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CFD Simulation of Thermal Mixing in Annulus Water Pool

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1. Introduction

Some studies have been carried out on thermal mixing phenomena induced by steam jet in a subcooled water pool. For Computational Fluid Dynamics (CFD) simulation of thermal mixing phenomena, it is very important that the model geometry and boundary conditions are appropriately adjusted to produce tests that would provide useful information for validating the corresponding computations with CFD. However, there are no experiment and analysis about the thermal mixing phenomena in annulus type pool like In-containment Refueling Water Storage Tank (IRWST).

In the present paper, the benchmark numerical calculation with a thermal mixing experiment in annulus type water tank was performed to develop an optimized 3-D evaluation methodology of thermal hydraulic behavior in APR1400 IRWST. A steam discharge through the sparger and the condensation phenomenon were modeled with the choking flow and the thermal mixing model in quenching tank using CFX v.11 with the steam condensation region model.

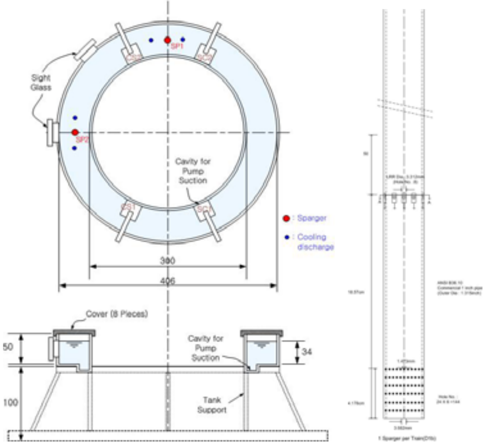
2. CFD simulation

The sophisticated computational analysis for steam condensation process is desired but the state-of-the arts of computational techniques are not still immature to provide the reasonable results. The discharged steam into the subcooled water pool is condensed over a short distance so that we can look at the liquid exiting in the condensation region for its effects on the pool thermal mixing. Therefore, we use the steam condensation region model in which the steam jet is condensed into water within the steam jet penetration length.

2.1. Annulus water pool experiment

The annulus water pool experiment was designed to provide data representative of the behavior of the prototype for CFD simulations of IRWST behavior and not to be distorting seriously the important phenomena actually taking place in prototypic IRWST. Furthermore, this test was performed to examine circulation and mixing in the IRWST pool and determine the temperature in the vicinity of the spargers in relation to the local temperature used in NUREG-0783.

As shown in Fig. 1, annulus water tank has inner diameter of 3 m, outer diameter of 4 m and height of 0.5 m. Two spargers were made of a 1 in. schedule 40 pipe with 144 side discharge holes, 8 LRR (Load Reduction Ring), and a bottom hole.



(a) Annulus Tank (b) Sparger

Fig. 1. Annulus water tank and sparger

Based on the Phenomena Identification and Ranking Table (PIRT) for thermal mixing phenomena in the IRWST [1], the test procedure and boundary conditions were chosen to simulate a postulated TLOFW accident in APR1400. To cool down the water pool, the water was sucked through 2 sumps at bottom of tank and cooling water discharged through 4 points at top of tank.

2.2. Condensation region model

For simplicity, we use a cylindrical control volume as a condensation region and it is assumed that the jet condensation length is 7 jet diameters. And the width of the jet can be calculated using Eq. (1) [2].

$$\frac{\text{Jet Width}}{x} = \tan 13^\circ \qquad (1)$$

For each discharge hole, the condensation region model without considering the complicated velocity profiles is established as in Fig. 1. For the complicated geometry in a prototype multi-hole sparger, we use the lumped condensation region model, in which the discharge holes are put together in a single cylindrical shape. Fig. 2 shows the lumped steam condensation region model.

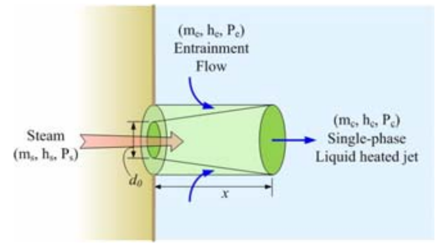


Fig. 2. Control volume of steam jet condensation region

For steam injection into water, the mass flow rate of condensed water is determined from the conservation of mass, momentum and energy equations, Eqs. (2)-(4). Mass and energy equilibrium at the interface of steam condensation region (Fig. 2) is simply expressed by stating that the exit flow rate from condensation region is equal to the sum of the injected steam flow rate and the entrained flow rate.

$$\dot{m}_s + \dot{m}_e = \dot{m}_c \qquad (2)$$

$$\rho_s V_s^2 A_s + P_s A_s + P_\infty (A_c - A_s) = P_c A_c + \rho_c V_c^2 A_c \qquad (3)$$

$$\dot{m}_s h_s + \dot{m}_e h_e = \dot{m}_c h_c \qquad (4)$$

The mass flow rate of steam measured is used as the steam velocity (V_s) with an assumption of a steam quality of one for solving the equations. And the measured enthalpy of steam is directly used as input of CFX calculation. The steam condensation region is modeled as source term to input the mass and energy of the steam into the water pool. Furthermore, the mass flow rate and enthalpy of the entrained water can be calculated by CFX itself.

The velocity and the enthalpy of the condensed water are obtained by using an assumed density value at 1.22 bar and the water temperature. The steam properties and all areas can be obtained from the experiment. And the calculated total pressure at the steam condensation region boundary is assumed to be the pressure of condensed water, P_c. The velocity of the condensed water, V_c is obtained by substituting the above data into Eq. (3). With these values, we can calculate the steam jet induced thermal mixing in subcooled water pool by using an appropriate turbulent model and some other physical models.

2.3. Grid model and boundary conditions

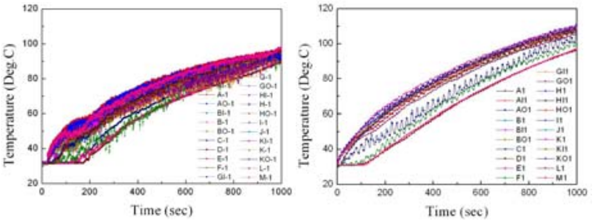
With finite volume formulation in the simulations, three-dimensional model has been developed for the annulus water pool. Because there are too many holes, it is impossible to model all holes as condensation region, respectively. Therefore, we introduced the lumped condensation region model. For each sparger, the LRR holes and side holes are modeled as only one LRR and one side lumped condensation region, respectively. A commercial software package CFX 11 has been used. Hexagonal meshes of approximately 660 thousands nodes have been created with ICEM code.

Transient simulations were carried out with a time step size of 0.1s with convergence criteria that the residual should fall below 10^{-4}. Data points at all thermocouple locations have been tracked in order to verify the asymptotic state of the solution.

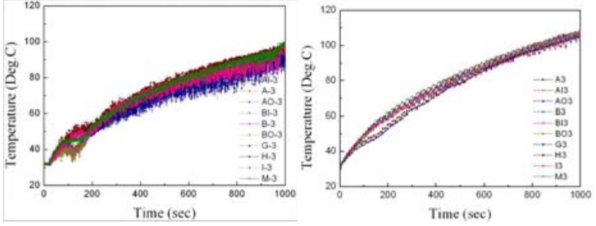
3. Results and discussion

This paper compares the results of the CFX analysis with the annulus water pool experiment with 31℃ of initial pool temperature and 500 kg/m^2-s of steam mass flux. Fig. 3 shows the comparison of the temperature measurements with the CFX analysis results for 1,000s. The comparison of the calculated and experimentally measured temperature profiles shows similar trends as a whole.

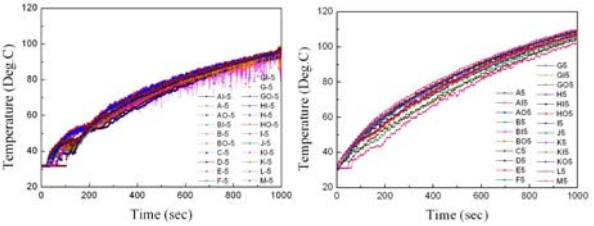
The flow field around side discharge holes of sparger is inclined toward bottom of tank due to the discharge flow through LRR. The graphs in Fig.3 are the temperature profile at 3 elevations. The temperatures at bottom of the pool are oscillating much more than those at other locations. On the whole, the CFX overestimates the temperature over the pool all locations.



(a) Experiment at 3cm (b) CFX analysis at 3cm



(c) Experiment at 11.7cm (d) CFX analysis at 11.7cm



(e) Experiment at 32cm (f) CFX analysis at 32cm

Fig. 3. Temperature profiles

4. Conclusion

CFD simulations have been performed for understanding thermal mixing phenomena caused by the steam jet in the annulus type water pool. This shape of tank reflects the prototype of APR1400 IRWST. A good agreement with the experimental data indicates the validity of the steam condensation region model in annulus water pool.

The success of the simulation demonstrated that CFD approaches are quite powerful to support the detailed physical understanding of the thermal mixing phenomena. This methodology can be applied to the thermal mixing analysis in actual APR1400 IRWST.

REFERENCES

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