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Modelling of metal flow and oxidation during furnace emptying using smoothed particle hydrodynamics

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ABSTRACT

In this paper the grid-free smoothed particle hydrodynamics (SPH) method has been used to predict the amount of oxide generated during a furnace tipping process, where the metal is poured into a launder. The free surface modelling capability of SPH and 3D visualisation of the fluid flow leads to a better understanding of the flow characteristics during the furnace tipping phase of the operation. Experimental mass flow rate measurements are used to validate the SPH simulation predictions. The relative amount of oxide generated during the furnace tipping phase and the phase of metal discharge from the ingot wheel are then predicted. Results indicate that the furnace tipping process can lead to as much as two thirds of the total oxide generated during melt transfer from the furnace to the ingot. This suggests that optimisation of furnace design and the tipping process could lead to significant improvements in the quality of the downstream products, such as ingot castings.

1. Introduction

In cast houses, liquid metal is transferred from various crucibles and furnaces and finally to a casting process. Depending on the operation these transfers may involve pouring a crucible into a furnace, emptying a furnace to a launder trough or flow from a launder to a casting process. Oxidation can occur to varying degrees during these operations, the oxide layer created on top of the molten aluminium breaks up, exposing fresh melt to air leading to further oxide formation and a mixture of oxide and un-oxidised melt known as dross. Transfer operations are major contributors to total melt loss, a significant economic and environmental issue. The creation of oxide in the melt also reduces the finished quality of the final downstream products by introducing inclusions that then must be removed. Thus, the ability to model and predict the amount of oxidation and dross formation for a given configuration is greatly desired to aid in improving these operations. Many different configurations are used in industry for these operations. For example, crucibles can be emptied using siphons or simple tilted pouring metal into the furnace. In the case of furnace to launder transfer, this can be via a tap hole in a stationary furnace or using a tilting furnace in order to have no cascade of metal out of the furnace. The nature of metal flow will determine the amount of fragmentation and break-up of the oxide layer. This in turn depends on such parameters as the tilt rate of the furnace or crucible, the falling height and the container spout design. Therefore it is important to understand the flow characteristics of a furnace tipping operation and relate these to the formation of oxide.

Solnordal et al. (2003) performed computational fluid dynamics (CFD) simulations of the flow and reactions in a flash furnace smelter. This work evaluated the gas flow in the furnace using a finite volume method and the associ-

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ated flow of solid metal feed by Lagrangian particle tracking. Khoei et al. (2003) used a finite element code to predict the temperature distribution in a rotary furnace during the aluminium recycling process. De et al. (2004) developed an analytical solution to predict the early stage of oxide formation in molten aluminium–magnesium alloys in a reverberatory furnace. Yang et al. (2004) numerically modelled the entrainment of oxide film defects during the filling of aluminium alloy castings. They used a volume of fluid (VOF) approach to model the free surface flow behaviour of the metal. Zhou et al. (2006) modelled the melting behaviour of aluminium scrap in a rotary furnace using a finite difference method. A population balance model was used to define the scrap with different properties such as size and shape. Recently Dispinar and Campbell (2007) investigated the effect of casting conditions such as the use of diffusers and casting techniques to reduce turbulence and fragmentation in a holding furnace experimentally on re-melt aluminium metal quality.

The studies reported here were undertaken as part of a project to develop a low oxide wheel design for ingot casting. This work involved the development of a series of wheel designs through trial simulations and experiments over a period of four years. Cleary et al. (2003) presents the early work carried out in this project. Prakash et al. (2007) provides more comprehensive details and a summary of the wheel design optimisation process. The experimental configuration used had a 500 kg crucible furnace emptying metal from a small drop (420 mm) into a launder feeding the casting wheel (Fig. 1). The relative contribution to dross levels in the ingot from the cascade from the furnace and the ingot mould filling needed

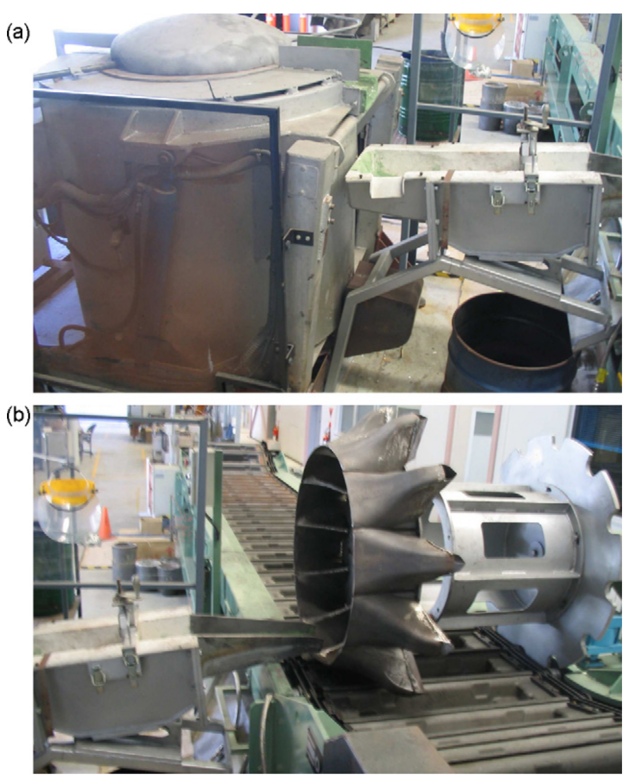

Fig. 1 – Experimental set-up to test ingot wheel designs (a) furnace containing molten aluminium, and (b) the ingot wheel and launder.

to be ascertained for that project. This would be very difficult to do experimentally and thus numerical modelling was used.

Currently, measurement of the amount of oxide generated during such operations is difficult. Available analysis methods include dissolution of the metal and weighing the remaining oxide as presented in Simensen et al. (1984). This type of analysis is only done on sample sizes less than 5 g or re-melting of the sample and passing a melt sample through a fine filter to collect and quantify the amount of oxide and other solids. Sampling issues arise due to the potential for oxide to settle or float[1] and the question of introducing further oxide during the re-melting process. Simulation was therefore used to predict the amount of oxide generated during furnace tipping. The grid-free smoothed particle hydrodynamics (SPH) method first developed by Gingold and Monaghan (1977) was chosen for the simulations due to its inherent advantages in:

(a) tracking free surface flows with fragmentation and break-up more accurately than is possible with traditional grid based methods;
(b) the ability to easily predict oxide formation and to track the advection of this oxide through subsequent flow, and;
(c) easy handling of the complicated motions of three dimensional objects involved in the furnace tipping operation. Previous work in simulating the wheel system for aluminium re-melt ingot casting presented in Prakash et al. (2007) is an example demonstrating this advantage of the SPH method.

Simulated and experimentally measured mass flow rates are compared to ensure that the simulation predictions are representative of the real flow. The simulation results are then used to predict the relative amount of oxide generated during the furnace tipping and the re-melt ingot casting operations. This estimate is useful in understanding the extent to which oxide is generated during such melt transfer operations.

2. The SPH method for fluid flow

The SPH method can be used for modelling coupled heat and mass flows. It is a particle based method and does not use conventional fixed grids or meshes to track the fluid and calculate the fluid velocities and therefore does not suffer from the inherent limitations of these methods for modelling moving bodies, complex fluid free surfaces and oxide formation. In SPH, material is represented as particles that move around in response to the fluid or solid stresses produced by the interaction with other particles. SPH is particularly well suited to momentum dominated flows, flows involving complex free surface behaviour and flows with complex physics such as solidification or flow through industrial porous media. In Cleary et al. (2002) SPH is used to model high pressure die casting (HPDC) and gravity die casting (GDC) processes. In this

[1] Oxide species in dross generally include amorphous oxides of aluminium and magnesium in magnesium containing alloys whose density is greater than the melt. However, considerable porosity is trapped in the dross reducing the bulk density to less than the melt allowing it to float.