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Comparison of the Phase-Change Models of Enthalpy-Porosity Methodology for Mushy Zone Problems in LIVE L7V test (22A-333)

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Introduction

- **Severe accident**
  - Partial or complete 'melt-down' of the reactor core
- **Severe accident management strategy: In-Vessel Retention (IVR)**
  - Integrity of reactor pressure vessel (RPV) is determined through … "thermal behavior" of the in-vessel core melts
  - Complex phenomena determining thermal behavior of the corium pool
    - Phase-change of the core melts (crust formation & mushy zone), conjugate heat transfer (CHT), natural convective flow, turbulence, etc.
- **Previous work**
  - **Development of numerical platform** which can simulate the important phenomena (phase change, CHT, natural convection) to evaluate thermal behavior of core melts
- **Objective:**
  - **Comparison of the phase-change models** of enthalpy porosity methodology for mixture material with LIVE L7V test

Numerical Methodology

- **Enthalpy-porosity methodology (EPM) for phase change application [1]**
  - One of the representative methodologies to simulate phase-change problem **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**
  - **EPM** considers a computational domain to be **a porous domain (ε, *here liquid fraction (g)*)** and divides it into **a liquid (*g*=1), a solid (*g*=0)**, and regions where phase change is in progress (between 0 and 1).
- **Governing equations (GE):**

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

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

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

- **Source terms in the GE:**

A(1): $A = -C(1-g_l)$

A(2): $A = -C\dfrac{(1-g_l)^2}{g_l^{\,3}+b}$

S(1): $S_h = -L\dfrac{\partial g_l}{\partial t}$

S(2): $S_h = -L\left(\dfrac{\partial g_l}{\partial t} + \vec{u}\cdot\nabla g_l\right)$

- Constant, *"C"* is a sufficiently large value (10^4 to 10^7) to make the velocity of solid region zero
- **Liquid fraction (*g*)** is directly determined based on the field temperature as below:

g(1): for pure material

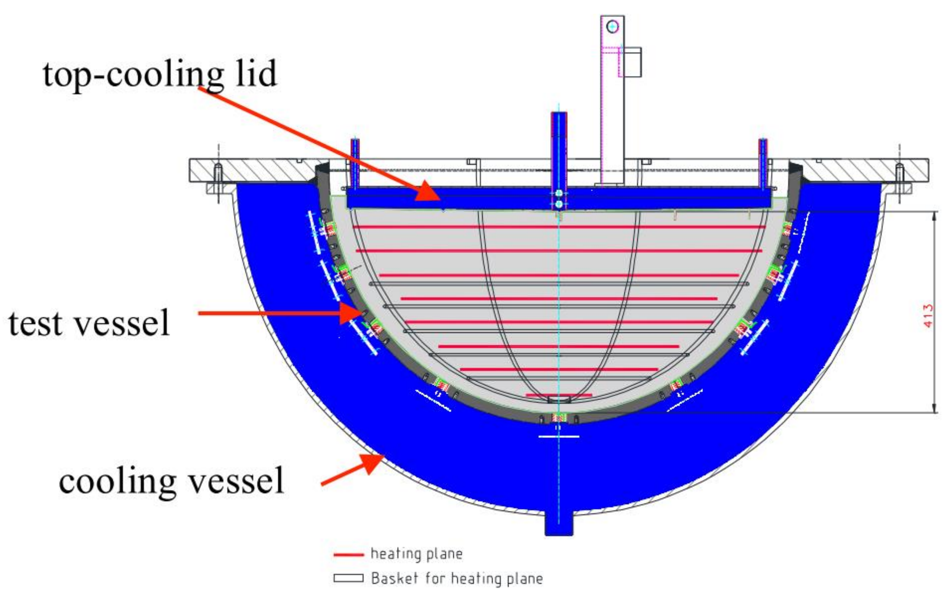
$$g_l = \begin{cases} 0 & T > T_m \\ 1 & T < T_m \end{cases}$$

g(2): for mixture material

$$g_l = \begin{cases} 0 & T > T_l \\ \left(\dfrac{T - T_s}{T_l - T_s}\right) & T_l > T > T_s \\ 1 & T < T_s \end{cases}$$

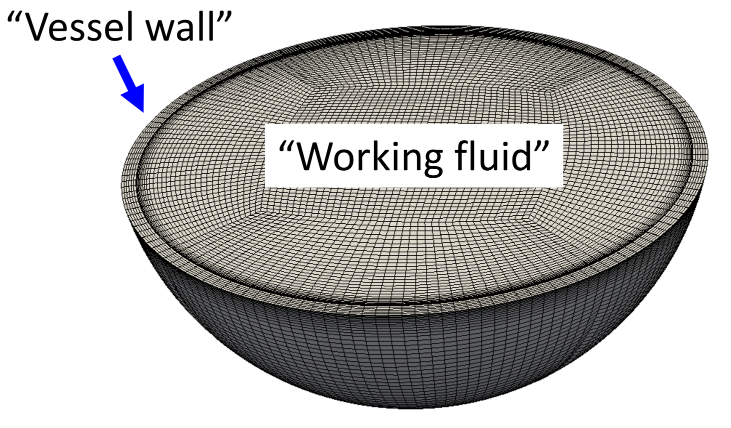
Model	g_l	A	S_h
EPM(T_{liq})	g(1)	A(1)	S(1)
EPM(T_{sol})	g(1)	A(1)	S(1)
EPM^+_a	g(2)	A(1)	S(1)
EPM^+_b	g(2)	A(1)	S(2)
EPM^+_c	g(2)	A(2)	S(1)
EPM^+_d	g(2)	A(2)	S(2)

- **LIVE test [2]**
  - **Geometry:** 3D hemisphere (R = 0.5 m), side vessel wall (thickness = 0.025 m), simulant height (H = 0.42m)
  - **Selected cases:** LIVE - L7V
    - Internal heat generation (29 kW)
    - Top and side cooling
  - **Simulant material**
    - **Non-eutectic binary mixture** of 20 mol% NaNO3 - 80 mol% KNO3



LIVE facility

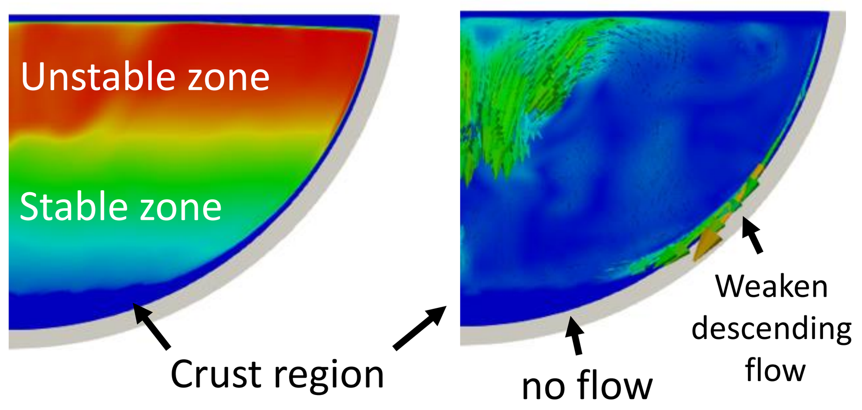
- **Numerical conditions for LIVE simulation**
  - **OpenFOAM** solver '`chtMultiRegionFoam`' for fluid flow and solid heat conduction along with **conjugate heat transfer**, is selected, and **modified** to include **EPM source terms** in the governing equations
  - **Numerical grid** is divided into two parts:
    - Working fluid region and vessel wall region
  - **Boundary conditions** :
    - Top surface of working fluid and side vessel wall: heat transfer coefficient (cooling)
    - Top surface of vessel wall: adiabatic condition



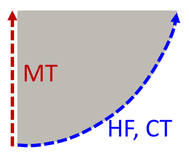
Numerical grid

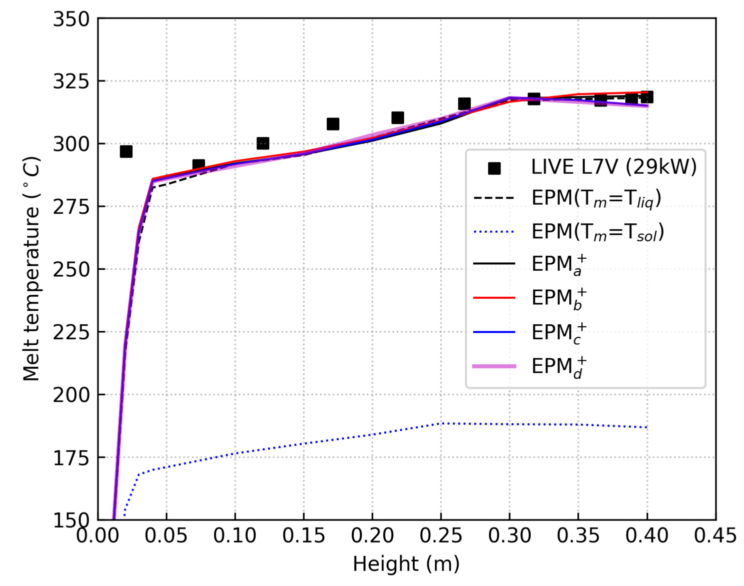
Results

- **Results of LIVE-L7V**
  - **Temperature** and **velocity contour:**
    - Unstable, Stable zone & Crust region
    - Weakened descending flow

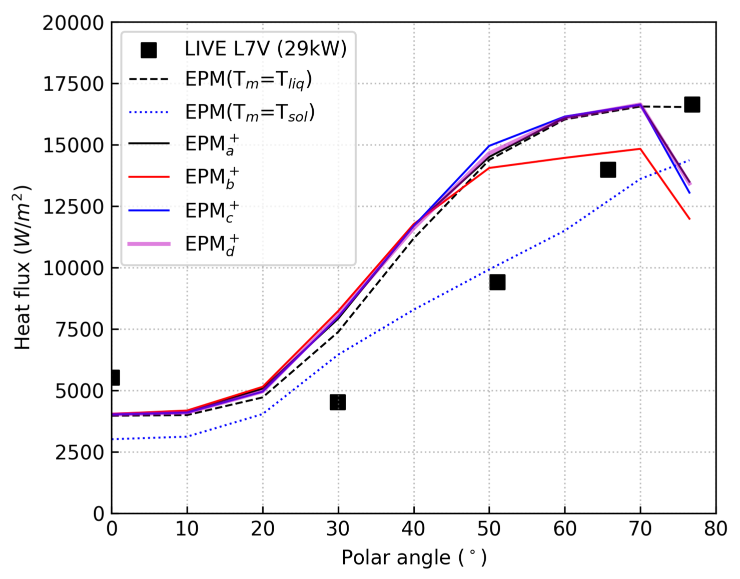


- **Comparison of the EPM models**
  - **Melt temperature (MT) and Heat flux (HF):**
    - Most EPM^+ & EPM (T_{liq}) show similar tendency



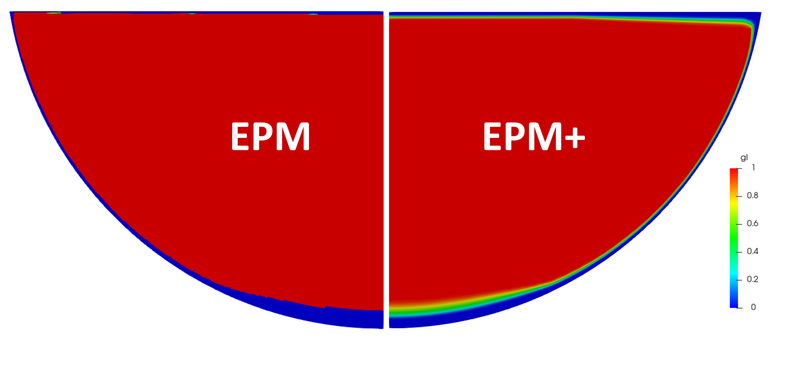


Melt temperature (MT) along the center

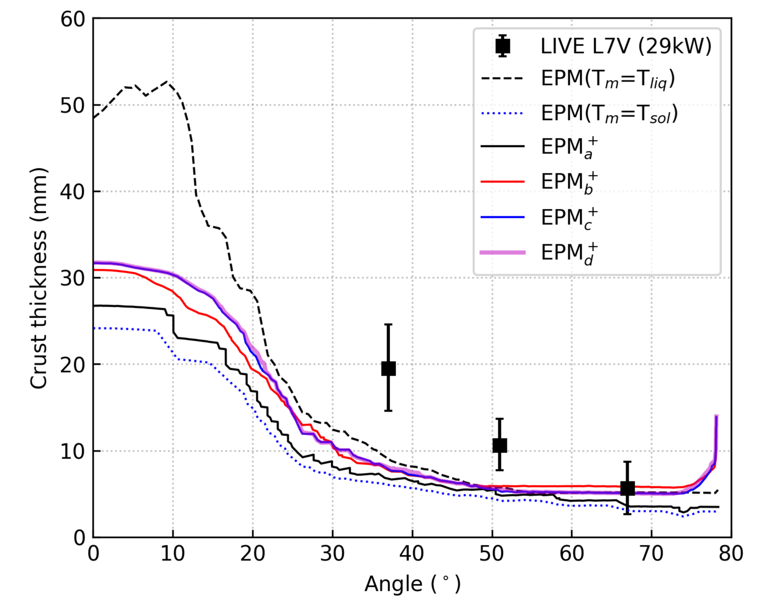


Heat flux (HF) along the vessel wall

- **Crust thickness (CT):**
  - Crust thickness is a maximum at the bottom of the vessel and, thinning along the vessel wall
  - EPM^+ can simulate the **mushy zone** (the liquid fraction (g_l) is between 0 and 1, while the liquid fraction is 0 or 1 in the previous EPM)
  - Results of EPM^+ show similar tendency between the EPM results



Liquid fraction



Crust thickness (CT) along the vessel wall

Conclusion and Future plan

- Previously, the **numerical platform (with EPM for pure material)** which can simulate the oxide pool behaviors was developed and validated with representative experiments (Gallium melting test, LIVE-L7V and LIVE-L7W). In this work, the **EPM models for mixture material** are implemented in the previous numerical platform. The results of EPM+ are validated and compared in the LIVE-L7V.
- As a future work, further study of the impact of mushy zone, property f(T), turbulence models, boundary conditions (adiabatic, radiation, etc.) are required.

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References

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