CFD modeling for validation of the 1/7th scale steam generator inlet plenum mixing experiment

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1. Introduction

Steam generated from the reactor core is transferred to the steam generator through the RCS hot leg during severe accident scenarios with high-pressure. If the RCS cold leg loop seal blocks the steam, the count-current flow through the steam generator tubes and hot leg is generated. The heat of hot steam is transferred to the secondary system via the steam generator and the cooled steam with high density flows through the lower part of the hot leg. If the reactor vessel is maintained intact with high pressure, the possibility of creep rupture of the hot leg, pressurize surge line and steam generator tubes increases. If the steam generator tubes are failed earlier than the failures of the other parts, these scenarios are termed consequential steam generator tube rupture (C-SGTR) [1].

The mixing fraction of steam in the inlet plenum of steam generator affects significantly to the thermal loads to the steam generator tubes. Westinghouse 1/7th scale experiments have been performed to simulate the natural circulation with the steam generator [2]. In order to apply the lessons of the experiments to the reactor cases, one of the experiments was validated using CFD with the assumptions of simplified porous tube bundle modeling and small number of mesh [3]. Therefore, it is required to validate the experiment with less modeling assumptions. In this study, the experiment is validated with full tube bundle modeling without simplification. And the effect of the hot leg modeling in CFD has been in investigated.

2. Modeling

In the previous study [3], the target experiment is SG-S3 and half of the hot leg and steam generator is modeled by establishing a vertical symmetry plane. The expanded view of computational mesh is shown in Fig. 1. The number of mesh used was about 500,000. The tube bundle is simplified to porous media with rectangular cross section as shown Fig 2.

In this study, the hot leg and steam generator is modeled with much more fine meshes. Fig. 3 shows the new computational mesh with full tube bundle modeling. Table 1 shows the summary of the analysis model. The heat transfer from the tube bundle is controlled using user-defined function (UDF) of Fluent in order to match total amount of removed heat from tubes to the experimental data.

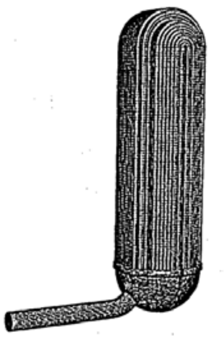
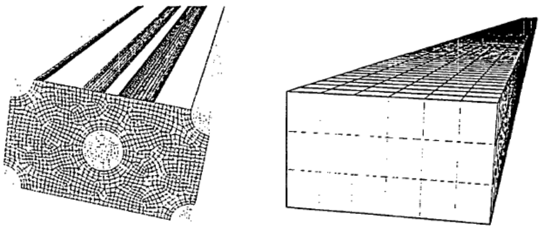


Fig. 1. Computational mesh used in NUREG-1781



(a) Real Geometry (b) Simplified Geometry

Fig. 2. Simplification of tube bundle in NUREG-1781

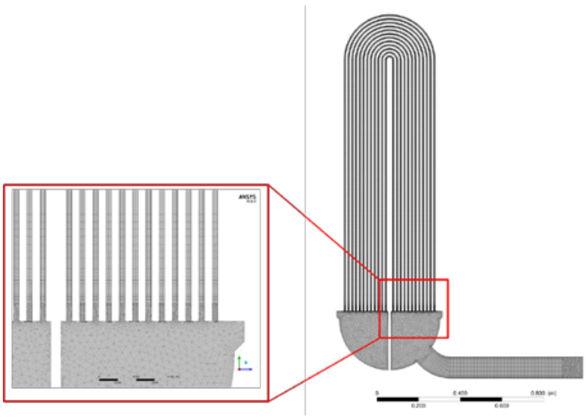


Fig. 3. Computational mesh without tube simplification

Table 1. Summary of analysis model

CFD Code	ANSYS Fluent R18.0
Geometry	3-dimensional, symmetry
Buoyancy	Full buoyancy model (ρ = f(T))
Tube bundle modeling	Full tube modeling
No. of meshes	8,190,000

3. Analysis results

The main purpose of the validation in this study is to match the number of hot and cold tubes and mixing fraction by simulating the behavior of fluid at the steam generator inlet plenum and tube bundle appropriately. The analysis conditions of the base case and 33 sensitivity cases are summarized in Table 2. The base case is selected based on the analysis conditions of NUREG-1781.

Table 2. Range of case studies

Time	**transient**, steady
Turbulence model	**Reynolds stress**, standard k-ε, k-ω SST,
Target heat transfer rate at the tube bundle	890, 1780, 2670 and **3560** W (25, 50, 75 and **100** %)
Heat transfer coefficient from the tube bundle	**250 W/m^2·K (fixed)** or UDF controlled
Tube wall toughness	**0** - 0.001 m
Secondary side temperature (tube wall)	324.55 - **337. 85** K
Inlet velocity	0.07315 - **0.1045** m/s

* Items in bold are conditions of the base case.

The analysis results are compared to the experimental data and previous analysis results with respect to the following variables;

- Heat loss at tubes
- Number of hot and cold tubes
- Average temperature of hot and cold tubes
- Average temperature of hot and cold flow at the end of the hot leg
- Mass flow rate through the tube bundles
- Mass flow rate at the end of hot leg

The monitoring location for the temperature and mass flow rate of hot leg and tubes are shown in Fig. 4.

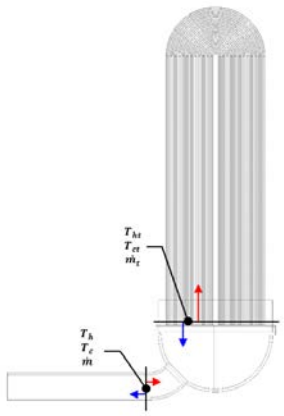


Fig. 4. Monitoring location for temperature and mass flow rate

The target heat transfer rate at the tube bundle increases gradually from 25 to 100 % of the experimental data. The previous analysis results with lower heat transfer rate is used as initial values for the next analysis of higher heat transfer rate. The analysis results are compared from Fig. 5 to 6. In Fig.5, the number of hot tubes are relatively high regardless of mass flow rate at hot leg. In Fig. 6, more mass flow rate at hot leg is calculated when 100 % target heat transfer rate at the tube bundle is assumed. The velocity distribution in Fig. 7 shows the instable mixing of hot and cold region at their interface of the hot leg. In order to improve the accuracy of the analysis, steam generator inlet plenum mixing condition is controlled according to the modeling method of the hot leg. The following three methods for the modeling of the hot leg shown in Table 3 are considered. The target heat transfer rate at the tube bundle is 100 % of the experimental data, not increasing from 25 to 100 %.

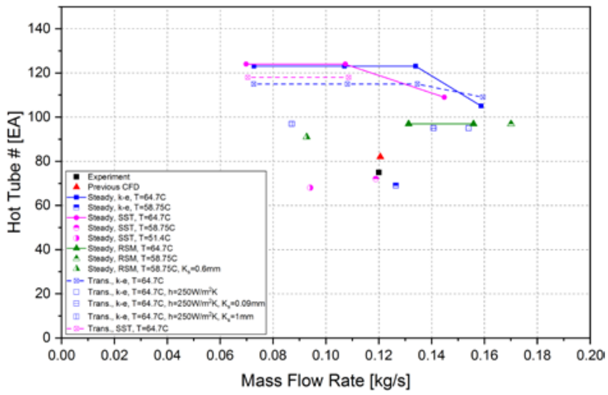


Fig. 5. Number of hot tubes according to hot leg mass flow rate

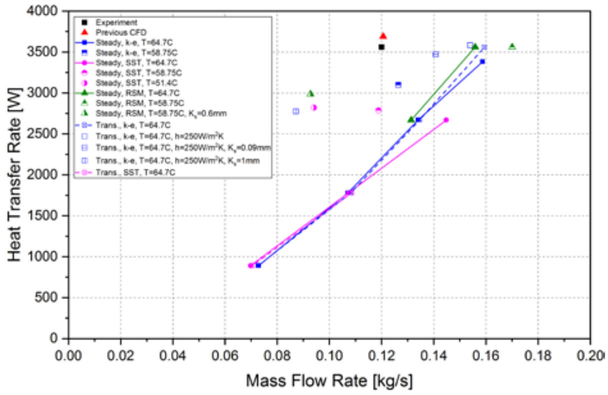


Fig. 6. Heat transfer rate at tube bundle according to hot leg mass flow rate

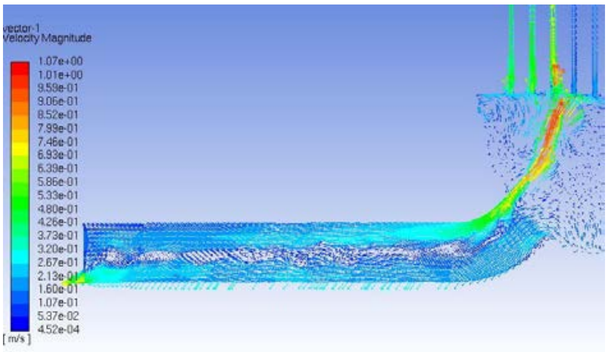


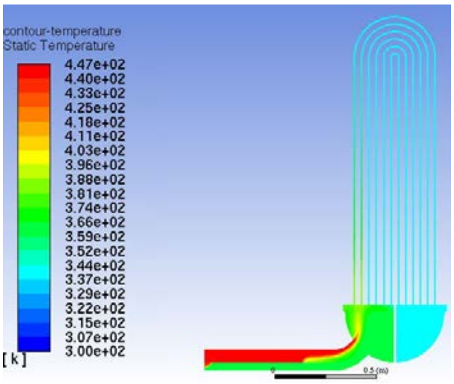
Fig. 7. Velocity vector of the base case

Table 3. Hot leg modeling methods

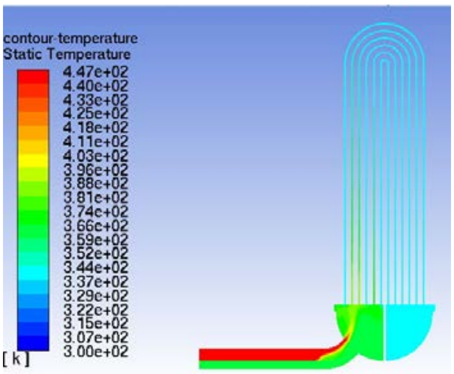
The geometry of the hot leg	Base case : division of inlet of hot leg only (upper inlet part (60%) and outlet at lower part (40 %))
	Division of the entire hot leg (60 :40)
	No hot leg modeling
Mesh density	Base case (8e6 cells)
	Fine mesh at hot leg (9e6 cells)
	Fine mesh at hot leg and inlet plenum (1e7 cells)

* All analyses are performed in steady-state condition.

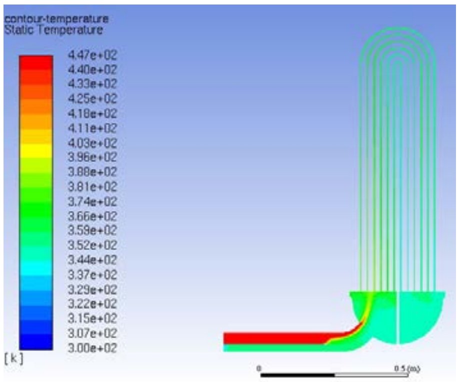
When the entire hot leg is divided by upper inlet part (60%) and outlet at lower part (40 %)), the reverse flow from the inlet plenum to the hot region of the hot leg is observed. Fig. 8 shows the temperature distribution with hot and cold region separation of the hot leg according to turbulence model. And Fig. 9 shows temperature distribution with no hot leg modeling.



(a) Standard k-ε



(b) k-ω SST



(c) Reynolds stress

Fig. 8 Temperature distribution with hot and cold region separation

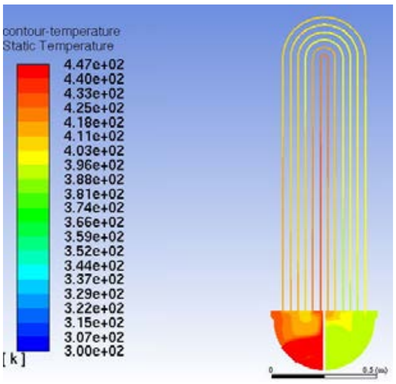
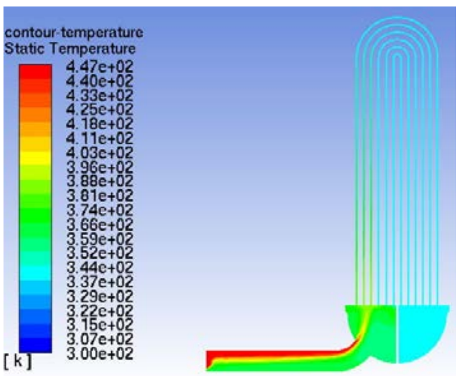
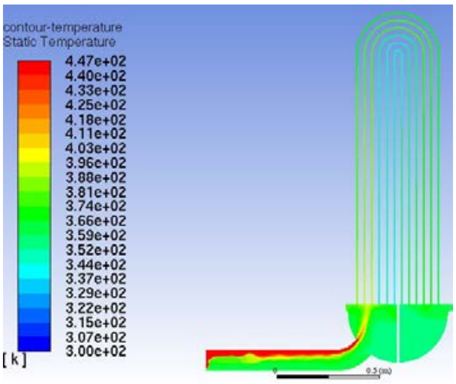


Fig. 9 Temperature distribution with no hot leg modeling

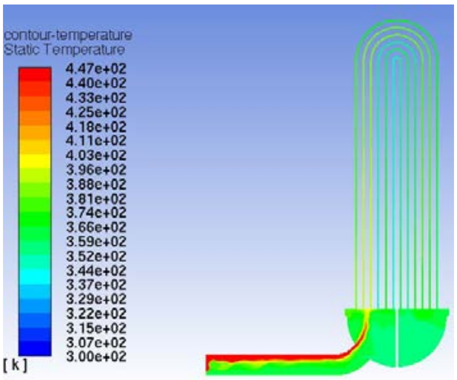
In Fig. 10, it is shown that the boundary between the hot and cold region of the hot leg becomes smooth when small number of mesh is used. The main results of hot leg modeling are summarized in Table. 4. For the various turbulence models, k-ω SST and Reynolds stress models can predict well matched number of hot tubes. When there is no hot leg, the temperatures of inlet plenum, hot and cold tubes are relatively higher than the other cases. Whereas the number of hot tubes are higher than experimental data if target heat transfer rate increases gradually, the number of hot tubes decreases if 100 % target heat transfer is applied.



(a) No. of mesh: 8e6



(b) No. of mesh: 9e6



(c) No. of mesh: 1e7

Fig. 10 Temperature distribution according to mesh density

Table 4. Summary of results according to hot leg modeling

Analysis conditions			Results		
Hot leg geometry	Turbulence model	No. of mesh	No. of hot tubes	Temperature of hot tube	Mixing fraction
Experiment			75	100.8	0.85
Hot and cold region separation at entire hot leg	Standard k-ε	8e6	54 (-28.0)	**101.2 (+0.4)**	**0.86 (+1.2)**
	k-ω SST		**75 (0.0)**	**96.7 (-4.1)**	0.92 (+8.2)
	Reynolds stress		**78 (+4.0)**	**99.8 (-1.0)**	**0.82 (-3.5)**
No hot leg	Reynolds stress		54 (-28.0)	147.1 (+45.9)	N/A
Hot and cold region separation only at inlet of hot leg	Reynolds stress	8e6	51 (-32.0)	**100.4 (-0.4)**	**0.85 (0.0)**
		9e6	65 (+13.3)	109.4 (+8.5)	**0.84 (-1.2)**
		1e7	66 (+12.0)	113.0 (+12.1)	**0.82 (-3.5)**

* Items in ( ) means difference with the experimental data in %.
* Items in bold are the analysis data within 5 % difference.

4. Conclusions

In this study, the 1/7th scale steam generator inlet plenum mixing has been validated using CFD. Full tube bundle is modeled without simplification and heat transfer coefficient from the tube is controlled by UDF. From the analysis results, the following conclusions can be drawn:

- When heat transfer rate from tube bundle is applied from 25 to 100 % gradually, more hot tubes are evaluated than the experimental data. For the similar level of mass flow rate at the hot leg, the less heat transfer rate from tube bundle than the experimental data is evaluated.
- When heat transfer rate from tube bundle is applied 100 % directly without gradual increase, the number of hot tubes, temperature of hot tubes and mixing fraction decreases and they approach to the experimental data.
- The modeling methods of the hot leg can affect inlet plenum flow and heat transfer characteristics of hot tubes. Instable flow patterns in the hot leg increases if mesh density increases.

The flow instability of the hot leg may result in the inconsistent analysis results. Therefore, the analysis including the reactor modeling will be performed as a future work.

ACKNOWLEDGEMENT

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[3] C. F. Boyd et al., CFD analysis of 1/7th scale steam generator inlet plenum mixing during a PWR severe accident, NUREG-1781, 2003.