the steam generator of PWR with natural circulation.

The mathematical model without reverse flow occurring in the U-tubes is used in the prediction of natural circulation flow in the whole primary circuit of the test loop to investigate the influence of reverse flow in the U-tubes on the overall loop mass flow rate. The calculated results show that in this case, the loop mass flow rate is significantly overpredicted. This indicates that in the analysis of natural circulation in the inverted U-tubes of the steam generator of PWR, reverse flow in the U-tubes must be taken into account.

Nomenclature

D: Diameter of U-tube (m)
f: Friction factor (—)
G: Mass flux (kg/m^2s)
g: Gravitational acceleration (m/s^2)
H: Outer surface area of U-tube (m^2)
h: Height of U-tube (m)
i: Enthalpy (J/kg)
K: Overall heat transfer coefficient (W/m^2K)
k: Thermal conductivity (W/mK)
l: Length of U-tube (m)
M: Mass flow rate (kg/s)
Nu: Nusselt number (—)
Pr: Prandtl number (—)
P: Pressure (Pa)
Q: Heat quantity (W)
q: Heat flux at outer surface of U-tube (W/m^2)
Re: Reynolds number (—)
T: Temperature (K)
α: Heat transfer coefficient (W/m^2K)
ΔP: Pressure drop (Pa)
ΔT: Mean temperature difference (K)
ξ: Coefficient of local resistance (—)
λ: Coefficient of frictional flow resistance (—)
ρ: Density (kg/m^3)
σ: Surface tension (N/m)

(Subscript)
c: Net primary circuit flow
ex: Outlet
f: Friction, liquid
g: Gravity, steam
h: Hot leg
i: Inner, individual U-tube
in: Inlet
n: Normal flow
o: Outer
pri: Primary side
r: Reverse flow
s: Secondary side
top: Top of U-bend
w: tube wall

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