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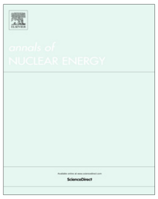

Large eddy simulation on turbulent heat transfer in reactor vessel lower head corium pools

Luteng Zhang, Simin Luo, Yapei Zhang, Wenxi Tian, G.H. Su *, Suizheng Qiu

Shaanxi Key Laboratory of Advanced Nuclear Energy and Technology, School of Nuclear Science and Technology, Xi'an Jiaotong University, No. 28, Xianning West Road, Xi'an 710049, China

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ABSTRACT

Due to the high-Rayleigh-number natural convection and strong turbulence in the volumetrically heated corium melt pools, it is difficult to capture the heat transfer characteristics in detail. The Large Eddy Simulation (LES) methods are more and more applicable to nuclear industry and have become powerful tools to analyze the complicated turbulent and multi-phase flows. In this paper, the Wall-Modeled LES (WMLES) method was employed for the simulation of three typical corium pool heat transfer experiments: BALI, LIVE and COPRA experiments. The melt pool temperature and heat flux from numerical simulations were in good comparison with experimental data. Then numerical simulation for the transient formation of two-layer corium pool was performed with prototypical corium to obtain the heat transfer data in reactor situation. There was a distinctive gap between the temperatures in two layers. The heat flux showed a decrease at the two-layer interface and a huge jump at the metal layer side. The thin metal layer on the top at the early stage of the two-layer formation will threaten the vessel integrity.

1. Introduction

In the postulated reactor severe accidents, the relocated core melt in the reactor vessel lower head will impose thermal loads towards the vessel wall. In-Vessel Retention (IVR) has already become one of the most important subjects of severe accident mitigation to maintain corium inside the vessel by natural convection and cavity flooding (Theofanous et al., 1997). The heat transfer characteristics of core melt in the reactor lower head have been studied experimentally and numerically in the past years. All these investigations were performed to understand the fundamental behavior for the homogeneous or stratified melt pool configurations inside the reactor vessel (Zhang et al., 2015b).

A series of experiments were carried out to study the corium pool heat transfer characteristics. These experimental facilities can be divided into three categories based on the geometry: quarter-circular slice pool, semi-circular slice pool, and hemispherical pool (Zhang et al., 2015a). And mostly, water and molten salt were used as the simulant materials. There was crust formation along the cooling boundary in the salt test as comparison to the water test. For the former two geometry types, the corium pool could reach to high Rayleigh numbers but the results need extrapolation to hemispherical geometry. However, due to the experimental cost and difficulties, many hemispherical facilities were in small scale with smaller Rayleigh numbers. Therefore, the experimental results and corresponding heat transfer relationships may introduce uncertainties for the reactor situation in the high Rayleigh range of 10^{15}–10^{17}.

Using the source-based SIMPLE algorithm based on a fixed grid method and k–ε turbulence model, Zhang et al. (2014) developed a two-dimensional numerical code for the convection-diffusion controlled mushy region phase-change problem to investigate the LIVE-L4 melt pool heat transfer characteristics subjected to a partial solidification process. Horvat and Mavko (2004) performed the transient calculations with the CFX 5.7 fluid dynamic software based on the SST turbulence model, and the results showed good comparison with the experimental results from Asfia and Dhir (1996). Buck et al. (2010) used the DIVA module of the ASTEC V1.3 code and the melt pool model of ATHLET-CD late-phase modules to simulate the LIVE experiment. Tran and Dinh (2009a) developed a phase-change effective convectivity model (PECM) to simulate the dynamics of the melt pool heat transfer in the lower head. The PECM method bypassed the Naiver-Stokes equations, and only to solve energy conservation equation using the Fluent solver. The convective terms were included in the energy equation to describe the turbulent natural convection heat transfer (Tran and Dinh, 2009b).

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* Corresponding author.
E-mail address: ghsu@mail.xjtu.edu.cn (G.H. Su).

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Nomenclature

c_p	heat capacity ($J{\cdot}kg^{-1}{\cdot}K^{-1}$)
C_w	constant = 0.325 or 0.15
C_{Smag}	constant = 0.2
d_w	distance to the closest wall (m)
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 fusion ($kJ{\cdot}kg^{-1}$)
q_{CHF}	critical heat flux along the curved wall ($MW{\cdot}m^{-2}$)
q_{local}	local heat flux along the curved wall ($W{\cdot}m^{-2}$)
q_{max}	maximum heat flux along the curved wall ($W{\cdot}m^{-2}$)
q_{mean}	average heat flux along the curved wall ($W{\cdot}m^{-2}$)
q_j	sub-grid scale flux ($W{\cdot}m^{-2}$)
q_v	heating power density ($W{\cdot}m^{-3}$)
Nu_{dn}	downward heat transfer Nusselt number ($\mathrm{Nu} = qH/\lambda\Delta T$)
Pr	Prandtl number ($\mathrm{Pr} = \nu/\alpha$)
R	pool radius (m)
Ra'	modified Rayleigh number ($\mathrm{Ra}' = g\beta q_v H^5/\lambda\nu\alpha$)
S	strain rate
$\bar{S}_{ij}$	rate-of-strain tensor for the resolved scale
T	temperature (°C/K)
t	time (s)
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 ($kg{\cdot}m^{-3}$)
λ	thermal conductivity ($W{\cdot}m^{-1}{\cdot}K^{-1}$)
μ	dynamic viscosity (Pa·s)
ν	kinematic viscosity ($m^2{\cdot}s^{-1}$)
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
LES	Large eddy Simulation
IVR	In-Vessel Retention
PECM	Phase-change Effective Connvectivity Model
SGS	Sub-Grid Scale
VOF	Volume of Fluid
WALE	Wall-Adapting Local Eddy-Viscosity model
WMLES	Wall-Modeled LES model

For the heat transfer of the melt pool, when the Rayleigh number of the melt exceeds the order of 10^{10}, the melt flow reaches to turbulence. Actually, the Rayleigh numbers of the melt pool in the reactor situation and several experiments were at the order of 10^{16}, leading to the strong turbulence in the melt pool. Dinh and Nourgaliev (1997) pointed out that the k–ε turbulence model has largely failed to predict thermal stratification and heat flux distributions accurately for a high-Rayleigh number volumetrically heated liquid pool.

High-resolution CFD methods, such as large eddy simulation and direct numerical simulation (DNS), are capable of capturing flow physics and providing useful insights in both Rayleigh–Bénard fluid layers and volumetrically heated liquid pools (Tran et al., 2010). Miassoedov et al. (2013) applied the CONV code, which is a thermal-hydraulic CFD code developed at IBRAE for the simulation of heat transfer in complex geometry, to simulate the LIVE-L4 experiment. The large eddy simulation (LES) scheme with no sub-grid scale (SGS) closure was realized in the code. The unsteady 2D/3D Navier–Stokes equations in natural "velocity–pressure" variables were solved with an efficient difference scheme.

Fukasawa et al. (2008) compared the turbulent models of the k–ε and the large eddy simulation to examine through the CEA BALI oxide and metal layer test (Bonnet and Seiler, 1999). The results indicate that the LES method is capable in describing flow physics and heat transfer characteristics. An implicit LES method without an explicit SGS model is employed by Tran et al. (2010). The implicit LES showed that the method works quite well in predicting natural convection heat transfer for transient cool down liquid pools. Besides, the melt pool Pr effect on heat transfer were also investigated by Dinh and Nourgaliev (1997) with CFD tools.

The advantages and limitations of the above methods or models were compared in the Table 1.

In this paper, we performed the numerical simulation with LES turbulence model for three typical corium pool experiments: BALI, LIVE and COPRA experiments. Then the numerical simulation with prototypical corium was performed to obtain the heat transfer data in reactor situation.

2. LES turbulence modeling

With the distinctive progress in numerical methods and computational power, the LES methods are more and more applicable to nuclear industry and have become powerful tools to analyze turbulent and multiphase flows in detail. Turbulent flows in corium pools are characterized by eddies with a wide range of time and

Table 1
Advantages and limitations of the corium pool simulation methods.

Methods	Advantages	Limitations
k–ε	The most common turbulence model and easily applied in the self-developed codes	Failed to predict detailed information for the corium pool with high Rayleigh number
CFD-based	The CFD solver could better deal with the complicated momentum equations	The simulation results relied on the turbulence model used in the codes
PECM	It could bypass solving the momentum equations, and only to solve the energy equation using Fluent solver	The results lacked the information of natural convection flow velocity
LES	It could capture the detailed heat transfer characteristics in high Rayleigh number corium pool. It could be used as reference calculation for accident prediction and model validation	The complicated calculation may be time consuming or cost computer resources