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Ablation and thermal stress analysis of RPV vessel under heating by core melt

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ABSTRACT

After a reactor core melts and collapses suddenly, the melting core accumulates on the base surface of the bottom head of a reactor pressure vessel (RPV), causing severe thermal ablation and thermal stress, endangering the safety of the RPV bottom head. In this study, a 1000-MW pressurized water reactor is considered an example to study the heat transfer ablation and thermal stress of an RPV lower head after a core collapses, by performing numerical simulations. A two-dimensional (2D) heat transfer model is used to analyze the coupling heat transfer between the wall surface of the RPV, two-layer melting corium pool, and outer water chamber. The transient 2D temperature and ablation of the lower head wall surface are calculated. The thermal stress of the RPV lower head and deformation are also investigated using ANSYS software. The results show that (1) The upper crust is the least thick, with a thickness of approximately 0.01 m, whereas the side crust is the thickest at approximately 0.12 m at the base of the lower head. (2) The minimum thickness of the bottom wall decreases linearly with time, starting from the collapse time of the core to 2500 s, when it becomes 0.04 m. It does not change thereafter, but the melting zone is further expanded. (3) The lower head wall starts to melt from 200 s after the core collapses. The melting mass first increases sharply, and subsequently, increases slightly with time. The total melted material is 3000 kg at 5000 s. (4) The heat flux at the inner and outer surfaces of the lower head immersed in the uranium melt layer increases with the azimuth angle, reaching a maximum value of 750 kw/m^2 and 250 kw/m^2, respectively, at the interface with the metal melt. The heat flux at the RPV inner wall covered by the metal melt is approximately constant at 400 kw/m^2, whereas that at the outer surface decreases with the azimuth angle. (5) The stress at the lower head is concentrated at the inner surface, with a maximum value of 625.65 MPa. The radial deformation increases with time only until 2200 s, with a maximum deformation of 28.39 mm occurring in the lower part of the RPV bottom.

1. Introduction

In-vessel retention via external reactor vessel cooling (IVR-ERVC) and installation of a core melt catcher outside a reactor pressure vessel (RPV) are two types of the most important methods for the mitigation of serious accidents occurring in third-generation pressurized water reactors (PWRs). The second method requires significant changes to be introduced in the reactor structure. Therefore, in China, advanced pressurized water reactor design is preferably achieved by IVR-ERVC. The concept of IVR-ERVC was first proposed by Professor Therfanous of University of California, Santa Barbara (UCSB) in 1989 as a backup safety facility for the VVER-440 reactor at the Loviisa pressurized water reactor (PWR) nuclear power plant in Finland (Theofanous et al., 1997), which subsequently became its unique design and was used in the AP600 and AP1000 reactors. In recent years, Chinese third-generation advanced PWRs (CAP1400, HPR1000) have also applied this design. When the core melt drops and melts through the support plate, it further falls to reach the RPV lower head. Moreover, if the water inside has evaporated, then the melting core causes local overheating and ablation and endangers the structural integrity of the RPV. Therefore, globally, numerous research studies have been conducted regarding the RPV performance under the condition of lower head heating caused by a melting corium.

The following are the research studies on the structure and effect of the wall heating on the lower head: Fu Xiaoliang et al. used the MELCOR program to analyze the entire process of the melting and collapsing of the CPR1000 reactor core to form a molten pool in the lower head. The layered structure of the molten pool in the lower head and thermal aggregation effect of the metal layer were also examined (Xiao-liang et al., 2010). Rae-Joon Park et al. used the SCDAP/RELAP5

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Nomenclature

h_m	height of melt metal layer, m
h_{m1}	height of melt metal layer below the top plane of RPV vessel, m
h_{m2}	height of melt metal layer above the top plane of RPV vessel, m
h_u	height of melt UOx layer, m
V_m	volume of melt metal layer, m^3
V_{m1}	volume of melt metal below the top plane of PRV vessel, m^3
V_{m2}	volume of melt metal above the top plane of RPV vessel, m^3
V_u	volume of melt UOx layer, m^3
R_{pv}	radius of the PRV vessel, m
T	Temperature, K
c	specific heat capacity, J/(kg_K)
r	radial position, m
z	axial position, m
$\dot{S}$, $\dot{q}_v$	heat source density, W/m^3
q	heat flux on the vessel wall, W/m^2
a	coefficients in the derivative equation of heat conduction in vessel wall, W/K
b	the source term in the derivative equation of heat conduction in vessel wall, W
R'	ratio of Nusselt number on top face of the corium to that on the side face
Nu	Nusselt number
Ra'	Rayleigh number
Gr	Grashof number
Pr	Prandt number
g	gravity acceleration, m/s^2
A	surface area, m^2
J	effective radiation heat flux, W/m^2
X	radiation angle coefficient
q_r	radiation heat flux, W/m^2

Greek letters

θ_u	Polar angle for the top level of melt UOx layer, sr
θ_m	Polar angle for the top level of melt UOx layer, sr
θ_{m1}	Polar angle for the top level of V_{m1}, sr
θ_{m2}	Polar angle for the top level of V_{m2}, sr
τ	Time, s
ρ	Density, kg/m^3
β	Volume expansion rate,
α	thermal conductivity, $\alpha = \lambda/\rho c$, m^2/s
ν	dynamic viscosity, kg/(m·s)
λ	heat conductive coefficient, W/(m·K)
δ	wall thickness, m
ε	emissivity
σ	Stefan-Boltzmann constant, $W/(m^2K^4)$

Subscripts

P, N, S, E, W	central volume and the neighbor volumes
n, s, r, e	volume boundary face
m	variable of melt metal
u	variable of melt UOx
dn	variable toward the downside boundary of corium
up	variable toward the top of corium
mb	bulk variable of the melt metal layer
pv	variable of pressure vessel

Superscripts

n	current time step
n + 1	the previous time step

and GEMINI2 codes to calculate the RPV failure process, pool structure, and oxide and metal layer composition and quality in case of a serious accident of the APR1400 reactor (Park et al., 2015). Guan Zhonghua et al. developed a computational cooling model of the core melt in the lower chamber, considering the effect of the heat dissipation in the unit volume of the AP600 and AP1000 reactor cores in regard to the heat collector (Zhong-hua et al., 2008). A. Liaqat et al. investigated the effect of the radiation parameters of the surface of the pool with the cross-line method. They found that under the condition of certain pool parameters, the radiation heat transfer from the molten pool surface to the RPV wall surface, calculated by the closed cavity-net radiation model, was higher than the convective heat transfer (Liaqat and Baytas, 2001). Y.P. Zhang et al. used an one-dimensional (1D) conduction model to calculate the RPV wall temperature and heat flux under coolant injection and anticipated depressurization conditions for the AP600 reactor in case of a serious accident (Zhang et al., 2011). Fei-Jan Tsai et al. used the RELAP-3D program to simulate the natural convection in the reactor cavity in the IVR-ERVC facility of the AP1000 reactor. The calculation results of the program were substituted in the critical heat flux (CHF) relation of the ULPU, SULTAN, SBLB, and KAIST IVR-ERVC design of the security boundary (Tsai, 2017).

In the numerical model study of the wall temperature of a lower head of an RPV, Bai Wei et al. developed a two-dimensional (2D) transient thermal conduction program for this system based on the finite element method, and manually calculated the two-phase heat transfer of the melt using a solid conduction model (Wei et al., 2013). Yue Jin et al. applied an IVR-ERVC analysis model and used the MLECOR program to study the volume of the melt core and wall temperature distribution of the molten pool for a three-loop PWR with 5000-MW heat power during the core disintegration; reforming, and formation of the molten pool (Jin et al., 2015). The Japan Atomic Energy Engineering Corporation developed an integrated module analysis program, called debris cool ability analysis (DCA), for a nuclear power plant under the condition of head debris cooling, by using a bulk parameter model to analyze the core melting, cooling shell, and RPV wall heat transfer and condensation. It was found that when the average temperature of the shell was set as the boundary temperature of the molten pool, the actual cooling shell temperature was lower than the melt pool temperature (Wei et al., 2017). Zhang Longfei et al. used a 2D finite element analysis model for a lower head (COUPLE) in RELAP/SCDAPSIM codes to analyze the temperature distribution and temperature increase process of the core debris bed and lower head after a severe accident of a 1000-MW PWR nuclear power plant (Zhang et al., 2012). Guo Tao et al. established a 1D analysis model of the wall temperature along the lower head thickness to calculate the steady-state temperature field of an RPV lower head using an IVR-ERVC reactor design (Tao et al., 2012). Commonly, the above studies of the heat transfer and wall temperature of the lower head were conducted for the same volume, component, and structure of the molten pool.

In an experimental study of the heat transfer in IVR, Tang Chaoli et al. examined a full-height non-dynamic 1D heat transfer and conducted flowing characteristic test REPEC-II for ERVC. They analyzed the natural circulation capacity and circulation features of an ERVC flow channel (Chaoli et al., 2014). Luteng Zhang, Suizheng Qiu et al. designed a third-generation nuclear reactor with 1/4th of the original lower head size. For this, a ¼-circular 2D slice experimental device was set up, which was filled with a non-eutectic molar ratio of 20% $NaNO_3$–80% KNO_3 and tested as a melt mimetic. The temperatures of