Heat Transfer Model of Lower Head Vessel Failure at SIMPLE code for simulating Severe Accident

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1. Introduction

Determination of the heat-up and ablation rate of lower head vessel wall is one of the important issues at in-vessel or ex-vessel severe accident analysis. Existing system codes to simulate the lower head vessel failure have assumed the initial wall temperature to the interface temperature T_{int} when the corium contacts to the vessel wall, which is derived by the transient heat conduction of semi-infinite medium with time-independent, constant, Dirichlet boundary condition [1,2]. However, real phenomena are easy to expect that boundary conditions (temperature of molten corium and heat flux into reactor cavity) causing the heat transfer at lower head vessel wall are the time-dependent. This results in significant difference of initial stage at the accident progress (i.e., heat-up) of the lower head vessel wall and can afford to impact vessel failure such as melting or creep. Present study introduces the heat transfer model at lower head vessel wall with time-dependent boundary condition to apply the SIMPLE code [3].

2. Methods and Results

2.1 Problem definition

When the reactor core is melted and core support plate is failed, highly superheated (or melted) solid suddenly contacts to the inner wall of lower head vessel. This leads to large temperature gradient inside wall and to increase the inner wall temperature until its melting temperature, which influences probability of the vessel wall ablation. Described model in the present study is related to the initial heat-up of lower head vessel wall with considering the formation of crust layer growth before the vessel wall ablation. By considering the energy balance at control volume (containing the corium, crust and vessel wall), heat transfer model is developed based on the time-dependent thermal penetration depth. This model covers the pending issue of in-vessel severe accident analysis at existing system code such as assumption of semi-infinite transient heat conduction with constant boundary condition.

2.2 Energy balance equation

Energy balance equations in developed model are solved by the explicit Euler and major assumptions are described as below;

i) Initial vessel wall temperature is uniform; inner wall and outer wall of lower head vessel is isothermal, $T_i = T_{vb}$ (=400K).
ii) Initial crust layer thickness is determined by the energy balance (Eq. 1)

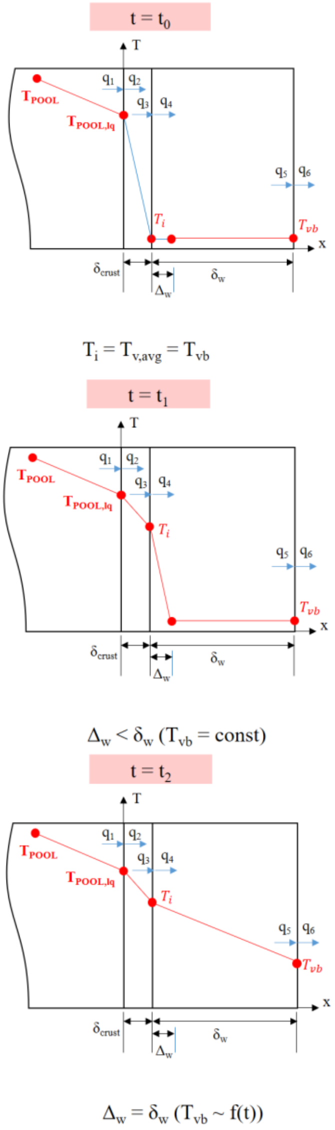

Fig. 2. Schematic of control volume to solve the heat transfer problem.

Heat transfer from the corium to the vessel wall is based on the energy balance equation in Eq. 1 and Ti among two unknown variables is expressed by Eq. 2. Δw is thermal penetration depth and this can be determined by the energy conservation equation of wall (Eq. 3) and energy balance of crust layer formation (Eq. 4). Average vessel temperature is defined by two stage. The first is when the thermal penetration depth is below the wall thickness, which means that the temperature of the wall vessel has a certain gradient because of finite thermal diffusivity (Eq. 5). In this case, the outer wall temperature is constant. The second is when the thermal penetration depth is same or beyond the wall thickness. This case includes the increase of outer wall temperature at lower head vessel (Eq.6).

$$\frac{k_{crust}}{\delta_{crust(t0)}}\left(T_{pool,lq}-T_i\right)=\frac{k_w}{\Delta_w}\left(T_i-T_{vb}\right) \quad (1)$$

$$T_i=\left[\frac{\left(\frac{k_{crust}}{\delta_{crust}}T_{pool,lq}+\frac{k_w}{\Delta_w}T_{vb}\right)}{\frac{k_{crust}}{\delta_{crust}}+\frac{k_w}{\Delta_w}}\right] \quad (2)$$

$$q_4=\left(\rho C_p\right)_W\delta_W\frac{\Delta}{\Delta t}\left(T_v^{avg}\right) \quad (3)$$

$$(q1-q2)\left(\frac{1}{\lambda_{POOL}\rho_{POOL}}\right)=\left(\frac{d\delta_{crust}}{dt}\right) \quad (4)$$

$$T_v^{avg}=\frac{1}{2}\Delta_w\left(T_i-T_{vb}\right)/\delta_w+T_{vb} \quad (5)$$

$$T_v^{avg}=\frac{1}{2}\Delta_w\left(T_i-T_{vb0}+T_{vb}-T_{vb0}\right)/\delta_w+T_{vb0} \quad (6)$$

$$a(\Delta_w)^2+b(\Delta_w)+c=0 \quad (7)$$

$$T_{vb}=\frac{T_V^{avg}\left(\frac{k_w}{\delta_w}+\frac{k_c}{\delta_c}\right)-\frac{1}{2}\frac{k_c}{\delta_c}T_{plq}}{\frac{k_w}{\delta_w}+\frac{1}{2}\frac{k_c}{\delta_c}} \quad (8)$$

Finally, we can obtain the two unknown variables (Ti and Δw) at Δw < δ and Ti and Tvb at Δw ≥δ from the energy balance equations (Eq. 7,8). The parameters (a,b and c) in Eq. 7 are derived from the Eq 1 to 5. Test calculation to evaluate the heat transfer of lower head vessel wall is summarized in Table I. Heat flux from the corium and the corium pool temperature is time-dependent. Thickness of lower head vessel wall is 0.2 m and material is selected by general stainless steel.

Table I: Heat transfer variables for test calculation

Symbol	Value	Unit	Description
q1	0.1 – 0.25	MW/m^2	Heat flux from the corium (Time-dependent)
q2=q3	-	W/m^2	Heat flux to the crust layer
q4	-	W/m^2	Heat flux from the crust layer
q5=q6	-	W/m^2	Heat flux from the wall
k_{crust}	1	W/m-K	Thermal conductivity of crust layer
k_w	32	W/m-K	Thermal conductivity of lower head vessel wall
ρ_w	8000	kg/m^3	Density of lower head vessel wall
ρ_{pool}	8191	kg/m^3	Density of corium
Cp_w	500	J/kg-K	Specific heat of lower head vessel wall
δ_w	0.2	m	Thickness of lower head vessel wall
δ_c	-	m	Thickness of crust layer
T_{pool}	2900-3050	K	Pool temperature of the corium (Time-dependent)
T_{poollq}	2800	K	Liquidus temperature of the corium
λ_{pool}	277	kJ/kg	Latent heat of corium
T_{ex}	400	K	Temperature of external coolant
H_{ex}	200	W/m^2-K	Heat transfer coefficient of external coolant
T_i	-	K	Temperature of lower head vessel inner wall
T_{vb}	-	K	Temperature of lower head vessel outer wall
T_{wmelt}	1800	K	Melting temperature of lower head vessel wall
Δ_w	-	m	Thermal penetration depth
T_v^{avg}	-	K	Average temperature of lower head vessel wall

2.3 Thermal penetration depth & crust thickness

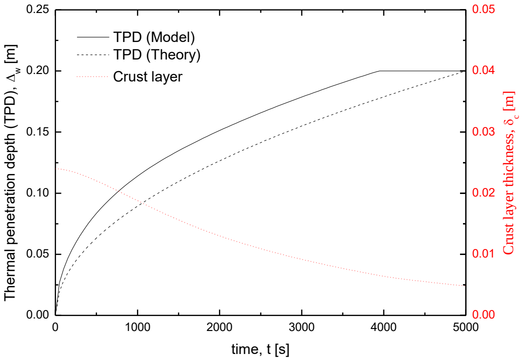

Fig. 3. Behavior of thermal penetration depth and crust layer thickness

Under transient heat conduction, thermal penetration depth $\Delta_{th} \sim (\alpha t)^{0.5}$ is function of the square root of time (t) because of the finite thermal diffusivity of medium where α is the thermal diffusivity [4]. Developed model well describes the thermal penetration depth from the inner to the outer wall of lower head vessel.

Crust layer thickness (δ_c) is determined by the energy balance between the heat transfer from the corium and the heat transfer to the vessel wall. Crust layer thickness is decreased according to the time and it is explained that the heat flux from the molten corium is higher than that to the vessel wall.

2.4 Temperature profile of lower head vessel wall

$$T(x,t) = [2q''(\alpha t/\pi)^{0.5}]/k \exp[-x^2/(4\alpha t)] – (q''x/k)\mathrm{erfc}\{x/[2(\alpha t)^{0.5}]\} \quad (9)$$

$$T(0,t) = 2q''[\alpha t/(k^2 \pi)]^{0.5} + T_i \quad (10)$$

Temperature distribution of semi-infinite medium with constant surface heat flux boundary condition is described by Eq. 9 and the inner wall temperature (x=0) is simplified as Eq. 10 [5]. Compared to theoretical model, the developed model of present study shows reasonable results of heat transfer at lower head vessel wall. Average, inner and outer vessel wall temperature is increased according to the time and slight discontinuity at the outer vessel wall temperature is due to the sudden increase of heat flux from the wall to the external coolant. Interestingly, depending on the heat flux boundary condition, the wall melting and its ablation at the inner wall of lower head vessel are determined. Maximum temperature of inner wall shows significant difference, which directly affects the sequence of event at in-vessel severe accident (i.e., lower head vessel failure). We expect that the developed model in the present study can contribute to the decrease of uncertainty in in-vessel lower head vessel failure analysis by considering the time-dependent boundary condition.

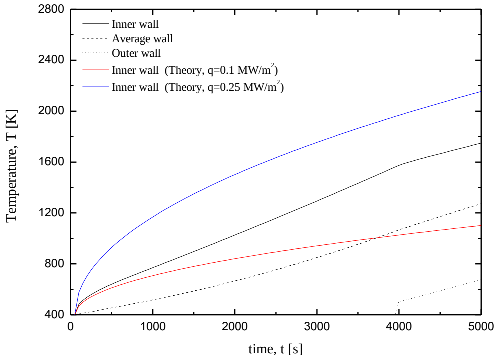

Fig. 4. Behavior of temperature profile of lower head vessel wall.

3. Conclusions

Heat transfer model the present study introduced show reasonable behavior of temperature profile of lower head vessel wall and crust layer thickness under time-dependent boundary condition. Slight discontinuity of vessel wall outer temperature is remaining issue and is going to be solved by considering the adequate external heat transfer condition (not zero). Described model is under extension to consider the vessel wall ablation when the inner wall temperature is beyond its melting temperature.

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