Analysis for the Thermal Mixing Characteristics of Steam Jet in the Subcooled Water Tank

H. S. Kang,[a] Y. S. Kim,[a] H. G. Chun,[a] Y. J. Yoon,[a] C. H. Song [a]
[a] Korea Atomic Energy Research Institute, P. O. Box 105,Yuseong,Taejon, Korea, 305-600, hskang3@kaeri.re.kr

1. Introduction

The experimental research has been performed to evaluate the steam condensation load and the thermal mixing phenomena in the subcooled water tank when the steam is discharged into the tank through the sparger[1, 2]. The test facility was modified from the previous one by installing several thermocouples around the sparger to measure the temperature of the steam and the entrained water flowing into the steam[2]. Major of objective of this test is to develop a condensation regime map for the design and the operation of APR1400 (Advanced Power Reactor 1400MWe) IRWST(In-containment Refueling Water Storage Tank). A CFD benchmark calculation for the test results has been performed to develop the methodology of a numerical analysis for thermal mixing between the steam and subcooled water. In the CFD analysis, the steam condensation phenomenon is treated by a simple model of the steam condensation region. The CFD analysis results for 30 seconds show a good agreement for the temperature distribution in the tank with those of the experiment.

2. Thermal Mixing Test

The thermal mixing test has been performed by changing the steam mass flux and the tank water temperature according to the steady state and the transient state[2]. The experimental facility modified from the B&C Loop consists of a pressurizer, a steam discharge line, a subcooled water tank, a steam sparger, and a steam generator, as shown in Fig. 1. The sparger at the discharge hole side, 64 of 1 cm diameter (4 rows, 16 holes/ row), is still made up of a 6 inch schedule 40S pipe and the diameter of the pipe just above the discharge holes is reduced to 2 inch. The bottom hole of a 2.5 cm diameter and the vent area of the LRR(Load Reduction Ring) are blocked in the test. These changes are intended to provide a constant steam flux for a long time in the test. In the tank, 8 thermocouples to measure in detail the temperature of the steam and the entrained water flowing into the steam are installed, and two measurement rigs of 27 thermocouples are installed to obtain the thermal mixing pattern. The second rig is installed to observe the extent of the thermal mixing along the circumferential direction in the tank.

3. Numerical Analysis

3.1 Critical Flow and Condensation Region Model

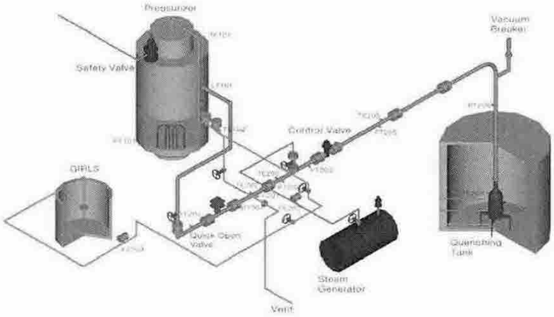

Figure 1. Schematic diagram of the test facility

In the thermal mixing test, the saturated steam at about 10 bar inside the sparger is initially discharged into the water at 26 °C at 1 bar in the tank. A choking is likely to happen at the location of the sparger holes during this situation. The discharged steam flows into the water in the tank as a jet flow, and then quickly condenses to water in a short time and length by a direct contact condensation[3]. The numerical modeling for this condensation process is so difficult that we used the steam condensation region model in which the steam is perfectly condensed to water within the steam penetration length. The calculated penetration length of the steam discharged from the surface holes, 1 cm of diameter, is about 5.3 cm. The width of the jet at the end of the penetration length can be calculated as 1.2cm, but this is only an approximated value based on the boundary layer theory. The mass flow rate of the condensed water and the entrained water at the outlet of the condensation region can be calculated from the mass, momentum, and energy conservation law over the condensation region.

3.2 Grid Model and Boundary Conditions

A multi-grid with an axis symmetric condition simulating the sparger and the subcooled water tank for the CFD calculation is generated. The axis symmetric model is introduced because the flow pattern in the tank was estimated as it varies little in the circumferential direction. Around the condensation region and the initial air/water interface region, the meshes are more densely distributed than the other regions to accommodate the expected high velocity and temperature gradients. The inlet boundary condition, the Dirichlet condition, is set at the end of the steam condensation region with a time dependent velocity and temperature. The pressure outlet boundary conditions, the Neumann condition, are set for the tanks upper region, which only allows for the outflow of air. The outlet conditions for the entrained water are applied to the upper and lower region of the steam condensation region by the negative value of the velocity with the inlet condition in the CFX4.4. The symmetry condition is applied to the center of the sparger pipe line.

3.3 Flow Field Models and Governing Equation

Thermal mixing phenomenon in the subcooled water tank is treated as an incompressible flow, a free surface flow of air between the water, a turbulent flow, and a buoyancy flow. Therefore, the governing equations used in this study are the Navier-Stokes and energy equations with a homogenous multi-fluid model. The turbulent flow is modeled by a standard k-ε turbulent model, and the buoyancy is modeled by the Boussinesq approximation.

3.4 Discussion on the CFX Results

Fig. 2 shows that the temperature distribution in the tank is varied according to the flow pattern as time passes. The temperature around the main flow path of the condensed water increases by 2~3 °C from the initial water temperature because of the thermal mixing between the condensed water and tank water which happens during the stream of the condensed water. From the figures, we can see that the temperature around the sparger increases little by little and may give an adverse effect to the stable steam condensation. Especially, the temperature in the lower region, below the sparger discharge head, increases more quickly than that of the upper region. The temperature distribution from 6.0 to 15.0 seconds definitely shows a typical circulation in the tank. It is that the condensed water discharged from the sparger flows upward and downward, and then turns its direction towards the side region and then changes its direction into the sparger. As time passes, Fig. 9 shows that one of the flows in the upper region again moves upward with a 45° angle and reaches the top position of the tank (35 seconds). In fact, this upward flow is only a virtual display in the CFD results, and that region is actually an air located area in the tank. This confused display arises from the characteristic of the VOF method where all the governing equations except each phase of the volume fraction is solved using the average value of both phases.

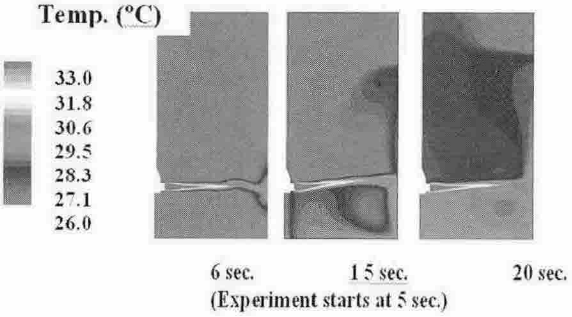

Figure 2. Temperature distribution of the CFD results

4. Conclusion

The comparison of the CFX results with the test data showed a good agreement as a whole, but some small temperature differences between the CFX results and the test data were shown at some locations of the thermocouples in the subcooled water tank. The CFX results at several locations show a higher temperature value and increased speed than those of the test results. This difference may have arisen from the fact that the temperature and the velocity of the calculated condensed water by the condensation region model are higher than the real value. However, CFX4.4 with the steam condensation region model can adequately simulate the thermal mixing behavior in the subcooled water tank with the minor limit. We can anticipate that the numerical model for the thermal mixing taking place for a long time in the IRWST of the APR1400 can be developed by this methodology.

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