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THE INFLUENCE OF MARANGONI INTERFACIAL FLOWS IN FLUX-LINE EROSION

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SYNOPSIS

Local erosion of solids in contact with gas/liquid or liquid/liquid interfaces is well known in many process industries. In many pyrometallurgical furnaces these erosion patterns are referred to as "slag-line" or "flux-line" erosion. In many attempts to model fluid flow in these furnaces the importance of Marangoni flows at the slag-metal interface have, to a large extent, been ignored completely. The results of modelling studies presented here have shown that these flows are of considerable significance and must be included in fluid flow simulations in order to account for the classical flux-line erosion profiles seen in many furnaces.

Key words: marangoni flow, erosion, slag-line, flux-line

1. INTRODUCTION

Local erosion of solids in contact with gas/liquid or liquid/liquid interfaces is a well known phenomenon. There exists many practical illustrations, for example in chemical engineering industries, ferrous and non-ferrous metallurgical furnaces and in the glass industry. In all these cases two or more fluid phases are in contact at interfaces and local thinning of reactor vessels or furnaces at the interface (flux-line) of the different fluids is seen frequently. The scale of flux-line erosion can vary tremendously. Figure 1 shows the erosion of

Fig. 1 Mo-crucible showing flux-line erosion profile

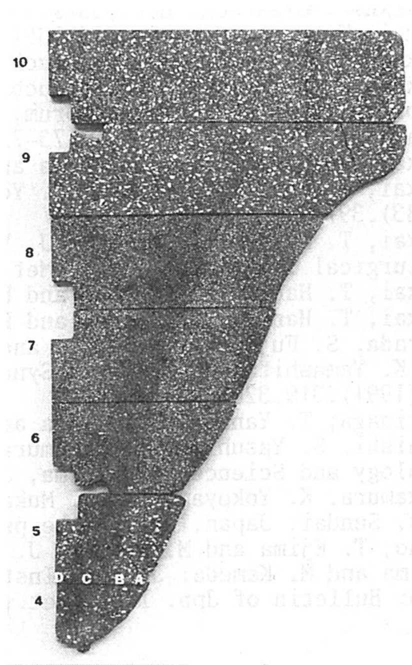

Fig. 2 Profile of refractory removed from an operating arc furnace

a molybdenum crucible (35mm diameter, 5mm wall thickness) containing a silicate slag (upper layer) and metal sulphide (lower layer) phase. This crucible had been used (once) for high temperature viscosity measurement. At this scale, the consequences of flux-line erosion are "mildly irritating" as opposed to catastrophic, although the dissolution of the molybdenum crucible will, inevitably, lead to some contamination of the silicate slag and thus, influence the obtained viscosity. In contrast to the scale seen in the crucible, Figure 2 shows the profile of a refractory lining removed from a large ferroalloy furnace. The original brick thickness was 400mm and it can be seen that at its thinnest point over 75% of the refractory had been removed. Flux-line erosion on this scale can be of a catastrophic nature and responsible for multi-million dollars worth of lost production because of the needs for relining.

Classical Marangoni flows arise from thermal or capillary gradients at the fluid surface, the direction of flow being from a locality of low to one of high surface tension. It has been suggested that these flows are the principal mechanism for producing flux-line erosion

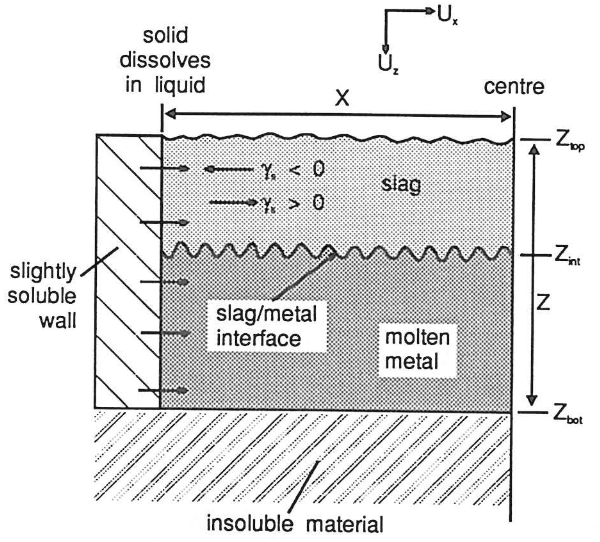

Fig. 3 Schematic representation of a pyrometallurgical furnace

[1]. If the refractory lining is soluble in the molten slag it can be expected that there is a significant difference in surface tension in the vicinity of the wall (relatively low) compared to the unadulterated slag (relatively high). The characteristic groove forming due to the existance of inflowing currents in the immediate locality of the liquid / liquid interface. The importance of Marangoni flows has been demonstrated on the experimental scale by Mukai [2,3,4] and at the 3rd International Slag Conference in Glasgow [3] a film was presented which supported this hypothesis, showing clearly the dissolution of a quartz crucible in a $PbO-SiO_2$ slag was associated with violent motion at the slag - metal (Pb) interface resulting in pronounced localisation of the erosion (i.e. flux-line erosion profile). Despite these practical observations, Marangoni flows have been ignored in many attempts to model mathematically heat and fluid flows in furnaces. The purpose of this study, which should be regarded as no more than a feasibility study, is to provide a better understanding of the relative importance of interfacial tension flows (Marangoni) and buoyancy convective flows in determining the erosion patterns at the walls of a "typical" pyrometallurgical furnace.

2. MATHEMATICAL MODEL

The physical concept which has been modelled consists of a two dimensional rectangular furnace, as indicated in Figure 3. Thermal energy is supplied through the slag to the molten metal. Initially the liquid in the furnace is stationary and as the process develops the slightly soluble furnace refractory wall starts to dissolve. In principal there are two main driving forces responsible for the convective motion of the liquid; a) buoyancy convection and b) the interfacial tension (Marangoni) flow arising at the slag / metal interface.

A more detailed description of the basis of the present modelling has been published elsewhere [5]. The model was developed by the Petten Establishment of the Commission of the European Communities and had been used previously to demonstrate the dominance of Marangoni convective flow in small scale phenomena involving high energy input which leads to localised melting, e.g. formation and shape determination of weld pools [6]. The possibilities of extending these modelling capabilities to investigate similar phenomena at much larger scales (i.e. industrial arc furnaces) has been explored in this joint research contract between Petten and Billiton Research B.V. The model was developed on the assumption that the two sorts of flow mentioned previously are responsible for any resultant erosion profiles and that any chemical agitation effects were neglected. By considering the Navier-Stokes equations coupled with the energy and diffusion equations the relative contributions of interfacial and buoyancy flows to the overall rate and shape of the erosion profile can be studied.

2.1 Flow Hydrodynamics

For the treatment of the flow hydrodynamics the appropriate governing equations, in vector form, are summarised as:

Equation of Continuity

$$(\nabla.\bar{v})=0 \qquad (1)$$

The Momentum Equations

$$\rho\frac{d\bar{v}}{dt}+\rho(\bar{v}.\nabla)\bar{v}=\nabla P+\mu\nabla^2\bar{v}-\rho\beta g(T-T_o) \qquad (2)$$

Equation of Energy

$$\frac{dT}{dt}+(\bar{v}.\rho)T=\frac{k}{\rho C_p}\nabla^2T \qquad (3)$$

Diffusion Equation

$$\frac{dc}{dt}+(\bar{v}.\nabla)c=D\nabla^2c \qquad (4)$$

Where ρ is density, P is the pressure, $\bar{v}$ is the velocity vector, T is the temperature, k is the thermal conductivity, C_p is heat capacity at constant pressure, β is the coefficient of expansion, c the distribution of the diffused species and D is the diffusion coefficient. The last term on the right hand side of equation (2) denotes the buoyancy force, which is caused by the density gradients within the system.

Using this model it has been attempted to predict erosion rates and depths from interfacial thermodynamic data. However, the paucity of such information has meant that results will be presented which consider the relative importance of each of the two principal types of flow.

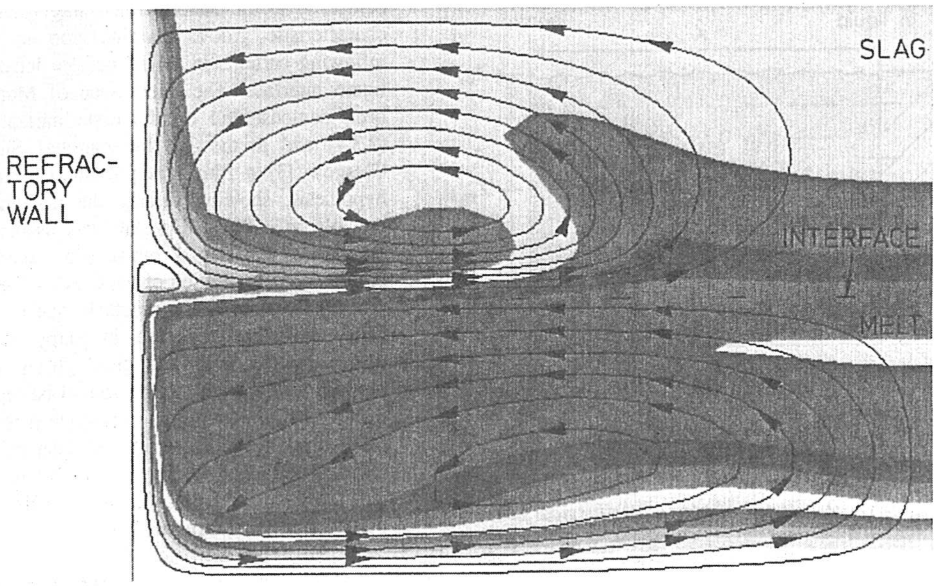

Fig. 4 Temperature/density distribution and flow lines

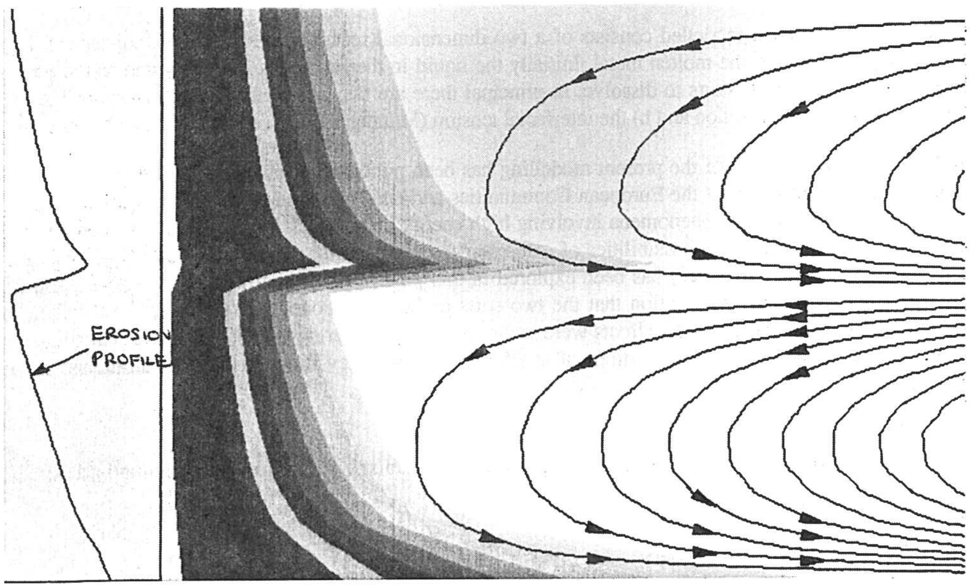

Fig. 5 Temperature/density distribution and flow lines

2.2 Results of modelling

In the absence of interfacial tension data the problem reduces to one of pure buoyancy in a confined system. Figure 4 depicts the temperature distribution and flow patterns inside the molten silicate slag and molten ferro-alloy. As expected the direction of motion (anticlockwise) is the same in both metal and slag layers. This type of flow would have a profound effect upon the resulting erosion profile. Figure 5 shows that relatively slow dissolution rates are expected throughout the wall, with the exception of a deep groove in the vicinity of the top surface of the slag and the molten metal. As this pattern is not encountered frequently in practice it is of interest to examine the behaviour of systems where the flow field is controlled by Marangoni interfacial flows and where buoyancy flows play a secondary role.

Classical Marangoni flow arises from thermal or chemical capillary gradients at the interface of fluids. Many furnaces are lined with a magnesia based refractory and it is well known that for slags from the system Fe_xO-MgO-SiO_2 (i.e. typical non ferrous metallurgical slags) an increase in MgO content results to increased surface tension values [7]. The surface tension of the slag adjacent to the wall may be significantly higher than that of the bulk slag (i.e. centre of furnace). This can give rise to classical Marangoni flows with currents moving from the centre of the furnace (low surface tension) towards the wall (high surface tension). The flow patterns and erosion profile predicted under this scenario is depicted in Figure 6. It can be seen that the flow pattern in the slag has been completely reversed compared to the previous situation. The magnitude of surface tension flows (determined by the exact nature of the surface tension data) has a profound effect on the shape of the local erosion pattern. However, in all cases the maximum erosion depth was developed at the interface between slag and molten metal.

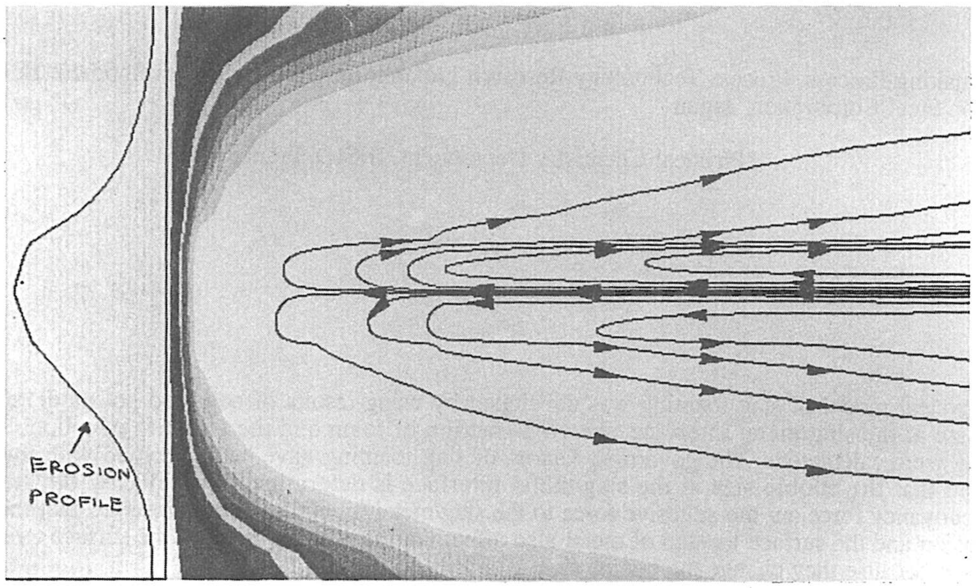

Fig. 6 Temperature/density distribution and flow lines

3. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The purpose of this feasibility study was to assess whether buoyancy or Marangoni flows were primarily responsible for the observed flux-line erosion patterns seen in many pyrometallurgical furnaces. Preliminary calculations have indicated that it is likely that Marangoni flows are significantly more important in this respect compared to conventional buoyancy flows.

Detailed knowledge of the interfacial tension between many specific slag and metal phases is not available (although it is encouraging that some research groups are attempting to redress this situation). Until such detailed (verified) data are available a parametric study of a range of values is necessary. This should provide a range of different erosion profiles and may help optimisation.

Perhaps more importantly, a better simulation of both heat and fluid flow in furnaces is required. Heat is often supplied via electrodes, introducing a further complication to the modelling procedure. The energy transfer from arc to bath and interaction between the arc and molten material require more accurate description. If this can be accommodated, flows driven by electromagnetic forces in addition to those caused by buoyancy and Marangoni forces. If this model can be developed successfully it will give the opportunity to optimise various key process parameters, such as power input, electrode position, bath depth, etc. in such a way that the flow and temperature fields can be created which result in minimum erosion rates and profiles, thereby extending the length of furnace campaigns by extending the lifetimes of refractory linings.

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