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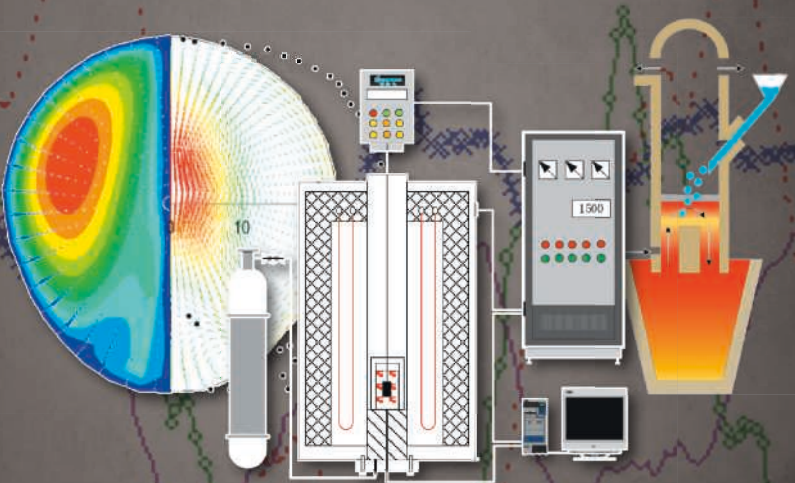

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Modelling of Metal Loss in Ferromanganese Furnace Tapping Operations

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Abstract During the pyrometallurgical production of industrial metals such as ferromanganese in electric smelting furnaces, molten slag and alloy phases are removed from the unit by tapping at regular intervals. Intermixing of the two phases may occur during the latter stages of the tapping process, and if not carefully managed, it can result in significant alloy being lost to the waste slag by entrainment. This paper presents the results of a computational fluid dynamics study of the multiphase free surface fluid flow in tapping ladles, with a specific focus on the impact of various design and operational parameters on alloy losses to the slag.

Keywords Modelling · Pyrometallurgy · Ferromanganese

Introduction

Manganese is an important commodity with a wide range of applications in the production of clean steels, speciality alloys, and various battery technologies. It is produced commercially in the form of ferromanganese (FeMn) by chemical reaction of ores containing manganese and iron oxides with carbonaceous reductants. This is performed at temperatures in excess of 1400 °C, using blast furnaces or electric smelters [8]. At such temperatures the raw materials and products are in the molten state, and form immiscible metallic (alloy) and oxide-rich (slag) phases.

Smelting furnaces are typically emptied of molten products by a process called *batch tapping*. This involves periodically opening a channel (the tap-hole) in a dedi-

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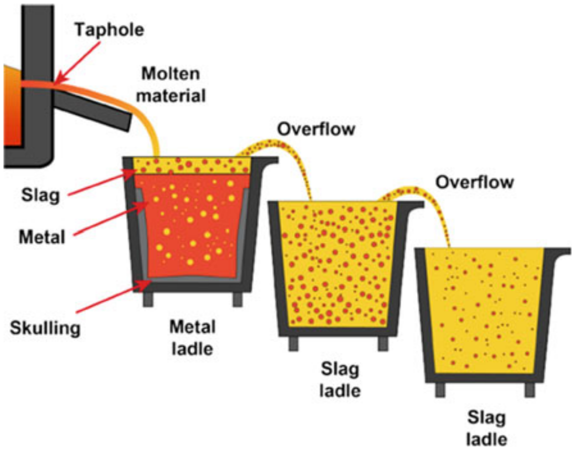

Fig. 1 Ferromanganese tapping process. (Color figure online)

cated section of the vessel sidewall, allowing the contents to drain out, and resealing it [11]. In FeMn processes, slag and alloy are tapped simultaneously through the same tap-hole. After exiting the tap-hole channel, the stream of molten material is directed along open launders and empties into a cascade of storage ladles. During this process, energy is imparted to the stream by turbulence in the flow and impact with solid and liquid surfaces. This causes break-up and intermixing of the slag–alloy phase interface, which is counteracted by settling and separation under gravity over time due to density differences between the slag and alloy phases. The tapping system is shown schematically in Fig. 1.

If too much mixing between the slag and alloy phases occurs, this may result in excessive quantities of valuable alloy product being discarded with the waste slag [1]. The presence of small alloy droplets in discarded slag may also pose environmental risks and can incur significant extra cost if treated downstream by crushing and separation. It is therefore preferable to achieve the best possible separation of the phases during the tapping operation, before they solidify.

Due to the hazardous nature of high-temperature processes, it is often difficult or impossible to obtain sufficient experimental data to perform effective design and optimisation. In this environment, computational modelling in the form of numerical experimentation and virtual prototyping is a particularly useful guidance tool to gain a deeper understanding of the problem, and assess the value of different changes to the design and operation of the tapping system.

A variety of computational fluid dynamics (CFD) methods are available for the study of dispersed multiphase flows such as those encountered in tapping systems. Perhaps the most commonly used are unresolved methods such as Eulerian models; in such methods, the phases are allowed to intermix, and small droplets with sizes below the mesh resolution are treated simply as part of the continuum. An alternative approach is to resolve small droplets directly via combined Eulerian–Lagrangian models; here, the bulk phases are treated as immiscible fluids, and small droplets are modelled as discrete particles. It is important to note that both of these methods depend on the accurate specification of a number of empirical closure terms which determine how mass, momentum, and energy transfer between the dispersed and continuum phases.

Previous modelling work on ferroalloy tapping systems has focused mainly on fluid flow and associated effects in tap-holes [4, 6, 10], although some pioneering work was conducted on ladle flow modelling using particle tracking methods in [3].

The present paper documents the development and application of a high-resolution multiphase flow model capable of predicting overflow and entrainment effects in ladle flows. Heat transfer is quite naturally expected to play a large role in furnace tapping systems, especially with the formation of solid crusts and skulls as the slag and alloy cool to their freezing points. However due to many additional uncertainties in the parameters required to include heat transfer coupling, the decision was taken to focus on fluid flow effects only in the present work. Once a deeper understanding of this aspect of the problem has been gained, additional physics such as heat transfer and phase change will be integrated into the model at a later date.

Model Description

In order to study the cascade tapping problem, a multiphase CFD model was developed using the OpenFOAM® open-source computational mechanics platform [9]. The `multiphaseInterFoam` solver included in standard distributions of OpenFOAM® was modified with interfacial tension force smoothing techniques adapted from [2], to improve accuracy and performance of flow predictions for problems with high surface tension and a large degree of interface break-up. The resulting solver implements a segregated finite-volume solution scheme on arbitrary unstructured meshes and uses the volume-of-fluids formulation to track the phase interfaces.

Accuracy of the computational method relative to fundamental physical and empirical correlations has been presented previously in tapping system flow problems with similar materials [7, 10]; however, a more detailed experimental validation of the multiphase ladle flow model is currently underway and will be published in a forthcoming paper.

For each case studied, multiple versions of the model were simulated at progressively finer mesh resolutions. Phase interface surfaces from the previous step were then used to define mesh refinement regions for the next. This enabled relatively high resolutions of the order 5 mm to be reached in the regions of interest while avoiding the computational overhead of dynamic mesh refinement. The final high-resolution models typically contained between 1.8 and 2.5 million volume elements.

Alloy and slag flowrates at the ladle outlet boundary were monitored as functions of time over the duration of each simulation and used to estimate the mass fraction of alloy under different conditions. In order to estimate the dispersion of the alloy phase in the form of suspended droplets in the slag layer, the simulation results were postprocessed by filtering the volume elements in the mesh to a threshold determined by the alloy phase fraction field. A connectivity analysis was then performed on the remaining set of elements, with all elements forming part of a connected component assumed to represent a single droplet. Each droplet's diameter was then estimated by determining the quantity of alloy present in the connected component and relating it to a sphere of equivalent volume. Using all the droplets observed for a particular case, size distribution functions and average droplet diameters could be calculated. Droplet sizes are a useful proxy for the mixing energy imparted during the impact of the tapping stream and also give some indication of how long any subsequent settling and separation processes may take to complete.

Results and Discussion

Application of the model to the FeMn ladle flow problem was conducted, consisting of sensitivity studies and responses to operational variables relative to a base case parameter set.

Base Case Results

The geometry used for the full-scale ladle model is shown in Fig. 2. It consists of an open-topped vessel with an inflow stream and a gravity-driven outflow weir. The walls of the vessel are specified as no-slip boundaries, while the upper surface and ladle outlet are assumed to be open to atmosphere. The position, shape, and angle (from horizontal) of the inlet stream was determined using reduced-order models of the furnace tap-hole [7] and additional CFD simulations of the tapping runner channel. The complete set of parameters used for the model is shown in Table 1.

Simulations were run for 20 s, with average values taken using the final 10 s after the initial conditions had decayed. Visualizations of the slag isosurface at the end of the simulations are shown in Fig. 3.

It is interesting to see that the impact of the tapping stream on the slag–alloy interface is much more severe and turbulent than the flow behaviour at the surface of the slag; a ladle flow may therefore appear more quiescent than it actually is when observed visually. The impact of the tapping stream causes considerable mixing of the phases and a strong upwelling plume of mixed alloy and slag in the immediate vicinity of the ladle outlet. This arrangement, with the tapping stream in line with the ladle overflow, would therefore expected to exacerbate alloy losses by entrainment.

The evolution of the alloy mass fraction at the ladle outlet as well as the average diameter of the suspended droplets in the slag layer are shown in Fig. 4.

Significant variability is observed in both parameters even over the relatively short time scales modelled here. This indicates that ladle flows are strongly dynamic

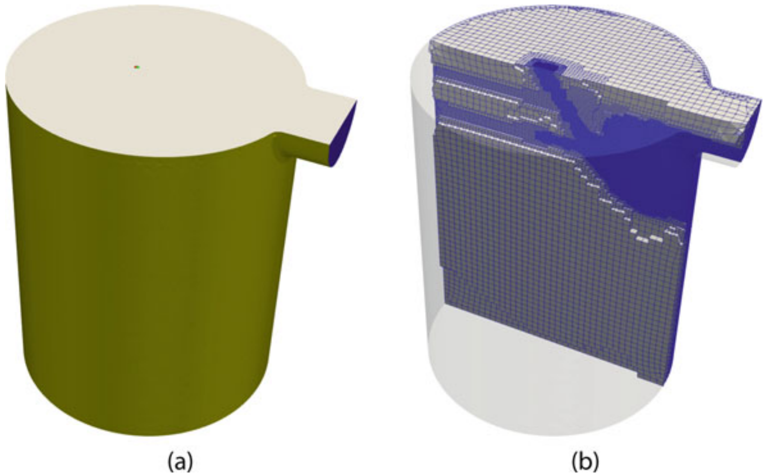

Fig. 2 **a** Ladle geometry, and **b** example computational mesh showing local refinements. (Color figure online)

Table 1 Base case ladle model parameters

Parameters	Values	Parameters	Values
Ladle height H_L	2.2 m	Ladle diameter D_L	2 m
Ladle offset y_i	0 m	Ladle angle α	0°
Outlet diameter d_o	0.6 m	Interfacial tension γ	0.5 N/m
Slag density ρ_s	3000 kg/m^3	Slag viscosity μ_s	0.1 Pa s
Alloy density ρ_m	6100 kg/m^3	Alloy viscosity μ_m	0.005 Pa s
Inlet slag flowrate $\dot{m}_s$	10 kg/s	Inlet alloy flowrate $\dot{m}_m$	10 kg/s
Inlet stream diameter d_i	0.0371 m	Inlet stream position x_i	−0.146 m
Inlet stream angle α_i	49°	Slag layer thickness h_s	0.3 m

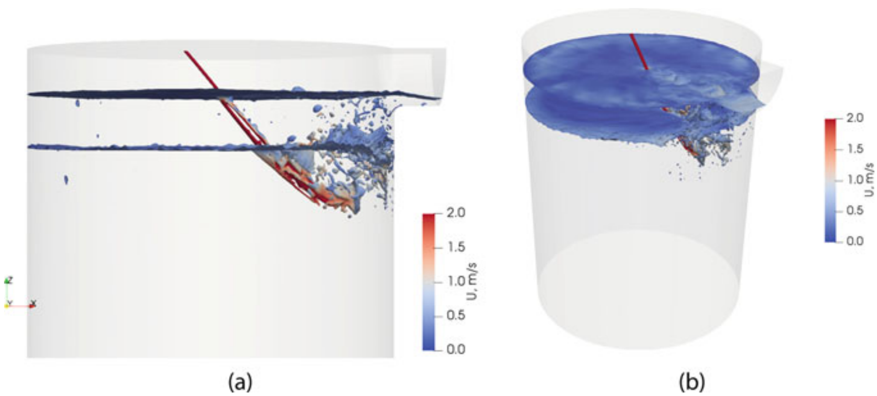

Fig. 3 Slag isosurface at t = 20 s, **a** side view, **b** isometric view. (Color figure online)

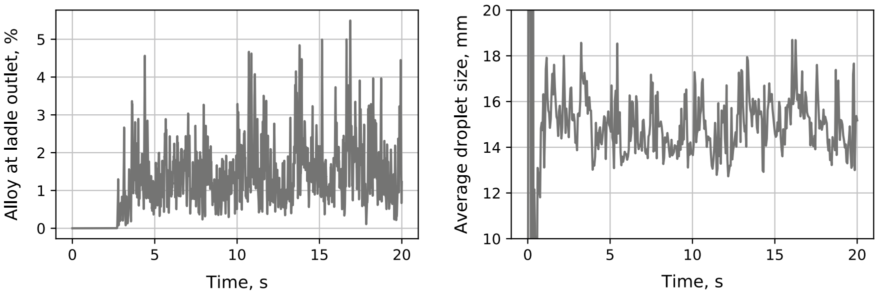

Fig. 4 Time series of outlet alloy fraction and average alloy droplet diameter, base case

phenomena, with the transient behaviour predominantly related to the impact and break-up of the incoming tapping stream as it contacts the alloy–slag interface.

Sensitivity to Fluid Properties

The model's sensitivity to the properties of the materials being tapped was investigated by varying each property up and down by a factor of 25% relative to the base case while keeping the rest of the model parameters fixed and examining the effect on the alloy fraction at the ladle outlet as well as the average diameter of the suspended droplets. The parameter values used for the simulations are shown in Table 2.

From the results shown in Fig. 5, it can be seen that slag density has a disproportionately large effect on the behaviour of the model. Increased density significantly increases losses to the ladle overflow and vice versa. Similarly, increased density also results in larger alloy droplets in the slag phase. By contrast, the slag viscosity and interfacial tension appear to have relatively limited impact. This suggests that the larger scale features of the flow and interface break-up in FeMn tapping ladles are dominated by the momentum of the flow, as opposed to much slower settling and coalescence phenomena which would be expected to be strongly affected by viscosity (settling velocity) and interfacial tension (droplet shape, capillary drainage).

Quantification of actual expected ranges for the fluid phase properties in a ferromanganese operation is difficult due to the extreme conditions under which the process operates, but certain broad statements can be made. Properties are functions of both their chemical composition and temperature; since product compositions

Table 2 Changes to base case parameters for sensitivity study

Parameters	Values (−25%)	Values (+25%)
Slag density ρ_s	2250 kg/m^3	3750 kg/m^3
Slag viscosity μ_s	0.075 Pa s	0.125 Pa s
Interfacial tension γ	0.375 N/m	0.625 N/m

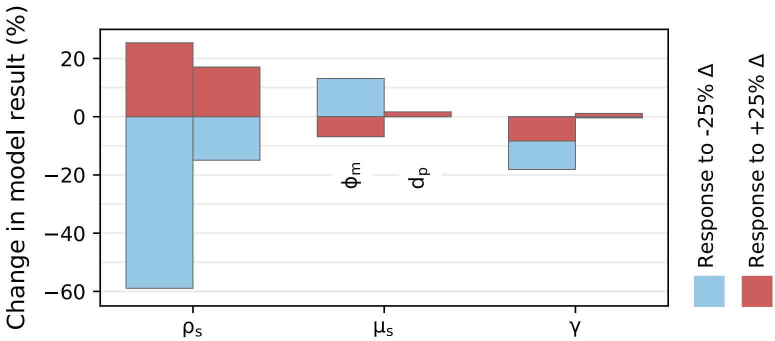

Fig. 5 Sensitivity of model to material properties (in each group the left column indicates relative change in alloy fraction ϕ_m in outlet stream, right column relative change in average droplet diameter d_p). (Color figure online)

are typically controlled tightly on any given furnace plant, the predominant effect is that of temperature of the tapping stream. The density range is proportional to the coefficient of expansion in the liquid state, which is usually small (of the order of 10^{-5}/K). Viscosities generally obey Arrhenius or similar dependencies on temperature and may therefore vary more extensively particularly near to the freezing point of the material. Interfacial tension is more strongly affected by the presence of surface-active chemical components such as oxygen and sulphur than temperature. The publications of Mills and coworkers are recommended for further reading [5].

Effect of Operational Parameters

In order to assess the impact of operational changes to the ladle positioning and fill levels, a series of simulation sets was executed in which only the parameter of interest was varied relative to the base case.

In the first set the ladle was rotated relative to the tapping stream, so that the outlet was positioned at a different point on the ladle circumference. Rotations between 0°and 90°were considered. The results are given in Figs. 6a and 7 and demonstrate a consistent decrease in the alloy lost to the overflow as the ladle is rotated. The largest changes occur at small angles, in agreement with the results obtained in [3] using different modelling methods. This is consistent with the observation that the inlet stream causes a plume of mixed alloy and slag against the ladle sidewall—positioning the outlet further away from this plume therefore reduces entrainment losses. The effect on the size of the dispersed alloy droplets in the slag layer is statistically negligible, which is not unexpected given that rotating the ladle angle does not appreciably affect the geometry of the mixing zone.

In the second simulation set, the ladle was offset (moved sideways, in the y-direction) relative to the tapping stream. Offsets between 0 60 cm were considered.

(a) Angle 90° (b) Offset 60 cm (c) Slag depth 10 cm

Fig. 6 Slag isosurfaces at $t = 20$ s for selected cases (velocity scale per Fig. 3). (Color figure online)

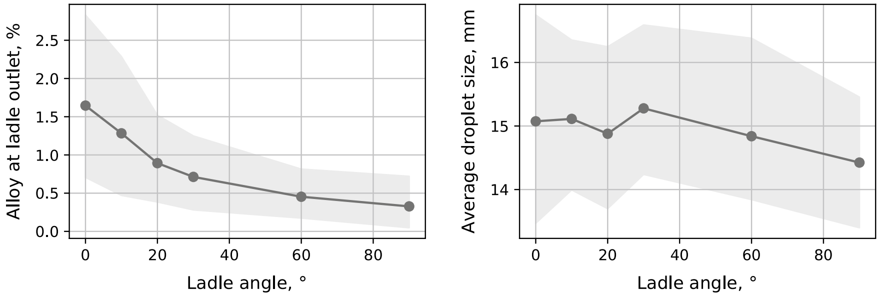

Fig. 7 Effect of ladle rotation angle relative to inlet stream (grey bands show 90% interval)

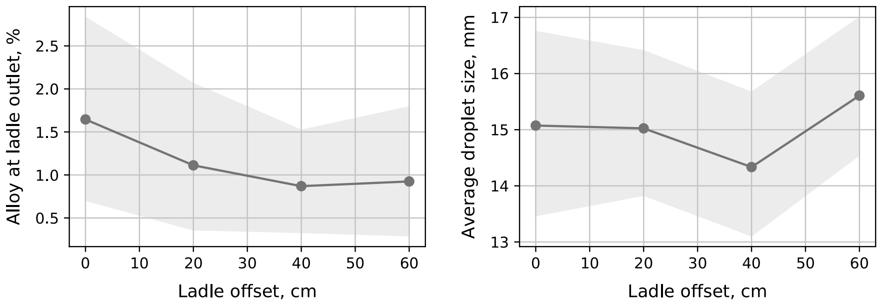

Fig. 8 Effect of ladle lateral offset relative to inlet stream (grey bands show 90% interval)

Figures 6b and 8 show the results, and again, the effect of moving the mixing plume away from the ladle outlet is seen to reduce alloy losses. However, this is only true up to a point, and when the ladle is offset too far, the tapping stream starts to impact much closer to the ladle sidewall. This generates more interfacial turbulence and mixing, as can be seen in the slight increase in alloy losses and the sharp increase in droplet sizes observed in 60 cm simulation.

In the final simulation set, the thickness of the slag layer in the ladle was altered between 10 and 50 cm. Results are shown in Figs. 6c and 9, and show a dramatic impact on the alloy carry-over losses as the slag thickness decreases past 20 cm (note

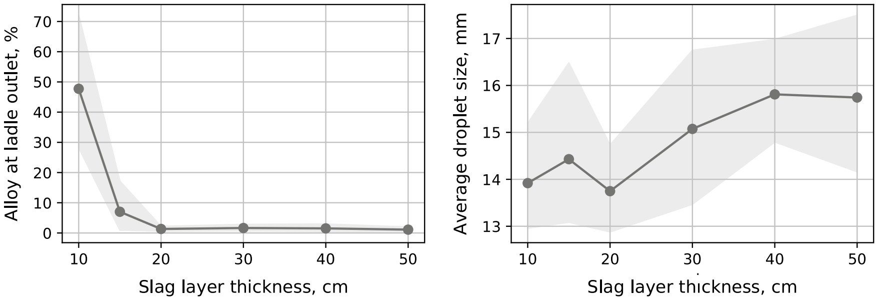

Fig. 9 Effect of slag layer thickness (grey bands show 90% interval)

the difference in scale compared to the previous two figures). This is due to a much larger and more alloy-dense portion of the mixing plume being exposed to the ladle overflow at shallower slag depths. The average droplet sizes also decrease slightly at lower slag depths—this seems somewhat counter-intuitive at first, but is most likely related to the reduced settling times for alloy droplets falling through the slag layer, which allows less time for smaller droplets to coalesce.

Conclusions

A high-resolution CFD model was successfully developed and used to study multiphase flows in ferromanganese furnace tapping ladles. The model showed that ladle flows are highly dynamic and that the momentum from the inlet tapping stream can cause significant large-scale mixing and flow structures at the alloy–slag interface.

The model was found to be most sensitive to the density of the tapped materials, with viscosity and interfacial tension playing a secondary role. The effect of the slag layer depth on alloy losses to the ladle outlet was found to be strong and highly nonlinear, which is in line with current practices at many furnace plants which use this as a measure of when to stop a tap. It was also seen that small improvements in alloy losses could be achieved by altering the position and layout of the ladle cascade, although the practicalities of making such changes on working plants would need careful consideration.

A great deal of work still remains to be done on this topic. In particular, the use of more sophisticated multiphase flow methods which can account for the presence of very small (<5 mm) alloy droplets dispersed in the slag is suggested, since the behaviour of such small droplets cannot be accurately captured in the current model. In addition, the effect of ladle skulling and freeze linings which can appreciably affect the flow geometry should also be investigated; this will require full coupling of heat transfer and phase change to the CFD model. The monitoring of entrainment of the gas phase into the tapping ladle, particularly where there is contact between molten alloy and air, would be interesting to explore in the context of re-oxidation losses. Finally, more experimental and problem-specific validation data is needed in order to assess the true accuracy and value of such models if they are to be used in virtual prototyping and digital twin applications in future.

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