Preliminary CFD Analysis for a Natural Circulation Flow between a Reactor and Steam Generator in an OPR100

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1. Introduction

KAERI is now performing a MELCOR analysis for the a temperature induced steam generator tube rupture accident (TI-SGTR) initiated by a station blackout in an optimized power reactor 1000 MWe (OPR1000) because the TI-SGTR is one of the most important accident scenarios and needs to be considered to confirm that an operating nuclear power plant meets regulations related on the severe accident [1]. To perform a 1-dimensional MELCOR analysis, some input parameters considering a 3-dimensional phenomenon, such as the mixing fraction, recirculation ratio, hot tube fraction in the SG inlet plenum and the discharge coefficient in the hot leg, are needed to simulate the natural circulation flow of a hot gas from the damaged reactor core to the steam generator in the OPR1000. Thus we have performed a 3-dimensional analysis for the natural circulation flow between the hot leg and the SG during a severe accident in the OPR1000 using a commercial code ANSYS CFX 19.1 with an established analysis methodology [2,3]. The established methodology was obtained through a CFD analysis for a natural circulation between a reactor and a SG in the Westinghouse 1/7 scaled-down test facility [3,4]. In addition, we quoted the method of modeling the boundary conditions applied in a CFD analysis for a Westinghouse type plant [5].

2. Development of a 3-Dimensional SG Model

2.1 Grid Model and Boundary Conditions

A 3-dimensional SG model was developed and validated on the basis of the OPR1000 design data [6]. The number of tubes in the SG model was reduced by a ratio of 1/8 and its diameter was increased 3 times compared to the SG design data of OPR1000. Thus, the pressure drop and heat transfer occurred when a coolant flows though the tubes in the SG model during a normal operation was simulated by a pressure loss coefficient and a heat transfer coefficient in the CFX. A 3-dimensional grid model simulating from the reactor to SG was developed and an analysis was performed with boundary conditions based on the preliminary MELCOR result [1]. A total of about 53,622,290 cells with a cell length of approximately 0.05 - 30 mm were generated in the base grid model (Table 1).

Table 1: Element Information in the Grid Model

	Case-1	**Case-2**	**Case-3**
Number of elements	53,622.290	58,648,507	49,156,461
-Tetrahedral	10,324,342	14,230,303	7,261,275
-Wedges	5,281,948	6,259,294	4,068,396
-Hexahedral	38,016,000	38,158,910	37,826,790

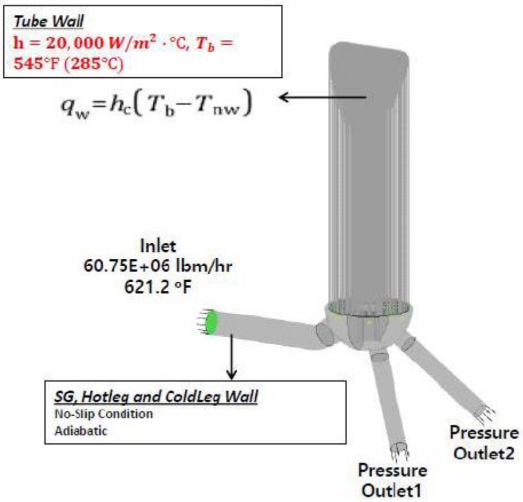


Fig. 1. Grid Model and Boundary Conditions for the SG

2.2 Validation Results

To validate the SG model, the pressure drop and heat transfer that occurs when the reactor coolant flows though the SG tubes during the normal operation was simulated by using a pressure loss coefficient through the tubes (Eqs. (1) and (2)) and a heat transfer coefficient (Fig. 1) given at the tube outer wall in the CFD calculation. The mass flow rate of the reactor coolant flowing to one SG during the normal operation is 60.75 × 10^6 lbm/hr [6]. In addition, various sensitivity calculations were performed by changing the mass flow rate, mesh distribution in the grid model and turbulent model in the SG model analysis. Through these calculation results (Fig. 2, Tables 2 to 5), we decided the proper grid model, the pressure coefficient, and the turbulent model to precisely predict a turbulent flow in the SG model. In particular, we knew that the velocity profile in the SG inlet plenum by the shear stress transport (SST) turbulence model was more reasonably predicted than other turbulence models (Fig. 3).

$$\frac{\partial(\rho U_i)}{\partial t}+\frac{\partial(\rho U_i U_j)}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\right]+(\rho-\rho_{ref})g_j+S_{M,i} \quad (1)$$

$$S_{M,i}=-K_{loss}\frac{\rho}{2}|U_i|U_i \quad (2)$$

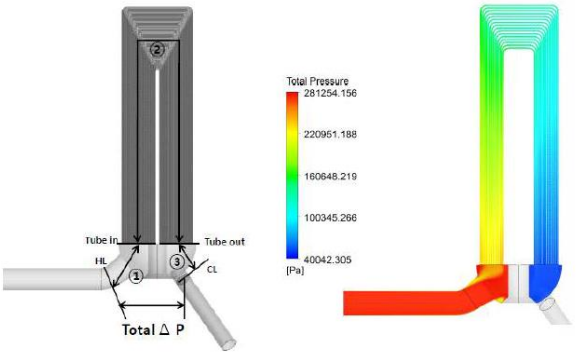


Fig. 2. Pressure Distribution by CFD using Standard k-ε Turbulent Model

Table 2: Comparison of Pressure Drop and Heat Transfer at Normal Operation between Design Datum and CFD Results (Grid Model Case-1, Standard k-ε Model, Normal Operation)

	CFD	**Design Data**
SG total ΔP [psi]	31.56	31.94
ΔP ① (Inlet Plenum)	3.28	3.35
ΔP ② (SG Tube)	27.16	27.78
ΔP ③ (Outlet Plenum)	1.12	0.81
Cold Leg Temp. [ºF] *Hot Leg Temp. : 621.2 ºF	564.8	564.5

Table 3: Comparison of Pressure Drop and Heat Transfer between SG Design Data and CFD Results (Grid Model Case-1, Standard k-ε Model)

	90%	**100%**	**110%**
SG total ΔP [psi]	26.35	31.56	40.51
ΔP ① (Inlet Plenum)	2.67	3.28	4.80
ΔP ② (SG Tube)	22.90	27.16	34.02
ΔP ③ (Outlet Plenum)	0.78	1.12	1.69
Cold Leg Temp. [ºF] *Hot Leg Temp. : 621.2 ºF	563.2	564.8	564.3

**100% : Normal operation condition

Table 4: Comparison of Pressure Drop and Heat Transfer between Design Datum and CFD Results (Grid Model Case-1, Normal Operation Condition)

	SST	**k-ε**	**RSM**
SG total ΔP [psi]	30.01	30.97	30.66
ΔP ① (Inlet Plenum)	1.65	2.34	5.51
ΔP ② (SG Tube)	27.54	27.72	28.41
ΔP ③ (Outlet Plenum)	0.82	0.91	0.74
Cold Leg Temp. [ºF] *Hot Leg Temp. : 621.2 ºF	564.3	564.4	564.8

Table 5: Comparison of Pressure Drop and Heat Transfer between Design Datum and CFD Results (SST Turbulent Model, Normal Operation Condition)

	Case-1	**Case-2**	**Case-3**
SG total ΔP [psi]	30.01	29.94	29.36
ΔP ① (Inlet Plenum)	1.65	1.40	1.36
ΔP ② (SG Tube)	27.54	27.75	27.24
ΔP ③ (Outlet Plenum)	0.82	0.79	0.76
Cold Leg Temp. [ºF] *Hot Leg Temp. : 621.2 ºF	564.3	564.3	564.3

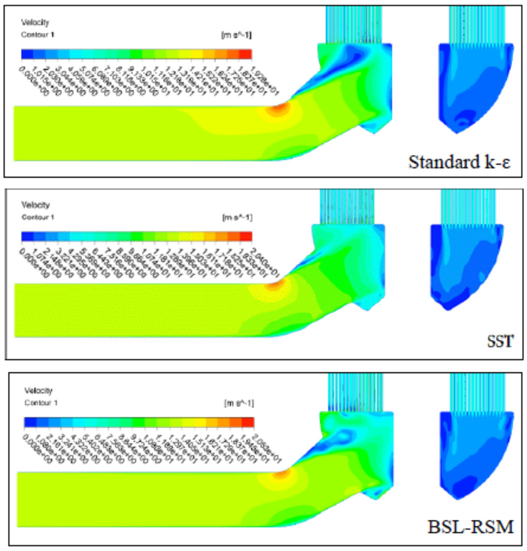


Fig. 3. Velocity Contours in the SG Inlet Plenum according to Turbulent Models

3. CFD Analysis

3.1 Grid Model and Flow Field Models

A 3-dimensional grid model simulating from the reactor to the SG in the OPR1000 was developed based on the validated SG model (Fig. 4) to analyze the natural circulation flow of the mixture gas of steam-H_2 in the hot leg and the SG inlet plenum. The end of the cold leg nozzle of the SG was blocked to simulate loop-seal phenomenon during the severe accident. A total of about 63,065,389 cells with tetrahedral, pyramids, wedge, and hexahedra elements were generated in the grid model.

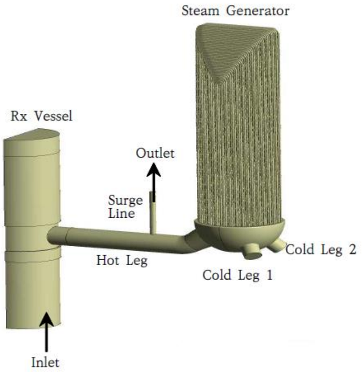


Fig. 4. Grid Model for Natural Circulation Flow in the Hot Leg and SG Inlet Plenum of OPR1000

The boundary conditions used for this natural circulation flow are shown in Table 6. These were obtained from the preliminary MELCOR analysis results for the TI-SGTR of OPR1000 [1]. The decay heat generation in the core was not simulated because the purpose of this calculation was only to calculate 3-dimensional flow mixing between the hot gas and the cold gas in the hot leg and SG inlet plenum. To simulate the mixture gas flowing to the pressurizer from the hot leg, the outlet condition was given at the upper region of the surge line. The inlet condition was set at the core inlet to induce the stabilized flow field of the mixture gas in the upper plenum of the reactor vessel [5]. The natural circulation flow field was solved by applying the mass conservation, the momentum conservation with a full buoyancy model, energy conservation implemented in the ANSYS CFX 19.1 [7]. A turbulent flow was modeled by the SST model with the scalable wall function.

Table 6: Boundary Conditions for Natural Circulation Flow

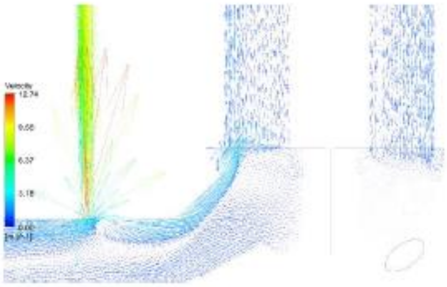
Inlet	Steam-H_2 gas : 13.24 kg/s, 929.18 ºC
Outlet	Zero reference pressure
Wall at SG Tubes	Heat transfer coeff. : 20.37 W/m^2 ºC' Ambient temp. : 613.75 ºC

3.2 Discussion on the CFD Results

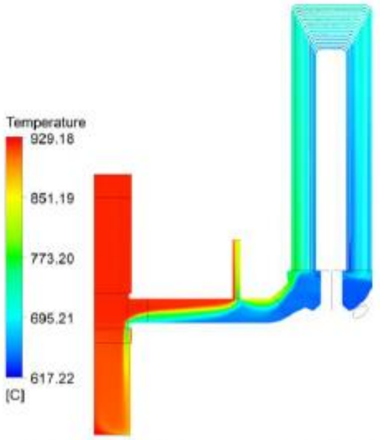
A steady state calculation was performed to obtain the converged solutions through approximately 3000 iterations. We assumed that the convergence criteria were satisfied when the normalized residuals of the pressure, velocity, turbulence, and enthalpy reached approximately 1.0×10^{-4}. The calculation results of the velocity profile and temperature distribution are shown in Fig. 5. Through the CFD results, we can know that the natural circulation flow pattern in the hot leg and SG inlet plenum is accurately simulated to produce the MELCOR input parameters. Finally, we proposed a mixing fraction of 0.84, recirculation ratio of 1.44, hot tube fraction of 0.424, and discharge coefficient of 0.16 for the MELCOR analysis through this CFD analysis (Table 7). These are located in the range between parameters of WH SG and Combustion Engineering (CE) SG (Table 8).

Table 7: MELCOR Input Parameters from CFD Results

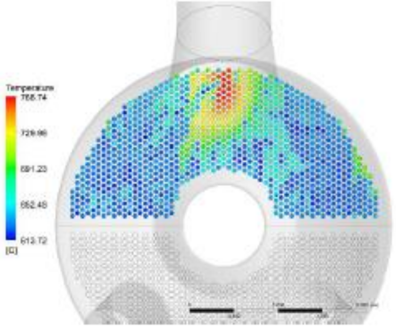
Parameter	Value
Recirculation ratio (r) $r = m_t / m_h$	1.44
Mixing fraction (f) $f = 1\text{-}r(T_{ht}\text{-}T_m)/(T_h\text{-}T_m)$	0.84
Hot tube fraction (a) *based on the areas of hot tube & cold tube	25.7%
Discharge coefficient (C_d) $Q = C_d\,(g \times D^5 \times \triangle \rho/\rho\,)^{1/2}$	0.16
T_h : gas temp. flowing to SG inlet plenum	744.8 ℃
T_{ht} : gas temp. flowing to upper region of SG tubes	684.2 ℃
T_{ct} : gas temp. returned from SG tubes	629.1 ℃
T_m : avg. temp. of the mixing zone	676.5 ℃
m_h : gas flow rate to SG inlet plenum	7.89 kg/s
m_t : gas flow rate to upper region of SG tubes	11.42 kg/s



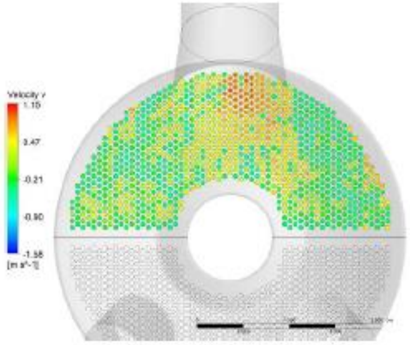
(a) Velocity profile in hot leg and SG inlet plenum



(b) Temp. distribution in reactor vessel, hot leg and SG



(c) Temp. distribution at the entrance of SG tubes



(d) Velocity distribution at the entrance of SG tubes

Fig. 5. CFD Results of Natural Circulation Flow in the Hot Leg and SG Inlet Plenum of the OPR1000

Table 8: Comparison of MELCOR Input Parameters between WH SG, CE SG, and OPR1000 SG

Parameter	WH SG	CE SG	OPR1000 SG
Recirculation ratio (r)	2.4	1.05	1.44
Mixing fraction (f)	0.96	0.65	0.84
Hot tube fraction (a)	41%	22%	25.7%
Discharge coeff. (C_d)	0.12	0.13-0.14	0.16

4. Conclusions and Further Work

KAERI performed a 3-dimensional analysis for a natural circulation flow in the hot leg and SG inlet plenum during a severe accident in an OPR1000 using a commercial code, ANSYS CFX 19.1, to determine the MELCOR input parameters. A 3-dimensional SG model was developed and validated on the basis of the OPR1000 design data. The MELCOR input parameters needed for the TI-SGTR analysis were presented on the basis of the preliminary CFD results. As a further work, we will have to recalculate the CFD analysis if new MELCOR results for the severe accident in the OPR1000 are produced.

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