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HEAT CONDUCTION AND HEAT EXCHANGE IN TECHNOLOGICAL PROCESSES

OPTIMIZATION OF TEMPERATURE REGIMES OF WALKING-BEAM HEATING FURNACES

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Methods and results of optimization of operating temperature conditions of walking-beam heating furnaces are presented. The influence of the distance between the steel blanks treated in such a furnace on the characteristics of the optimum regimes of their heating has been investigated.

Heating furnaces used in ferrous metallurgy are among the largest industrial consumers of natural gas. The power consumption of these furnaces is directly dependent on their output and the conditions under which a metal is heated in them. Optimization of the temperature regimes of heating furnaces designed and put into operation several decades ago makes it possible, in many cases, to decrease both the amount of gas expended for heating of steel blanks and the loss in the metal due to its oxidization in the high-temperature atmosphere of the furnaces. Since metals have a high cost, the scale that develops on them leads to high expenses. The energy and economy characteristics of the operating temperature conditions of a furnace are determined by a large number of factors, namely, by the flow rate of the gas burnt in the zones of the furnace, determining the temperature distribution of smoke gases along its length; the dimension and shape of the blanks treated and the distance between them; the properties of the furnace lining; the velocity of movement of the blanks along the furnace bottom, etc.. In calculations of new temperature regimes of furnaces, the distribution of the gas flow rate in them usually receives the bulk of the attention, and the other factors are considered as secondary. In the present work, we have performed optimization calculations of technological regimes of operation of walking-beam furnaces with account for the distances between the steel blanks treated in them. The calculations were carried out with the use of a mathematical model of conjugate heating of steel blanks in walking-beam furnaces, developed in [1]; at the moment this model provides the best relation between the accuracy and rate of calculations.

We calculated the walking-beam heating furnace of a 320 RUP BMZ mill. One and the same geometric and physical parameters of the furnace and of the blanks treated in it were used in the calculations of its operating conditions. The height and width of the furnace were respectively equal to 1.57 and 12.5 m. Four zones of different length were considered: the methodical zone (9.48 m), the first weld zone (6.68 m), the second weld zone (6.35 m), and the soaking zone (6.7 m). The bottom of the furnace was made from a refractory concrete of thickness 200 mm, and its roof and walls were made from a refractory concrete (200 mm) and a lightweight chamotte (50 mm). Blanks St3 steel were used. The heat of scale oxidization was equal to 5 MJ/kg, the heat of gas combustion was 44.4 MJ/kg, the temperature of the gas mixture supplied for combustion was 390^{o}C, the temperature of the metal in the furnace was 110^{o}C, and the ambient temperature was 20^{o}C. The economy characteristics of the operating conditions of the furnace were calculated for the steel of price 300 arb. units/t and the natural gas of price 72 arb. units for 1000 m^3.

One of the main characteristics of the operating temperature conditions of a furnace is the temperature distribution of smoke gases over its zones. It should be noted that a heating furnace is controlled in accordance with a regime map determining the temperatures of the zones of this furnace in accordance with its output and, therefore, the flow rate of the working gas. A computer program used in our calculations was based on this principle and al-

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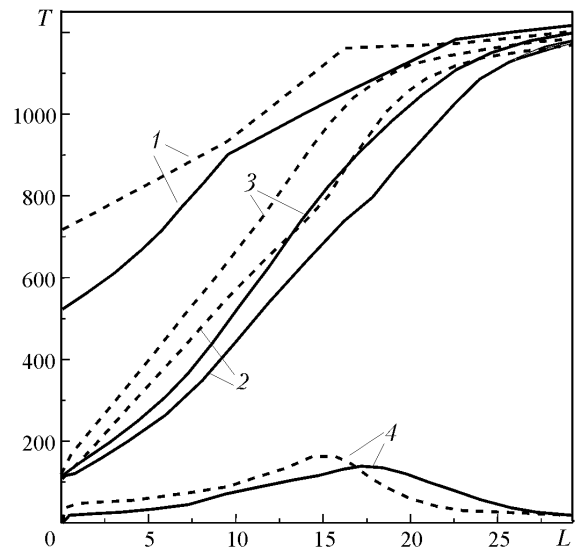

Fig. 1. Distribution of the temperature characteristics of the regimes of heating of a metal in a walking-beam furnace over the length of the furnace, corresponding to the local (dashed curves) and global (solid curves) minima of the goal function: 1) temperature of the smoke gases; 2) minimum temperature of the metal; 3) maximum temperature of the metal; 4) maximum temperature difference in the cross section of a blank. T, ^{o}C; L, m.

lowed us to calculate the regime of operation of the heating furnace by the temperature distribution of smoke gases along its length. To optimize the operating conditions of a heating furnace it is necessary to find the temperature distribution of smoke gases in this furnace, at which the specific expenses for heating of blanks in it are minimum. For the walking-beam furnace considered, the temperatures T_1, T_2, ..., and T_5 were determined at five its points: at the boundaries of the zones, at the beginning of the furnace, and at its end. It was assumed that the temperature distribution of smoke gases between these points is linear. Thus, the temperature regime of the furnace was optimized by the five parameters.

The following goal function was minimized in the process of solving the problem on optimization of the furnace considered:

$$F(T_1, ..., T_5) = C_g G_g / P + K_1 C_m m_{ox} . \tag{1}$$

The indicated function determines the main specific expenses for heating of steel blanks (in arb. units per one ton of the metal). These expenses comprise the cost of the natural gas burnt in the process of work of the furnace in a given regime (the first term in (1)) and the cost of the metal transformed into the scale as a result of heating of the blanks. An optimum regime was calculated in accordance with the technological requirements for the steel heated on condition that $T_{fin} \geq (1190 \pm 5)^{o}$C and $\Delta T_{max} < 180^{o}$C with the use of the fastest-descent gradient method [2]. A new temperature distribution of smoke gases along the furnace was determined from the previous temperature distribution by the formula

$$T_i^{(j+1)} = T_i^{(j)} + \lambda^{(j)} v_{(i)}^{(j)} , \quad i = 1 \dots 5 . \tag{2}$$

The direction of the step $v_{(i)}^{(j)}$, i.e., the rate of descent to the minimum, is determined by the finite-difference derivative, in which the value of the function $F(T_1, ..., T_5)$ for each temperature distribution is determined from solution of the problem on heating of steel blanks in the furnace [1]:

$$T_i^{(j+1)} = T_i^{(j)} + \lambda^{(j)} v_{(i)}^{(j)} , \quad i = 1 \dots 5 . \tag{2}$$

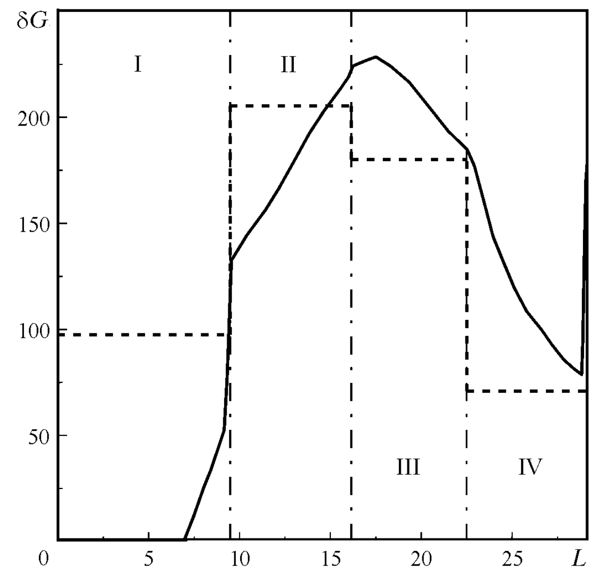

Fig. 2. Distribution of the gas flow rate over the length of the furnace operating in the regimes corresponding to the local (dashed lines) and global (solid curves) minima of the goal function: I) methodical zone; II) first weld zone; III) second weld zone; IV) soaking zone, δG, m^2/h; L, m.

It should be noted that the multiparameter goal function $F(T_1, ..., T_5)$ considered can have several minima, among which only one minimum is global and the other minima are local. It was established in the process of calculations that the goal function has a local minimum in a regime close to the temperature regime used at present for the furnace of the 320 mill. At the same time, a much more economic regime (which only conditionally can be considered as a global minimum) is established at regime parameters differing markedly from the regime parameters used at present. Figure 1 shows the distributions of the temperature of smoke gases, the minimum and maximum temperatures of steel blanks, and the maximum temperature difference in the cross section of a blank along the length of the furnace, which correspond to the local and global minima of the goal function and were calculated for the distance between the blanks s = 75 mm. Note that the average velocity of movement of the bottom is equal to 4.7 mm/sec in this case. It is seen from the distributions of the gas flow rate along the length of the furnace, calculated for the two above-indicated regimes of heating (Fig. 2), that this regimes differ mainly by the gas-flow rates in the methodical zone of the furnace. Our calculation has shown that, due to the counterflow heat transfer in the furnace considered, large convective flows of hot smoke gases propagating from the first weld zone to the methodical zone provide a necessary heating of the metal even at a small amount (about 100 m^3/h) of the gas burnt in this zone. This circumstance makes it possible to decrease both the gas consumption and the scaling by decreasing the residence time of a blank in the high-temperature zone of the furnace (Fig. 1). It should be noted that, in the majority of furnaces, the gas-flow rate is controlled section by section; in this case, several rows of gas burners, positioned along the length of a section, work with equal gas-flow rates. However, it follows from our calculations (Fig. 2) that, to increase the quality and improve the economy characteristics of the heating process in the furnace considered, it is necessary to control the gas flow rates of all the gas burners separately.

The characterizes of the optimum regimes of heating of steel blanks in the walking-beam furnace considered, which correspond to the local and global minima of the goal function and were calculated for different distances between blanks at a furnace output of 120 t/h, are given in Tables 1 and 2. The most important characteristics of the operating conditions of a furnace are the specific scaling and the fuel utilization factor (FUF) determined by the gas-flow rate. This factor represents the mass of an equivalent fuel with a combustion heat of 29.3 MJ/kg expended for heating of one ton of blanks to a definite temperature. For comparison, we present the regime parameters of heating of steel blanks, calculated by a plant regime map for the space between the blanks s = 75 mm: scaling, 7.2 kg/t; gas flow rate, 3931 m^3/h (1015 m^3/h in the methodical zone, 1392 m^3/h in the first weld zone, 1100 m^3/h in the second weld zone, 424 m^3/h in the soaking zone); T_{out} = 724^{o}C; ΔT_{max} = 175^{o}C; goal-function value, 4.04 arb. units/t. The

TABLE 1. Characteristics of the Operating Conditions of the Walking-Beam Furnace of a 320 Mill Providing Optimum Specific Expenses at Different Distances s Between the Faces of Square Blanks of Cross Section 125×125 mm (the Numerator and Denominator are the Local and Global Minima)

s, mm	m_{ox}, kg/t	G_g, m^3/h	FUF, kg/t	T_{out}, °C	ΔT_{max}, °C	ΔT_{fin}, °C	Specific expenses, arb. units/t			Economy	
							burning of gas	scaling	in all	arb. units/t	%
50	$\frac{7.3}{6.1}$	$\frac{3888}{3347}$	$\frac{37.1}{31.9}$	$\frac{721}{510}$	$\frac{156}{134}$	$\frac{17}{23}$	$\frac{2.33}{2.01}$	$\frac{1.70}{1.42}$	$\frac{4.03}{3.43}$	0.60	14.8
75	$\frac{6.9}{5.8}$	$\frac{3916}{3397}$	$\frac{37.3}{32.4}$	$\frac{722}{520}$	$\frac{164}{140}$	$\frac{16}{21}$	$\frac{2.35}{2.04}$	$\frac{1.61}{1.35}$	$\frac{3.96}{3.39}$	0.57	14.3
100	$\frac{6.5}{5.5}$	$\frac{3923}{3432}$	$\frac{37.4}{32.7}$	$\frac{720}{531}$	$\frac{176}{148}$	$\frac{16}{24}$	$\frac{2.35}{2.06}$	$\frac{1.52}{1.28}$	$\frac{3.87}{3.34}$	0.53	13.6
125	$\frac{6.1}{5.2}$	$\frac{3935}{3464}$	$\frac{37.5}{33.0}$	$\frac{721}{542}$	$\frac{192}{158}$	$\frac{16}{27}$	$\frac{2.36}{2.08}$	$\frac{1.42}{1.21}$	$\frac{3.78}{3.29}$	0.49	12.9
150	$\frac{5.8}{4.9}$	$\frac{3942}{3496}$	$\frac{37.6}{33.3}$	$\frac{722}{553}$	$\frac{208}{170}$	$\frac{18}{31}$	$\frac{2.36}{2.10}$	$\frac{1.35}{1.14}$	$\frac{3.72}{3.24}$	0.48	12.9

TABLE 2. Flow Rate (m^3/h) of the Gas Burnt in Different Zones of the Walking-Beam Furnace Operating in the Optimum Regimes of Heating of Steel Blanks (125×125 mm) at Different Distances s Between the Faces of the Blanks [1 and 2) Local and Global Minima]

s, mm	Methodical zone		First weld zone		Second weld zone		Soaking zone	
	1	2	1	2	1	2	1	2
50	975	103	1366	1180	1095	1327	453	737
75	925	79	1372	1164	1144	1362	475	792
100	853	62	1363	1131	1208	1398	500	841
125	790	47	1337	1087	1281	1433	527	896
150	729	35	1300	1035	1353	1462	560	964

redistribution of the burnt-gas flow rate over the zones of the furnace operating in the regimes corresponding to the global minimum of the goal function makes it possible to obtain an economy of more than 10% at the cost of a decrease in the gas flow rate and in the scaling as well as to decrease the maximum temperature difference in the cross section of a blank. All this provides not only an economy of resources, but also a high-quality heating of blanks. Note that the furnace can work in these regimes only with the use of burners whose power can be varied widely because the gas flow rate in the methodical zone of the furnace operating in the indicated regimes is much smaller than in the other zones.

The distance between the blanks treated in the furnace considered substantially influences the specific expenses for their heating because an increase in this distance leads to an increase in the velocity of movement of the blanks along the bottom of the furnace, which makes it possible to maintain its. The specific gas flow rate increases insignificantly (by 1–2%) in this case. However, an increase in the velocity of the furnace bottom leads to a significant increase in the scaling (by 15–20%) due to the decrease in the residence time of a blank in the high-temperature zone of the furnace, in which the scaling is most intensive. When the distance between the blanks changes from 50 to 150 mm, the specific expenses for heating of one ton of the metal decrease by 7.5%. A significant increase in the distance between the blanks (>100 mm) leads to an increase in the temperature difference in the cross section of a blank, which increases the probability of its thermal deformation. At the same time, in the regimes corresponding to the global minimum of the goal function, this difference is smaller by 20–30°C.

Thus the method developed for optimization of the operating conditions of a walking-beam furnace and the mathematical model of heating of steel blanks in this furnace allow one to determine the optimum regimes of heating of these blanks with account for the distance between them along the furnace bottom. In this case, the optimization of the operating temperature conditions of the furnace without its modernization makes it possible to obtain a large economy (10–15%) of the energy and materials expended for heating of the metal in it.

NOTATION

C_g, cost of the natural gas burnt for heating of blanks, arb. units/m^3; G_g, gas flow rate in the process of work of a furnace m^3/h; C_m, cost of the metal treated, arb. units/t; L, distance along the length of the furnace, m; m_{ox}, specific scaling in the process of heating of a steel blank, kg/t; P, output of the furnace in the regime considered, t/h; s, distance between the faces of blanks, mm; T, temperature, ^{o}C; T_{fin}, finite temperature of a blank, ^{o}C; ΔT_{max}, maximum temperature difference in the cross section of a blank treated under given temperature conditions, ^{o}C; ΔT_{fin}, temperature difference in the cross section of the blank removed from the furnace, ^{o}C; K_1 = 0.778, coefficient accounting for the chemical composition of the scale (of FeO predominantly); δG, specific gas flow rate per unit of the furnace length, m^2/h; $\lambda^{(j)}$, step of descent to the goal-function minimum. Subscripts: fin, final; g, gas; max, maximum; m, metal; ox, scale; out, outflow of smoke gases.

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