PARAMETRIC CFD ANALYSES TO SIMULATE STRATIFIED FLOWS

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ABSTRACT
CFD analysis is widely adopted for determination of design characteristics of major equipment with flexible geometry and flow. However, the accuracy of CFD analysis strongly depends on the numerical model, governing equation and simulation parameters. A thermal stratification phenomenon can lead to unanticipated damages of nuclear piping because of the stresses caused by different fluid densities due to stratified flow. In this paper, systematic CFD analyses are performed for surge line which is one of primary piping system by using representative commercial code to investigate key parameters; (1) mesh size and time step effect (2) turbulence parameter effect (3) material property approximation effect (4) conjugate heat transfer effect (5) insurge and outsurge flow effect. From numerical analysis results related to the items (1) through (3), the optimum CFD model as well as reasonable input parameters was determined. With regard to the item (4), thermal difference was bigger as 82~208% than without considering conjugate heat transfer. On the other hand, for the item (5), stratified flows were come out clearer in outsurge flow. Based on the parametric CFD analyses to simulate stratified flows, most of numerical issues were resolved while further investigation is required for the conjugate heat transfer effect.

INTRODUCTION
Thermal stratification phenomenon is the condition that two fluid layers which have a different temperature maintain stability because of buoyancy due to a difference of density in the piping system where hot and cold fluids flow. Such phenomenon can cause bending moments because of temperature difference between higher and lower position of the piping system. These moments can cause occurrence of unexpected deformation. Also serious damage such as cracking from thermal fatigue can be occurred at nuclear piping by iterating thermal stratification phenomenon [1-2].

Recent observations at operating plants and subsequent USNRC requirements have identified flow stratification in surge lines as a phenomenon that must be considered in the design basis of surge lines [3]. While computational fluid dynamics (CFD) analysis is widely adopted for determination of design characteristics of major equipment with flexible geometry and flow, however, the accuracy of CFD analysis solutions strongly depends on the numerical model, governing equation and simulation parameters.

In the present research, by using a commercial program, systematic numerical analyses are performed for the surge line which is one of primary piping system of pressurized water reactor. The effect of analysis parameters such as mesh size and time step, turbulence characteristics, material property approximation technique, conjugate heat transfer analysis technique and insurge/outsurge flow condition are investigated. Based on these parametric analysis results, reasonable input parameters and the optimum analysis model are determined. Then, detailed CFD analyses are carried out to simulate stratified flows and resulting specific features with recommendations are fully discussed.

ANALYSIS CONDITIONS
Geometry
In this study, a typical surge line is considered which connects pressurizer and hot leg of reactor coolant system (RCS). The model, which is shown in Fig. 1, is adopted from KORI unit 1, an operating commercial nuclear power plant in Korea. Temperature data are measured from three different locations of section ‘A’, ‘B’ and ‘C’ as illustrated in Fig. 1. In order to check the temperature difference, they are measured on
top and bottom of piping, respectively. A 3-dimensional CFD model is used to match the real geometry for the analysis.

![Geometry of surge line](image)

**Fig. 1 Geometry of surge line**

**Boundary condition**

The thermal stratification is mainly influenced by the temperature difference. Since the biggest deformation is expected from the maximum temperature difference, the heat up condition is considered for the simulation.

There are two stratification situations to be considered in surge line under the heat up condition. One is the outsurge flow; while the surge line is occupied by the cold fluid with temperature of 324.7 K, the hot fluid of 491.3 K is flowing down to the pipe from the pressurizer side nozzle. The other is insurge flow; while the piping is occupied by hot water of 491.3 K, the cold fluid of 324.7 K is flowing into the pipe from the hot leg side nozzle. The inlet velocity is set to 0.07 m/s for both cases.

\( k-\varepsilon \) turbulent model is suitable for simulation of turbulent flow. \( k \) and \( \varepsilon \) mean the turbulent kinetic energy and turbulent dissipation rate which are set to \( 1.62 \times 10^{-5} \) and \( 5.97 \times 10^{-7} \) respectively, according to the reference [4]. Analyses are performed by using a commercial CFD code, Fluent 6.2.

**Material property**

Since the fluid mostly consists of water, fluid material properties of water are used as shown in Fig. 2. Geometry and material properties of piping material of SA376 TP316 steel are listed in Table 1.

![Material properties of fluid](image)

**Fig. 2 Material properties of fluid**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter of pipe</td>
<td>323.85 mm</td>
</tr>
<tr>
<td>Thickness of pipe</td>
<td>33.45 mm</td>
</tr>
<tr>
<td>Density</td>
<td>7,833.411 kg/m³</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>500.1721 J/kg-K</td>
</tr>
<tr>
<td>Conductivity of pipe</td>
<td>13.88915 W/m-K</td>
</tr>
</tbody>
</table>

**PARAMETRIC ANALYSIS RESULTS**

In this study, parametric analyses are performed to investigate the effect of following parameters.

**Mesh size and time step effect**

The mesh size and the time step are one of key factors determining the CFD analysis accuracy. To obtain the optimal mesh size, three different models were applied as summarized in Fig. 3 and Table 2. Also, four different time steps of 0.1, 0.2, 0.5 and 1.0 are considered for the accuracy verification. As shown in Fig. 4, the mesh size difference was no significant in terms of temperature between case (a) and (b). Case (c), however, showed a considerable amount of difference at all sections. The effect of time step was no significant up to 0.5. However, the result from time step of 1.0 was determined to be not reliable. Based on the parametric analysis, the mesh size is set to case (b) and the time step is set to 0.5.
Fig. 3 Different mesh types at pipe section

(a) Coarse mesh  (b) Intermediate mesh  (c) Fine mesh

Table 2 Number of nodes and cells on three mesh types

<table>
<thead>
<tr>
<th>Mesh type</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes</td>
<td>356,697</td>
<td>237,159</td>
<td>153,387</td>
</tr>
<tr>
<td>Number of cells</td>
<td>340,992</td>
<td>250,368</td>
<td>143,040</td>
</tr>
</tbody>
</table>

Turbulence parameter effect

Since the Reynolds number of pipe flow exceeds 12,000, the flow is considered to be turbulent, and thus, the $k$-$\varepsilon$ model is applied to simulate the flow aforementioned. $k$ and $\varepsilon$ values are used to define the surge line flow. In order to verify the $k$-$\varepsilon$ value dependency on the analysis result, two different cases were considered as summarized in Table 3. As shown in Fig. 5, both cases resulted in same temperature values for all three different sections. And thus, it is concluded that $k$-$\varepsilon$ values are not sensitive for the case considered.
Table 3 Two cases of \( k-\varepsilon \) parameter

<table>
<thead>
<tr>
<th>( k-\varepsilon ) of the reference</th>
<th>1.6236( \times 10^{-5} )</th>
<th>5.97( \times 10^{-7} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k-\varepsilon ) of the contrast</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Material property approximation effect

It is usual to apply the polynomial approximation in simulating thermal stratification. The Boussinesq approximation, however, is used frequently to save the analysis time and effort. While the polynomial approximation uses different density for corresponding temperature, the Boussinesq model assumes the density at a constant for the entire analysis except for the buoyancy term in the momentum equation (1) at follows:

\[
(\rho - \rho_0)g \approx -\rho_0 \beta (T - T_0)g
\]

Here, \( \rho_0 \) is the (constant) density of the flow, \( T_0 \) is the operating temperature, and \( \beta \) is the thermal expansion coefficient.

Analysis results for both cases are compared in Fig. 6 at three different sections. For all cases, the Boussinesq model resulted in a deviation from the polynomial model after 200 seconds. While the polynomial approximation showed a disappearance of stratification, the Boussinesq approximation showed a stable two layers flow after a certain amount of time. Since the stratification is supposed to be disappeared with continuous invasion of hot fluid, the polynomial approximation is determined to be reasonable for the surge line flow.

DETAILED ANALYSIS RESULTS

Conjugate heat transfer effect

It is usual to ignore the pipe wall effect in the CFD analysis. However, the amount of heat flux through the pipe may influence the overall temperature distribution in surge line stratification phenomenon. For this reason, the conjugate heat transfer effect due to pipe wall was investigated.

Figure 7 shows the difference between vases with and without conjugate heat transfer effect at three different locations. The maximum temperature difference between top and bottom was observed from the section ‘A’. As shown in Fig. 7 (a), the analysis case with pipe wall heat transfer effect showed 82% higher value compared to that of without pipe wall effect in terms of the temperature difference between top and bottom side after 500 seconds of analysis time. Also, the temperature increase in bottom side is observed to be much slower due to the pipe wall heat transfer. This implies that the analysis without considering pipe wall effect may result in unconservative prediction in simulating stratification behavior at surge line.

Fig. 6 The effect of density approximation model

Figure 8 shows snapshots for temperature distributions at section A for three different times of 100, 200 and 300 seconds for both cases. As shown in Fig. 8 (a), the temperature at the top side for the case with pipe wall is much lower than that of without pipe wall due to the heat transfer through the pipe. However, not a significant difference is observed from the bottom side. After 500 seconds, the temperature at the top side shows almost same values. However, the temperature distribution at the bottom side shows a big difference as shown
in Fig. 8 (c). Since the pipe wall rapidly flows out the heat from the hot fluid, the temperature increase is much slower at the bottom side.

![Fig. 7](image)

**Fig. 7** The effect of the conjugate heat transfer in a case of the outsurge condition

![Fig. 8](image)

**Fig. 8** Snapshot of simulated temperature distributions at section ‘A’

### Insurge flow and outsurge flow effect

The surge line experiences the iteration of outsurge and insurge flow. The insurge flow is the opposite condition to the outsurge flow. That is, the cold fluid is flowing into the hot fluid filled piping system from the hot leg nozzle. The insurge flow is also simulated with and without considering conjugate heat transfer effect due to the pipe wall. As shown in Fig. 9, the maximum temperature difference between top and bottom side is observed from section ‘B’. The temperature difference with pipe wall effect was 208% bigger than that of without pipe wall effect. The difference was more considerable in case of insurge flow compared to outsurge flow.
CONCLUSION

In this study, parameters which affect temperature transient calculation of thermal stratification are observed. As a result, the effect of parameters such as mesh size, time step, \( k-\varepsilon \) values and density approximation method are investigated and the a simulation procedure for surge line stratification behavior is proposed. Also, the conjugate heat transfer effect due to the pipe wall is investigated for insurge and outsurge flows. The pipe wall effect produced significant difference in terms of fluid temperature as expected. While the maximum temperature difference between top and bottom side is observed from location A which is close to the pressurizer in case of outsurge flow, it is observed from location B which is middle of surge line in case of insurge flow. The pipe wall effect is observed to be more severe in case of insurge flow. Since temperature difference with insurge flow is different from that with insurge flow, the situation of surge flow should be defined clearly in order to get the accurate temperature distribution in piping system.

ACKNOWLEDGMENTS

The authors are grateful for the support provided by a grant from Post BK(Brain Korea) 21 Center at Sungkyunkwan university and Korea Institute of Nuclear Safety(KINS).

REFERENCES