Heat losses from ladles during teeming

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SYNOPSIS

In an investigation of the loss of temperature by liquid steel during a teeming operation, a numerical technique was used to calculate the heat flows and the rate of temperature drop over the entire teeming operation. The calculations show that, before teeming, approximately 50 per cent of the heat loss is into the ladle wall at the level of the metal. As teeming progresses, the amount of heat lost by radiation to the wall above the metal line increases. The effect of variables, such as initial metal temperature, the preheat of the ladle and ladle cover, and delays, on the rate of temperature loss by the metal were determined.

SAMEVATTING

Daar is in 'n ondersoek na die temperatuurverlies van vloeibare staal tydens 'n gietproses van 'n syfertegniek gebruik gemaak om die warmtevloei en tempo van die temperatuurdaling oor die hele gietproses te bereken. Die berekenings toon dat ongeveer 50 persent van die warmteverlies voor die gieting aan die oppervlak van die metaal in die wand van die gietlepel in is. Namate die gieting vorder, neem die hoeveelheid warmte wat deur straling na die wand bokant die metaalvlak verlore gaan, toe. Die uitwerking van veranderlikes soos die aanvanklike metaaltemperatuur, die voorverhitting van die gietlepel en sy deksel, en vertragings, op die tempo van die temperatuurverlies deur die metaal is bepaal.

INTRODUCTION

The quantitative assessment of the heat losses that occur when molten steel is held or transferred in ladles is important in process-design considerations, because the temperature of the metal may have to meet rigid specifications in certain stages of the processing sequence. The particular case considered in this investigation is a teeming ladle filled from a steelmaking furnace and ready for subsequent use in continuous casting or in the production of steel ingots.

The principal mechanisms responsible for heat loss from the molten metal are conduction into the walls of the ladle, and radiation from the top exposed surface of the metal (possibly augmented by natural convection).

The conductive loss can be calculated by an exact determination of the partial differential equations involved[1] or by a numerical approach[2].

The determination of the radiation component of the heat loss is less straight forward. The radiative heat loss from the surface of molten steel held in a ladle has been considered[3]. However, during teeming the radiation heat-transfer condition is complicated by the fact that the temperature of the section of the ladle wall that has been in contact with the molten metal is high compared with the temperature of the rest of the wall.

The purpose of this paper is to present a general formulation of the problem, the solution of which should permit the definition of the relative amounts of heat loss from the molten metal and the rate of temperature loss by the metal during teeming. The variables that will be investigated include initial steel temperature, geometry, thermal properties, and various modes of preheat.

THE PROBLEM

For simplicity, the ladle is regarded as cylindrical (Fig. 1). The molten metal is added to a ladle having a preheat that is assumed to be uniform throughout the ladle refractory. The problem is to calculate the net rate of heat loss from the molten metal as a function of holding and teeming time at various ladle geometries, initial temperature distributions, and thermal properties of the system.

The following assumptions are made.

(1) The gas within the ladle enclosure is transparent with respect to radiation. This is correct when gases such as carbon dioxide and hydrogen oxide are present in only small concentrations.

(2) Convection within the enclosure can be neglected. At the high temperatures involved, thermal radiation predominates over natural convection, and this assumption therefore appears reasonable.

(3) Owing to the difference in temperature between the section of the ladle wall that is in contact with the molten metal and that which is above the molten metal, temperature gradients are considered in both the x- and y-direction. It is necessary to consider a temperature gradient in the y-direction because of the temperature changes imposed on the ladle wall during teeming of the metal.

(4) As the wall thickness is small compared with the vessel diameter, conduction through the wall is regarded as planar, thus permitting a numerical solution of the problem.

(5) The thermal conductivities and diffusivities of the refractories are considered to be independent of temperature. This is an oversimplification. However, it is desirable in order to render the results more general for comparison.

(6) The temperature of the metal is homogeneous. This assumption is reasonable owing to the large amount of natural convection that will be generated[4] as a result of heat losses from the surface of the molten metal. Further direct experimental support is provided by the work of Hlinka and Miller[5], who demonstrate that good mixing will

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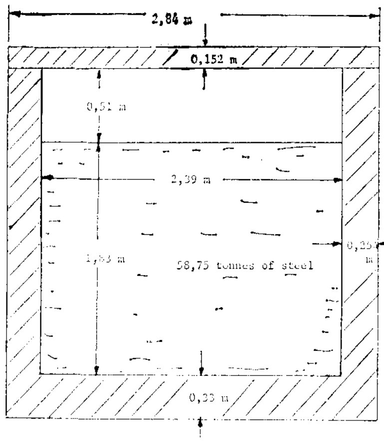


Fig. 1—Dimensions of the refractory ladle, and the data used in the calculations

Initial metal temperature	1 540 °C
Ladle preheat	400 °C
Cover preheat	21 °C
Ambient temperature	20 °C
Thermal conductivity	0,002 5 cal $cm^{-1}s^{-1}$ $°C^{-1}$
Heat capacity of refractory	0,156 cal g^{-1} $°C^{-1}$
Thermal diffusivity of refractory	0,008 05 cm^2s^{-1}
Heat capacity of molten steel	0,184 cal g^{-1} $°C^{-1}$
Molten steel emissivity	0,28
Refractory emissivity	0,75
Density of molten steel	7,20 g cm^{-3}
Density of refractory	1,99 g cm^{-3}
Casting rate	1,47 t min^{-1}
Holding time	40 min

occur under conditions approximating those considered here.

(7) All surfaces are grey, and are diffuse emitters and reflectors of radiation. This is a normal assumption and seems justified here, where rough surfaces of not readily defined radiation properties are being considered.

(8) The temperature outside the walls is constant at the ambient temperature.

(9) The surface of the molten steel is free of slag. The effect of slag on the radiation heat loss has been investigated by Szekely and his co-workers[6, 7].

Within the framework of the assumptions, a heat balance can be established over the three bounding surfaces of the molten steel. The conduction of heat through the refractory is calculated according to the methods described by Dusinberre[2]. The heat-transfer coefficients for natural convection from the ladle top, walls, and bottom are taken from Schuhmann[8]. The radiation enclosure between the upper surface of the molten steel, the ladle enclosure, and the top is treated as a three-body radiation problem[9], and the radiation emitted from the ladle enclosure is integrated numerically over the height of the ladle enclosure.

The system was solved by use of a numerical technique involving a stepwise integration. The IBM 360/75 digital computer of the University of the Witwatersrand was used for this purpose. Details of the numerical

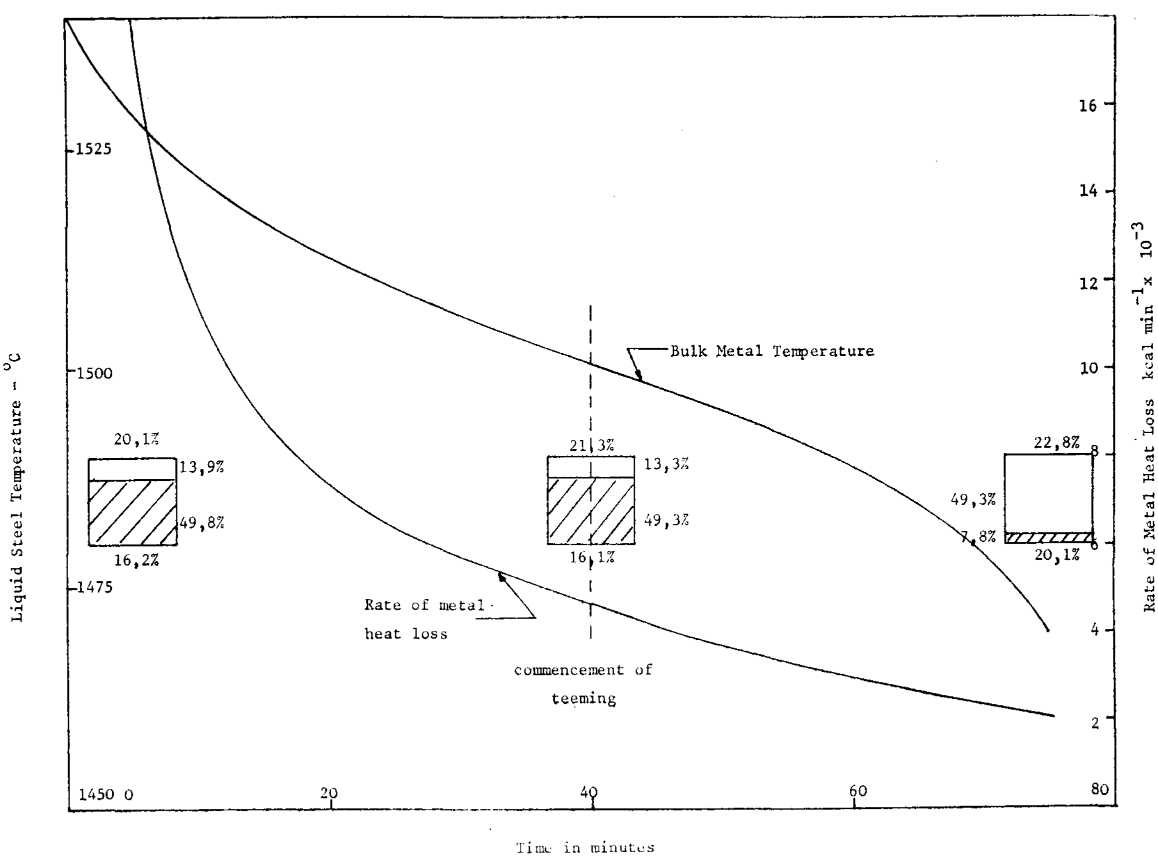


Fig. 2—The rate of heat and temperature loss from the liquid steel for the conditions described in Fig. 1

technique are given in the Appendix.

RESULTS

The computed results are presented in Figs. 2 to 9, the properties used for the calculations being given in Fig. 1. The parameters were varied, the values in Fig. 1 always being used as the standard condition. The examples given here were chosen to illustrate the effect of variables that are thought to be of significance in practice. The general case investigated is plotted in Figs. 2 and 3.

Heat is lost from the metal by radiation to the enclosure above the melt line and by conduction through

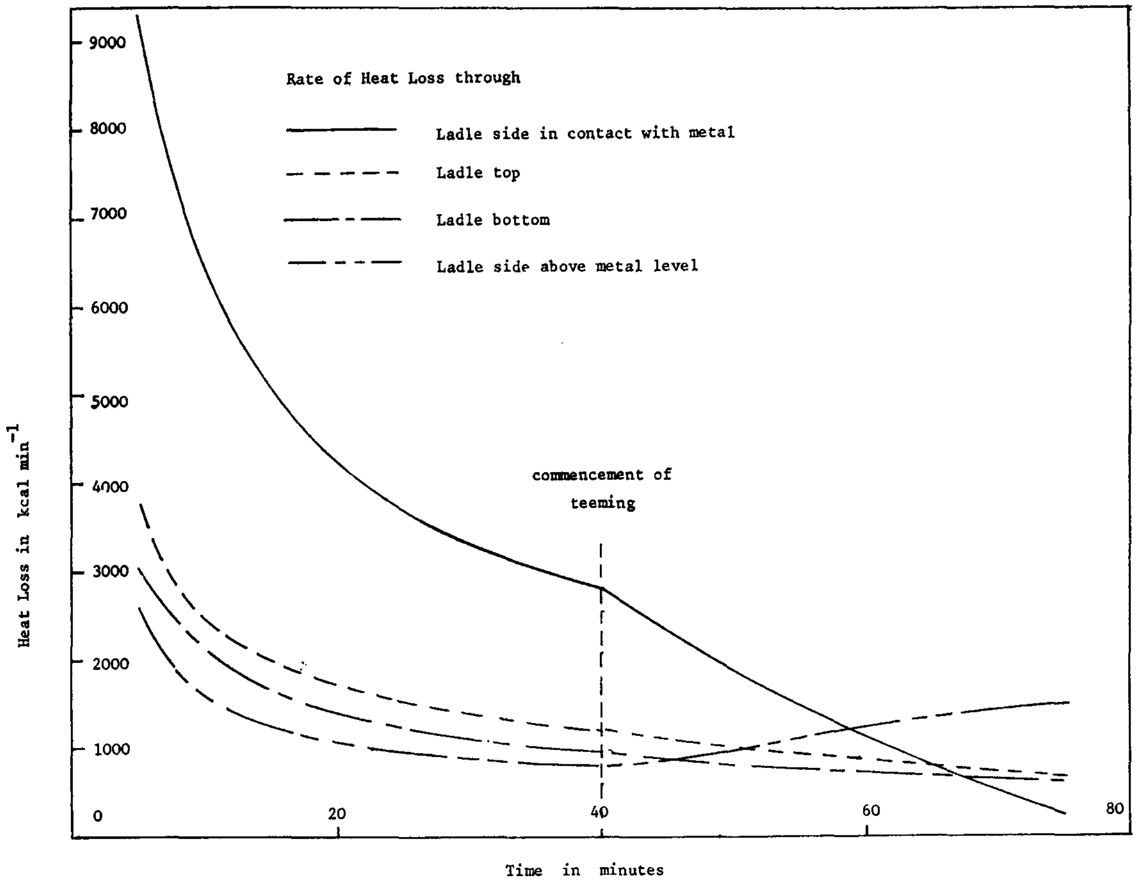


Fig. 3—The rate at which heat is lost from the different segments of the ladle

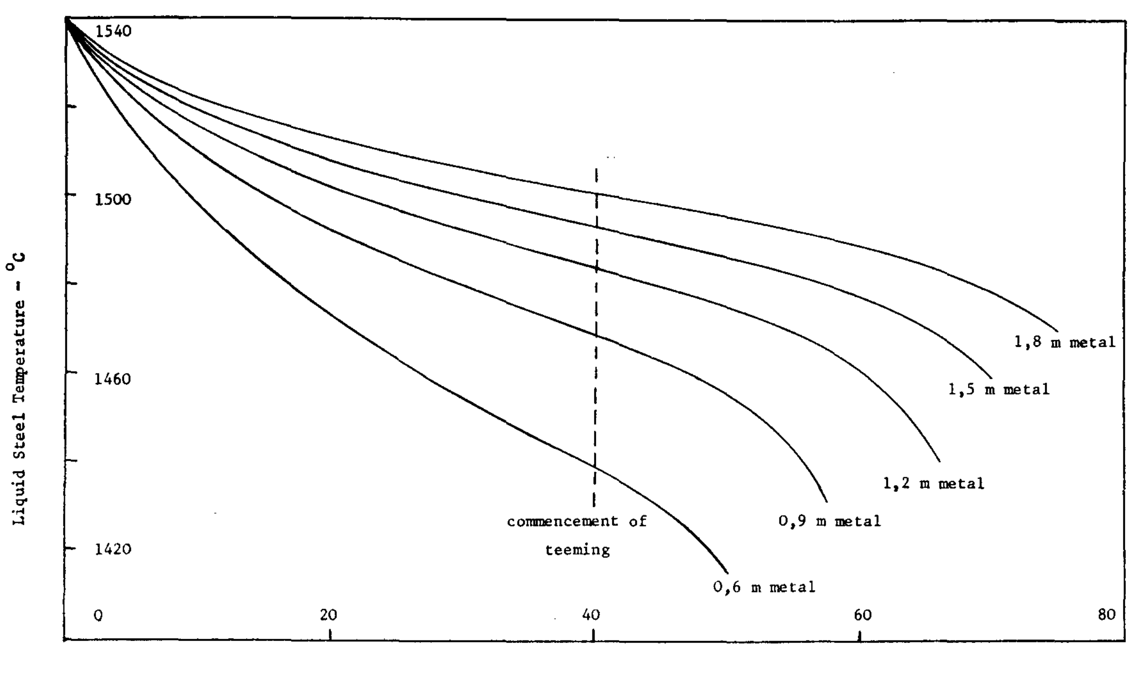


Fig. 4—The variation in temperature loss from the bulk steel for different degrees of ladle fill

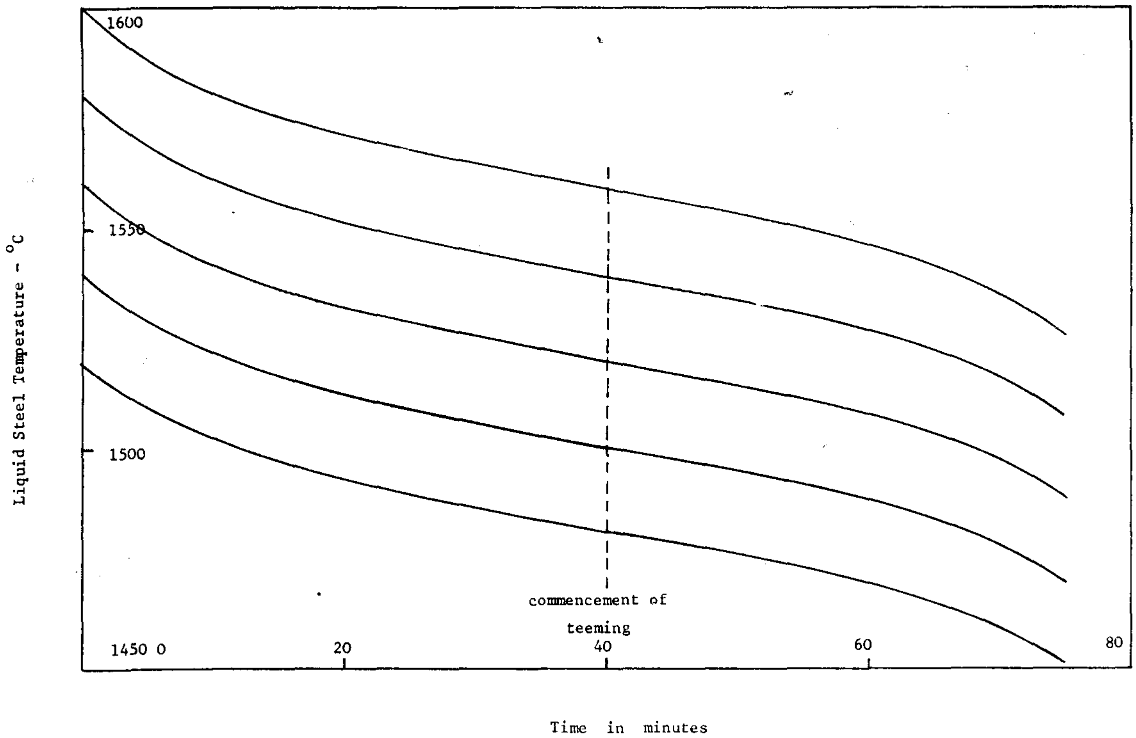


Fig. 5—The variation in temperature loss from the bulk steel for different initial steel temperatures

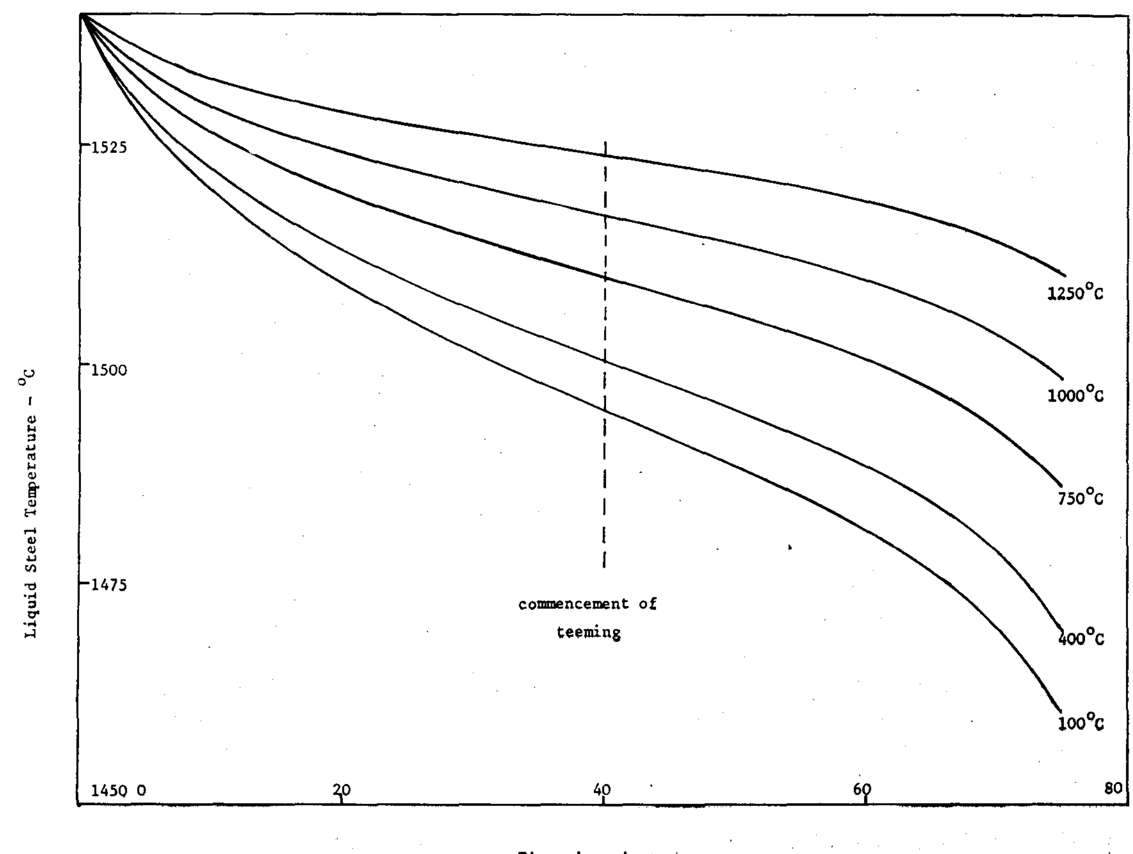


Fig. 6—The effect of ladle preheat on the rate of temperature loss from the molten steel

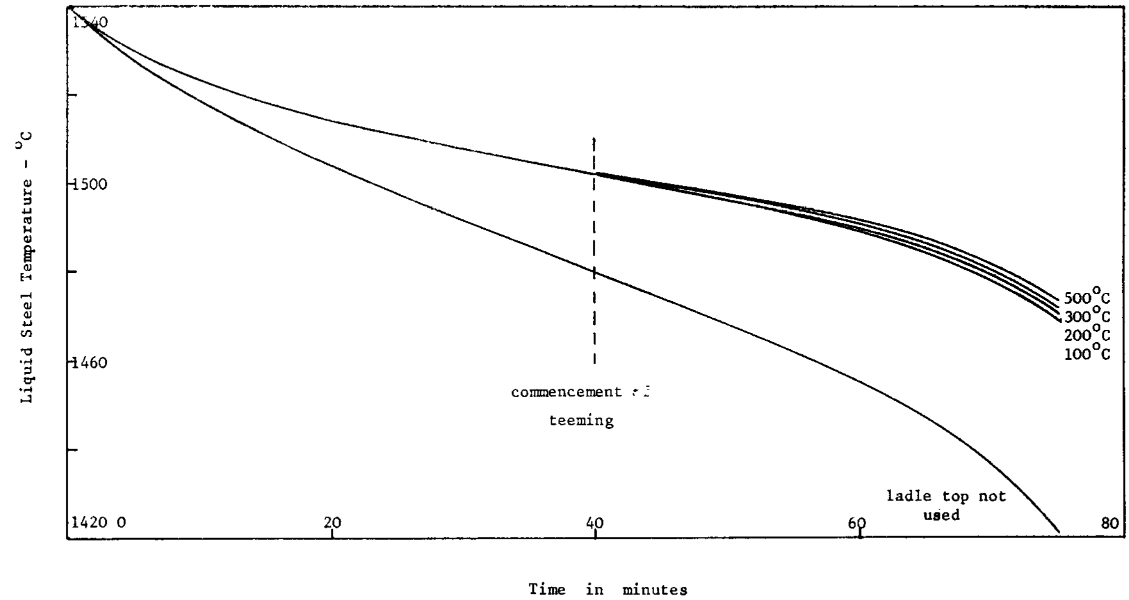


Fig. 7—The effect of ladle-top preheat on the rate of temperature loss from the molten steel

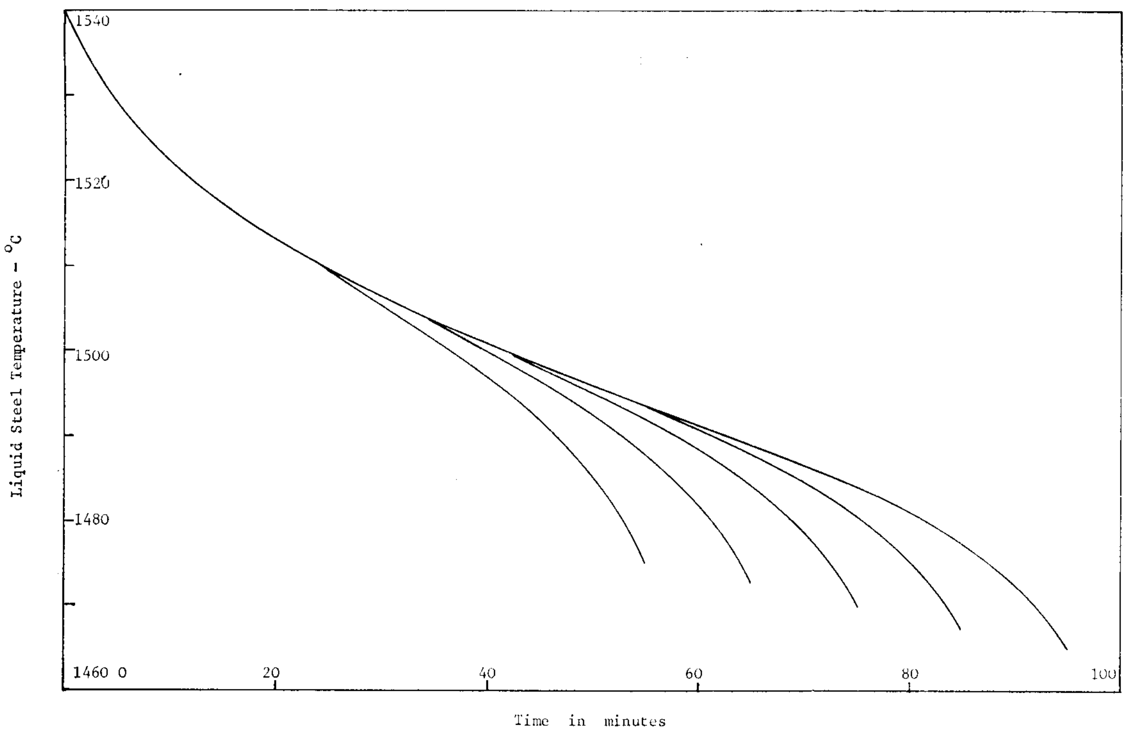


Fig. 8—The effect of delay before teeming on the rate of temperature loss from the molten steel

the brickwork under the melt line. As heat is lost from the metal by unsteady conduction of heat through the brickwork, the rate at which heat is lost (and thus the rate of temperature changes in the metal) decreases with time. However, during teeming a smaller and smaller volume of metal gives up approximately the same amount of heat to the brickwork, and the rate of temperature lost by the metal increases. At the end of the teeming operation, the rate of temperature loss approaches infinity, with the result that ladle skulls would form at the later stages of teeming—a common occurrence in practice. Such severe temperature drops can be minimized by the presence of a slag layer, which in turn can eliminate the frequency and extent of ladle skull formation. Thus Fig. 4 illustrates the detrimental effect, on the temperature of the metal, of failure to use the full capacity of the ladle.

Calculations show that the heat lost by the molten metal is used to heat up the brickwork of the ladle. This means that virtually no heat is lost through the brickwork to the surrounding air, and the ambient temperature will have relatively little effect on the heat lost by the molten metal. The outside surface of the ladle should not show any appreciable increase in temperature during the operation. Fig. 5 shows that the initial temperature of the metal has very little effect on the rate of temperature lost by the metal. Fig. 6 shows how the preheat temperature of the ladle affects the heat lost by conduction through the ladle walls. On the other hand, there is no significant gain when the cover of the ladle is preheated (Fig. 7). This is due to the relatively small surface area of the lid compared with that of the ladle. However, in the absence of a reflecting lid, the rate of heat loss of the metal is increased substantially. Fig. 8 shows that the penalty for delay before the commencement of teeming is about $\frac{1}{4}$ °C for every minute's delay.

TABLE I
THE TYPES OF FIREBRICK CONSIDERED

Type	Density	Mean thermal conductivity	Heat capacity
	g cm^{-3}	cal cm^{-1}s^{-1} °C^{-1}	cal g^{-1} °C^{-1}
41 % Al_2O_3	1,99	0,002 5	0,156
37 % Al_2O_3	2,05	0,002 1	0,160
30 % porosity	1,84	0,002 5	0,144
Insulating brick (used only for the ladle bottom)	0,74	0,000 9	0,058

The effect of brick quality on the rate of heat loss by the metal in the ladle was investigated. Table I lists the different bricks considered, and Fig. 9 shows the expected performance of the ladles when these bricks are used.

CONCLUSIONS

It has been shown that theoretical calculations can indicate the rate of heat loss from a molten metal contained in a refractory ladle. Theoretical calculations have an advantage over measurements taken on site in that the former permit the testing of variables affecting the heat loss and indicate the amount of heat lost in each segment of the ladle.

Based on the findings presented, a number of recommendations can be made for the reduction of heat losses. As already pointed out, ladle preheat is important, and it would be advantageous to 'up end' the ladle and play the burners on the base of the ladle, where the preheat is most useful during the teeming operation. If ladles could be re-used every two hours or so, temperature losses from the metal could be reduced. A common practical problem in the preheating of a

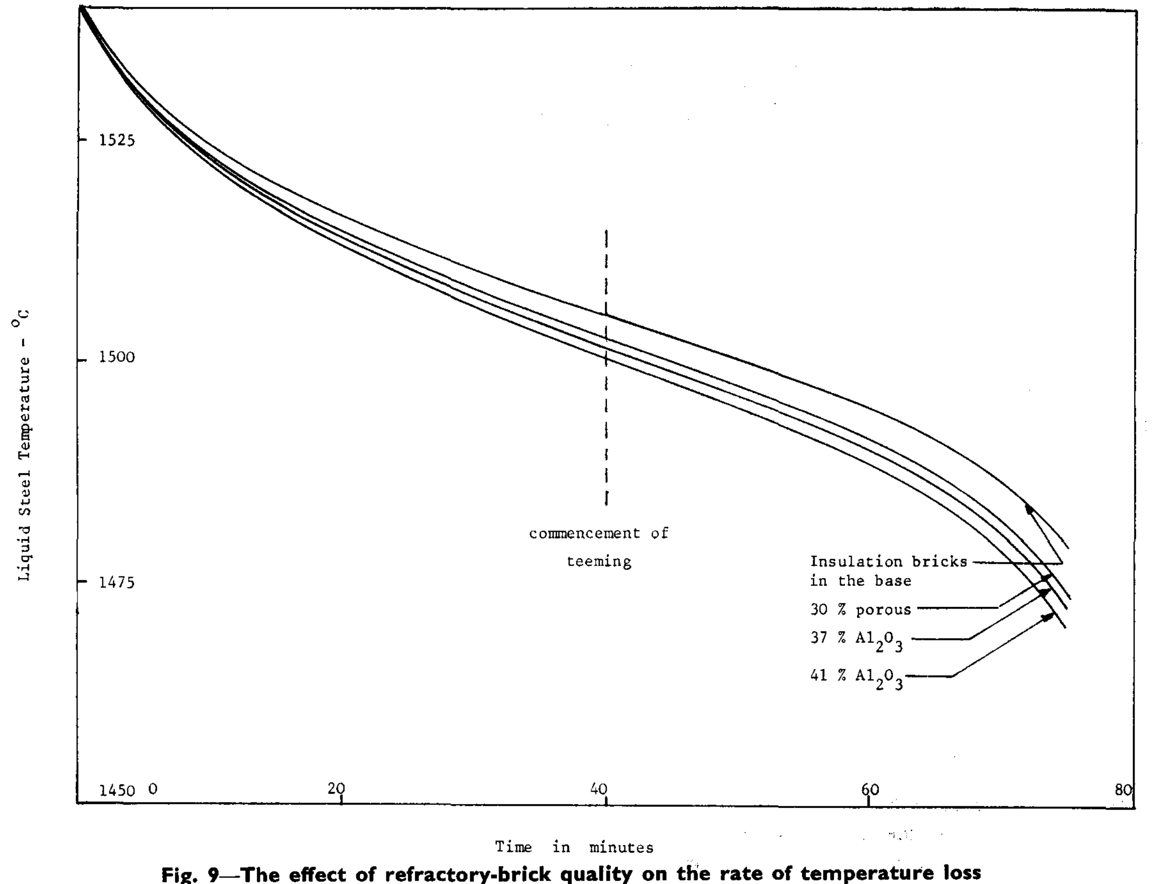


Fig. 9—The effect of refractory-brick quality on the rate of temperature loss from the molten steel

ladle to a high temperature is that slag remaining in the ladle will tend to flow and clog the stopper rod. This problem can be partly overcome by use of a slide-gate nozzle.

The advantage of a ladle cover was shown to arise from the accompanying reduction of radiation losses during holding and teeming of the metal. Reduction in the emissivity of the molten steel surface by additions of vermiculite can result in a lower rate of heat loss by radiation from the steel surface. Preheating of the cover, however, offers little improvement to the operation.

For good insulation, the best refractory bricks for the ladle would have a low thermal conductivity, a low density, and a low heat capacity. Porous bricks would satisfy these requirements and could be used as a sandwich layer in the base of the ladle, which is the last part of the brickwork to be in contact with the molten metal.

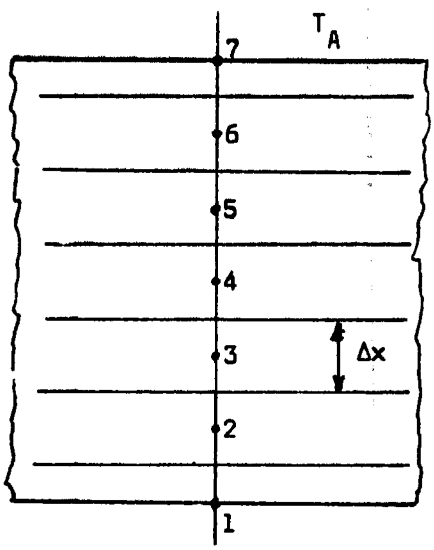
APPENDIX

A rectangular grid was constructed over the refractory of the ladle, the ladle being regarded as four different sections: the lid, the bottom, the sides in contact with the molten metal, and the sides above the level of molten metal.

The initial temperature distribution was known, and the computation began by an estimation of the initial values for the heat lost by the metal to the four different sections of the ladle. The values of the net heat fluxes thus calculated were considered constant for a finite time period (taken as 1 minute), and were used in the calculation of the temperature distribution within the system at the end of that time period.

Cover of the Ladle

The cover of the ladle is subdivided vertically into six slices.



$$T_{7,t+\Delta t}=T_{7,t}(1-2(M+H_c))+2MT_{6,t}+2H_cT_A,$$

$$T_{n,t+\Delta t}=T_{n,t}(1-2M)+M(T_{n+1,t}+T_{n-1,t})$$

$2 \leqslant n \leqslant 6$, and

$$T_{1,t+\Delta t}=T_{1,t}(1-2(M+H_r))+2MT_{2,t}+2H_rT_M,$$

where $M=\dfrac{a\Delta t}{\Delta x^2}$,

$$H=\frac{hM\ \Delta x}{k},$$

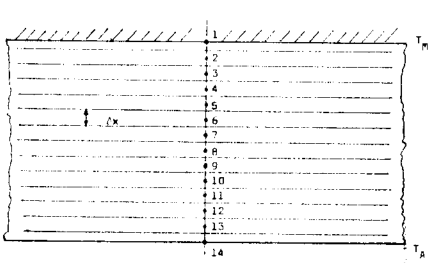
$h_c=0{,}38\ (T_{7,t}-T_A)^{0,25}$, and

$$h_r=\frac{\dot{q}_r\Delta t}{A(T_M-T_{1,t})}.$$

$\dot{q}_r$ is the radiative heat flux from the surface of the molten metal.

Bottom of the Ladle

The bottom of the ladle is subdivided vertically into thirteen slices:



$$T_{1,t+\Delta t}=T_M$$

This represents the maximum heat transfer rate from the metal—a heat-transfer boundary layer is not considered.

$$T_{n,t+\Delta t}=T_{n,t}(1-2M)+M(T_{n+1,t}+T_{n-1,t})$$

$2 \leqslant n \leqslant 13,$

$$T_{14,t+\Delta t}+T_{14,t}(1-2(M+H_c))+2MT_{13,t}+2H_cT_A,$$

where $M=\dfrac{a\Delta t}{\Delta x^2}$, and

$$H_c=\frac{h_cM\Delta x}{k}.$$

Heat loss by conduction from the metal through the refractory is determined according to Fourier's Law:

$\dot{q}=-kA\dfrac{dT}{dx}$ metal/refractory interface, where $\dot{q}$ represents the amount of heat lost over the time interval (1 minute). The heat lost from the surface of the metal by radiation is determined according to the three-body enclosure described by Hottel and Sarofim[9]. The three radiating surfaces are the molten metal, the cover of the ladle, and its side wall. The black-body radiation from the side wall of the ladle is the sum of black-body radiation from the area of each slice.

Side of the Ladle

The side of the ladle is subdivided into ten slices horizontally, and the vertical thickness of each slice corresponds to the distance the metal is teemed in the time interval (for 1 minute at a teeming rate of 1,47 tonnes per minute, the ladle wall is subdivided into 52 slices).

For heat conduction in the vertical direction,

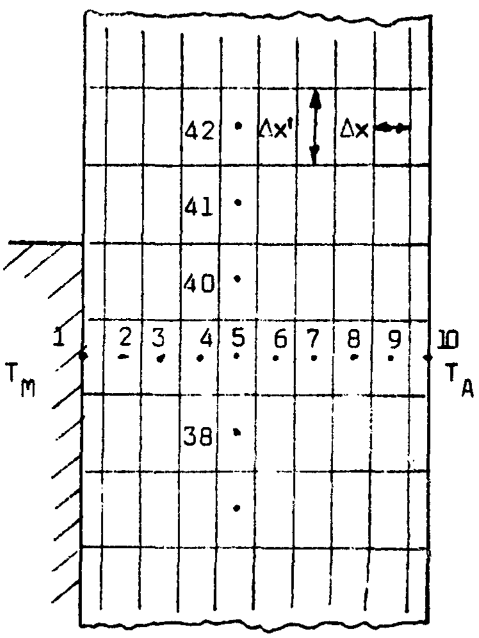
$$T_{n,t+\Delta t}=T_{n,t}(1-2M)+M(T_{n+1,t}+T_{n-1,t}),$$

where $M=\dfrac{a\Delta t}{\Delta x'^2}$.

The subsequent heat loss of the metal is converted into a temperature loss over the time interval of 1 minute:

$$\Delta T=\frac{q}{m\,Cp},$$

where q =heat loss in one minute,
m =mass of metal losing heat,
Cp =heat capacity of liquid metal, and
ΔT=temperature lost by metal.



$$T_{1,t+\Delta t}=T_{1,t}(1-2(M+H_r))+2MT_{2,t}+2H_rT_M.$$

Above metal level,

$$T_{1,t+\Delta t}=T_M \text{ (neglecting any boundary layer at the wall)},$$

$$T_{n,t+\Delta t}=T_{n,t}(1-2M)+M(T_{n+1,t}+T_{n-1,t})$$

$$2\leqslant n\leqslant 9, \text{ and}$$

$$T_{10,t+\Delta t}=T_{10,t}(1-2(M+H_c))+2MT_{9,t}+2H_cT_A,$$

where $M=\dfrac{a\Delta t}{\Delta x^2}$, and

$$H=\frac{hM\Delta x}{k}.$$

$$h_c=0{,}27(T_{10,t}-T_A)^{0{,}25}, \text{ and}$$

$$h_r=\frac{\dot{q}_r\Delta t}{A(T_M-T_{1,t})}.$$

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Diluents for the solvent extraction of metals

A symposium on the above subject is to be given by the Solvent Extraction and Ion Exchange Group of the Society of Chemical Industry on 21st February, 1974, in Bristol, England. For the following day, a works visit has been arranged to Imperial Smelting Corporation, Avonmouth.

Further information can be obtained from Mr T. V. Healy, Applied Chemistry Division, Building 220, A.E.R.E., Harwell, Didcot, Berks, England.