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AN EVALUATION OF MOLTEN LEAD MIXING IN SODIUM COOLANT BY DIFFUSION FOR APPLICATION TO PAHR

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In post-accident heat removal (PAHR) applications the use of a lead slab is being considered for protecting a porous bed of steel shots in ex-vessel cavity from direct impingement of molten steel or fuel upon vessel failure following a hypothetical core dissembly accident in an LMFBR. The porous bed is provided to increase coolability of the fuel debris by the sodium coolant. The objective of the present study are (1) to determine melting rates of lead slabs of various thicknesses in contact with sodium coolant and (2) to evaluate the extent of penetration and mixing rates of molten lead into sodium coolant by molecular diffusion alone.

The study of simultaneous molecular diffusion of heat and mass in a liquid-liquid system especially with large density differences such as those that exist between molten lead and sodium presents a considerable challenge in view of the following two considerations: (1) the rate of molecular mass diffusion is considerably slower than that for heat diffusion and therefore the extent of the penetration of mass diffusion at any given time is significantly smaller than that for heat diffusion, and (2) owing to large density difference between sodium and lead, the constant mixture density approximation for mass diffusion is not valid and therefore analytical solution though available for constant density approximation, is not applicable to lead-sodium

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diffusion. The enormous difference in the diffusion rates for heat and mass introduces stiffness in the system of ODEs resulting from spatial discretization of the PDEs governing these two diffusion processes. Significant difference in penetration distances of heat and mass diffusion results in a extremely poor spatial resolution for mass diffusion if the same mesh distribution is used in physical coordinates. In order to overcome this problem, a special adaptive coordinate system [denoted by η_c, see part (a) of Fig. 1] which causes a stretching of physical coordinates, is introduced for mass diffusion. For heat diffusion and phase change special coordinate systems [denoted by η in part (a) of Fig. 1] which immobilize the melt interface and deal with material inhomogeneity are introduced. The orthogonal collocation method [1] with Hermite splines as approximating functions and Gaussian quadrature points as the collocation points is used for spatial discretization. The resulting system of ODEs in time is solved by using a standard library subroutine LSODI [2]. This routine makes use of Gear's multistep backward differentiation formulas for stiff equations.

Figure 1 shows the results of these computations. Part (b) of this figure displays the temperature distribution for the case of a very thick lead slab, also shown in this figure, the analytical solution for the temperature profile, these two solutions agree extremely well with no discernable difference. Part (c) of Fig. 1 gives the position of interface as a function of time for various thicknesses of lead (denoted by symbol L) and for Stefan's number, $Se = (T_\infty - T_M)\, C_{PM}/\Delta H = 2.375$, where T_M is the melting temperature of lead, T_∞ initial temperature of sodium, C_{PM} is the specific heat of molten lead, and ΔH is the heat of fusion of lead. The solution for $L \to \infty$, agrees extremely well with the analytical solution, however, for finite thicknesses, the calculated solutions agree with analytical solutions for $L \to \infty$, only for short times at the beginning until the heat diffusion penetrates the thickness of lead. After such time, the melting rates increase progressively with decreasing thickness. Part (d) displays the results for mass concentration profiles of lead in sodium. These profiles are obtained both using constant and variable mixture density approximations (i.e. for non-zero value of $\gamma = \rho_N^{-1} - \rho_M^{-1}$, ρ_N being density of Na, and ρ_M density of molten Pb) for mass diffusion. As the figure shows, these two profiles are significantly different, clearly showing the limitations of the constant density approximation. Also shown in this part is the analytical solution for constant density approximation, this solution agrees extremely well with the calculated solution. A comparison between part (b) and (d) clearly demonstrate the enormous difference in the penetration distances of heat and mass diffusion. Even after passage of one hour from the time sodium came into contact with lead, the penetration distance of lead into sodium is less 5 mm. This clearly indicates if the diffusion is only mechanism for lead mixing, lead will stay separated from sodium. Before any significant mixing can take place, it will sink to the bottom of the porous steel bed upon melting and thus will not participate to any significant extent in removing heat by natural convection from the fuel debris lying on the top of the porous steel shot bed.

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Figure Caption

Fig. 1. Temperature, mass concentration distributions, and the melt interface position as a function of time following contact between lead slab and sodium coolant.

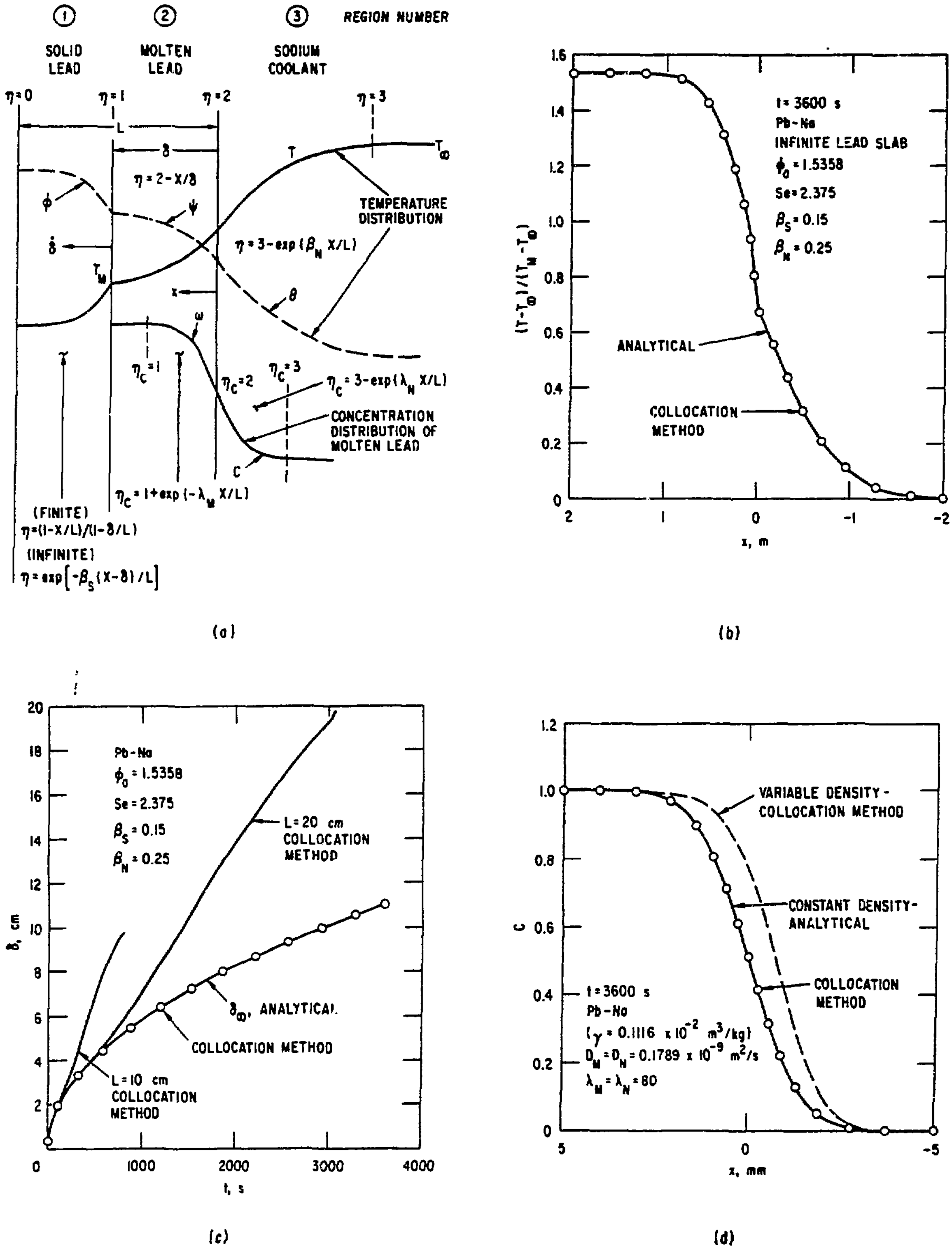

Fig. 1. Temperature, mass concentration distributions, and the melt interface position as a function of time following contact between lead slab and sodium coolant.