Essential Readings in Light Metals: Cast Shop for Aluminum Production.
Edited by John F. Grandfield and Dmitry G. Eskin.

SETTLING OF INCLUSIONS IN HOLDING FURNACES : MODELING AND EXPERIMENTAL RESULTS

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ABSTRACT

Description of settling phenomena usually refers to falling particles in a liquid, following Stokes law. But the thermal convection always takes place in holding furnaces due to temperature heterogeneity, and the behaviour of the inclusions can be dramatically influenced by the liquid metal motion. A numerical model based on turbulent fluid flow calculations in an holding furnace and on trajectories calculations of a family of inclusions has been developed. Results are compared with experiments on a lab. scale and on an industrial scale furnace. An analysis of the governing parameters will be presented.

INTRODUCTION

Nowadays, in any discussion of clean metal, and hence of removal of inclusions, the technique that normally comes first to mind is fluxing in degassing ladles [1] followed by filtration [2] of the liquid metal at the casting stage. As regards filtration in particular, increasingly sophisticated techniques are being developed which raise operating costs substantially, even though their benefits have not in fact been clearly established [3]. Quite a few operators continue to cling to the myth of the absolute filter, able to yield a perfectly stable and controlled product, whatever the standard of cleanliness of the input metal. Clearly, however, quality leaving the treatment ladle depends on quality entering the ladle [4], generally in direct ratio, and filters cannot resolve problems or deficiencies affecting upstream operations, e.g. melting or holding.

This being so, when considering ways of improving control of final product quality, it seems essential to take a fresh look at a longer-established technique in everyday use in the casthouse, but not previously investigated in depth. This is the practice of allowing the metal to stand in the holding furnace prior to casting so that non-metallic inclusions, which are generally heavier than the liquid aluminium, can settle out in the furnace. This very rough and ready method, while involving no great capital cost, can nonetheless drastically limit productivity and therefore needs to be optimised.

To date, however, failing any reliable method of determining concentrations of inclusions and in the absence of any detailed under standing of the mechanism of settling, holding times, if any, can vary very considerably from one casthouse to another. A further factor is that furnace technology and design vary even more widely from one casthouse or producer to another, some making systematic use of tilting furnaces, others employing bottom-tapped stationary furnaces, some deliberately limiting the depth of the melt - in the belief that this will speed-up settling - while others use coreless induction furnaces, which are by definition deep and in which the melt is stirred by the action of the electromagnetic forces.

Recents studies [5] have, nevertheless, thrown significant light on inclusion settling phenomena and called into question some of the conventional wisdom in this connection, although not offering any quantitative answers.
Based on inclusion counts performed by PoDFA and LiMCA, inclusion-settling histograms were constructed for various furnace geometries. One of the conclusions of the study was however that the behaviour of inclusions in a holding furnace did not obey Stokes's law, which the authors consider to be due largely to the action of convection currents. However, the model they propose, and which hypothesises a perfectly stirred reactor, is somewhat remote from reality.

The two-part study reported here was therefore undertaken with a view to closer analysis, directed towards a clearer understanding of the mechanisms of settling in holding furnaces and the establishment of basic principles of operation for application in Pechiney Group casthouses.
The first stage was to construct a numerical model based on calculations of turbulent motion due to natural convection and of the trajectories described by inclusions in the melt.
Secondarily, the predictions of the model were compared with the results of inclusion counts performed on a laboratory-scale furnace and on an industrial furnace, respectively. Comparison and interpretation of the data so obtained enabled the mechanisms governing settling and the principal parameters of the process to be clearly identified.

CONSTRUCTION OF THE MODEL

The approach to modelling under discussion here is equally applicable to furnaces heated above the melt (electric, gas-fired or oil-fired) and to coreless induction furnaces. However, for the sake of clarity, only the first of these cases will be considered in what follows, particularly since it undoubtedly corresponds to the majority practice in aluminim cast houses.

In this case, therefore, the melt occupies a volume of roughly rectangular cross-section. Without going into the complexities of the thermal analysis of these furnaces [6] it can be said, in simple terms, and solely as concerns the melt, that the melt is top-heated by radiant and/or convected heat, while loss of heat occurs through the side walls and base of the furnace. This might at first sight appear to represent a stable configuration, since the colder metal lies below the heated metal in proximity to the free surface. However, when account is taken of heat loss through the side walls, it will be appreciated that recirculation can occur as a result of natural convection, as illustrated by the diagrammatic representation of the cross-section of a holding furnace in Fig. 1.

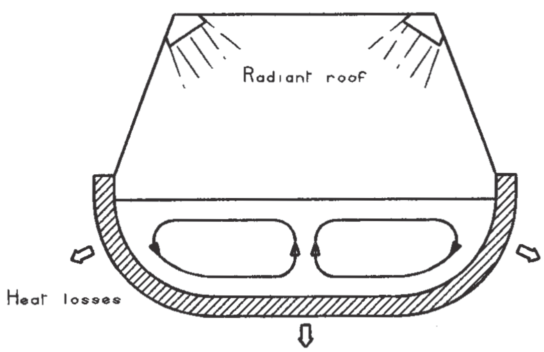


Figure 1 : Diagrammatic view of a holding furnace : recirculation due to natural convection.

The model developed to describe inclusion settling is based on consecutive calculations (i) of patterns of flow and heat transfer in the melt, and (ii) of motion through the melt by inclusions of a given size.

Calculation of patterns of flow and heat transfer in the melt.

An analysis based on orders of magnitude (appended) found maximum linear velocities for the liquid metal of the order of 0.07 m/s and that, because of the dimensions of the furnaces, flow would be turbulent. The methods employed to solve the Navier-Stokes equations and thermal equations for turbulent flow are now familiar and need not be discussed here. In this case, the FIDAP commercial package, comprising a "k - ε" turbulence model, was utilised.

Although three-dimensional computation is possible with this type of package it was preferred to stick to a simpler approach employing a 2-D computation for a vertical section similar to that shown in Fig. 1 (in fact, on grounds of symmetry, only half of this section was modelled). Unlike an earlier study of a similar kind [7], in which boundary conditions were more schematic, heat losses were represented in our model via a constant heat transfer coefficient ; the temperature of the free surface of the melt, on the other hand, was assumed to be constant.

Calculation of the path taken by an inclusion in the melt.

Calculations of particle motion in fluid flow fields are fairly well documented [8], especially in chemical engineering. However, since applications in metallurgy are currently few and far between, it may be helpful to set out the underlying principles.

For the physical analysis, the balance of forces acting instantaneously on the particle is determined and the acceleration of the particle calculated in accordance with the fundamental law of mechanic. For the numerical calculation, acceleration has to be integrated twice to determine the trajectory of the particle. More precisely, the particle is subject to the action of three forces, namely :

i) its weight
ii) the local pressure gradient
iii) drag.

> Note : Where the dynamic pressure is close to the metallostatic pressure, particle weight and pressure gradient merge as buoyancy. The particular significance of pressure gradient emerges only where electromagnetic forces are operating (as in the induction furnace).

For the sake of simplicity, the model assumes inclusions to be spherical and therefore uniquely identified by their diameter. At the later stage a more realistic assumption that shapes could sometimes be elongated will be examined. In this case not only position but also orientation in space and angular acceleration will be determined. Similarly, in the absence of published data, the possible effect on drag coefficients of non-wettability was disregarded.

These three forces are invariably taken into account in models of the process of removal of inclusions. However, an analysis in more depth reveals that other effects can strongly influence particle behaviour, so that additional factors have to be written into the equation describing the motion of the particle. These, comprising non-permanent effects (added mass and Basset's history term), the rotation of the particle under conditions of shear flow and the possible proximity of a wall, tend to be neglected in most models of trajectory, certain of them, however, have a significant contribution to make, as detailed in the Appendix, and were therefore included in the model under discussion.

Finally, therefore, the equation of motion for the inclusion is of the form :

$$\rho_P \, Vol \frac{dU_P}{dt} = -\frac{\Pi}{8} d^2 \rho_l C_D |U_P - U_F| (U_P - U_F)$$

$$- \frac{\rho_l \, Vol \, \Delta a}{2} \frac{d(U_P - U_F)}{dt}$$

$$- \frac{3d^2 \Delta h}{2} \sqrt{\Pi \rho_l \mu} \int_0^t \left[\frac{d(U_P - U_F)}{dt}\right]_{t=s} \frac{ds}{\sqrt{t-s}}$$

$$+ (\rho_p - \rho_l) \, g \, Vol$$

where U_P is the velocity and U_P - U_F the relative velocity of the inclusion.

Based on a comparison of various mathematical treatments of a simple case, a means of solving this equation was selected which represents a good compromise as between (i) precision and stability to the time scale and (ii) computation time.

Allowing for turbulence

How turbulence was taken into account in the trajectory model is discussed separately since this has only an indirect impact. It is entirely realistic to consider that turbulence will affect our knowledge of fluid velocity. Hence, to the mean component of fluid velocity has to be added a velocity fluctuation which can be tied in with the turbulence parameters. Therefore, in a manner similar to that proposed by Johanssen [9], velocity fluctuations were randomly determined (from turbulent kinetic energy) and added, for each increment of time, to the mean fluid velocities. Thus, for a given initial position of the particle, a set of possible trajectories was obtained, reflecting the chaotic nature of turbulence. In practice, given the impossibility of running calculations for every member of the set, calculations were confined to a statistically significant number of trajectories chosen at random (fig. 2).

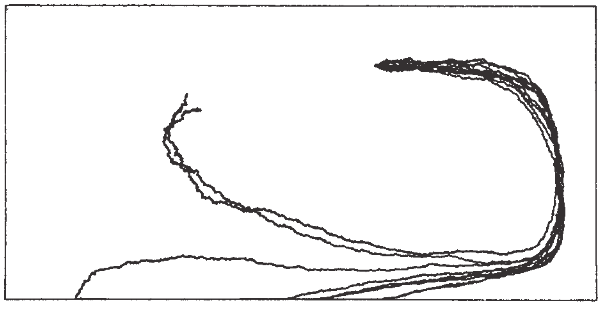


Figure 2 : Turbulent paths taken by a 30 μm particle

Use of trajectory calculations to construct a settling function.

The objective was to progress from a very incomplete item of data - the trajectory of an inclusion - to a more general evaluation of the percentage of inclusions settling out so as to be able to compare the predictions of the model with the results of experimental observation.

First, the assumption was made that any inclusion reaching a wall will cling to it, and hence has "settled out". Secondly, a discrete population of inclusions and the trajectories they would describe over a period of time were considered.
Initially, the furnace melt was considered to be perfectly stirred and hence the distribution of inclusions in space to be initially uniform. Distribution was further assumed to be an exponential function of inclusion diameter, this according with normal observation [5]. Finally, rates of settling versus time were calculated as the ratios, by volume, of inclusions settled out to the initial total of inclusions present. More detailed analysis by size range could also be envisaged.

EXPERIMENTAL DATA / COMPARISON WITH CALCULATED DATA

Two kinds of furnace will be discussed : (a) an experimental, small-capacity (max. 1 tonne), radiant-roof electric furnace of virtually rectangular cross-section and dimensions of 2 x 0.8 metres, in which melt depth for a 750 kg charge was approx. 0.2 m ; (b) an oil-fired furnace with a design capacity of 35 tonnes, the bottom of which was radiused around the edges, as illustrated by Fig. 6.

In both cases, the measurements made related :

i) to evaluation of temperatures in the melt and estimating heat losses for the purpose of determining values of heat transfer coefficients for the numerical calculations ;

ii) to rates of settling, determined by concentrating and counting inclusions to measure average concentrations in the holding furnace at intervals throughout the waiting period in the furnace.

Laboratory-scale experimental furnace

Direct measurements of temperature in the molten aluminium failed to reveal any significant thermal gradient detectable by the thermocouples from top to bottom of the furnace. Nevertheless, from an overall estimate of heat losses by the furnace, based on the temperature drop with the heating off, an overall heat transfer coefficient of the order of 10 $W/m^2/K$ was estimated for the walls. This was consistent with data on the furnace brickwork. The natural convection flow field calculated using this coefficient is shown in Fig.3, maximum velocities being 3 mm/s. Also, the maximum temperature variation in the furnace was of the order of 6°C (Fig. 4). A point to note as regards the isotherms shown in Fig. 4 is that natural convection currents had very little effect on temperature distribution, as was to be expected given aluminium's very small Prandtl number (3.10^{-2}).

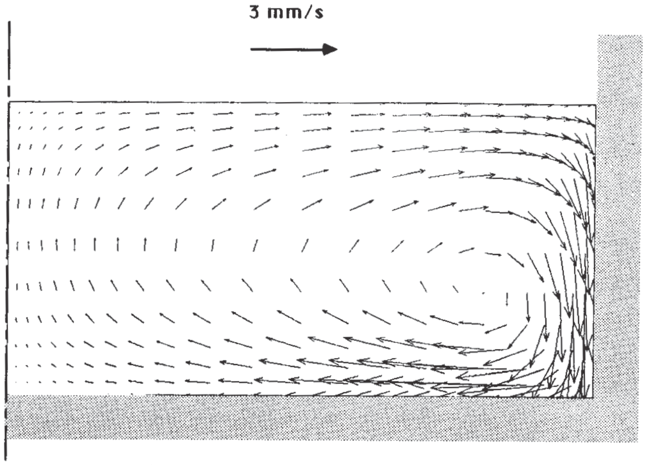


Figure 3 : Velocity field in the laboratory-scale furnace.

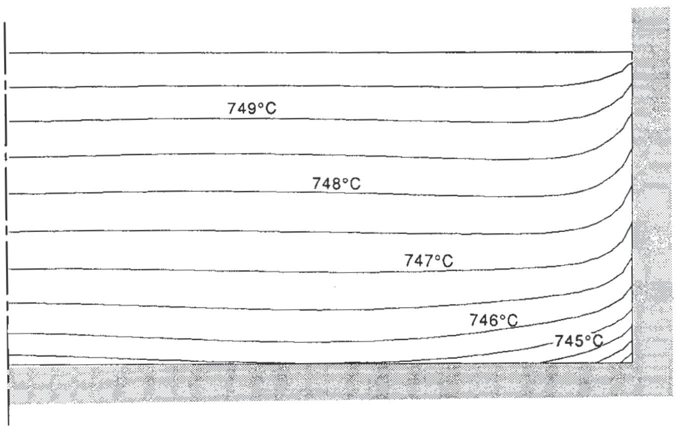


Figure 4 : Isotherms in the laboratory-scale furnace

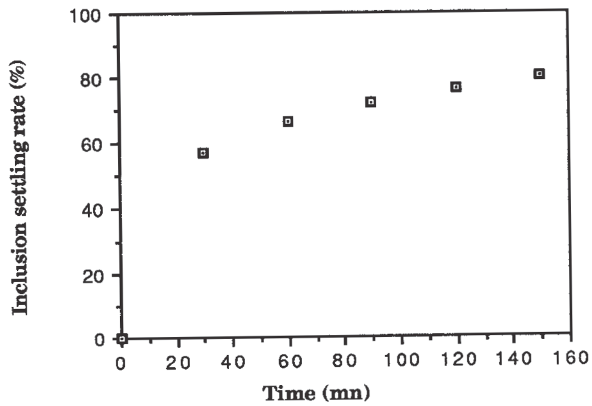
Inclusion settling rates with respect to time are shown in Fig. 5a for the experimental data and in Fig. 5b for the results of numerical calculations for conditions similar to the experimental conditions. Two consecutive stages in the process of settling are clearly observable, in agreement with earlier observations [5], namely :

a) a rapid reduction in inclusion concentration over roughly the first half-hour of waiting time,

b) a slow reduction over the next two hours.

This is particularly instructive if consideration is being given to a multipronged strategy of optimisation of waiting time (with respect to productibity, product quality, etc.). A physical interpretation of these observations is offered in the next paragraph.

Points to note are (i) that the uncertainty affecting the experimental data is of the order of 20 % and (ii) that certain of the assumptions and/or parameters written into the numerical model are still subject to debate. Nonetheless, the degree of agreement between experimental and predicted data is already good enough to validate the numerical method as a means of advancing understanding of settling phenomena and hence assisting with better furnace design.



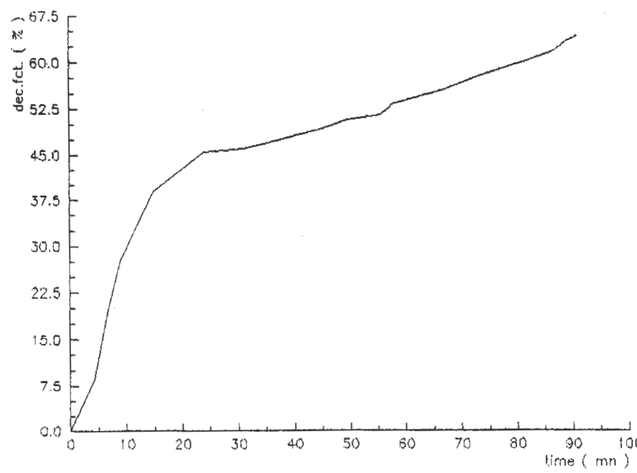


Figure 5 : Inclusion settling rates in the lab-scale furnace :
a) experimental data
b) results predicted by the model.

Industrial furnace

As for the laboratory-scale furnace, direct measurement of thermal gradients in the melt proved difficult. Observed temperature differences did not exceed 10° C (burner switched off), prompting surprise at the very high value for maximum differences of 50°C suggested by other investigators [7] for industrial furnaces. A mean heat transfer coefficient of 3 $W/m^2/K$ was determined, again by the indirect route, reflecting the superior insulation of the larger furnace.

Fig. 6 maps calculated velocities for this furnace, which, by virtue of its dimensions, are significantly higher than for the experimental furnace (of the order of 13 mm/s max.).

Measured inclusion settling rates (Fig. 7a) exhibited a greater degree of scatter than for the small furnace, to be explained in part by the difficulty of achieving accurate measurements in the working casthouse. Overall, however, the pattern was much the same : an initially rapid fall in concentration followed by a very slow decline. The duration of the initial period was observed to be longer than for the experimental furnace (some 50 minutes as against 30 minutes for Fig. 5a), which is explicable by the fact that the melt was four times as deep.

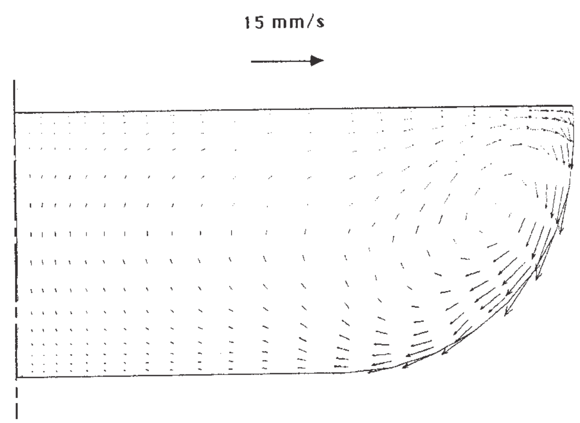


Figure 6 : Velocity field in the industrial furnace.

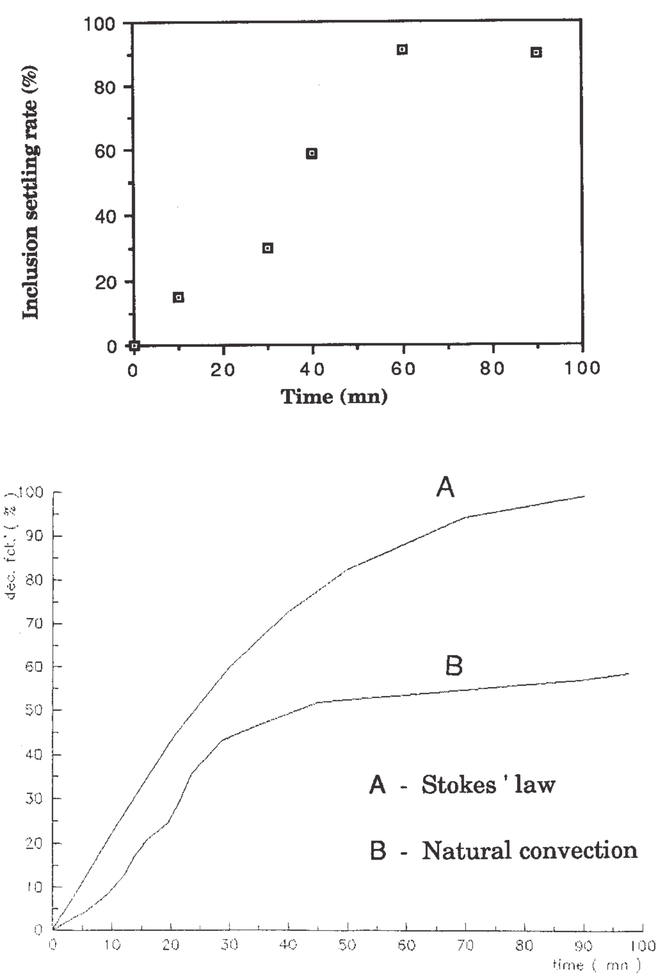


Figure 7 : Inclusion settling rates in the industrial furnace :
a) experimental data
b) results predicted by the model.

Fig. 7b shows the inclusion settling rates predicted by the model, the pattern of which was identical to that exhibited by the experimental data.

Interestingly, if the settling curve predicted by the model for a totally still melt, i.e. undisturbed by natural convection, is super-imposed on Fig. 7b, it is seen that, while the two plots are fairly similar over the initial phase of rapid decrease in inclusion concentration, recirculation of the molten metal subsequently slows the rate of settling appreciably. This is clear evidence of the case for taking recirculating motion into account in the numerical model.

DISCUSSION OF RESULTS

Given the number of parameters - furnace geometry/insulation, initial distribution of inclusions, etc. - directly influencing the theoretical predictions presented above, the direct discussion of results and their physical interpretation is no easy matter. This being so, it was felt it would be helpful to analyse the impact of certain parameters on inclusion settling in rather more straightforward, if more approximate, configurations, or with the help of simplified models.

First, in any analysis of the influence of the motion of the fluid on the settling phenomenon, the typical velocity of the fluid has to be compared to the terminal velocity in free fall (the Stokes velocity) of the particle. The Stokes velocity is the maximum velocity attained by a particle falling through a motionless fluid and corresponds to the point at which the relative weight of the particle just balances the viscous drag exerted by the fluid.

For small particles, this velocity is given by :

$$U_{Stokes} = \frac{d^2 \, \Delta\rho \, g}{18 \, \mu}$$

where $\Delta\rho$ denotes the difference in the densities of the particles and of the fluid, respectively, and
μ the viscosity of the fluid.

In the case of a particle in a fluid moving vertically downwards (i.e. parallel to the action of gravity) at a constant velocity U_{fluid}, the calculation is a simple one. Under steady-state conditions, i.e. once the particle has attained maximum velocity, the interval of time Δt it takes to travel a distance L, is given by :

$$\Delta t = \frac{L}{U_{fluid} + U_{stokes}}$$

Fig. 8 is a plot on log paper of Δt versus particle diameter.

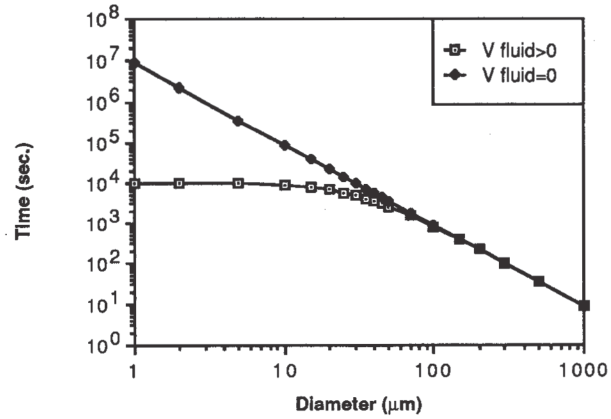


Figure 8 : Diameter v. time taken to travel a given distance : simplified case assuming uniform motion

Where the fluid is motionless, a straight-line graph of slope minus 2 is obtained, consistent with Stokes's law and indicating that the smaller the particle the longer the settling time.

Where the fluid is in motion, two distinct kinds of behaviour are observed, depending on how particle diameter, D, compares with a characteristic diameter, D_{Stokes}, defined as the diameter for which the Stokes velocity of the particle is identical to the velocity of the fluid. Thus :

- large particles ($D > D_{Stokes}$) continue to behave very much in accordance with Stokes's law and are not greatly influenced by the velocity of the fluid ;
- small particles ($D < D_{Stokes}$), on the other hand, are entrained at a velocity close to that of the fluid, so that their behaviour is unaffected by differences in size.

Now, to take a typical case, assuming a velocity U_{fluid} of the order of 1 mm/s and particles of density 4.5 g/cm^3 the value of D_{Stokes} is of the order of 50 μm, thus clearly indicating that the behaviour of the bulk of the inclusions it is currently sought to eliminate is governed by the movements of the molten metal.

The simplified case presented in Fig. 8 nevertheless has to be examined further to take account of the recirculating motion of liquid metal in a furnace. Thus, while the two velocities - Stokes velocity and fluid velocity - will at certain points add together, at others they will tend to cancel each other out, thereby enabling some inclusions to remain in suspension. This can lead to some very interesting kinds of behaviour, as exemplified in Fig. 9.

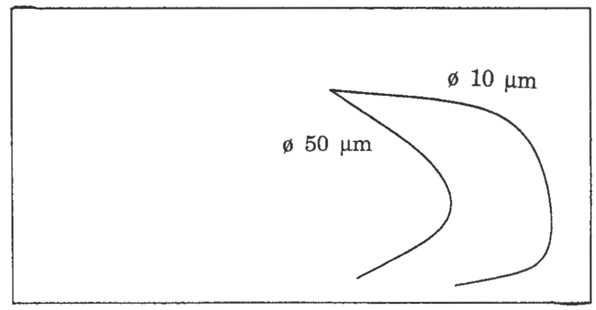


Figure 9 : Initial trajectories of two inclusions of diameters 10 and 50 μm, respectively (lab-scale furnace).

Fig. 9 refers to two particles of differing size (10 μm and 50 μm) released simultaneously at a point near the top of the recirculating loop generated by natural convection. The smaller particle, strongly influenced by the motion of the fluid, tends to follow the streamlines and, by virtue of the locally high fluid velocities, travels a relatively substantial distance. The larger particle, in contrast, tends to follow a more nearly vertical path from the outset, thereby entering the "eye" of the recirculating loop, where the fluid velocities are lower, so that, finally, it travels a shorter distance than the smaller particle, which might seem paradoxical if considered solely in terms of Stokes's law.

Similarly, Fig. 10 refers to three particles of differing diameter (10, 40 and 100 μm) initially occupying the same position. The behaviour of the biggest particle is entirely normal and more or less consistent with Stokes's law. The 10 and 40 μm particles, however, tend to follow the motion of the fluid and are therefore swept into the vortex and fail to settle out even after very long periods (80 minutes). This kind of behaviour can explain the shape of the curve in Fig. 7b : after the initial period of rapid settling of inclusions which are little influenced by the motion of the liquid metal the rate of settling slows virtually to nil because small inclusions are trapped within the vortex.

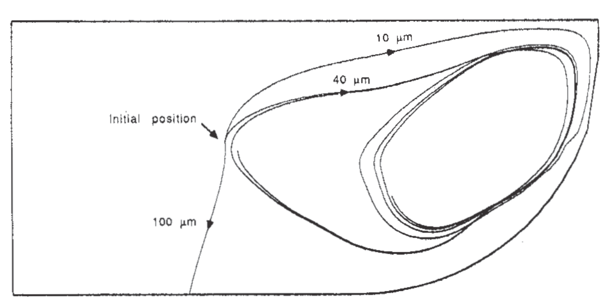


Figure 10 : Trajectories of three inclusions (10, 40 and 100 μm) (industrial furnace).

It is true that investigators who have considered how particles are taken into suspension generally refer to the turbulent characteristics of the fluid and inter alia to velocity fluctuations [10]. This is nevertheless a domain in which both theory and experimental data are limited and subject to differing interpretations. It was therefore preferred, in this study of inclusion settling in holding furnaces, to focus on some simple physical considerations.

Thus, Clift [8] has reported that the influence of turbulence makes itself felt where particle diameters are less than the "scale of turbulence", L, characteristic of the turbulent fluid and corresponding to the size of the vortices with most kinetic energy. The value of L can be calculated from a knowledge of velocity fluctuation, u', and turbulent energy dissipation, ε, by means of an expression of the form :

$$L \sim \frac{u'^3}{\varepsilon} \sim \frac{1}{\varepsilon}\left(\frac{2k}{3}\right)^{3/2}$$

In the case of the laboratory-scale furnace, the value of u' is ca. 2 mm/s, so that L = 80 mm approx.

Clearly, it follows from this that each and every inclusion will be affected by turbulence in the fluid. Hence, the possibility of removal of an inclusion from the recirculating liquid metal will be determined, to virtually equal extents, both by its tendency to follow the mean pattern of flow, as illustrated by Fig. 10, and by the impact of turbulence on its trajectory. This is why the complete model takes account of the impact of turbulence on calculations of trajectories.

Needless to say, it is not suggested that these considerations can replace the full calculations discussed previously. They do however highlight the specific behaviour of small inclusions, as well as revealing more clearly the need to take account of all the phenomena involved, the complexities of which are such that this is only possible via mathematical modelling.

CONCLUSION

A numerical model of movements due to natural convection currents in a holding furnace and of the behaviour of inclusions present in the melt was employed to compute theoretical settling rates for different configurations and these predictions compared with actual inclusion counts performed during waiting periods.

The degree of agreement observed suggests that the model could be of real value in advancing understanding of settling phenomena in holding furnaces. Notwithstanding the numerous approximations involved in the construction of the model and the uncertainties affecting the nature, size and morphology of inclusions, on all of which progress is anticipated, it is already possible to use this quantitative method to compare various furnace geometries and guide the design of holding furnaces.

A major feature of the interpretation is the comparison as between the relative value of typical fluid velocity and the terminal velocity of the inclusion in free fall (the Stokes velocity). This indicates that the largest inclusions are not greatly affected by movement due to a moderate degree of natural convection in the melt and settle out rapidly, thereby contributing to the initially steep slope of the settling curve (typically over the first half-hour). The behaviour of the smallest inclusions, on the other hand, is much harder to analyse, being sensitive to recirculation in the melt and even to fluctuations accompanying turbulence ; in simple terms, the rate of settling was found to be slower than in the absence of convection, but to be relatively unaffected by size.

APPENDIX

ORDER OF MAGNITUDE OF MAXIMUM VELOCITY OF THE MOLTEN METAL IN THE FURNACE

Movement of the liquid metal is caused by natural convection currents due to the variation of density with temperature. In the Boussinesq approximation, density can be expressed in the form :

$$\rho = \rho_0\,(1 - \beta\,(T - T_0))$$

where ρ_0 and T_0 characterise a reference condition (fluid well away from the wall).

and β is the coefficient of expansion.

The thermohydraulic equations can then be expressed in the dimensionless form :

$$\nabla^*.\,V^* = 0$$

$$\frac{DV^*}{Dt^*} \sim -\nabla^* p^* - \frac{Gr}{Re^2} T^* + \frac{1}{Re}\nabla^*\,.\,[\mu\,\nabla^* V^*]$$

$$\frac{DT^*}{Dt^*} = \frac{1}{Pe}\nabla^{2*}\,T^*$$

$$\text{avec } V^* = \frac{V}{V_o},\quad t^* = \frac{t\,V_o}{H},\quad \nabla^* = H\nabla\,,$$

$$p^* = \frac{p + \rho_o g z}{\rho_o V_o^2},\quad T^* = \frac{T - T_o}{T_{wall} - T_o}$$

Thus for natural convection, the velocity scale V_0 can be determined from :

$$Re = (Gr)^{1/2}$$

whence $V_0 = (g\,\beta\,\Delta T\,H)^{1/2} \sim 0.07$ m/s

H is the length scale (H = 0.5 mm)

$\Delta T = T_0 - T_{wall}$ is the temperature scale ($\Delta T \sim 10°$ C)

ADDITIONNAL FACTORS IN THE EQUATION DESCRIBING THE MOTION OF A PARTICLE IN A FLUID

In the ideal case of flow unaffected by the proximity of a wall, the only factors to be considered are the weight of the particle, the pressure gradient and viscous drag ; in practice, however, other factors have to be allowed for.

First, there are non-permanent effects associated with the acceleration of the particle and which can be modelled as two factors [8], viz :

i) The "added mass" effect

$$-\frac{\rho_l \, Vol \, \Delta a}{2} \; \frac{d(U_P - U_F)}{dt}$$

This describes a reaction of an ideal fluid to the acceleration of the particle, which causes acceleration of the fluid, thereby setting up a notional force which can be interpreted as an increase in inertia. This notional force is proportional to the volume of the particle and its acceleration with respect to the fluid. Application of the model to simple cases has shown this force to be negligible.

ii) Basset history term

$$-\frac{3d^2 \Delta h}{2} \sqrt{\Pi \rho_l \mu} \int_0^t \left[\frac{d\,(U_P - U_F)}{dt}\right]_{t=s} \frac{ds}{\sqrt{t-s}}$$

This corresponds to a reaction of a non-ideal fluid to the acceleration of the particle. The interaction of this acceleration with the viscosity of the fluid generates vortices in the wake of the particle which diffuse into the bulk of the fluid. The acceleration of the fluid at any instant will therefore be determined by the previous history of acceleration of the particle. A notional force is set up. The situation is as if the fluid possessed a memory.
Numerical calculations have shown that disregarding this effect could lead to errors in determination of the final position of the particle amounting to some 25 % of the path already travelled by the particle.

Allowance also has to be made for the effect of rotation of the particle, arising either from shear flow or from the proximity of a wall. The pressure field acting on the surface of the particle is asymmetrical, effectively altering drag and generating a lifting force perpendicular to the wall [11].

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