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ENERGY-ENVIRONMENTAL ANALYSIS OF COMBUSTION OF FUEL GASES IN HEATING FURNACES OF METALLURGICAL AND ENGINEERING PLANTS

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Results of an energy-environmental analysis of the expediency of purifying artificial fuel gases are given. Experimental investigations have been carried out in industrial furnaces of modern structure where various kinds of high- and low-calorific gaseous fuels are used.

Energy consumption in high-temperature heat technologies and the environmentally polluting discharge of heat technologies, aside from the quality of the manufactured product, are practically always related to the paramount factors which are taken into account in the development and adoption of these technologies.

The elemental composition of natural and artificial fuel gases includes, in addition to the fuel components, also carbon dioxide and steam. In artificial gas, up to 12–14% of CO_2 and 2% of H_2O (blast-furnace gas) is present against 0.05% of CO_2 and 0.5% of H_2O in natural fuel gas. In the case of combustion of natural gas, a great amount of the air nitrogen is contained in the flame per 1 m^3 of the initial fuel, which creates prerequisites for the formation of a great amount of nitrogen oxides with high temperatures in the burner stone of an incinerator.

This composition of the initial fuel gas enables the authors to make the assumption of the significant features of the processes of formation of CO_2, H_2, and NO_x in combustion of natural and artificial fuels (blast-furnace gas, gas of wood waste, etc.).

The authors compared the concentrations of $[NO_x]$ measured along the length of the heating furnaces of 320/150 and 850 mills operating under the conditions of the Belarusian Metallurgical Plant (BMP) with the concentrations that correspond to the existing standards of Germany (with a fixed $[NO_x]_{3\%}$ as well) recalculated according to the state standards of Japan (228 mg/m^3) and the USA (150 mg/m^3) for metallurgical furnaces with a temperature level of 1590 K [1]. We note that, aside from the standards which try to tie environmental requirements to equipment with an actually possible decrease in the toxic discharge of fuel-efficient devices under the conditions of the tangible influence of preheating of the air-oxidizer, German requirements on the NO_x discharge exist which restrict the limiting content of $[NO_x]$ for $[O_2] = 3\%$ to the level of 100 mg/m^3 in operation of units with natural fuel gas [1].

The measurements showed the high level of NO_x in the heating furnaces of the 850 and 320/150 mills of the BMP, which, above all, is attributable to the preheating of the air-oxidizer to 823 K. The results of measuring the actual content of NO_x in combustion products are given in Fig. 1.

As is seen from the figure, a high level of $[NO_x]$ is observed in the furnace of the 850 mill.

Since in the German standards the values of $[NO_x]_{5\%}$ are specified for the actual content of O_2 and corresponding $\alpha \geq 1.0$, the value of $[NO_x]_\alpha$ is calculated from the formula

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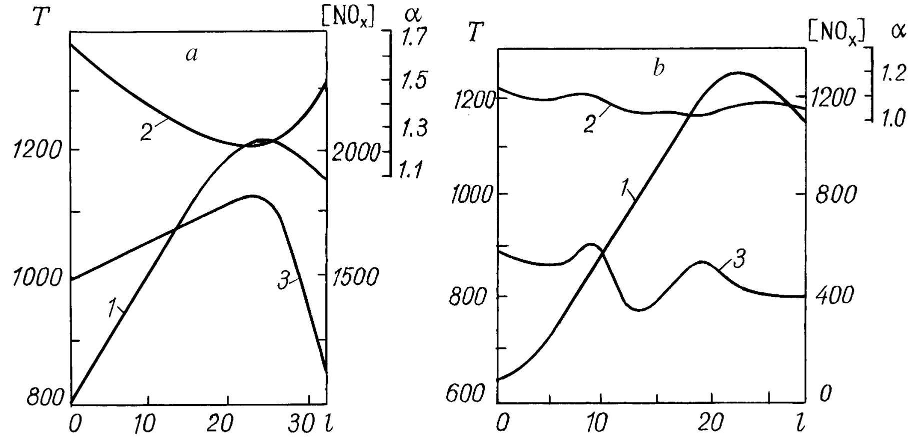

Fig. 1. Measurements of the concentration of NO_x along the furnace length [a) heating furnace of the 850 mill; b) heating furnace of the 320/150 mill]: 1) temperature of the combustion products along the furnace length; 2) flow-rate coefficient of the air; 3) concentration of NO_x along the furnace length. T, °C; NO_x, mg/m^3; l, m.

$$[NO_x]_\alpha = 2.04\,[NO_x]_{5\%}\,\frac{21-[O_2]_\alpha}{21-5} = 0.1275\,[NO_x]_{5\%}\,(21-[O_2]_\alpha)\,,\quad \mathrm{mg/m}^3\,.$$

Based on the comparison of the actual and normalized data, we have drawn the conclusion that it is difficult to combine the high energy indices of the BMP heating furnaces and the efficiency of fuel utilization with environmental restrictions in operation of the furnaces. The above is particularly true of the heating system with burners of the Bloom company. In the furnace of the 850 mill, a high absolute concentration of nitrogen oxides (more than 2 mg/m^3) that corresponds to a twofold relative excess over the German standards is observed. Comparison of the results of testing the BMP furnaces and the estimative data obtained from the empirical formula for rolling furnaces is also not in favor of the Bloom burners.

Comparison of $[NO_x]_\alpha$ with the foreign standards for the two furnaces points to the necessity of modernizing burner devices of the BMP furnaces with walking beams and a walking hearth [2].

In combustion of artificial fuel gases (blast-furnace gas) in heating furnaces of the Dnieper Integrated Iron and Steel Works (DIISW), additional difficulties arise which are associated with the appearance of a great amount of dissociation carbon oxide, formed of CO_2, in the combustion products. Therefore, the necessity of purifying artificial gases (blast-furnace gas) of carbon dioxide is quite obvious (Fig. 2).

In the scheme (Fig. 2), possible cases of feeding the working mixture of a fuel gas to the burner stone of an incinerator are considered in general terms. The unpurified blast-furnace gas contains 12% of CO_2 in the first case and 2% of CO_2 in the second case (for a flow-rate coefficient of 1.08). As a result of combustion in the presence of a charge heated to a high temperature, 26 and 10% of CO_2 is formed, respectively. In the technological zones (welding and malleablizing ones) and the burner stone, the dissociation of CO_2 ($2CO_2 \rightarrow 2CO + O_2$) and the reoxidation of the formed CO to CO_2 will occur in accordance with the dissociation coefficient K_{CO_2}. The remaining part of the carbon oxide will be discharged to the environment. In accordance with the upper half (see Fig. 2), this part of the polluting discharge will turn out to be much larger than the lower part (even on condition that the flow-rate coefficient of the air-oxidizer will be increased from 1.08 to 1.2).

In combustion of the unpurified artificial fuel gas, in addition to the increased polluting effect, the factor of unjustified energy consumption by the dissociation of $CO_2(H_2O)$ is also operating. The less CO_2

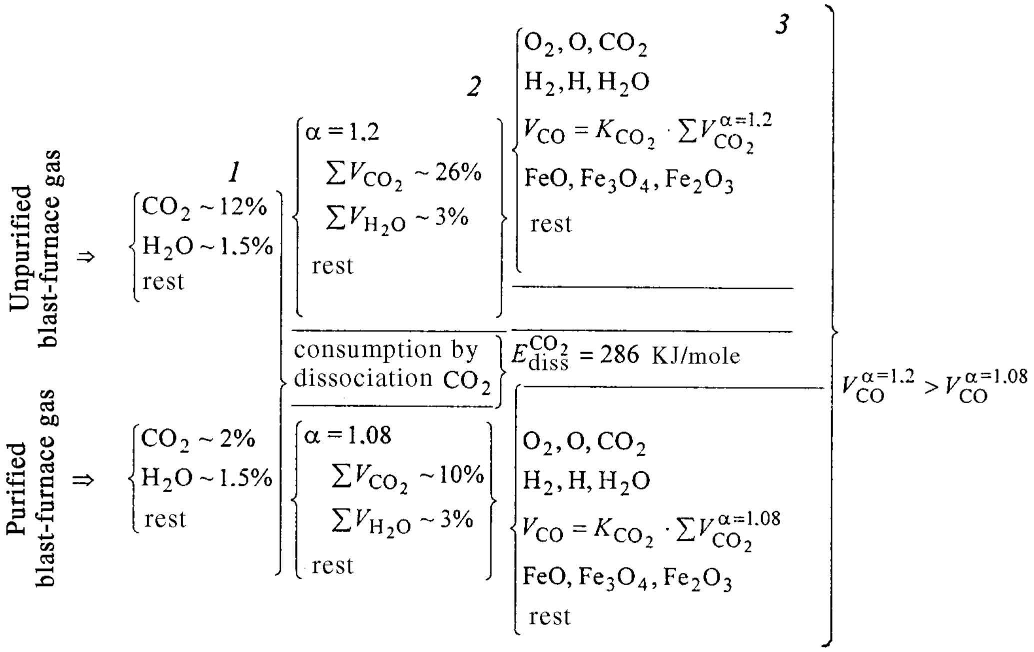

Fig. 2. Scheme of formation of the polluting discharge: 1) initial fuel; 2) burner stone of a high-temperature unit; 3) working space for heating a metal prior to plastic deformation.

arrives at the burner stone, the lower the loss of the heat of combustion of the fuel that goes to decompose these molecules of CO_2 ($E_{\text{diss}}^{CO_2}$ = 286 kJ/mole).

Furthermore, owing to the extraction of the ballast component of the fuel (carbon dioxide and water) the heat of combustion referred to 1 m^3 of the initial fuel will increase.

Selection of the scheme of purification of artificial gases of the ballast that dissociates at high temperatures must rest upon the particular features of the elemental composition. In particular, artificial fuel gases contain much CO_2 and an insignificant amount of steam, which fully justifies the use of molecular sieves for this purpose.

In investigations with aim of reducing the CO discharge from high-temperature units (heating furnaces with the temperature of the smoke at the level of 1500–1700 K), it was shown [3] that the use of $Me_{2/n}.O.Al_2O_3.SiO_2$ synthetic molecular sieves with CaA or MgA as a sorbent which is in the thermofluidized state in purification of an artificial gaseous fuel (removal of CO_2 from the blast-furnace gas) makes it possible to realize a heat technology ideal in energy terms. In the specific case of purification (enrichment) of a blast-furnace gas, the energy consumption is reduced twofold owing to the low heat capacity of the molecular sieves (c_p = 1.04 at the beginning of the process and 1.5 at the end of the process), as compared to the aqueous solution of monoethanolamine ($CH_2CH_2OHNH_2$) (MEA) that has a heat capacity at the level of 4.2 kJ/(kg·K).

The sorbent CaA (MgA) is a dispersed material quite amenable to fluidization that makes it possible to improve the kinetic characteristics of the system by a factor of 10–15 as compared to the use of the solution of monoethanolamine in packed-type apparatuses. All this ensures low energy consumption of the heat technology of treatment.

The low content of water in the blast-furnace gas (less than 2%) also creates extremely favorable conditions for sorption-desorption processes ($p_{H_2O} << p_{CO_2}$) using the CaA or MgA sorbent.

The adsorption distribution in the thermofluidized bed of a microspherical sorbent is presented in Fig. 3.

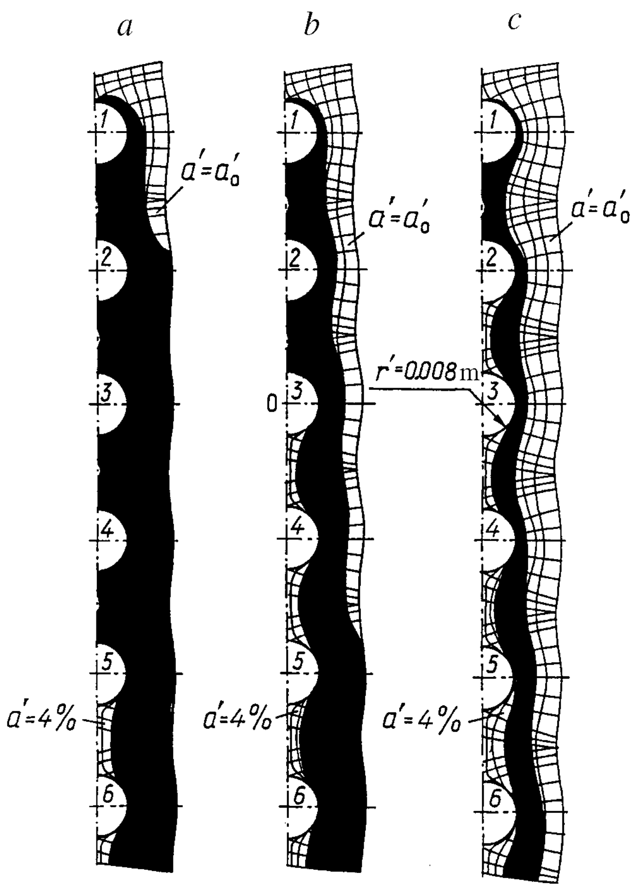

Fig. 3. Adsorption isolines in cylindrical coordinates (numerical calculation, the desorbed part of the bed is darkened): a–c) numerical calculation is carried out using formulas (1)–(3).

Numerical modeling was carried out in accordance with the modified expression of Yu. S. Teplitskii [4]

$$D = \begin{cases} 0.13\,(w - w_0)\,X_0 \left(\dfrac{4Y_0Z_0/\pi}{X}\right)^{0.5} \left[\dfrac{(w - w_0)^2}{gX}\right]^{-0.15} & \text{for } \varepsilon \geq 0.5\,; \\[2ex] 0.94\,\dfrac{1 + 0.807 \cdot 10^{-2}\,(T - 273)}{(c_s + a'c_g)\,(1 - \varepsilon)\,\rho_s} \log \dfrac{0.74 - 0.31\,(1 - \varepsilon_0)}{0.74 - (1 - \varepsilon_0)} & \text{for } \varepsilon < 0.5\,, \end{cases} \tag{1}$$

and using the formulas of Borodulya [5]

$$a_{\text{eff}} = 1.4\nu \left(\frac{w}{w_{\text{f}}} - 1\right)^{0.35} \text{Ar}^{0.12} \left(\frac{H}{D'}\right)^{0.05} \tag{2}$$

and Wicke and Trawinski [6]

$$D = 2.76 \cdot 10^{-2} w d^{0.85}\,. \tag{3}$$

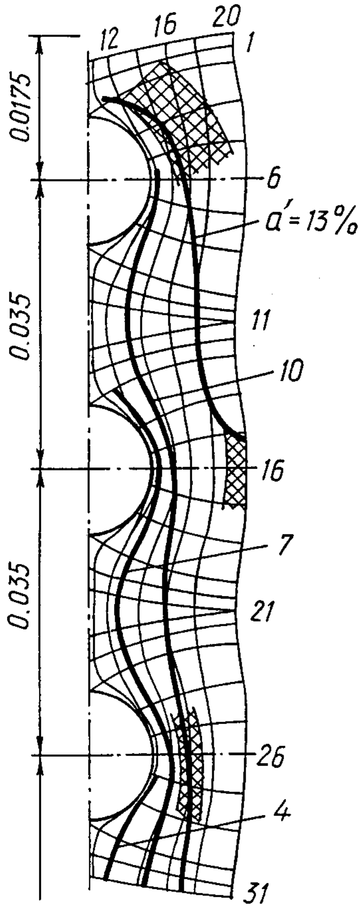

Fig. 4. Adsorption isolines (numerical calculation) for a system heat power of 30 kW/m^2 (the region of the full-scale experiment is dashed): 1–31 and 12–20) points of curvilinear coordinates.

For processing the experiment carried out by the authors, the following model of heat and mass transfer for a sphere with boundary conditions of the first kind was proposed:

$$\frac{da'}{dt}=\frac{1}{r^2}\frac{d}{dr}\left[r^2 D\exp\left(-\frac{E_0}{RT}\right)\frac{da'}{dr}\right]; \tag{4}$$

$$\rho_s c_s\frac{dT}{dt}=\frac{1}{r^2}\frac{d}{dr}\left[r^2\lambda_s\frac{dT}{dr}+\rho_s H_a\frac{da'}{dr}\right]; \tag{5}$$

$$a'_{t=0}=a'_0\,;\quad T_{t=0}=T_0\,; \tag{6}$$

$$a'_{r=r_0}=0\,;\quad \left(\frac{da'}{dr}\right)_{r=0}=0\,;\quad \left(\frac{dT}{dr}\right)_{r=0}=0\,; \tag{7}$$

$$T_{r=r_0}=T_{\text{sat}}\ \text{ for }\ 0=t\le t_{\text{sat}}\,;\quad T_{r=r_0}=T_0\ \text{ for }\ 0=t>t_{\text{sat}}\,. \tag{8}$$

In (4)–(8), allowance is made for the temperature dependence of the diffusion coefficient and for the heat of desorption. We disregard the influence of the thermodiffusional component of the thermal-conductivity coefficient, since it is much smaller than the thermal conductivity of the crystal lattice. Condition (8) assigns the heat pulse of length and amplitude T_{sat}, while condition (7) reflects the fact that the partial pressure of the sorbent around a particle is zero.

Models partly similar to (4)–(8) are known in the literature. However, in them, no allowance was made for the temperature dependence of the diffusion coefficient and the energy equation was averaged over the volume. Furthermore, model (4)–(8) differs from the models proposed in earlier works.

For finding the average adsorption of a portion of zeolite involved in the experiment, we performed the averaging

$$\bar{a}' = \frac{3}{t_{\text{exp}}} \int_0^{t_{\text{exp}}} \int_0^{r_0} a'(r, t)\, r^2\, dr\, dt\,.$$

Comparison of the full-scale and numerical experiments is given in Fig. 4.

Finally, it should be noted that the expediency of purification of artificial gas of carbon dioxide is fully governed by the amount of damage inflicted on the environment by the CO discharge. Therefore, in combustion of artificial gas in steam-generator furnaces (low temperatures of combustion products), the above considerations can lose their topicality, and insignificant damage from the pollution of the air basin with carbon oxide should be covered by payment of the corresponding tax on the CO discharge or by building purification structures on the source side of the discharge of smoke from the unit.

NOTATION

D, mixing coefficient; D', diameter of the tube; w, velocity; X, Y, Z, coordinates; ε, porosity; a', adsorption; α, thermal-diffusivity coefficient; c, heat capacity; d and r, diameter and radius of the particles, respectively; r', radius of the tube; t, time; E, activation energy; R, gas constant; T, temperature; V, volume of the gas; ρ, density; ν, viscosity, H, heat of adsorption; α, thermal-conductivity coefficient; g, free-fall acceleration; p, partial pressure. Subscripts: g and s, gas phase and solid phase, respectively; 0, initial value; w, wall; eff, effective value; f, final value; a and ε, sorbed phase and desorbed phase, respectively; sat, saturation.

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