HEAT TECHNOLOGY

MEANS OF CUTTING FUEL CONSUMPTION IN KILNS OF THE REFRACTORIES INDUSTRY

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Increasing the effectiveness of using fuel and the energy efficiency of heating equipment is an important national economic problem whose resolution in the country is attracting a great deal of attention. This problem faces the refractories industry, which every year uses more than 3 million tons of standard fuel. The complexity of the problem in the production of refractories is connected with the variety of furnace designs, schedules and methods of operation, and the different levels and potential for heat-engineering improvements of the plant. An all-round analysis of the factors affecting the consumption of fuel enables us to identify the main means of reducing it, to develop measures of increasing the effectiveness of using fuel in furnace installations.

The first point is the need to update still further the industry's kilns and furnaces, the introduction of modern contraflow-recuperative firing units (PROA) instead of outdated designs (annular, gas-chamber, periodic, etc.), which have higher (sometimes by several orders) fuel consumptions with low levels of mechanization.

Of all the possible furnace schemes, the PROA is heatwise the best, providing the minimum fuel consumptions to be obtained [1]. In the ideal case (isoentropic process) PROA, realizing the contraflows with an inversion of heat exchange at maximum temperatures, in a fixed working schedule, do not require expenditure of fuel, using as a working instrument the energy introduced at a single time during their starting up [2]. Although existing PROA schemes (tunnel, rotary, shaft furnaces) are still not perfect, their advantages are obvious compared with other forms. This fact was one of the causes of the wide use of PROA in world practice, including the refractories industry of the USSR, where they constitute approximately one-half of the furnace stock and are responsible for firing the largest part of refractories output.

Subsequently, the contribution of PROA in the industry will rise, although it will not reach 100% because of the technological advantages that in some cases may be inherent in furnaces of other designs, e.g., mechanized and automated periodic kilns ensuring, with an increased fuel consumption, effective control of the firing regimes in all of its stages, the convenience of achieving cyclic working graphs for the enterprise, organizing low-tonnage production of complicated shapes and large articles.

Secondly, an important trend in cutting fuel consumption is the increase in energy efficiency factors, associated with PROA with the optimum design and schedules, heat insulation, and heating and working schedules. Most reserves exist in the matter of improving rotary kilns, and this potential may be realized by fitting them with high-temperature heat exchangers (decarbonizers, dehydrators), new layer coolers and high-efficiency controllable burners. In recent years, the All-Union Institute of Refractories and the Institute for Research into the Gas Industry (VNIIpromgaz) have developed a series of standardized gas burners GDG (Fig. 1) including burners of 10 sizes with natural gas consumptions of from 1000 to 8000 m^3/h. The burners are being introduced in rotary kilns of diameter 4.04 and length 170 m, diameter 3.14 and length 90 m (inside) for firing magnesite, which will improve the control of the firing process, speed up the heat exchange in the kilns, and reduce the specific consumption of fuel by 4-5% [3].

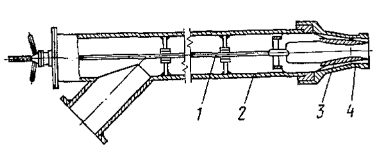

Fig. 1. Gas burner GDG: 1) draft of throttle; 2) frame; 3) throttle; 4) nozzle.

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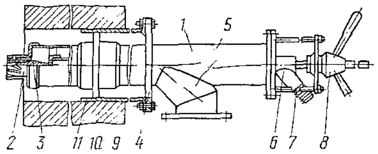

Fig. 2

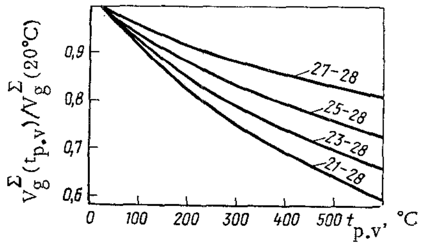

Fig. 3

Fig. 2. Gas burner GTP: 1) frame; 2) gas—air nozzle; 3) gas nozzle; 4) flange; 5) connecting pipe; 6) gas pipe; 7) sleeve; 8) mixing device; 9) centering flange; 10) tunnel; 11) ring.

Fig. 3. Effect of preheating primary air $t_{p.\,v}$ on the fuel consumption; numbers on the curves indicate the numbers of the positions at which primary air is fed in the warmed state; V_g^Σ ($t_{p.\,v}$) is the consumption of fuel in the kiln during preheating of primary air; V_g^Σ(20°C) — the same without preheating.

A series of standardized gas burners GTP (Fig. 2) has been designed for heating tunnel kilns, including burners of 10 standard sizes with a natural-gas consumption of from 2 to 200 m^3/h. The burners provide a substantial reduction in fuel in tunnel kilns, the possibility of controlling the distribution through the setting channels, which is especially important with variations in the assortment of articles being fired, and in the setting schemes. The burners are being introduced in tunnel kilns at the Magnezit Combine for firing temperatures of 1600-1900°C. Following reconstruction of the kilns, there have been improvements in the cost-benefit indices, the quality of the fired products, and a reduction in specific fuel consumption of 14-15%.

Fuel consumption is markedly affected by the choice of working parameters for the furnace, and these are chosen partly by empirical means, without detailed analysis of the kinetics of the physicochemical process of firing and the optimum methods of realizing them in industrial equipment. Valuable results may be obtained from mathematical modeling on computers of the heat-engineering process of firing and optimization of the technological parameters of firing.

With this aim, the Institute developed a mathematical model for the working of the firing zone of a tunnel kiln. The model was used to prepare a program for an electronic computer facilitating, in particular, an analysis of the effect of various factors on fuel consumption, ensuring the required temperature schedule in the firing zone. The investigation of the work of the model on the ES-1200 computer showed that the model possesses a good degree of correspondence [7] to the real firing zones which is wide enough for practical applications.

Below we present some results of computer modeling for the burner process of a large tunnel kiln with a temperature potential of 1900°C for firing [4], demonstrating the effectiveness of using computers for developing measures of reducing fuel consumption.

The work of a firing zone was modeled including eight combustion chambers, in the first of which (through the gas duct) it is necessary to maintain a temperature of 1600°C, in the second 1750°C, and in the others 1900°C. It was assumed that a lattice-type setting of magnesia—spinel goods was being fired, having a temperature of 1600°C at the entrance to the zone. The design of the hearth corresponded to that used at the Magnezit Combine [8]; its hot-face temperature equaled the average temperature of the articles. The firing cycle was 78 h; fuel — natural gas from the Gazlinsk deposits. Calculations established that the energy of gases leaving the firing zone for the variants being examined is adequate to ensure the energy demands of the preheat zone, i. e., the consumption of fuel in the kiln is determined in this case by the organization of the heating schedule of the firing zone.

One of the methods examined for reducing the fuel consumed by the kiln was preheating of the primary air entering the gas-burner device of the firing zone. The results of modeling are shown in Fig. 3. An investigation was made for the following combination of factors, determining the working of the firing zone: energy utilization coefficient in the cooling zone $\eta = 0.3$; temperature of secondary air at entrance to firing zone $t_{v.\,v} = 1300°C$, coefficient of primary air consumption $\alpha_{p.\,v} = 0.75$; heat given up by flue gases (to

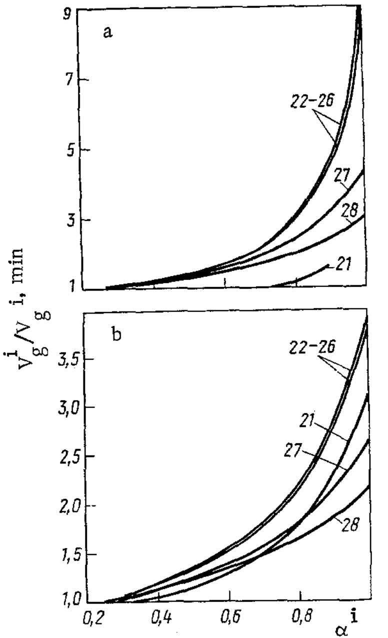

Fig. 4

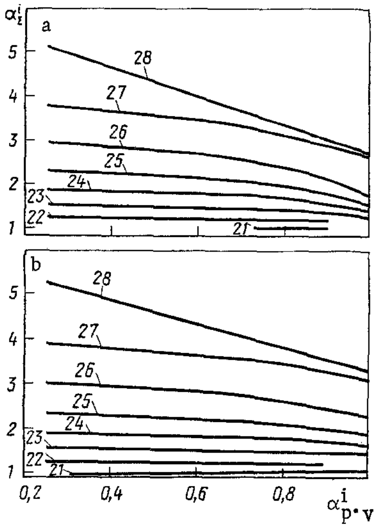

Fig. 5

Fig. 4. Effect of coefficient of primary-air consumption $\alpha^i_{p.\,v}$ on fuel consumption when $t_{p.\,v} = 20$ (a) and 300°C (b); numbers on the curves indicate positions; for $k > i$, $\alpha^k_{p.\,v} = 0.25$; V^i_g is the fuel consumption at the i-th position; $V_g^{i,min}$ is the minimum gas consumption at the i-th position when controlling with respect to $\alpha^i_{p.v.}$.

Fig. 5. Effect of coefficient of primary air consumption $\alpha^i_{p.\,v}$ on the coefficient of total consumption of oxidizer α^i_Σ when $t_{p.\,v} = 20$ (a) and 300°C (b); numbers on the curves indicate the numbers of the position; for $k > i$, $\alpha^k_{p.\,v} = 0.25$.

setting, cars, and structure of kiln) equal to that calculated for this kiln by the methods stated in [9]; coefficient of completeness of mixing of gases in the combustion chambers $\varkappa = t_k/t_p = 1$ (t_k and t_p are, respectively, the stated and calculated temperatures in the chambers); temperature of primary air in all burners expect those supplied with preheated air $t_{p.\,v} = 20$°C.

We modeled a series of working versions for the firing zone with different temperatures (from 20 to 600°C) for the primary air and different numbers of positions (from 2 to 8) supplied with preheated air. Figure 3 shows that with the input, for example, to the burner of air heated to 300°C, the fuel consumption drops by 25%. Thus, the conversion of the high-temperature tunnel kilns to hot blowing in the burners on account of the excess air in the cooling zone reduces the fuel consumption.

The fuel consumption is largely affected by the regulation of the gas-burner devices, characterized in particular by the coefficient of consumption of primary air $\alpha^i_{p.\,v}$ (i is the position number). Figure 4 shows the results of modeling the work of the firing zone with different coefficients for air consumption at the burners. In all burners at positions following the i-th, we maintain a constant coefficient of consumption equal to 0.25, and the $\alpha^i_{p.\,v}$ is regulated within the limits from 0.25 to 1.0. The choice for the lower limit of $\alpha_{p.\,v} = 0.25$ is because with lower $\alpha_{p.\,v}$ values it is difficult to get satisfactory distance-throw of fuel jet from the burner and good mixing of gases in the combination chamber. The other factors determining the operation of the firing zone were taken to be equal to the above-mentioned ones ($t_{p.\,v} = 20$°C).

As the modeling results showed, at all positions except No. 21 (flue, adjacent to preheat zone) it is possible to work (when $\varkappa = 1$) with $\alpha_{p.\,a} = 0.25$ requiring the minimum fuel consumption with respect to $\alpha_{p.\,a}$. When $\alpha^i_{p.\,v}$ changes, the fuel consumption grows especially rapidly when $\alpha^i_{p.\,v} > 0.8$. At position No. 21 the minumum consumption of fuel is attained when $\alpha_{p.\,v} = 0.74$. When $\alpha_{p.\,v} < 0.73$ in the chamber we cannot guarantee the required temperature. The effect of changing $\alpha^i_{p.\,v}$ on the fuel consumption is weakened with

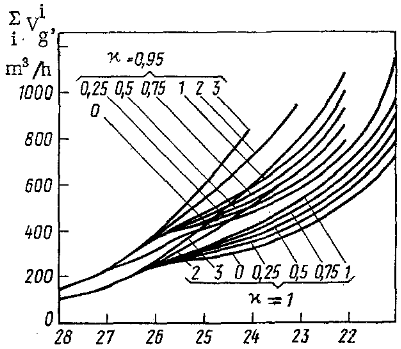

Fig. 6. Change in the fuel consumption $\sum\limits_i V_g^i$ across the length of the firing zone with different heat insulation Q on the structure (indicated on curves).

a rise in $t_{p.\,v}$, which is illustrated by the results of modeling for $t_{p.\,v} = 300°C$ for all positions (see Fig. 4b).

With an increase in the temperature of the primary air, there is a fall in $\alpha_{p.\,v}$ at position No. 21 corresponding to the minimum of the fuel consumption. For conditions similar to the above, but when $t_{p.\,v}^{21-28} = 300°C$, the minimum fuel consumption corresponds to $\alpha_{p.\,v}^{22-28} = 0.25$, and $\alpha_{p.\,v}^{21} = 0.31$. When $t_{p.\,v}^{21-28} = 600°C$, $\alpha_{p.\,v}^{21-28} = 0.25$ is permitted.

The change in these conditions as for Fig. 4 with respect to the coefficient of the total oxidizer consumption α_{Σ}^{i} as a function of $\alpha_{p.\,v}^{i}$ is shown in Fig. 5. By total oxidizers here we understand the mixture of primary air entering the chamber from the gas burner device, and the tunnel oxidizer — the flue gases entering the chamber from the preceding position along the gas path. The reduction in the coefficient of consumption of total oxidizer with a rise in the coefficient of consumption of primary air (when $\alpha_{p.\,v} < 1$) is explained by the fact that with a rise in $\alpha_{p.\,v}^{i}$ in the total oxidizer of the i-th chamber there is a fall in the proportion of oxygen moving to the i-th chamber from the preceding position (mainly oxygen contained originally in the secondary air). An increase in $\alpha_{p.\,v}^{i}$ increases the proportion of oxygen in the total oxidizer from the primary air, and reduces the proportion of oxygen from the tunnel oxidizer.

The important effect of the quality of the heat insulation of the kiln structure and the degree of completeness of mixing of the gas in the chambers on the fuel consumption is illustrated by the results of modeling shown in Fig. 6, where along the ordinate are shown the accumulated (from position No. 28 to position No. 21) consumptions of heat $\sum\limits_i V_g^i$. The quality of the heat insulation was characterized by the parameter Q, equal to the ratio of the heat given off to the structure to the heat given off corresponding to the original variant, selected as being typical for the design of actual kilns. For clarity's sake the points of the graph corresponding to different positions are joined with solid lines (but this has no physical significance). Modeling was done for the following conditions: $\eta = 0.3$, $t_{v.\,v} = 1300°C$, $\alpha_{p.\,v} = 0.75$, $t_{p.\,v} = 20°C$. It was assumed that the quality of the heat insulation at the transmission positions Nos. 27 and 28 is kept unchanged.

The value Q = 0 corresponds to the adiabatic structure, Q = 1 to the existing heat insulation. The imperfection of certain curves in Fig. 6 is due to the fact that at these positions either the required temperature for any fuel consumption cannot be attained or the fuel consumed at the position exceeds 500 m³/h. Figure 6 shows the marked effect of Q and especially ϰ on the fuel consumption. Doubling the quality of the heat insulation in the firing zone (when Q = 1 and Q = 0.5; ϰ = 1) yields fuel savings equal to 13%. With a rise in ϰ depending on the quality of the heating system from 0.95 to 1 the consumption of fuel at positions Nos. 22-28 (when Q = 1) is reduced by 33%, and the previously absent possibility of realizing the stated temperature at No. 21 position is manifest. This shows the great importance of improving the system of heating the kilns, their burner equipment, and the fuel combustion schedules.

It was shown above that certain factors influence the fuel consumption in a tunnel kiln. It should be noted, however, that in solving the problem of optimizing the schedule in tunnel kilns the fuel consumption

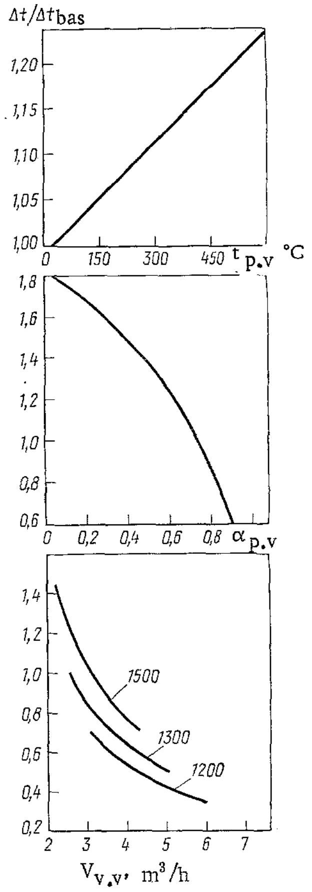

Fig. 7. Effect of $t_{p.v}$, $\alpha_{p.v}$, and $V_{v.v}$ on the drop in gas temperatures over the setting length in the latter positions of the high-temperature soaking; numbers on the curves indicate the temperatures of the primary air, °C.

itself cannot serve as the criterion for the optimal solution — the purpose function. The latter will have an incomparably more complex form, since we must take into account the whole complexity of basic factors linked with the quality and economic nature of the firing process.

These factors, e.g., include [10] the temperature heterogeneity in firing the goods across the length of the setting, depending on the corresponding drop in temperature of the gases Δt in the latter (before the start of cooling) positions of the high-temperature soaking. The factors governing the consumption of fuel, needed to ensure the required temperatures of gases in the chambers, also affect the magnitude of Δt. An illustration of this is the results of modeling shown in Fig. 7, where $V_{v.v}$ is the consumption of secondary air; Δt_{bas} is the drop in the temperature of the gases in conditions indicated for Fig. 3 ($\alpha_{p.v}$ and $t_{p.v}$ vary simultaneously for all positions in the zone). It follows from these data that any change in $\alpha_{p.v}$, $t_{p.v}$, and $V_{v.v}$, causing an increase in the heat loading of the leading and transmission positions will cause a reduction in the longitudinal drop in temperature over the length of the setting of the leading positions (the latter in the soaking section) i.e., to an increase in the uniformity of firing of the goods.

Thirdly, an important aspect of the work of reducing the fuel consumption is to improve its normalizing, the determination of the energy efficiency of existing and newly planned kilns, the identification and elimination of causes leading to the reduction in efficiency in any particular actual case. We should mention that until recently the utilization coefficients of PROA in general have not been taken into account, and various attempts at such a calculation proved to be unsuccessful. As a result, the factor of specific fuel consumption is widely used, critically depending on the type of raw material being fired and not giving a proper assessment of the quality of the heating equipment. The method of calculating the coefficient of utilization for PROA was first reported in [1, 2]. Starting from the results obtained, in order to compute the energy utilization factors for PROA (η_q) it is possible to put forward the following equation:

$$\eta_q = \frac{q_{fx} + q_M^* + q_c^*}{q_T + q_{ok} + q_M^* + q_c^*},$$

where q_{fx} is the consumption of heat for the physicochemical processes in the material being fired, kJ/kg; q_M^*, q_c^*, accumulations of heat in the materials being fired and the accompanying materials before the site of inversion, kJ/kg; q_T, energy of the fuel, kJ/kg; q_{ok}, heat used for heating the oxidizer entering the kiln, kJ/kg. The values of all the energy items relate to 1 kg of discharged product.

Using this equation, we calculated the energy utilization coefficients for three high-temperature PROA units at the Magnezit combine with essentially different designs: a tunnel kiln measuring (inside) 156 × 3.2 × 0.725 m, a rotary kiln measuring 170 × 4.04 m, and a shaft furnace measuring 12 × 2.88 m. It was established that the utilization coefficients of the tunnel furnace and rotary furnace differ only slightly, and are close to 40%; the factor for the shaft furnace is much higher, and reaches 70%. Thus, the energywise more improved PROA proved to be the shaft furnace in which the specific consumption of standard fuel for firing magnesite was 250 kg/ton [5] compared with 365 kg/ton for the rotary kiln [6]. In firing high-grade briqueted, granulated or narrow-fraction materials, the shaft furnaces, due to their favorable economics, have more promise for further use and development.

CONCLUSIONS

A reduction in fuel consumption in kilns of the refractories industry can be obtained through the further introduction of contraflow-recuperative firing units (PROA), improving their design and operating schedules, optimizing the firing processes on the basis of mathematical modeling.

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