Transactions of the Korean Nuclear Society Virtual Spring Meeting
July 9-10, 2020

Implementation of Wall Steam Condensation in a Containment Analysis Code

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1. Introduction

During a loss-of-coolant accident in a pressurized water reactor that use water as a coolant to cool the reactor, hot pressurized water is released to the containment atmosphere in the form of steam by flash boiling. As the accident progresses, the reactor loses its ability to remove residual heat, creating large amounts of water vapor and releasing it into the containment. Water vapor released from the reactor increases the pressure of the containment, which may damage the containment integrity. In particular, in the case of a severe accident leading to core damage, the nuclear fuel cladding oxidizes with high temperature water vapor to produce a large amount of hydrogen and accumulates with water vapor in the reactor building.

As the amount of water vapor in the containment increases, the concentration of hydrogen is lowered, thus reducing the possibility of hydrogen explosion, but overpressure of the containment building may occur due to water vapor. On the contrary, if the concentration of water vapor in the containment is lowered by the steam condensation, the containment pressure may be lowered. But, the concentration of hydrogen can be increased in the containment, which increases the possibility of flame acceleration or DDT [1].

As such, the risk of hydrogen in containment buildings in a severe accident is related to the distribution and behavior of water vapor. Water vapor released into the containment can be condensed and converted into droplets or wall films, depending on the thermal hydraulic conditions within the containment. Failure to accurately predict water vapor condensation will result in unreliable concentrations of local hydrogen in the containment, making it difficult to evaluate hydrogen explosion risk. Therefore, in order to evaluate the safety of hydrogen in containment buildings during severe accidents, it is necessary to strictly evaluate the condensation of water vapor as well as the mixing of hydrogen and water vapor.

A lumped-parameter (LP) based integrated analysis code is used to calculate the behavior and distribution of water vapor and hydrogen released from a reactor to a containment in a severe accident. The LP codes such as MELCOR [2] have been used to evaluate hydrogen safety in a reactor containment under severe accident conditions by using correlation-based water vapor condensation models.

However, under severe accident conditions, prototypic experiments of the behavior of hydrogen and steam in containment buildings are difficult to conduct, so it is required to be evaluated in a practical and best-estimate manner. We are developing a turbulence-resolved multi-dimensional analysis code to complement the LP integrated analysis code. In this study, a module of the code for simulation of steam condensation is developed.

2. Methods

2.1 Condensation of Water Vapor

There are two factors to quantify water vapor condensation: condensation amount and condensation rate. The amount of condensation is an inventory required to transition from the supersaturation state of water vapor to the saturated state, and the condensation rate corresponds to the rate at which this water amount is condensed. The amount of condensation is determined by the atmospheric pressure and temperature and the wall temperature, but the condensation rate depends on the presence of non-condensable gases.

The dominant factor of the rate at which liquid films are formed in pure water vapor is heat transfer, whereas when non-condensable gas is included, material diffusion becomes the dominant factor and is known as a diffusion-controlled condensation. In the event of an accident, the containment atmosphere contains non-condensable gases such as air and hydrogen, so the condensation model governed by gas species diffusion is considered.

2.2 Modeling Approach for Wall Condensation

The development of an analytical model to simulate the wall condensation is difficult in many respects. A typical one relates to a condensate film condensed on a wall surface. The condensed liquid film is very thin, several millimeters thick, and also participates in heat transfer, creating a liquid film flow by gravity and atmospheric flow. Methods for simulating condensed liquid films range from volume of fluid (VOF) to quasi-three-dimensional finite area methods and static liquid film models that only participate in heat transfer in a simple way. In addition, it is necessary to consider the heat transfer of the wall structure together because the heat generated by condensation of water vapor is continuously transferred through the liquid film to the wall surface. In this study, it was assumed that the condensed liquid film do not grow more than a certain thickness (rain-out) and the kinematic behavior of the liquid film is ignored and it is simply participating in heat transfer.

The wall condensation rate or condensation mass flow rate of water vapor is expressed by the rate of diffusion through non-condensable gases as shown in Eq. (1).

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

Therefore, the mass flow rate of water vapor removed by water condensation on the wall depends on the water vapor diffusion coefficient at the wall.

Here three types of models were implemented in a code module for simulation of the wall condensation.

- Type-0 model:

The simplest model uses the condensation heat transfer correlation [3] to find the mass flow rate of condensed water vapor.

$$\begin{cases} h_c = 51104 + 2044 T_{sat} & 22^o C \le T_{sat} \le 100^o C \\ h_c = 255510 & 100^o C \le T_{sat} \end{cases} \qquad (2)$$

$$h_t = \frac{1}{1/h_w + 1/h_c} \qquad [W/m^2 K]$$

$$q'' = h_t (T_i - T_w) \qquad [W/m^2]$$

$$\dot{m}_v'' = \frac{q''}{h_{fg}} \qquad [kg/m^2 s]$$

- Type-1 model

In the type-1 model, the mass flow rate of condensed water vapor is obtained using the material diffusion correlation obtained from the Chilton-Colburn analogy.

Laminar flow: $Sh = 0.664 \mathrm{Re}_L^{1/2} Sc^{1/3}$, when $\mathrm{Re} < 5 \times 10^5$
Turbulent flow: $Sh = 0.037 \mathrm{Re}_L^{4/5} Sc^{1/3}$ (3)

A representative length is required to obtain the gas diffusion coefficient from *Sh* number. Here, the distance from the wall to the center of an adjacent cell (δ) is used.

$$Sh = \frac{h_m \delta}{D} \rightarrow h_m = Sh \frac{D}{\delta} \qquad (4)$$

, where D is a molecular diffusion coefficient. Using h_m, the mass flow rate of water vapor that disappears due to condensation can be obtained from eq. (1).

- Type-2 model

In the type-2 model, the mass flow rate of water vapor is calculated using the wall heat transfer coefficient calculated from the turbulence model and the Chilton-Colburn analogy. First, the wall heat transfer coefficient should be obtained using a wall function. Here, Jayatilleke thermal wall function is used.

$$\text{if } y^+ < y_T^+, \quad T^+ = \mathrm{Pr}\, y^+ + \frac{1}{2} \rho \,\mathrm{Pr} \frac{u_\tau U^2}{q_w} \qquad (5)$$

$$\text{if } y^+ \ge y_T^+, \; T^+ = \mathrm{Pr}_t (U^+ + P) + \frac{1}{2} \rho \frac{u_\tau U^2}{q_w} \left[\mathrm{Pr}_t U^2 + (\mathrm{Pr} - \mathrm{Pr}_t) U_c^2 \right]$$

$$k_w = q_w \frac{y}{(T_w - T_p)} = \frac{\rho C_p u_\tau (T_w - T_p)}{T^+} \frac{y}{(T_w - T_p)} = \frac{\rho C_p u_\tau y}{T^+}$$

When y^+ is obtained, T^+ and k_w is obtained from eq. (5). The wall heat transfer coefficient is $h = k_w/\delta$. Similarly, the water diffusion coefficient can be obtained from the heat transfer coefficient using the Chilton-Colburn analogy.

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

3. Results

In order to validate the water vapor condensation analysis module implemented in this study, a CONAN experiment [4] conducted by the University of Pisa was selected. The CONAN experiment is one of the experiments to simulate the heat transfer by condensation of water vapor mixed with non-condensable gas. Unlike the water condensation experiment by natural convection (Dehbi et al. Experiment [5]), water vapor condensation was tested under the forced flow conditions of a mixed gas of water vapor and air.

3.1 Modeling of CONAN experiments

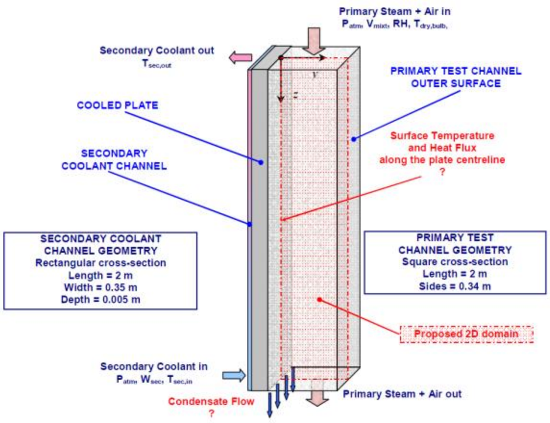

Fig. 1. Schematic of the test conditions of CONAN [4] experiment

In the experiment, the air-water vapor mixture gas is introduced at a constant velocity from the upper channel inlet and flows out through the lower outlet. In the channel device, the temperature of the cooling plate was kept constant by using a coolant flow to one wall surface as shown in Fig. 1. Insulating conditions could be applied to the other surfaces. The table 1 summarizes the thermal and hydraulic conditions of the experimental cases used to verify the analysis module of the water vapor condensation.

Table 1. Test conditions for CONAN experiment

Test Name	Vin [m/s]	Tin [K]	NC mass fraction	Twall [K]
P10-T30-V25	2.57	348.6	0.7070	304
P15-T30-V25	2.61	356.5	0.5722	303.5
P20-T30-V25	2.59	364.5	0.3590	305.25
P25-T30-V25	2.60	366.8	0.2789	305.95

In the verification analysis of the condensation analysis module, the analysis domain was modeled in a two-dimensional plane with respect to the central cross-section of the CONAN test channel, which is similar to Patil and Maurya [6]. The analysis grid model applied is shown in Fig. 2.

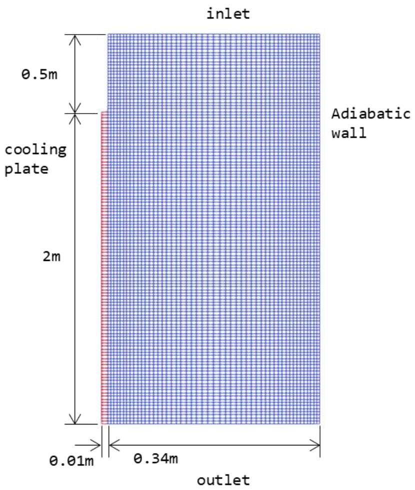

Fig. 2. Mesh configuration of fluid and solid regions (scaled by 2x-Xaxis, 0.5x-Yaxis) [7]

The thermal properties of the two gas components used in the CONAN experiment (water vapor and air) are obtained from the JANAF data. As a turbulence model, the k-omega-SST RANS model was applied. The material properties for the cooling plate structure are as follows.

Table 2. Properties of aluminum, 6061 Temper-O

Density [kg/m3]: 2710
Thermal conductivity [W/m/K]: 180
Specific Heat Capacity [J/kg/K]: 1.256E+03

3.2 Results of Validation

The three types of the steam condensation models were implemented in a single code module.

They were applied for the CONAN test cases listed in the Table 1. Fig. 3 shows the condensation heat fluxes obtained by the three types of the condensation models along the cooling wall for theP25-T30-V25 case.

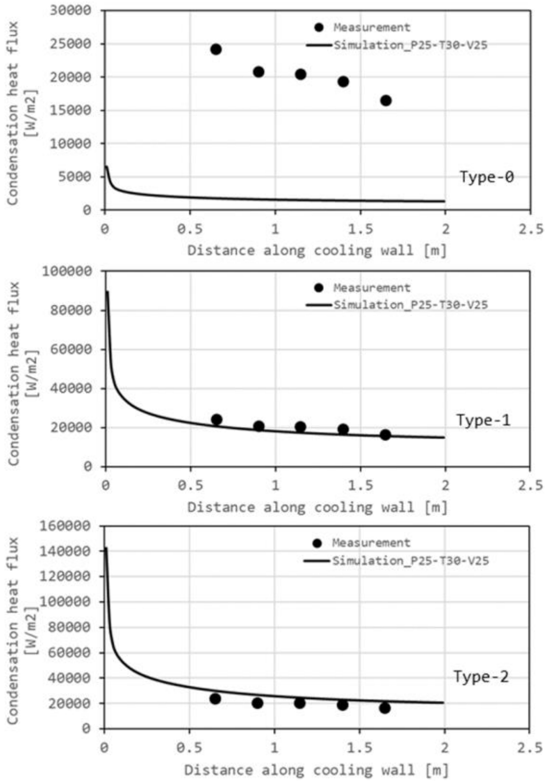

Fig. 3. Comparisons of wall condensation heat fluxes from different condensation models for the P25-T30-V25 case.

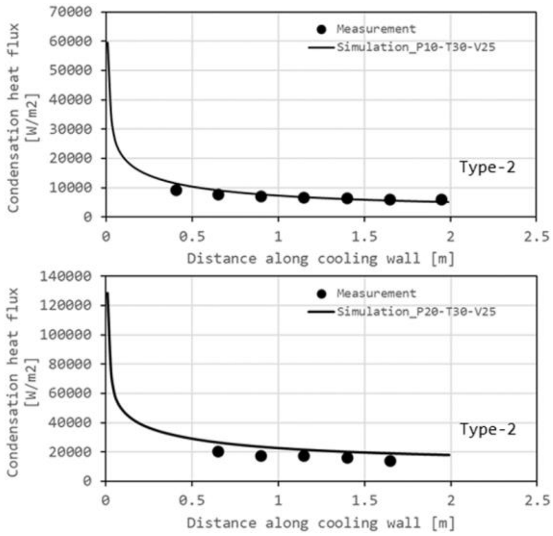

Fig. 4. Wall condensation heat fluxes by type-2 model for P10-T30-V25 and P20-T30-V25 test cases

In the case of the type-0 model, the wall condensation heat flux was predicted very low compared to the experimental results. This is a sufficiently predictable result because the correlation of the condensation heat transfer is not general. For the type-1 model and the type-2 model, the overall level of accuracy is reasonable for all the analysis conditions. In the case of Type-1, it tends to underestimate the results of experiments. On the other hand, in the case of type 2, it was interpreted as the trend of results slightly higher than the experimental results.

As can be expected, the type-2 model is very generalized because it was derived based on the universal law of the wall. Fig. 4 shows the wall condensation heat fluxes by the type-2 model for P10-T30-V25 and P20-T30-V25 test cases. It is thought that the type-2 model gives a reliable condensation rate of water vapor for the CONAN test cases.

3. Conclusions

In this study, we have developed the steam condensation module of the containmentFoam code [8], which is a detailed analysis code of steam and hydrogen behaviors in a containment building, for an analysis of wall steam condensation and wall heat transfer of condensation heat.

In addition, simulations of the CONAN tests were performed to verify the developed wall steam condensation analysis module. The results of the CONAN experiments for the test cases according to the thermal and hydraulic conditions were compared with results calculated by the developed steam condensation analysis module. And it was confirmed that the developed analysis module predicts well steam condensations on a wall.

ACKNOWLEDGMENTS

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

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