SLAG LADLE INSULATION

Slag from Pasminco's lead–zinc smelters, which is rich in zinc, is transferred in thirteen tonne capacity ladles from the blast furnace to the slag fuming furnace. The cycle time is about three hours. The Study Group was asked to examine whether heat could be conserved by some insulation strategy, without at any stage overheating the steel of the ladle.

1. Introduction

Pasminco metals–BHAS produce about 200,000 tonnes of lead and 40,000 tonnes of zinc annually at a lead–zinc blast furnace in Port Pirie. Slag produced from the lead smelting phase of the processing of lead–zinc ores contains a considerable amount of zinc. During the last twenty five years, it has been economic to process both current and stockpiled slag in a slag fuming furnace to recover the zinc.

In the smelting process, the molten slag from the lead smelter is passed to the zinc recovery process as soon as possible. This involves transporting the molten slag in thirteen tonne capacity ladles; the cycle time for those ladles is about three hours. The slag may be in transit for up to one and a half hours. Normally ladles are transported three at a time on a trolley from the blast furnace to the zinc fuming furnace.

An important part of the economics of the process is the conservation of heat. The slag freezes to some extent to form a 'skull', and has to be re-melted; the solid slag can interfere with the handling procedures. Drastic measures like "knocking" are used to break the crust to allow slag to pour out. Therefore it would be desirable to conserve heat by insulation as much as possible, and that was one of the issues to be studied at the MISG.

An extra difficulty is that the temperatures involved are quite high. The slag freezes at about 1100°C, while the steel material of the ladle loses strength at about 600°C. So an insulation strategy which raised the wall temperatures significantly could not be used. In fact, the layer of frozen slag which forms on the walls is essential to preserve the steel.

An illustration of the slag ladle is given in figure 1. The ladle is made of 50 mm thick steel, and weighs six tonnes. Its heat capacity is a significant part of the total heat budget.

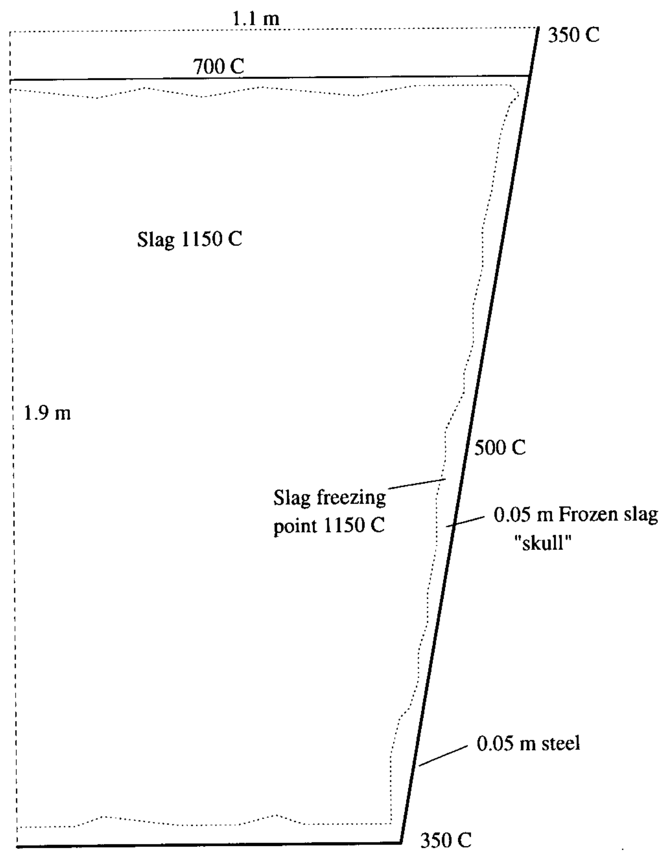

Figure 1: A slag ladle prior to pouring.

Broadly, the insulation strategies considered were:

1. Use of a lid, possibly insulated.
2. Insulation involving the walls, such as placing in an enclosed space.
3. Insulation on the return journey only, to conserve the heat retained in the steel.

The best strategy of all would be to insulate the interior of the ladle, but we understood that that would be impracticable.

In the text following, SI units are used.

2. Modelling the heat transfer processes

The basic physical processes which are to be modelled are:

1. Radiation. Because of the high temperatures involved, this is often the dominant mode of heat transfer. It is governed by the Stefan-Boltzmann law (Rohsenow *et al.*, 1985)

$$\text{flux} = e\sigma(T^4 - T_a^4) \tag{1}$$

   where e is the surface emissivity, $\sigma = 5.67 \times 10^{-8}$ watt $\text{m}^{-2}K^{-4}$ is the Stefan Boltzmann constant, T is the surface temperature, and T_a is the ambient temperature.

2. Convection. Convection through air boundary layers at vertical walls is the most important convective transfer process. It is described by a Nusselt number Nu and a Rayleigh number Ra. The Nusselt number is a dimensionless representation of the convective heat flux, defined by:

$$Nu = \frac{qL}{Ak\Delta T} \tag{2}$$

   where q is the flux, A the area (so q/A is the flux density), L is a characteristic length, usually the height of the wall, k is the thermal conductivity of the boundary layer material (here air), and ΔT is the temperature difference across the boundary layer.

   The Rayleigh number expresses the role of thermal buoyancy, and is here given by

$$Ra = \frac{g\beta\Delta T L^3}{\nu\alpha} \tag{3}$$

   where g is the acceleration due to gravity, β is the volume coefficient of expansion of the material, α is the thermal diffusivity and ν is the kinematic viscosity.

   The boundary layer heat transfer can be calculated from a semi-empirical formula relating these two dimensionless numbers. It is:

$$Nu = ((Nu_l)^6 + (Nu_t)^6)^{1/6} \tag{4}$$

   where

$$Nu_l = C_1 Ra^{1/4}, \quad C_1 \approx 0.5,$$

$$Nu_t = C_2 Ra^{1/3}, \quad C_2 \approx 0.091$$

Nu_l and Nu_t are the Nusselt numbers for laminar and turbulent convection, respectively. Equation (4) combines these two numbers to manage a continuous change from the laminar to turbulent regimes at about $Ra \approx 10^9$.

In the purely turbulent regime, combining equations (2-4) and rearranging gives

$$\frac{q}{A} = C_2 k (\frac{g\beta}{\nu\alpha})^{\frac{1}{3}} \Delta T^{\frac{4}{3}} \tag{5}$$

Convection from the top horizontal surface was ignored, because the area is smaller, the air speed is less than that adjacent to a vertical surface, and because the temperature was hotter, so that in any case radiation dominated.

3. Phase change. The slag is a glassy material, without a definite melting point. We were unable to find any data on latent heat of freezing, and it is possible that there isn't any, with the lack of apparent crystallisation. Consequently, we ignored latent heat.

4. Conduction. This is, of course, governed by the heat equation:

$$\rho C \frac{\partial T}{\partial t} = \nabla . \mathbf{q} = \nabla . (k \nabla T) \tag{6}$$

where ρ is the density, C is the specific heat, k is the thermal conductivity. A useful concept from this equation is the time constant, τ, for conduction, given by

$$\tau = \frac{L^2}{\alpha} = \frac{\rho C L^2}{k}$$

which is an indication of the time required to achieve a steady-state.

3. Physical observations and data

As is often the case with hot molten materials, it is difficult to measure many things, and physical properties can be hard to obtain. In this case, the molten slag properties, and their variation with temperature, are not well established. We used the following data, mostly obtained from Pasminco or Rohsenow *et al.* (1983):

Slag specific heat	950 J/kg
Slag freezing point	1100°C
Slag Thermal Diffusivity	$6 \times 10^{-7} m^2 s^{-1}$
Emissivity	0.7
External wall temperature (bottom)	350°C
External wall temperature (middle)	500°C
External wall temperature (top)	350°C
Temperature of top slag surface	700°C
Charging temperature of slag	1200°C
Average discharge temperature of liquid	1150°C
Skull thickness (average)	0.05 m
Steel	
Density	7850 kg m^{-3}
Specific Heat	670 J/kg
Thermal conductivity	30 W/m/K
Thermal diffusivity	$6 \times 10^{-6} m^2 s^{-1}$
Emissivity of dirty surface	0.7
Air 400K	
Dynamic viscosity	2.43×10^{-5} Pa s
Kinematic Viscosity	$2.64 \times 10^{-5} \ m^2 s^{-1}$
Density	$0.871 kg \ m^{-3}$
Thermal diffusivity	$3.8 \times 10^{-5} \ m^2 s^{-1}$
Thermal conductivity	3.36×10^{-5} W/m/K

4. Heat budgets

1. **Heat lost by slag during transfer**

   Here we worked on an observation that on average, of the thirteen tonnes of slag, three froze, and reached an estimated average temperature of 700°C, while the remaining ten tonnes dropped by 50°C from its original 1200°C. With the specific heat of slag (liquid and solid) given at 950 J/Kg, the total heat lost is:

$$10000 \times 950 \times 50 + 3000 \times 950 \times 500 \approx 19 \times 10^8 J$$

2. **Heat lost to environment during transfer**

   Time of journey — 1 hour.

   Side walls:

$$\text{Radiation flux density} = 5.67 \times 10^{-8} * 0.7 * (700^4 - 300^4)$$
$$\approx 9000 \ W/m^2$$

$$\text{Total radiation loss } = 9000\ W/m^2 \times 12m^2 * 3600s = 3.9 \times 10^8 J$$

Convection (working at average air temp 400K:

$$Ra = \frac{10ms^{-2} \times (700-300)/500 \times 8m^3}{2.64 \times 10^{-5} \times 3.8 \times 10^{-5}} = 6.4 \times 10^{10}$$

$$Nu_t = 0.091 \times Ra^{1/3} = 364, \quad Nu_l = 0.5 \times Ra^{1/4} = 251$$

$$Nu = ((364)^6 + (251)^6)^{1/6} = 370$$

$$q/A = Nu \times k \times \Delta T/L = 370 \times 3.36 \times 10^{-2} \times 400/2 = 2500\ Wm^{-2}$$

$$\text{Convective loss} = 2500 \times 12 \times 3600 \approx 1.3 \times 10^8 J$$

Top Surface Radiation:

$$\text{Radiation flux density} = 5.67 \times 10^{-8} * 0.7 * (1000^4 - 300^4)$$

$$\approx 36000 W/m^2$$

$$\text{Total radiation loss } = 36000 W/m^2 \times 3m^2 * 3600s = 3.9 \times 10^8 J$$

$$\text{Total exterior loss } = 3000 \times 12 \times 3600 = 9 \times 10^8 J \tag{7}$$

By subtraction, heat retained in steel ladle is:

$$(19-9) \times 10^8 = 10^9 J \tag{8}$$

which is sufficient to raise the average temperature of the steel by 250K.

3. **The return trip**

The heat stored in the steel on discharge of the slag is substantial, and it is shown here that most is lost on the return trip. It could be retained by insulation, although then the ladle would run significantly hotter at all stages.

On its return, the surface temperature of the steel is governed by the differential equation:

$$MC\frac{dT}{dt} = -Ae\sigma(T^4 - T_a^4) \tag{9}$$

where M is the ladle mass, T_a the ambient temperature, and A the ladle surface area (inner surfaces included).

This can be solved: $$\int_{T_0}^{T} \frac{dT}{(T^4 - T_a^4)} = -\frac{Ae\sigma t}{MC}$$

or using the trapezoidal rule:

$$\frac{T - T_0}{(\frac{T+T_0}{2})^4 - T_0^4} = -\frac{Ae\sigma t}{MC} \tag{10}$$

This equation determines the temperature decay of the steel shell. The time constant for conduction in the steel is

$$L^2/\alpha = 0.05^2/(6 \times 10^{-6}) \approx 400s$$

indicating that conduction in the steel will not significantly delay heat loss.

We now calculate the radiative losses in 1 hour, using (10):

Inside side walls	240 MJ
Inside bottom	54 MJ
Outside side walls	288 MJ
Outside bottom	43 MJ

It is possible the last figure should not be included, because the bottom is generally not exposed. However, the heat loss there is quite small. The total loss in one hour is 625 MJ, which compares with the 1000 MJ gained by the steel shell while the ladle is full. The values are not expected to balance, because there are also convective heat losses.

It is interesting to cost this loss, at an energy value of 10 cents per Kw hr, or about 3 cents per MJ which is probably close to the cost of energy used to reheat the slag. Each ladle trip would lose about $20 in heat radiated on the return journey. This is about $1000 per day, or $350 K per year. So it is certainly worth taking measures to save the energy if possible.

5. Skull dynamics and thickness

The sidewall skull is the only thing that prevents the steel being heated to unsustainable temperatures, so it is of interest to see what determines its thickness and thermal behaviour. There are various considerations which do ensure that the thickness is fairly stable and predictable.

Firstly it should be noted that the solid slag is quite a poor conductor. Nevertheless, a large part of the heat lost has to pass through it. That means that there is a substantial temperature drop across it. It also means that a significant part of the heat lost does not pass right through the skull, but comes from the further cooling of its outer layers.

We believed that as a reasonable approximation the liquid slag could be taken as generally well stirred, with a convective boundary layer close to the freezing zone. The reason for this belief is that the temperature, being close to the freezing point, must be held fairly constant, despite the large heat fluxes. The inner boundary condition, therefore, is approximately that of a constant flux at the freezing temperature. This is not so different from the condition that would be obtained in a semi-infinite solid slag conduction solution, and this is the most reasonable known solution for comparison. The characteristic distance associated with this problem is $\sqrt{\alpha t} = \sqrt{2 \times 10^{-7} \times 3.6 \times 10^{3}} = 0.027$ m. The layer thickness is approximately this distance multiplied by $\log((1150 - 400)/(1150 - 1100)) \approx 2.5$ or about 0.07m, which is close to the estimated value.

The skull dynamics, and the requirement not to overheat the steel, ensure that there is an inevitable loss of heat into the steel. This is the amount of heat loss required to freeze a skull thick enough to keep the steel temperature down. So while it is desirable to conserve the heat carried in the ladle, it essential to ensure that it retains sufficient cooling capacity to create this protective skull.

Since the skull dynamic behaviour is important, and not obvious, it was modelled using the program *Fastflo*™ being developed at CSIRO Division of Mathematics and Statistics. Simplifying assumptions made were

- The thermal conductivity of liquid slag was twenty times that of solid.
- Radiation from the outer wall was the only form of heat loss.
- The temperature at the inside of the domain (10 cm from the wall) was held constant at 1150^{o}C.
- The initial temperature of the steel was 100^{o}C in figure 2(a) and 300^{o}C in figure 2(b).
- Otherwise, all thermal and fluid properties were independent of temperature.

Figure 2 shows the course of events during the first hour, in the steel wall of the ladle and the inner 10cm of slag. It is a temperature contour plot in a space-time plane; the bottom of the plot is the exterior wall. The top 1100^{o}C contour represents the edge of the skull. It is clear that this grows rapidly initially and then stabilises. The extent to which it stabilises the temperature in the steel is clear from the near horizontal contours at the interface. An interesting effect of the skull growth is the plateau reached by the outer wall temperature in figure 2(a), and the maximum reached in figure 2(b). This occurs because a large part of the heat in the steel enters in the first few minutes, and supply at that rate is not continued because of the relatively insulating skull.

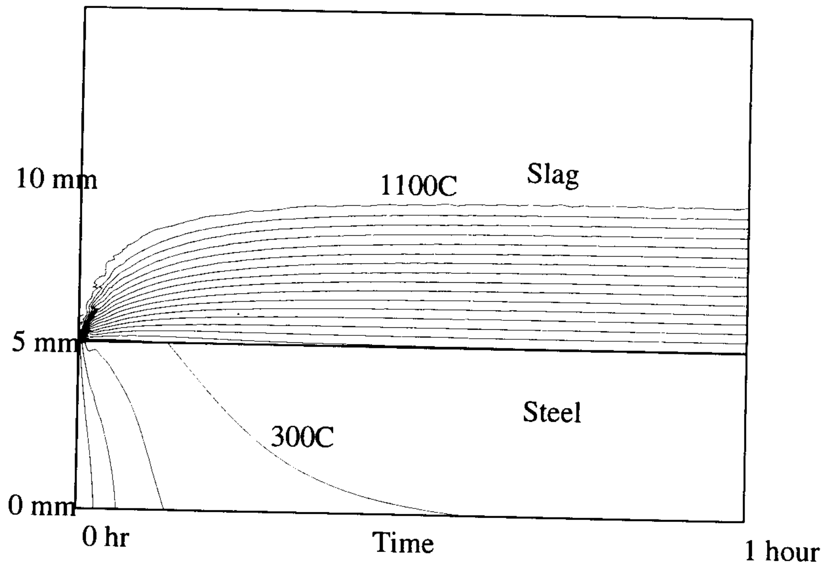

Figure 2(a): Skull formation at side wall. Steel initially at 100 C.
Temperature contours {100C, 150C ...1100C} in space-time plane.

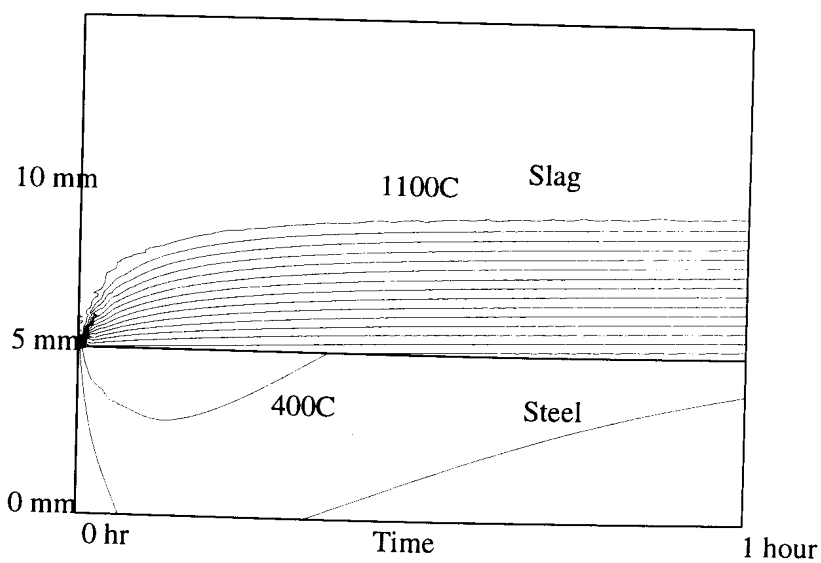

Figure 2(b): Skull formation at side wall. Steel initially at 300 C.
Temperature contours {300C, 350C ...1100C} in space-time plane.

Some possible inferences from figures 2(a, b) are:

- The skull thickness is not greatly affected by the initial steel temperature.
- At the higher temperature, the greater effect of radiation ensures that the temperature rise is smaller, and passes through a peak.

However it should be emphasised that this is a preliminary analysis, not actually done at the MISG, and that more research would be needed before the conclusions could be fully relied on. They are however promising, suggesting that the initial steel temperature does not have a great effect on the maximum temperature reached, provided free radiation while charged is permitted.

These are some details of the computer model. The solution algorithm was finite element in both space and time, with an unstructured mesh of quadratic triangle elements. There were 3840 elements, with a total of 7839 nodes. The mesh was concentrated about the steel/slag interface at t=0. A Newton–Raphson algorithm converged in four iterations.

The roughness of the contours near t=0 is caused by the initial temperature discontinuity, and the roughness of the 1100°C isotherm is caused by the discontinuity of the thermal conductivity at the phase interface. A virtue of the fully finite element procedure used is that it remains stable despite the numerical difficulties associated with the discontinuities.

6. Discussion

Surprisingly, according to our calculations, the amount of heat stored in the ladle at discharge is almost as much as the heat lost during the transfer of the full ladle. Most of this heat is then lost to the air in the return cycle.

The considerations in the previous section suggest that while there is a limit to the extent to which this return heat can be conserved, because of the steel running hotter, nevertheless there may be more scope for insulation on the return trip than was originally anticipated at the MISG.

A useful observation was that the majority of the heat lost from the slag was not from the cooling of the part that remained liquid, nor the cooling represented by the initial solidification, but rather from further cooling of the slag that had already frozen. Although this is only about three tonnes, its temperature drop is on average about 500°K.

7. Recommendations

1. **Insulated lid.**

   An insulated lid is a good idea. During slag transport it will block the top radiative flux, which is about 40% of the total heat loss. The coupling to the side wall temperature is through the liquid, and since this can vary only slightly, the coupling is weak. So there should be little increase in the temperature of the steel.

   It is likely that with an effective lid, the top skull will almost vanish, with the temperature at about 1100°C. The bottom surface of the lid would have to come into radiative equilibrium with this — i.e. at about the same temperature. So here also the thermal endurance of whatever material makes up this surface is of concern.

   Both for the lid to be effective, and for the temperature to be tolerated, an appropriate insulating material would be needed. The aim might be to reduce the flux density from 100 kW m^{-2} to about 5 kW m^{-2}, so that $h \approx 5Wm^{-2}K^{-1}$. According to the published ratings, about 30 mm thick Durablanket on the underside should achieve this. Exterior insulation would also prevent heat loss, but would not protect the steel.

2. **Insulate the ladle on the return trip only (perhaps)**

   A blanket, or insulated storage cavity, could be added to save up to 600 MJ per ladle per trip, *but* this saving would be more closely coupled to the steel temperature. It would be hotter on subsequent loading, and would run at a higher temperature at all stages. The preliminary calculations of the previous section suggest that this effect may be of only moderate importance — the rise in peak temperature may be only about half the rise in initial temperature. However, these calculations would need to be done more fully, and even then we would strongly advise close monitoring of the steel temperature during the subsequent loaded phase, even if the insulating effect had been removed during that phase.

3. **Do not insulate, externally, while loaded**

   Doing so would directly raise the steel temperature, and very little saving could be achieved before the limiting temperature was reached.

4. **Monitor the wall temperature for overheating**

   Any effort to save heat will have some tendency to raise the steel temperature. The monitoring should allow for the inside wall being at least 60°C greater than the outside.

References

W.M. Rohsenow, J.P. Hartnett and E.N. Ganic, (Eds), *Handbook of heat transfer fundamentals* (McGraw-Hill, NY, 1985).

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