Thermal-Hydraulics Evaluation Program Development for U-type Steam Generator of APR1400

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1. Introduction

The APR1400 steam generators represent the uprated and evolutionary design from the OPR1000 operating steam generators. Reactor coolant enters the inlet plenum through the primary inlet nozzle, flows up through the tube sheet and U-type tube, and returns through the tube sheet to the outlet plenum and exits through the two outlet nozzles. Feed water enters the economizer region at the tube sheet on the cold leg side of the tube bundle. Above the flow distribution plate, feed water flows upward in axial counter flow, being heated by forced convection to near saturation conditions at the top of the economizer.

Heat transfer by nucleate boiling occurs in the evaporator as the secondary fluid flows upward continually increasing in steam quality. In most previous studies, a steam generator is designed to be optimized to remove heat and to produce steam vapor. Because of its importance, theoretical and experimental researches have been performed on forced convection boiling heat transfer [1, 2].

The purpose of this study is to establish a thermal hydraulic evaluation program for evaluating operating parameters of steam generator in order to develop an NSSS (Nuclear Steam Supply System) thermal performance evaluation program for assessing thermal power, operating characteristics of RCS (Reactor Coolant system) and steam generator, and so on.

The analytical modeling of a steam generator is employed based on the empirical correlation equations and theory.

2. Methods and Results

Heat transfer is calculated independently in the convection and boiling region. The size of the tube length is calculated for a given number of tubes, primary temperature and steam pressure, and the thermal performance of the steam generator is estimated for a fixed number of tubes and tube length, primary temperature or steam pressure. The axial-flow economizer region and evaporator region require separate analyses due to the different modes of heat transfer.

2.1 Theoretical calculation of steam generator

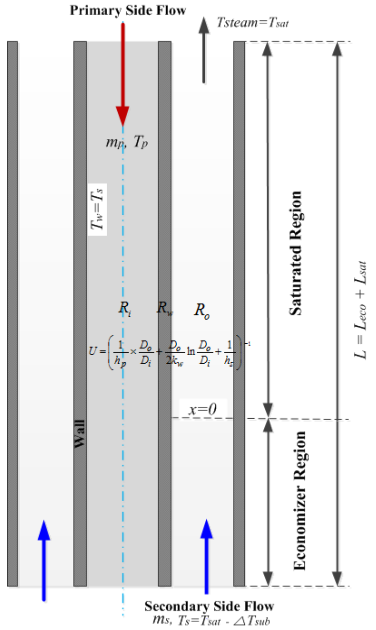

Fig. 1 Schematic diagram of energy balance in each cotinuum.

Typical thermal sizing is related to the calculations required for the heat transfer area to meet specified conditions [3]. Fig. 1 is a schematic diagram for calculating each heat transfer area. In general, it is possible to calculate the heat transfer of each area by applying the energy equations for the three physical continuums.

-primary side

$$Q = m_p (H_{pin} - H_{pout})$$

-tube side

$$Q = UA\Delta T_m = UA_i (T_{hot} - T_{cold}) / \ln\left[\frac{T_{hot} - T_{sat}}{T_{cold} - T_{sat}}\right]$$

-secondary side

$$Q = m_s (H_{s,in} - H_{s,out})$$

The overall heat transfer coefficient can be calculated as follows.

$$U = \left(\frac{1}{h_p} \times \frac{D_o}{D_i} + \frac{D_o}{2k_w} \ln\frac{D_o}{D_i} + \frac{1}{h_s}\right)^{-1}$$

Here, Q, M, H, U, A, D and T are thermal power, mass flow rate, enthalpy, overall heat transfer, heat transfer area, tube diameter and temperature respectively. And subscripts p, s, o, i and w represent primary side, secondary side, outer wall, inner wall and tube wall respectively.

All other parameters are usually fixed at the specified value. In most thermal-hydraulics performance calculations, the heat transfer area is fixed and the variable of interest is the inlet or outlet of primary temperature or secondary pressure. Even though the total heat load and various thermal hydraulic values of the steam generator are known, the heat load provided to the evaporator and economizer regions cannot be defined explicitly. This requires an iterative solution.

The assumptions applied to the thermal-hydraulics evaluation program of steam generator are as follows.

(a) Steady state conditions
(b) The heat transfer model considers the average primary flow per tube for the average tube length
(c) Nucleate boiling is the mode of heat transfer in the evaporator region
(d) The secondary side temperature is constant at saturation conditions throughout the evaporator
(e) Heat transfer in the economizer is by forced convection with axial counter-flow
(f) The pinch temperature is defined as the point where the economizer and evaporator heat flux is the same at the interface of the economizer and the evaporator.

The boiling equation of the evaporator can use the Rohsenow correlation [4]. The difference between the wall and the internal saturation temperature and the Rohsenow correlation equation are defined as,

$$\Delta T_{sat} = T_w - T_{sat}$$

$$\Delta T_{sat} = \left(q''\right)^{1/3} C_{sf} \Pr_l^{1.7} \left\{ \frac{1}{\mu_l h_{lv}} \left[\frac{\sigma}{g(\rho_l - \rho_v)} \right]^{1/2} \right\}$$

The heat transfer coefficient in the Nusselt number was defined as,

$$h_o = \frac{q''}{\left[T_w - T_{sat}(P_l)\right]}$$

Here T_w is the surface temperature and P_l is the ambient temperature. Therefore, the heat transfer coefficient (h_o) can be expressed as,

$$h_o = \frac{\left(q''\right)^{2/3}}{C_{sf} \Pr_l^{1.7} \left\{ \frac{1}{\mu_l h_{lv}} \left[\frac{\sigma}{g(\rho_l - \rho_v)} \right]^{1/2} \right\}}$$

Here, T, q'', h_{lv}, C_p, μ, σ, C_{sf} are temperature, heat flux, latent heat of vaporization, specific heat, viscosity, interfacial tension and constant value for different liquid-surface combination respectively, and s l and v of subscript are liquid and vapor. The value of C_{sf} is applied to 0.013 in the thermal-hydraulics evaluation program [4, 5].

2.2 Evaluation of Thermal Performance

Table I: Steam Generator Parameters on APR1400

Input Parameters	Symbol	Value
Core/SG Thermal Rating	P_{core}	2000MWt
Primary side		
Operating pressure	P_p	15.5MPa
Primary inlet temperature	$T_{p,inlet}$	323.9°C
Primary outlet temperature	$T_{p,outlet}$	290.6°C
Primary mass flowrate	m_p	37.78×10^6 kg/hr
Secondary side		
Saturation pressure	P_s	6.9MPa
Saturation temperature	T_{sat}	285.0°C
Feedwater temperature	T_{feed}	232.2°C
Secondary mass flowrate	m_s	4.07×10^6 kg/hr

Table 1 shows the typical steam generator operating parameters under normal operating conditions. The sizing of the steam generator calculates the length of the tube according to the thermal power, the primary flow, the primary temperature, and the secondary guaranteed steam pressure.

On the contrary, the developed steam generator thermal hydraulic evaluation program can independently predict the primary side temperature condition and the secondary side saturation pressure with the minimum operation data obtained on the primary side or the secondary side, with the number of tubes and the average length as fixed variables. When the RCS flow rate, saturation pressure of steam generator, main feed flow rate, and feed water temperature are applied to the performance evaluation program, the primary outlet temperature is 289.6 ℃ and the primary inlet temperature is 323.1 ℃. This error is estimated to be 0.34% for the primary outlet temperature and 0.25% for the primary inlet temperature. Also, if the RCS flow rate, primary side temperature, secondary side main water flow, and main water temperature are applied to the performance variable program, the steam generator pressure is estimated to be 7.0 MPa, 1.54% higher than the design variable.

The thermal-hydraulics evaluation program of steam generator can be utilized to predict steam generator thermal performance related variables by evaluating the applicable operating variables.

3. Conclusions

The developed thermal-hydraulics evaluation program of steam generator predicted approximately 0.3% lower primary side temperature and the steam generator pressure was estimated to be approximately 1.5% high.

The evaluation program is acceptable for estimating operation parameters of the currently operating power plant can be used to evaluate the operating variables of the power plant.

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