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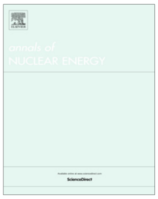

A two dimensional approach for temperature distribution in reactor lower head during severe accident

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ABSTRACT

In order to evaluate the safety margin during a postulated severe accident, a module named ASAP-2D (Accident Simulation on Pressure vessel-2 Dimensional), which can be implemented into the severe accident simulation codes (such as ATHLET-CD), is developed in Shanghai Jiao Tong University. Based on two-dimensional spherical coordinates, heat conduction equation for transient state is solved implicitly. Together with solid vessel thickness, heat flux distribution and heat transfer coefficient at outer vessel surface are obtained. Heat transfer regime when critical heat flux has been exceeded (POST-CHF regime) could be simulated in the code, and the transition behavior of boiling crisis (from spatial and temporal points of view) can be predicted.

The module is verified against a one-dimensional analytical solution with uniform heat flux distribution, and afterwards this module is applied to the benchmark illustrated in NUREG/CR-6849. Benchmark calculation indicates that maximum heat flux at outer surface of RPV could be around 20% lower than that of at inner surface due to two-dimensional heat conduction. Then a preliminary analysis is performed on the integrity of the reactor vessel for which the geometric parameters and boundary conditions are derived from a large scale advanced pressurized water reactor. Results indicate that heat flux remains lower than critical heat flux. Sensitivity analysis indicates that outer heat flux distribution is more sensitive to input heat flux distribution and the transition boiling correlation than mass flow rate in external reactor vessel cooling (ERVC) channel, and the correlation for molten vessel and ERVC coolant inlet temperature.

According to the results achieved, the new developed module shows good applicability to simulate the pressure vessel behavior during melt pool formation. Thus it can be applied for the future study of the severe accidents relating to lower head integrity.

1. Introduction

Fukushima accident has arisen international attention on the nuclear energy safety, especially under severe accident (SA) condition (Wittneben, 2012). Therefore in spite of core melt frequency (CMF) per reactor year for currently operating reactors has been reduced as low as 1×10^{-4} (Schulz, 2006), plenty of work needs to be done to prevent the release of the radioactive material to environment under severe accident. In order to ensure radioactive material is under control different severe accident management (SAM) strategies are developed. One of candidate strategies is in-vessel retention (IVR) strategy, which has been approved to be part of SAM for Loviisa plant (Theofanous et al., 1996). Then IVR strategy was proposed for AP600, AP1000 (Westinghouse design), SWR-1000 (KERENA) and Korea APR-1400 design. In-vessel retention is an effective severe accident management strategy provided that the margin between critical heat flux and lower head heat flux is large enough.

The success of IVR strategy strongly relies on heat removal capability through external reactor vessel cooling (ERVC). In order to investigate integrity of lower head, several improvements have been done to current system codes to simulate thermal hydraulic behavior of molten materials in lower head, including MELCOR (Gauntt, 2005), SCDAP/RELAP5 (The SCDAP/RELAP5-3D Code Development Team, 2003), MAAP (MAAP code development Team, 1994), ATHLET-CD (Austregesilo, 2012). Alternatively, some codes are specially developed to evaluate integrity of the reactor pressure vessel (RPV) wall cooled from outside, such as VESSEL, MVITA (Sehgal et al., 2003), ERI-IVRAM (Esmaili and Khatib-Rahbar, 2004) and VESTA (Rempe et al., 1997). Since the temperature field of lower head is decisive factor in identifying the effectiveness of IVR

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Nomenclature

General symbols

A_{in}	inner lower head surface area (m^2)
A_{out}	outer lower head surface area (m^2)
c	specific heat capacity (vessel wall) (J/kg K)
cp	specific heat capacity (fluid) (J/kg K)
Gj	external vessel mass flow rate (kg/s)
g	gravity acceleration (m/s^2)
hc	heat transfer coefficient for convection (W/m^2 K)
h_f	fluid enthalpy in external vessel channel (J/kg)
h_{fb}	heat transfer coefficient for film boiling (W/m^2 K)
h_{ls}	saturation enthalpy of liquid phase (J/kg)
h_{lv}	latent heat of vaporization (J/kg)
h'_{lv}	effective latent heat of vaporization (J/kg)
h_{nb}	heat transfer coefficient for nucleate boiling (J/kg)
h_{onb}	enthalpy corresponding to onset nucleate boiling (J/kg)
h_{out}	heat transfer coefficient at outer vessel (W/m^2 K)
h_{sat}	saturated liquid enthalpy (J/kg)
h_{vs}	saturation enthalpy of vapor phase (J/kg)
j	control volume number
L	characteristic length (m)
N	iteration step
N_{onb}	control volume number of first nucleate boiling volume
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
q_a	heat flux for convection caused bubble agitation (W/m^2)
q_{chf}	critical heat flux (W/m^2)
q_e	heat flux for latent heat for vapor formation (W/m^2)
q_{in}	inner vessel heat flux (W/m^2)
q_{out}	outer vessel heat flux (W/m^2)
q_{sp}	heat flux for single-phase convection (W/m^2)
r	distance from inner vessel wall (m)
Ra	Rayleigh number
Re	Reynolds number
r_{in}	inner radius of lower head (m)
r_{out}	outer radius of lower head (m)
t	time step (s)
T	temperature (K)
T_{chf}	wall temperature corresponding to q_{chf} (K)
T_f	fluid temperature in external vessel channel (K)
T_{melt}	melting temperature for vessel wall (K)
T_{mfb}	minimum film boiling temperature (K)
T_{onb}	wall temperature corresponding to onset nucleate boiling (K)
T_{sat}	saturated fluid temperature (K)
x_{qm}	mass quality

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K^{-1})
ε	pumping factor
θ	angle from bottom center of lower head (°)
λ	thermal conductivity (W/m K)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

CHF	critical heat flux
in	inner surface of vessel
l	liquid phase
out	outer surface of vessel
onb	onset nucleate boiling
s	saturate sate
v	vapor phase

strategy, it is important to obtain relative accurate temperature field of lower head. Despite the progress that has been made in these years, there are still some parts need to be improved. Thus key phenomenon in lower head during severe accident should be considered. After an investigation of the IVR process, the important features in the IVR analysis are summarized as followed:

(1) Lower head is part of spherical shell, as is shown in Fig. 1, heat conduction in lower head occurs both r direction and θ direction, besides inner surface area is smaller than outer one.
(2) The thermal conductivity of lower head material varies with temperature.
(3) Heat transfer could be enhanced when vessel wall is partly molten due to the convection.
(4) Wide range of external vessel heat transfer correlations including POST-CHF correlations are needed to predict the surface temperature after occurrence of CHF.

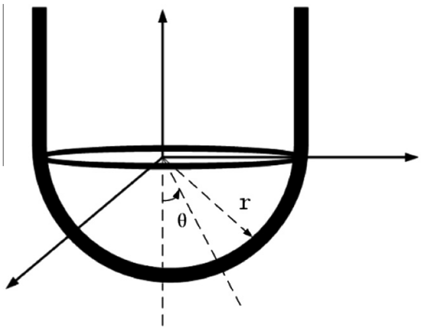

Fig. 1. Two dimensional heat conduction.

Heat transfer models applied in different codes are summarized in Table 1. It can be seen that current codes have challenges in describing some of above features in lower head. To be specific, in ATHLET-CD (Austregesilo, 2012), ERI-IVRAM (Esmaili and Khatib-Rahbar, 2004) and VESTA (Rempe et al., 1997), one-dimensional heat conduction model in lower head is applied. This simplified model used to be reasonable due to their conservative estimation. However the margin to CHF is small when relatively larger thermal power reactor is applied. It is important to predict local heat flux more accurately by applying at least two-dimensional heat conduction model in lower head. In fact heat flux at outer vessel wall would be flattened due to heat conduction in θ direction. Due to larger surface area, average outer surface heat flux (q_{out}) is lower than that of inner surface (q_{in}). This difference between q_{in} and q_{out} will increase with increasing lower head radius. For instance in large-scale advanced PWR in China, the difference is about 14%. However most of these codes neglect this difference. So when IVR analysis is performed, two-dimensional heat conduction model in spherical coordinate should be considered for some cases.

Apparently, thermal conductivity varies with temperature, however, in ERI-IVRAM (Esmaili and Khatib-Rahbar, 2004) and VESTA (Rempe et al., 1997) constant lower head thermal conductivity is used. Heat flux distribution in lower head would not show much

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