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Implementation of Enthalpy-Porosity Methodology in OpenFOAM for Validation of LIVE L7V and L7W tests

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1. Introduction

In-Vessel Retention (IVR) is one of the severe accident management strategies of nuclear power plants. In this strategy, the thermal behavior of the core melts relocated to the reactor pressure vessel (RPV) is one of the important factors to determine the integrity of the RPV. The thermal behavior of the in-vessel core melt is determined through the following various phenomena: natural convective flow, phase-change of the core melt, conjugate heat transfer between melt and vessel wall, heat transfer of the external vessel, etc. Although the LIVE experiment was performed under a relatively low Rayleigh number condition, most of the above-mentioned phenomena are included. In particular, one of the goals of LIVE experiment is to investigate the effect of phase-change phenomenon on the heat transfer characteristics by using a phase-change material as a working fluid.

In this paper, a numerical platform that can simulate the LIVE experiment including phase-change phenomenon was developed using OpenFOAM. The OpenFOAM code is modified to include an enthalpy-porosity methodology (EPM) which can model melting or solidification problem, and validated with experimental data.

2. Numerical method

2.1 Enthalpy-porosity methodology for phase change application

Enthalpy-porosity methodology (EPM) is one of the representative analysis methodologies to investigate phenomenon of phase change including melting or solidification [1]. It has the advantage of being able to simulate the convective/diffusion phase-change problems in a fixed-grid system. Latent heat is contained as a heat source or sink in the energy equation, and various methodologies could be done to make the velocity in the solid region as zero. The Enthalpy-porosity methodology (EPM) is a methodology that considers a computational domain to be a porous (ε) domain and divides it into a liquid (ε=1), a solid (ε=0), and regions where phase change is in progress (between 0 and 1). In this study, the notation of the liquid fraction (g_l) were used instead of porosity (ε).

The governing equations below include EPM, and it can be seen that the momentum equation in Eq. (2) and the temperature equation in Eq. (3) contain it as a source term, respectively. For example, for the region of the liquid (g_l=1), A is zero, and the equation of motion becomes the same as the original momentum equation. The variable A can be derived as Eq. (4) for non-isothermal problem and Eq. (5) for isothermal problem, where C is a sufficiently large value, around mainly between 10^4 to 10^7, to make the velocity of the solid region zero. The variable b in the denominator of Eq. (4) mainly uses 0.001. Meanwhile, L in the Eq. (6) represents the latent heat.

$$\nabla \cdot \vec{u} = 0 \tag{1}$$

$$\frac{\partial \vec{u}}{\partial t} + \nabla \cdot (\vec{u}\vec{u}) = -\nabla p_m + \nabla \tau_{ij} + A\vec{u} \tag{2}$$

$$\frac{\partial c_p T}{\partial t} + \vec{u} \cdot \nabla (c_p T) = \nabla \cdot (\frac{\kappa}{\rho} \nabla T) + S_h \tag{3}$$

$$A = -C \frac{(1-g_l)^2}{{g_l}^3 + b} \tag{4}$$

$$A = -C(1-g_l) \tag{5}$$

$$S_h = -L \frac{\partial g_l}{\partial t} \tag{6}$$

The selected methodology in this study is an isothermal one, and the liquid fraction is directly determined based on the field temperature during the simulation (Eq.7). In addition, for the temperature equation, a sufficient number of repetitions are required for every step to converge the liquid fraction value.

$$g_l = \begin{cases} 0 & T < T_m \\ 1 & T > T_m \end{cases} \tag{7}$$

2.2 LIVE test [2]

The LIVE experiment was conducted to investigate the thermal behavior of core melt during IVR. Since the salt (a non-eutectic binary mixture of 20 mol% $NaNO_3$-80 mol% KNO_3 composition) was used as a simulant material for specific cases, the solidification along the vessel wall can be simulated. Fig. 1 shows the LIVE facilities, which consists of a 3D hemisphere (R = 0.5m), a side vessel wall (thickness = 0.025m), and an upper lid. The height of the upper lid can be adjusted according to the conditions, and the height of the lid is fixed to 0.42m

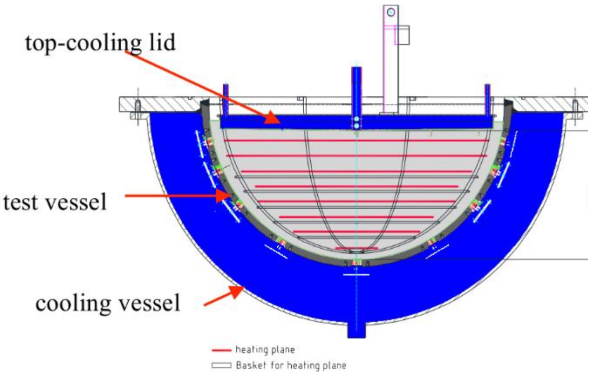


Fig. 1. LIVE test facility (with top-cooling lid)

in this study. Inside the hemisphere, there is a spiral heater, which simulates decay heat. A sufficient amount of water is supplied outside the side wall surface and the upper lid to maintain constant cooling conditions.

Two cases are selected in this report, L7W and L7V. Both experiments are lateral and upper cooling conditions, and the working fluid is water (L7W) and salt (L7V), respectively. The phase-change along the cooling boundary condition is expected only in L7V case. Table I shows the main thermal-physical properties of salt used in the L7V. The vessel wall is SS316Ti and has a thermal conductivity of 14.6 W/m-K, heat capacity of 500 J/kg-K, and a density of 7,870 kg/m^3. In this study, it was assumed that the phase-change occurs at the liquidus temperature.

2.3 Numerical conditions for LIVE simulation

Fig. 2 shows the grid system used in the simulation. The grid was largely divided into a working fluid region and a vessel wall region, and in particular, the grid for the fluid region was clustered near the wall to capture the near wall behavior. After performing the grid test, the optimal number of grids both conditions is selected about 500,000. The time step was determined as 0.1 seconds, which satisfied the Courant and Diffusion number in the fluid and solid regions sufficiently small. In this study, the OpenFOAM was used, and the ‘`chtMultiRegion-Foam`’ which is a solver for fluid flow and solid heat conduction, along with conjugate heat transfer between regions and the likes. The solver was modified to include EPM.

3. Results

3.1 Validation of the EPM (Gallium melting test)

Before applying the modified solver in the LIVE cases, the representative Gallium melting experiment was selected to validate the solver. The detailed information of Gallium melting test is described in [3]. The temperature of left and right wall is 311.15 K and 301.15 K, respectively, and the top and bottom wall are adiabatic. A two-dimensional computational domain was used for validation.

Table I: Thermal-physical properties of 20 mol% NaNO$_3$-80 mol% KNO$_3$ [2]

Parameters	Values
Density	1868 kg/m^3
Dynamic viscosity	1.81×10^{-3} kg/m-s
Thermal conductivity (liq.)	0.439 W/m-K
Thermal conductivity (sol.)	0.6 W/m-K
Specific heat capacity (liq.)	1331 J/kg-K
Specific heat capacity (sol.)	1060 J/kg-K
Liquidus temperature	557 K
Solidus temperature	439 K
Latent heat of fusion (L)	161,956 J/kg

Fig. 2. Grid used for the simulation.

Fig. 3 shows the melting front of the gallium over time. The simulation result is generally well matched with the experiment, including the tendency such as active melting at the top. It is confirmed that the methodology and the modified solver selected in this study were suitable for the phase-change problem.

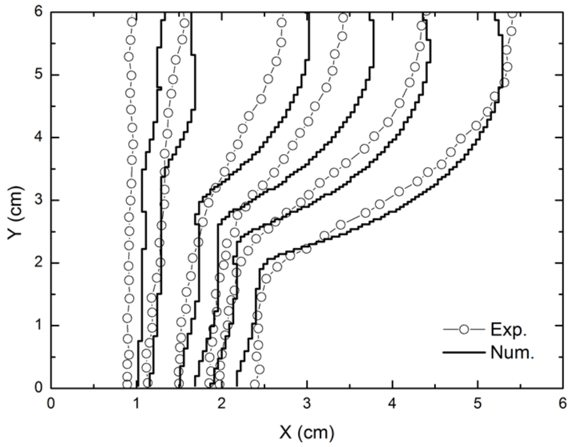


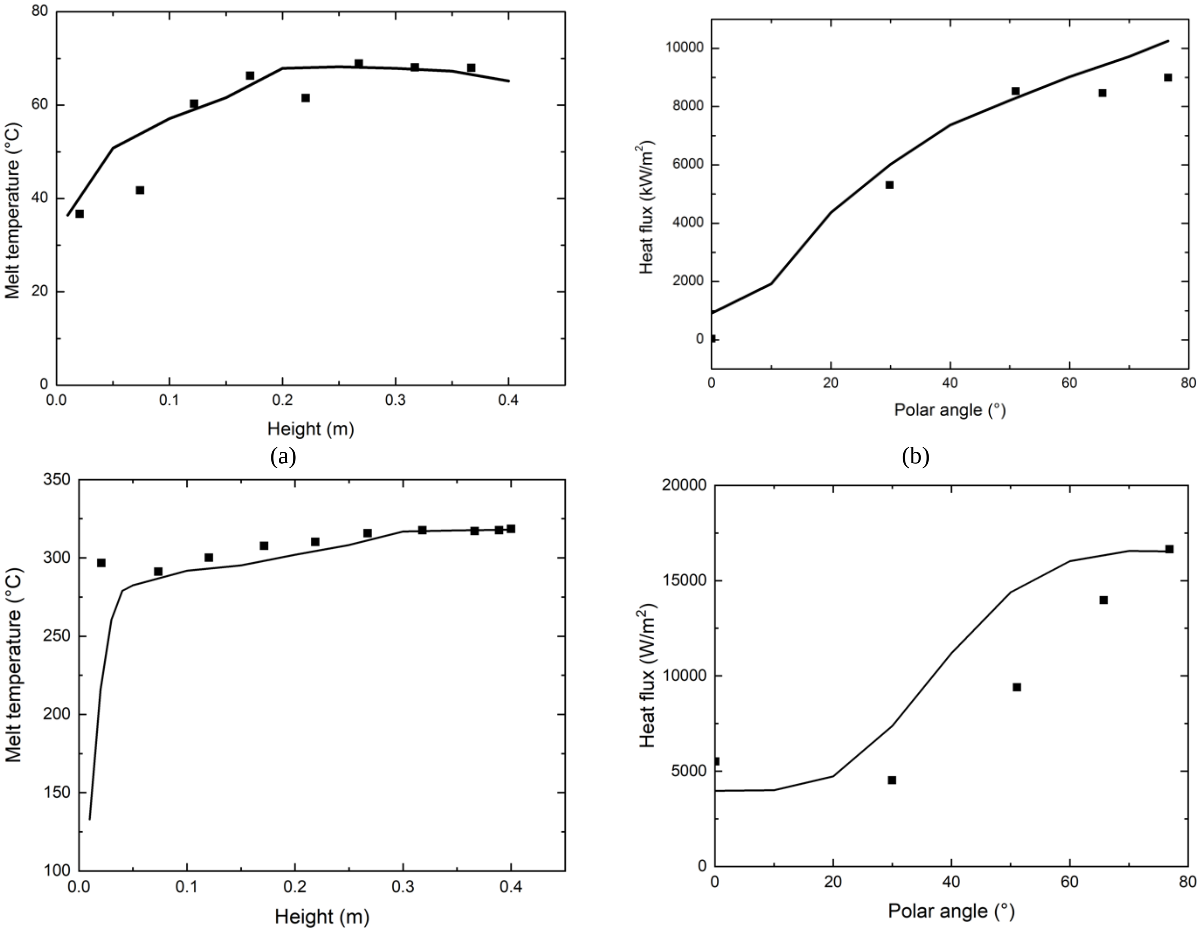
Fig. 3. Comparison of the melting front with experiment.

3.2 Results of LIVE-L7W and LIVE-L7V

Fig. 4 shows the validation results of melt temperature and heat flux along the vessel wall of L7W and L7V.It was confirmed in Fig. 4 (a) and (b) that the general behavior of the pool temperature was well simulated. It can be observed that the temperature of the upper part of the pool becomes homogeneous due to the convective flow. Except to the lower part (height < 0.05 m) of the L7V which is a solidified region, the overall temperature of the liquid phase was well predicted in Fig. 4 (c). The calculated heat flux distribution ~~is~~ well reproduced the general characteristics of both conditions. The measured crust data exists from about 35° (the angle of bottom of the pool is zero), and it can be seen that the crust thickness decreases as the angle increases. The tendency of forming a maximum thickness crust at the bottom and thinning toward the top of the vessel is similarly predicted. Discrepancies of wall heat flux values, as well as the crust thickness, were anticipated due to the current solver's limitations that the phase-change temperature of the mixture is determined with a single temperature, not solidus and liquidus temperature.

4. Conclusions

The thermal behavior of the in-vessel core melt is determined through the following various phenomena: natural convective flow, phase change, conjugate heat transfer between melt and vessel wall, and heat transfer of the outer wall. The LIVE experiment includes various phenomena in real circumstance including phase-change of simulant melt, although it was conducted in a relatively low Rayleigh number condition. In this study, the numerical platform which can simulate above mentioned behaviors was developed and validated with representative experiments (Gallium melting, LIVE-L7V and LIVE-L7W). It is expected that the analysis of the nuclear power plant scale can be performed in the future after improving the numerical platform, and the priority for future work is to include non-isothermal method in the current solver.



(a) (b)

(c) (d)

Fig. 4. Validation results of L7W (top) and L7V (bottom):
vertical melt temperature at 0.175m from the center line (a) and (c),
heat flux profile along the vessel wall (b) and (d)

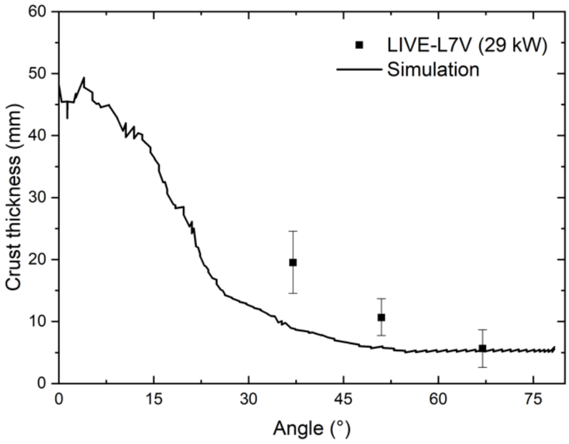


Fig. 5. Crust thickness along the inner vessel wall (LIVE-L7V)

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