Methodology of HPME/DCH analysis in CINEMA code

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1. Introduction

High Pressure Melt Ejection and Direct Containment Heating (HPME / DCH) is severe accident that core melts in the lower head of the Reactor Pressure Vessel (RPV) and is discharged into the reactor cavity and entrained to upper dome when a reactor core-melt accident occurs. In this process, DCH phenomenon threats integrity of the containment building by heating the containment atmosphere, increasing the building pressure, and generating hydrogen combustion. This phenomenon is modeled by the HPME / DCH analysis module in SACAP code which is an external phenomenon analysis module.

CINEMA (Code for INterpreted severe accidEnt Management Analysis), which is a comprehensive severe accident analysis code currently developed, consists of In-vessel accident analysis module, Ex-vessel accident analysis module, and a fission product behavior module. In this paper, we analyze the actual DCH phenomenon observation experiment using HPME / DCH analysis module which is one of the Ex-vessel accident analysis modules and compare the experiment results.

The objective of this module development is not a detailed physical description of the HPME / DCH phenomenon, but validation of integrity of containment building in calculating the mass and energy source change from the conservative point of view. Therefore, the module is designed by using the correlation that observes the change rate of mass and energy source with time in designing the module considering the linkage and integration between In, Ex-vessel accident analysis module. When HPME/DCH event occurs, pressure and temperature in containment building increase as the atmosphere heats up. We compare the actual experimental result with predicted value.

2. Analysis Module Design

The HPME/DCH analysis module has the following configuration. Initially, the information of flow rate of the gas corium discharged from RPV, geometry and material properties in control volume of cavity is received, and calculation is performed to determine HPME occurrence criteria. If the HPME does not occur, the flow rate and state of the containment building are not updated. When the HPME phenomenon occurs exceeding the minimum criteria, the amount of energy change due to direct containment heating and the gas mass change in the containment building are updated. This process is shown in Figure 1.

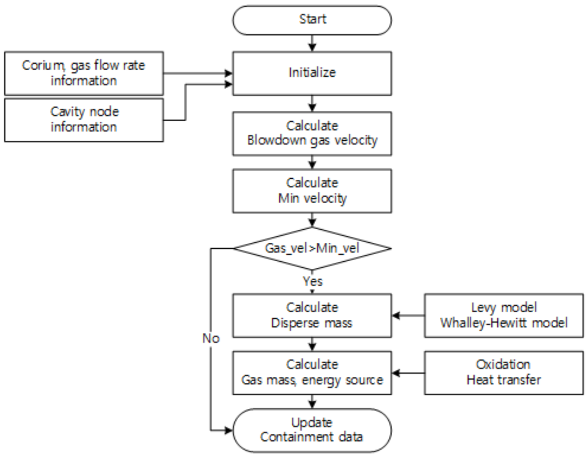

Figure 1 HPME/DCH analysis flow chart

2.1 Corium blowdown

In order to verify the validity of the HPME/DCH severe accident analysis module of the SACAP code, DCH experiment is selected and several parameters are directly specified by the user. At this time, the variables specified for the validation are the gas and corium flow rate. As corium dispersion in the reactor cavity is determined by the flow rate of the corium, gas discharged from the RPV due to a major accident, the numerical values are predicted and recorded in the input file for the experiment validation.

The DCH phenomenon can be divided into three stages. First, when the RPV failure occurs, the corium and gas are discharged. Next, after the corium is deposited on the bottom of the reactor cavity it is swept away by the released gas and entrained out of the reactor cavity. Corium which transferred to upper dome is reacted with steam. Finally, oxidation and thermal energy transfer to containment building atmosphere occurs. However, the HPME / DCH analysis module calculates the above three processes as occurring within one time step. Therefore, blowdown, entrainment, and heat transfer occur simultaneously.

The initial blowdown process is assumed as a single phase discharge. In practice, the process of corium blowdown takes place through a single-phase discharge in which only the melt is released at first, followed by two-phase discharge in which the melt and gas are released together, and finally, a single-phase discharge in which the gas is finally released. However, as an independent HPME/DCH analysis module, the blowdown process is conservatively set to implement the DCH phenomenon. The mass flow rate in the corium blowdown process decreases over time in proportion to height of the melt accumulated under the RPV for the two-phase discharge process. However, since the effect of pressure is dominant, code input value is set by reducing the flow rate in accordance with the decrease of the pressure in the single-phase discharge process.

The blowdown corium mass flow rate is given by the following equation[1].

$$\dot{m}_d = 0.6\rho_d A_h \sqrt{\frac{2\Delta P}{\rho_d}}$$

The discharge gas flow rate is determined by the vessel pressure. The gas flow rate according to the pressure is as follows[2].

$$\dot{m}_g = 0.6 A_h \gamma^0 \sqrt{\gamma P \rho_g}$$

The minimum gas velocity at which HPME event occurs is given by[3]

$$U_{\min} = 3.7\frac{\left[g\sigma\left(\rho_D - \rho_g\right)^{1/4}\right]}{\sqrt{\rho_g}}$$

The gas velocity according to the blowdown mass flow rate is as follows.

$$U_{ent} = \frac{\dot{m}_g}{A_c \rho_c}$$

As the hot corium is discharged through the reactor vessel failure area, the area is worn and widened. Since the gas discharge of the reactor vessel occurs after the expansion of the failure area by the hot corium, it is correct to assume the final area size rather than the initial size in the analysis. This HPME / DCH analysis module does not take into account the area change by expanding of the damaged area of the reactor vessel.

2.2 Corium dispersion

The amount of corium that is entrained per hour is determined by the gas velocity and corium mass flow rate in the reactor cavity. The dispersion model in the SACAP code calculates the entrainment rate per timestep and derives the dispersed mass by multiplying the rate by one timestep. Existing models have an entrainment fraction model for calculating the final corium mass fraction and an entrainment rate model for calculating the mass flow per time. This HPME/DCH analysis module in SACAP code calculates the changes in internal conditions such as pressure and temperature per time. Therefore, Whalley-Hewitt model and Levy model are applied that calculate the mass change with time. The entrainment rate of each model is calculated as follows.

- Levy model[4]

$$d\delta = K_c f_1 f_2 Eu^{2.3}\left[\frac{2P_c}{\sigma}\right]\sqrt{\frac{2P_c}{\rho_d}}\left[\frac{\mu_g}{\mu_d}\right]^{0.26}\delta\sqrt{1+300\frac{\delta}{D_c}}dt$$

$$f_1 = \left[\frac{(d_{s,h}/S_s)}{(d_h/S)}\right]^2\sqrt{\frac{R_s T_{0,s}}{RT_0}}$$

$$f_2 = \frac{\rho_{s,d}}{\rho_d}$$

-Whalley-Hewitt model[5]

$$dm_d = 0.0025K_c\left(1+360\frac{m_d}{A_{ww}D_c}\right)\left(\frac{\rho_g v_g^2 \mu_d}{\sigma}\right)\left(\frac{\sigma}{\sigma_s}\right)^{0.7826}dt$$

The cavity constant k_c, which is included in the above models, is an unfixed user-specified constant that varies according to the shape of the power plant and the discharge conditions of the melt, which is an optional constant for quantitatively analyze HPME/DCH experiments.

2.3 Mass, heat transfer

In the oxidation process, steam and hydrogen, total gas mass and energy source change are calculated and transferred to the associated Ex-vessel accident analysis module. The amount of hydrogen transferred to the hydrogen combustion analysis module includes the amount of hydrogen injected into the upper dome from the RPV and the amount produced by the chemical reaction of the metal components. The amount of energy transferred to the containment building thermal hydraulics analysis module is the amount of change in the oxidation energy due to the internal energy of the melts and gases, the vapor, and the chemical reaction of the melt.

The concept of reduction of equivalent unit volume is set up to calculate the oxidation reaction. If the unit metal reacting oxidation is equivalent to the sphere, the volume of the sphere will decrease with time as the oxidation reaction occurs. Since the oxidation takes place in the whole region of the equivalent sphere, sphere volume will decrease gradually during maintaining the shape of the sphere. The reduction in volume is determined by the decrease in the spherical radius over time. The ratio of the reduced volume to the initial equivalent sphere volume is the oxidation rate of the unit metal.

The amount of oxidized over time differs depending on the chemical reactivity of the metal. For example, if the amount of steam present is less than the amount of steam needed to be finally oxidized, steam reacts first with Zr in the core melt. The remaining vapor after the reaction reacts with the next more reactive metal. The amount of metal oxidation amount and the hydrogen production amount are calculated through this process.

The chemical reaction formula of the metal component in the corium is as follows.

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$$
$$2Cr + 3H_2O \rightarrow Cr_2O_3 + 3H_2$$
$$Fe + H_2O \rightarrow FeO + H_2$$
$$Ni + H_2O \rightarrow NiO + H_2$$

The oxidation energy due to this chemical reaction is calculated as follows.

$$Q_{ox} = m_D \left(\frac{\phi_{ox,Zr} f_{Zr} Q_{Zr}}{M_{Zr}} + \frac{\phi_{ox,Cr} f_{Cr} Q_{Cr}}{M_{Cr}} + \frac{\phi_{ox,Fe} f_{Fe} Q_{Fe}}{M_{Fe}} + \cdots \right)$$

The oxidation rate is given as follows[6][7].

$$\phi_{ox} = 1 - \left(1 - \frac{x}{r}\right)^3$$
$$x = \sqrt{K t_0}$$
$$r = N_{we} \frac{\sigma}{\rho_g v_g^2}$$

In energy transfer calculation, some assumptions for model design are established. The temperature and pressure of containment buildings change continuously over time. However, the HPME/DCH analysis module shows discontinuous calculated value because it performs computations depending on timestep. The corium that is entrained and oxidized during every timestep does not transfer heat completely during that timestep interval. However, analysis model set assumption that the energy is transferred until the corium reaches thermal equilibrium during each timestep. Physically, the amount of melt gradually decreases over time, eventually reaching equilibrium for a long time. The time it takes to reach thermal equilibrium is much longer than the interval of the timestep. However, the HPME/DCH analysis module is designed to calculate the maximum transferred energy for the oxidized corium per timestep from a conservative point of view.

Assuming the thermal equilibrium state of corium and gas in containment node, the final temperature of the entrained corium can be calculated as follows.

$$T_f \begin{pmatrix} m_g C_v + (m_{st} + \Delta m) C_s \\ + m_{DCH} C_D \end{pmatrix} = \begin{pmatrix} m_{DCH}(C_D T_D + \gamma_D) + m_{st} U_{st}(T_i) \\ + \Delta m U_{st}(T_V) + m_g C_v T_i + Q_{ox} \end{pmatrix}$$

The amount of transferred energy when the corium reaches the final temperature is calculated as follows.

$$E_0 = m_{DCH} \left(C_D \left(T_D - T_f \right) + \gamma_D \right) + Q_{ox}$$

3. Dome definition

In HPME/DCH analysis module, there are two options for setting up corium transfer to containment. If the entrained corium transfers to upper dome in containment, the single dome model is used to calculate corium amount physically by setting only one control volume. The multi dome model is set to transfer fraction that is defined by user corresponding to the several dome.

The single dome model calculates the transfer rate using the area which the entrained corium passes through. There are two processes that are transferred from the reactor cavity to the upper dome. One process is transfer through annular gap surrounding RPV that corium reaches upper dome directly. The other process is that corium is passed through the subcompartment connected to the reactor cavity and transferred to the upper dome.

Figure 2 shows the containment structure. In Figure 1, it is shown that corium transfers to upper dome through annular gap and subcompartment.

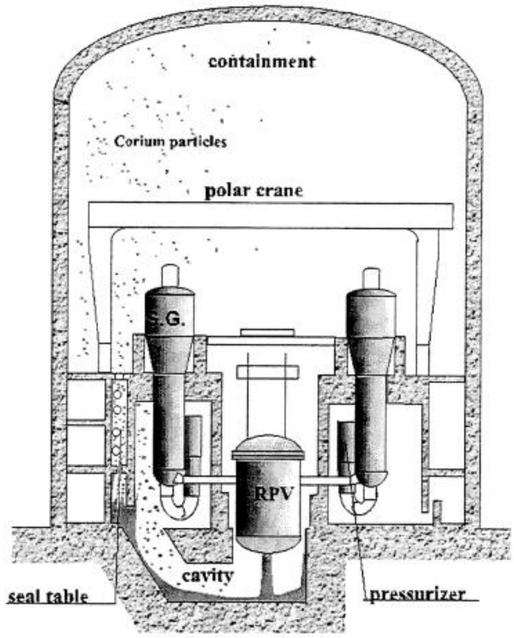

Figure 2 Zion plant cavity, containment structure

The transfer fraction that is scattered in the annular gap is as follows[8].

$$f_{gap} = \frac{A_c}{A_T + A_c}$$

The transfer through subcompartment is very complicated mechanism due to collision between corium and the subcompartment wall, but for some simple structures, transfer fraction can be calculated by the ratio of the area of the each subcompartment inlet and outlet. In this model, for the 41 number of the Westinghouse nuclear plant, fraction of the entrained corium passing through subcompartment is conservatively assumed to be 0.05. Of course, if corium does not transfer through the lower compartment, you can input fraction value to 0.
The fraction reached upper dome considering the annular gap and subcompartment is calculated as follows.

$$f_{dome} = 0.9 f_{gap} + f_{sub} \left(1 - f_{gap} \right)$$

4. Experiment condition

In order to interpret the HPME/DCH phenomenon, Sandia National Laboratory (SNL) in USA has built an experimental database to verify the phenomenon by reducing the number of structure in various power plants. In this report, the DCH integral experiment of Zion plant was selected. Next, pressure and temperature rise of the containment building according to initial conditions were calculated by using HPME/DCH analysis module in SACAP code. Eventually, a comparison to SNL experiment value is performed.

4.1 Cavity geometry

In HPME/DCH analysis module, the calculations are performed by placing the cavity into one control volume. The RPV is connected to the upper part of the cavity, and exit area of reactor cavity is connected to the subcompartment. The factors required to calculate the scattering of the melt in cavity are cavity wall area, hydraulic diameter, and cavity flow area. Figure 3 shows the schematic of the reactor cavity for the Zion type nuclear power plant.

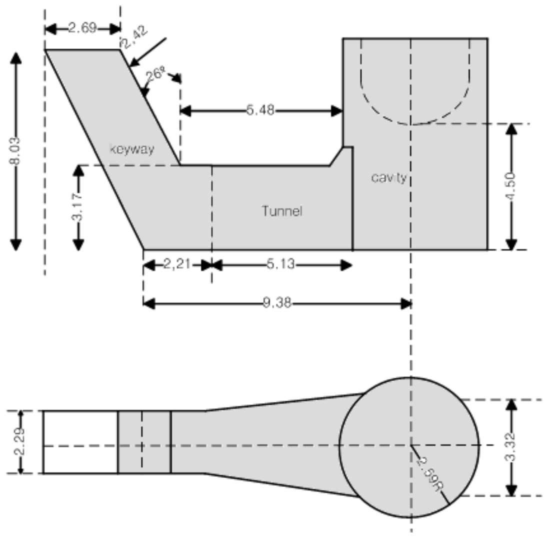

Figure 3 Schematic diagram of cavity in Zion plant

4.2 Initial condition

HPME/DCH analysis module is designed to calculate the entrainment rate by receiving the flow rate and material properties of the gas and corium from the in-vessel phenomenon analysis module. However, the user designates the flow rate directly for the module verification. Gas and corium flow rate are determined by RPV pressure, which is the factor that determines the velocity of the gas. The pressure change value is based on the graph tendency shown in the SNL IET-1R experiment[6]. The reason for selecting the IET-1R experiment is that it is an experiment that minimizes the possibility of hydrogen combustion after the corium is released into the dome. The pressure change of the RPV is shown in Fig 4. The initial discharge pressure is 6.3MPa. RPV pressure drops sharply with the release of corium, gas. It is assumed that gas temperature state is isothermal regardless of PRV pressure drops.

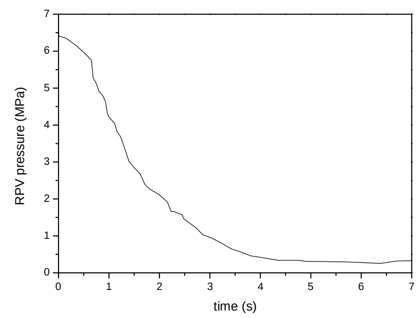

Figure 4 Time vs RPV driving pressure

The pressure change of the cavity is shown in Fig 5. After the corium is discharged, corium begins to entrain from 0.4 seconds, and entrainment continues until 0.75 seconds. The RPV pressure at the entrainment starting point is 0.22MPa. The RPV pressure at 0.75 seconds, which is the end of the entrainment, is 0.32MPa. Therefore, when flow rate is input to the analysis module, the gas and corium flow rate are calculated based on the pressure at the start and end of entrainment. This analysis module assumes that if the gas velocity drops below the minimum gas velocity, the melt does not entrain.

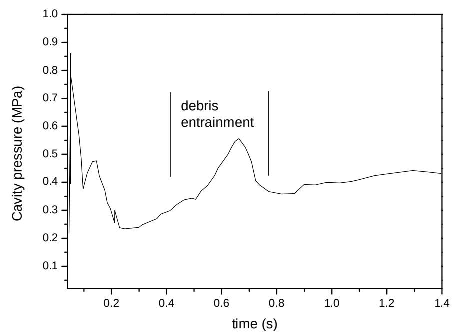

Figure 5 Time vs Cavity pressure

In the entrainment calculation, the cavity constant Kc, which varies according to cavity geometry and the properties of the corium and gas, is selected by the user. We use the Whalley-Hewitt model and the Levy model to compare the results.

Table 1 summarizes the initial conditions of the experiment and the physical properties of gas and corium,.

Table 1 IET-1R experiment initial condition

Description	Value
Cavity pressure(MPa)	2
Dome pressure(MPa)	2
gas temperature (K)	600
Cavity temperature (K)	300
Dome temperature (K)	300
Cavity volume (m3)	0.245
Dome volume (m3)	89.8
flow area (m2)	0.0524
Wall area (m2)	1.519

blowdown gas	steam		
blowdown corium	Thermite		
	Al_2O_3	Fe	Cr
Corium mass fraction	0.34	0.52	0.14

5. Result

Experiments were carried out using initial conditions and the results are as follows.

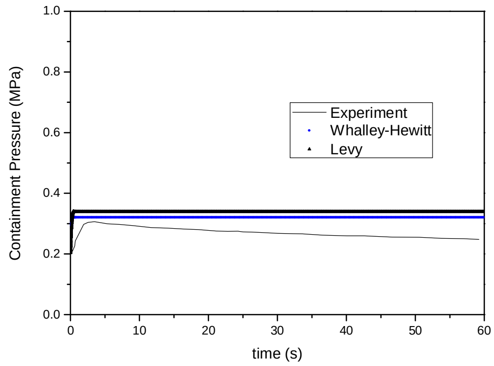

Figure 6 Time vs Containment pressure

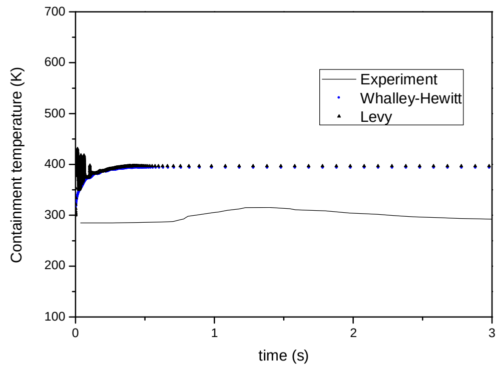

Figure 7 Time vs Containment temperature

In the verification using the DCH analysis module, only the pressure and temperature rise of the containment building due to corium entrainment are compared with experiment value. So, no modeling was done for any decrease of pressure and temperature after entrainment conclusion.

Although slightly difference, two entrainment rate models yield values similar to maximum pressure, temperature values in the experiment. Experimentally, the increase of maximum pressure in DCH development is 0.306MPa and the maximum temperature is 315K. For Whalley-Hewitt model, it is calculated that the increase of maximum pressure is 0.32MPa and maximum temperature is 393K after 0.4 second when the cavity constant Kc_WH = 10. For Levy model, it is calculated as maximum pressure 0.338MPa and maximum temperature 396K after 0.4 second when the cavity constant Kc_levy is 0.2. The other constants of the Levy model, R_s, rho_s, T_s, S_s, and D_s, were set to the same value as the experimental conditions and were eliminated in the equation.

As shown in Figure 6 and 7, the time to reach maximum pressure and temperature is shorter than the time calculated using the code. This is because the analysis module simultaneously analyzes the blowdown, entrainment, and oxidation and energy transfer processes in each timestep, but there is actually a slight time interval between blowdown and entrainment process. In fact, it is very complicated and uncertain to calculate precisely the time interval from blowdown to the occurrence of entrainment and the energy transfer time because it is the limit of the analysis model itself. This DCH analysis module does not solely analyze the phenomenon but links it with in-vessel phenomena analysis module. The data transferred to the DCH analysis module is the gas and corium flow rate. Since corium discharge phenomenon is not taken into account in the DCH analysis module, it takes a way to calculate the entrainment to the cavity for linked flow rate data during each timestep. Therefore, this calculation process is considers blowdown and entrainment process simultaneously. Point in observation of the DCH phenomenon are the pressure and the temperature rise that affect the integrity of the containment building, therefore, it is applicable that maximum temperature and pressure rising time is calculated to be slightly faster than the actual maximum time.

In this report, heat conduction is not considered. Considering the heat transfer between conductor and atmosphere, pressure and temperature decrease with time. The purpose of the HPME / DCH phenomenon analysis is to assess the maximum pressure and temperature rise due to the evaluation of the integrity of the containment building during temperature and pressure rise. Therefore, temperature and pressure calculated by HPME/DCH analysis module does not change over time.

In this validation, the cavity constant defined by the user are slightly different from the known value (Kc_WH = 43, Kc_levy = 0.0073) in the existing analysis codes. This is because the DCH analysis module of the SACAP code calculates maximum energy transfer in each timestep, so it is possible that a difference between known value and it which user defined exists. In addition, cavity constant need to be found appropriately values through the sensitivity analysis in the DCH experiment for other nuclear power plants that do not have reference materials because it is unfixed constant that vary not only with the structure of cavity but also with the initial material property condition in cavity.

6. Conclusion

Through validation performed in this paper, it was confirmed that the HPME/DCH analysis module predicts maximum pressure and temperature rise. There are several constants that the user should define in this process. It is considered that additional research is needed for these constants. When the complete linkage with the in-vessel phenomena analysis module is made, the severe accident scenario of the domestic nuclear power plant will be set up to predict the integrity of the containment building. In order to validate HPME/DCH phenomenon, only the temperature and pressure rise by corium dispersion and oxidation were observed in this paper It is necessary to take into account other ex-vessel phenomena for precise analysis, which is a future study. Therefore, more research and validation for the module accuracy are needed in future.

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Nomenclature

A_c	cavity flow area
A_h	RPV failure area
A_{ww}	RPV failure area
C_v	gas specific heat in containment
C_s	steam specific heat
C_d	corium specific heat
d_{sh}	standard failure diameter
d_h	failure diameter
ΔP	RPV driving pressure
δ	corium thickness on cavity
D_c	cavity hydraulic diameter
$Eu = \frac{\rho_g v_g^2}{2P_c}$	Euler number
f_{metal}	corium metal fraction
γ	specific heat ratio
$\gamma^0 = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$	gamma function
γ_d	corium latent heat
g	gravitational acceleration
K	Arrhenius constant
K_c	cavity constant
m_g	gas mass in containment
m_{st}	steam mass in containment
Δm	blowdown steam mass
m_{dch}	entrainment corium mass
m_d	corium mass
M_{metal}	metal component molecule weight
μ_g	gas viscosity
μ_d	corium viscosity
N_{we}	Weber number
P_c	cavity pressure
Q_{metal}	metal component oxidation heat
Q_{ox}	oxidation energy
ρ_g	blowdown gas density
ρ_d	corium density
ρ_c	gas density in cavity
ρ_s	standard corium density
R_s	standard gas constant
R	gas constant
σ_s	standard surface tension
σ	surface tension
S_s	standard cavity scale
S	cavity scale
T_s	standard gas temperature
T_g	gas temperature
T_v	gas temperature in RPV
T_i	gas temperature in containment
t_0	timestep
U_{st}	steam internal energy

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