Validation of Melting Computation Method for Reactor Vessel Ablation under External Reactor Vessel Cooling Conditions

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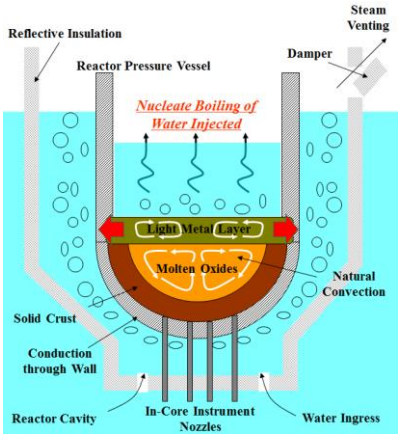
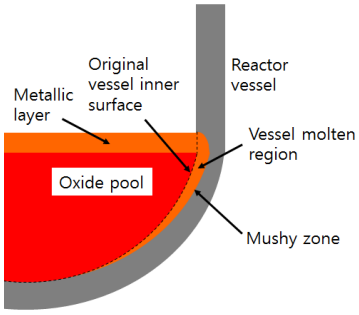
1. Introduction

In-vessel corium retention (IVR) by external reactor vessel cooling (ERVC) shown in Fig. 1(a) has been regarded as a favorable severe accident management for decades. In order for the IVR to be successful, the heat flux at the outer surface of the vessel should be less than critical heat flux (CHF) mostly at the metallic region where heat flux may sharply concentrate.

This is called as 'focusing effect', which is a situation where metallic layer above heavy oxide molten pools, when it is thin, may focus heat load to the reactor vessel as shown in Fig. 1a (red-colored arrows). This has been generally regarded as a critical issue for successful IVR since the reactor vessel remaining thickness pertaining its original strength at this region is much smaller or even the vessel would melt through [1].



(a) External reactor vessel cooling



(b) Melt vessel interaction

Fig. 1. In-vessel retention with external vessel cooling.

For illustration of the focusing effect issue, a simple conduction-only computation for a bare slab considering heat loads from two depths of metallic layer with same heat flux is performed as shown in Fig. 2. Important result is that the temperature of the vessel goes higher for the thick heat load rather than for the thin case. For the same heat flux, thick load is thus more threatening the vessel and this is because thick heat load retards heat diffusion in vertical directions. Therefore, 'thin or thick' is not a major factor for estimating the reactor vessel remaining thickness.

This is also justified by relatively old assessment using MVITA code, which indicated that multi-dimensional heat diffusion through the thick, highly-conductive, steel vessel significantly reduces the effect of any local hot spot occurring on the inner side of the vessel, such as the heat fluxes peaking in the thick metallic layers or the high heat fluxes imposed by the thin metallic layers [2].

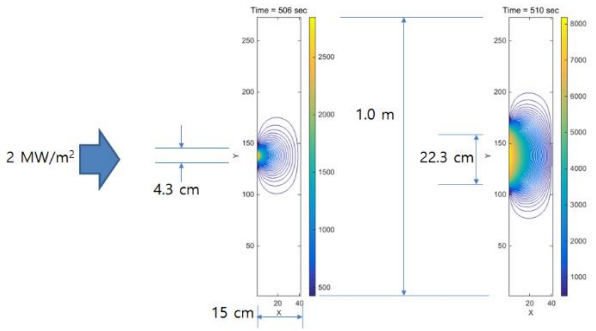


Fig. 2. Conduction-only computations for a bare slab.

On the other hand, as shown in Fig. 1b, the reactor vessel, suffering from the focused heat load from the lighter molten metal layer, should partially melt. This is a kind of melting problem composed of conduction and melting in solid region, solid-liquid interaction and natural convection winthin the liquid region. The molten vessel would mix with the metallic layer but would not mix with the oxide pool since a solid crust forms in between.

Nevertheless, most severe accident analysis codes and Stefan problem treat the vessel molten region as purely conducting [1] or simulated by using effective conductivity assumption which mimics convection [3]. However, this is arbitrary method to speed up

computations and generally known as inaccurate so we cannot find precise vessel remaining thickness pertaining its original strength. This is also proved by Achard et al. [4], who compared a purely convective finite difference enthalpy method with experimental data and found significant discrepancies thus deducing that it is necessary to consider natural convection.

Therefore, as mentioned previously, three-dimensional computation considering not only the solid conduction but also its melting and natural convection in the molten region is essential to accurately account for the reactor vessel transient behavior. Present paper thus tries to provide a validated method of melting calculation for later application to a reactor vessel ERVC problem. Previous experiment of Gau and Viskanta [5] for gallium melting in a two-dimensional cavity is used as a benchmarking case of the melting computation by using the STAR-CCM+ code [6]. Melt front (solid-liquid interface) advancement and naturally convective velocity magnitudes in molten region is compared with the experiment [5] and the computations of previous authors [7,8], respectively.

2. Method and Analysis

2.1 Gallium melting experiment in 2D cavity

Gau and Viskanta [5] conducted an experiment on melting of pure gallium in two-dimensional rectangular cavity and their experiment is used as a benchmarking case of the present computation. The two-dimensional cavity is shown in Fig. 3, which has 4.5 cm of height and 9.0 cm of width and was initially filled with pure solid gallium slightly below its melting temperature (302.9 K). Initially, the temperature on the left-hand wall was raised to 311.5 K and the right-hand wall temperature was kept at 301.5 K. The upper and the lower walls were insulated.

As time passes by, melting proceeds from the left-hand vertical wall to rightward as shown by thick solid arrow lines in Fig. 3. In the liquid region, natural convection occurs due to gravitational force and the density change.

2.2 Validation of Melting Computation

Present computational domain with rectangular meshes for simulation of this gallium melting is thus also set in a two-dimensional rectangular cavity with the same size as shown in Fig. 3. The cavity's initial temperature is uniformly set at 301.5 K, which is slightly below gallium liquidus temperature of 302.9 K. Top and bottom walls are also kept adiabatic. The computation is performed using STAR CCM+ code [6].

For the flow condition in the molten (liquid) region, laminar condition is assumed since the Rayleigh number calculated is 325,000 and the previous computation by Mansutti and Bucchignani [8] shows the velocity ranges below 0.01 m/sec. For all the walls, no-slip conditions are applied. The cavity was divided into the 16,200 rectangular uniform elements (180x90). The number of meshes is relatively larger than FDM computations by Mansutti and Bucchignani [8].

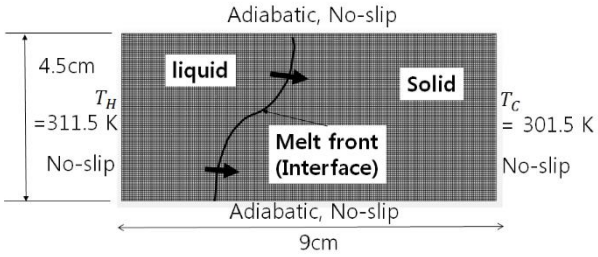


Fig. 3. Computational domain of two-dimensional rectangular cavity.

Following is the brief summary of models used for the present computation using STAR CCM+ code [6]. For the two phases of liquid and solid, VOF (volume of fluid) model is applied with following functions:

- Phase change based on enthalpy of a volume
- Laminar natural convection in liquid region
- Mushroom region between solid and liquid
- Temperature dependent density
- Flow stopping criteria of solid fraction, 0.99

The VOF model [6] assumes that all immiscible fluid phases present in a control volume share velocity, pressure, and temperature fields. Therefore, the same set of basic governing equations describing momentum, mass, and energy transport in a single-phase flow is solved. The equations are calculated as functions of the physical properties of its constituent phase and their volume fractions.

The conservation equation that describes the transport of volume fractions α_i for the liquid zone (solid fraction $\alpha_s = 0$) and mushy zone ($0 < \alpha_s < 1$) is

$$\frac{d}{dt}\int_V \alpha_i dV + \int_S \alpha_i \left(v - v_g\right)\cdot da = \int_V \left(s_{\alpha_i} - \frac{\alpha_i}{\rho_i}\frac{D_{\rho_i}}{Dt}\right) dV \quad (1)$$

where v is the flow velocity, v_g is the grid velocity, V is the cell volume, S_{α_i} is the source or sink of the i th phase, and D_{ρ_i}/D_t is the material or Lagrangian derivative of the phase densities ρ_i.

For basic melting-solidification, the enthalpy of the liquid-solid phase h_{ls} includes the latent heat of fusion h_{fusion} as following:

$$h_{ls} = h_{ls} + (1 - \alpha_s)h_{fusion} \quad (2)$$

The relative solid volume fraction α_s is defined as the portion of the volume of the liquid-solid phase which is in the solid state. α_s is a function of temperature as following:

$$\alpha_s = 1 \quad \text{if } T < 0 \tag{3a}$$
$$\alpha_s = f(T) \quad \text{if } 0 < T < 1 \tag{3b}$$
$$\alpha_s = 0 \quad \text{if } 1 < T \tag{3c}$$

where T is the normalized temperature that is defined as:

$$T = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \tag{4}$$

The function $f(T)$ in Eq.(3) is called the fraction solid curve. For a linear dependence between α_s and T, $f(T)$ is defined as:

$$f(T) = 1 - T \tag{5}$$

The physical properties of gallium used are given in Table 1. For the density, temperature dependent values [9] are used as following:

$$\rho = C_1 - C_2(T - T_{ref}) \tag{6}$$

where C_1 and C_2 are 6,077 kg/m^3 and 0.611 $kg/m^3\,K$, respectively.

Table 1: Physical properties of gallium

Property	Value
Density	Temperature Dependent (Eq. (6))
Reference density	6,095 kg/m^3
Latent Heat of fusion	80,160 J/kg
Specific Heat capacity	381.5 $J/kg\,k$
Liquidus temperature	302.9 K
Solidus temperature	302.9 K
Thermal conductivity	40.0 $W/m\,k$

The viscosity of the mushy zone where liquid and solid coexist is important part for convection computation. For this, switching function for Metzner Slurry Viscosity [10] and Carman-Kozeny Mushy Zone Permeability Model [11] are used. Both models cover different ranges of solidification state. The state of solidification is expressed by the solid volume fraction. The critical solid fraction α_{cr} separates the applicable ranges of the two models as following:

$\alpha_s \leq \alpha_{cr}$: Slurry viscosity model [10]
$\alpha_{cr} < \alpha_s$: Mushy zone permeability model [11]

where α_{cr} has a value of 0.27.

For the numerical side, implicit unsteady calculation is performed with time step size of 0.1 sec and inner iteration of 50 between every time step is used, making sure that all the normalized residuals are below $1x10^{-4}$ between each time step.

3. Results and Discussion

Figure 4 shows the two cases of the computations for the gallium conductivity of 32 W/m.k and 40 W/m.k. The blue region is liquid and the red region is solid. There are thin mushy zone in between.

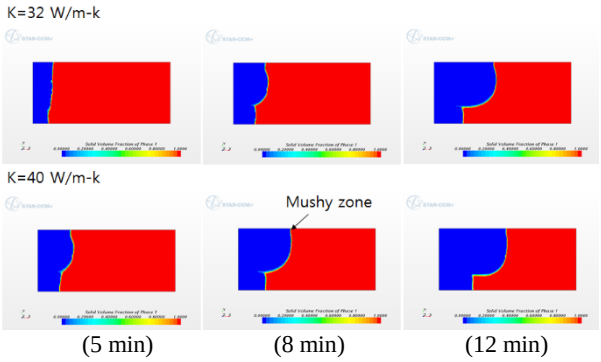


Fig. 4. Solid-liquid interface with mushy zone moving according to time for two gallium conductivities.

It is found that the gallium conductivity of 32 W/m.K which was used by the previous computations [7,8] gives slower solid-liquid interface advancement in the present computation than the experiment [5]. However, the computation with the conductivity of 40 W/m.K shows best agreement as shown in Fig. 5. According to the literature [9], the conductivity of 40 W/m.K is the reasonable value for this temperature region and thus justifies our result.

Figure 5 shows that the melting front interface advancement for solid gallium conductivity of 40 W/m.K gives good agreement with the experimental result from Gau and Viskanta [5] and X-FEM analysis by Uchibori and Ohshima [7]. Even though there is some discrepancy between the experiment and the present calculation, it can be regarded that the difference is within the experimental, modeling and numerical uncertainties.

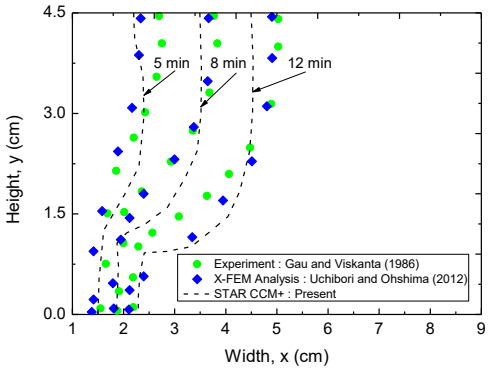


Fig. 5. Comparison of melting front with experimental data [5] and previous calculation [7].

Figure 6 shows the streamline in liquid gallium (molten region) at 12 min. Two major Benard convection

cells are formed which are generally found in most natural convection problems of liquid metals: upper one is larger than the lower one due to growing speed of the flow at the upper region.

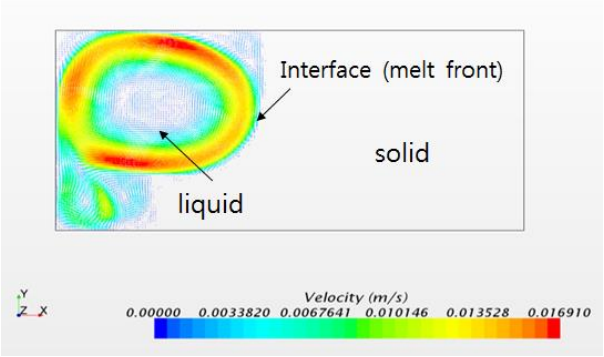


Fig. 6. Solid-liquid interface, vector velocity in gallium melt.

Mansutti and Bucchignani [8] set up governing equations for the liquid and the solid phase described respectively as an incompressible viscous fluid and an isotropic linearly elastic incompressible material. Finite difference method (FDM) momentum and energy equations are solved for the liquid part. However, mushy zone was not considered and jump conditions are used with equating velocity, momentum and heat transfer at the interface. Also, constant material properties are used and Boussinesq-Oberbeck approximation is needed for the buoyancy force. No slip between liquid and solid is assumed.

Table 2 shows the present maximum and minimum values of x-direction and y-direction flow velocities at 32 seconds, which are compared with the three mesh sensitivity computation results reported by Mansutti and Bucchignani [8]. In the present computation, number of computational cells are 180x90, which is larger than those of Mansutti and Bucchignani [8].

Table 2: Magnitudes of velocity components at 32 sec

	Mansutti and Bucchignani [6] (FDM [1])			Present (FVM [2])
Mesh	40 x 11	60 x 17	90 x 25	180 x 90
u_{max}	8.19E-3	6.2E-3	5.8E-3	6.8E-3
u_{min}	-7.1E-3	-6.3E-3	-5.7E-3	-7.2E-3
v_{max}	3.9E-2	2.9E-2	2.0E-2	2.3E-3
v_{min}	-1.3E-3	-1.3E-3	-1.3E-3	-2.1E-3

[1] FDM: finite difference method
[2] FVM: finite volume method

In the computations of Mansutti and Bucchignani [8], however, convergence of the computations according to the increasing number of cells are uncertain. Therefore, our computation is compared with their 90x25 mesh case (assuming it is convergent calculation) and it can be stated that the present computation is very comparable to their computation.

4. Conclusions

Validation of computational method of solid melting is performed for an existing experiment for gallium melting in a two-dimensional cavity. The result shows that present computation of melt front advancement is in good agreement with experimental data and existing computations. This method can be and will be later applied to accurate estimation of the reactor vessel ablation behavior under external vessel cooling conditions for diverse inner corium heat load conditions.

Acknowledgements

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