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3D SPH SIMULATIONS OF THE ALUMINIUM INGOT CASTING PROCESS

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ABSTRACT

Full three dimensional SPH simulations of the aluminium ingot casting process were performed as part of a CAST project to develop and optimise a quality competitive high flow rate wheel design. The interior and exterior oxide content in the ingots was predicted using a linear oxide growth rate model based on exposure of fluid to the air. Simulation results were used to make design modifications to the wheel and launder design in order to minimise the oxide content in the cast ingots generated by the flow through the wheel and into the ingots. With a view to increasing the number of ingots produced per hour while maintaining the ingot quality, simulations were also carried out to compare the oxide content at two different feed rates of the molten aluminium. Results indicate that SPH can be employed as a useful tool for design optimization of such systems.

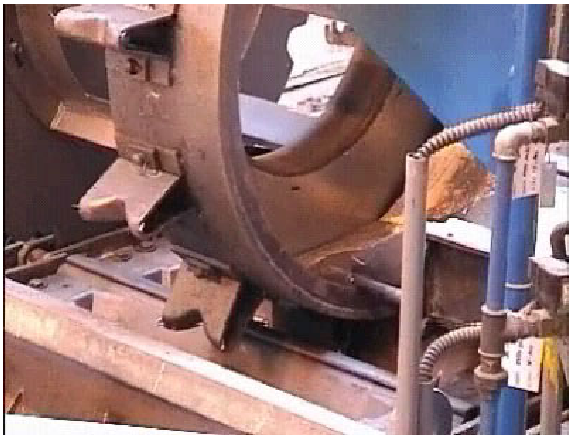
NOMENCLATURE

W_{oxide}	oxide content (Kg)
S_{area}	surface area (m^2)
k_l	rate constant (Kg/m^{2}s)
t	time (s)

INTRODUCTION

The ingot chain conveyer casting process is very commercially important to the aluminium industry, with hundreds of machines in operation and millions of tonnes cast every year by this method. In this process, cast iron moulds on a conveyer are fed with molten metal, usually by a wheel type filling system (Figure 1). The ingot moulds have a translational motion synchronized with the motion of the wheel. The flow thus generated is complex and highly three dimensional. These moulds are water cooled using a water spray or by immersion into a water bath. The machine is run at a speed such that the 22.5 kg ingots are solid when they reach the end of the conveyor where they are knocked out, cooled further and stacked into bundles. A typical production rate is around 18-20 tonnes per hour (Whiteley, 1997).

There are several major issues related to the manufacture of aluminium ingots of good quality at a competitive production rate. One of the important quality attributes of the ingots is the amount of dross present and the appearance of the ingot. This dross is produced during the filling of the mould. Smelter operators have a need to increase casting machine throughput. Inevitably this means that the filling time is reduced and there may be greater potential for more turbulence and dross generation. Some new machines with longer lines are running at rates of 24 tonne per hr and there are plans for 30 tonne per hour machines.



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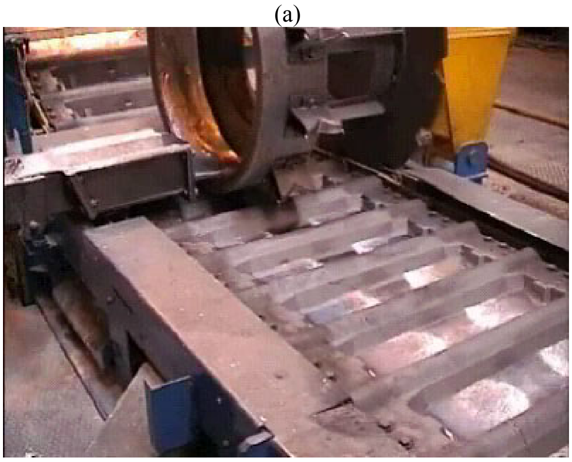

(b)

Figure 1: An example of an ingot casting machine system showing (a) the casting wheel and (b) the ingots at the bottom.

Operators are reluctant to test new designs in production and this makes the development of new designs problematic. ODT Engineering manufacture ingot casting machines and desired to develop a new wheel design which matched the performance of the best wheels available at 30 tonne an hour and produce acceptable

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quality ingots. This would set a new bench mark for ingot casting machines. Modelling of this type of system is a very difficult proposition. Most conventional fluid flow packages cannot handle the difficulty of moving the solid surfaces (wheel and mould) within the domain easily. Modelling of oxide generation is also a relatively new area. In order to address these issues a CAST project was commenced using Smoothed Particle Hydrodynamics (SPH), a Lagrangian method, for modelling this complex system.

MODELLING

SPH (smooth particle hydrodynamics) is a relatively unknown method for modelling coupled fluid flows, solid structures and heat transfer with some unique capabilities. SPH is particle based rather than using conventional fixed grids or meshes to track the fluid and calculate the fluid velocities. The fluid is represented as "*blobs*" of fluid or solids that move around in response to the fluid or solid stresses produced by the interaction with other particles (Gingold and Monaghan, 1977, Monaghan, 1994 and Cleary 1998). Complex geometries can be handled so it is suitable for complex industrial simulation particularly where solid and fluid move together and is ideally suited to the modelling of ingot casting. CAST/CSIRO has been using SPH for high pressure die casting simulations of complex industrial components (Ha et al., 2003a). Extensive water and x-rayed metal flow validation studies of SPH have been conducted including a recent comparison with 3D water analogue experiments (Ha et al., 2000, Ha and Cleary 2000 and Ha et al., 2003b).

SPH Simulation

The simulations were carried out using the Lagrangian method for modelling heat and mass flows, called Smoothed Particle Hydrodynamics. Materials are approximated by particles that are free to move around rather than by fixed grids or meshes. The governing partial differential equations are converted into equations of motion for these particles and to rates of change of their properties (such as temperature and solidification state). The isothermal equations used for the present simulations can be found in Cleary et al. (2002). SPH is particularly well suited to momentum dominated flows, flows involving complex free surface behaviour and flows involving complex physics such as solidification or flow through industrial porous media. It is also useful for flows around moving objects, since there are no mesh structures to be stretched or distorted. For further information about SPH refer to Monaghan (1992), Monaghan (1994), Cleary (1998) and Cleary et al. (2002).

For complex three dimensional simulations such as in the simulations of the ingot casting process, there are three main steps in generating SPH simulations; pre-processing, simulation and post-processing. These three stages are explained briefly below.

Pre-Processing

The pre-processing stage involves the creation of solid geometries for the different parts of an ingot casting assembly required for the SPH simulations. These are the feed launder, the ingot wheel and the ingot moulds. Using engineering drawings provided by ODT Engineering and including some design modifications, seven different solid models were developed using the CAD package SOLIDWORKS. The basic difference in these models was in the design of the wheel and/or the feed launder. The ingot mould geometry remained unchanged for all seven cases. An example of the SOLIDWORKS model for the base case consisting of the three component types is shown in Figure 2.

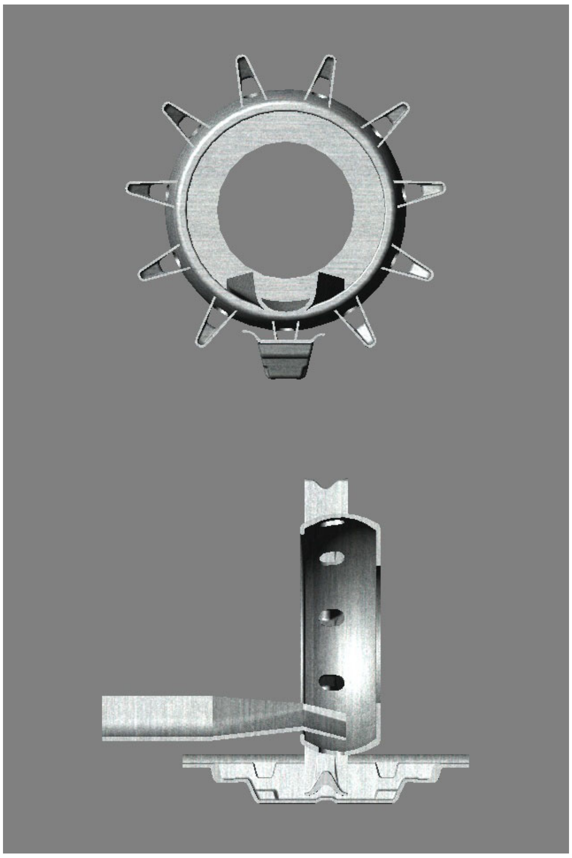


Figure 2: Base Case wheel design used in the industry

The solid models produced were then used to generate meshed surfaces with the 3D meshing software HYPERMESH. The meshed components were passed through in-house SPH pre-processing software that converts 3D meshes into SPH particle data. The pre-processor converts the nodes either into SPH boundary nodes or SPH inflow locations. An inflow flag is assigned to nodes at the boundary of the feed launder. Fluid particles (in this case liquid aluminium) are generated from these inflow locations at the end of the launder opposite the wheel and they flow along the launder, into the wheel and finally down into the ingot mould.

Simulations

Once the pre-processing stage is complete, the SPH particle data is read into the SPH simulation code. A bank of four ingot moulds was used for all seven simulations. The simulations were carried out to produce ingots at the rate of 30 tonnes/hr. The synchronised linear ingot mould bank speed was 6 m/min. The rotational speed of the ingot wheel was adjusted accordingly. Seven different wheel geometries were simulated. The base case wheel design (Figure 2) was also simulated with an ingot casting rate of 20 tonnes/hr (or synchronised linear ingot mould bank speed of 4 m/min) for comparison. Each simulation was run until all four moulds were filled. The time delay in fluid flow through the launder and wheel meant that the first mould was only partially filled in all cases.

The output from the SPH simulation includes oxidation information for the SPH particles representing liquid aluminium. Since SPH is a particle based code, the calculation of the oxide formation and transport is straightforward with the oxide information carried along automatically by the particles. Thus, SPH is a very good tool for predicting oxide content using a particular oxide growth model. The oxide data obtained includes the total oxide content in a mould as well as the interior and surface oxide content.

Post-Processing

Videos that give detailed insight into the mould filling process as well as flow velocities and oxide distribution during the filling can be produced. The particle positions obtained from the SPH simulations are used to generate animations that provide insight into the mould filling process. The graphics visualisation data file generated by the SPH code contains position, velocity and oxide information. The particle positions are triangulated to give a mesh structure. This step is essential since a mesh gives the data structure and depth for the purpose of visualisation. The triangulated data with the scalar information is generated in a format that is readable by ENSIGHT which is software used for visualisation. The geometry and position information for the solid parts namely the wheel, mould bank and the launder are read in separately into ENSIGHT. Camera positions are chosen that appropriately assist in highlighting a particular phenomenon. Having fixed the camera position, pictures of the state of fluid flow at each time frame are generated using ENSIGHT. The individual frames are then converted into a movie using Adobe Premiere.

DROSS GENERATION

Oxide grows on the surface of the molten aluminium. The growth rate is generally dependent on the melt temperature and the alloy composition. This oxide layer can be broken by flow of the aluminium creating new surface. The surface may be folded over on itself entraining the oxide films. Any splashing will result in droplets of melt surrounded by oxide film which become dross on the melt surface. Most of the studies presented in the literature (Cochran et. al, 1977, Field et. al, 1987, Bergsmark et. al, 1989 and Impey et. al, 1988) report oxidation kinetics over long periods of time usually ranging from minutes to hours in stagnant melts. Few studies have examined oxide/dross generation during melt transfer (which is a rapid process) yet it is well known that considerable dross is generated during pouring from one height to another or during flow under or over obstacles. Tests by Baker et al., (1995) indicate that the amount of dross is proportional to the falling height.

Oxide Modelling

Following the results of Baker et al. we use a linear growth model of the form:

$$\frac{dW_{oxide}}{dt} = k_l S_{area} \qquad \textbf{eq 1}$$

where W_{oxide} is the oxide content, S_{area} is the exposed surface area k_l is the rate constant and t is time. The authors empirically calculated the rate constant to be $k_l = 4.21\,\mu m/s$ or $10.9\times10^{-3}\,kg/m^2s$

The units of k_l depend upon the method used to follow the reaction (Birks and Meier, 1982). Where oxide scale thickness is measured, then k_l has the units m/s. If mass gain measurements were to be used then the appropriate linear rate constant would have units of kg/m^2s. In our case, we would be more interested in the amount of oxide formed, so we use the value of $10.9\text{x}10^{-3}\,kg/m^2s$ as our rate constant.

DESIGNS

Seven different wheel designs were simulated in the full SPH models. The base reference case was an existing wheel design used in the aluminium casting industry (Figure 2). This design suffered from a number of cascades and unnecessary changes in fluid flow direction. A process of design evolution was used to optimise the design by assessing the results and modifying the design. The final design (provisional patent lodged) minimises flow direction changes, and falling height and gently guides the flow into the mould along the long axis of the moulds so that little of the liquid jet is directed against the mould walls.

RESULTS AND DISCUSSION

Model results are presented in the form of pictures showing surface oxide levels (Figure 3) and velocity and flow patterns (Figure 4). Ingot weight and oxide content data are presented in Table 1 and Figure 5. The wheel in Figure 3 and Figure 4 is made semi-transparent in order to clearly show the flow pattern and oxide levels.

An oblique side view is chosen in Figure 3 whereas a front view along the launder in the direction of the flow is used in Figure 4. In Figure 3 the oxide content is coloured from blue (minimum) to red (maximum) depending on the amount of surface oxide present.

An oxide reset plane is used at the tip of the launder just before the flow starts going into the wheel. This was used to reset the oxide values to zero so that one could determine oxide generation only due to the flow into the wheel and through to the ingot moulds.

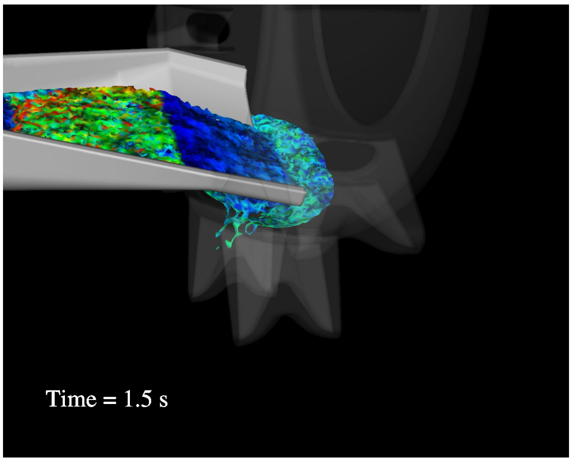
The fluid flows through the launder, into the wheel and finally into the mould through the nozzles. In the original design (Figure 2), the flow and oxide information of which is discussed here, at the end of the launder its profile becomes steeper. This results in an increase in the fluid velocity under gravity before entering the wheel (Figure 3a and Figure 4a).

The fluid then strikes the back of the wheel and the flow is reflected forming a pool in the base of the wheel (Figure 3b and Figure 4b). This fluid feeds into each nozzle through outlet ports in the base of the wheel (Figure 2). Due to this constriction the weight of accumulated fluid in the wheel generates a high velocity flow into the top of the nozzle (Figure 3c and Figure 4c). The use of two nozzle outlets splits the flow creating higher surface area to volume. Material entering the ingot mould reflects off the front and back walls of each mould (Figure 3b and Figure 3c). These two waves meet in the centre of the mould again causing increased splashing and significant surface fragmentation. All these features tend to increase surface area and oxidation in the old design.

Figure 3d and Figure 4d show the system when filling of the third ingot is almost complete. From the frames in Figure 4 one can see that the wheel rotates in the anticlockwise direction and the ingot moulds move to the right. In the later stages of the filling process the flow becomes established with the flow into the mould following a somewhat repetitive pattern.

The model predicts that it takes 3-4 ingots before the pool of fluid in the wheel has sufficiently built up for the system to stabilise in terms of ingot weight and oxide content (Figure 5).

The oxide level predictions for the 20 tonnes/hr and 30 tonnes/hr original design are quite comparable (Table 1). This suggests that at both production rates the flow characteristics in terms of the amount of new surface exposed should be similar. In other words the oxide content seems to be independent of the Reynolds number for this range of fluid velocity. Predictions indicate that the optimised design should produce ingots with much lower oxide levels than the established design (Table 1). In most cases the oxide was split equally between the surface and the interior of the ingot.



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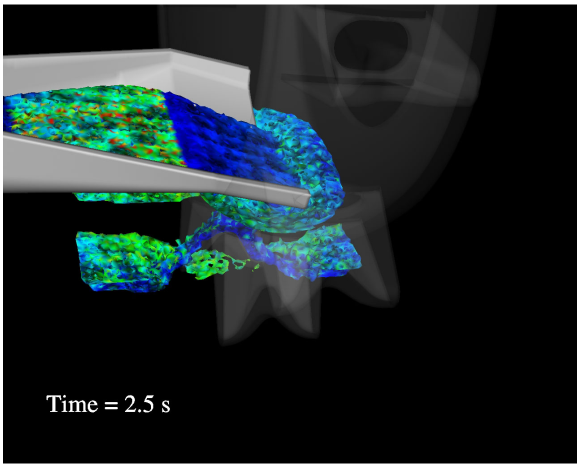

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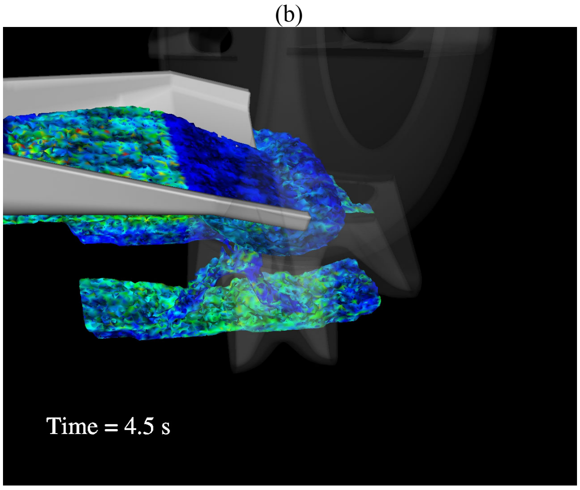

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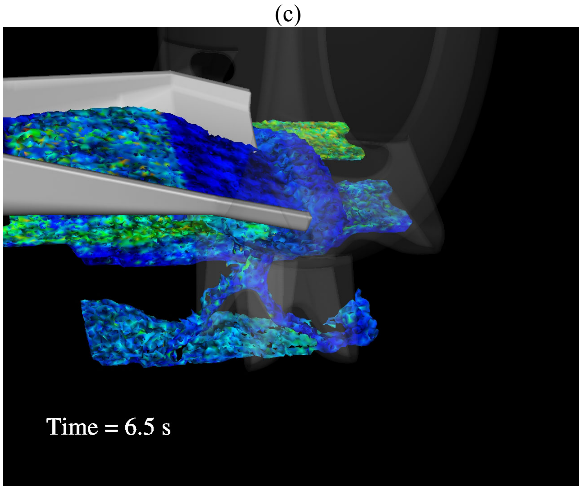
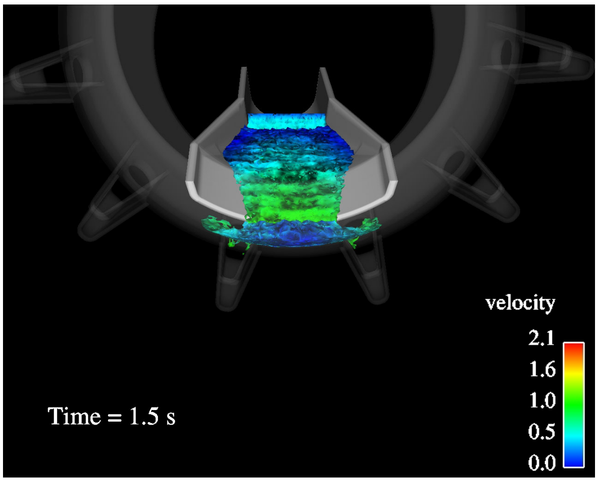


(d)

Figure 3: Predicted oxide distribution and flow pattern for original wheel design at different times shown with an oblique side view.



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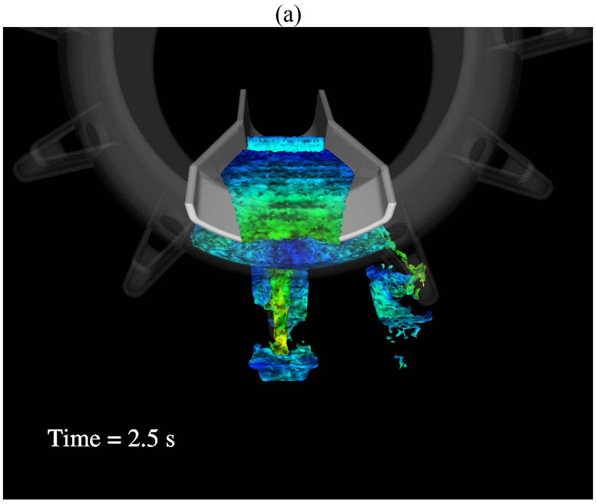

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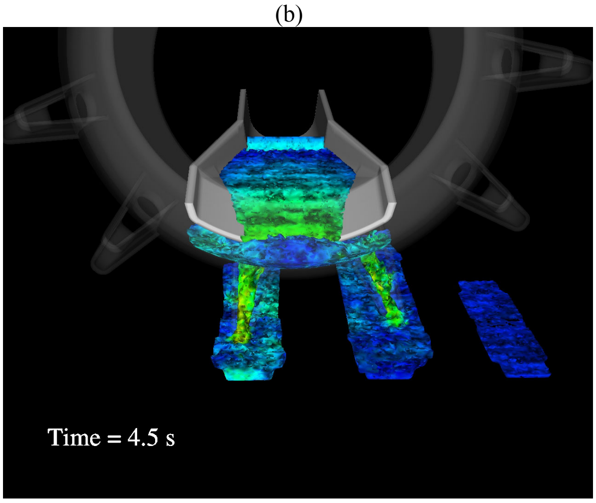

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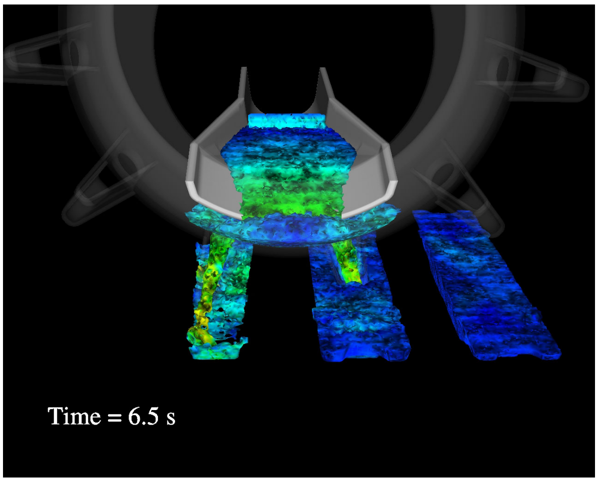

(d)

Figure 4: Predicted velocities for original wheel design at different times shown with a front view along the launder and in the direction of the flow. Note that the moulds are moving from left to right.

Wheel Design	Ingot Mould Rate (tonne/hr)	Oxide Content (g/Kg)
Original	30	0.95
Original	20	0.92
Optimised	30	0.51

Table 1: Oxide levels in the third ingot predicted by SPH simulations for wheels run at 20 and 30 tonnes/hr

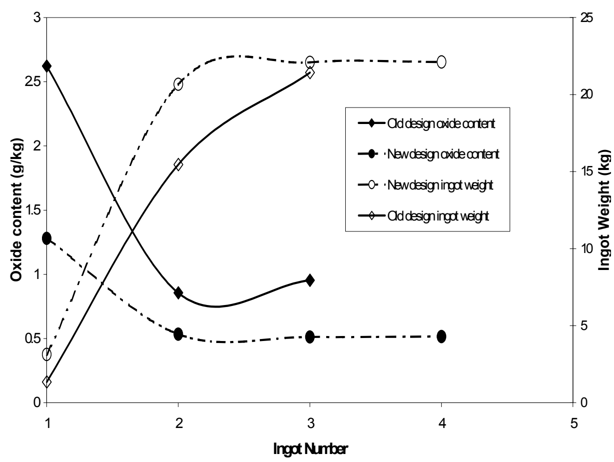

Figure 5: Predicted ingot oxide content and weights for the old and new wheel designs at 30 tonnes/hr

CONCLUSION AND FURTHER WORK

The model results give confidence that the new wheel design should perform well at 30 tonnes per hour. In order to further test the new wheel design, a 9 m long mini-caster was built by ODT and installed in CSIRO's Preston laboratories in May 2003 with an existing 500 kg tilting furnace (Figure 6). Full size 22.5 kg ingots will be cast at 30 tonnes per hour with a full-scale new wheel design and assessed for oxide level.

Figure 6: New ingot wheel design being experimentally tested at CSIRO's Preston Laboratories. Note that the actual wheel is hidden since an application for a patent is being made for this design.

ACKNOWLEDGMENTS

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