# TUBE INLET ORIFICE DESIGN OF A ONCE-

# THROUGH STEAM GENERATOR CONSIDERING

# OPERATION STRATEGIES

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**Abstract**

A numerical study is conducted for a thermal-hydraulic performance analysis and secondary side screw-type tube inlet orifice design of a once-through steam generator (OTSG). Various tube-plugging conditions and power levels are considered, and the secondary coolant inlet temperature is adjusted to maintain a constant level of thermal power. Comprehensive numerical solutions are acquired to evaluate the thermal-hydraulic performance and minimum orifice length of the OTSG under various operating conditions. The results obtained show that constant thermal power can be maintained by properly adjusting the secondary coolant inlet temperature with variation of the steam outlet superheat degree and secondary coolant pressure drop when the OTSG operates at a high power level. The lowest power level results in the highest minimum orifice length, and non-plugged condition practically limits the orifice length criterion. This OTSG performance and orifice length are compared with those when the secondary coolant flow rate or secondary coolant outlet pressure is controlled for constant thermal power operation. The secondary coolant outlet pressure control operation with the highest secondary coolant pressure provides the smallest tube inlet orifice. The orifice size is almost unchanged with respect to the constant thermal power operation strategy when the secondary coolant control parameter is the inlet temperature or flow rate because both schemes provide nearly identical secondary coolant pressures.

## INTRODUCTION

An integral-type pressurized water reactor employs OTSGs owing to their advantages of compactness and simplicity of the flow path arrangement [1]. Fig. 1a shows an exterior view of an OTSG of th type considered in this study, which uses helically coiled tubes. 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 outside the tubes releases thermal energy to the secondary side. The secondary feedwater inside the tubes absorbs heat from the primary coolant and changes to superheated steam.

 

*(a) (b)*

*FIG. 1. Helically coiled tube OTSG: (a) exterior view and (b) screw-type tube inlet orifice.*

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 the 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].

For this reason, a screw-type tube inlet orifice was introduced and a detailed orifice design was implemented for the marine reactor X (MRX, Japan Atomic Energy Research Institute-developed integral reactor) OTSG [3]. In Reference [3], the orifice length was evaluated when the secondary coolant outlet pressure was controlled to maintain constant thermal power of the OTSG. Reference [4] employed another operation strategy instead of a secondary coolant outlet pressure control approach. The secondary coolant flow rate was adjusted for constant thermal power operation and the corresponding orifice design results were compared with those in Reference [3]. In this paper, a different operation strategy of secondary coolant inlet temperature control is applied. The intention of this paper is to compare the orifice design results of these three different constant thermal power operation strategies. It is noted that the present study is an expanded and complemented study of References [3, 4].

## ANALYSIS METHOD

### OTSG performance

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 for thermal-hydraulic design and performance analyses of OTSGs using helically coiled tubes [1]. In the ONCESG code, the OTSG is represented by one characteristic tube that is divided into the subcooled, two-phase, and superheated regions according to the water-steam mixture state inside the characteristic tube. The governing equations, basic thermal-sizing equation, algorithm for locating the heat-transfer region boundaries, and overall solution method are delineated in Reference [1]. In the present simulations, the friction factors and heat transfer coefficients are calculated using the SKBK correlations for both the tube side and shell side of the helical tubes. The MRX OTSG design data [3] is used for comparison of the OTSG thermal-hydraulic performance and orifice design results with References [3, 4].

The thermal-hydraulic performance of the OTSG is investigated in terms of the secondary coolant outlet superheat degree and secondary coolant pressure drop. The power level ranges from 5% to 100% and the steam generator (SG) condition is divided into five steps according to the plugging ratio, as defined in Table 1. Here, SG condition-1 represents the initial stage of the OTSG operation without tube plugging, whereas SG condition-5 denotes the final stage when the OTSG experiences tube plugging of *α* = 10.3%. The average tube length of the OTSG is 47.0 m with 10.3% tube plugging ratio and 5% design uncertainty [3].

TABLE 1. STEAM GENERATOR CONDITIONS

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| SG condition | 1 | 2 | 3 | 4 | 5 |
| Plugging ratio, *α* [%] | 0.0 | 10.3 | 5.2 | 7.7 | 10.3 |
| No. of tubes, *N* [ea] | 388 | 378 | 368 | 358 | 348 |

### Tube inlet orifice

Consider a screw-type tube inlet orifice, as sketched in Fig. 1b. The orifice has a narrow spiral flow channel that provides high flow resistance. Introducing the minimum hydraulic resistance ratio, orifice pressure drop, and geometry formulas gave an orifice length criterion for flow stabilization as follows [3]:

  (1)

where

  (2)

  (3)

Here, *L*ori\_min and *K*ori\_min are the minimum orifice length and minimum orifice loss coefficient for suppression of the flow oscillation below the allowable level, respectively. A detailed derivation of the minimum orifice length is given in Reference [3]. In the present study, the orifice design parameter ranges of 2.0 mm ≤ *w* ≤ 3.0 mm, 10° ≤ *θ* ≤ 12°, δ = 0.01 mm, *d*ori = 14.8 mm; *κ*min = 1.92 [3-5] are applied, and the orifice length is calculated at various power levels and tube-plugging conditions for an orifice design comparison.

## Results and discussion

### OTSG performance

The constant thermal power operation strategies of the secondary coolant outlet pressure control or secondary coolant flow rate control were suggested because the thermal power of the OTSG was decreased by plugging the tubes [3, 4]. Here, instead of those operation methods, the secondary coolant inlet temperature is adjusted to maintain constant thermal power according to the SG condition.

The secondary coolant inlet temperature at various power levels is presented in Fig. 2 for SG condition-1 and SG condition-5 when the secondary coolant flow rate is determined proportionally according to the OTSG power and the secondary coolant outlet pressure is fixed regardless of the SG condition. The secondary coolant inlet temperature decreases with the power level. The reduction in the secondary coolant inlet temperature is more pronounced as the OTSG power increases, whereas it is almost unchanged at low power levels. The high power levels also result in an apparent difference in the secondary coolant inlet temperature according to the SG condition. On the other hand, these two different temperatures merge to almost the same value, as the OTSG power level dwindles. The variation of the other control parameters in References [3, 4] is also provided in Fig. 2 for comparison. The secondary coolant flow rate is almost unchanged with respect to the SG condition when the secondary coolant flow rate scheme is applied, and the secondary coolant outlet pressure control scheme shows a trend of control parameter variation similar to that of the secondary coolant inlet temperature control scheme.



*FIG. 2. Control parameter variation according to the power level.*

Secondary coolant inlet temperature curves for constant thermal power operation and the corresponding thermal-hydraulic performance curves are presented in Fig. 3 for the 100% and 20% power levels. It can be seen that the secondary coolant inlet temperature for constant-power operation dwindles as the SG condition worsens from SG condition-1 to SG condition-5 when the OTSG operates at the 100% power level. This indicates that gradual reduction of the secondary coolant inlet temperature is necessary for long-term constant-power operation. The outlet degree of superheat decreases with the change of the SG condition from 1 to 5 owing to the decrease in the secondary coolant inlet temperature. The secondary coolant pressure drop increases due to the increased flow resistance caused by tube plugging. This implies that a constant level of thermal power can be maintained by properly decreasing the secondary coolant inlet temperature at the expense of a lowered outlet degree of superheat and an increase in the secondary coolant pressure drop when the SG experiences tube plugging. However, the secondary coolant inlet temperature for constant-power operation is nearly constant when the OTSG power level is low, and this creates an almost unchanged outlet degree of superheat.



*FIG. 3. Control parameter curves for constant thermal power operation and corresponding performance curves.*

The other control parameter curves and corresponding performance curves [3, 4] are also presented in Fig. 3 for performance comparison. The SG condition-5 at the 100% power level shows the identical thermal-hydraulic performance regardless of the operation strategy (see Fig. 2), because it was chosen as the OTSG design condition [3]. The *T*in control operation allows a relatively high inlet temperature compared to the other operation strategies except when the OTSG operates at the 100% power level under the SG condition-5. The *m* control operation and *P*out control operation provide a relatively low flow rate and a relatively high outlet pressure, respectively.

### Tube inlet orifice

Fig. 4 shows the variation of the minimum orifice length *L*ori\_min according to the tube-plugging condition when the screw-type tube inlet orifice has a channel geometry of *w* = 3.0 mm and *θ* = 12°. The minimum orifice length ranges from 183.3 mm to 197.5 mm for 100% power level and from 283.5 mm to 286.5 mm for 20% power level when the secondary coolant inlet temperature control scheme is applied to the OTSG operation. 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 [5]; accordingly, this brings forth a higher orifice loss coefficient (see Equation (3)). Thus, the secondary coolant flow rate for the minimum power level should be chosen as the orifice design condition; this implies that the orifice length is determined by the lowest power level considered during power operation of the plant. Compared to the *T*in control approach, the secondary coolant flow rate control approach shows a similar *L*ori\_min range and the secondary coolant outlet pressure control scheme provides a much lower *L*ori\_min range.

Each power level has its own highest minimum orifice length at the non-plugged condition except the 100% power level of the *P*out control scheme because this operating condition yields the lowest secondary coolant flow rate per tube. A minimum orifice length of *L*ori\_min = 283.5 mm can be selected for the *T*in control scheme if the lowest power level is 20% and the SG condition is 5, which means 40 tubes are plugged. However, the OTSG can operate under a 0% tube-plugging condition, requiring a minimum orifice length of *L*ori\_min = 286.5 mm. The orifice length should be longer than the minimum orifice length (see Equation (1)); thus, the required minimum orifice length to limit the flow oscillations to below the allowable level regardless of the operating condition should be the longest one. This means that the orifice length should be at least 286.5 mm (i.e., *L*ori ≥ 286.5 mm) to ensure stable power operation at power levels of 20%-100% when the *T*in control method is applied to the OTSG operation.

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 the lowest power level consequently gives the longest 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*, by decreasing the inlet and exit loss coefficients and the flow resistance in the orifice core, results in a large increase of the minimum orifice length [3, 4]. To suppress the flow oscillation below the allowable level at 5% power operation, the orifice length should be at least 324.0 mm (i.e., *L*ori ≥ 324.0 mm) when the *T*in control operation is employed and the orifice channel geometry is *w* = 3.0 mm and *θ* = 12°. For the identical design conditions, the *m* control operation and *P*out control operation give the minimum orifice length criterion of *L*ori ≥ 325.0 mm [4] and *L*ori ≥ 266.2 mm [3], respectively.



*FIG. 4. Minimum orifice length according to the tube-plugging condition (w = 3.0 mm and θ = 12°)*

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*FIG. 5. Required minimum orifice length according to the power level.*

Fig. 6a illustrates the minimum orifice length and magnitude of each term in Equation (2), and Fig. 6b shows the minimum orifice loss coefficient and magnitude of each term in Equation (3) according to the secondary coolant control parameter when the OTSG power level is 5% under the non-plugged condition and when the orifice channel has the geometry of *w* = 3.0 mm and *θ* = 12°. The left columns show the orifice design results when the secondary coolant inlet temperature is controlled for constant thermal power operation, as in the present study, while the middle columns represent the orifice design results when the secondary coolant flow rate is controlled as in Reference [4]. The right columns are the orifice design results when the secondary coolant outlet pressure is controlled as in Reference [3].

The first term *K*ori\_min*ρ*e*v*e2, second term *K*i*ρ*i*v*c\_12, and third term *K*e*ρ*c\_2*v*c\_22 in the numerator of the right- hand side of Equation (2) are designated as Term-1, Term-2, and Term-3, respectively, in Fig. 6a. Term-4 is the denominator on the right-hand side of Equation (2). As indicated in Fig. 6a, the minimum orifice lengths for the *T*in control scheme and *m* control scheme are almost the same, and the *P*out control operation provides the lowest *L*ori\_min value. Term-1 shows the greatest variation between all terms and it acts positively to reduce the value of *L*ori\_min as the *P*out control applies to the OTSG operation instead of the *T*in control method or *m* control method, as decreasing Term-1 results in a decrease of *L*ori\_min (see Equation (2)). This means that Term-1 of *K*ori\_min*ρ*e*v*e2 plays an explicit role in reducing *L*ori\_min. As depicted in Fig. 6b, *ρ*e*v*e2 remains nearly identical regardless of the control parameter. Therefore, it is evident that *K*ori\_min is the key parameter to reduce Term-1.

 

*(a) (b)*

*FIG. 6. Comparison of the orifice design results according to the secondary coolant control parameter (Q = 5MW, w = 3.0 mm and θ = 12°): (a) minimum orifice length and (b) minimum orifice loss coefficient.*

The minimum orifice loss coefficient *K*ori\_min decreases with a decrease of the pressure drop in the two-phase and superheated regions and with an increase of the pressure drop in the subcooled region and an increase in *ρ*e*v*e2, as can be seen in Equation (3). Thus, it is clear from Fig. 6b that the variation of Δ*P*sup mainly affects how *K*ori\_min decreases as the constant thermal power operation strategy changes from *T*in control or *m* control to *P*out control. The *P*out control operation provides a relatively short superheated region and a higher secondary coolant density compared to the *T*in control operation or *m* control operation, as highlighted in Fig. 7. This results in a lower pressure drop despite the fact that the secondary coolant flow rate is not relatively low. The secondary coolant flow rate is 2.33 kg/s at the 5% power level for the *T*in control scheme and *P*out control scheme, which is determined proportionally according to the OTSG power, whereas it drops to 2.31 kg/s to maintain 5% thermal power for SG condition-1 under the *m* control operation, as presented in Fig. 2. The *P*out control operation can maintain the secondary coolant pressure at a level higher than that possible with the *T*in control operation or *m* control operation, resulting in a higher secondary coolant density. It can be concluded that the *P*out control operation with a relatively high pressure provides the benefit of the smallest tube inlet orifice size because the flow instability becomes more severe at a low system pressure [2].

## CONCLUSIONS

The thermal-hydraulic performance and screw-type tube inlet orifice length of an OTSG have been evaluated for the secondary coolant inlet temperature control operation. The SG condition is divided into five steps according to the tube plugging ratio, and the OTSG performance and orifice design results are compared according to the constant thermal power operation strategy. The secondary coolant inlet temperature curve for constant-power operation and the corresponding thermal-hydraulic performance curves are obtained. The results reveal that long-term constant full-power operation is achievable if properly decreasing the secondary coolant inlet temperature at the expense of a decrease in the steam outlet superheat degree and an increase in the secondary coolant pressure drop as the OTSG undergoes a heat transfer area reduction due to tube plugging. For low-power operation, however, it is not necessary to adjust the secondary coolant inlet temperature because it remains nearly unchanged in any tube-plugging condition. The *T*in control operation, *m* control operation, and *P*out control operation allow a relatively high inlet temperature, a relatively low flow rate, and a relatively high outlet pressure compared to the other different operation strategies, respectively, except when the OTSG operates at the 100% power level under the SG condition-5.



*FIG. 7. Pressure, temperature, and density distributions along the tube (Q = 5 MW and α = 0%).*

The orifice design results show that the lowest power level during the power operation of a plant in a non-plugged condition provides a limiting case with regard to determining the orifice length. The minimum orifice length is increased by increasing the incline angle and width of the orifice channel. To ensure stable operation in a power range of 5%-100%, the orifice length should be at least 324.0 mm (i.e., *L*ori ≥ 324.0 mm) when the orifice has a channel geometry of *w* = 3.0 mm and *θ* = 12°. This orifice length is almost identical to *L*ori\_min = 325.0 mm, which is the design result when, instead of the *T*in control, the secondary coolant flow rate control is applied to OTSG operation. However, the secondary coolant outlet pressure control scheme decreases the minimum orifice length to *L*ori\_min = 266.2 mm. The *P*out control operation provides a relatively high secondary coolant pressure compared to the other operation strategies of *T*in control or *m* control and results in a reduced orifice length because the flow instability becomes less severe at a high pressure.

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