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Modeling and Validation of Steam Condensation for Containment Thermal Hydraulic Analysis during a Severe Accident

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1. Introduction

In the event of an accident such as loss of coolant in a pressurized water reactor that uses water as a nuclear reactor coolant, a large amount of hot steam is generated and released into the atmosphere of the containment building. In the event of a severe accident that leads to core damage, the fuel cladding undergoes an oxidation reaction with the hot steam, producing a large amount of hydrogen, which is released into the containment building along with the steam. The water vapor released into the containment building mixes with the air inside the containment building and partially condenses into mist, or condenses on the walls of the containment building and the condensate flows down the wall in the form of droplets or liquid films. However, a large amount of the water vapor does not condense and remains within the containment building.

The large amount of water vapor released into the containment building can greatly reduce the possibility of combustion and explosion of hydrogen by diluting it. However, as water vapor condenses, the concentration of hydrogen increases, and the possibility of flame acceleration increases again. Therefore, quantitative evaluation of water vapor condensation is required to control hydrogen in the containment building.

In this study, modeling and validation results of homogeneous bulk condensation and wall condensation of water vapor were introduced.

2. Modeling

Since the volume fraction of fog generated by condensation in the containment building is very small, less than 10^{-8}, when applying the Eulerian method, many repeated calculations may be required to obtain a rigorous solution to the behavior of the liquid phase, and therefore use of the mass fraction of the condensed fog droplets is advantageous in terms of numerical stability to obtain it. In addition, only the mass conservation of the condensed droplets can be considered by assuming that the temperature and velocity of the condensed fog particles, which are microscale in size, are in mechanical and thermal equilibrium with the gas phase.

2.1 Equations for gas-fog mixture

Equations (1) through (4) represent the governing equations for the gas phase assuming thermal and mechanical equilibrium with the fog phase [1].

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{U}) = S_\rho \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \boldsymbol{U}) + \nabla \cdot (\rho \boldsymbol{U}\boldsymbol{U}) - \nabla \cdot \boldsymbol{R} = -\nabla \mathrm{p} + \rho \boldsymbol{g} + \boldsymbol{S}_m \tag{2}$$

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho Y_i \boldsymbol{U}) - \nabla \cdot \boldsymbol{J}_i = S_{Y_i} \tag{3}$$

$$\frac{\partial}{\partial t}(\rho h_s) + \nabla \cdot (\rho h_s \boldsymbol{U}) - \nabla \cdot \boldsymbol{q} = \frac{\partial p}{\partial t} - \left[\frac{\partial}{\partial t}(\rho K) + \nabla \cdot (\rho K \boldsymbol{U})\right] + S_h \tag{4}$$

, where S_ρ, $\boldsymbol{S}_m$, S_{Y_i} and S_h are mass, momentum, species and enthalpy changes by condensation or any other physical processes. The mass faction of the fog phase is defined as a ratio of fog mass to gas mass instead of the total mass of fog and gas.

$$\alpha = \frac{m_f}{m_g} \tag{5}$$

Eq. (6) is the fog mass transport equation, and the rate of water vapor condensation and fog evaporation, S_α, is simply modeled by Eq. (7).

$$\frac{\partial}{\partial t}(\rho_g \alpha) + \nabla(\rho_g \boldsymbol{U} \alpha) - \nabla(\Gamma_t \nabla \alpha) = S_\alpha \tag{6}$$

$$S_\alpha = C_{bulk}(\rho_{sat} - \rho_{h2o}) \tag{7}$$

, where S_α is a source of fog mass by vapor condensation. C_{bulk} in Eq. (7) is a constant for numerical stability and the default value is 0.5.

2.2 Equations for wall condensation

The wall condensation of water vapor mixed with a non-condensable gas is limited by the mass diffusion rate. So, the condensation mass flux is expressed as the mass diffusion rate of water vapor through the non-condensable gas. Reference [1] describes the equation of the water vapor diffusion rate in a discretized form as shown in Eq. (8).

$$\dot{m}_v'' = \rho \frac{D_w}{\delta} \frac{(Y_{vi} - Y_{vw})}{(1 - Y_{vw})} = \rho h_m \frac{(Y_{vi} - Y_{vw})}{(1 - Y_{vw})} \tag{8}$$

The mass flux of water vapor removed by condensation on the wall is determined by the water vapor diffusion coefficient on the wall, and therefore condensation models are currently implemented by how to define D_w or h_m.

One of the most mechanistic models for wall condensation is to use a turbulence model and a wall function. The condensation mass flux of water vapor on the wall is obtained using the wall heat transfer coefficient calculated from the wall function and Chilton-Colburn analogy. First, T^+ is obtained from the wall function.

$$if\ y^+ < y_T^+,\quad T^+ = Pry^+ + \frac{1}{2}\rho\frac{u_\tau U^2}{q_w}Pr \tag{9}$$

$$if\ y^+ \geq y_T^+,\quad T^+ = Pr_t(U^+ + P) + \frac{1}{2}\rho\frac{u_\tau U^2}{q_w}[Pr_t U^2 + (Pr - Pr_t)U_c^2] \tag{10}$$

The wall heat transfer coefficient h can be obtained from the relationship between T^+ and the wall heat flux.

$$h = \frac{k_w}{\delta} = \frac{q_w}{(T_w - T_p)} = \frac{\rho C_p u_\tau (T_w - T_p)}{T^+}\frac{1}{(T_w - T_p)} = \frac{\rho C_p u_\tau}{T^+} \tag{11}$$

Here, using Chilton-Colburn analogy, the mass diffusion coefficient can be obtained from the heat transfer coefficient h.

$$h_m = \frac{h}{\rho C_p} Pr^{2/3} Sc^{-2/3} \tag{12}$$

3. Validation Results

2.1 Simulation of CONAN wall condensation tests

The CONAN experiment [2] is a forced convection water vapor condensation experiment conducted at the University of Pisa, Italy, and evaluated the water vapor condensation rate under various flow conditions. Fig. 1 shows the CONAN test facility. The primary loop is in the form of a duct (width 0.34 m, height 0.34 m) and flows a mixed gas of air and water vapor. The secondary loop is a device for cooling the water vapor condensation wall of an aluminum plate (45 mm thick, 2 m long). The 3rd loop is used as a loop to remove heat from the 2nd loop. The condensation test section has a channel-shaped structure with a cross section of 0.34x0.34m and a length of 2m.

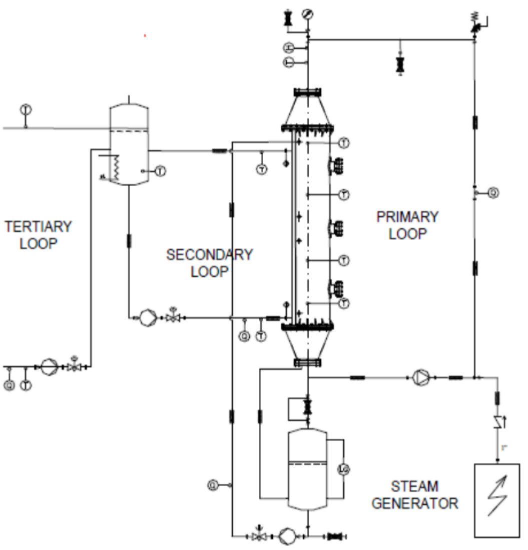

Fig.1. CONAN test facility

The CONAN experiment was conducted under a total of 129 conditions. To analyze the CONAN experiment, three-dimensional geometry modeling and grid generation were performed for the duct including the condensation wall, as shown in Fig. 2. The grid size was 132×50×50, and 50 cells were created in the vertical direction of the primary flow.

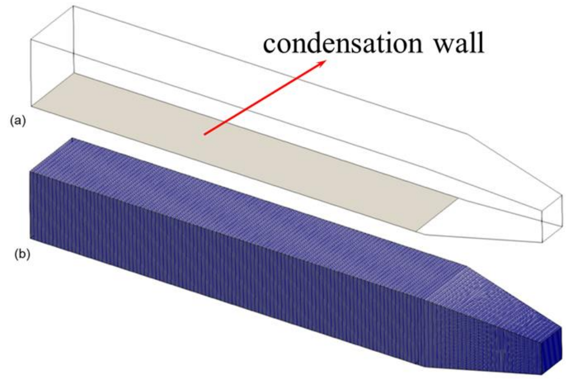

Fig.2. 3D geometry modeling and grid for CONAN condensation ducts

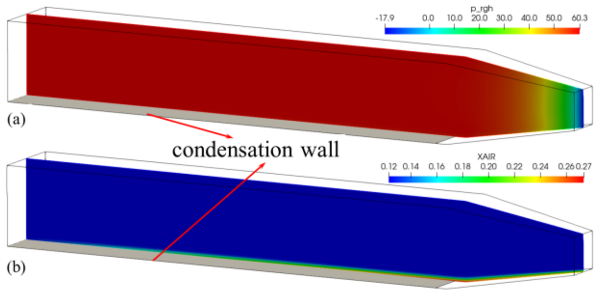

Fig. 3. 3D analysis of CONAN condensation duct, (a) pressure distribution, (b) water vapor concentration distribution

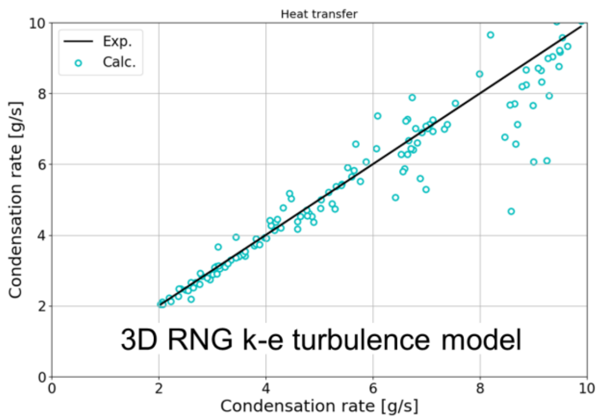

Fig. 4. 3D analysis results of CONAN experiment, comparison of water vapor condensation rate

Fig. 3 shows the pressure distribution and water vapor concentration distribution at the central cross section as a result of the 3D analysis. As shown in Fig. 3(a), because the pressure has a gradient in the direction of the primary flow within the duct, it can be thought that it is similar to a typical parabolic duct flow.

Fig. 3(b) shows the concentration of water vapor. It can be seen that water vapor condensation on the condensation wall at the bottom of the duct creates a water vapor concentration gradient in the vertical direction of the wall. In the 3D analysis, RNG k-ε and uniform wall temperature distribution were applied. Fig. 4 compares the calculation results of water vapor condensation rate with experimental values for 129 test conditions.

2.2 Simulation of TOSQAN wall condensation test

As shown in Fig. 5, the TOSQAN test facility [3] is a cylindrical vessel with an inner diameter of 1.5m and a height of 4.8m and includes a sump at the bottom to remove condensate.

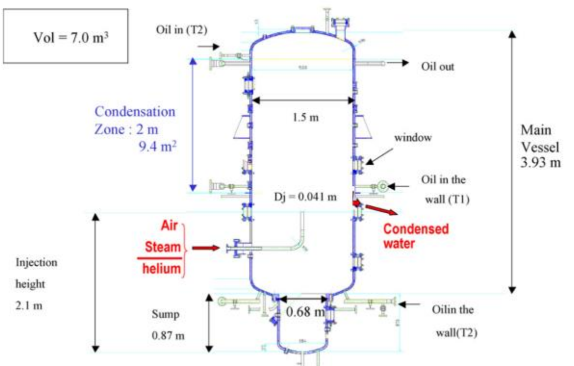

Fig. 5. TOSQAN test facility

The temperature of the outer wall of the pressure vessel is controlled by the oil jacket, and in particular, the temperature of the wall in the middle is lowered to induce condensation of water vapor. A vertical pipe is installed in the center of the vessel to inject water vapor and non-condensable gas (here, air and helium).

The experiment was conducted in a series of phases, and the injection conditions were varied in each phase by changing the injection rate and the injection material. Fig. 6 shows the injection rates of the gas species in the TOSQAN ISP-47 test.

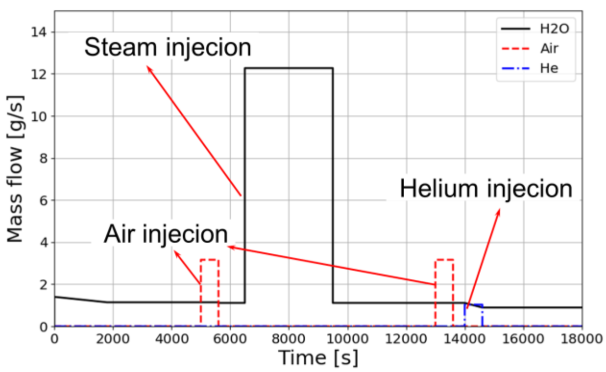

Fig. 6. TOSQAN ISP-47 test conditions.

For the analysis of the experiment, a grid was generated as shown in Fig. 7, and the wall was composed of three patches considering the condensation wall. (Upper wall: 122 °C, Condensation wall: 101.3 °C, Lower wall: 123.5 °C)

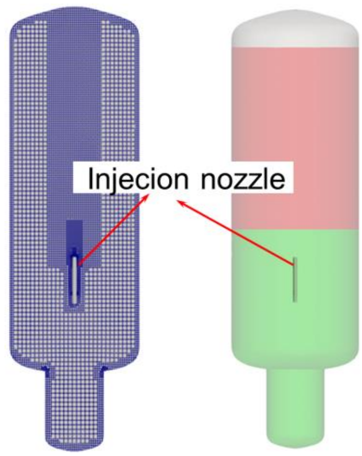

Fig. 7. Computational mesh and wall patches

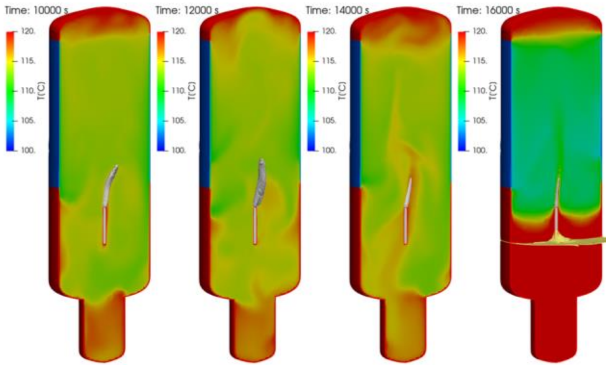

Fig. 8. Change of temperature distribution in the TOSQAN test vessel over time.

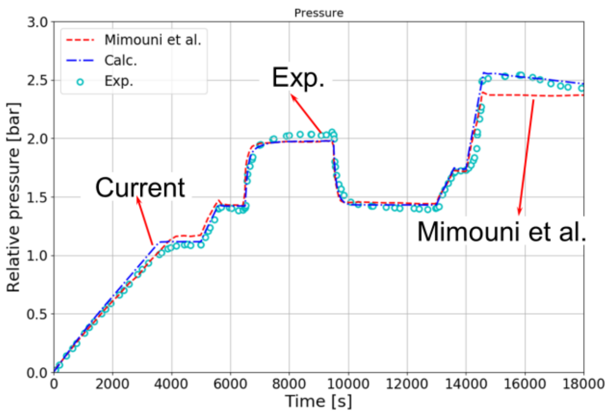

Fig. 9. Comparison of pressure change over time.

Fig. 8 shows the temperature distribution within the pressure vessel over time and the iso-concentration surfaces of water vapor and helium obtained from the analysis. Fig. 9 shows the calculated pressure compared with the experimental data and the result calculated with Neptune_CFD by Mimouni et al. It can be seen that the calculated result is similar to the result of Mimouni et al. or better match the experimental data. Fig. 10 compares the water vapor concentration distribution of the calculated results with the experimental results. It is thought that the wall condensation analysis module of the 3D code simulates flow phenomena including water vapor condensation well.

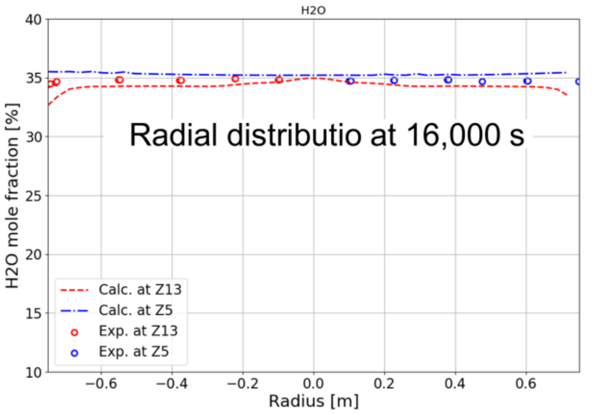

Fig. 10. Distribution of water vapor concentrations along the radial direction

2.3 Simulation of bulk condensation in adiabatic cavity

Because it is difficult to find an appropriate condensation experiment to verify the volumetric condensation analysis model, a virtual problem was proposed and an analysis was performed to verify the volumetric condensation analysis model by comparing the calculated water vapor partial pressure and the theoretical saturation water vapor pressure. The problem used in the verification analysis is that while air and water vapor are mixed in a cubic-shaped compartment, heat is removed and water vapor condenses due to a drop in the temperature of the gas.

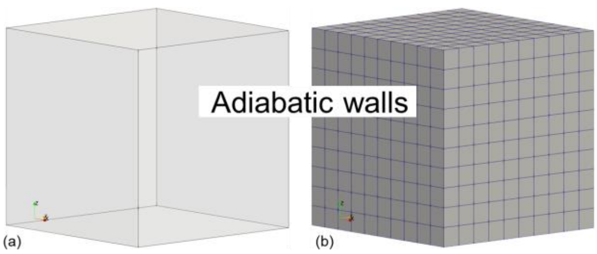

Fig. 11. Volumetric condensation model verification problem, (a) compartment geometry, (b) analytical grid.

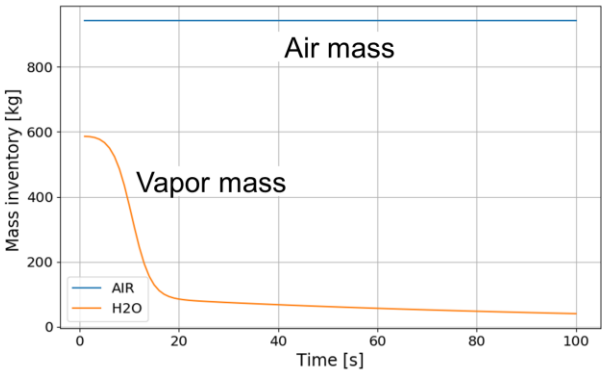

Fig. 12. Water vapor and air mass variations over time.

Fig. 11 is a schematic of the problem for verification of the volumetric condensation analysis model. It is a hexahedral compartment with a width, length, and height of 10 m each. The analysis grid is shown in Fig. 11(b).

A mass of a non-condensable gas in a flow region must be conserved during a condensation occurs. To show the characteristic of the mass conservation of the numerical scheme implemented for water vapor condensation, the air mass in the cavity was integrated and monitored during the simulation. As shown in Fig. 12, it is confirmed that the current numerical scheme for the bulk condensation conserves the mass of the non-condensable gas well.

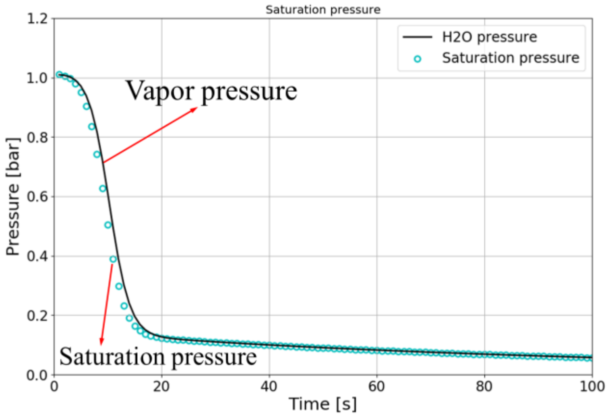

Fig. 13. Changes in partial pressure and saturation pressure of water vapor

Fig. 13 compares the calculated water vapor partial pressure with the saturation pressure at the temperature. As shown in the figure, the water vapor pressure and the saturation pressure are decreasing in the same pattern. In particular, it can be seen that the water vapor pressure is in a supersaturated state, slightly higher than the saturation pressure, during the process of rapidly decreasing water vapor pressure up to 20 seconds. It is judged to be physically reasonable for slight oversaturation, rather than subsaturation, to occur.

4. Summary and Future Work

In order to verify the wall condensation analysis module of the 3D analysis code for the containment thermal hydraulics, analyses of the CONAN and the TOSQAN experiments were performed. By comparing the water vapor condensation rate and the pressure change in the vessel due to water vapor condensation with the experimental results, it was confirmed that the wall condensation module is very reliable. And, a problem for the hypothetical volumetric condensation phenomenon was created and numerically solved, and the analysis results were compared with the theoretical saturation pressure of water vapor to confirm that the simulation of the volumetric condensation was physically valid.

The numerical simulation of the CONAN test shows large discrepancy compared to the measured data in the region of the high condensation rates. It is necessary to review the test and numerical results physically and numerically in more detail as a future work.

ACKNOWLEDGMENTS

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