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Conjugate heat transfer analysis for in-vessel retention with external reactor vessel cooling

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ABSTRACT

A conjugate heat transfer analysis method for the thermal integrity of a reactor vessel under external reactor vessel cooling conditions is developed to resolve light metal layer focusing effect issue for in-vessel retention. The method calculates steady-state three-dimensional temperature distribution of a reactor vessel using coupled conjugate heat transfer between in-vessel three-layered stratified corium (metallic pool, oxide pool and heavy metal and polar-angle dependent boiling heat transfer at the outer surface of a reactor vessel). The three-layer corium heat transfer model is utilizing lumped-parameter thermal-resistance circuit method. For the ex-vessel boiling boundary conditions, nucleate, transition and film boiling are considered. The thermal integrity of a reactor vessel is addressed in terms of heat flux at the outer-most nodes of the vessel and remaining thickness profile. The vessel three-dimensional heat conduction is validated against a commercial code. It is found that even though the internal heat flux from the metal layer goes far beyond critical heat flux (CHF) the heat flux from the outermost nodes of the vessel may be maintained below CHF due to massive vessel heat diffusion. The heat diffusion throughout the vessel is more pronounced for relatively low heat generation rate in an oxide pool. Parametric calculations are performed considering thermal conditions such as peak heat flux from a light metal layer, heat generation in an oxide pool and external boiling conditions. The major finding is that the most crucial factor for success of in-vessel retention is not the mass of the molten light metal above the oxide pool but the heat generation rate inside an oxide pool and the three-dimensional vessel heat transfer provides much larger minimum vessel thickness.

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1. Introduction

In-vessel corium retention (IVR) by external reactor vessel cooling (ERVC) as shown in Fig. 1 is a favorable severe accident management and thus has been studied for decades. In order for the IVR to be successful, the heat flux at the outer surface of the vessel should be less than critical heat flux (CHF) or vessel failure can occur by focused heat load from the metal layer especially in the case of high-power reactors and thus the focusing effect has been regarded as a crucial factor for successful IVR.

Under these conditions, it has been considered that the most important phenomena are pessimistic configuration of the corium pool which has been known to divide into two- or three-layers. For the three-layers, uranium can transfer from the oxide pool to the metal layer and subsequently the metal density increases and may become greater than that of the molten oxide. These results in a layer inversion so that the heavy metal thus formed can move below the oxide pool (Powers and Behbahani, 2004). Due to this layer inversion, the top light metallic layer can be much thinner and thus more concentrate the heat flux to the vessel wall in contact with the metal layer.

The heat transfer mechanism for the IVR configuration shown in Fig. 1 is a coupled conjugate heat transfer problem consisting of the corium natural convection, three-dimensional (3D) conduction through the massive reactor vessel and non-linear boiling heat transfer at the external surface of the vessel. Although the heat flux from the light metal layer has been regarded as an important factor in the IVR evaluation, one more important thing to be carefully treated is the massive reactor vessel itself in that it has a strong effect of heat diffusion which alleviates focused heat load from the top metallic region to the lower temperature regions at the upper cylindrical part and lower hemispherical part. Therefore, even though the heat flux from the top metal layer to the vessel inside is larger than CHF, it might not be so at the external surface. Therefore, integrated multi-dimensional fine-node conjugate heat transfer of the reactor vessel coupled with inner heat flux boundary and outer convective boundary conditions is essential

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Nomenclature

A	area, m^2
c_{pl}	water specific heat at constant pressure, W/kg
g	gravitational acceleration, m^2/s
h	heat transfer coefficient, W/m^2-K
h_{boil}	nucleate boiling heat transfer coefficient, W/m^2-K
h_{trans}	transition boiling heat transfer coefficient, W/m^2-K
h_{film}	film boiling heat transfer coefficient, W/m^2-K
h_{fg}	heat of vaporization for water, W/kg
k	thermal conductivity, W/m-K
L	length
N_r	number of radial nodes
Nu	Nusselt number
Pr	Prandtl number
Q'''	volumetric heat generation rate, W/m^3
q''	average heat flux, W/m^2
R	vessel inner radius
Ra	Rayleigh number
Ra'	modified Rayleigh number
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
ΔT_{sat}	$T_w - T_f$
V	volume, m^3
δ	thickness of vessel or crust, m
ε	emissivity
ρ	density, kg/m^3
μ	viscosity, N s/m^2
σ	Stefan–Boltzmann constant
σ_l	liquid surface tension, N/m
θ	polar angle along hemispherical lower head
θ_p	maximum polar angle

Subscripts

c	oxide crust
cu	upper oxide crust
cl	lower oxide crust
cr	critical
cw	sidewall oxide crust
dn	downward
f	external water
h	heat transfer coefficient, heavy metal layer
hb	bottom surface of heavy metal layer
hm	heavy metal
hs	vessel wall in heavy metal layer
ht	top surface of heavy metal layer
I, J, K, L	indices for corium layers and crusts
i, j	indices of nodes of the vessel
l	liquid
lb	bottom surface of light metal layer
lm	light metal
ls	vessel wall in light metal layer
lt	top surface of light metal layer
lw	sidewall of oxide pool
o, ox	oxide pool
s	vessel upper internal structure or internal surface
v	vapor
w	vessel wall
wi	inside of vessel wall
wo	outside of vessel wall

Superscripts

cyl	cylindrical vessel part
sph	hemispherical vessel part

to capture this 3D effect and should be elaborated in the IVR evaluations. However, historically it has not been so.

Heat transfer problem of the IVR with ERVC needs a set of models for the three-layered corium, the crust, the reactor vessel and the external cooling. Individual models to be found from the literature are those by Theofanous et al. (1997), Esmaili and Khatib-Rahbar (2004) and Zhang et al. (2010) and typical integral severe accident analysis codes such as MAAP (Electric Power Research Institute, 1994), MELCOR (Gauntt et al., 2000), SCDAP (Siefken et al., 2001), ASTEC (Tarabelli et al., 2007) and AIDA (Pautz, 2011) have their own models.

Theofanous et al. (1997) originally used a two-layered corium model and recently Esmaili and Khatib-Rahbar (2004) and Zhang et al. (2010) developed three-layered corium models. However, all these models did not consider 3D conjugate heat transfer through the vessel. Esmaili and Khatib-Rahbar (2004) even neglected heat transfer from the oxide pool to the lower heavy metal layer. Theofanous et al. (1997) used bounding approach so that the detailed vessel conduction is not considered but 2D heat conduction through a part of a reactor vessel contacting high heat flux region of the lower hemisphere.

For the integrated codes, the MAAP (Electric Power Research Institute, 1994), MELCOR (Gauntt et al., 2000), SCDAP (Siefken et al., 2001) and AIDA (Pautz, 2011) incorporate two-layer corium configurations and ASTEC (Tarabelli et al., 2007) uses three-layers. All these integral codes consider formation and 1D conduction of the crust. For the reactor vessel part, these codes calculate 2D and/or 3D temperature distributions but the MAAP (Electric Power Research Institute, 1994), MELCOR (Gauntt et al., 2000) and SCDAP (Siefken et al., 2001) does not consider cylindrical part of the vessel, which, on the other hand, is considered in the ASTEC (Tarabelli et al., 2007) and AIDA (Pautz, 2011). Especially, Tusheva et al. (2015) in their investigation on the IVR of the VVER-1000 reactor, the ablation of the vessel wall was modeled in ANSYS in the following way: those elements which have at least one node with a temperature above the solidus temperature of the steel are selected and the material properties of the adjacent melt region was imposed on these elements for the thermal solution. Solidification at later times was not considered.

For the external cooling, the MAAP (Electric Power Research Institute, 1994) and the MELCOR (Gauntt et al., 2000) use nucleate boiling model and the SCDAP (Siefken et al., 2001) uses subcooled nucleate boiling correlations and critical heat flux (CHF) of Riley (2012) as a function of position by angles and the transition boiling is obtained by extrapolation from the CHF to minimum heat flux with heat transfer coefficient of 375 W/m^2-K.

Summarizing, the individual IVR models and the integral codes state above do not handle coupled conjugate heat transfer between three components of the corium, reactor vessel and external water with detailed 3D calculation of temperature distributions in the whole reactor vessel consisting of hemispherical and cylindrical parts.

Present paper thus tries to find a solution to the light metal layer issue of the IVR by using an integrated conjugate heat transfer analysis method with fine 3D heat conduction in a reactor vessel wall. The present model, as shown in Fig. 1, calculates the

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