Enthalpy Porosity Method for CFD Simulation of Natural Convection Phenomenon for Phase Change Problems in the Molten Pool and its Importance during Melting of Solids

Priyanshu Goyal, Anu Dutta, V. Verma,I. Thangamani R. K. Singh
Bhabha Atomic Research Centre, Mumbai, India.

Introduction: This paper intends to bring out the effect of natural convection phenomena for thermal analysis of transportation casks by considering a validation problem reported in open literature.

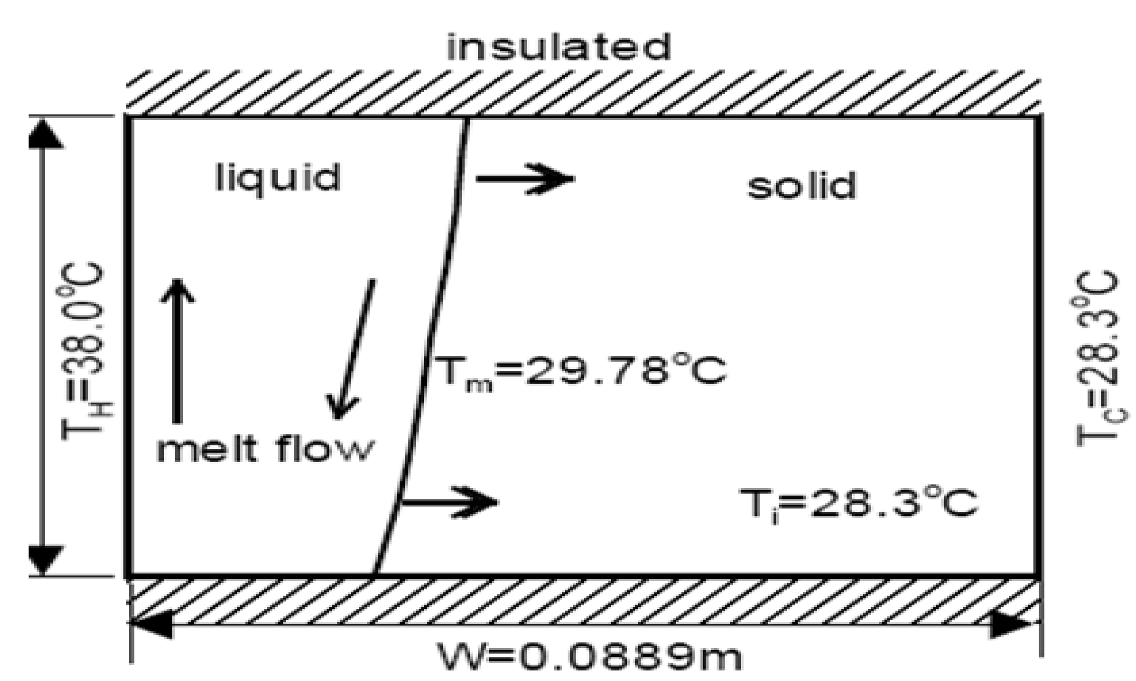

Fig. 1: Simple Schematic showing the configuration of cavity considered for melting analysis

Numerical Approach: To model the phase change phenomenon, enthalpy-porosity technique has been employed; the density variations in the liquid region are modeled using Boussiniesq approximation to account for the natural convection in the melted region.

Energy eq:

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial(\rho u h)}{\partial x} + \frac{\partial(\rho v h)}{\partial y} = \frac{\partial}{\partial x}\left(\alpha \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(\alpha \frac{\partial h}{\partial y}\right) + S_h$$

u-momentum eq:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u u)}{\partial x} + \frac{\partial(\rho v u)}{\partial y} = \frac{\partial}{\partial x}\left(\mu \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) - \frac{\partial p}{\partial x} + A u \quad (2)$$

v-momentum eq:

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho u v)}{\partial x} + \frac{\partial(\rho v v)}{\partial y} = \frac{\partial}{\partial x}\left(\mu \frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial v}{\partial y}\right) - \frac{\partial p}{\partial y} + A v + S_b \quad (3)$$

Continuity eq:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y}) = 0 \qquad s = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \text{ with } T_{solidus}<T<T_{liquidus}$$

$$S_b = \frac{\rho_{ref}\, g\beta(h - h_{ref})}{c_p} \qquad S_h = \frac{\partial(\rho \Delta H)}{\partial t} + \frac{\partial(\rho \Delta H)}{\partial x} + \frac{\partial(\rho \Delta H)}{\partial y} \qquad \Delta H = sL$$

For studying the effect of natural convection during melting, two cases have been studied: Case 1 involves effect of natural convection while Case 2 is solved without considering the density variations in the melted (liquid) region so as to make buoyancy (natural convection) effects inactive. The density variations in the liquid region are modeled using Boussiniesq approximation to account for the natural convection in the melted region. The transient analysis was carried out by using appropriate source terms in commercial multiphysics code COMSOL 4.0

Results: The melt fronts obtained at various times have been compared with experimental and shown in Fig. 2. It is observed that both the qualitative behaviour and acute morphology of the experimental melt fronts have been realistically obtained in the numerical study.

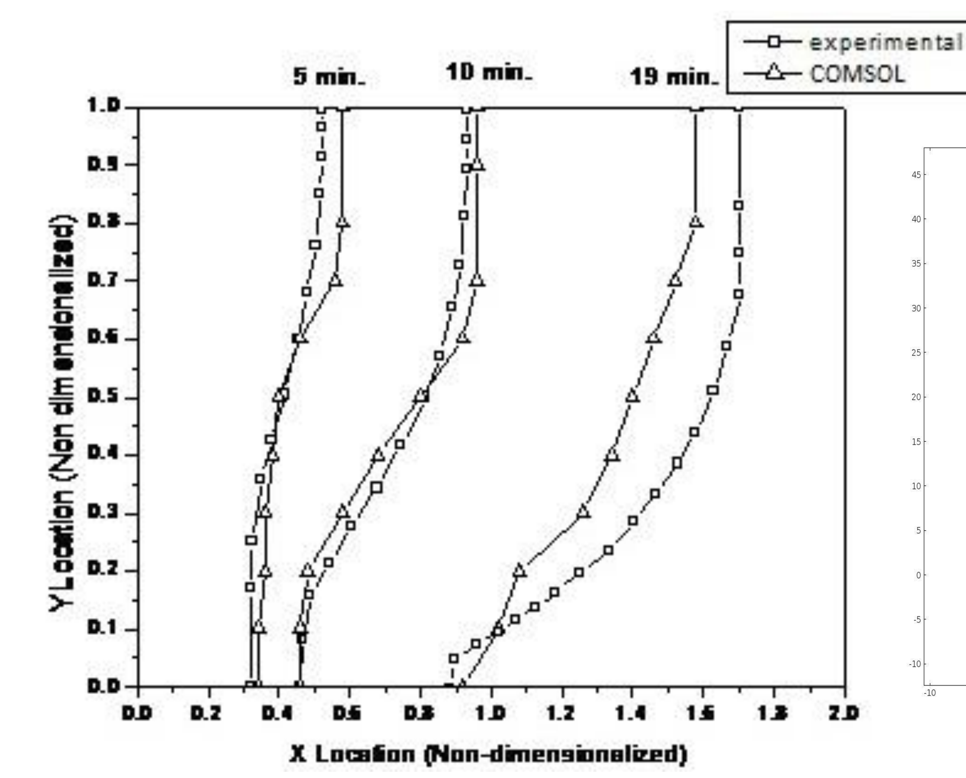

Figure 2. Comparison between experimental and predicted melt-fronts at different times

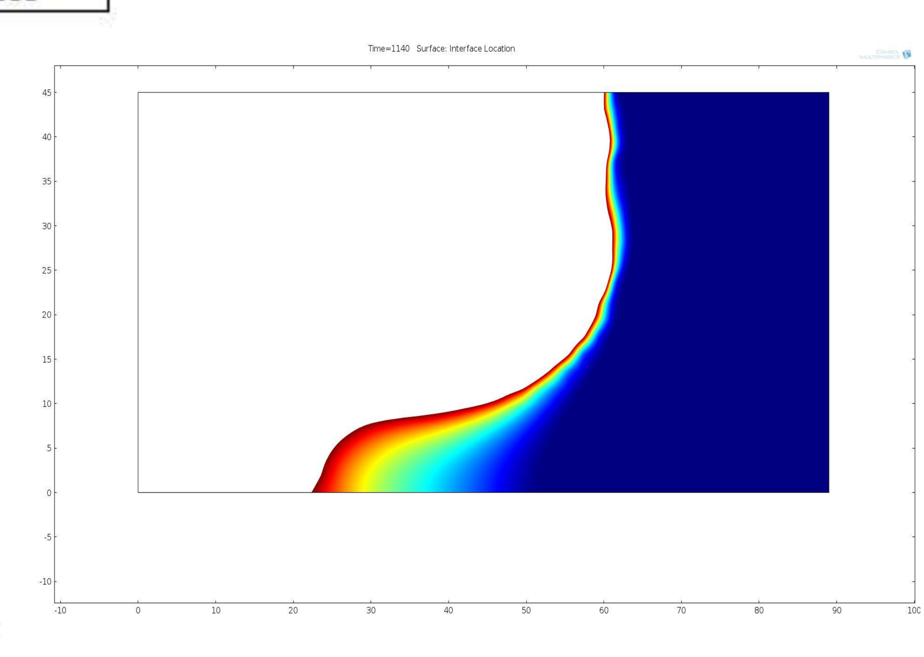

Figure 3. Predicted melt-front at the end of 19 minutes

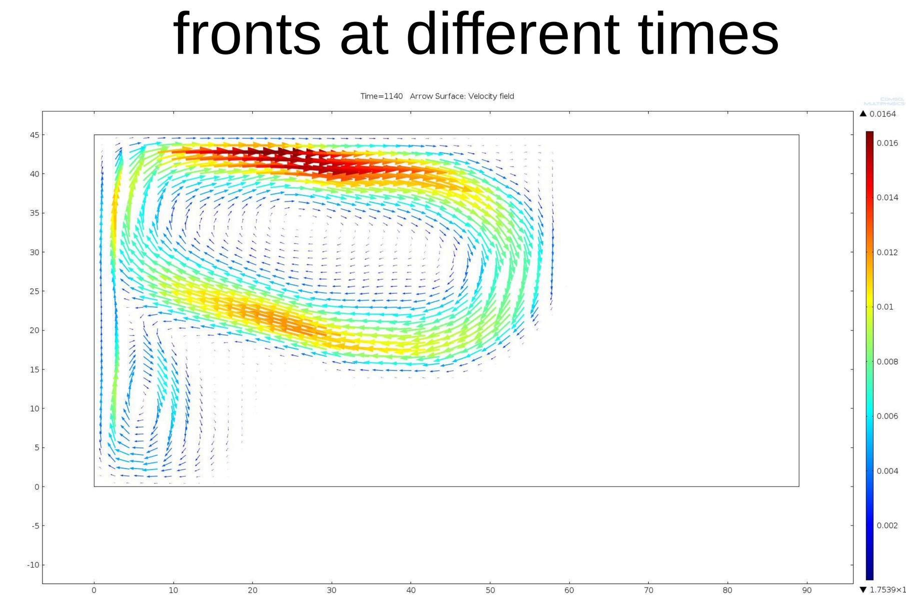

Figure 4. Velocity Vector Plots at the end of 19 minutes

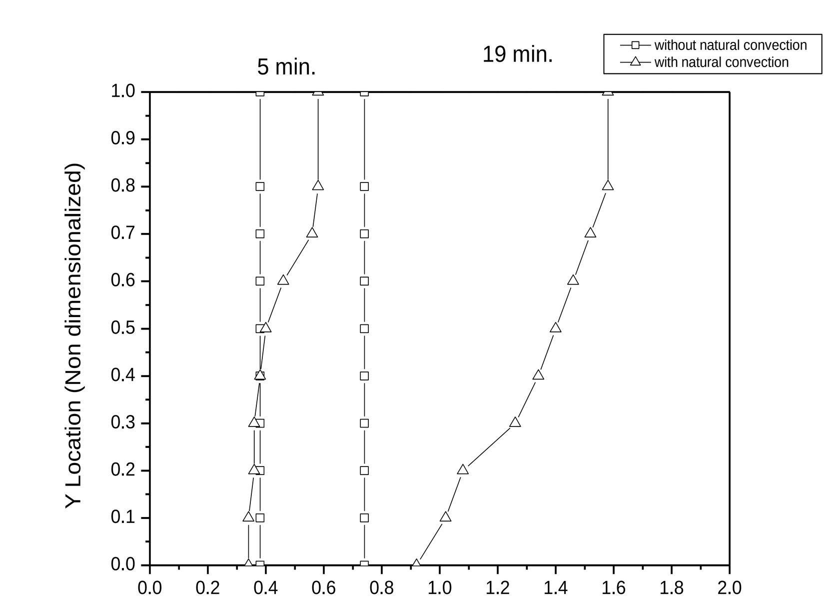

Figure 5. Comparison between predicted melt-fronts with and without natural convection

Conclusions: Natural convection with the help of user defined source terms incorporating Enthalpy-Porosity technique is modeled. An important conclusion drawn from the present study is that conduction analysis alone (neglecting natural convection) is not adequate to accurately model the phase change problems. The future studies will involve to model the actual cask geometry considering natural convection with the help of enthalpy porosity technique.

References:

[1] Code for Safety in Transport of Radioactive Materials, AERB Code No. SC/TR-1, 1986, Page 46
[2] Gau, C. and Viskanta, R., 1986, “Melting and Solidification of a Pure Metal on a Vertical Wall,”*Journal of Heat Transfer – Transactions of the ASME*, Vol. 108, pp. 174~181.

Excerpt from the Proceedings of the 2013 COMSOL Conference in Bangalore