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Research Paper

Large eddy simulation for the thermal behavior of one-layer and two-layer corium pool configurations in HPR1000 reactor

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HIGHLIGHTS

- Large eddy simulations were performed for the thermal behavior in corium pools with high Rayleigh number.
- The heat transfer and wall melting progress were mitigated at the layer interface due to the slow flow in the mushy zone.
- The strong turbulence in the oxide layer could not entrain the top metal layer based on the KH instability theory.
- The molten salt and LBE were chosen as the appropriate simulant materials for the two-layer corium pool.

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ABSTRACT

The Large Eddy Simulation (LES) methods were employed to analyze the turbulent heat transfer characteristics in detail for volumetrically heated corium pools. The main components and property parameters were calculated for the one-layer and two-layer configurations in the HPR1000 reactor. The numerical simulations were performed based on the WMLES turbulence model, phase change model, as well as the VOF model to describe thermal behaviors in the corium pool such as natural convection flow, pool temperature field and heat flux distribution. Then based on the Kelvin-Helmholtz (KH) instability theory, the calculated velocity vector difference between the two-layer flows at the interface was lower than the KH instability critical value. The high Rayleigh number natural convection in the bottom oxide pool was still not able to entrain the top metal layer. The molten salt (20 mol% $NaNO_3$-80 mol% KNO_3) and the Lead-Bismuth eutectic (44.5 wt% Pb-55.5 wt% Bi) were chosen as the appropriate simulant materials for the two-layer corium pool. The simulation results presented similar thermal characteristics compared with those from the prototypical reactor two-layer case, which could provide guidance for further research.

1. Introduction

The most challenging aspect of employing nuclear fission energy is to regulate the decay heat removal, especially in the accident situations. That is, although the fission process can be terminated quite readily, the fragments of previously fissioned nuclei remain unstable with decay energy emitting. This energy is quite substantial and is sufficient to melt the fuel elements within the rather structurally substantial RPV (Reactor Pressure Vessel). Containing the fission products is of the utmost importance so as not to exacerbate a design basic accident. There are three barriers that contain the fission products: fuel cladding, RPV and containment building [1]. During a severe accident in the PWR (Pressurized Water Reactor), the core may melt into high-temperature corium and then relocate into the RPV lower plenum. As the RPV will hold up the disruption of the nuclear core, its integrity is vitally important for the nuclear safety analysis.

In-vessel corium is the mixture made up from molten core materials composed of (U, Zr)O_2 + Zr + Fe + fission products. The corium is generally simplified as a U-Zr-O-Fe system and is characterized by the Zr oxidization degree and U/Zr ratio [2]. The formation of a hemispherical corium pool with internal decay heat in the lower head will threaten the integrity of RPV. IVR (In-Vessel Retention)-ERVC (External Reactor Vessel Cooling) technology is one of the most important strategies to mitigate a severe accident by maintaining corium inside the vessel by employing cavity flooding, as shown in Fig. 1 [3]. The thermal load distributions along the lower head wall are determined by the natural

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Nomenclature

c_p	specific heat capacity ($J\cdot kg^{-1}\cdot K^{-1}$)
crm	corium
C_{Smag}	constant = 0.2
C_w	constant = 0.325 or 0.15
d_w	distance to the closest wall (m)
f_d	correction coefficient of volatile fission products
f_m	mass fraction
f_{ml}	mole fraction
f_v	volume fraction
g	gravitational acceleration ($m\cdot s^{-2}$)
h_{max}	maximum edge length of the cell (m)
h_{wn}	wall normal grid spacing (m)
H	pool height (m)
ΔH	latent heat of melting ($J\cdot kg^{-1}$)
me	metal layer
ox	oxide layer
P_0	thermal power (MW)
Pr	Prandtl number ($Pr = \nu/\alpha$)
q	local heat flux along the curved wall ($W\cdot m^{-2}$)
q_{avg}	average heat flux along the curved wall ($W\cdot m^{-2}$)
q_{CHF}	critical heat flux along the curved wall ($MW\cdot m^{-2}$)
q_{max}	maximum heat flux along the curved wall ($W\cdot m^{-2}$)
q_j	sub-grid scale flux ($W\cdot m^{-2}$)
q_v	power density ($W\cdot m^{-3}$)
Q_d	decay power (MW)
Ra'	modified Rayleigh number ($Ra' = g\beta q_v H^5/\lambda\nu\alpha$)
S	strain rate
$\bar{S}_{ij}$	rate-of-strain tensor for the resolved scale
T_{liq}	liquidus temperature (°C/K)
T_{sol}	solidus temperature (°C/K)
t	time (s)
u	velocity ($m\cdot s^{-1}$)
V	volume of the computational cell (m^3)
y^+	the normal to the wall inner scaling

Greek symbols

α	thermal diffusivity ($m^2\cdot s^{-1}$)
β	thermal expansion coefficient (K^{-1})
ρ	density ($kg\cdot m^{-3}$)
σ	surface tension ($N\cdot m^{-2}$)
λ	thermal conductivity ($W\cdot m^{-1}\cdot K^{-1}$)
ν	kinematic viscosity ($m^2\cdot s^{-1}$)
ν_t	turbulent kinematic viscosity ($m^2\cdot s^{-1}$)
η	dynamic viscosity (Pa·s)
θ	angle along the curved wall (°)
κ	von Kármán constant = 0.41
τ_{ij}	sub-grid scale stress (Pa)
μ_t	sub-grid scale turbulent viscosity ($m^2\cdot s^{-1}$)
ϕ	sub-grid scale turbulent flux of a scalar

Abbreviations

CHF	Critical Heat Flux
DNS	Direct Numerical Simulation
ERVC	External Reactor Vessel Cooling
KH	Kelvin-Helmholtz
LES	Large Eddy Simulation
IVR	In-Vessel Retention
PECM	Phase-change Effective Convectivity Model
WMLES	Wall-Modeled LES model

convection heat transfer in the corium pool with high Rayleigh number reaching up to 10^{16}. The strong turbulence in the corium pool make it difficult to capture the thermal stratification and heat transfer characteristics in detail.

Dinh and Nourgaliev [4] indicated that the k-ε turbulence model was not able to accurately predict the thermal behavior in volumetrically heated corium pool with high Rayleigh numbers. Tran and Dinh [5,6] developed the PECM (Phase-change Effective Convectivity Model) method to describe strong turbulence, which bypassed the Naiver-Stokes equation and only to solve the energy equation with convective terms included. Zhang et al. [7] developed the 2D numerical model

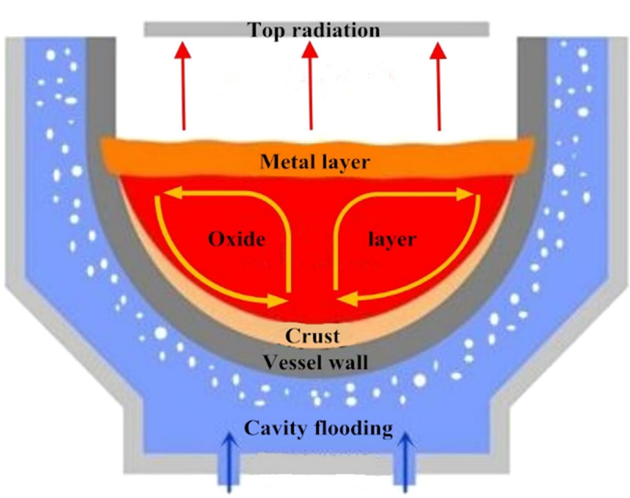

Fig. 1. Schematic diagram of corium relocation and IVR-ERVC.

based on the SIMPLE algorithm for the simulation of the partial solidification process with diffusive convection.

The LES (Large Eddy Simulation) methods are more and more applicable as powerful tools to analyze strong turbulence and complicated multi-phase flow problems. Fukasawa et al. [8] performed the simulation for the BALI experiment with both the k-ε model and the LES model. Tran et al. [9] and Luo et al. [10] also employed the LES method for the corium pool heat transfer simulation and the results showed good comparison.

In this paper, the numerical simulations were performed based on the LES turbulence model for the thermal behavior in the one-layer and two-layer hemispherical corium pool configurations in HPR1000 reactor. Furthermore, the layer interface instability and the simulant material selection were investigated.

2. Turbulence modeling of WMLES

Due to high Rayleigh numbers and strong turbulence in volumetrically heated corium pools, it's difficult to capture natural convection heat transfer behavior in detail. It's known that turbulent flows are characterized by eddies with a wide range of length and time scales, in which the largest eddies are comparable to the characteristic length of main flow and the smallest eddies are responsible for the turbulent kinetic energy dissipation. The numerical simulation by solving the Navier-Stokes equations can be achieved with the DNS method. However, DNS is computationally consuming and may introduce difficulties for practical engineering problems.

With the progress in model development and numerical algorithm, the LES methods are more and more applicable to the thermal engineering and nuclear industry and have become powerful tools to simulate and analyze the turbulent and multiphase flows [11,12]. The