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FLOW MODELLING THE ISF CONTINUOUS TAPPER

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ABSTRACT

Recent development of continuous tapping for the ISF lead zinc blast furnace has focussed attention on the flow from within the furnace hearth via the forebay to the forehearth. The two phases, molten lead and slag pass by means of underflow and overflow weirs while undergoing liquation and mixing at various stages in transit. A transparent room temperature model was constructed at one quarter scale to model the tapper flow using various fluid pairs to simulate the two phase flow. The volumetric flow rate of the lighter slag phase is about ten times greater than the denser metallic phase. The dominant feature of the flow appears to be the driving effect of the lighter phase inducing a recirculating pattern in the dense phase and significantly modifying its residence time distribution.

INTRODUCTION

Pasminco Metals-Sulphide operate an Imperial Smelting Furnace (ISF) at Cockle Creek, N.S.W. The ISF is a blast furnace that smelts lead/zinc sinter to simultaneously produce lead and zinc metal. Lead and slag are tapped from the furnace bottom while zinc is recovered from off gases in a lead splash condenser (Firkin 1980).

The furnace is approximately 9 metres high, rectangular in shape with rounded ends. The shaft tapers gently down to the hearth where it is 6 metres at its widest and 2 metres at its narrowest. Originally slag and lead were intermittently drained from the hearth through a water cooled tapping breast in the middle of its rounded narrow end. However because of the increasingly high slag fall experienced over the last decade, and the productivity limitations of the intermittent slagging practice, a continuous tapper was installed in 1985.

This continuous tapper was based on the Roy tapper (Roy 1963) used extensively on lead blast furnaces. The principle of the tapper is an underflow /overflow weir whereby slag and lead continuously leave the furnace while maintaining a gas seal by the large volume of liquid lead held within the hearth and forebay (Holliday et al 1987). The introduction of a continuous tapper to the ISF at Cockle Creek represents a world first. Although it has improved productivity and metals recovery it has also introduced some unique fluid drainage phenomena. It was with these phenomena in mind that a two phase fluid flow modelling investigation was undertaken. The aim of the investigation was to simulate lead and slag flow through a scaled slice model of the ISF lower shaft, hearth and continuous tapper.

THE CONTINUOUS TAPPER

The continuous tapper consists of an external ceramic brick lined forebay connected to the furnace by a 200x300 mm underflow slot. The slot is submerged under molten lead to a depth determined by an overflow weir at the forebay exit. Lead, slag and small amounts of speiss/matte discharge from the furnace under the underflow and then over the overflow while the furnace gas seal is maintained by the lead. The principle of the tapper operation is thus a steady state balance of internal gas pressure plus slag head with the external head of lead in the forebay.

Despite the simple nature of the geometry of the tapper, operating experience has demonstrated that the draining of slag and lead through the underflow /overflow system can produce some unusual and unexpected flow dynamics, among which is included loss of flow or surges of either phase under apparently steady state conditions. Geometric and dynamic modelling of the system was therefore seen as an appropriate way of investigating the inherent fluid behaviour underlying these excursions.

MODELLING CRITERIA

The problem of finding a suitable model for ISF continuous tapping was approached by surveying hearth drainage models for batch tapping systems in the absence of any available data for a continuous one. In a study by Pinczewski et al (1983) a mercury-glycerol-air Hele-Shaw model was used for packed bed simulation of iron and slag drainage from the blast furnace. The model showed large fluid head gradients on drainage and, under certain conditions, gas fingering through the glycerol layer. However while this model serves as an example of a simulation of a batch tapped process with fast initial drainage rates its relevance to the continuously tapped ISF may be minimal as ISF tapping is basically a steady state process with the continuous outflow being balanced by a continuous inflow to the hearth region.

Two important assumptions, common to both the Pinczewski model and the tapper model, were (i) although the furnace is not rectangular in shape the outflow at the drainage end would be centreline flow and (ii) the height and position of the tuyeres and raceways above the liquid layer is such that, under normal operation, they have no great effect on the liquid surface.

Similitude Criteria and Design

The initial response to the problem of designing a flow system model is to make an inspectional analysis after Rayleigh (Kline 1965). Thus if one decides on the significant forces governing the flow dynamics, criteria of similitude and the appropriate model scaling are readily determined. However, at the initial stages in a reconnaissance such as this where much is conjecture any decision on the relative significance of forces and effects tends to be preemptive. Thus the decision on model size and model fluids are usually empirical with post-hoc justification and analysis. Using Chesters' analysis (1975) the criterion for complete similitude for two phase flows may be identified as identical Morton numbers in both prototype and model. The Morton number may be regarded either as a measure of the property ratios required or of the fluid force ratios i.e.

$$\text{Morton Number} = \frac{g\mu^4}{\rho\sigma^3} = Re^4 Fr/We^3$$

The scale ratio of model:prototype required following this analysis and using the available fluid pairs suitable for room temperature transparent modelling is 1.25:1.0 for a water/oil pair and about 0.9:1.0 for a saturated zinc chloride/oil pair. This was not a pratical solution and the choice of a smaller scale was made for empirical reasons noted below.

The first experimenter and builder of the model (D.V.) listed as his design criteria - (i) structural integrity commensurate with the following (ii) adequate sightlines for visualisation (iii) "hand sized"dimensions as a physical minimum for ease of manipulation and modification (iv) scaled sufficiently large enough to observe phenomena such as the possible existence of interfacial gradients between phases.

Finally the decision to proceed with a quarter scale two dimensional centreline model 75 mm thick meant that the tapper underflow section was in complete three dimensional similarity with the prototype tapper i.e. 75 mm is the correct quarter scale width at the underflow weir.

Having fixed two parameters, namely scale ratio and geometric similarity, the effect of the remaining parameters and their variation on dynamic similarity must be considered. This means considering the available fluid pairs that may be used and their flow rates - both absolute and relative. Table 1 lists the properties. Two obvious requirements are immiscibility of the pair and at least one must be transparent - preferably both.

Table 1 lists the properties of some possible model fluids. Zinc chloride and oil have the closest density ratio while water and oil have a similar viscosity ratio to the lead and slag. Tetrachloroethylene and water are included to demonstrate the unsuitability of two water-like fluids to model the slag/metal pair.

Table 2 was generated by assuming that the characteristic dimension for these property groups was the fractional height of the underflow weir occupied by each fluid. The lead was assumed to occupy the lower two thirds of the underflow, while slag occupied the upper one third. Using these proportions a cross sectional area may be estimated for conversion between velocities and flowrates. Subsequent flow visualisation indicates that the lead may occupy significantly more than this proportion of the underflow weir passage.

TABLE 1 Lead model fluids

Fluid	Density (kg/m^3)	Viscosity (kg/ms)	Surface Tension (kg/s^2)
Water	1000.	0.001	0.070
Zinc chloride	1900.	0.013	0.072
Tetrachlor ethylene	1630.	0.013	0.03
Mercury	13600.	0.016	0.465
Kerosene	800.	0.0025	0.028

(ii) Slag model fluids

"Talpa"oil (20W-30)	890	0.214	0.1
Glycerol	1260	1.5	0.022

(iii) Property Ratios

	Density	Viscosity	Surface Tension
Lead/Slag	2.47	0.0002	1.2
Water/Oil	1.12	0.0005	0.7
$ZnCl_2$/Oil	2.13	0.006	0.72
C_2Cl_4/H_2O	1.63	1.0	0.43

TABLE 2

Characteristic Values of Nondimensional Variables

	Re	We	Fr	Mo
Lead	3500	2.5×10^{-2}	6×10^{-6}	1.6×10^{-14}
Slag	100	2.9×10^{-3}	2.3×10^{-3}	1.1×10^{-4}
Water	$3.3\times10^{4}\times V$	$4.6\times10^{2}\times V^2$	$3.1\times V^2$	2.5×10^{-11}
Oil	$74\times V$	$1.5\times10^{2}\times V^2$	$6.1\times V^2$	2.3×10^{-2}
$ZnCl^2$	$2.7\times10^{4}\times V$	$3.8\times10^{3}\times V^2$	$0.77\times V^2$	1.4×10^{-7}

TABLE 3

Predicted Flowrates

Flowrate basis (1/s)	Re	We	Fr	Time
Water	0.3	1.8×10^{-2}	3.5×10^{-3}	1.8×10^{-3}
Oil	1.6	5.5×10^{-3}	2.4×10^{-2}	1.2×10^{-2}
$ZnCl_2$	0.32	6.5×10^{-3}	7.x10-3	$2.\times10^{-3}$

The flowrates in Table 3 tnus generated from each similitude parameter are indicative of the conflicting similitude requirements for modelling. Expressing the comparison by the volumetric flow rate serves to identify the distortion of the criteria in terms of the only operating variable available on the model. The Froude, Weber and geometrically scaled time flow rates are reasonably close in magnitude but differ significantly from the Reynolds criterion flow rate. Choice of the appropriate flow rate is further constrained by the practical limits of the model requiring as it does a gravitational flow down through a packed bed, under and over a weir while mixing and unmixing. For the experimental runs, water and zinc chloride solution flow rates matched the range of Froude similarity and the oil flow approximated Weber and Froude requirements. Subsequent observations indicate that the flow pattern and dispersion of the two phases were appropriate and conformed to the prototype.

The model is shown in vertical section in Figure (1). It consists of a hardwood frame mounted on a hardened glass frontplate with a perspex backplate. The interior shapes were made in balsa with rubber seal strips. A 5mm grid on a transparent sheet was laid on the glass wall as a scale reference for position measurement. Time scale was provided by a video time generator giving a time base on all videotapes made.

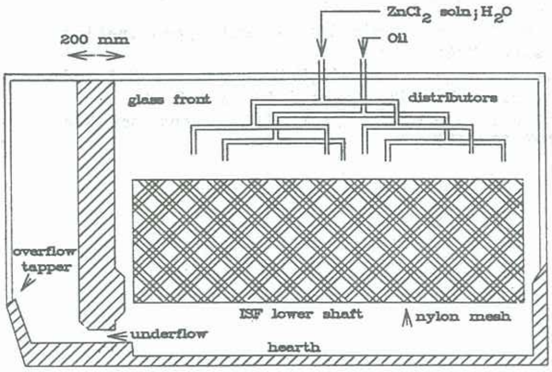

Figure (1) Front view of model of ISF lower shaft, hearth and continuous tapper

FLOW OBSERVATIONS

The plan was for (i) measurement of fluid head with varying flow of both phases; (ii) flow visualisation and velocity measurements within the transparent "lead" phase; (iii) residence time distribution analyses. All experimental flows were videotaped.

Firstly "slag" flow rate was varied up to 0.1 ls^{-1} while lead flow was constant at 0.0034 ls^{-1}. Then lead flow rate was varied up to 0.011s^{-1} with slag flow at 0.0034 ls^{-1}. In each case flow velocities and fluid heads in the hearth/lower shaft were measured. In all these experiments the "slag" flow was a continuous thin film of varying thickness that hugged the underflow wall. However when the overflow height was increased significantly the thickness of the film was considerably reduced and, on reaching the forebay, the film accelerated and broke into droplets during its vertical ascent along the forebay wall after passage through the underflow weir.

For all experimental runs, at all flow rates investigated, there was no gradient in the head of the phases within either hearth or forebay, that is ,within the accuracy of measurement of $^+/_-$ 1mm over the 2 metres of the model, the surface of each phase was horizontal at all times. This observation is at variance with the gradients hypothesised by Holliday et al (1987) and observed by Pinczewski (1983)

It was found that, in general, increasing the "slag" flow rate increased the overall head for constant "lead" flowrate while increasing the "lead" flow rate decreased the overall head for constant "slag" flow rate. It appeared that the effect of increasing the flow of one phase was to increase its volume fraction in the hearth initially, and then to increase its outflow rate, after a new steady state was attained. Thus in the case of increased "lead" flow some "slag" was displaced from the builtup head to make room for the extra "lead". When a new steady state had been established inflows once again matched outflows for both phases but the proportion of stored "slag" as head was decreased - thereby decreasing the overall head. The opposite situation occurred for increasing "slag" flow at constant "lead" flow.

Flow Visualisation

Flow visualisation experiments were carried out in the model using wood chips as tracer particles. After saturating the chips in zinc chloride solution their density was close enough to the "lead" phase and moved about in the model with apparent neutral buoyancy tracing the fluid motion. Flow visualisation experiments were performed both with single "lead" phase and with "lead" and "slag". Velocity calculations for fluid elements were done by direct tracking against the grid on still frame video with the timebase.

Several series of observations indicated a standard flow pattern. Tracer particles injected into the forebay were swept along with the "slag /lead" inflow, rose to the top of the forebay then moved in an arc towards the bottom of the forebay. Before reaching the floor of the forebay the particles moved in a reversed flow back through the lower half of the under flow weir i.e., in a direction opposite to the original "slag/lead" inflow. The bottom quarter of the underflow weir passage consisted of a stagnant region which extended the entire length of the forebay and the hearth. There was no movement of tracer particles in this stagnant region. The backflow passed above the stagnant layer, travelling opposite to the outflow direction, until they reentered the hearth region. Finally they reach a turnround point where they were reentrained by the outflow current of the "slag/lead" flow thence back to the forebay. A smaller recirculation loop was also observed close to the outflow (Figure (2)).

Of particular note were the broad patterns of flow , illustrated in Figure (2) which never reached a steady state. They oscillated about the central region of the flow in a seemingly chaotic manner over long periods of time despite the steadiness of the input flows.

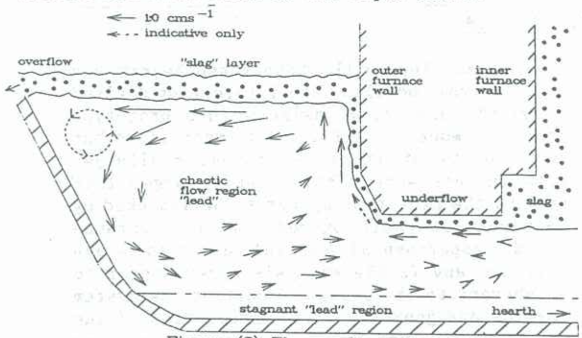

Figure (2) Flow pattern in underflow and tapper region of model

Residence Time Flows

Measurements of residence time distribution were done on the "lead" phase. The prototype ISF was also being traced at this time using radioactive tracers so an opportunity for a modelling comparison would eventually be available. It may be assumed that a similarity of residence time distribution would indicate a succesful simulation.

Tracing the residence time of zinc chloride solution as the lead model proved impossible with the chromatographic technique used so water was used as the lead phase. Figure (3) shows typical residence time curves. A notable feature is the difference between the distribution in one or two phase flow. The difference became apparent during calibration of the apparatus using flow only of the "lead" phase. When the second phase (oil or "slag") was introduced a significant change in the "lead" residence time was produced. This change may be attributed to the driving effect of the slag flow. As it moves under the weir ,up the back wall of the forebay and across the surface of the forebay the slag acts to produce the general recirculating flow pattern noted above. The denser phase (water) now recirculates vigourously to the extent of backflowing through the delivery channel. The oscillatory nature of the flow internally in the forebay in the short term and the surges characteristic of longer time periods make simple residence time models based on steady state networks inapplicable.

The "slag" phase flows at up to ten times the volume flow rate of the "lead" phase. It also moves through the underflow weir at a very high velocity in a small fraction of the cross section. This "slag" flow is driven by the available head of "slag" at the weir entry. This high speed stream is responsible for accelerating a part of the "lead" to an excessive velocity producing the recirculating backflow

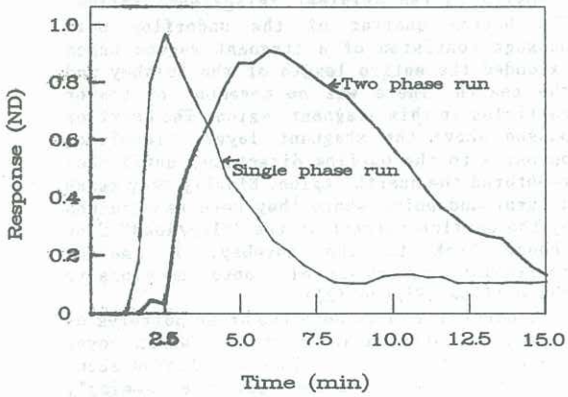

Figure (3) Residence distribution graphs

CONCLUSION

Two phase flow in the tapper and hearth may be effectively modeled. The information derived is useful, providing insights into prototype flows. The model is difficult to manipulate but some aspects of its flow present challenges worth further work. The unsteady surges that occur in the prototype appear to be mimicked by the model but their unpredictable occurrence outside experimental control at this stage precludes any facile analysis. They appear to be inherent to the system - part of the system dynamics and geometry . The interaction of the two flows in modifying the residence time characteristics of the lower volume flow seems interesting and worthy of further investigation.

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NOTATION

Fr	Froude Number
g	gravitational acceleration
Re	Reynolds Number
We	Weber Number
σ	surface tension
μ	dynamic viscosity
ρ	density

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