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Optimum thermal sizing and operating conditions for once through steam generator

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1. Introduction

Thermal-hydraulic characteristics of in-vessel steam generator should be evaluated to ensure natural circulation design. The straight tube type steam generator has a problem that it is necessary to absorb the thermal expansion difference between the shell and the heat transfer tube bundle. The steam generator is designed to be optimized so as 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.

The purpose of this study is to predict the thermal behavior and to perform optimum thermal sizing of once through steam generator.

To estimate the tube thermal sizing and operating conditions of the steam generator, the analytical modeling is employed on the basis of the empirical correlation equations and theory. The optimized algorithm model, Non-dominated Sorting Genetic Algorithm (NSGA)-II, uses for this analysis.

2. Methods and Results

By the experimental study, Mori-Nakayama [1] developed a correlation equation of heat transfer coefficient of single-phase that includes the effect of coil diameter as the inner diameter of the helical coil. Zukauskas et. al [2] presented a correlation equation for the heat transfer of single-phase that takes into account the distance between the tube and the tube diameter and the array based on the experimental study of the outside of the tube bundle. Shah [3] presented a correlation equation with the tube condensation for heat transfer coefficient based on the theoretical research and experiment of the annular tube and the straight tube. Osakabe [4] compared the theoretical numerical modeling of an integrated steam generator with the experimental heat transfer phenomenon of the tube. In addition, the modeling was applied to the calculation of the reactor vessel size. J. Yoon et. al [5] carried out numerical modeling based on the relationship of theory and experiment of the helical steam generator and suggested thermal-sizing method of the steam generator. Jose Zambrana et. Al [6] studied the boiling phenomenon the subcooled region (partial flow boiling, fully developed boiling, significant void flow) by using the equation of thermal efficiency and experimental theory, and presented a method of vertical tube length calculation.

2.1 Assumptions of one dimensional analytical model

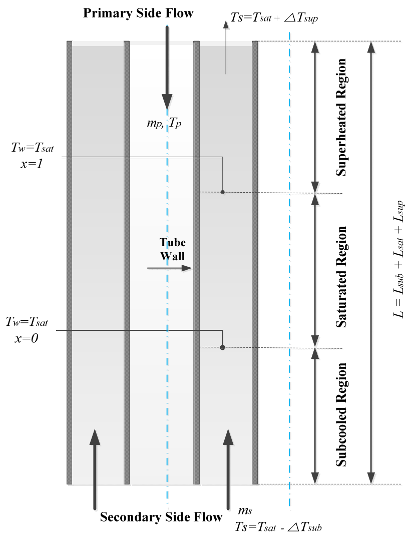

Fig.1 Modeling of water/steam flow in steam generator

Table I: Steam generator parameters

Input Parameters	Symbol	Value
Core/SG Thermal Rating	P_{core}	200MWt
Tube pitch		25.4mm
Tube side		
Operating pressure	P_s	6.5MPa
Saturation temperature	T_{sat}	280.8^{o}C
Superheated exit temperature	$T_{s,outlet}$	300.8^{o}C
Shell-side		
Operating pressure	P_p	15.5MPa
Primary inlet temperature	$T_{p,inlet}$	310.0^{o}C

Steam generator is arranged between the riser and the reactor vessel wall, the steam generator tubes have a triangular pattern, and tube pitch is constant 25.4mm.

The primary flow coolant passes over the outside of tubes, and the heat is transferred to the secondary feedwater. The feedwater flows up through inside of the tubes and the heat from the primary coolant is transferred to generate the superheated steam.

The once through steam generator is modeled by one characteristic tube. Shown in Fig. 1 is the schematic of the steady-state heat transfer regions along the steam generator tube. The primary coolant flows outside the tube in the opposite direction and transfers heat to the secondary coolant. The secondary feedwater flows up through a straight inside tube. The following three heat transfer regions are assumed in the steam generator secondary side: (1) subcooled water convection region, (2) saturated boiling region, and (3) steam convection region. The secondary feedwater enters the steam generator tube in a subcooled state and leaves in a superheated steam condition. In addition, the assumptions made for the physical model are listed below.

(1) The tubes are represented by one characteristic tube model, as shown in Fig. 1.
(2) The axial thermal conduction of tube wall is neglected.
(3) The tube side flow and heat transfer is divided into three regions: the single-phase water, the two-phase convective nucleate boiling region, post-dry-out, and superheated steam region.
(4) Thermal equilibrium is established between water and steam phase in boiling region.
(5) The shell side is single phase water.

If thermal power and inlet and exit temperature are given, the required primary mass flowrate to remove the thermal energy is as the following equation.

$$\dot{m}_p = \frac{P_{core}}{c_p \Delta T_{core}} = \frac{P_{core}}{c_p (T_{p,outlet} - T_{p,inlet})} \qquad (1)$$

The feedwater flow rate of the steam generator can be defined as the change in specific enthalpy of the inlet and outlet.

$$\Delta e_s = e_{s,outlet} - e_{s,inlet} = c_s T_{sub} + e_{lv} + c_v T_{\sup} \qquad (2)$$

$$\dot{m}_s = \frac{P_{core}}{\Delta e_s} = \frac{P_{core}}{c_s T_{sub} + e_{lv} + c_v T_{\sup}} \qquad (3)$$

The thermal conductivity for the tube material, Inconel 690, is calculated as a function of temperature as follows.

$$k_w = 11.396 + 0.0187T \ (\mathrm{W/m℃}) \qquad (4)$$

This thermal conductivity equation can be used within the temperature range from 20^{o}C to 400^{o}C. [5] The calculated heat transfer correlations are summarized as follows.

Tube-side

(1) Single phase region
(Subcooled region and superheated region)

$$\text{Dittus-Boelter: } Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{n} \qquad (6)$$

$$\left(n = 0.4\ (heating), 0.3 (cooling)\ ,\ 2500 < \mathrm{Re} < 1.24\times10^{5}\ ,\ \frac{L}{D} > 60 \right)$$

(2) Saturated boiling Region

$$\text{Thom: } h = \frac{1}{0.02253}\exp\left(\frac{p_{sat}}{8.69}\right)(q'')^{1/2} \qquad (7)$$

Shell-Side

$$\text{(1) Weismann: } Nu = C\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3} \qquad (8)$$

$$C = 0.026\left(\frac{P}{D}\right) - 0.06 \ \left(0.5 \le \mathrm{Pr} \le 1.5\ ,\ 1.1 \le \frac{P}{D} \le 1.5 \right)$$

Exit temperature of tube-side is 300.8^{o}C with superheat 20^{o}C and inlet temperature of shell-side is 310 ^{o}C.
Table II is a range of design of experiments with the initial parameter for the optimal calculation. This is to find an optimal solution of the multi objective function by using the NSGA-II [9] algorithm. Goals of multi-objective optimization are to minimize tube length, pressure drop and tube number. Tube side inlet feedwater temperature is assumed under subcooled condition.

Table II: Constraint conditions of design of experiment

Parameters	Constraint conditions
Tube OD	17mm ~ 20mm
Tube wall thickness	1mm ~ 1.4mm
Tube side	
Mass flowrate	102.684kg/s ~ 125.503kg/s
Shell-side	
Mass flowrate	1643.84kg/s ~ 2009.13kg/s
Tube number	2000 ~ 6000

2.2 Result

The feedwater temperature profile of tube-side and the outlet temperature of the shell-side are shown in Fig.2.
The temperature gradient of shell side outlet is less sensitive mass flow change. The feedwater temperature gradient of tube-side is sensitive to mass flow change.
The feedwater temperature of tube-side is based on the thermal power. In order to have a subcooled margin of feedwater temperature, 20^{o}C, the operating conditions at feedwater flowrate up to 115.425 kg/s can be selected for an optimized design parameter. A length of tubes for input conditions is shown as a function of tube numbers in Fig.3. In various input conditions, if number of tube is 2500ea, the tube length is 12.0m or more. The length of tubes is greater than 8.0m for number of tubes, 4500ea.
Parallel coordinates chart can determine optimal combination of tube thermal sizing as shown in Fig. 4.
Assuming that length of tube is less than 10.0m with the constraint of feedwater temperature below 260^{o}C, outer diameter of tube 19.0mm and the number of tube more than 3000ea. The shell-side mass flow has a range from 1789.95kg/s to 2009.132kg/s and the tube-side mass flowrate has a range from 289.38kg/s to 291.91kg/s.

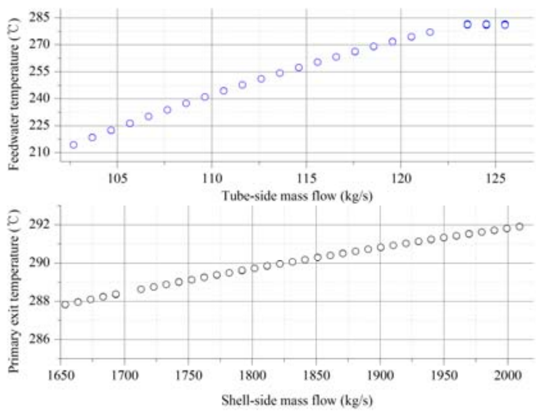

Fig.2 Temperature profile about mass flow rate

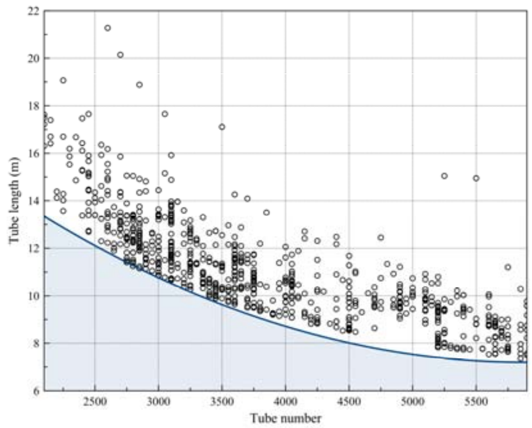

Fig. 3 Tube length distribution for tube number

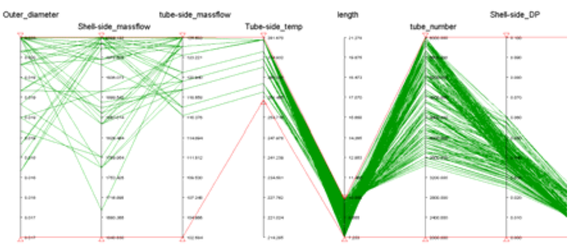

Fig.4 Parallel coordinates chart for optimal design

3. Conclusions

This research is focused on the design of in-vessel steam generator. An one dimensional analysis code is developed to evaluate previous researches and to optimize steam generator design parameters. The results of one-dimensional analysis need to be verified with experimental data.

Goals of multi-objective optimization are to minimize tube length, pressure drop and tube number. Feedwater flow rate up to 115.425kg/s is selected so as to have margin of feedwater temperature 20^{o}C.

For the design of 200MWth once through steam generator, it is evaluated that the tube length shall be over 12.0m for the number of tubes, 2500ea, and the length of the tube shall be over 8.0m for the number of tubes, 4500ea. The parallel coordinates chart can be provided to determine the optimal combination of number of tube, pressure drop, tube diameter and length.

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