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Modelling of the erosion of refractories by Marangoni flows

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This study is concerned with the industrially important problem of the erosion and degradation of ceramic crucibles containing liquid metals or glasses. A model has been developed which can describe the patterns of erosion in terms of the interplay between Marangoni and buoyancy forces in the melt and the disruption of the concentration gradients of dissolved species from the containment wall. The model predicts significant erosion effects which are highly system dependent and thus the elaboration of the model and its useful application depends critically on the availability of capillarity and thermochemical data relevant to the complex systems under study.

Keywords: flux-line erosion; Marangoni flows; capillarity; Navier–Stokes equation; refractory crucibles

1. Introduction

The phenomenon often referred to as ‘flux-line erosion’ has long been recognized in the metal and glass production industries as a problem for ceramic containment vessels. This consists essentially of the scouring erosion at high temperatures of the inner walls of the refractory crucible, generally where the interface between the liquid metal and slag, or the glass and its layer of flux, meets the wall. A variety of erosion profiles has been encountered—for example, ‘waist’ formation, ‘necking’, ‘cut’ formation—these shapes depending on the temperature and in particular, the chemistry of the solid and molten phases. It is a highly destructive process, leading to the degradation of the vessel and its costly replacement.

We have developed a mathematical treatment for this process based on the model of a partly immersed solid in a reactive liquid which undergoes slow dissolution, giving rise to a concentration gradient of relevant solute species away from the wall (Tsotridis *et al.* 1992). The erosion pattern is governed by the interference and disruption of the concentration gradients by convective streaming arising from buoyancy and surface tension forces. Furthermore, the model assumes that the material of the containment vessel is homogeneous down to molecular levels, that is, effects due to microstructure, inclusions and grain boundaries are discounted. The dissolved anion or cation species from, for example, an oxide ceramic wall may adsorb on liquid phase interfaces, giving rise to localized interfacial tension gradients which actuate the Marangoni flows, the direction of flow depending on whether the solutes are positively or negatively adsorbed. The model assumes these currents can sweep away the

dissolved wall species, thus exposing or blocking fresh wall material to the dissolution process.

In addition to the above capillary driven flow mechanism, there is an interplay with a more conventional convective flow mechanism. This arises from the fact that dissolved species in the melt adjacent to the vertical wall will change the physical properties of the melt, in particular the localized melt density, thereby leading to concentration buoyancy flows. The relative strength and interactions between these basic flow types will determine the rate of wall erosion and the shape of the erosion profile.

The model has been formulated by coupling the Navier–Stokes equation with the diffusion equation. The velocity field is determined by the equations of motion and conservation of mass, whereas the concentration distribution is determined by the convective diffusion equation. These equations are mutually dependent since the surface tension is a function of concentration. The concentration distribution depends on the velocity distribution, the driving forces for the flow deriving from adsorption-induced surface tension and buoyancy forces due to density gradients.

In this study, we have developed a two-dimensional transient flow computer program which solves simultaneously the equations of motion and diffusion. This allows the delineation of the flow patterns inside the melt as well as the concentration distributions. Positive Marangoni values tend to create erosion patterns in the immediate vicinity of the free surface. The study shows that even very low values of surface tension gradients produce remarkable effects on the patterns of erosion which are similar to those observed in practice for certain system combinations.

The surface or interfacial tensions resulting from diffusive concentration gradients are, of course, highly system sensitive and, faced with a dearth of relevant capillarity and thermochemical information for complex systems, the use of the present model in a predictive sense is, at this stage, disappointingly limited. First, there is required an assessment of the validity of the present model, which is in fact being carried out currently on a simple system with few components and for which the surface tension and all requisite thermochemical information is being separately measured. Following this, and with a programme of measurement of physical and thermochemical data on complex practical systems, we believe that it will eventually be possible to predict those sensitive surface active species which must be controlled in a given system in order to minimize erosion degradation, and hence extend the life of industrial refractories.

References

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