Development of Lower Plenum Molten Pool Module of Severe Accident Analysis Code in Korea

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1. Introduction

After Fukushima accident in 2011, the importance of severe accident analysis is emphasized not only in the nuclear engineering but also public. In the line of severe accident analysis and prediction of it, the development of integrated severe accident analysis code has been started by the collaboration of three institutes in Korea. KAERI (Korea Atomic Energy Research Institute) is responsible to develop modules related to the in-vessel phenomena, while FNC (Future & Challenge) and KHNP (Korea Hydro & Nuclear Power Co., Ltd.) are to the containment and severe accident mitigation facility, respectively.

To simulate a severe accident progression of nuclear power plant and forecast reactor pressure vessel failure, we develop computational software called COMPASS (COre Meltdown Progression Accident Simulation Software) for whole physical phenomena inside the reactor pressure vessel from a core heat-up to a vessel failure [1]. As a part of COMPASS project, in the first phase of COMPASS development (2011 ~ 2014), we focused on the molten pool behavior in the lower plenum, heat-up and ablation of reactor vessel wall. Input from the core module of COMPASS is relocated melt composition and mass in time. Using this, we calculate temperatures of molten pools, overlying water, steam and debris bed, etc.

Various models and correlations are tested to predict the molten pool behavior in the lower plenum, and modelled as simple as possible for fast calculation of the code. Molten pool behavior is described based on the lumped parameter model. Heat transfers in between oxidic, metallic molten pools, overlying water, steam and debris bed are considered in the present study. The models and correlations used in this study are appropriately selected by the physical conditions of severe accident progression.

Interaction between molten pools and reactor vessel wall is also simulated based on the lumped parameter model. Heat transfers between oxidic pool, thin crust of oxidic pool and reactor vessel wall are considered and we solve simple energy balance equations for the crust thickness of oxidic pool and reactor vessel wall. As a result, we simulate a benchmark calculation for APR1400 nuclear power plant, with assumption of relocated mass from the core is constant in time such that 0.2ton/sec. We discuss about the molten pool behavior and wall ablation, to validate our models and correlations used in the COMPASS.

2. Overview of the module and numerical details

2.1 Overview of the module

We call the lower plenum module of COMPASS code as SIMPLE (Severe In-vessel Melt Progression in Lower plenum Environment) module [2]. SIMPLE module is possible to run in a stand-alone manner. In the present study, computational results come from the stand-alone SIMPLE module not from the whole COMPASS code.

SIMPLE module calculates the thermal hydraulic behavior of the relocated molten pool in the lower plenum based on the following steps as shown in figure 1 for SIMPLE calculation framework. As shown in the figure 1, present module calculates thermal hydraulic behavior of particulate debris bed, metallic pool, oxidic pool, crust, vessel wall, steam and water.

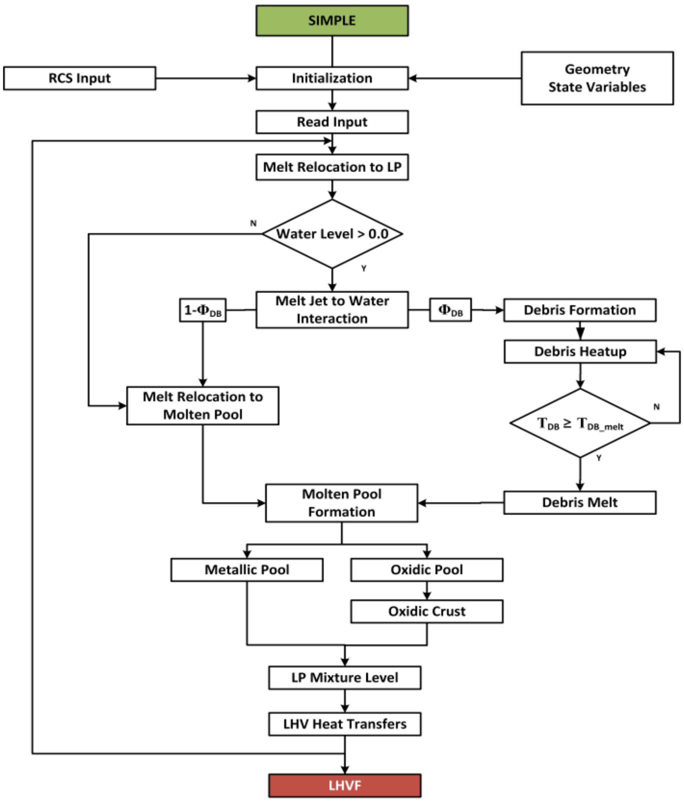

Fig. 1 SIMPLE calculation framework

2.2 Overview of the inputs and assumptions

SIMPLE code receives the core melt relocation information from the COMPASS core module as an input in a form of transient time. Following information is needed to calculate SIMPLE module:

- Core and lower plenum pressure
- Inlet coolant flow from the downcomer (temperature and corresponding enthalpy)
- Initial coolant level in the lower plenum
- Initial conditions of independent variables.

Following assumptions are used for SIMPLE module:

- Uniform mixture of relocated melt composition is assumed (including UO_2, ZrO_2, SS, etc.)
- Uniform distribution of relocated melt
- Bulk average of relocated melt temperature
- Structural materials are assumed to be included in the relocated core melt.

In the present study, one-dimensional grid distribution of lower plenum is applied. The number of zones of the annulus grid is a user input. We used 4 annular rings to discretize the lower plenum.

3. Models and correlations used in SIMPLE

3.1 Melt jet-coolant interaction

To simulate quenching of melted corium from the core, we assume the corium is relocated as a form of continuous liquid jet. Following assumptions are used for the melted jet-coolant interaction in the lower plenum:

- If there is water in the lower plenum, melt jet interacts with the water, breaks up into debris particulates and settled as particulate debris bed in the lower plenum water. Settled particulate debris bed is the heated up and re-melted.
- Melted corium is immediately separated and distributed into the metallic and oxidic pools.
- If there is no water in the lower plenum, melt jet impinges into the lower head vessel and metallic components are added to the metallic pool and oxidic components are added to the oxidic pool.

Relocated liquid corium jet impinges into the water in the lower plenum and interacts with the water and breaks up. A fraction of the impinging melt is added to the particulate debris bed and others relocate directly into the molten pool in the lower plenum. The jet break up fraction is determined based on the previous experimental results.

For jet impingement, we use Ricou-Spalding entrainment model [3], to analyze characteristics of corium jet which interacts with respect to the coolant in the lower plenum. After calculate the jet impingement, quenching of the impinging corium jet in the water is considered. We have a few assumptions about heat transfer from debris particles to surrounding water during the melt jet impingement and breakup:

- Melt drop time is a user input and assumed to be 0.1 second as a default value. This input is used for the initial drop time of the core melt.
- Each fragmented debris particle is assumed to be covered with the vapor blanket film in the lower plenum and the heat transfer mode is assumed as the convection and radiation.

As a result, heat transfer from the corium jet to the coolant is calculated separately into the water and vapor steam, and it is determined by film boiling heat transfer of Dhir and Purohit model [4]. Detailed model description is available in the report [2].

3.2 Particulate debris bed

Particulate debris bed is formed by the corium jet break up, impingement and quenching. Therefore we solve the mass and energy conservation equations for the particulate debris bed, with a few assumptions about its dynamics.

- Relocated particulate debris bed is heated up and re-melts after its formation.
- Melted particulate debris bed is separated and added to the metallic and oxidic molten pool according to the melt composition.

The mass balance of the particulate debris bed is given as,

$$\frac{\partial m_{DB}}{\partial t} = w_{DB,inlet} - w_{DB,melt} \, . \qquad (1)$$

Here, m_{DB} is the mass of particulate debris bed, $w_{DB,inlet}$ is mass inflow rate after the jet break-up, and $w_{DB,melt}$ is mass outflow rate by the melting of particles.

The energy balance is also formulated from the first principle of the control volume above the molten metallic pool assuming uniform porosity,

$$\frac{\partial m_{DB} h_{DB}}{\partial t} = w_{DB,inlet} h_{DB,inlet} - w_{DB,melt} h_{DB,melt} + q_{DB,dh} + q_{MP,up} - q_{DB,\mathrm{w}} - q_{dbc} - q_{DB,rad} \, . \qquad (2)$$

Here, h_{DB} is the enthalpy of particulate debris bed, $q_{DB,dh}$ is the decaying heat generation from the particulate debris bed, $q_{MP,up}$ is the heat transfer from metallic molten pool, $q_{DB,\mathrm{w}}$ is the heat transfer to overlaying water, q_{dbc} is the heat transfer to the vapor by natural convection (debris bed coolability), and $q_{DB,rad}$ is the radiation heat transfer to the structure. Each terms of mass and energy conservation is carefully modeled and selected from the previous literatures and correlations.

3.3 Metallic molten pool

Molten pool of corium in the lower plenum is formed from direct core melt relocation to the lower plenum and the particulate debris bed melt relocation after it is melted in the lower plenum. Physically, there are three ways to form molten pool in the lower plenum.

- Settled particulate debris bed is heated up and melts when the temperature is equal to the melt temperature.
- Fraction of core melt directly relocates to the bottom of the lower head through the water and form molten pool.
- Core melt directly impinges to the lower head vessel when there is no water in the lower plenum.

To simplify the physics inside the molten pool, we consider two-layer model (metallic and oxidic). Including this, there are a few assumptions about molten corium pool behavior in the lower plenum:

- No crust is assumed for the metallic molten pool.
- Due to density differences between oxidic materials (UO_2, ZrO_2) and metallic materials (Zr, SS, In), the molten pool is separated into upper metallic and lower oxidic molten pools.
- The metallic and oxidic materials are separated immediately in the lower plenum.
- The composition of the molten pool components is identical to the composition of the input relocating core melt.

The mass balance of the metallic pool is given as,

$$\frac{\partial m_{MP}}{\partial t} = w_{inlet,MP}^{dbj} + w_{DB,MP}\,. \qquad (3)$$

Here, m_{MP} is the mass of metallic molten pool, $w_{inlet,MP}^{dbj}$ is mass inflow rate from the jet break-up, and $w_{DB,MP}$ is mass inflow rate by the melting of particles to the metallic pool.

The energy balance is formulated from the first principle of the control volume about metallic pool, melt-relocation, melted particulate debris bed and heat transfer around the metallic pool:

$$\begin{aligned}\frac{\partial m_{MP} h_{MP}}{\partial t} &= w_{inlet,MP}^{dbj} h_{inlet,MP} + w_{DB,MP} h_{DB,melt} \\ &+ q_{MP,b} - q_{MP,up} - q_{MP,w}\end{aligned}\,. \qquad (4)$$

Here, h_{MP} is the enthalpy of metallic pool, $q_{MP,b}$ is heat transfer from the bottom of metallic pool, $q_{MP,up}$ is the heat transfer to the particulate debris bed, and $q_{MP,\mathrm{w}}$ is heat transfer of natural convection to the lower head wall. Each terms of mass and energy conservation is selected such as Globe-Dropkin [5], Bromley [6], Churchill-Chu [7], etc.

3.4 Oxidic molten pool

The mass balance of the oxidic pool is given as,

$$\frac{\partial m_{OP}}{\partial t} = w_{inlet,\mathrm{O}P}^{dbj} + w_{DB,\mathrm{O}P} - w_{\mathrm{O}P,crust}^{up} - w_{\mathrm{O}P,crust}^{w}\,. \qquad (5)$$

Here, m_{OP} is the mass of oxidic molten pool, $w_{inlet,OP}^{dbj}$ is mass inflow rate from the jet break-up, and $w_{DB,OP}$ is mass inflow rate by the melting of particles to the metallic pool, $w_{OP,crust}^{up}$ and $w_{OP,crust}^{w}$ are the mass outflows to the solidified oxidic materials on the upper part and side wall.

The energy balance is derived including heat transfer around the oxidic pool:

$$\begin{aligned}\frac{\partial m_{OP} h_{OP}}{\partial t} &= w_{inlet,OP}^{dbj} h_{inlet,OP} + w_{DB,\mathrm{O}P} h_{DB,melt} \\ &- w_{OP,crust}^{up}(C_{p,crust} T_{OP,melt}) - w_{OP,crust}^{w}(C_{p,crust} T_{OP,melt})\,. \\ &- q_{OP,dh} - q_{OP,up} - q_{OP,w}\end{aligned} \qquad (6)$$

Here, h_{OP} is the enthalpy of oxidic pool, $q_{OP,dh}$ is decaying heat in the oxidic pool, $q_{OP,up}$ is the heat transfer to the metallic pool, and $q_{OP,\mathrm{w}}$ is heat transfer of natural convection to the lower head wall.

Crust calculation for the oxidic molten pool is separately performed in the SIMPLE module. Wall ablation is calculated in time with input from the oxidic pool temperature and lower head vessel position. Using this time dependent lower head wall thickness, we can evaluate lower head failure.

3.5 Coolant in the lower plenum

To estimate coolant mass in the lower plenum, we use two-fluid model. The mass and energy balance equations are separately solved for the water and vapor steam.

The mass balance of the water and steam are given as,

$$\frac{\partial m_w}{\partial t} = w_{inlet,w} - w_{outlet,w} - w_{evap}\,. \qquad (7)$$

$$\frac{\partial m_{stm}}{\partial t} = w_{inlet,stm} - w_{outlet,stm} + w_{evap}\,. \qquad (8)$$

Here, m_w and m_{stm} are the mass of water and steam, $w_{inlet,w}$ and $w_{inlet,stm}$ are the inlet mass flow rate of water and steam, $w_{outlet,w}$ and $w_{outlet,stm}$ are the outlet mass flow rate of water and steam to the core, and $w_{evaporation}$ is the mass flow rate of evaporation.

The energy balance of the water and steam are given as,

$$\begin{aligned}\frac{\partial m_w h_w}{\partial t} &= w_{inlet,w} h_{inlet,w} - w_{outlet,w} h_{outlet,w} \\ &- w_{evap} h_g + q_{qnc,w} + q_{DB,w} + q_{surf}\end{aligned}\,. \qquad (9)$$

$$\frac{\partial m_{stm} h_{stm}}{\partial t} = w_{inlet,stm} h_{inlet,stm} - w_{outlet,stm} h_{outlet,stm} + w_{evap} h_g + q_{qnc,stm} - q_{dbc} - q_{surf} + q_{conv,stm} \quad (10)$$

Here, h_w and h_{stm} are the enthalpy of water and steam, h_g is enthalpy of steam at saturation temperature, $q_{qnc,w}$ is quenching heat transfer from the liquid debris jet to water, $q_{DB,w}$ is heat transfer from the particulate debris bed to the water, q_{surf} is surface heat transfer between the steam and liquid interface, $q_{qnc,stm}$ is quenching heat transfer from the liquid debris jet to steam, q_{dbc} is debris bed coolability, and $q_{conv,stm}$ is convection heat transfer from the particulate debris bed to the steam.

Solving these mass and energy conservations, instantaneous water level is obtained. Using the instantaneous water level, heat transfer inside the lower plenum is calculated and updated.

4. Results

4.1 Test case: corium mass relocation = 0.2ton/sec

Following assumptions are used for the simulation:

- Reference plant: APR1400
- Melt composition
    - UO2 = 67% (67 ton)
    - ZrO2 = 9% (9 ton)
    - Zr = 9% (9 ton)
    - SS = 14% (14 ton)
    - Inconel = 1% (1 ton)
    - Total = 100% (100 ton)
- Time Step: 0.05 second
- Water and steam inlet flow from the downcomer to the lower plenum were assumed to be zero.
- Melt Temperature: $T_{jet,melt} = 3200K$
- Rate of Constant Core Melt Relocation 100,000kg in 500 sec: 200 kg/sec
- Decay heat: 2% of APR1400 total core power

SIMPLE program is used to predict the molten pool behavior in the lower plenum after the melted corium relocated into the lower plenum with constant rate of melt relocation from the core support plate. 100 tons of the corium melt relocated into the lower plenum with 200 kg/sec as shown in figure 2. After 500 seconds, the corium melt stopped to relocate.

Initially the lower plenum was filled with the water and the water level (or depth) in the lower plenum decrease as the melt relocates and evaporates the water. Thus the lower plenum water mass decreases and steam mass increases as the water evaporates by the melt jet-water fuel coolant interactions and the steam flows to the core as shown in figure 3.

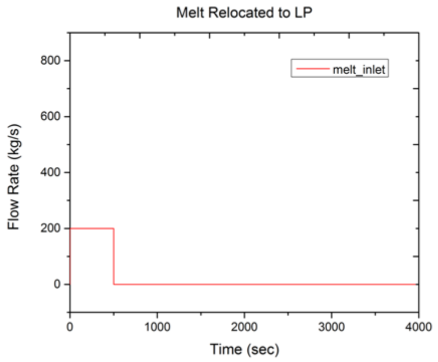

Fig. 2 Rate of constant melt relocation to lower plenum

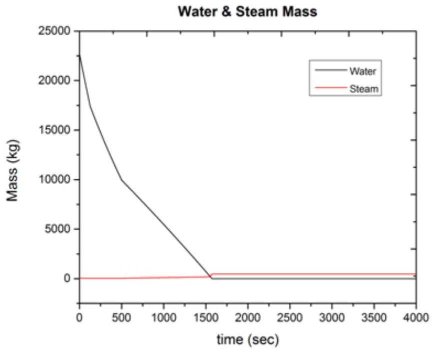

Fig. 3 Water and steam mass in the lower plenum

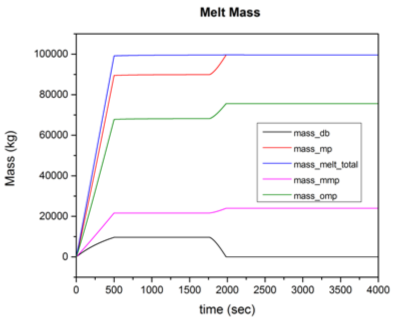

Fig. 4 Relocated masses in the lower plenum

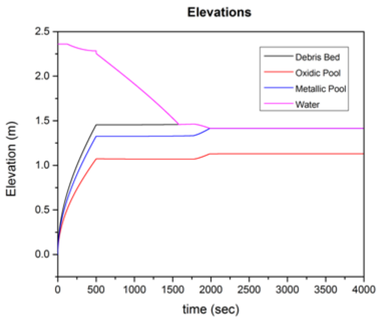

Fig. 5 Elevation of masses in the lower plenum

Figures 4 and 5 show the masses of the melts and debris bed, and corresponding elevations of the melts, debris bed and water, respectively. As the corium melt starts to relocate into the lower plenum, a fraction of the melt becomes the debris bed by the melt jet-water interactions and the rest of the melt directly relocates into the bottom of the lower plenum as assumed for this analysis and immediately separates into metallic molten pool and oxidic molten pool due to density differences. Debris bed is quickly heated up after the water dries out and melted into the molten pool at 1900 seconds. The melted debris bed then added to the metallic and oxidic pools depending on the composition as shown in figure 5.

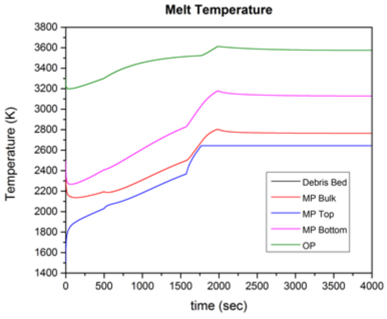

Fig. 6 Temperatures of relocated masses in the lower plenum

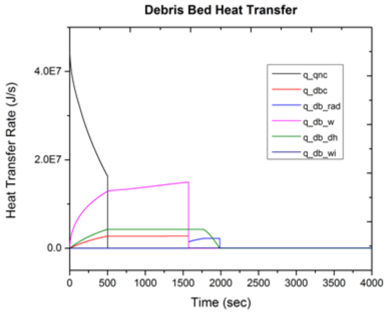

Fig. 7 Particulate debris bed heat transfer rates in the lower plenum

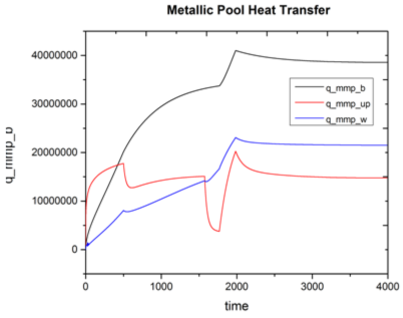

Fig. 8 Metallic pool heat transfer rates in the lower plenum

Figure 6 shows the melt temperatures. Particulate debris bed temperature increases gradually as the water evaporates and dries out and rapidly increases and melt after overlaying water dries out. Bulk and top of the metallic pool temperatures shows similar trends as the water dries out, however, oxidic pool bulk temperature maintained at high temperature and shows quite different behavior from other melts due to the fact that it is well below water level and it also has volumetric decay heat generation. Figure 7 is the particulate debris bed heat transfer behavior and shows that the quenching id the highest heat transfer mechanism during melt relocation and it is decreasing as the water inventory in the lower plenum decreases and the debris coolability is the major heat transfer mode after the melt stop relocating into the lower plenum. Figure 8 shows the metallic pool heat transfer modes. Both bottom and upwards natural convection heat transfers were calculated using Globe-Dropkin correlation. Since there is no volumetric heat generation in the metallic pool, the natural convection heat transfer from the bottom should be divided into the upwards natural convection heat transfer and LHV side wall heat transfer. The bottom metallic pool natural convection heat transfer is increasing as the melt relocates into the lower plenum and rapidly increasing after the water dries out and maintained at superheated state. Upward molten pool natural convection heat transfer of the molten pool increases as the melt relocates and decreases and maintained steady until the water dries out and decreases rapidly as the debris bed temperature rapidly increases and increases rapidly again as the debris bed all melted and relocates to the molten pool as shown in figure 8. Figure 9 shows the oxidic pool heat transfers for the upward and lower head vessel side wall as well as the volumetric decay heat generation.

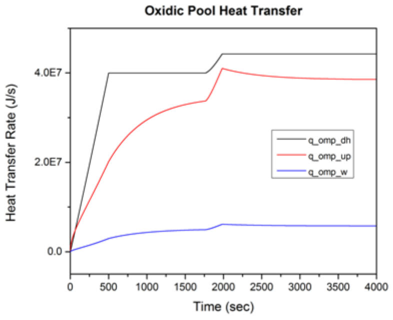

Fig. 9 Oxidic pool heat transfer rates in the lower plenum

5. Conclusions

Stand-alone SIMPLE program is developed as the lower plenum molten pool module for the COMPASS in-vessel severe accident analysis code.

SIMPLE program formulates the mass and energy balance for water, steam, particulate debris bed, molten corium pools and oxidic crust from the first principle and uses models and correlations as the constitutive relations for the governing equations. Limited steam table and the material properties are provided in the program. Stand-alone SIMPLE program only uses limited input from the core, RCS and LHVF module from the COMPASS code.

SIMPLE program calculates the behavior of the water and steam in the lower plenum, heat transfer mechanisms through the interfaces among the water, steam, corium jet, debris bed, metallic and oxidic pools as well as the crust above the oxidic pool.

The case of uniform melt relocation was tested for the verification and limited validation of the SIMPLE program.

The numerical result shows reasonable response for the molten pool behavior in the lower plenum after the corium melt relocated into the lower plenum.

More qualitative validation of the SIMPLE program is required using experimental data.

The SIMPLE program will be merged in the COMPASS code as the lower plenum module to provide the lower plenum molten pool behavior during the severe accident analysis.

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