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Tube Inlet Orifice Design of a Once-Through Steam Generator Considering Various Operating Conditions

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1. Introduction

An integral-type pressurized water reactor employs once-through steam generators (OTSGs) owing to its advantages in compactness and simplicity of the flow path arrangements [1]. Figure 1 shows the exterior view of a OTSG using helically coiled tubes as considered in this study. In general, the OTSG operates under counter flow conditions. The primary coolant flows down across the helically coiled tube bundle, and the secondary feedwater flows up through the helically coiled tubes. The primary coolant flows outside the tubes and releases thermal energy into the secondary side to produce steam. The secondary feedwater inside the tube absorbs heat from the primary coolant and changes to superheated steam.

Such a phase change of the secondary feedwater brings forth density-wave oscillations, which lead to flow oscillations. These take place as a result of phase lag and feedback among flow rate, pressure drop, and phase-change processes. Increasing the system pressure, and increasing the inlet hydraulic resistance in particular, are stabilizing, whereas increasing the outlet hydraulic resistance and increasing the pressure loss in the two-phase flow region are destabilizing [2]. Therefore, it is necessary to install an orifice inside the tube at the entrance region for flow stabilization because such density-wave oscillations are suppressed by the strong stabilizing effect of the added single-phase resistance.

In the tube inlet orifice design, tube plugging and low power operation should be considered because the orifice design condition is affected by the tube number and OTSG power level. Thus, this paper aims to investigate how to design the tube inlet orifice considering the tube plugging and OTSG power level.

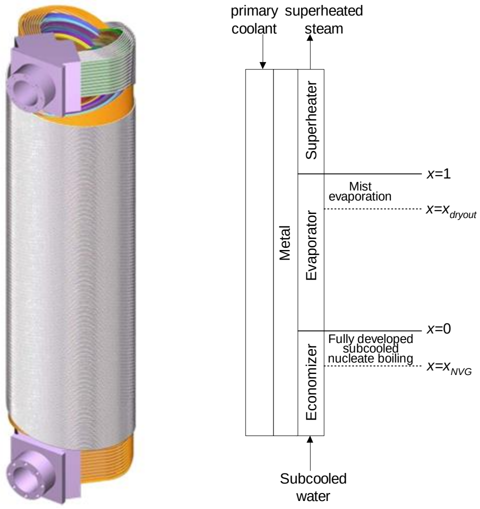

Fig. 1. Exterior view of the helically coiled tube OTSG and heat transfer regions in a characteristic tube [1].

2. Analysis Method

To evaluate the thermal-hydraulic performance of such a helically coiled tube OTSG, a well-established numerical code, ONCESG, is used. The ONCESG code was developed at the Korea Atomic Energy Research Institute (KAERI) for a thermal-hydraulic design and performance analysis of a OTSG using helically coiled tubes [1]. In the ONCESG code, the OTSG is represented by one characteristic tube as schematically displayed in Fig. 1. The characteristic tube is divided into three major heat transfer regions, i.e., economizer, evaporator, and superheater regions, according to the water-steam mixture state inside the characteristic tube. In the present simulation, the friction factors and heat transfer coefficients are calculated using SKBK correlations for both the tube side and shell side of the helical tubes.

Consider a screw-type tube inlet orifice, as sketched in Fig. 2. The orifice has a narrow spiral flow channel that provides high flow resistance. To determine the orifice size, it is useful to introduce the hydraulic resistance ratio which indicates a measure of the pressure drop in the orifice and the subcooled region in

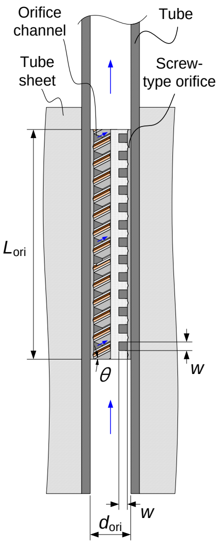

Fig. 2. Configuration of the screw-type tube inlet orifice.

comparison to the pressure drop in the two-phase and superheated regions

$$\kappa = \left(\Delta P_{\mathrm{ori}} + \Delta P_{\mathrm{sub}}\right) \big/ \left(\Delta P_{\mathrm{two}} + \Delta P_{\mathrm{sup}}\right). \qquad (1)$$

In Reference 3, a criterion for suppression of the flow rate fluctuation amplitude within an allowable level was suggested as follows:

$$\kappa \geq \kappa_{\mathrm{min}}. \qquad (2)$$

Here, the minimum hydraulic resistance ratio of $\kappa_{\mathrm{min}} = 1.92$ is applied to the proposed design of the OTSG secondary side tube inlet orifice [3]. The pressure drop through the orifice can be expressed in terms of the orifice loss coefficient K_{ori}, feedwater density at the orifice exit ρ_{e}, and the tube cross-sectional average velocity at the orifice exit v_{e}:

$$\Delta P_{\mathrm{ori}} = 0.5 K_{\mathrm{ori}} \rho_{\mathrm{e}} v_{\mathrm{e}}^{2}. \qquad (3)$$

Combining Eqs. (1), (2), and (3) gives the orifice loss coefficient criterion for flow stabilization as follows:

$$K_{\mathrm{ori}} \geq K_{\mathrm{ori\_min}}, \qquad (4)$$

where

$$K_{\mathrm{ori\_min}} = 2\left[\kappa_{\mathrm{min}}\left(\Delta P_{\mathrm{two}} + \Delta P_{\mathrm{sup}}\right) - \Delta P_{\mathrm{sub}}\right] \big/ \left(\rho_{\mathrm{e}} v_{\mathrm{e}}^{2}\right). \qquad (5)$$

Here, $K_{\mathrm{ori\_min}}$ is the minimum orifice loss coefficient for suppression of the flow oscillation below the allowable level.

Introducing the orifice pressure drop and geometry formulas gives an orifice length criterion for flow stabilization as follows:

$$L_{\mathrm{ori}} \geq L_{\mathrm{ori\_min}}, \qquad (6)$$

where

$$L_{\mathrm{ori\_min}} = \frac{K_{\mathrm{ori\_min}} \rho_{\mathrm{e}} v_{\mathrm{e}}^{2} - K_{\mathrm{i}} \rho_{\mathrm{i}} v_{\mathrm{c\_1}}^{2} - K_{\mathrm{e}} \rho_{\mathrm{c\_2}} v_{\mathrm{c\_2}}^{2}}{\left[f/w + 0.1\big/\left(\pi D_{\mathrm{avg}}\right)\right] \rho_{\mathrm{c\_1}} v_{\mathrm{c\_1}}^{2}} \sin\theta. \qquad (7)$$

Here, $L_{\mathrm{ori\_min}}$ is the minimum orifice length for suppression of flow oscillation below the allowable level, w is the orifice channel width, θ is the incline angle of the orifice channel, and v_{c} is the cross-sectional average velocity in the orifice channel. The subscripts 1 and 2 denote the beginning and end of the orifice channel, respectively. The inlet loss coefficients K_{i} and exit loss coefficient K_{e} are [4]

$$K_{\mathrm{i}} = 0.5\left(1 - 4w^{2}/\pi d_{\mathrm{ori}}^{2}\right)^{3/4}, \qquad (8)$$

$$K_{\mathrm{e}} = \left(1 - 4w^{2}/\pi d_{\mathrm{ori}}^{2}\right)^{2}, \qquad (9)$$

and friction factor f and average coiling diameter D_{avg} are [5]

$$f = 0.11\left(68/\mathrm{Re} + \delta/w\right)^{0.25}, \qquad (10)$$

$$D_{\mathrm{avg}} = d_{\mathrm{ori}} - w. \qquad (11)$$

Here, d_{ori} is the orifice diameter, Re is the Reynolds number based on the orifice channel width w, and δ is the surface roughness on the orifice channel.

In the present study, the design data of the MRX OTSG (JAERI-developed integral reactor) [1] is used and the orifice length is calculated at various power levels and tube plugging conditions. The power level ranges from 20% to 100% and the tube plugging condition is divided into five steps as defined in Table 1. The orifice design parameter ranges are 2.0 mm ≤ w ≤ 3.0 mm, 10° ≤ θ ≤ 12°, δ = 0.01 mm, and d_{ori} = 14.8 mm, and the orifice diameter of d_{ori} = 14.8 mm is equal to the tube inner diameter.

3. Results and Discussion

The required average tube length of the helically coiled tube OTSG for transferring a constant thermal power is listed in Table 2 according to the tube plugging ratio. As expected, the average tube length increases with the tube plugging ratio to compensate for the reduced heat transfer area by tube plugging. Here, a helically coiled tube OTSG with an average tube length of 47.0 m is employed for the orifice length calculation considering the tube plugging ratio of 10.3%.

The secondary feedwater flow rate is adjusted to maintain a constant thermal power according to the tube plugging condition and it is almost proportional to the power level, as shown in Fig. 3. The minimum orifice length when the screw-type orifice has the channel geometry of w = 3.0 mm and θ = 12° is presented in Fig. 4. The minimum orifice length ranges from 183.3 mm to 198.9 mm for 100% power level, and from 285.1 mm to 288.0 mm for 20% power level. As expected, the low power level results in a higher minimum orifice length because the flow instability tends to be more severe at a low feedwater flow rate [3] and it accordingly brings forth a higher orifice loss coefficient, see Eq. (5). Thus,

Table 1. Tube plugging conditions.

Plugging condition	1	2	3	4	5
Plugging ratio [%]	0.0	2.6	5.2	7.7	10.3
Tube no. in use [ea]	388	378	368	358	348

Table 2. Required average tube length for constant thermal power (100 MW).

Plugging ratio [%]	0.0	2.6	5.2	7.7	10.3
Avg. tube length [m]	40.4	41.8	43.4	45.1	**47.0**

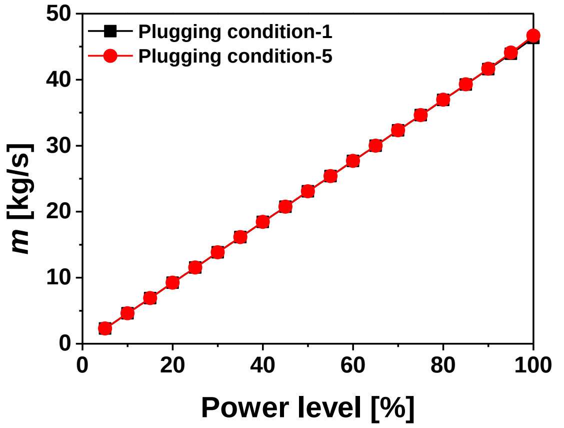

Fig. 3. Secondary feedwater flow rate versus the power level.

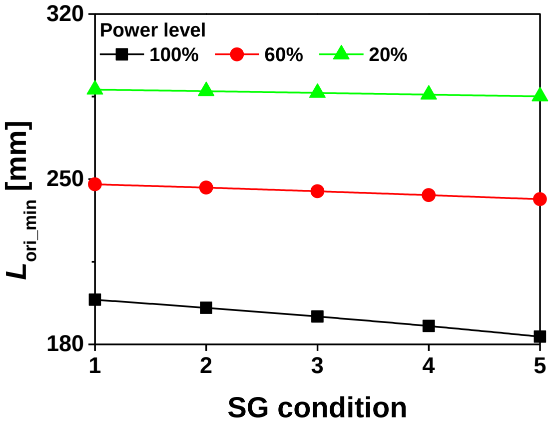

Fig. 4. Minimum orifice length according to the tube plugging condition (w = 3.0 mm and $\theta = 12^\circ$).

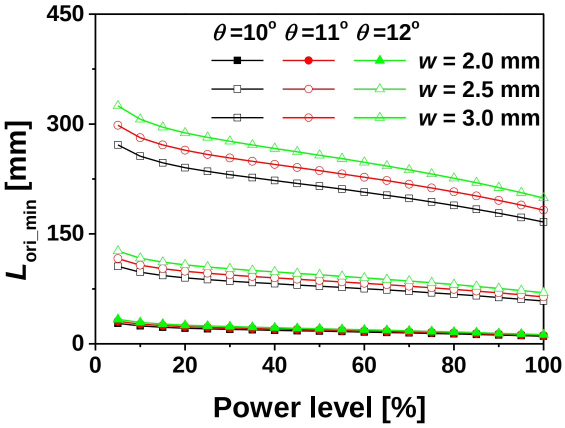

Fig. 5. Required minimum orifice length according to the power level.

the secondary feedwater flow rate for the minimum power level should be chosen as the orifice design condition, and this implies that the orifice length is determined by the lowest power level considered in the plant power operation.

A minimum orifice length of L_{ori_min} = 285.1 mm can be selected if the lowest power level is 20% and the tube plugging condition is 5 which means 40 tubes are plugged in. However, the OTSG can operate under 0% tube plugging condition, which requires a minimum orifice length of L_{ori_min} = 288.0 mm. The orifice length should be higher than the minimum orifice length, see Eq. (6), and thus the required minimum orifice length to limit the flow oscillations to below the allowable level regardless of the operating condition should be the highest one. This means the orifice length should be at least 288.0 mm (i.e., $L_{ori} \geq 288.0$ mm) to ensure the stable power operation in the power level of 20%−100%.

The required minimum orifice length at various power levels is presented in Fig. 5 according to the width and incline angle of the orifice channel. The minimum orifice length decreases with the thermal power, and thus the lowest power level gives the highest minimum orifice length. It is also noticeable that the minimum orifice length increases with the orifice channel incline angle θ. It is intuitively understandable that the orifice length should be increased to maintain the orifice channel flow length as the incline angle of the channel becomes steeper. An increase in the orifice channel width w results in a large increase of minimum orifice length by decreasing the inlet and exit loss coefficients and the flow resistance in the orifice core. To suppress the flow oscillation below the allowable level at the 5% power operation, the orifice length should be at least 325.0 mm (i.e., $L_{ori} \geq 325.0$ mm) when the orifice channel geometry is w = 3.0 mm and $\theta = 12^\circ$.

4. Conclusions

The screw-type tube inlet orifice length criterion of the OTSG secondary side for flow stabilization has been determined using ONCESG code. To investigate the effect of the tube plugging on the orifice length, the tube plugging condition is divided into five steps. The secondary feedwater flow rate is adjusted according to the tube plugging condition for a constant power operation. The required minimum orifice length is obtained and the results show that the lowest power level in the plant power operation with non-plugging condition provides a limiting case for the orifice length determination. The required minimum orifice length is increased by increasing the incline angle and width of the orifice channel. To ensure the stable operation in the power range of 5%−100%, the orifice length should be at least 325.0 mm (i.e., $L_{ori} \geq 325.0$ mm) for w = 3.0 mm and $\theta = 12^\circ$.

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