THERMAL CALCULATION OF A MULTISECTIONAL FURNACE FOR FLUIDIZED ENDOTHERMIC CALCINATION

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A method of over-all thermal calculation of a multi-sectional furnace with heating and cooling sections for fluidized endothermic calcination of loose materials is described.

Methods of calculation of multistage fluidized-bed heat exchangers have been given in [1–3]. In [4] a method of combined calculation for a multistage heat exhanger (heating zones) and a calcination zone was considered. A heat-engineering analysis of an aggregate containing heating, calcination, and cooling sections was attempted in [5]. However, an over-all method of thermal calculation of a multisectional furnace (with heating, calcination, and cooling sections) has not yet been devised.

We consider a multisectional furnace for fluidized endothermic calcination with n − 1 heating sections, a calcination section, and m − 1 cooling sections (Fig. 1).

We regard each section as a mixing heat exchanger, i.e., we assume that the temperatures of the gases and solid material on leaving the layer are the same. Then the heat balance equation of the n-th section is

$$VKC_g(t_{n-1}-t_n)\eta_{sur}=GC'(t_n-t_{n+1}), \tag{1}$$

where

$$C'=\xi\left(1-\frac{\eta_{en}}{100}\right)\left(C_1+\frac{\Sigma q}{t_1-t_0}\right)$$

is the reduced specific heat of the raw material in the case of total heat consumption on endo- and exothermic processes in the temperature range t_0-t_1. In the case where the thermal processes are completed at t_2 (i.e., in the first heating section in the path of the gases) Σq refers to the difference $t_2 - t_0$. The error due to such averaging is not too large for engineering requirements if the heat is sufficiently well utilized (which, of course, is our aim).

The heat balance equation of the calcination section is

$$V(Q-KC_gt_1+LC_a t_{2c})\eta_{sur}=G[C'(t_1-t_2)+q]. \tag{2}$$

The values of C' and q are substituted into Eq. (2) according to where the heat consumption is concentrated (or dispersed). If the heat is consumed in the temperature range (t_0-t_1), C' is substituted from the formula given above and q is eliminated from Eq. (2).

When q is consumed in the range (t_0-t_2) q is again eliminated from (2) and

$$C'=\xi(1-\eta_{en}/100)C_1.$$

The same value of C' is substituted into (2) in the case of isothermic consumption of heat in the calcination section at t_1 and q remains in (2).

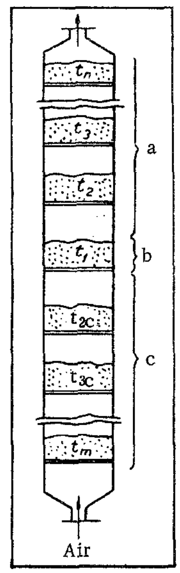

Fig. 1. Diagram of multisectional fluosolids furnace: a) n − 1 heating sections; b) calcination; c) m − 1 cooling sections.

The heat balance equation of the m-th cooling section is

$$VLC_a(t_m-t_{m+1})=GC_{pr}(t_{m-1}-t_m)\eta_{sur}. \tag{3}$$

We write the reduced equations in the form been determined)

$$\left(\frac{V}{G}\right)_n=\frac{C'}{KC_g\eta_{sur}}\,\frac{t_n-t_{n+1}}{t_{n-1}-t_n}, \tag{4}$$

$$(V/G)_1=[C'(t_1-t_2)+q]/(Q-KC_gt_1+LC_at_{2c})\eta_{sur} \tag{4a}$$

$$\left(\frac{V}{G}\right)_m=\frac{C_{pr}\eta_{sur}}{LC_a}\,\frac{t_{m-1}-t_m}{t_m-t_{m+1}}. \tag{4b}$$

Assuming $C'/KC_g\eta_{sur}$ = const and $(V/G)_n$ = const, for a given n we can write from (4)

$$\frac{t_2-t_3}{t_1-t_2}=\frac{t_3-t_4}{t_2-t_3}=\ldots=\frac{t_n-t_0}{t_{n-1}-t_n}=\frac{1}{X_n}. \tag{5}$$

From this expression with a known t_1 (determined by the particular technological process) and a prescribed t_2 we determine the temperature X_n for any n.

Multiplying all of relations (5), of which there will obviously be n − 1, we obtain

$$1/X^{n-1}=(t_n-t_0)/(t_1-t_2).$$

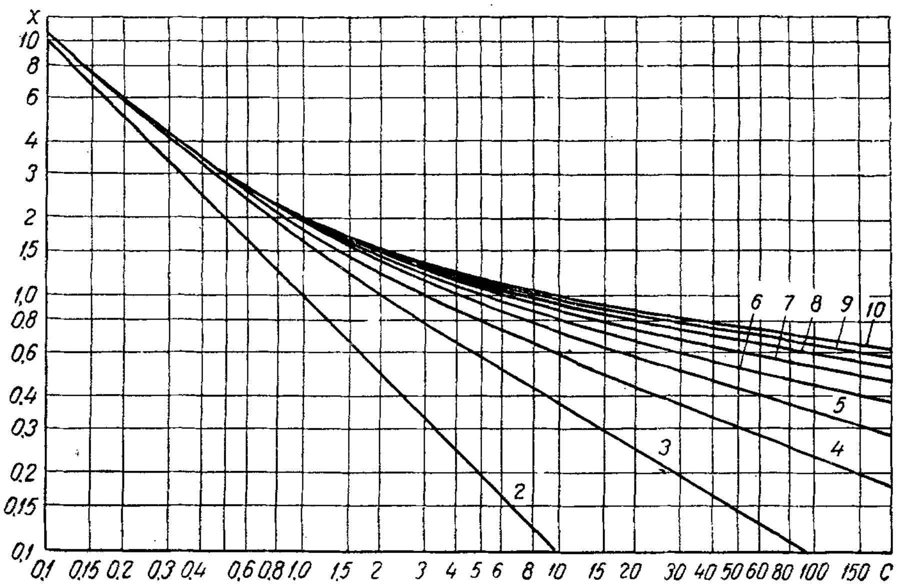

Fig. 2. Nomogram of approximate solution of equation $Cx^n - (C + 1)x^{n-1} + 1 = 0$. The figures on the curves are the values of n.

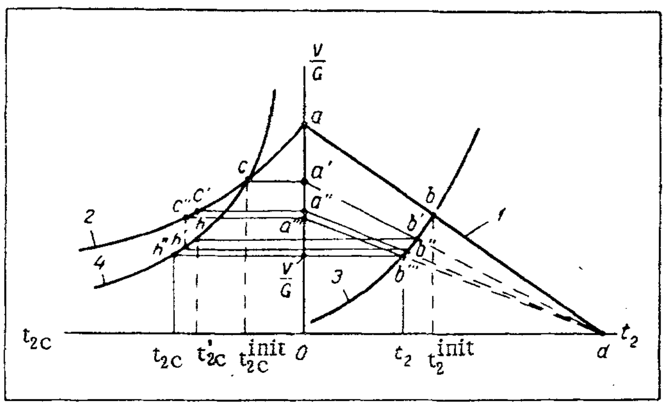

Fig. 3. Nomogram for calculation of a multisectional fluosolids furnace: 1) from (4a) with $t_{2c} = 0$; 2) from (4a) with $t_2 = 0$; 3) from (4') for a given n; 4) from (4b') for a given m.

On multiplication, beginning with the second simplex, we find

$$1/X^{n-2} = (t_n - t_0)/(t_2 - t_3). \quad (6)$$

A similar expression can be obtained for the subsequent sections and, finally, beginning from the n-th

$$1/X^{n-n} = 1. \quad (6')$$

Addition of the reciprocals of the found values, beginning with second, gives

$$X^{n-2} + X^{n-3} + \dots + 1 = (t_2 - t_0)/(t_n - t_0). \quad (7)$$

Substituting the values of $t_n - t_0$ from (6) and putting

$$C = (t_2 - t_0)/(t_1 - t_2),$$

we obtain

$$CX^{n-1} - (X^{n-2} + X^{n-3} + \dots + 1) = 0. \quad (8)$$

The expression in the brackets is the sum of the terms of a geometric progression. After transformations we obtain

$$CX^n - (C+1)X^{n-1} + 1 = 0. \quad (9)$$

This equation was analyzed in [4]. Figure 2 gives the nomogram for its solution. Using the nomogram with a known t_1 and a prescribed t_2 (after C has been determined) we find for any n the value of X_n and then from (4) we determine the specific gas flow

$$\left(\frac{V}{G}\right)_n = \frac{C'}{KC_g\eta_{sur}} \frac{1}{X_n}. \quad (4')$$

A similar solution is possible for the cooling sections. Assuming

$$C_{pr}\,\eta_{sur}/LC_a = \text{const}, \quad (V/G)_m = \text{const}$$

for a given m, we can write from (4b)

$$\frac{t_1 - t_2}{t_2 - t_3} = \frac{t_2 - t_3}{t_3 - t_4} = \dots = \frac{t_{m-1} - t_m}{t_m - t_0} = X_m. \quad (10)$$

Equating the reciprocals

$$\frac{t_2 - t_3}{t_1 - t_2} = \frac{t_3 - t_4}{t_2 - t_3} = \dots = \frac{t_m - t_0}{t_{m-1} - t_m} = \frac{1}{X_m}, \quad (11)$$

we reduce the problem to the preceding one and obtain the same equation

$$CX^m - (C+1)X^{m-1} + 1 = 0. \quad (9')$$

Using the same nomogram in Fig. 2 with known t_1 and prescribed t_{2c} (after C has been determined) we find for any m the value of X_m and then from (4b) we determine the specific gas flow

$$\left(\frac{V}{G}\right)_m = \frac{C_{pr}\eta_{sur}}{LC_a} X_m. \quad (4b')$$

Thus, for prescribed values of t_2 and t_{2c} we can determine the specific gas flows for the heating and cooling sections:

$$(V/G)_n = f_n(t_2), \quad (12)$$

$$(V/G)_m = f_m(t_{2c}). \quad (13)$$

Similarly, for the first (calcination) section we can write

$$(V/G)_1 = f_1(t_2, \ t_{2c}). \quad (14)$$

For a given furnace with fixed n and m we obviously have the equality

$$(V/G)_n = (V/G)_1 = (V/G)_m.$$

Then (12), (13), and (14) can be regarded as a system of three equations with three unknowns, V/G, t_2, and t_{2c}.

We solve this equation graphically, since relations (12) and (13) have already been obtained graphically by means of a nomogram (Fig. 2) by the method of successive approximations. For this purpose we unite the two quadrants with axes V/G and t_2, and V/G and t_{2c}, along V/G, as shown in Fig. 3. In the right quadrant we draw the curve from Eq. (4a) with $t_{2c} = 0$ and in the left quadrant we draw the curve from the same equation with $t_2 = 0$. The two curves must obviously originate from point *a*, where $t_2 = t_{2c} = 0$. In the right quadrant we then draw the curve from Eq. (4b) corresponding to its own m. This completes the construction of the calculation nomogram.

On analyzing the nomogram we note that in the right quadrant the point b of intersection of (4) and (4a) for $t_{2c} = 0$ gives the values t_2^{init} and $(V/G)_n^{init}$ in the absence of cooling sections. Similarly, the point c of intersection of the curves (4b) and (4a) for $t_2 = 0$ gives the values t_{2c}^{init} and $(V/G)_m^{init}$ in the absence of heating sections. In the case of the presence of both heating and cooling sections their mutual effect must obviously be taken into account.

We first consider the left quadrant. The point c gives the value of t_{2c}^{init}. We introduce a correction for t_{2c}^{init} in Eq. (4a) for the right quadrant. This "lowers" the line *a*-d and it occupies the position *a'*-d. The point *a'* can be found graphically by producing the line c*a'* parallel to the x axis until it cuts the y axis.

The new position of the line *a'*-d on intersection with the curve (4') gives the new position of the point b'. This reduces the flow of gas (ordinate of point b') and, accordingly, of air; this alters the conditions in the cooling section and at the same V/G point h appears on the curve (4b). The new value of t_{2c} corresponds on the curve (4a) at $t_2 = 0$ to point c'. Introducing the correction in correspondence with this point in Eq. (4a) we obtain the point *a"*, we produce the line *a"*-d, we obtain the new position of the point b", then h, c", and so on.

Two, three, and sometimes four repetitions of this "circuit" enable us to determine sufficiently accurately the final position of the points b and h, corresponding to the required values of t_2, t_{2c}, and V/G.

From these data from the heat balance of the n heating sections

$$\left(\frac{V}{G}\right)_n = \frac{C'}{KC_g\eta_{sur}} \frac{t_2 - t_0}{t_1 - t_n}$$

we determine the temperature of the last, n-th section (i.e., the emergent gases)

$$t_n = t_1 - \frac{C'}{KC_g\eta_{sur}} \frac{t_2 - t_0}{V/G}$$

or any preceding section

$$t_{n-1} = t_1 - \frac{C'}{KC_g\eta_{sur}} \frac{t_2 - t_n}{V/G},$$

$$t_{n-2} = t_1 - \frac{C'}{KC_g\eta_{sur}} \frac{t_2 - t_{n-1}}{V/G},$$

$$\cdots$$

It is worthwhile to perform such a calculation as a check from the last section t_n to t_2. Disagreement between the obtained value of t_2 and that found graphically from the nomogram in Fig. 3 indicates an error in the constructions or calculations.

If there are no errors there will be complete coincidence and the correctness of the calculations and constructions will be verified.

From the heat balance equation of the m cooling sections

$$\left(\frac{V}{G}\right)_m = \frac{C_{pr}\eta_{sur}}{LC_a} \cdot \frac{t_1 - t_m}{t_2 - t_0}$$

we determine

$$t_m = t_1 - \frac{V}{G} \frac{LC_a}{C_{pr}\eta_{sur}} (t_2 - t_0)$$

and then to t_{2c}

$$t_{m-1} = t_1 - \frac{V}{G} \frac{LC_a}{C_{pr}\eta_{sur}} (t_2 - t_m),$$

$$t_{m-2} = t_1 - \frac{V}{G} \frac{LC_a}{C_{pr}\eta_{sur}} (t_2 - t_{m-1}).$$

We consider the solution for prescribed n and m.

For a choice of optimum furnace parameters the position for different n and m must be analyzed. To perform such an analysis we have drawn the family of curves (4) for n in the right quadrant of the nomogram in Fig. 3 and the family of curves (4b) for m in the left quadrant. For any n and m the solutions are identical to that described.

Such a solution for different n and m enables us to find the relation

$$V/G = f(n, m), \qquad (15)$$

whose value allows an approach to the assessment of the energy consumption of the aggregate and a choice of the optimum number of sections in the furnace. The graphically found relation (15) determines the fuel (heat) consumption for the process. With increase in n and m the specific heat consumption will decrease but in this case the consumption of electrical power on compression of the blast will increase. Hence, with increase in the number of sections there will be an energy optimum at which further increase in n and m will lead to an increase in the total power consumption (fuel plus electricity).

We define the specific electric power consumption per unit production as

$$\mathrm{E} = \frac{V}{G}(n, m) \frac{L\Sigma H}{10^3 \eta_b}, \qquad (16)$$

where

$$\Sigma H = H_0 + H_1 + H_n(n-1) + H_m(m-1).$$

The total power consumption will then be

$$\Sigma Q = \frac{V}{G} Q_F + \mathrm{E}\frac{1}{\eta_s}. \qquad (17)$$

Since relation (15) is found graphically, the results of the calculations from (16) and (17) can best be represented on a graph, which gives a clear picture of the position of the power optimum.

It should be noted that the technical and economic optimum will have a slightly smaller number of sections than the power optimum, since the provision of extra sections will make the construction more expensive and complicate the operation of the furnace. Moreover, the choice of the number of sections may be affected by several additional factors, the required smoke temperature before gas cleaning, the possibility or necessity of discharging the hot product, and so on. All these additional factors can be adequately assessed only in specific plant conditions. Yet the power optimum is still the dominant factor. As an illustration of this we will consider a specific case.

Example of calculation. We have to determine the optimum number of sections of a multisectional fluosolids furnace for the calcination of cement clinker with the following initial data:

$$\xi = 1.6,\quad \eta_{en} = 6\%,\quad \eta_{sur} = 0.95,\quad \eta_b = 75\%,$$
$$\eta_s = 24.6\%,\quad t_1 = 1450°\,\mathrm{C},\quad t_0 = 0,\quad C_1 = C_{pr} =$$
$$= 0.96\ \mathrm{kJ/kg\cdot deg},\quad C_g = 1.46\ \mathrm{kJ/kg\cdot deg},$$
$$C_a = 1.25\ \mathrm{kJ/kg\cdot deg},$$
$$Q_F = 35500\ \mathrm{kJ/nm^3},\quad q = 1750\ \mathrm{kJ/kg},\quad K_{\alpha=1.1} = 11.56,$$
$$L_{\alpha=1.1} = 10.56,\quad W = 13\%,$$
$$H_0 = 4900\,\mathrm{N/m^2},\ H_1 = 14700\,\mathrm{N/m^2},\ H_n = H_m = 6850\,\mathrm{N/m^2}.$$

In the calculation of clinker the main heat consumption occurs in the temperature range t_0–t_1 and, hence, we will introduce q into the effective specific heat.

The calculation nomogram constructed from relationships (4), (4a), and (4b) by means of the nomogram in Fig. 2 and for prescribed t_2 and t_{2c} is shown in Fig. 4. The values of V/G found from it for values of n and m from 1 to 10 are shown in the form or relationship (15) on the graph in Fig. 5. On the same graph we have plotted the values of the specific electric power consumption found from formula (16) and also the curves of the total power consumption from relationship (17).

As the graph in Fig. 5 reveals, the minimum power consumption for our case is attained when n = 4 and m = 5 (a 4-1-4 scheme, i.e., four heating sections, one calcination section, and four cooling sections). But the technical and economic optimum, as mentioned above, must lie a little "to the left" (i.e., the number of sections must be fewer). In addition, the temperature of the emergent gases in a 4-1-4 scheme is 60° C, which will create difficult conditions for gas cleaning (adhesion to dust due to the "shift" of the dew point

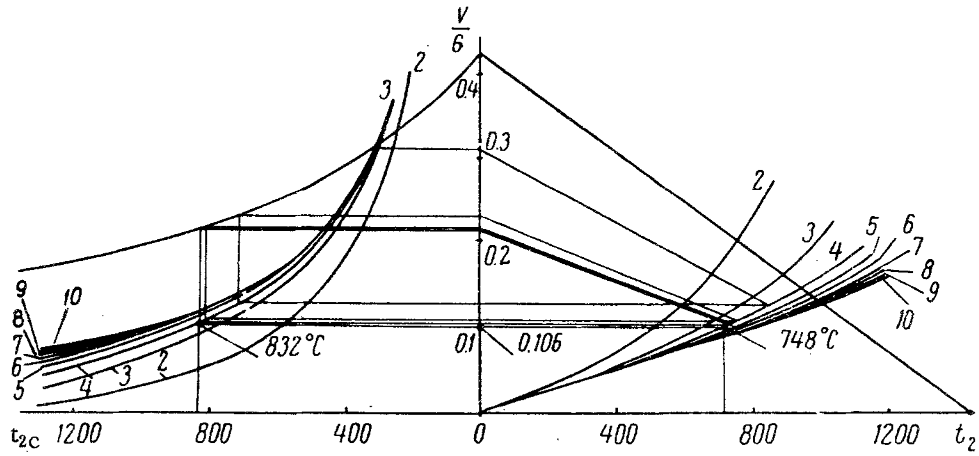

Fig. 4. Nomogram for calculation of a multisectional fluosolids clinkering furnace. The figures on the right of the curves are the values of n and those on the left are the values of m.

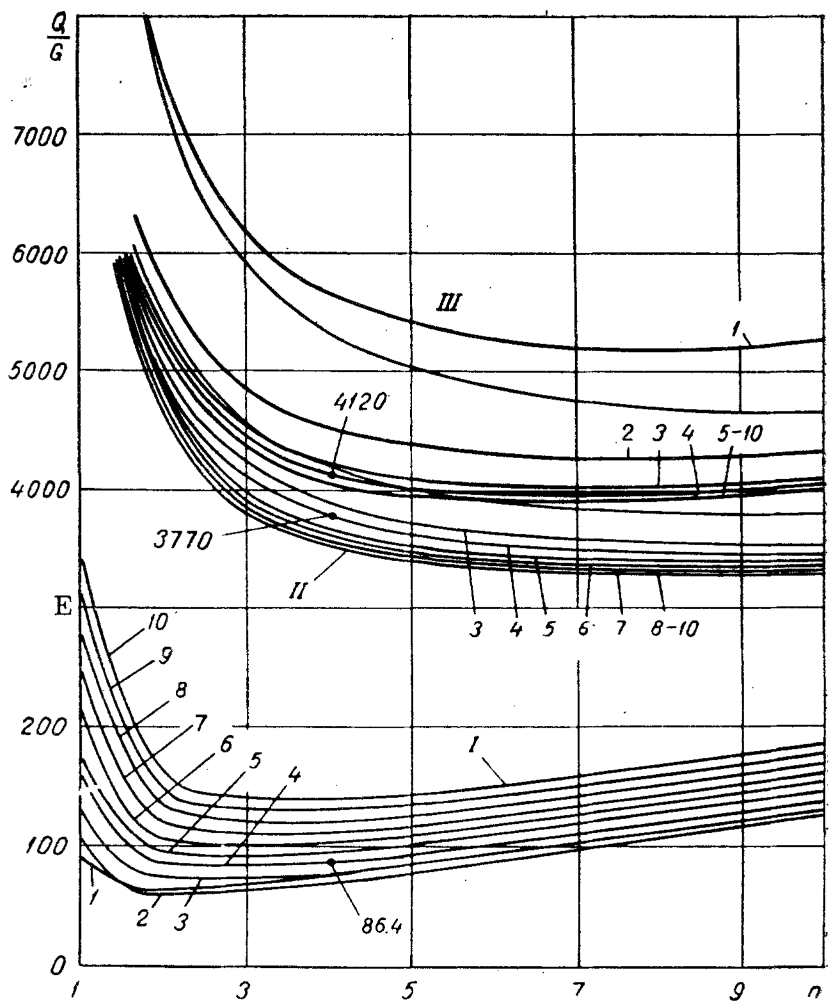

Fig. 5. Consumption of heat Q, kJ/kg and electric power E, kJ/kg by a fluosolids clinkering furnace (working point m = = 4, n = 4; 3-1-3 scheme; n − 1 is the number of heating sections; m − 1 is the number of cooling sections): I) for E; II) for Q; III) ΣE + Q; the figures on the curves are the values of m.

for gas cleaning). Hence, it will presumably be better to have a 3-1-3 scheme. The temperature of the emergent gases will be 125° C and of the emergent material will be 168° C.

The specific power consumption in the work of a seven-section 3-1-3 furnace is 3770 kJ/kg of heat and 86.4 kJ/kg of electric power. The total power consumption from relationship (17) with due allowance for the efficiency of the electric power station is 4120 kJ/kg.

The points corresponding to this position (n = 4 and m = 4) are marked on the graph in Figs. 4 and 5.

NOTATION

V, G is the hourly flow of gas (fuel) and final product, nm^3/hr, kg/hr; K, L are the yield of combustion products and air flow per nm^3 of gas (fuel), nm^3/nm^3; C_a, C_g, C_1, C_{pr} is the specific heats of air, gases, raw material, and final product, $kJ/nm^3 \cdot deg$, kJ//kg · deg; q is the heat consumption on thermal process per kg of final product, kJ/kg; ξ is the raw material consumption coefficient; η_{en} is the percentage entrainment from top section; η_{sur} is the coefficient of heat loss to surroundings; η_b, η_s is the efficiencies of blower and electric power station; Q_F is the calorific value of the gas (fuel, kJ/nm^3; t_1, t_2, t_n, t_{2c}, t_m are the temperatures of first, second, n-th, second cooling, and m-th sections, deg; E is the specific electric power consumption, kJ/kg; H_0, H_1, H_n, H_m are the head losses on supply lines, on first section, on heating sections, and on cooling sections, N/m^2.

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