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[1], Anu Dutta[1], V.Verma[1], I. Thangamani[1], R.K. Singh[1]

[1]Bhabha Atomic Research Centre, Mumbai, India

Abstract

Shielded transportation casks are commonly used for the transportation of radioactive waste materials/spent fuel. A typical radioactive material transportation cask consists of a rectangular shaped box with an inner cavity to store the radioactive material for transportation. In order to minimize the radiation dose to the public domain, lead sandwiched between two stainless steel liners provides the necessary shielding. The cask contains radioactive material which is a source of internal heat generation due to decay of radioactive products. Besides heat generation in the radioactive material due to decay, there is also small amount of heat generated in the lead due to gamma attenuation. The cask has to maintain its structural integrity under normal and accidental (fire) conditions. Design approval of such casks by the regulatory authority is subject to its demonstration of compliance with a thermal test (among other tests), which consists of exposure of the cask to hydrocarbon fuel/air fire on all sides with a flame temperature of about 800°C for a period of 30 minutes. During the fire test, the radiative flux from the fire is incident on the outer surface of the cask, which will cause rapid heating of the various inner elements of the cask, which may cause melting of the shielding material i.e. lead. The melting of lead can cause loss of shielding capability due to relocation of molten lead in lower region, thus creating space in the top region. The molten lead may come out in case of mechanical seal failure due to high temperature and radiation dose may leak into the public domain. Therefore, it is of utmost importance to calculate the amount of lead melted during the fire test so as to assess the loss of shielding. The confirmation of design compliance mentioned above is generally shown by carrying out detailed steady-state and transient thermal analysis of the cask which involves solving the basic transient 3-D conduction equation (ignoring natural convection) for the appropriate radiative and convective boundary conditions. However, ignoring the natural (buoyancy driven) convection because of the density gradients in the molten pool of the lead may lead to a significant error in the predictions of both the extent of melting of lead and of the pattern of melt front propagation during the transients. Not much literature is available for thermal analysis of transportation casks involving natural convection in the molten pool. This is due to the fact that numerical simulation of convective flow and heat transfer in presence of phase change is a challenging task because the heat transfer is coupled with the turbulent flow field in 3D in a global domain where the pure solid and the pure liquid phases are separated by an ever-changing interface. Because of the complex geometry of the cask, at first, a simple problem reported in

open literature has been considered for demonstrating the effect of natural convection during melting of lead. This present paper briefly describes the numerical model and the effect of neglecting natural convection phenomena for thermal analysis of transportation casks.

Keywords: Natural Convection, Melting, Transportation cask, shielding material

Reference

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Figures used in the abstract

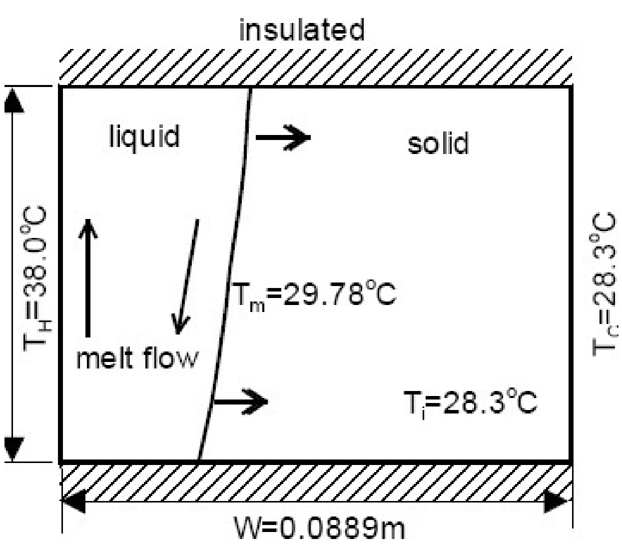

Figure 1: Simple Schematic showing the configuration of cavity considered for melting analysis

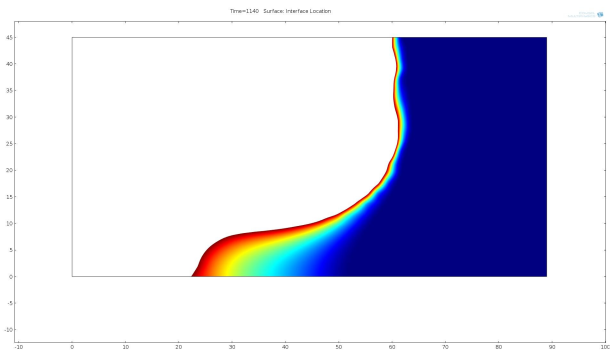

Figure 2: Interface location at the end of 19 minutes

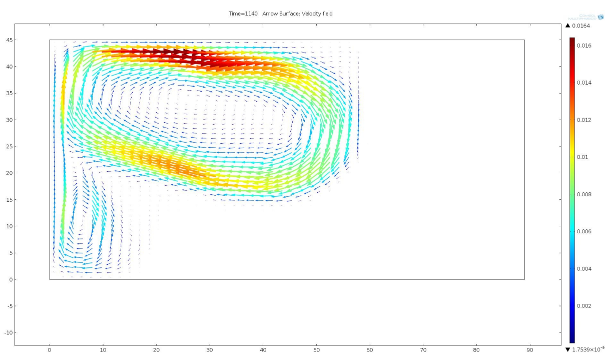

Figure 3: Velocity Vector Plot at the end of 19 minutes

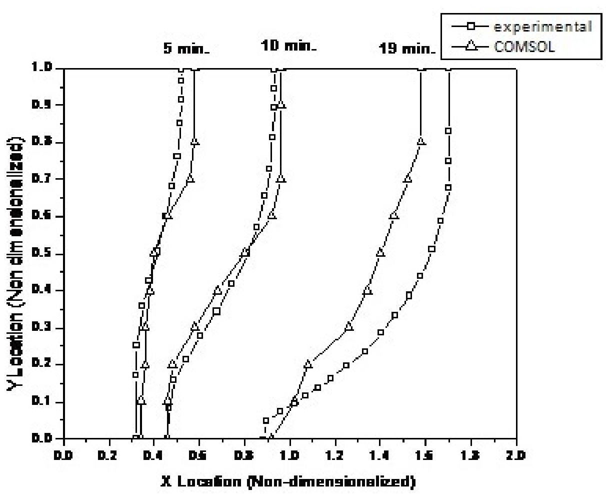

Figure 4: Comparison between experimental and predicted melt-fronts at different times