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A Correlation for Downward Melt Penetration into a Miscible Low-Density Substrate*

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Downward penetration of a sacrificial bed material or a concrete basemat structure by an overlying layer of core melt resulting from a hypothetical core disruptive accident has been a major issue in post accident heat removal studies. One characteristic feature of this problem is that the solid substrate, when molten, is miscible with and lighter than the core melt so that the rate of penetration is strongly dependent upon the motion of natural convection in the melt layer driven by the density difference between the core melt and the molten substrate. This fundamentally interesting and technologically important problem has been investigated by a number of researchers[1-3]. Significantly different melting rates, however, were observed in these studies. Questions concerning the occurrence of flow transition and its effect on melt penetration remain to be answered. Thus far, no melting-rate correlation applicable over the entire range of density differences envisioned in hypothetical situations has been established.

To promote our understanding of the phenomena and to strengthen the data base of melt penetration, simulation experiments were conducted using various kinds of salt solutions (KI, NaCl, $CaCl_2$, and $MgCl_2$ solutions) as the working fluid and an air-bubble-free ice slab as the solid substrate. The test chamber was a double-walled lucite cylinder with wall diameters of 0.051 m and 0.070 m, respectively, fitted at the bottom with an aluminum plate. The space

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between the two cylindrical walls was evacuated to reduce heat transfer in the radial direction. The "clear" ice slab, which was approximately 0.10 m, was grown on top of the aluminum plate inside the test chambers using a method developed previously[4]. During each run, a premixed solution conditioned to a prescribed temperature was introduced on top of the ice slab. The ice was initially at a uniform temperature of ~ 272 K. The temperature of the salt solution ranged from 293 to 330 K whereas the bulk density of the solution ranged from 1006 to 1440 kg/m^3. The depth of the solution layer was about 0.12 m. Natural convection melting of the ice initiated almost immediately upon contact with the salt solution. Time variation of the moving interface was measured by a cathetometer with 1×10^{-5} m resolution. Thermocouples with outputs recorded by a multi-channel recorder were used to determine the temperature transients of the system. The solid-liquid interface morphology and the micro-physical process near the melting front were also observed photographically.

Within the ranges of the temperature and the density ratio explored in the experiments, the downward melting rate was found to be almost independent of temperature difference between the salt solution and the ice substrate. Two distinctly different flow patterns were observed in the solution layer. One corresponds to the low-density-ratio case and the other, the high-density-ratio case. Flow transition was observed for density ratios ranging from 1.05 to 1.08. The downward melting rate was very sensitive to the density ratio, especially near the transition region. A photographic study of the roughness of the melting front also showed two distinctly different shapes of the solid-liquid interface. In the low-density-ratio case, the interface was less wavy and the average wavelength was much larger than observed in the high-density-ratio case. No transition to an upper turbulent flow regime was found in this study as observed previously by Farhadieh and Baker[1].

Under all conditions, ice melting was achieved by the release of melt streamers (i.e., the fresh water) from the crests of the wavy interface upward into the salt solution layer. Observations of the melting interface and the wavelength or the spacing between the streamers indicated that flow transition would change the micro-physical process near the ice surface. However, it would not significantly alter the overall melting rate. In Fig. 1, fifty-two sets of melting data obtained in this study are presented with the thirty-five data points reported by previous workers[1-3]. Although flow transition was observed at density ratios between 1.05 to 1.08, the data does not show a tendency of changing slope in this region. It is, therefore, adequate to develop a correlation for the melting rate by a linear regression analysis. This gives

$$\dot{m} = 0.15\ (\rho/\rho_m - 1)^{0.776}, \quad 1.006 < \rho/\rho_m < 3.3\ , \tag{1}$$

where ρ and ρ_m are the densities of the solution and the molten substrate, respectively, and $\dot{m}$ is the mass flux based on the rate of melting of the substrate. The use of the above correlation, which covers almost the entire range of density ratios envisioned in hypothetical accidents, would greatly facilitate the task of computer modeling.

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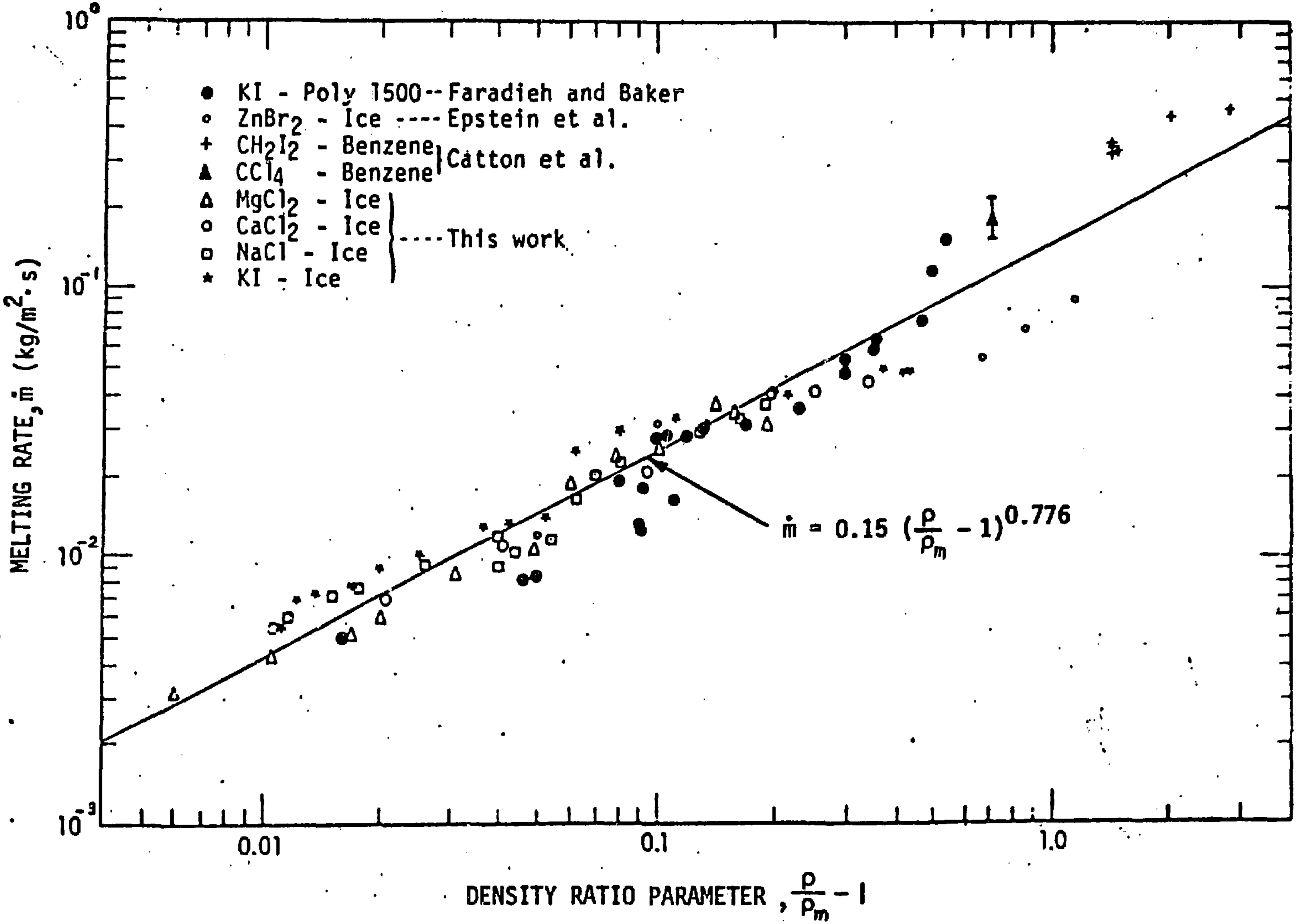

Figure 1. Correlation of the melting data for downward melt penetration into a miscible low-density substrate.

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