Spray Modeling for 3-D Analysis of Hydrogen and Spray Droplet Flow in the APR1400 Containment

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1. Introduction

Spray system of a nuclear power plant (NPP) containment is an important means of preventing overpressure through decompression of the atmosphere inside the containment building and is used for accident management during design-based and severe accidents. Spraying water in the containment controls the pressure by lowering the temperature of the atmosphere and inducing condensation of water vapor distributed in the atmosphere.

Under severe accident conditions, the operation of spray system in a reactor containment will affect the behavior of hydrogen, at the same time with fulfilling the intrinsic purpose of pressure control in the containment. Therefore, spray system for a containment depressurization should be operated in such a way that there is minimal or manageable negative impact on hydrogen safety [1, 2, 3]. This is a study on the development of spray analysis model for the detailed analysis of the thermal hydraulic and the hydrogen behaviors in containment buildings during the operation of the containment spray under severe accident conditions. Numerical and physical models of a Lagrange-based particle analysis included in OpenFOAM [4] were analyzed, and the Lagrangian model was evaluated by a simulation of a spray experiment [5]. Through this, an improvement direction of the Lagrange model was derived for applying it to analyses of the steam condensation and hydrogen behavior by a spray operation in a reactor containment during a severe accident. A software module based on the Lagrangian spray model for an analysis hydrogen behaviors affected by a containment spray during a severe accident was developed by improving the model especially in modeling of phase change of spray droplets, condensate film on a containment wall and spray nozzle rings. An input model was developed for the analysis of APR1400, a nuclear power plant operating in Korea, and steam and hydrogen behaviors in the containment during a spray operation was 3-dimensionally simulated.

2. Methods

2.1 Condensation of Water Vapor

During water droplets injected from a spray nozzle are travelling through the containment atmosphere, it may condense water vapor included in the atmosphere and it is also probable that it is evaporated. So, two-way phase change must be considered for the water droplets. The phase change of droplet water and water vapor mixed with non-condensable gases is governed by gas species diffusion rate. The mass transfer by the diffusion is denoted by Eq. (1)

$$\dot{m}_{h20} = W_{h2o} k_c (C_s - C_{\inf}) A_d \ [kg/s] \quad (1)$$

, where W_{h20} is the water molecular weight, k_c is mass transfer coefficient, and A_d is surface area of a water droplet. The mole concentrations on a droplet surface (C_s) and a point away from the surface (C_{inf}) are calculated as follows.

$$C_s = \frac{p_{sat}(T_{droplet})}{R_u T_{droplet}}, \quad C_{\inf} = \frac{x_{h2o} p}{R_u T} \quad (2)$$

Here, the mass transfer coefficient is based on the Ranz-Marshall correlation.

$$Sh = 2 + 0.6 \mathrm{Re}_d^{1/2} Sc^{1/3} \quad (3)$$

$$Sc = \frac{\nu}{D_{h2o}}$$

Finally, mass transfer coefficient is obtained as follows.

$$Sh = \frac{k_c d}{D_{h20}} \ \Rightarrow \ k_c = Sh \frac{D_{h2o}}{d} \quad (4)$$

When $\dot{m}_{h20}$ is positive, a spray droplet is going to be evaporated. If it is negative, condensation of vapor on the surface of a droplet can occur.

2.2 Modeling of spray nozzle ring

The containment spray system is characterized in that a number of injectors are arranged at regular heights in an annular shape, and each nozzle injector is designed with injection directions as necessary. The *ringConeInjection* model, the currently developed annular injector arrangement model, was developed to set the injector annular arrangement having the same height and the same injection direction. First, the annular arrangement of injectors can be set in two ways, according to the *angleDistributionType*. The *autoAngleDistribution* type model applies a constant angular spacing and the *manualAngleDistribution* type model applies a user-specified arbitrary angle distribution. Fig. 1 shows the geometric description of the equal spacing arrangement according to the number of injectors.

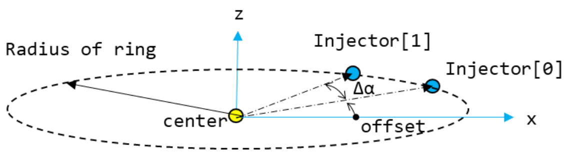

Fig. 1 Geometrical description of *antoAngleDistribution* type

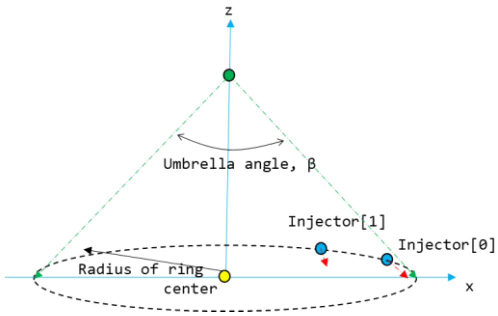

Fig. 2 Geometrical description of umbrella-angle

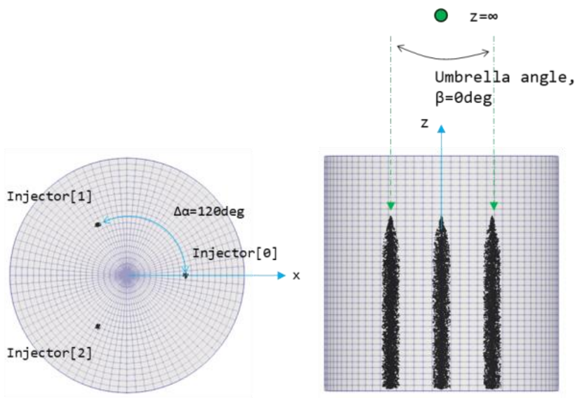

Fig. 3 Configuration of nozzle positions and directions for vertical injection

The same annular placement radius and injection axis direction are assumed for one injector annular placement model (*ringConeInjection*). In order to model the injectors arranged in an annular direction to have the same injector axis or ejection direction relative to the annular direction, the so-called umbrella operation was geometrically applied. Therefore, in order to define the injector axis, the umbrella angle (β) is defined as shown in Fig. 2 in order to model the adjustment of the umbrella fan angle with respect to the annular central axis. For example, for an injector located in the xz plane, the injector axis or injection direction is defined as β / 2. Umbrella angle is applied as *ringConeAngle* in the current model keyword, and the unit is degree. Fig. 3 shows the configuration of three equally-distributed spray nozzles as a ring at the same elevation and same vertical injection. Fig. 4 is the cases for nozzle ring configurations with 75° outer and inner injection directions from the vertical axis.

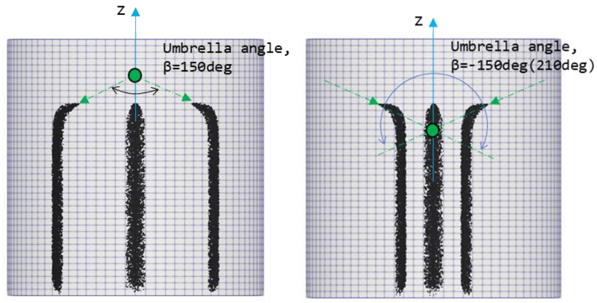

Fig. 4 Configuration of nozzle positions and directions for 75° outer (left) and inner (right) injection

3. Results

The Lagrange-based particle analysis module included in OpenFOAM were validated by solving a TOSQAN experiment. The results may be found in Ref. [6]. Here only the preliminary results from a spray analysis in APR1400 are described.

3.1 Modeling of APR1400 spray nozzles

The spay system of the APR1400 containment consists of two completely separate multi-line systems. The two spray water pumps supply cooling water to the upper area of the containment building through two heat exchangers. It provides a relatively uniform distribution of spray water droplets over a horizontal sectional area in the containment building. The spray system of APR1400 consists of two trains, and each train consists of a main spray nozzle system and a secondary spray nozzle system. The main spray nozzle system is equipped with 296 nozzles in four nozzle rings in the upper dome area of the containment building and 11 spray nozzles in the annular compartment. The 111 auxiliary spray nozzles are installed in the annular compartment.

Preliminary analysis of spray in the APR1400 containment was performed. The purpose of this preliminary analysis is to evaluate the applicability of the Lagrange spray analysis algorithm and the feasibility of the developed spray analysis modules to the analysis of the behavior of hydrogen in spray operation of containment buildings under severe accident conditions. The spray nozzle ring input model was made for a simple containment geometry which has a same diameter of the hemispherical dome of the APR1400 containment. As shown in Table 1, four rings of spray nozzles are installed in the dome region. The first nozzle ring installed at the lowest elevation has two nozzle groups with vertical and horizontal directions of water injection. Similarly, ring 2 and ring 3 have three injection directions, and ring 4 has two injection directions. From this study it was found that spray droplets injected horizontally may directly impinge on the containment vertical walls. In order to model the horizontal injection of spray, it is required to model the interaction of spray droplets and surface films on the wall. Study of the interaction is postponed as a future work. And the spray nozzle rings were modeled as vertical injections only in this study. Table 1 shows the modeled 10 nozzle rings with vertical injections. Fig. 5 shows the spray nozzles configured by 10 nozzle rings in the containment dome.

Table 1. Data of the spray nozzles installed in APR1400

ring name	dir.	No	EL	y	ring radius	mod. EL	mod ring radius	dir
ring1	vertical	42	291.5	37	61.764706	291.5	61.76470588	vertical
114	horizontal	72	291.5	37	61.764706	268.6838	70.58823529	vertical
ring2	vertical	36	308.9167	54.41667	48.529412	308.9167	48.52941176	vertical
112	75deg	36	308.9167	54.41667	48.529412	314.4706	41.47058824	vertical
	horizontal	40	308.9167	54.41667	48.529412	300.6232	56.47058824	vertical
ring3	vertical	16	322.25	67.75	25.588235	322.25	25.58823529	vertical
52	75deg	12	322.25	67.75	25.588235	324.5106	18.52941176	vertical
	horizontal	24	322.25	67.75	25.588235	318.6919	33.52941176	vertical
ring4	vertical	12	326.6667	72.16667	10.588235	326.6667	10.58823529	vertical
18	45 deg	6	326.6667	72.16667	10.588235	327.3057	4.411764706	vertical

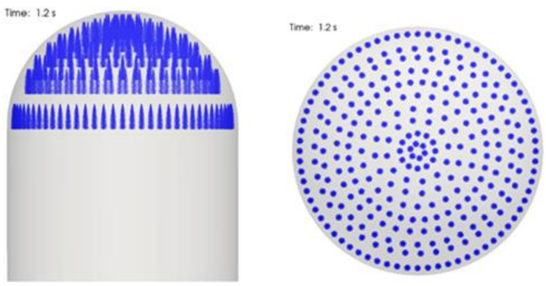

Fig. 5 Modeling of Spray nozzle rings in APR1400

The verified model of spray nozzle configuration was applied to the APR1400 containment whose geometry was modeled by a 3D CAD software. A mesh for the spray analysis in the APR1400 containment was generated. The number of cells in the generated mesh is about 1.2 million. The preliminary calculations assume the following initial conditions:

Table 2. Thermo-hydraulic conditions for a simulation of spray in APR1400

Pressure	2 bar
Temperature	373.15 K
H2 concentration	8 vol%
Steam concentration	40 vol%
Spray droplet temperature	323 K
Spray droplet diameter	0.2 mm

3.2 Preliminary results of spray analysis in APR1400

The initial conditions in the APR1400 containment for the simulation of spray is denoted in Table 2. It was assumed that hydrogen and steam are uniformly distributed in the containment with concentrations of 8 and 40 vol% respectively. Fig. 6 shows the behavior of the spray droplets after the spray has been activated in the APR1400 containment building. Current calculations do not take into account the spray nozzles installed in an annular compartment located below the operating deck.

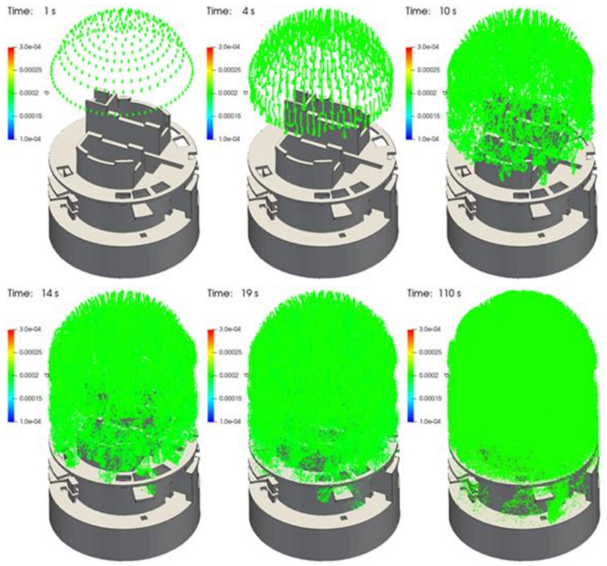

Fig. 6 Distributions of spray droplets in the APR1400

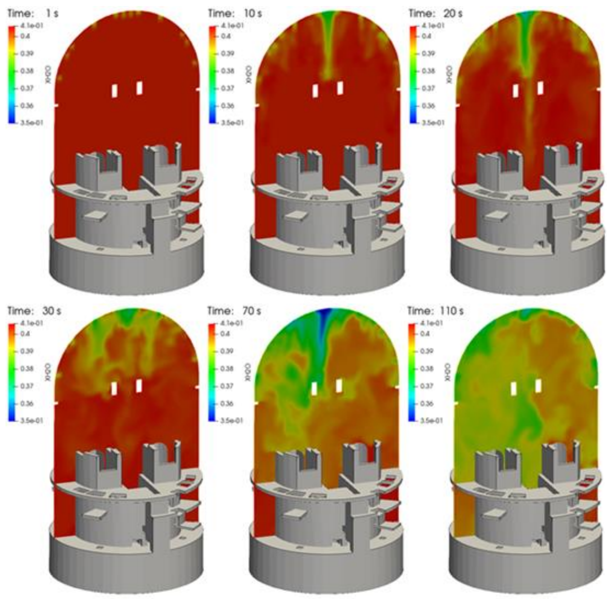

Fig. 7 Distributions of steam in the APR1400 containment during spray activation.

The droplets sprayed from the nozzles move in the containment atmosphere, and the temperature of the droplets rises by heat transfer, while simultaneously condensing the water vapor contained in the atmosphere.

On the other hand, if the droplet temperature rises while the droplets move, water vapor may evaporate on the surface of the droplets, so that the droplet sizes may decrease. Fig. 7 shows the change in water vapor concentration by water droplets over time in the containment. In addition, since the temperature of the droplets directly sprayed from the nozzles is relatively low, the water vapor condenses more quickly in the upper part of the containment building.

Fig. 8 shows the change in hydrogen concentration due to condensation of water vapor by spray droplets over time in the APR1400 containment. It can be seen that the hydrogen concentration is gradually increasing, as opposed to the decrease in water vapor concentration due to spray droplets. The peculiar point is that the largest change in water vapor and hydrogen concentration occurs at the bottom of the apex of the containment building. The cause of this has not been analyzed yet, but it is expected that this is mainly due to the composition of the spray nozzle ring and the feature of no spray nozzles at the top of the dome.

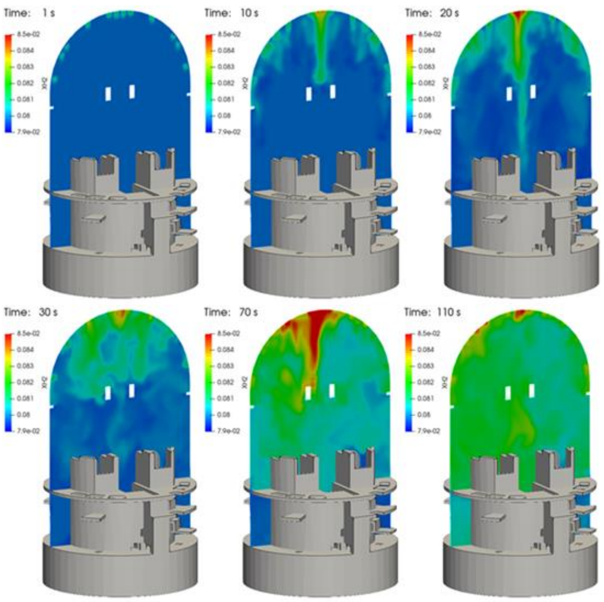

Fig. 8. Distributions of hydrogen in the APR1400 containment during spray activation

It is known that condensation of water vapor occurs when spray is operating in the atmosphere of a containment in which hydrogen is distributed, thereby increasing the concentration of hydrogen somewhat. One of the issues of concern from a hydrogen safety point of view is that the concentration of hydrogen may increase as the concentration of water vapor decreases, thereby increasing the probability of hydrogen combustion and explosion.

The preliminary analysis of the spray droplet behavior in APR1400 shows that the concentration of hydrogen increases due to water vapor condensation in the dome region, as shown in Figure 8, while the hydrogen is well mixed by a strong mixing flow caused by droplets behavior. It shows that it can be mixed. In addition, through this preliminary calculation of the spray droplet behavior in the APR1400 containment, it can be seen that the developed spray analysis module works properly.

4. Conclusions

This is a study on the development of spray analysis model for the detailed analysis of the thermal hydraulics and the hydrogen behaviors in containment buildings during the operation of the containment spray under severe accident conditions.

A software module based on the Lagrangian spray model for an analysis of hydrogen behaviors affected by a containment spray during a severe accident was developed by improving the model especially in modeling of phase change of spray droplets, condensate film on a containment wall and spray nozzle rings and so on. An input model was developed for the analysis of APR1400 and steam and hydrogen behaviors in the containment during a spray operation was 3-dimensionally simulated. And it was confirmed that the developed module is applicable to containment spray analyses during severe accidents.

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