FLUIDIZED-BED MUFFLE HEATING FOR PROCESS OVENS

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A fluidized bed for muffle heating increases oven throughput and muffle service life [1, 2]; the accelerated heating means that the oven length can be reduced, and operation can be mechanized without the need to mount components of finite length such as tubes and rods [1, 2]. Some grades of chromium and other steels oxidize rapidly [3] (the surface darkens), so the muffle may be supplied with a protective gas [1, 2]. Also, a muffle is heated by such a bed much more evenly than by electrical heaters or by fuel burners.

This gives interest to calculation of the basic parameters of such a system [2] and comparison with ones already in existence, such as electrical muffles.

In part of length dx, a muffle receives the following heat flux from the coarse bed:

$$dq = \alpha_{cb}(T_{cb} - T_m)\, p_m dx. \tag{1}$$

The following is the resultant flux from muffle-component exchange:

$$dq = \varepsilon_{m,2} C_0 \cdot 10^{-8} (T_m^4 - T^4)\, p_m dx. \tag{2}$$

A component passing through section dx is heated by dT in °K and receives the following amount of heat:

$$dq = cgu dT. \tag{3}$$

The degree of blackness of the muffle-component system is calculated in the usual way [4]. The subsequent calculations involve the following assumptions: the muffle and components are circular thermally thin cylinders, whose values for Bi do not exceed 0.25; the outside and inside diameters of the muffle are the same, $F_m/F_2 = d_m/d_2$; the muffle is filled with a protective gas, which contains no triatomic components and is diathermic. The air surrounding the muffle in the electrical furnace is also transparent to the radiation.

We solve the system of equations derived from (1) and (2) to get

$$T_m^4 + T_m \frac{10^8 \alpha_{cb}}{\varepsilon_{m,2} C_0} - \left(T^4 + T_{cb} \frac{10^8 \alpha_{cb}}{\varepsilon_{m,2} C_0} \right) = 0, \tag{4}$$

from which the muffle temperature may be determined; the only physically significant root of an equation of the type

$$z^4 + mz + e = 0 \tag{5}$$

coincides [5] with the positive root of

$$z^2 + \frac{\sqrt{8y}}{2} z + \left(y - \frac{m}{\sqrt{8y}} \right) = 0, \tag{6}$$

where

$$y = \sqrt[3]{-a + \sqrt{a^2 + p^3}} + \sqrt[3]{-a - \sqrt{a^2 + p^3}}\,. \tag{7}$$

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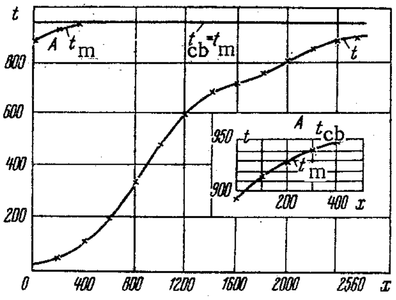

Fig. 1

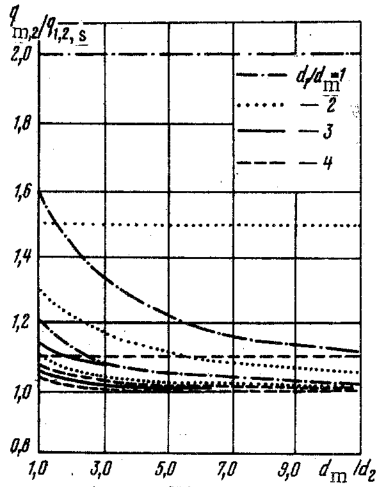

Fig. 2

Fig. 1. Temperature distribution along the length x (mm) of the muffle containing a set of tubes.

Fig. 2. Relation of $q_{m,2}/q_{1,2,s}$ to $d_{1,2}$, and d_m for various degrees blackness in the component surface and d_1/d_m of: 1) 1; 2) 2; 3) 5; 4) 10. The lower curve for each d_1/d_m is for $\varepsilon_2 = 0.2$; the middle one is for $\varepsilon_2 = 0.6$; and the upper for $\varepsilon_2 = 1.0$.

We use (4)-(7) to estimate the muffle temperature on maximum heat uptake, i.e., when the metal enters the oven, on the assumption that the surfaces of muffle and component are absolutely black ($\varepsilon_m = \varepsilon_2 = \varepsilon_{m,2} = 1$), while the diameter of the components is close to that of the muffle ($d_m \simeq d_2$; $F_m \simeq F_2$). We assume that $T' = 300$°K and $T_{cb} = 1300$°K from [6] for a fluidized bed of corundum particles of size not more than 320 μm, which gives $\alpha_{cb} = 1000$ W/m^2·deg; under these idealized conditions, $T_m = 1150$°K, i.e., it is 150°K below the bed temperature.

Usually one employs a black oxidized muffle with a high ε_m (value 0.95 [7] for nichrome) and a clean surface of the component heated in a nonoxidizing medium, having $\varepsilon_2 \simeq 0.1$-0.4 [7]. We calculate the muffle temperature with $T' = 300$°K, $T_{cb} = 1300$°K, $\varepsilon_2 = 0.4$, $\varepsilon_m = 0.95$ and $F_m \simeq F_2$ to get $T_m = 1285$°K, i.e., only 15°K below the bed temperature, which is confirmed by experiment [2]. The difference between the temperatures of the bed and muffle tends rapidly to zero as the component temperature increases (Fig. 1). The measurements were made on a working oven at the Pervoural'sk New Tube plant in 1972 (number of tubes in the bundle 3, tubes 30 × 1.5 mm, material steel 10 tube speed 1 m/min, bed temperature 950°C).

The heat calculation for the bed + muffle + component then amounts to calculating the radiative heat transfer for a system of two bodies only: the muffle with its temperature constant along the length and across the cross-section, this being equal to the temperature T_{cb} of the oven medium, and the component with the current temperature T, the muffle screens the component very little.

If the coefficients for heat transfer from the bed are small (large particles), one can use (4)-(7) to estimate the muffle temperature.

A muffle in an electric furnace differs from this system of heat-exchanges in bodies in that it is a screen that attributes the heat flux to a considerable extent [4], and that flux through a cylindrical screen s can be calculated from the following formula for a heater of temperature T_1 surrounding the screen on all sides:

$$q_{1,2,s} = \varepsilon_{1,2,s} C_0 \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T}{100} \right)^4 \right] F_1. \tag{8}$$

Here

$$\varepsilon_{1,2,s} = \frac{1}{\frac{1}{\varepsilon_{1,2}} + \frac{F_1}{F_m}\left(\frac{2}{\varepsilon_m} - 1 \right)}, \quad \varepsilon_{1,2} = \frac{1}{\frac{1}{\varepsilon_1} + \frac{F_1}{F_2}\left(\frac{1}{\varepsilon_2} - 1 \right)}, \tag{9}$$

where F_1 is the internal surface of the continuous heater.

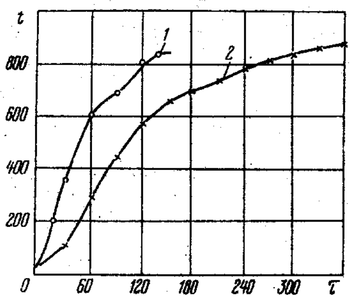

Fig. 3

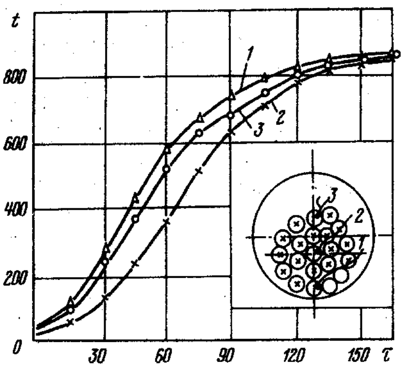

Fig. 4

Fig. 3. Tube heating in: 1) a five-muffle fluidized-bed oven; 2) an open-flame five-muffle oven; τ in sec.

Fig. 4. Temperature distribution in a tube bundle in a muffle furnace with a fluidized bed: 1-3) points of thermocouple attachment. τ in sec.

As $F_i/F_c = d_i/d_c$, we can compare the fluxes received by the component in a fluidized-bed system and an electrical one with identical temperatures for the bed and heater ($T_{cb} = T_1$); in the case of the bed,

$$q_{m2} = \varepsilon_{m2} C_0 \left[\left(\frac{T_{cb}}{100} \right)^4 - \left(\frac{T}{100} \right)^4 \right] F_m \tag{10}$$

Then

$$\frac{q_{m2}}{q_{1,2,s}} = \frac{\varepsilon_{m2}}{\varepsilon_{1,2,s}} \cdot \frac{d_m}{d_1}. \tag{11}$$

Figure 2 shows results from (11) on the assumption that the heater surface and both surfaces of the muffle are absolutely black ($\varepsilon_1 = \varepsilon_m = 1$); it is clear that $q_{m,2}/q_{1,2,s}$ is always greater than 1. The advantages of a fluidized bed are greatest when one makes the best use of the working volume in the muffle (when $d_m/d_2 \to 1$) and heating components for which ε_2 is high.

The heat flux through the muffle in an electric oven is much reduced [4] if the muffle screen has low blackness; the muffle in a flame oven also acts as a screen and reduces the resultant flux, although to a smaller extent than that from a solid heater.

The curves of Figure 2 were obtained for idealized heating of muffles by external radiation; in fact, the electric heaters take up only a very small area of the surrounding cylindrical surface, while a muffle is heated only from one side in a flame oven. This all adds to the advantage from using a fluidized bed, and the actual factor is substantially larger than that indicated by Fig. 2.

Figure 3 shows curves for tube heating in muffle furnaces; in each case the temperature in the working space was 920°C, with 6 tubes in a muffle, with tubes of steel 10, each 10 × 1 mm, the tube speed being 0.6 m/min. The muffle dimensions were as follows: in the fluidized-bed case tubular 114 × 10 mm; in the flame oven oval 60 × 130 mm with a wall thickness of 6 mm. Figure 3 shows that the fluidized-bed furnace with 320 μm corundum heats the tube over twice as rapidly as the flame oven.

The muffle has almost exactly the bed temperature when heating the component, so one can calculate the temperature of a thin component moving along the oven simply by considering (2) and (3) together, where $T_{cb} = T_m$:

$$\varepsilon_{m2} C_0 \cdot 10^{-8} (T_{cb}^4 - T^4)\, p_m dx = c_p g u dT. \tag{12}$$

An equation of the type of (12) has been solved [8] to determine the metal heating time τ (here $x = u\tau$) and has been widely used in calculations; we use this solution to put

$$x = \frac{gu}{p_m} \cdot \frac{10^8 c_p}{\varepsilon_{m2} C_0} \cdot \frac{100^4}{4T_m^3} \left\{ \left(\ln \frac{1 + \frac{T}{T_m}}{1 - \frac{T}{T_m}} + 2 \operatorname{arctg} \frac{T}{T_m} \right) - \left(\ln \frac{1 + \frac{T'}{T_m}}{1 - \frac{T'}{T_m}} + 2 \operatorname{arctg} \frac{T'}{T_m} \right) \right\}. \tag{13}$$

Here T' is a temperature of the metal at entry to the muffle. In calculating T = f(x) for T = f(τ) one must remember that the combinations enclosed in parentheses have been presented as graphs and tables [9-11].

Formula (13) enables one to calculate the muffle or oven length in designing an oven to a given heating temperature T for the metal.

If a bundle of components is being heated, for instance a bundle of tubes, one needs to know the effective thermal conductivity of the bundle, which can be calculated as in [10]. Calculation of λ_s as in [10] for a bundle of tubes in a muffle oven [1, 2] enables one to estimate Bi, which does not exceed 0.5; it is found [9] that one can assume for practical purposes that the heating of such a body is uniform over the cross-section. Experiments in fact revealed a certain temperature difference over the cross-section of the bundle (Fig. 4), but the temperatures of all tubes in the bundle had become virtually equal at the end of the muffle. The speed was 0.8 m/min, the bed temperature 960°C, the muffle (Kh23N18 steel) was 114 × 10 mm, there were 21 tubes in a bundle, made of steel 10, the tubes were 8 × 1.5 mm.

When tubes of steel 10 or 20 are heated, the surfaces remain completely free from scale (pale) [1, 2], but the thermal decomposition of the lubricant makes them mat and slightly rough; this substantially increases the surface blackness [12], which in turn improves the performance of the fluidized bed (Fig. 2).

NOTATION

α_{cb}	is the heat transfer coefficient from bed to muffle, W/m^2-deg;
τ	is the current time, sec;
ε_m, ε_1, ε_2	are the emissivity of surfaces of muffle, electric heater, and component;
d_m, d_1, d_2, F_m, F_1, F_2	are the diameters (m) and surface areas (m^2);
p_m	is the perimeter of cross-section of muffle, m;
c	is the specific heat of metal, J/kg-deg;
g	is the mass of 1 meter of metal, kg/m;
u	is the velocity, m/sec;
T_{sb}, T_m, T	are the temperatures of fluidized bed, muffle, and metal in °K;
t_{sb}, t_m, t	are the same, °C;
T'	is the temperature of component at entrance, °K;
x	is the current longitudinal dimension of furnace, m;
q	is the heat flux, W;
Bi	is the Biot number for component;
Q_l^p	is the minimum heat of combustion, J/Nm^3;
C_0	is the black-body radiation coefficient, W/m^2-deg^4;

$a = -m^2/16$;
$p = -l/3$.

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