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Numerical Analysis for the Steam Condensation by the Spray Water in the TOSQAN Test Using OpenFOAM

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1. Introduction

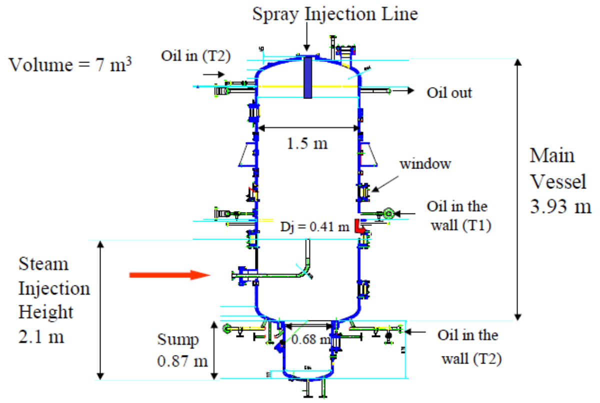
The operation of a spray system in a nuclear power plant can decrease the temperature of gas mixture of the air-steam-hydrogen as well as affect the hydrogen concentration by condensing the steam in the containment during a severe accident [1,2]. The containment wall integrity during the severe accidents may be accurately predicted if we know the local concentration and temperature distribution of the air-steam-hydrogen mixture gas under the spray water operation in the containment. A spray analysis module based on the Lagrangian particle model in OpenFOAM was developed to accurately predict the behavior of the spray water in the containment during the severe accidents [2,3]. KAERI performed a validation analysis for the steam condensation owing to the spray water using the developed spray analysis module against the Tonus Qualification Analytique (TOSQAN) Test-101 which was conducted by IRSN in France [4,5].

2. TOSQAN Test [4,5]

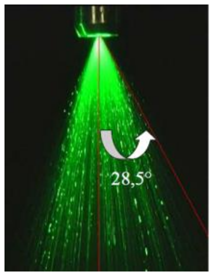
2.1 Test Facility

The TOSQAN facility consisted of a closed cylindrical vessel (volume 7 m^3, inner diameter 1.5 m, height 4.8 m) with a spray nozzle, spray circuit system using a pump, and drain pipes for measuring a depressurization process through water vapor condensation by the spray water (Fig. 1). The spray nozzle is located at the vessel axis and 0.65 m below from the vessel top. The initial gas conditions of pressure, temperature, and steam volume fraction in the vessel, as shown in Table 1, was set by heating the vessel wall and injecting the air and steam to the vessel. The spray water was discharged with a flow rate 29.96 g/s, angle 57°, and temperature 22.1 to 119.1 °C (Table 2). The injected spray water moved downward and drained at approximately rate of 29.0 g/s from the vessel bottom. The wall temperatures were maintained at approximately 120 °C during the test period such as Table 3.

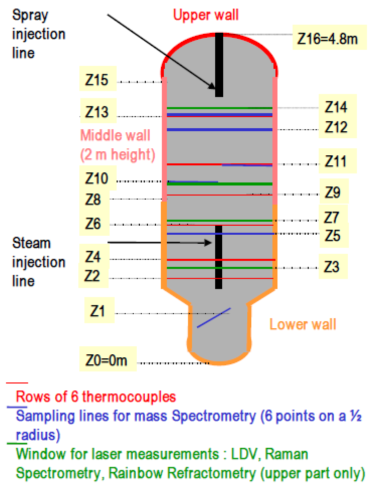
To measure the gas temperature, approximately 150 thermocouples were installed along the main flow region and near the walls. The steam volume fraction (SVF) was measured using a mass spectrometry with 54 sampling points. Distribution of liquid droplet velocities at 5 cm, 15 cm, 25 cm, 35cm and 45 cm from the nozzle outlet were measured by a Particle Image Velocimetry (PIV). Distribution of liquid droplet diameter was measured using the technique of interferometrics laser imaging for droplet sizing (ILIDS) at height of 2.8 m in the vessel



(a) Schematic diagram of test facility



(b) Spray nozzle



(c) Location of measuring devices

Fig. 1. TOSQAN Facility [4,5]

Table 1: Initial conditions at Test-101 [4]

Gas Mixture	Temperature	Pressure	Steam volume fraction
Air-Steam	131 °C	2.5 bar	0.6

Table 2: Conditions of spray water at Test-101 [4]

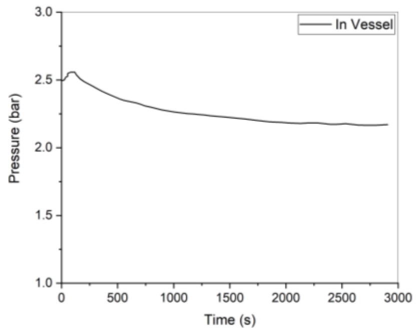
Flow rate	Angle	Initial size	Temperature (°C)
29.96 g/s	55°	130 μm	t = 0 s : 119.1 t = 311 s : 22.1 t = 1000s : 27.7

Table 3: Wall temperature conditions at Test-101 [4]

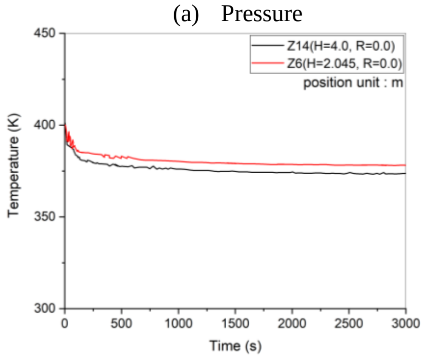
Time (s)	Upper	Middle	Lower
0 – 102	121.4	121.6	121.3
107 – 300	120.8	120.4	120.3
306 - 601	120.3	120.0	119.4
End of Test	119.3	120.1	115.4

2.2 Test Data

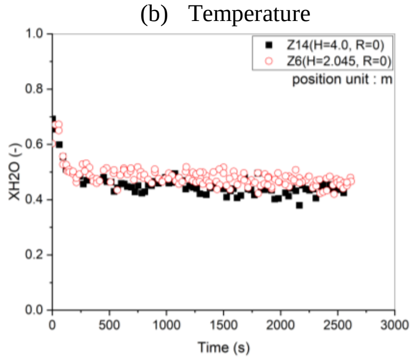
Fig. 2 shows the measured data of the pressure, gas temperatures, and SVFs in the vessel for 3,000 s during the spray water injection. The temperatures and SVFs were measured at the height of 2.045 m (Z6) and 4.0 m (Z14) along the axis of the vessel. The gas temperature at Z14 is approximately 5 °C lower than that at Z6, and the SVF at Z14 shows approximately 0.05 lower than that at Z6. This difference may be resulted from that the location of Z14 is more closed to the colder water discharged from the spray nozzle.



(a) Pressure



(b) Temperature



(c) Steam volume fraction

Fig. 2. Measured data in the TOSQAN Test 101 [4,5]

3. CFD Analysis

3.1 Grid Model and Flow Field Models

A 3-dimensional grid model simulating the TOSQAN facility was constructed to analyze the vapor condensation owing to the spray water such as Fig. 3. The spray nozzle was modeled by the full cone nozzle injection in the OpenFOAM-v2012 [6] through indicating the positon in the grid model. A total of about 74,088 hexahedral cells with a cell length of approximately 20 - 40 mm were generated in the grid model. A wall condition with time dependent temperatures, as shown in Table 3, was applied on the outer surface of the grid model.

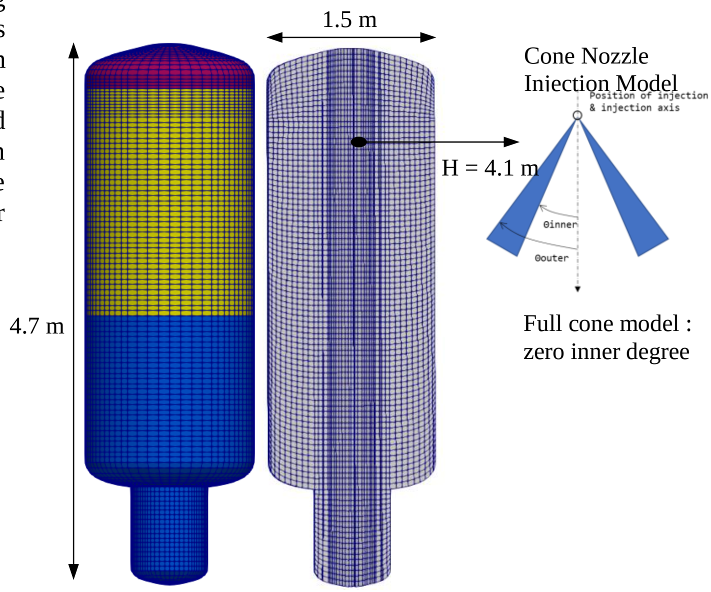


Fig. 3. Grid model for the TOSQAN facility

OpenFOAM-v2012 with the Lagrangian-Eulerian model [2,6] was chosen for the simulation of the behavior of the steam condensation owing to the injected spray water in the TOSQAN Test-101. The Lagrangian method using a force balance (Eqs. (1) to (4)) was used to simulate the injection of the spray water through the full cone nozzle model (Table 4) located at 5 cm below the spray nozzle outlet because the measured data at 5 cm from the spray nozzle outlet was used as the inlet boundary condition [5]. A heat transfer phenomenon in the Lagrangian method was calculated by the convective heat transfer law such as Eq. (5) and the heat transfer coefficient (h) proposed by Ranz and Marashell (Eq. (6)) [2,6]. The steam condensation owing to the spray water was simulated using the modified liquid evaporation model which is based on the diffusion law (Eq. (7)) in the OpenFOAM-v2012 [2]. The Eulerian method using the mass conservation, Navier-Stokes momentum and heat transfer equations was applied to analyze the steam-air mixture behavior under the spray water injection. A turbulent flow was modeled by the standard k-ε model. The time step size used in the transient calculation of

3,000 s was approximately 0.001 to 0.5 ms for obtaining converged solutions.

Table 4: Parameters of the full cone nozzle injection model

Spray Model (Lagrangian method)
- Diameter (d_{10}) distribution = mass Rosin Rammler model - Mass flow rate = 29.96 g/s - U_{mag} = 12.46 m/s - Nozzle outer diameter = 0.54 m - Nozzle outer angle = 57° - Parcel Per Second (PPS) = 5000 [#/s] *Inlet conditions were determined based on measured data at Z = -5 cm from the nozzle outlet.
mass Rosin Rammler model
$f(d,D,k) = \frac{k}{D}\left(\frac{d}{D}\right)^{k-1} \exp\left[-\left(\frac{d}{D}\right)^{k}\right]$ - Diameter : d - Min. / Max. diameter = 10 µm / 800 µm - Mean diameter (D)= 220 µm - Shape factor (k) = 1.5

$$m_p \frac{du_p}{dt} = F_D + F_G + F_P \quad (1)$$

where,

$$F_D = C_D \frac{\pi d_p^2}{8} \rho (U - u_p)\left|U - u_p\right| \quad (2)$$

$$F_G = m_p g \left(1 - \frac{\rho}{\rho_p}\right) \quad (3)$$

$$F_P = -\frac{\pi d_p^3}{6} \nabla p \quad (4)$$

$$m_p c_p \frac{dT_p}{dt} = hA_p (T_\infty - T_p) - \frac{dm_p}{dt} h_{fg} \quad (5)$$

$$\mathrm{Nu} = \frac{hd_p}{k_\infty} = 2.0 + 0.6 Re_d^{0.5} Pr^{\frac{1}{3}} \quad (6)$$

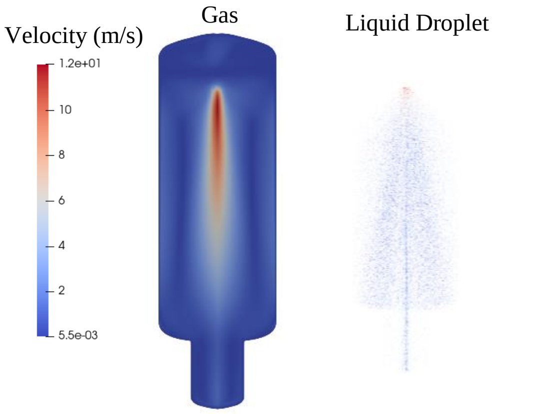
$$N_i = k_c (C_{is} - C_{i_\infty}) \quad (7)$$

where,

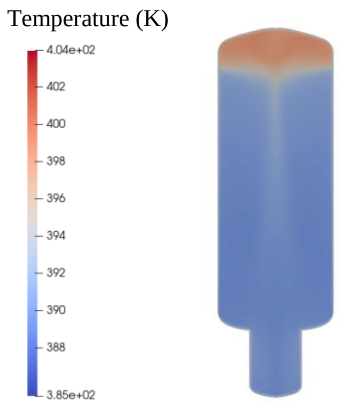
m_p: mass of the particle
T_p : temperature of the particle
N_i : molar flux of vapor
k_c : mass transfer coefficient
C_{is} : vapor concentration at the droplet surface
$C_{i\infty}$: vapor concentration in the bulk gas

3.2 Discussion on the CFD Analysis Results

The CFD analysis results for the steam condensation owing to the spray water in the TOSQAN Test-101 are shown in Figs. 4 and 5. Fig. 4 shows that the predicted velocity of the droplet and gas by OpenFOAM can reasonably simulate the spray water discharging to the downward direction from the spray nozzle and the air-steam mixture flow induced by the droplet discharge. According to the comparison results between the CFD results and the test data (Fig. 5), the CFD results accurately predicted the decrease trend of pressure, temperature, and SVF with an error range of approximately 10% as the time passes. However, the calculated pressure behavior shows approximately 0.25 bar lower than the measured data from approximately 2000 s to 3000 s. This discrepancy may be caused that the CFD analysis does not simulate the water pool formation at the sump region in the test. In addition, the CFD results does not predict the rapid decrease of the SVF from 100 s to 300 s as shown in the test data. We will investigate the reason of this difference including the proposed condensation model (Eq. (7)).

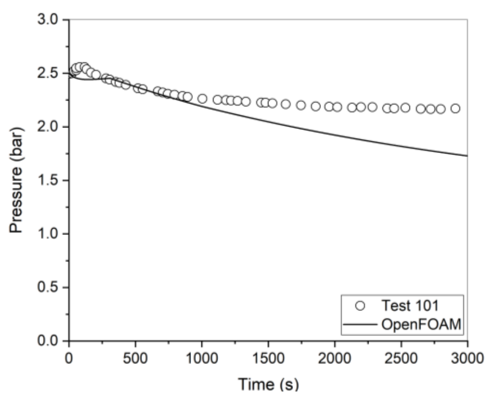


(a) Droplets and gas velocity along the center plane

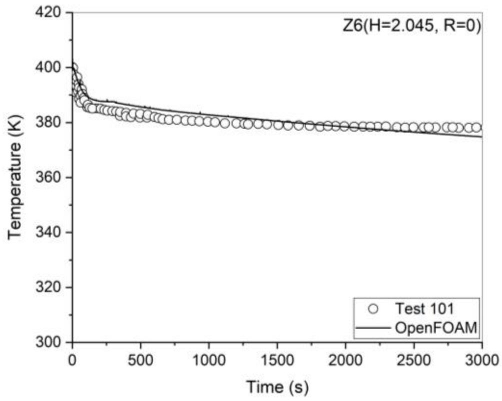


(b) Gas temperature distribution along the center plane

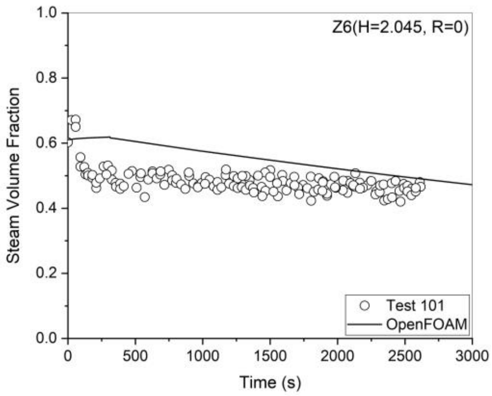
Fig. 4. Velocity and temperature distributions at 100 s



(a) Pressure



(b) Temperature



(c) Steam volume fraction (SVF)

Fig. 5. Comparison of pressure, temperature, and SVF between test data and OpenFOAM results

4. Conclusions and Further Work

KAERI performed the CFD calculation against the depressurization process owing to the steam condensation by the spray water in the TOSQAN Test-101 to validate the developed spray module based on the Lagrangian particle model in OpenFOAM-v2012. We reasonably simulated the decrease trend of pressure, temperature, and steam volume fraction in the vessel with an error range of approximately 10% when compared to the test data. However, the CFD results did not simulate the rapid decrease of the steam volume fraction at early stage of the spray water injection when compared to the test data. To reduce this discrepancy between the CFD results and the test data, we will have to investigate the proposed condensation model based on the diffusion law in the OpenFOAM-v2012. This validation results may decrease the uncertainty occurred when the spray analysis module is applied to a real nuclear power plant.

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