Numerical Simulation on Flow Distribution in Inlet Plenum of Steam Generator

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1. Introduction

In the 150-MWe Korean prototype SFR, integral once-through type, counter-flow shell-and-tube heat exchanger with straight vertical tubes was adopted for steam generators. Reliable operation of the steam generators has been a key issue through operating experience of foreign sodium-cooled fast reactors because it is one of the most important components deciding the plant availability and reliability.

The temperature differences between parts of the large scale steam generator during operation have to be carefully estimated because it has a number of long and straight tubes. Non-uniformity in sodium flow and temperature distributions might cause mechanical integrity problems such as tube buckling and tube-to-tube sheet junction failure in the straight tubes. According to previous studies [1-4], the flow distribution in the inlet plenum of the sodium-heated steam generator was assessed, and proper flow distributors were designed to make uniform sodium flow distribution.

This work reports a numerical study on the sodium flow at the inlet plenum of the PGSFR steam generator based on multidimensional numerical analysis. Optimization of porosity of flow distributors for achieving circumferentially uniform flow at the entrance of the tube bundle is carried out with the STAR-CCM+ CFD package.

2. Methods and Results

2.1 Domain of Analysis

In order to determine porosities of the flow distributors at the inlet plenum of the steam generator, a three-dimensional flow part of the inlet plenum was analyzed as an analysis domain (Fig. 1). Three porous plates, including two horizontal doughnut-type baffles and a single vertical shell, are installed at the inlet plenum as the flow distributors. Sodium enters the inlet plenum through the sodium inlet nozzle and flows upwards in an annular space where the two horizontal flow distributors exist. Finally, circumferential flow imbalance caused by the sodium introduced from one side is mitigated by the vertical flow distributors, which leads to uniform flow distribution at tube bundle entrance region. For efficient calculation, flow distributors, tube support plates, and tube bundle region were treated as porous regions. A polyhedral mesh with prism layer cells was generated on the geometric domains with a base size of 3 cm, which was selected through a mesh dependency study comparing radial velocity profiles of 2.5, 3, and 5 cm cases. The number of cells was about 1.36 million.

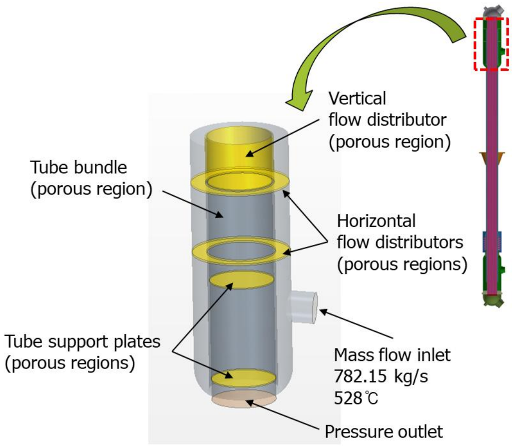

Fig. 1. Modeling of SG inlet plenum.

2.2 Computational Analysis

Numerical simulations were carried out using commercial computational fluid dynamic package, STAR-CCM+ V11.02.009. Flow analysis model was only employed but heat transfer was not taken into account. The SST (Shear Stress Transport) k-ω model was adopted as the turbulence model based on a previous study comparing experimental results and numerical results of the inlet plenum [2]. Mass flow inlet and pressure outlet were applied as boundary conditions at inlet and outlet, respectively. Porous inertial resistances of each porous region were acquired with pressure drop models as shown in Table I. Parametric study with porosities of distributors was conducted step by step. In the first step, optimizing the porosity of two horizontal flow distributors was performed. Then, optimizing the porosity of the vertical flow distributor was conducted at the fixed porosity of the horizontal plates. For the parametric study, the porosity of the horizontal flow distributors ranging from 20 to 100% and the porosity of the vertical flow distributor ranging from 5 to 45% were assessed to make uniform flow at the tube bundle entrance and minimize the pressure drop at the distributor devices.

2.3 Computational Results and Discussion

Figs. 2 shows sodium velocity fields on the vertical and horizontal sections during normal operation at the various porosity combination of the flow distributors. When porosities of both horizontal and vertical distributors are 100% (Fig. 2a), which means there are no distributors, the sodium introduced from the inlet nozzle flowed upwards through the annular space, and enters the tube bundle unevenly at the top of the inlet plenum. The uniformity of the sodium flow at the tube bundle entrance was effectively improved as the porosity of the horizontal flow distributors decreased to 45% (Fig. 2b). It was shown that when the porosity of the vertical distributor changed to 15%, a really good uniformity was achieved axially and radially at the window of the tube bundle entrance (Fig 2c). Sodium velocity fields in a horizontal section which is located 5 cm above the window bottom were also obtained (Fig. 2d). As the porosities of the horizontal and vertical flow distributors decreased to 45% and 15%, respectively, a circumferentially uniform flow was achieved. Radial velocity profiles along the window height at various angles were analyzed (Fig. 3). As the porosity of the horizontal flow distributor changed from 100% to 45%, the differences between the radial velocity profiles obtained from various angles were reduced (Figs 3a and 3b). Also, radial velocities along the height at various angles had a similar trend and decreased with the height. At the porosity combination of 45% and 15% for the horizontal and vertical flow distributors, the radial velocities became almost the same at any angles and elevation (Fig. 3c). As the sodium flow distribution became circumferentially uniform, the maximum radial velocity was also found to be decreased accordingly.

A non-uniformity index (NUI) to quantify the non-uniformity of the sodium flow at the tube bundle entrance was defined as

$$NUI = \frac{\sqrt{\sum_S (u_r - \bar{u}_r)^2 / N}}{\bar{u}_r},$$

where, u_r, $\bar{u}_r$, and N are the radial velocity on the window surface of the tube bundle entrance, the surface average of u_r, and the number of data points, respectively. As the flow distribution becomes uniform on the analysis surface, the NUI value decreases. As the porosity of the vertical distributors decreased at fixed 45% porosity of the horizontal flow distributors, the NUI value decreased but the reduced extent was gradually diminished (Fig. 4a). However, the total pressure drop at the inlet plenum abruptly increased at the porosity range of less than about 15% (Fig. 4b). In conclusion, the optimal porosity for the vertical flow distributor which makes the uniform flow distribution and minimizes the pressure drop was evaluated to be about 15%.

Table I: Pressure drop models for porous regions.

Porous region	Pressure drop
Flow distributor or tube support plates [5]	$\Delta p = 0.8\left[0.707(1-P)^{0.375} + 1 - P\right]^2 \left(\frac{1}{P^2}\right) \cdot \frac{1}{2}\rho u^2$
Cross flow in tube bundle [6]	$\Delta p = Nf\chi \cdot \frac{1}{2}\rho\left(\frac{S_T}{S_T - D}\right)^2 u^2$
Parallel flow in tube bundle [6]	$\Delta p = f\frac{l}{D_h} \cdot \frac{1}{2}\rho u^2$
Nomenclature	p: pressure P: porosity ρ: sodium density u: sodium velocity N: tube rows f: friction factor χ: correction factor S_T: tube pitch D: tube outer diameter D_h: hydraulic diameter l: tube length

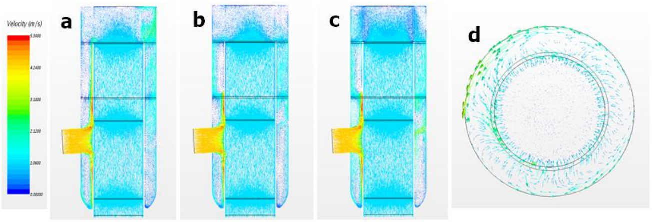

Fig. 2. Vertical and horizontal velocity distributions with the change of the porosities of the distributors; (a) horizontal plate porosity – 100% and vertical shell porosity – 100%, (b) horizontal plate porosity – 45% and vertical shell porosity – 100%, (c) horizontal plate porosity – 45% and vertical shell porosity – 15%, (d) horizontal plate porosity – 45% and vertical shell porosity – 15% .

3. Conclusions

Prior to the experimental validation of the PGSFR steam generator, numerical sodium flow analysis was carried out to optimize the porosities of the flow distributors at the inlet plenum during normal operation. The porosities of the flow distributors were determined to be 45% and 15% for the horizontal and vertical flow distributors, respectively, considering the flow uniformity and pressure drop.

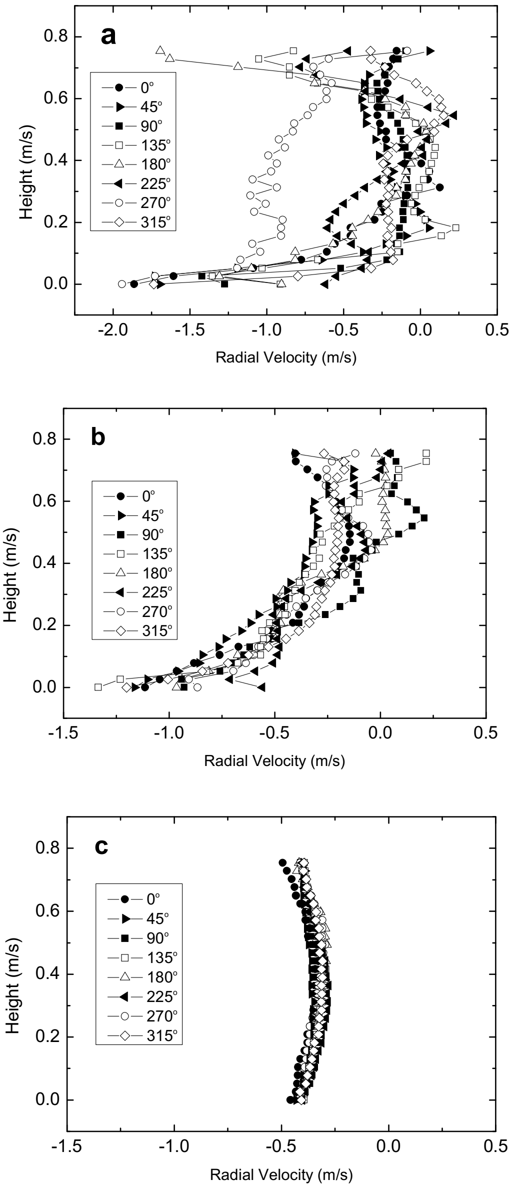

Fig. 3. Vertical and horizontal velocity distributions at different angles of the tube bundle entrance region with the change of the porosities of the distributors; (a) horizontal plate porosity – 100% and vertical shell porosity – 100%, (b) horizontal plate porosity – 45% and vertical shell porosity – 100%, (c) horizontal plate porosity – 45% and vertical shell porosity – 15%.

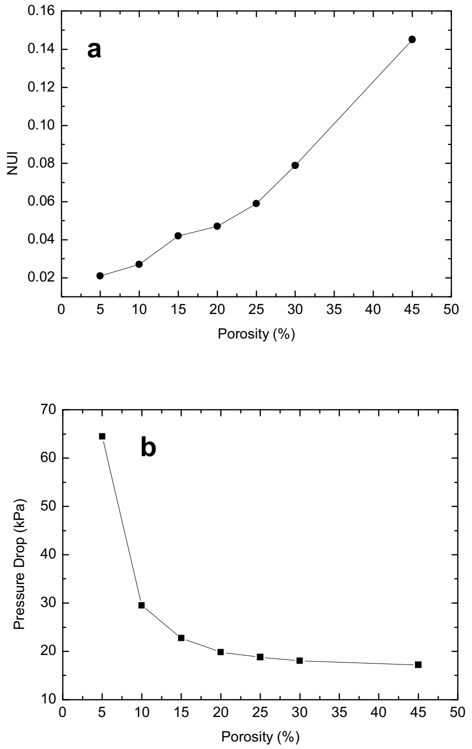

Fig. 4. Non-uniformity index and pressure drop with respect to the porosity of the vertical distributor.

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