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Sensitivity Analysis on Steam Generator Volume to Feedwater Temperature for Small Modular Reactor

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1. Introduction

In nuclear power plants, the steam generator is a pivotal component for converting nuclear energy into steam. The steam generator necessitates maintaining appropriate temperature and flowrate of feedwater for efficient heat transfer and stable operation. Particularly, the temperature of the feedwater significantly influences the operation and performance of the steam generator.

In recent decades, extensive research has been conducted on analyzing the temperature and pressure in steam generators [1]. Such studies provide crucial insights for achieving more efficient and safe operation of steam generators. However, much of this research has predominantly relied on pre-determined feedwater temperature, and the effect of feedwater temperature to the size of steam generator was not analyzed extensively. Since the size of small modular reactor (SMR) is greatly affected by the steam generator, it seems necessary to understand how the feedwater temperature affects the SMR size.

Therefore, this study aims to analyze the sensitivity of steam generator's volume to the feedwater temperature that can be applied to a Pressurized Water Reactor (PWR)-type small modular reactor (SMR). For this analysis, a steam generator design tool based on one-dimensional finite difference method (FDM) is utilized. FDM is a numerical analysis approximate derivative using finite differences to solve differential equations by discretizing both spatial and temporal. From this approach, the changes in the steam generator volume under diverse operating conditions are investigated to gain insights into the performance and compactness of steam generators accordingly.

2. Methodology

In this section, the steam generator design and operating conditions are discussed. The computation model used to design steam generator is also illustrated.

2.1 Steam Generator Design Approach

The steam generator (SG) type considered in this study is a Once Through Steam Generator (OTSG), in which a counterflow heat transfer occurs through straight, vertical tubes. The structure can be easily understood from Fig. 1. The secondary coolant flows upward inside the SG tubes, surrounded by the primary coolant flowing downward. Assuming steady-state conditions and all channels being homogeneous, a unit channel is considered to have the same amount of heat transfer rate. The volume of SG ($V_{minimum}$) is highly dependent on the heat transfer area and volume. The volume can be simply calculated by multiplying the number of tubes ($N_{2nd,channel}$) to unit channel's heat transfer volume. A unit channel volume is the value multiplying the pitch length ($P_{2nd,channel}$) square with height of heat exchange (L_{height}). The minimum volume of the SG is thus obtained by equation (1).

$$V_{minimum} = N_{2nd,channel} \times L_{height} \times {P_{2nd,channel}}^2 \quad (1)$$

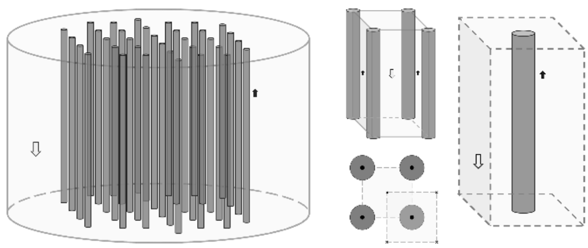

Fig. 1. The overall design (left) and the unit subchannel (right) of the SG.

2.2 Thermal Design of OTSG

In the OTSG of a PWR, the secondary side experiences various flow regimes, starting from sub-cooled state to superheated steam. During such transitions in flow regimes, the heat transfer coefficient changes significantly. Thus, a one-dimensional FDM is used in model to reflect the different flow characteristics of different meshes, rather than the log-mean-temperature-difference (LMTD) method [2].

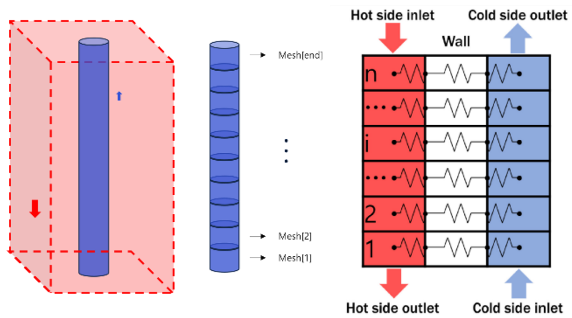

Fig. 2. One-dimensional FDM of a unit channel (left) and the thermal resistance network model (right).

To compute the heat flux within a certain mesh, the heat transfer coefficient and the temperature difference should be computed. Each mesh brings the value from the previous meshes, through a boundary condition. At the beginning of the calculation, the operation parameters of the system's primary loop and secondary loop are required. In this study, the primary loop was modeled to the value of SMART (PWR-type SMR), and the secondary loop was modeled to an assumed condition. The operation parameters are summarized in Table 1 [3].

Table I: SG reference design parameters.

Parameter	Primary loop	Secondary loop
SG inlet temperature [C]	323	200
SG outlet temperature [C]	295.7	296.4
Operating pressure [MPa]	15	5.2
Mass flow rate [kg/s]	2062.47	161.55
SG Heat transfer rate [MWt]	330	
Number of channels	18000	
Height of channel [m]	3.84	
Diameter of channel [mm]	12.7	
Length of pitch	25.4	
Tube thickness [mm]	1.2	
Tube thermal conductivity [W/m*k]	16.3	
P/D ratio	2	

Each mesh's heat transfer coefficient is determined by the function of dimensionless numbers and thermodynamic parameters, including cold side wall temperature, heat flux, void fraction. The flow regimes are divided into six cases, also including the post-critical heat flux state. Each case uses different equations for calculating the heat transfer and drag coefficients. The heat transfer coefficient correlations used for each case are listed in Table II, referring to the correlation models used in the TRACE/RELAP code [4]. While the computation model used in this study is capable of covering all six flow regimes, the flow regimes occurring in the proposed SG are single-phase liquid, nucleate boiling, and superheated steam regimes.

Table II: Equations for calculating the heat flux according to flow patterns

Case	Equation	Used correlation or data for HTC
Single phase (Newton)	$\dot{q}''_{Newton} = h(T_w - T_c)$	Sleicher & Rouse
Inverted annular film Boiling	$\dot{q}'' = h(T_w - T_{sat}) + \frac{\sigma_{SB}({T_w}^4 - {T_l}^4)}{\frac{1}{\varepsilon_l\sqrt{1-\alpha}} + (\frac{1}{\varepsilon_w} - 1)}$	Fung & Cachard
Inverted slug film Boiling	$\dot{q}'' = x(2-x)\dot{q}''_{IAFB} + (1 - x(2-x))\dot{q}''_{DF}$	
Dispersed flow	$\dot{q}'' = \frac{k_g}{D_h} Nu_{wg,FC} * \Psi_{2\Phi}(T_w - T_g) + F_{wl}\sigma_{SB}({T_w}^4 - {T_{sv}}^4) + F_{wg}\sigma_{SB}({T_w}^4 - {T_{sg}}^4)$	Sleicher & Rouse & Filonenko & Gnielinski
Nucleate boiling	$\dot{q}'' = h_{wl}(T_w - T_{sat}) + (\frac{h_0 F_P}{{\dot{q}''_0}^n})^{\frac{1}{1-n}}(T_w - T_{sat})^{\frac{1}{1-n}}$	Gnielinski

The calculated heat flux is a key parameter for mesh's overall heat transfer coefficient of cold side, which will be used for calculating the overall heat transfer rate (Q) and the overall thermal resistance (U), presented in equations (2) and (3). From the overall heat transfer rate, the temperature of cold side wall can be calculated.

$$Q = UA\Delta T \tag{2}$$

$$U = \frac{1}{\frac{1}{(hA)_{hot}} + \frac{\ln\left(\frac{D_o}{D_i}\right)}{2\pi \cdot k_{wall} \cdot dl} + \frac{1}{(hA)_{cold}}} \tag{3}$$

2.3 Computation Model Description

The computation model was modeled using MATLAB, and the calculation process is shown in Fig. 3. Starting from the given operation parameters, the model calculates the values for each part of the mesh. Then, the values for the heat transfer between the secondary fluid and the wall are calculated, where the temperature is assumed to be the average value of the respective fluid temperatures. The calculated values are then compared to the new secondary system wall temperature to calculate the overall thermal resistance and the relative error is calculated. If the relative error is greater than one part in ten thousand, the new secondary system wall temperature is used to calculate the fluid interaction with the secondary system wall again. Otherwise, the calculation is considered valid, and the calculation of the next mesh is started using the calculated values of the previous mesh as boundary conditions. The calculation continues until the calculation of the last mesh is valid.

During the computing process, dimensionless numbers are calculated by each mesh's flow types and thermodynamic values determined by the 'REFPROP' function from NIST (National Institute of Standards and Technology). Moreover, the critical heat flux (CHF) conditions are checked based on the CHF table [5]. The validity of mesh calculation was determined by the relative error of cold side wall temperature. The convergence of the wall temperature is monitored during the iteration process.

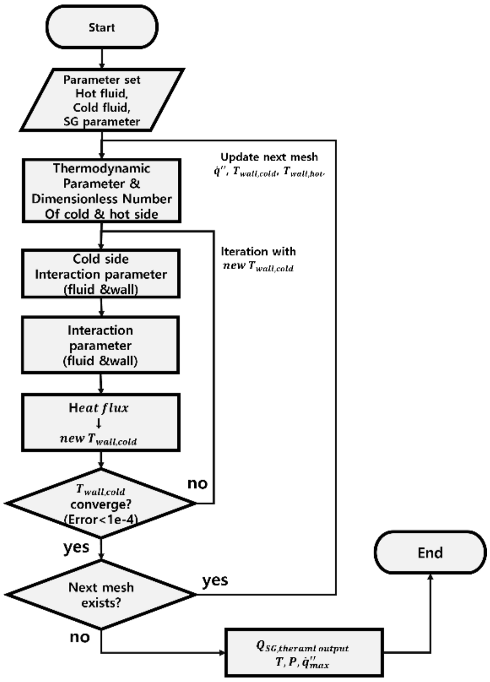

Fig. 3. Flow chart of the SG computation Model.

3. Results and Discussions

3.1 Designed Steam Generator

To investigate the trend between minimum required volume of SG and the feedwater temperature. The computation was run by varying the feedwater temperature and the mass flowrate. The mass flow rate change due to feedwater temperature is calculated with the enthalpy difference using the given inlet and outlet temperatures, which can be identified by Fig. 4. Therefore, the modified diameter due to mass flowrate is required to keep the mass flux as constant and pressure drop at a similar level for each design case.

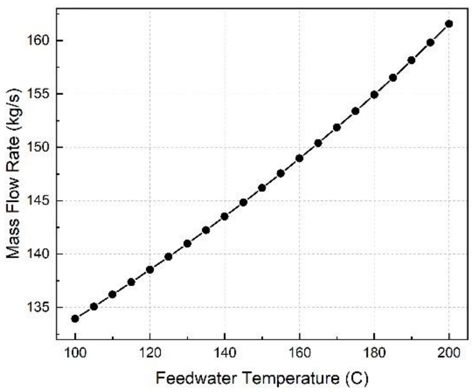

Fig. 4. Feedwater mass flowrate of SG by feedwater temperature at 330MWt thermal output

The minimum SG volume is plotted as a function of feedwater temperature in Fig. 5. It is observed that the lower the feedwater temperature, the smaller the minimum SG volume becomes to transfer the same amount of heat for the fixed turbine inlet temperature. The regression was successful, which resulted in a relative error of less than 1% in the heat output value for the same superheated steam temperature.

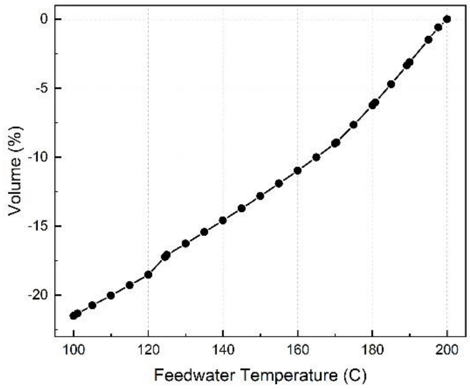

Fig. 5. Minimum volume of SG by feedwater temperature at 330MWt thermal output

For a steam generator assuming the same outlet temperature and heat output, it can be seen that as the feedwater temperature decreases, the percentage decrease in flow is having similar ratio with percentage decrease in volume. However, for SMRs with multiple applications, such as district heating and seawater desalination, rather than just generating electricity, there will be different interpretations of this figure depending on the application.

4. Conclusions and Further Works

In this study, a sensitivity analysis was performed on the SG volume of a PWR-type SMR while feedwater temperature was decreased. Here, the one-dimensional FDM-based method was employed instead of a simple LMTD method to reflect the changes in the flow regimes inside the SG. The effect of decreasing the feedwater temperature on the SG volume was investigated. It was observed that the lower the feedwater temperature, the lower the minimum heat transfer volume.

Although the validity of the proposed computational model has been assured by previous papers related to the 'KAIST HXD'[6], there are several limitations in this preliminary analysis. First, the SG geometry has been simplified as a bundle of multiple straight tubes transferring the same amount of heat. Second, the pressure drop and other affection due to structures including orifice is not considered in the channel.

As for the direction of subsequent research, it includes validating the result with experimental data and evaluating the sensitivity of various parameters such as P/D ratio, number of tubes, and pressure drop to derive optimal volume values.

ACKNOWLEDGEMENT

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