THERMAL REGIME OF BATCH FURNACES FOR HEATING METAL IN A FLUIDIZED BED

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An analytical investigation is made of the temperature variation in a fluidized-bed furnace, and in a part with low thermal resistance being heated in it.

Fluidized-bed furnaces and baths are characterized by considerably greater intensity (in comparison with radiative and convective furnaces) of heat transfer to the heated part due to active mixing of the fine-grained material in the bed. This leads to appreciable variation of bed temperature with time in batch furnaces.

Cold parts placed in the bed rapidly remove the heat accumulated in it, which results in a drop in bed temperature. Later, as the parts are heated, the bed temperature gradually increases due to the heat supplied by electric heaters or released in the bed by the combustion of gas.

Quantitatively, heat transfer between the bed and the part is described by two equilibrium equations:

$$G_c c_c dt_c = kF(t_b - t_c)d\tau, \quad (1)$$

$$(Q_g - Q_f - Q_{loss})d\tau = kF(t_b - t_c)d\tau + G_b c_b dt_b. \quad (2)$$

If the thermal resistance of the part is large, the coefficient k depends on time. For small values of Bi, k is assumed to be equal to the coefficient of heat transfer α to the surface of the part and to be constant during heating. This case is considered below.

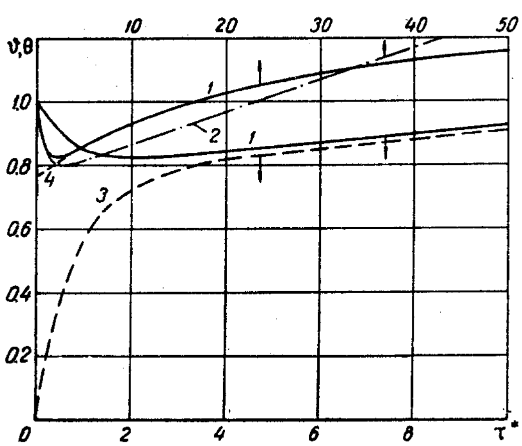

Fig. 1. Dynamics of temperature variation for bed (1, 2, 4) and part (3) at T = 0.2; R = 0.3, Θ_M = 1.2: 1) according to Eq. (8); 2) Eq. (5); 3) Eqs. (8), (9); 4) Eq. (12).

The heat output Q_g in the bed depends on the amount of fuel burnt or on the power of the electric heaters.

In the problem examined Q_g is assumed to be independent of time, i.e., $(dQ/d\tau)_g = 0$.

The heat lost with the fluidizing agent leaving the bed Q_f is determined by the mass flow rate and heat capacity of the latter, and also by its inlet and outlet temperatures.

The extremely intense mixing of fine-grained material in the bed leads to almost perfect uniformity of temperature over the thickness of the bed. Therefore the temperature of the fluidizing agent at the bed outlet is practically equal to the bed temperature.

We shall reduce the equations to dimensionless form:

$$\Theta = \frac{t_b - t_i}{t_0 - t_i}; \quad \vartheta = \frac{t_c - t_i}{t_0 - t_i}; \quad T = \frac{V f c f}{kF}; \quad R = \frac{G_c c_c}{G_b c_b},$$

$$\Theta_M = \frac{Q_g - Q_{loss} + V f c f (t_{in} - t_i)}{V_f c_f (t_0 - t_i)}; \quad \tau^* = \frac{\tau kF}{G_c c_c}.$$

The quantity $T = \frac{V_f c_f (t_0 - t)}{kF(t_0 - t)}$ is the ratio of the heat lost with the outflowing gases at $\tau = 0$ to the heat transmitted to the parts at the same time, if the initial temperature of the parts t_i is equal to that of the fluidizing agent entering the bed, t_{in}, and Θ_m is the dimensionless bed temperature under steady conditions for a given Q_g. Then the heat generated in the bed is expended in losses to the outflowing gases and the surrounding medium ($Q_g = Q_{loss} + Q_f$). Θ_m is the limiting value to which the bed temperature tends during the heating process (as $\tau \to \infty$). When the bed is in the steady state until the part begins to be heated, $\Theta_m = 1$. However, heating of a part in batch furnaces may begin before transition to the steady state. In this case Θ_m may differ from unity.

The remaining dimensionless quantities do not require explanation.

We shall write (1) and (2) in terms of the new variables:

$$d\vartheta/d\tau^* = \Theta - \vartheta, \quad (1')$$

$$\frac{1}{R}\frac{d\Theta}{d\tau^*} = T\Theta_M + \vartheta - (1 + T)\Theta. \quad (2')$$

The boundary conditions are: at $\tau^* = 0$, $\Theta = 1$, $\vartheta = 0$.

We rewrite (2) in the form

$$d\Theta/d\tau = RT(\Theta_M - \Theta) - R(\Theta - \vartheta). \quad (2'')$$

During the heating (or cooling) of parts in the fluidized bed, its temperature ususally varies only slightly, i.e., Θ does not differ much from unity. If we set $P = RT(\Theta_m - \Theta)$ and assume $P = \text{const}$ in the first approximation, then instead of (2") we obtain

$$d\Theta/d\tau^* = P - R(\Theta - \vartheta). \tag{3}$$

Physically, this simplification means that we neglect variation of the losses associated with the outflowing fluidizing agent, either because its temperature does not change much ($\Theta = \text{const}$), or because the losses themselves are small ($\Theta_m \gg \Theta$).

To solve the system of equations (1')–(3), special analog schemes were proposed; these allowed us to find the relations $\Theta = f(\tau^*)$ and $\vartheta = \varphi(\tau^*)$ for several values of the parameters P and R. At the same time, this system, with the boundary conditions given above, is easily solved analytically:

$$\vartheta = \frac{1}{1+R}\left[1 - \frac{P}{1+R}\right] \times \\ \times \{1 - \exp[-(R-1)\tau^*]\} + P\tau^*, \tag{4}$$

$$\Theta = \frac{1}{1+R}\left[1 - \frac{P}{1+R}\right] \times \\ \times \{1 + R\exp[-(R+1)\tau^*]\} + P(\tau^* + 1). \tag{5}$$

The temperature difference between fluidized bed and part is

$$\frac{t_b - t_c}{t_0 - t_i} = \frac{P}{1+R} + \left(1 - \frac{P}{1+R}\right)\exp[-(1+R)\tau^*]. \tag{6}$$

It is clear from (4)–(6) that in the majority of cases the temperature Θ of the fluidized bed first decreases from unity to Θ_{min}, and then begins to increase again. At large values of τ^*, when the exponential is equal to zero, the dependence of Θ on τ^* becomes linear. The temperature ϑ of the part increases monotonically, while the difference $\Theta - \vartheta$ tends to the constant value characteristic of a regular regime of the second kind.

Analysis of (5) shows that the minimum bed temperature is attained when $\tau^* = \frac{1}{R+1}\ln R\left(1 - \frac{P}{R+1}\right)P^{-1}$:

$$\Theta_{min} = P + \frac{1}{R+1} + \frac{P}{R+1} \times \\ \times \left[\frac{R}{R+1} + \ln\left(\frac{R}{P} - \frac{R}{R+1}\right)\right]. \tag{7}$$

Equations (3–7) are only suitable for calculating furnaces with electric heaters, which usually operate in the region of relatively low bed temperatures, and with with low flow rates of fluidizing agent, i.e., low heating losses ($\Theta \ll \Theta_m$).

In furnaces in which fuel is burned in the fluidized bed, the flow rate of fluidizing air determines the amount of fuel consumed, i.e., the quantity Q_g. The losses in heating the air prove to be appreciable, which makes it necessary to use an exact solution of equations (1) and (2):

$$\vartheta = \Theta_M - (2D)^{-1}\{[1 - \Theta_M(n-D)]\exp[-(n+D)\tau^*] + \\ + [\Theta_M(n+D) - 1]\exp[-(n-D)\tau^*]\}, \tag{8}$$

$$\Theta = \vartheta + (2D)^{-1}\{[RT\Theta_M - (n-D)]\exp[-(n+D)\tau^*] + \\ + [D + n - RT\Theta_M]\exp[-(n-D)\tau^*]\}, \tag{9}$$

$$\Theta_{min} = \Theta_M - \frac{\sqrt{ab}}{RT}\left(\frac{a}{b}\right)^{n/2D}, \tag{10}$$

where

$$n = [R(1+T)+1]/2; \quad D = \sqrt{n^2 - RT}; \\ a = [1 - (n-D)][RT\Theta_M - (n-D)]; \\ b = [n + D - 1][n + D - RT\Theta_M]. \tag{11}$$

The relations computed from (8), (9), and (5) are presented in Fig. 1. It can be seen that in this case the exact and approximate solutions for the bed temperature (curves 1 and 2) do not differ very much.

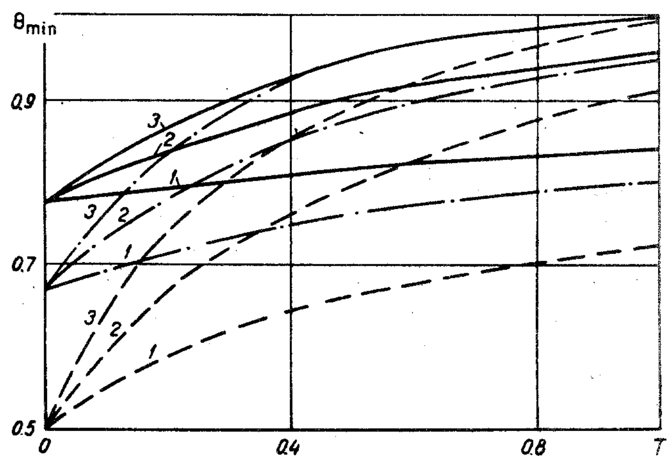

Fig. 2. Dependence of minimum bed temperature on the dimensionless parameters T, R, and Θ_M for R = = 1.0 (broken line), 0.5 (dash-dot), and 0.3 (continuous line): 1) Θ_M = 1; 2) 1.5; 3) 2.

Clearly, the discrepancy would be greater at higher values of the product RT. Also shown for comparison (curve 4) is the relation obtained under the assumption that the temperatures of the parts and of the bed are instantaneously equal at $\tau = 0$, and that then the parts and the bed warm up as one entity as heat is supplied. In this event

$$\Theta = \Theta_M - [\Theta_M - (1+R)^{-1}]\exp[-RT\tau^*]. \tag{12}$$

Beginning from $\tau^* = 3$, equations (12) and (8), (9) give practically identical results in our case. This is because up to $\tau^* = 3$ the part is heated (curve 3) to a temperature that is practically equal to that of the bed, while subsequently they are heated essentially simultaneously.

Three different kinds of relation $\Theta(\tau^*)$ are possible in principle. If $\Theta_m > (T+1)/T$ or $P > R$ for equation (5), the bed temperature Θ increases monotonically from 1 to Θ_m (according to (5), to ∞), since the amount of heat transmitted to the part at the time of its immersion in the bed is less than the difference $Q_g - Q_{loss} - Q_f$. If $R \geq (1-\Theta_m)/\Theta_m[1 + T(1-\Theta_m)]$, the bed temperature Θ decreased monotonically from 1 to Θ_m: at $\tau = 0$ the bed was strongly overheated as compared with Θ_m and gradually cooled, releasing its excess heat to the parts and the outflowing gas.

At all intermediate values of Θ_m the function $\Theta(\tau)$ has the character indicated in Fig. 1 (curve 1).

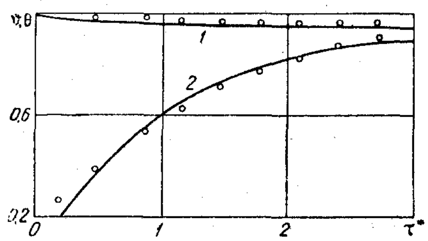

Fig. 3. Dynamics of temperature variation for bed (1) and part (2) in an experimental furnace with gas heating at kF = 20.9 W/deg, R = 0.0765, $\Theta_M = 1$.

The principal advantage of fluidized-bed furnaces is a 5- to 7-fold increase in heating rate in comparison with the ordinary convection furnaces; this is particularly important for relatively thin parts with low internal thermal resistance. As our experiments on heating connecting rods in a fluidized bed indicate, the substantial reduction of heating time means that the depletion of carbon from the surface and scale formation can be almost entirely avoided, especially if gas is burned in the bed with insufficient air. When heated to 900° C (heating and soaking time 3–5 min) the rod has only a thin film, reminiscent of burnishing, on its surface. In industrial conditions, however, this advantage can be realized only if the heating process is properly organized.

It can be seen from Fig. 1, that by the time the bed temperature reaches its minimum value, the temperature of the heated parts is practically equal to that of the bed. Further heating of the part runs parallel with heating of the bed, i. e., proceeds considerably more slowly, since the rate is determined not by heat transfer between the bed and the part, but by the heat introduced into the bed. In these conditions rapid heating in a fluidized bed may be accomplished, in principle, either by increasing the heat output or by preliminary overheating of the bed.

The first alternative is more suited to furnaces with electrical heaters, the heat output of which does not depend on the flow rate of fluidizing agent and may be controlled over a wide range. The fact is that an increase of power (i. e., an increase of P in (6) or of Θ_M in (9)) leads to an increase in the temperature difference between the bed and the part, i. e., to a lag of the part temperature behind that of the bed during heating. This follows particularly clearly from equation (6): the minimum temperature difference between the bed and the part (as $\tau^* \to \infty$) is directly proportional to P.

In order to attain a specified part temperature in these conditions, we must arrange for the bed to be held at the constant temperature required not only to equalize the temperatures but frequently also to make possible phase transitions in the metal. For maintaining a constant bed temperature, the heat output may be appreciably reduced.

In furnaces with gas heating, the power supplied can be varied only over much narrower limits than in electric furnaces. An increase in the amount of fuel injected at a specified fuel ratio requires a corresponding increase in the air flow rate. This leads to an increase in the depth of the fluidized bed and in the height to which material is ejected from the bed, which in the case of a shallow furnace may cause appreciable curtainment of the fine-grained material.

Therefore, for gas furnaces the second alternative is to be preferred, especially in heating a few small parts, when parameter R is small. In this case the bed is preheated to a temperature such that, after the parts have been inserted, the minimum temperature Θ_{min} turns out to be the required heating temperature. When the bed attains Θ_{min}, the heat output is lowered, so that the bed temperature remains constant.

In heating large parts, when R is large, the heat accumulated in the bed may prove to be insufficient to heat the parts to the prescribed temperature. In that case we must adopt an intermediate scheme, in which the bed is preheated to the maximum possible temperature, and after the parts are placed in it and the bed temperature falls below the required value, then the bed and the parts are heated to the prescribed temperature, whereupon the heat output is reduced in order to give an isothermal soak. In all cases the operating regime of a furnace with gas heating must be so chosen that the minimum temperature is not less than 800° C, since stable burning of the gas in the bed is difficult at lower temperatures. A graph for determining the minimum bed temperature, constructed on the basis of Eq. (10), is given in Fig. 2.

Strictly speaking, all the relations given here are valid for thin bodies, when $Bi = \alpha r/\lambda \to 0$, and therefore $k \equiv \alpha$. They may also be used approximately for massive parts if one applies the relation [3] $k = \alpha / (1 + (Bi/\varphi))$, in which the coefficient φ depends on the body shape. For example, for nearly spherical parts $\varphi = 5$.

The theory was verified in an experimental furnace with two-stage burning of bottle gas in a fluidized bed. The furnace diameter was 147 mm, and the distance from the grid to the second nozzles was 500 mm. Copper specimens (diameter 55 mm) were heated in the furnace. In reducing the test data, the (total) heat capacity of the fluidized material was added to that of the chamber walls, whose temperature practically coincided with that of the bed. On the whole, the experimental data showed good agreement with theory

(Fig. 3). A certain scatter of the experimental points is explained by variation of the heat capacity of the specimen and of the heat transfer coefficient with temperature, this not being allowed for in the analysis.

NOTATION

c_b, c_c, c_r) heat capacity of the fine-grained material, of the part, and of the gases flowing out of the bed; F) heat-release surface of parts; G_c, G_b) mass of parts and fine-grained material in the bed; k) coefficient of heat transfer from bed to part; r) radius of circular or half-thickness of flat part; t_0, t_b, t_i, t_c) respectively, the initial and variable temperatures of the bed and the parts; t_{in}) temperature of air entering the bed; Q_g, Q_f, Q_{loss}) heat output in bed, heat expended in heating the fluidizing agent, and heat lost to the surrounding medium; V_r) flow rate of fluidizing agent; α) coefficient of heat transfer from part to bed; λ) thermal conductivity of material of part; τ) part heating time; $\vartheta = (t_c - t_i)/(t_0 - t_i)$ and $\Theta = (t_b - t_i)/(t_0 - t_i)$ dimensionless temperatures of part and bed; Θ_{min}) minimum dimensionless bed temperature.

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