APPLICATION OF THE IMPLICIT FINITE-DIFFERENCES PROCEDURE FOR THE EVALUATION OF SCRAP MELTING IN AN ACID CONVERTER

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Calculations of steel scrap melting in an acid converter have been made with the aid of a Minsk-22 digital computer and the results are presented here.

One problem in controlling the acid-converter process is to determine the temperature of the liquid metal (pig iron) during the blow, the changes in this temperature being largely determined by the dynamics of the steel scrap melting process.

A procedure for the approximate calculation of scrap melting in an acid converter at constant temperature and constant composition of the liquid phase has been presented in [1]. An analogous problem has been solved in [2] for certain given values of these process parameters. In neither work was the effect of the melting rate on the temperature of the liquid metal indicated.

For the period during which the scrap melts, the problem can be stated mathematically in the following general form.

1. Heat transfer (scrap)

$$\frac{\partial t}{\partial \tau} = a\left[\frac{\partial^2 t}{\partial x^2} + \frac{(2\nu+1)}{x}\cdot\frac{\partial t}{\partial x}\right],\ 0 < x < R_0 - s(\tau); \tag{1}$$

$$t(x,\ 0) = \varphi(x); \tag{2}$$

$$\left.\frac{\partial t}{\partial x}\right|_{x=0} = 0,\ t(s,\ \tau) = t_s; \tag{3}$$

$$\alpha(t_{\text{M}} - t_s) = \varkappa\rho\,\frac{ds}{d\tau} + \lambda\left.\frac{\partial t}{\partial x}\right|_{x=R_0-s(\tau)} \tag{4}$$

2. Mass transfer (scrap)

$$\frac{\partial C}{\partial \tau} = D\left[\frac{\partial^2 C}{\partial x^2} + \frac{(2\nu+1)}{x}\cdot\frac{\partial C}{\partial x}\right],\ 0 < x < R_0 - s(\tau); \tag{5}$$

$$C(x,\ 0) = C_0; \tag{6}$$

$$\left.\frac{\partial C}{\partial x}\right|_{x=0} = 0;\ C(s,\ \tau) = C_s; \tag{7}$$

$$\beta(C_{\text{M}} - C_s) = (C_s - C_p)\,\frac{ds}{d\tau} + D\left.\frac{\partial C}{\partial x}\right|_{x=R_0-s(\tau)} \tag{8}$$

The melting temperature t_s and the carbon concentration at the surface of liquid metal C_s are interrelated by the equation for the liquidus line on the iron–carbon phase diagram.

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3. The temperature of liquid metal t_M is determined by the heat power generated during oxidation of the pig iron impurities, by the rate of heat supply to the cold material (scrap) for raising its temperature and melting it, and by the heat losses in the converter. According to [3],

$$dt_{\text{M}} = \frac{\sum_{j=1}^{k} Q_j W_j \eta_j - Q_{\text{cool}} - Q_{\text{loss}}}{G_{\text{M}} c_{\text{M}} + G_{\text{sl}} c_{\text{sl}}} \, d\tau. \quad (9)$$

The coefficient η_j indicates the fraction of the heat in the j-th reaction that is expended in heating the liquid metal and the fraction $(1-\eta_j)$ that escapes from the vessel together with the flue gases.

With certain simplifications, Eqs. (1)-(9) can be solved either by the explicit or by the implicit finite-differences procedure.

We will use the implicit procedure here, after having first simplified the conditions of the problem. The mass flow toward the surface of the melting body will be assumed to result solely in carburizing the surface layer; in this calculation the carbon concentration gradient across this surface is $\Delta C = C_s - C_0$.

In terms of finite differences, conditions (1)-(9) can be expressed as follows:

$$\frac{t_{i,n} - t_{i,n-1}}{\tau_n} = a \left[\frac{t_{i+1,n} - 2t_{i,n} + t_{i-1,n}}{h^2} + \frac{(2\nu + 1)}{x_i} \cdot \frac{(t_{i,n} - t_{i-1,n})}{h} \right],$$

$$i = 1, 2, \ldots, N-n-1, \; n = 1, 2, \ldots, N-2; \quad (10)$$

$$\frac{t_{0,n} - t_{0,n-1}}{\tau_n} = (4\nu + 4)\, a \, \frac{t_{1,n} - t_{0,n}}{h^2},$$

$$n = 1, 2, \ldots, N-2; \quad (11)$$

$$t_{N-n,n} = t_{s,n}, \; n = 1, 2, \ldots, N; \quad (12)$$

$$t_{i,0} = \varphi(x_i), \; i = 0, 1, 2, \ldots, N; \quad (13)$$

$$q_{n-1} = \alpha_{n-1}(t_{\text{M},n-1} - t_{s,n-1}) = \varkappa\rho \frac{h}{\tau_n} + \lambda \frac{t_{N-n,n} - t_{N-n-1,n}}{h}, \; n = 1, 2, \ldots, N-1; \quad (14)$$

$$\tau_N = \tau_{N-1};$$

$$C_{i,0} = C_0, \; i = 0, 1, 2, \ldots, N; \quad (15)$$

$$\beta_n (C_{\text{M},n} - C_{s,n}) = D \frac{C_s - C_0}{h}, \; n = 1, 2, \ldots, N-1; \quad (16)$$

$$t_{\text{M},n} = t_{\text{M},n-1} + \frac{\left(\sum_{j=1}^{k} Q_j W_j \eta_j - q_{n-1} F_{n-1} - Q_{\text{loss}} \right) \tau_n + \Delta V_{n-1} \rho c_{\text{M}} (t_{\text{M},n+1} - t_{s,n})}{m G_{\text{M},n-1} c_{\text{M}}}, \quad (17)$$

$$G_{\text{M},n} = G_{\text{M},n-1} + \Delta V_{n-1} \rho - \sum_{j=1}^{k} W_j \tau_n, \quad (18)$$

$$C_{\text{M},n} = \frac{G_{\text{M},n-1} C_{\text{M},n-1} - 100 (W_{\text{CO}} + W_{\text{CO}_2}) \tau_n}{G_{\text{M},n}}, \quad (19)$$

$$n = 1, 2, \ldots, N-1. \quad (20)$$

The equation of the liquidus line on the iron–carbon phase diagram can be written as follows:

$$t_{s,n} = 1539 - 90 C_{s,n}. \quad (21)$$

Corresponding to Eqs. (10)-(15), the body is broken down into N equal layers of height h. The time interval is chosen depending on n so that only one successive layer melts during the respective period τ_n. The system of nonlinear equations (10)-(15) will be solved by the iteration method [5], for which we write

$$0 < \tau_n^0 < \frac{\varkappa\rho h}{q_{n-1}}$$

and (10)-(13) are solved for $t_{i,n}^0$. From the equation

$$\tau_n^{\xi+1} = \frac{1}{q_{n-1}} \left(\varkappa\rho h + \tau_n^{\xi} \lambda \frac{t_{N-n,n}^{\xi} - t_{N-n-1,n}^{\xi}}{h} \right), \; \xi = 0, 1, 2, \ldots \quad (22)$$

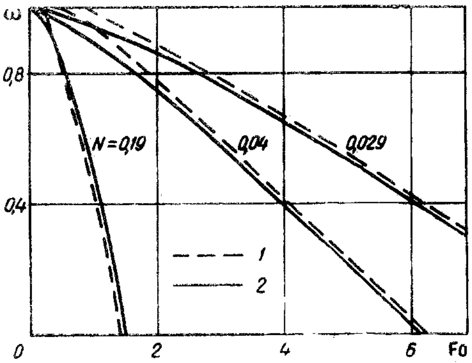

Fig. 1. Dynamics of melting steel cylinders in an iron–carbon bath with a constant thermal flux: 1) test data; 2) calculated values.

we determine τ_n^1, when $\xi = 0$. Then from (10)-(13), using this value of τ_n^1, we calculate $t_{i,n}^1$, etc. The process of determining the melting time of a given layer and the temperature field in the remaining mass is complete when $\tau_n^{\xi+1} - \tau_n^{\xi} \approx 0$.

Having determined τ_n from (17)-(21), we find all the necessary data for calculating the thermal flux which enters into the solution of Eqs. (10)-(15) for the next time interval.

The heat losses in the converter stack are determined by special calculations as losses through a plane single-layer wall, according to the procedure shown in [6], with a given power-law variation of the thermal flux on the active side of the wall and with quasisteady-state conditions at the stack.

In order to check the validity of the proposed procedure, we have made control calculations assuming a constant thermal flux and compared them with laboratory test data on melting (dissolving) cylindrical steel specimens in liquid iron containing 2.5-3.5% carbon at temperatures within the 1573-1673°K range. These tests were performed in an induction furnace containing a 150 kg charge. Cold specimens 32-51 mm in diameter and 200 mm long were first weighed and then dropped into the melt one after another, held there for a definite length of time, and then weighed again. The criterial melting numbers and the thermal flux were calculated for each specimen according to the equation [1]:

$$(2\nu + 2)\,\mathrm{Fo} = \frac{1-\omega}{2N_c} + \frac{1}{(2\nu+4)}\left[1 - \exp(-A\mathrm{Fo})\right],$$

where

$$\omega = 1 - \frac{s}{R_0};\quad A = (2\nu+2)(2\nu+4);$$

$$N_c = \frac{c_s\, q\, R_0}{2(2\nu+2)\varkappa\lambda}. \tag{23}$$

With the values of q and N_c for the cylinders found here, the melting process was calculated according to Eqs. (10)-(15).

Since the process of melting (dissolving) actually begins only after the solidifying crust has softened under a definite temperature distribution over the mass section, the initial temperature distribution in the cylinders is in this procedure determined approximately from the heating conditions applicable to the mass here under constraints of the first kind. The heating time is taken equal to the time in which the ingot crust solidifies and softens – this time being determined by test.

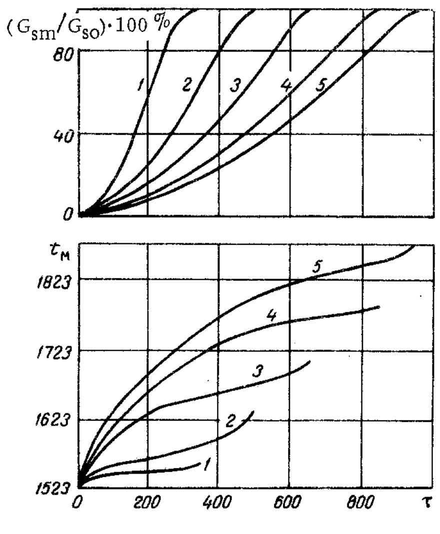

Fig. 2. Melting of cylinder-shaped scrap in a converter and changing temperature of the liquid metal during the blow: 1) R_0 = 0.034 m; 2) 0.051 m; 3) 0.085 m; 4) 0.17 m; 5) 0.25 m. τ, sec; t_M, °K.

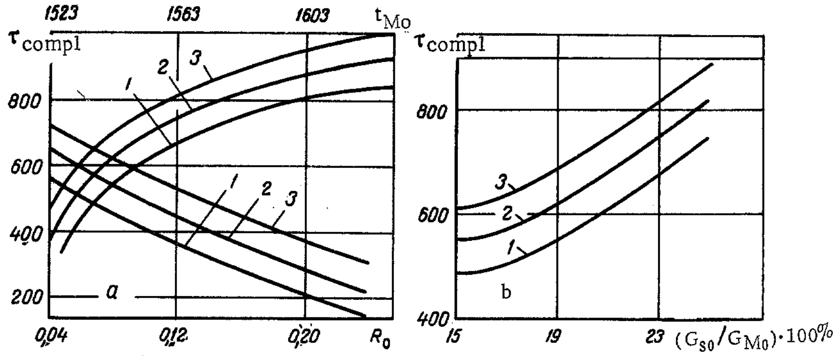

Fig. 3. Effects of the initial temperature of the liquid metal bath and of the shape, the size, and the amount of scrap on the completion time of scrap melting; spherical (1), cylindrical (2), and plate (3) scrap: a) for the upper curves $\tau_{compl} = f(R_0)$ at $(G_{S0}/G_{M0}) \cdot 100 = 20\%$, $t_{M0} = 1523°K$; for the lower curves $\tau_{compl} = f(t_{M0})$ at $(G_{S0}/G_{M0}) \cdot 100 = 20\%$, $R_0 = 0.085$ m; b) $\tau_{compl} = f(G_{S0})$ at $R_0 = 0.085$ m and $t_{M0} = 1523°K$. (τ_{compl}, sec).

The calculated results and some test data are shown in Fig. 1. The curves plotted from both seem to agree closely. Therefore, the procedure (10)-(21) with properly chosen values of $q(\tau)$ is suitable for rather accurately calculating the dynamics of scrap melting in an acid converter.

Specific calculations of scrap melting (dissolving) in a 100,000 kg converter were made on a Minsk-22 digital computer: for various scrap sizes, shapes, and weights, as well as for various initial pig-iron temperatures.

To determine the temperature of liquid metal, the melting time was tentatively broken down into three periods: 1) the first period of carbon, silicon, manganese, and iron oxidation; 2) the second period of only carbon oxidation; and 3) the third period of carbon and iron oxidation. The lengths of these periods, the initial concentrations of impurities, and the mass rates of their oxidation during each period, as well as other pertinent data, were based on practical experience at one of the metallurgical plants. The initial values of the heat-transfer and the mass-transfer coefficients were taken from [7, 8]. The maximum value of coefficient α was determined from actual results of melting nickel–steel scrap in a 55,000 kg converter. For the period of intensive scrap melting [1], when the temperature gradient across the mass is almost zero and the temperature of the liquid metal is above the melting point, we calculated

$$\alpha_{max} = (1.6 - 1.7) \cdot 10^4 \ \mathrm{W/m^2 \cdot deg},$$

and, by the analogy between heat and mass transfer, we found that approximately

$$\beta_{max} = \beta_0 \frac{\alpha_{max}}{\alpha_0}.$$

The trend of changes in the coefficients of heat and mass transfer was assumed to follow the changes in the rate of pig-iron decarburization.

As illustration, we show in Fig. 2 a few melting curves for scrap shaped into cylinders and temperature curves for the liquid metal during the blow until the completion of the melting process. It is evident here that, with all other conditions unchanged, an increase of the scrap size causes a rise in the temperature of the liquid metal during the initial melting period and ensures a more steady cooling effect, which has a beneficial influence on refining and slag formation.

Increasing the amount of immersed scrap by 1000 kg lowers the temperature of the metal by 10-15°K toward the eighth minute of blowing.

Calculations have shown that with a scrap size $R_0 > 0.085$ m the entire melting process becomes unsteady: the thermal flux is expended on melting the surface layers and heating the inner core.

The graphs in Fig. 3 represent the effects of the initial temperature of the pig iron and of the size, the shape, and the amount of immersed scrap on the time of completion of scrap melting.

The proposed calculation procedure is relatively simple and makes it possible to evaluate the effect of various factors on the rate of scrap melting in an acid converter as well as the effect of the melting dynamics on the ingot temperature.

NOTATION

t is the temperature of the melting body;
α, λ are the thermal diffusivity and thermal conductivity of the body;
$\varkappa$ is the specific heat of melting;
q is the heat flux intensity;
Q_j is the thermal effect of the j-th reaction;
Q_{cool} is the heat absorbed by the melting body;
Q_{loss} is the heat loss through the converter stack;
c_M, c_{sl}, c_s are the heat capacity of metal, slag, and scrap, respectively;
W_j is the mass rate of oxidation of the j-th element;
W_{CO}, W_{CO_2} are the mass rate of carbon oxidation into CO and CO_2, respectively;
η_j is the coefficient of heat utilization of the j-th reaction;
C_s, C_p are the carbon concentration along the liquidus line and along the solidus line on the iron −carbon phase diagram;
C_0 is the initial carbon concentration in the scrap;
D is the diffusion constant for carbon in steel;
R is the radius of the melting body;
S is the moving melting boundary;
ρ is the density of the scrap;
G_M, G_{sl}, G_s are the weight of metal, slag, and scrap, respectively;
Fo is the Fourier number;
n is the number of the time interval;
ν is the shape factor for the melting body: $\nu = -1/2$ for a plate; $\nu = 0$ for a cylinder; $\nu = 1/2$ for a sphere;
F_n is the surface area of the melting body;
k is the quantity of impurities in pig iron during each of the melting stages.
$m = G_M c_M + G_{sl} c_{sl} / G_M c_M = 1.14$ [3].

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