HEAT TRANSFER DURING FIRST STAGE OF CONVERTER MELTING

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A mathematical analysis applicable from the start of melting to "blow-through" is given. The varying liquid temperature and the growth kinetic and melting of the cast iron layer on scrap metal surfaces are assessed.

In steel converter melting, liquid pig iron is often poured onto cold metal scrap which absorbs heat at a high rate from the iron. As a result the temperature of the iron is lowered and a solid layer may be formed on the surface of the scrap [1, 2]. As the scrap is heated the growth of the cast iron crust slows and finally stops when thermal equilibrium is reached at its inner and outer boundaries. A gradual remelting of this layer then begins.

The crystallization of a melt when a plate is immersed in it has been analyzed [3-5]. Solidification and subsequent melting of layer on the surface of such scrap in a converter is also reported [1, 2] for constant liquid temperature.

In practice the liquid temperature does not remain constant because mass of the cold scrap is often an appreciable fraction (25%) of the iron. It is therefore of interest to study the solidification of the liquid iron under conditions of changing temperature. Further, for operational reasons it is important to estimate quantitatively the cooling effect of the scrap on the liquid.

The authors investigated the crystallization in a melt by cooling the liquid bath and made estimates of its temperature which allowed the cooling effect of scrap to be determined from the first stage of converter operation.

The heat transfer during this period is similar to that in heating an infinite steel plate under a layer of liquid iron (Fig. 1).

The following assumptions were made: 1) the solidifying iron layer is taken to be a "fine" body of temperature t_s; 2) at the time of contact of the liquid iron with the scrap material the surface temperature rises continuously to t_s and remains constant at this value during the lifetime of the solidified iron layer; 3) all heat emitted by the iron is taken up by the scrap (the bath was well insulated from the surroundings); 4) at any time the liquid temperature is kept constant throughout the liquid by intense circulation; 5) the time of cooling the melt is divided into stages during which the liquid temperature remains constant and at the end of which it drops instantaneously ("step" temperature changes in liquid iron); 6) all the scrap for melting is made up of pieces (plates) in similar contact with the liquid; 7) the thermophysical data are constant.

The mathematic representation of these conditions of heat-transfer is

$$\frac{\partial t}{\partial \tau} = a \frac{\partial^2 t}{\partial x^2}, \quad 0 < x < s_0, \quad \tau > 0$$

with the boundary conditions

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TABLE 1.

Sample number	Initial height of liquid layer of iron, m	Initial temperature, °K	Heat transfer coefficient, W/(m²deg)	Time of solid growth, sec	Time of solid layer existence, sec	Maximum solid layer thickness, m	Liquid temperature at completion of solid layer remelting, °K	Decrease in liquid iron temperature during the existence of solid layer, °K
1	0,44	1623	8374	24	77	$11{,}3\cdot10^{-3}$	1588,7	34,3
2	0,308	1623	8374	25	89	$11{,}5\cdot10^{-3}$	1567,6	55,4
3	0,22	1623	8374	28	114	$11{,}7\cdot10^{-3}$	1534,4	88,6
4	0,088	1623	8374	21	67	$10{,}9\cdot10^{-3}$	1493,3	129,7
5	0,44	1623	6280	45	167	$19{,}6\cdot10^{-3}$	1575,2	47,8
6	0,308	1573	8374	61	339	$21{,}1\cdot10^{-3}$	1479	144

$$t(x,\ 0) = t_0,\quad t(s_0,\ \tau) = t(s_0 + \xi,\ \tau) = t_s,\quad \frac{\partial t(0,\ \tau)}{\partial x} = 0,$$

$$\alpha(\bar{t} - t_s) + r\gamma\frac{d\xi}{d\tau} = \lambda\frac{\partial t}{\partial x} \tag{1}$$

and the thermal equilibrium equation for the time $d\tau$

$$c\gamma h d\bar{t} + c\gamma d\xi(\bar{t} - t_s) + r\gamma d\xi = q, \tag{2}$$

where q is the heat absorbed by the plate.

This model was treated using a finite differences method. The equations (1) and (2) for any time interval were expressed by the finite difference as follows

$$\alpha(\bar{t}_{k-1} - t_s)\,\Delta\tau + r\gamma\Delta\xi_k = \frac{2\lambda}{\Delta x}(t_s - t_{1,k-1})\Delta\tau, \tag{3}$$

$$c\gamma\left(h_0 - \sum_{i=1}^{k}\Delta\xi_i\right)(\bar{t}_{k-1} - \bar{t}_k) + c\gamma\Delta\xi_k(\bar{t}_{k-1} - t_s) + r\gamma\Delta\xi_k$$

$$= c_{\text{T}}\gamma_{\text{T}}\Delta x(t_{1,k} - t_{1,k-1}) + \frac{\lambda}{\Delta x}(t_{1,k-1} - t_{2,k-1})\Delta\tau, \tag{4}$$

where $t_{1,k} = t_{1,k-1} + a\Delta\tau/(\Delta x)^2\,(2t_s - 3t_{1,k-1} + t_{2,k-1})$. Equations (3) and (4) give

$$\Delta\xi_k = \frac{\Delta\tau}{r\gamma}\left[\frac{2\lambda}{\Delta x}(t_s - t_{1,k-1}) - \alpha(\bar{t}_{k-1} - t_s)\right],$$

$$\bar{t}_k = \bar{t}_{k-1} + \frac{\Delta\xi_k}{a_k}(\bar{t}_{k-1} - t_s) + \frac{r\gamma\Delta\xi_k}{c\gamma a_k} - \frac{c_{\text{T}}\gamma_{\text{T}}\Delta x}{c\gamma a_k}$$

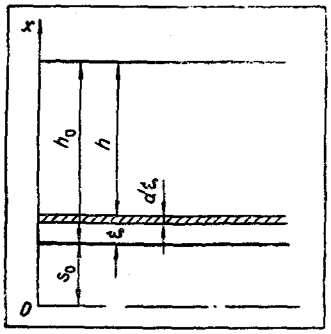

Fig. 1

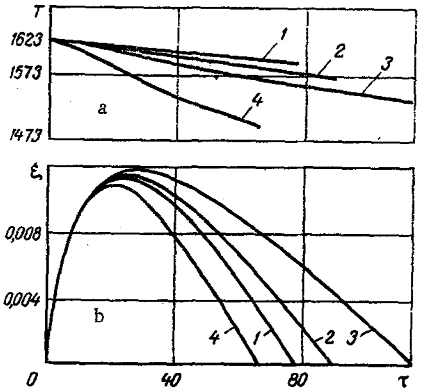

Fig. 2

Fig. 1. To calculation of solidification of cast iron layer on plate surface.

Fig. 2. Variation of liquid cast iron temperature within the period of crust existence for different initial heights of cast iron layer over plate (a) and dynamics of freezing up and melting of cast iron crust on plate surface (b).

$$\times (t_{1,k} - t_{1,k-1}) - \frac{\lambda \Delta\tau (t_{1,k-1} - t_{2,k-1})}{\Delta x c \gamma a_k} .$$

Here $a_k = h_0 - \sum_{i=1}^{k} \Delta\xi_i$.

Using the above model calculations were made by computer of the solidification kinetics and of the remelting of the iron layer, of the heating of the plate and the cooling of the liquid added to a height h_0 and the heat transfer coefficients. These parameters refer to the melting of steel in a 100 ton converter with scrap material of various sizes and constitute a total of some 25% of the liquid iron mass.

Calculations were made using the cleared difference procedure. Values of Δx and $\Delta\tau$ (corresponding to the accuracy requirements) were taken to be 0.01 m and 1 sec (the maximum allowable $\Delta\tau$ value with this Δx was 13 sec).

The calculations results are given in Fig. 2a, b and in Table 1.

Calculations show that the interference between the phases is irregular. There is a uniform increase in solid layer thickness up to a maximum (it varied from run to run) value until the layer remelts (Fig. 2b).

Calculated temperatures were obtained for liquid iron at the end of the first stage and agree with the experimental data which were obtained by measurements in the liquid bath with a thermocouple [6].

NOTATION

t_S	is the melting point of iron cast;
t_0, t	are the initial and instantaneous temperature of plate;
s_0	is the half-thickness of plate;
$\overline{t}$	is the instantaneous temperature of liquid iron cast;
τ	is the time;
x,	is the distance along plate thickness;
α	is the heat transfer coefficient;
a	is the thermal diffusivity;
h_0, h	are the initial and instantaneous hight of liquid iron cast over plate;
ξ	is the instantaneous thickness of solidified iron cast layer;
r	is the latent heat of iron cast melting;
λ	is the thermal conductivity of plate;
c, c_T	are the heat capacity of liquid iron cast and plate;
γ, γ_T	are the density of liquid iron cast and plate.

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