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Three-Layer Modeling of Corium on a Reactor Vessel Lower Plenum

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1. Introduction

Since the TMI accident, a plenty of research has been performed about the severe accident phenomenology. The phenomena considered in nuclear power plants are hydrogen combustion, direct containment heating, steam explosion and ex-vessel corium cooling. In the ex-vessel cooling strategy, reactor cavity is flooded to cool the corium after vessel failure. On the other hand, there is another attractive strategy in which a vessel thermal failure is prevented and corium is cooled by water submerged on the exterior. This is called In-Vessel Retention (IVR) through External Reactor Vessel Cooling (ERVC) [1]. This concept would become more attractive after Fukushima accident [2].

The analyses of IVR-EVRC using three-layers of corium have been performed by Esmaili et al. [3] and Zhang et al. [4]. They applied the model to calculate thermal response of the AP1000 lower head under ERVC. However, limitation of their models is that vessel outside temperature is only one variable, also it is assumed that top surface of heavy metal layer is insulated from the oxide bottom crust.

On the other hand, the main objective of the present paper is to present a three-layer corium model considering different outer wall temperatures for the three layers of corium and un-insulated condition between the oxide bottom crust and the lowest heavy metal. The present mathematical model considers three heavy metal masses and the results are compared with the two-layer model of Theofanous [1].

2. Mathematical Model for Three Layers of Corium

The model is based on conceptual three melt layers shown in Fig 1. The melt configuration assumes a stratified molten pool consisting of heavy metallic bottom layer of U-Zr (in the bottom), a ceramic layer of UO_2-ZrO_2 (in the middle), and a light metal layer Fe-Zr (on top). The model assumes fully molten ceramic material in the oxide pool and no existence of uranium metal in the light metal layer.

The governing equations of three-layer model are presented in the following sections.

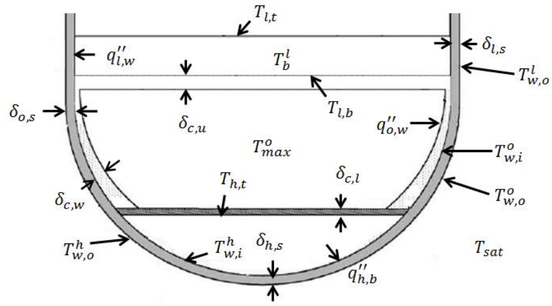

Fig 1. Three-layer melt configuration in the lower head

2.1 Governing equations

The conservation of energy equation can be written for each layer based on the following assumption [3]:

1. The heat generation in the vessel wall is negligible.
2. The radiation heat transfer from the light metal layer to the top surface is insufficient to form a curst
3. The potential impacts of materials interactions are not considered.

- Light metallic layer

$$Q_l'''V_l + q_{l,b}''A_{l,b} = q_{l,t}''A_{l,t} + q_{l,w}''A_{l,w} \qquad (1)$$

- Middle Oxide Pool

$$Q_o'''V_o = q_{o,t}''A_{o,t} + q_{o,w}''A_{o,w} + q_{o,b}''A_{o,b} \qquad (2)$$
$$q_{l,b}''A_{l,b} = Q_c'''V_{c,u} + q_{o,t}''A_{o,t} \qquad (3)$$
$$q_{w,i}''A_{w,i} = Q_c'''V_{c,w} + q_{o,w}''A_{o,w} \qquad (4)$$
$$q_{o,b}''A_{o,b} + Q_c'''V_{c,l} = q_{h,t}''A_{h,t} \qquad (5)$$

- Bottom heavy metal layer

$$q_{h,t}''A_{h,t} + Q_h'''V_h = q_{h,b}''A_{h,b} \qquad (6)$$

Additional equations for the heat fluxes appearing in Eqs.(1)~(6) are presented in section 2.2.

2.2 Constitutive equations

2.2.1 Light metal layer

The heat flux from light metal layer to upper surface can be calculated as:

Nomenclature

A	area, m^2
h	heat transfer coefficient, W/m^2-K
h_{boil}	boiling heat transfer coefficient, W/m^2-K
k	thermal conductivity, W/m-K
L_c	characteristic length of the heavy metal
Q'''	volumetric heat generation rate, W/m^3
q''	average heat flux, W/m^2
T	temperature, K
T_b^l	bulk temperature of light metal layer, K
T_m^o	melting temperature of oxide pool, K
T_m^v	melting temperature of vessel wall, K
T_{max}^o	maximum temperature of oxide pool, K
V	volume, m^3
δ	thickness, m
ε	emissivity
σ	Stefan-Boltzmann constant

Superscripts

h	heavy metal layer
l	light metallic layer
o	oxide pool

Subscripts

c	oxide crust
c,u	upper oxide crust
c,l	lower oxide crust
c,w	sidewall oxide crust
h	heavy metal layer
h,b	bottom surface of heavy metal layer
h,s	vessel wall in heavy metal layer
h,t	top surface of the heavy metal layer
l	light metal layer
l,b	bottom surface of the light metallic layer
l,s	vessel wall in light metallic layer
l,t	top surface of the light metallic layer
l,w	sidewall of the light metallic layer
o	oxide pool
o,b	bottom surface of the oxide pool
o,s	vessel wall in oxide pool
o,t	top surface of the oxide pool
o,w	sidewall of the oxide pool
s	other structure
sat	cavity water
w	vessel wall
w,i	inside of vessel wall
w,o	outside of vessel wall

$$q''_{l,t} = h_{l,t}\left(T_b^l - T_{l,t}\right) \tag{7}$$

The radiation heat transfer between the upper surface of light metallic layer and the other structure in the reactor vessel is given by

$$q''_{l,t} = \sigma\left(T_{l,t}^4 - T_s^4\right)\left[\frac{1}{\varepsilon_{l,t}} + \frac{1-\varepsilon_s}{\varepsilon_s}\frac{A_{l,t}}{A_s}\right]^{-1} \tag{8}$$

The other heat fluxes are given as following:

- heat flux from light metallic layer to the vessel wall
$$q''_{l,w} = h_{l,w}\left(T_b^l - T_m^v\right) \tag{9}$$

- heat flux through vessel sidewall
$$q''_{l,w} = \frac{k_w}{\delta_{l,s}}\left(T_m^v - T_{w,o}^l\right) \tag{10}$$

- heat flux from vessel outside surface to cavity water
$$q''_{l,w} = h_{boil}\left(T_{w,o}^l - T_{sat}\right) \tag{11}$$

- heat flux from top surface of the oxide crust to bottom surface of the light metallic layer
$$q''_{l,b} = h_{l,b}\left(T_{l,b} - T_b^l\right) \tag{12}$$

2.2.2 Oxide pool

The heat flux from the oxide pool to the sidewall curst of the oxide pool can be written as:

$$q''_{o,w} = h_{o,w}\left(T_{max}^o - T_m^o\right) \tag{13}$$

Considering a uniform volumetric heat generation rate in the oxide side crust, the heat flux at the inner and the outer boundaries of the oxide crust can be expressed as:

$$q''_{o,w} = \frac{k_c}{\delta_{c,w}}\left(T_m^o - T_{w,i}^o\right) - \frac{Q_c'''\delta_{c,w}}{2} \tag{14}$$

$$q''_{w,i} = \frac{k_c}{\delta_{c,w}}\left(T_m^o - T_{w,i}^o\right) + \frac{Q_c'''\delta_{c,w}}{2} \tag{15}$$

Since heat generation can be neglected in the vessel wall, the heat flux by conduction through the lower head can be calculated as:

$$q''_{w,i} = \frac{k_w}{\delta_{o,s}}\left(T_{w,i}^o - T_{w,o}^o\right) \tag{16}$$

And the other heat fluxes are given as following:

- heat flux from the vessel wall to cavity water
$$q''_{w,i} = q''_{w,o} = h_{boil}\left(T_{w,o}^o - T_{sat}\right) \tag{17}$$

- heat flux to the light metallic layer through the upper oxide curst
$$q''_{o,t} = h_{o,t}\left(T_{max}^o - T_m^o\right) \tag{18}$$

- heat flux by conduction through the upper oxide curst

$$q''_{l,b} = \frac{k_c}{\delta_{c,u}}\left(T_m^o - T_{l,b}\right) \quad (19)$$

- heat fluxes through the lower oxide crust

$$q''_{o,b} = h_{o,b}(T_{max}^o - T_m^o) \quad (20)$$

$$q''_{h,t} = \frac{k_c}{\delta_{c,l}}\left(T_m^o - T_{h,t}\right) \quad (21)$$

2.2.3 Heavy metal layer

The heat transfer from the lower oxide crust to heavy metal layer is zero in the ERI model [3] since they assumed insulated bottom crust of the oxide pool. Therefore, the heat flux to the bottom surface of the heavy metallic layer is simply estimated using only the volumetric heating inside the heavy metal as follows:

$$q''_{h,b} = Q'''_h V_h / A_{h,b} \quad (22)$$

However, this model may be misleading since insulation of the bottom crust of the oxide pool has no basis and thus in the present model the heat transfer from the bottom oxide crust to heavy metal layer is assumed non-zero. Therefore, the heat flux from the top surface of the heavy metal layer to the bottom surface of heavy metal layer can be estimated using:

$$q''_{h,t} = \frac{k_h}{L_c}\left(T_{h,t} - T_{w,i}^h\right) \quad (23)$$

Since the heat flux characteristics in heavy metal layer is complicated, the heat transfer by conduction is assumed. The heat flux through the vessel wall in the heavy metal layer can be thus expressed as:

$$q''_{h,b} = \frac{k_w}{\delta_{h,s}}\left(T_{w,i}^h - T_{w,o}^h\right) \quad (24)$$

Finally, the heat flux from the vessel wall in heavy metal layer to the cavity water can be obtained as following:

$$q''_{h,b} = h_{boil}\left(T_{w,o}^h - T_{sat}\right) \quad (25)$$

For the boiling heat transfer, constant value of $500\ \mathrm{kW/m^2}$-K is assumed.

2.2.4 Solution method

The equation presented above are a system of non-linear equations and they are solved using a Newton-Raphson method of MATLAB [5].

3. Results and discussion

The input data of present model is presented in Table 1. The analysis for three heavy metal masses and for the ERI data [3] is performed by the present model. Conditions for the three cases are shown in Table 2. Resulting heat flux distributions are shown in Fig 2.

Table 1. Input data of three layers model

Reactor diameter (m)		4.7
Fuel (UO_2) Mass (ton)		119.98
Zr Mass (ton)		33.58
Lower plenum Volume (m^3)		27.2
Lower plenum	Thermal conductivity (W/m-K)	32
	Melting temperature (K)	1600
Oxide pool	Thermal conductivity (W/m-K)	5.3
	Kinematic viscosity (m^2/sec)	5.7×10^{-7}
	Volumetric power (MW/m^3)	1.3
	Thermal diffusivity (m^2/sec)	1.12×10^{-6}
	Thermal expansion coefficient (K^{-1})	1.05×10^{-4}
Oxide crust	Thermal conductivity (W/m-K)	2.8
	Volumetric power (MW/m^3)	1.3
Metal layer	Thermal conductivity (W/m-K)	25
	Melting temperature (K)	1600
Upper steel layer surface emissivity		0.45
Upper structure emissivity		0.8
Upper structure area (m^2)		75.4
Upper structure temperature (K)		950
Water saturation temperature (K)		400

Table 2. Conditions for three cases

Parameter	Case 1	Case 2	Case 3
Heavy metal mass molten (ton)	1	10	20
Light metal mass molten (ton)	41.79	31.79	21.79
Zirconium oxidation fraction	0.5	0.5	0.5

The peak heat flux from the upper light metallic region for 20 tons of heavy metal layer case is 1.568 $\mathrm{MW/m^2}$. The peak heat flux for 10 tons of heavy metal case is 1.521 $\mathrm{MW/m^2}$ and the peak heat flux for 1 ton of heavy metal case is 1.392 $\mathrm{MW/m^2}$. The heat flux varies by 0.2 $\mathrm{MW/m^2}$ for 1 to 20 tons of heavy metal mass. The effect of heavy metal mass is not that significant.

The peak heat from the upper light metallic region obtained using the two layer model of Theofanous [1] is 1.125 MW/m^2. Compared with this two-layer model, the heat flux obtained using the present three-layer model is larger and thus more conservative. Thus it can be stated that the two-layer model underestimates the heat flux to the lower head. The peak heat flux using the present model applying ERI data for the AP1000 is 0.909 MW/m^2.

The heat flux ratios (heat flux divided by critical heat flux at the exterior surface [1]) for each cases in Fig. 2 is shown in Fig. 3. The heat flux ratios for the three layer models are all greater than 1.0 and failure of a reactor vessel is expected.

Effect of external water temperature from 360 to 400 K is also studied for the 10 tons of heavy metal. The range of temperatures are determined considering 375 K as a saturation temperature at lower containment pressure (1 atm), and 365 K for subcooling of 10 K (365 K) due to increased pressure due to deep water head and 400 K as a saturation temperature at elevated containment pressure.

Fig 3 shows the resulting temperatures of oxide pool, metallic layer bottom, and in/outside temperatures of the reactor vessel on the light metal region. The temperatures are not sensitive to the external water temperature. Even though we used constant convective heat transfer coefficient at the exterior surface of the reactor vessel, it would not be quite different for varying heat transfer coefficient.

Remaining reactor vessel thicknesses and oxide crust thickness are also presented in Table 3 for external water temperature of 365, 375 and 400 K. The vessel thickness is slightly dependent on the external water temperature but the oxide thickness is not sensitive.

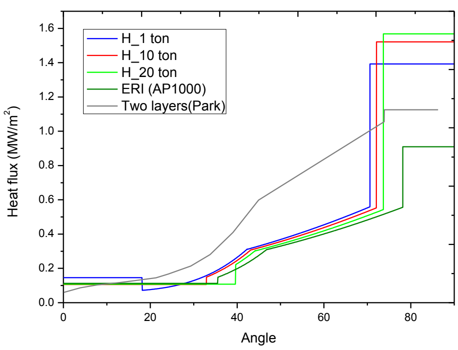

Fig 2. Heat flux distribution

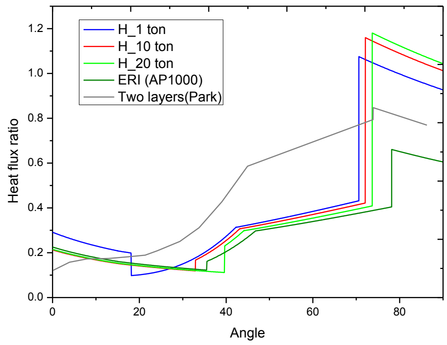

Fig 3. Heat flux ratio (q''/q''_{CHF}) distribution

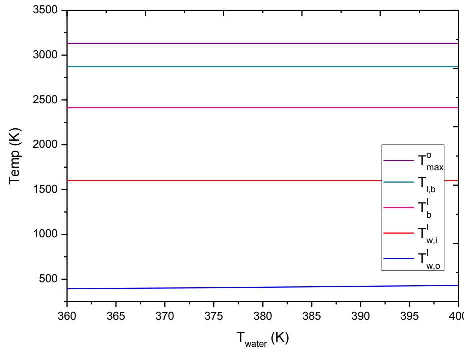

Fig 4. Effect of external water temperature of oxide pool and metallic layer region.

Table 3. Effect of external water temperature on the remaining vessel thickness and oxide crust thickness

T_{water}(K)	$\delta_{l,s}$ (m)	$\delta_{o,s}$ (m)	$\delta_{c,w}$ (m)
400	0.0246	0.141	0.0098
375	0.0251	0.144	0.0098
365	0.0253	0.145	0.0098

4. Conclusion

A three layer corium model considering all the outer wall temperatures of separated corium layers are employed to study in-vessel corium coolability of the APR 1400. The maximum peak heat flux for 10 tons of heavy metal case is 1.521 MW/m^2 and the heat flux varies by 0.2 MW/m^2 for 1 to 20 tons of heavy metal mass. The effect of heavy metal mass is not significant. Corium temperature, crust thickness and reactor vessel remaining thickness are not sensitive to the external water temperature. However, three-layer corium model is more conservative than two layer model.

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5. Reference

[1] J. W. Park, S. J. Oh, H. T. Kim, Y. H. Lee, D. W. Jerng, Assessment of In-Vessel Core Debris Coolability for The APR1400 Design, Korea Hydro & Nuclear Power Co., Ltd., 2001.

[2] EPRI, Severe Accident Management Guidance Technical Basis Report, Volume 1: Candidate High-Level Actions and Their Effects, 1025295, 2012 .

[3] H. Esmaili, M. Khatib-Rahbar, Analysis of In-Vessel Retention and Ex-Vessel Fuel Coolant Interaction for AP1000, Energy Research, Inc., NUREG/CR-6849, ERI/NRC-04-201, 2004.

[4] Y. P. Zhang, S. Z. Qiu, G. H. Su, W. X. Tian, Analysis of safety margin of in-vessel retention for AP1000, Nuclear Engineering and Design, Vol. 240, pp.2023-2033, 2010.

[5] Mathwarks, Inc., MATLAB Optimization Toolbox, 2013.