Lagrangian Analysis of the Spray Cooling Test in the THAI Facility

Hyung Seok Kang* and Jongtae Kim
Korea Atomic Energy Research Institute, 989-111, Daedeok-daero, Yuseong, Daejeon, 305-353, Republic of Korea
**Corresponding author: hskang3@kaeri.re.kr*

1. Introduction

The operation of a spray system in a nuclear power plant may prevent a possible damage on the containment wall by decreasing the temperature of the mixture gas of air-steam-hydrogen in the containment during a severe accident. To accurately predict a local steam concentration under a spray water operation, a CFD (Computational Fluid Dynamic) analysis using a Lagrangian method is being used because the change of a local steam concentration can affect a hydrogen combustion phenomenon. In this paper discussion is focused on the spray cooling test conducted in the THAI facility to investigate the influence of water spray operation on the temperature change of steam-air mixture gas [1, 2]. The test results of the spray cooling have been extensively used by the project partners for further development and validation of computational codes within the frame of the OECD THAI-2 project [1].

2. Experimental Research [1, 2]

2.1 Test Facility

Main component of the facility is a cylindrical stainless steel vessel of 9.2 m height and 3.2 m diameter with a total volume of 60 m³ (Fig. 1). The vessel outer wall is completely enveloped by a 120 mm rockwool thermal insulation. A full cone whirl spray nozzle was used for the tests. The spray nozzle outlet was positioned vertically downward at elevation H = 7.4 m in the geometric center of the vessel. A spray angle of 30° was selected to exclude any change in spray patterns due to interactions with the vessel walls. An air-driven axial fan installed in the lower plenum of the vessel was used to allow homogenization of the vessel gas atmosphere prior to the start of the spray operation. To monitor the gas temperature change during the spray operation, 16 fast sheathed thermocouples (TCs) with outer diameter 0.5 mm were installed at 13 different elevations in the vessel. The measurement uncertainty of gas concentration, temperature, and pressure is shown in Table 1.

Table 1: Uncertainty of Measuring Devices

Gas concentration	Thermocouple	Pressure
±0.5 vol%	±2.5 °C up to 333 °C ±0.75% above 333 °C	±4 mbar

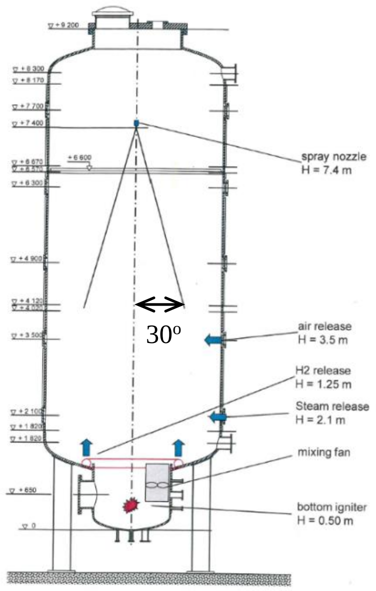


Fig. 1. THAI Facility for Spray Cooling Test

2.2 Test Specification and Test Procedure

Table 2 summarizes the specified initial test condition for the spray cooling test. The preconditioning process was performed to meet the specified initial condition before the start of the spray operation. The spray water with about 21 °C to 30 °C was injected for 200 s to cool down the mixture gas with its initial temperature of about 90 °C (Fig. 2).

Table 2: Initial Test Conditions as Specified

Parameters	Value
Vessel pressure	1.5 bar
Gas temperature	90 °C
H_2 concentration	None
Steam content	25 vol%
Spray water - Temperature - Mass flow rate - Droplet size(d_{32})	21 - 30 °C ~ 1 kg/s ~ 600 μm

2.3 Discussion on Test Results

Fig. 2 shows the transients of the gas temperatures and the spray water temperature in the spray cooling test. There are slight differences in the temperature decreases according to the TC elevations. The slower temperature decreases from its initial temperature to about 85 °C are shown at elevation from H = 8.4 m to H = 9.0 m. This may be resulted from that the spray water is discharged downward from the nozzle at elevation H = 7.4 m. Whereas the faster temperature decrease from its initial temperature to about 70 ºC at elevation from H = 0.7 m to H = 4.9 m indicates that the injected spray water with 30º angle from the nozzle passes over TCs in the lower parts than higher parts in the vessel as shown in Fig. 1. The faster decreased temperatures start to increase from about 70 ºC to about 73 ºC for about 170 s - 200 s. This may be caused from the change of the spray water temperature at this period (Fig. 1).

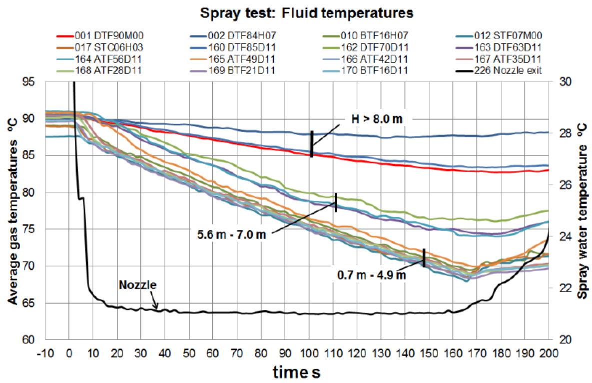


Fig. 2. Measured Data of the Spray Cooling Test

3. CFD Analysis

3.1 Grid Model and Flow Field Models

A 3-dimensional grid model including a spray nozzle with a half symmetric condition was constructed to represent the THAI facility (Fig. 3). The spray nozzle was modeled such as a semispherical shape to assure the spray angle 30º. A total of about 1,562,000 hexahedral cells with a cell length of 2 mm - 30 mm were generated in the grid model [3]. A wall condition with a constant temperature of about 363 K was applied on the outer surface of the grid model.

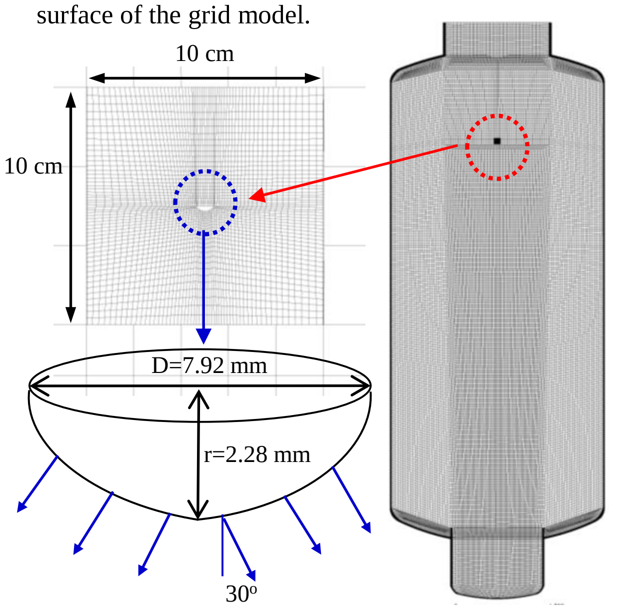


Fig. 3. Grid Model for the Spray Cooling Test

ANSYS CFX-19.1 [4] with the Lagrangian-Eulerian model was chosen for the simulation of the steam cooling owing to the spray water in the vessel. The Lagrangian method was used to simulate the spray water injection through the nozzle shown in Table 3. The spray water temperature was given according to the test data as shown in Fig. 2. The Eulerian model was applied to analyze the behavior of the mixture gas of steam-air under the spray operation. A heat transfer phenomenon between the spray water and steam-air mixture gas was modeled by an energy conservation law such as Eq. (1) where Q_C is a convective heat transfer (Eqs. (2) and (3)), Q_M is a heat transfer associated with phase change (Eq. (4)), and Q_R is a radiative heat transfer (Eq. (5)) [4]. If the vapor pressure of the spray water by Eq. (6) is higher than the ambient gas pressure, the evaporation model is applied to the spray water. Otherwise, the diffusion model is used to calculate the mass transfer between the spray water and the mixture gas of steam-air (Eq. (7)). A turbulent flow was modeled by the shear stress transport turbulent model [4]. The time step size in the transient calculation of 100 s was 1 ms - 2.5 ms for obtaining converged solutions.

Table 3: Spray Water Model

Spray Model (Lagrangian method)
- Diameter (d_{32}) = 0.6 mm - Mass flow rate = 1 kg/s (U = 19.89 m/s) - Nozzle diameter = 7.92 mm - Ejected particle number = 2657 [1/s]
Phase Change Model (Spray Water)
- $P_{vap} > P_{amb}$: Evaporation - $P_{vap} < P_{amb}$: Diffusion or Convection

$$\sum\left(m_C C_p\right)\frac{dT_p}{dt} = Q_C + Q_M + Q_R \tag{1}$$

$$Q_C = \pi d \lambda Nu (T_G - T) \tag{2}$$

$$Nu = 2 + 0.6 Re^{0.5}\left(\mu \frac{C_p}{\lambda}\right)^{1/3} \tag{3}$$

$$Q_M = \sum \frac{dm_C}{dt} V \tag{4}$$

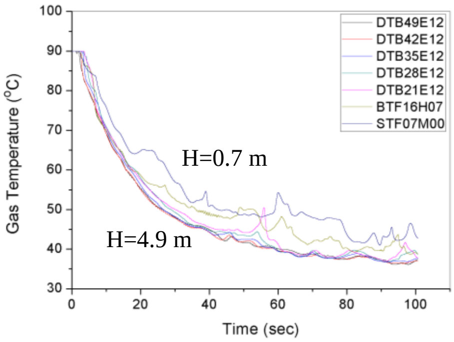
$$Q_R = \varepsilon_p \pi d_p^2 \left(\pi I - \sigma n^2 T_p^4\right) \tag{5}$$

$$P_{vap} = P_{scale}\exp\left(A - \frac{B}{T_p + C}\right) \tag{6}$$

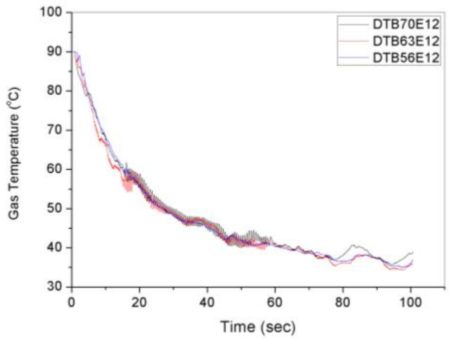
$$\frac{dm_p}{dt} = \pi d_p \rho D Sh \frac{W_C}{W_G}\ln\left(\frac{1-X_S^V}{1-X_{vap}^V}\right) \tag{7}$$

3.2 Discussion on the CFD Results

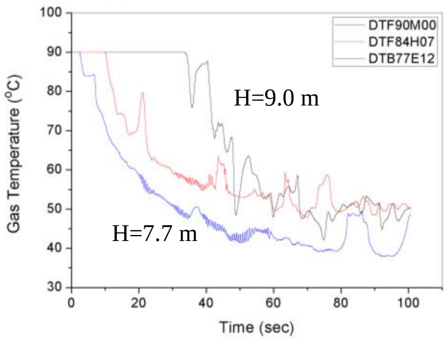
The CFD results for the spray cooling test are shown in Figs. 4 to 7. Fig. 4 shows that the CFD results can simulate the temperature decrease of steam-air mixture from the initial temperature of about 90 ºC to about 40 ºC - 50 ºC according to the elevation using the Lagrangian-Eulerian. However, the CFD results overestimate the extent of the cooling rate of steam-air mixture owing to the spray water when compared to the test data. This may be explained by the fact that the convective heat transfer between the spray water and the mixture gas occured greater than that of test. Fig. 5 shows the pressure transient at elevation H = 4.9 m as time passes. The pressure decrease is resulted from the temperature decrease of the mixture gas. Figs. 6 and 7 show the calculated temperature contours and velocity profiles as the time passes, respectively.



(a) Elevation H = 0.7 m to H = 4.9 m



(b) Elevation H = 5.6 m to H = 7.0 m



(c) Elevation H = 7.7 m to H = 9.0 m

Fig. 4. Predicted Temperatures by CFX-19.1

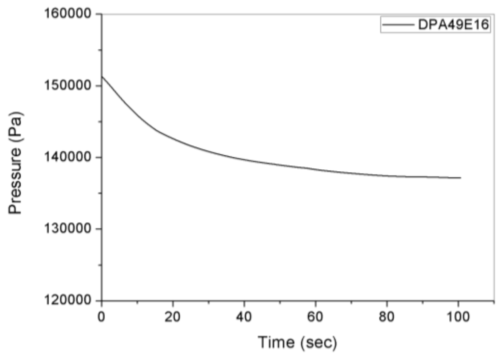


Fig. 5. Predicted Pressure (H = 4.9 m) by CFX-19.1

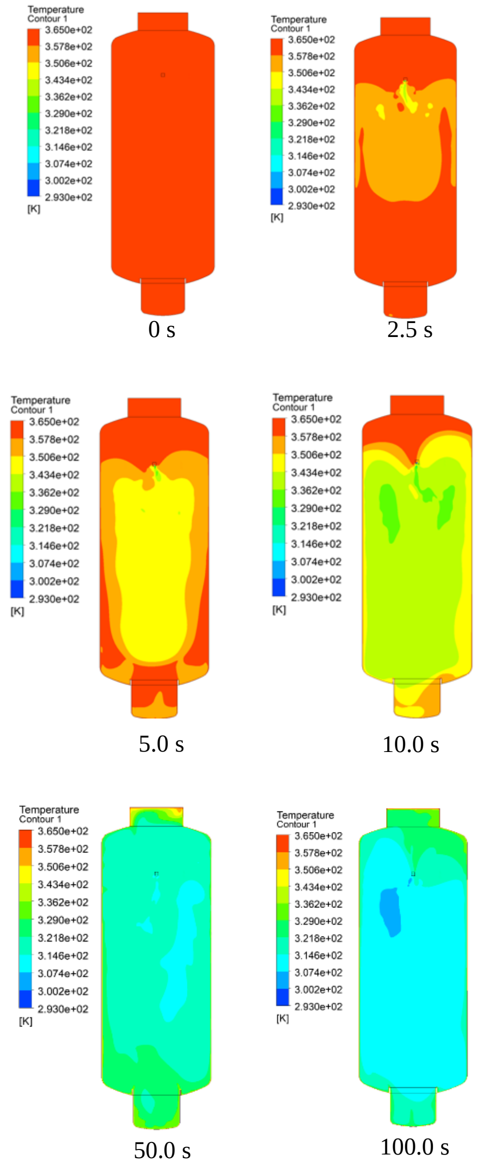


Fig. 6. Temperature Contours according to Time Pass

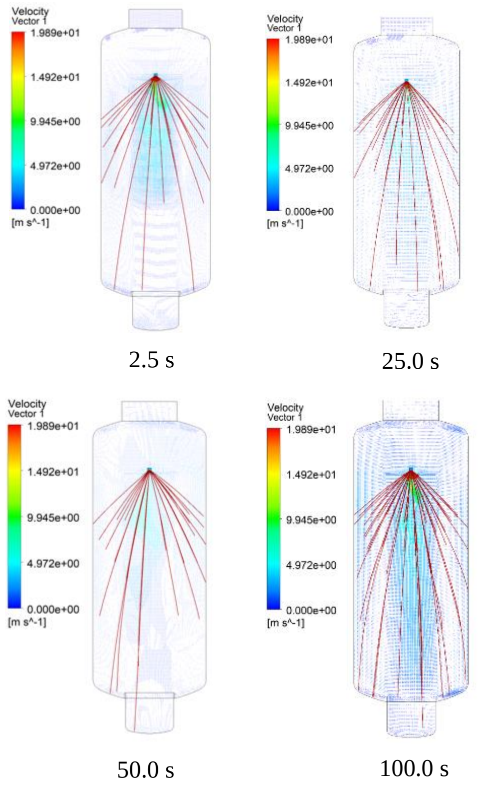


Fig. 7. Velocity Profile under the Spray Operation

4. Conclusions and Further Work

KAERI performed the CFD calculation of the spray cooling test conducted in the THAI facility to observe an applicability of the Lagrangian-Eulerian model for further development and validation of computational codes within the frame of the OECD THAI-2 project. We reasonably simulated the cooling of the steam-air mixture in the tests. However, the CFD results overestimated approximately 2.5 times the extent of the cooling rate of the mixture gas owing to the spray water when compared to the test data. To reduce this discrepancy between the CFD results and test data, we will have to investigate the correlation of the convective heat transfer between the spray water and the steam-air gas during the spray operation.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science, ICT, and Future Planning) (No. 2017M2A8A4015277)

REFERENCES

[1] T. Kanzleiter, S. Gupta, K. Fischer, G. Ahrens, G. Langer, A. Kühnel, G. Poss, G. Langrock, F. Funke: Hydrogen and Fission Product Issues Relevant for Containment Safety Assessment under Severe Accident Conditions. OECD-NEA THAI Project Final Report No. 150 1326–FR 1, Becker Technologies GmbH, Eschborn, Germany, June 2010.

[2] S. Gupta, B. Balewski, A. Kuhnel, M. Colombet, Hydrogen Combustion during Spray Operation: Tests HD-30, HD-31, HD-32, 3rd PRG and MB Meeting of THAI-2 Project, Paris, Nov 19-21, 2012.

[3] H. S. Kang, S.-W. Hong, Sanjeev, CFD Analysis for H2 Flame Propagation during Spray Operation in the THAI Facility, Proc. of KNS Spring Meeting, Jeju, Korea, May 7-8, 2015.

[4] Ansys Inc., ANSYS CFX-19 Manual, 2018.