REDUCTION OF THE NO_x GENERATION THROUGH ENHANCING HEAT TRANSFER IN A FURNACE

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The possibility of reducing the NO_x concentration through enhancing heat transfer in a furnace is demonstrated. A method for approximate calculation of the reduction of the NO_x concentration, with an intermediate radiator placed in the flame, is proposed.

The combustion of an organic fuel is accompanied by the formation of toxic nitrogen oxides. In accordance with current views, there are three sources of NO_2 generation: "thermal" NO, "quick" NO, and "fuel" NO.

In the combustion of a gas, which is the basic fuel for industrial power boilers, the "thermal" NO are dominant; for their generation the deciding factor is a maximal temperature of the flame T_{max}. The available so-called "technological" methods of NO_x suppression are based on weakening the effect of this factor, i.e., on decreasing the maximal level of temperatures in the furnace volume. This is realized by the following methods which have enjoyed the widest application:

1) recirculation of cooled products to the combustion zone;
2) two-step combustion;
3) introduction of water or a vapor to the combustion zone.

Employment of the indicated methods involves detrimental consequences, such as a decrease in the coefficient of fuel utilization, an increase in the capital outlays and service cost (the first two methods), or the possibility of the origination of other toxic components (the third method). At the same time, a decrease in T_{max} and, hence, in the NO_x concentration without adverse repercussions is possible through enhancing heat transfer between the flame and the heat-absorbing surfaces of a reaction chamber.

It is well known that during heat exchange in a furnace, the CO_2 and H_2O pairs play the key role in the combustion of a gaseous fuel. At temperatures characteristic of furnace chambers of boiler units, these gases emit and absorb energy in separate bands of the infrared spectral region. Here, because the spectral absorption bands of CO_2 and H_2O overlap, part of the emission from one gas is absorbed by another gas, thus resulting in a decrease in the total degree of blackness of the gas mixture.

By placing a solid having a continuous radiation spectrum in distinction to gases in the flame core, i.e., in the maximal temperature zone, it is possible to enhance heat transfer in the furnace chamber, thereby decreasing T_{max}. In a number of works studying the effect of intermediate radiators on heat transfer in cooled chambers, the increase in heat transfer in the combustion chamber was as large as 19-26% [1] and in some cases amounted to 40% [2].

The present authors propose a method for approximate calculation of the reduction in the NO_x concentration, with an intermediate radiator placed in the flame.

The formulated problem is solved under the following main assumptions:

the intermediate radiator is a single geometric body, the radiator surface is isothermal, with the temperature $T_{rad} = KT_{max}$, where K is the proportionality factor whose value is close to unity, according to the experimental data.

Since it is of interest to determine the relative concentration of NO, we may use the formula suggested by B. Ya. Zel'dovich [3] for calculating equilibrium concentrations

$$[C_{NO}] = 4.6\sqrt{C_{O_2}C_{N_2}}\exp[-21500/RT], \qquad (1)$$

and the empirical formula derived from processing experimental data [4]:

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$$\frac{[C_{\mathrm{NO}}]_{\mathrm{f}}}{[C_{\mathrm{NO}}]_0} = \left(\frac{T}{T_0}\right)^{\beta}, \quad \beta = 10 - 12. \tag{2}$$

In Eqs. (1) and (2), T_0 and T are the maximal temperatures of the flame without and with a radiator.

We determine the maximal temperature of the flame $T_{\max}$ by considering a one-dimensional scheme of the process, based on experimental data, taking it to be observable on the level of positioning of the furnace devices, as is done in [5].

The heat balance equation for the elementary layer of the flame may be written as

$$-dH_{\mathrm{g}} = \sigma_0 \varepsilon_{\mathrm{f}} T^4 dF_{\mathrm{r}}. \tag{3}$$

On dividing the variables and on integration, Eq. (3) acquires the form

$$-\int_{T_{\max}}^{T''_{\mathrm{T}}} \frac{dT}{T^4} = \int^{F_{\mathrm{r}}-F_{\max}} \frac{\sigma_0 \varepsilon_{\mathrm{f}}}{B_{\mathrm{p}} V_{\mathrm{g}} C_{\mathrm{g}}} dF. \tag{4}$$

We will introduce the Boltzmann criterion $\mathrm{Bo} = \varphi B_{\mathrm{p}} V_{\mathrm{g}} C_{\mathrm{g}} / \sigma \psi F_{\mathrm{w}} A^3{}_{\mathrm{a}}$ and make the substitution $F_{\max}/F_{\mathrm{r}} = X_{\max}$. After some manipulations we arrive at

$$T_{\max} = \frac{T_{\mathrm{a}}}{\sqrt[3]{\left(\frac{T_{\mathrm{a}}}{T''_{\mathrm{f}}}\right)^3 + 3\frac{\varepsilon_{\mathrm{f}}}{\mathrm{Bo}}(1 - X_{\max})}}. \tag{5}$$

This equation relates the maximal temperature of the flame to the adiabatic temperature of the gas combustion and the temperature at the furnace exit. The calculation of T_{a} is carried out by familiar methods, or by the graphoanalytical method, or by the iteration method on a computer. The gas temperature at the furnace exit T''_{f} is determined from the thermal calculation of the furnace in accordance with [6], also using available computer programs.

Thus, the problem reduces to determining T''_{f}, with an intermediate radiator located in the flame, depending on the radiator characteristics, specifically, surface area and radiative properties. To this end, we simultaneously solve the heat balance equations for the furnace with no radiator (6) and with a radiator (7):

$$Q_1 = \varphi_1 (Q_{\mathrm{f}} - H''_1), \tag{6}$$

$$Q_2 + Q_{\mathrm{rad}} = \varphi_2 (Q_{\mathrm{f}} - H''_2). \tag{7}$$

Having expressed Q_{f} from Eqs. (6) and (7) and having equated the right sides of the equations, we obtain

$$1/\varphi_1 (Q_1 + \varphi_1 H''_1) = 1/\varphi_2 (Q_2 + Q_{\mathrm{rad}} + \varphi_2 H''_2). \tag{8}$$

Setting $\varphi_1 = \varphi_2 = \varphi$, we have

$$Q_1 + \varphi H''_1 = Q_2 + Q_{\mathrm{rad}} + \varphi H''_2, \tag{9}$$

We determine Q_1 and H''_1 from the furnace calculation according to [6].

We define the heat absorption of the heating surfaces from the flame with a radiator Q_2 by the equation

$$Q_2 = \frac{F_{\mathrm{ct}} \sigma_0 \psi M T''_{\mathrm{f}} T^3_{\mathrm{a}}}{B \sqrt[3]{\frac{1}{M^2}\left(\frac{T_{\mathrm{a}}}{T''_{\mathrm{f}}} - 1\right)^2}}, \tag{10}$$

assuming the gas temperature at the furnace exit T''_{f}.

The resultant radiation flux between the radiator and the radiation-absorbing surface of the furnace is identified using the balance method by the formula

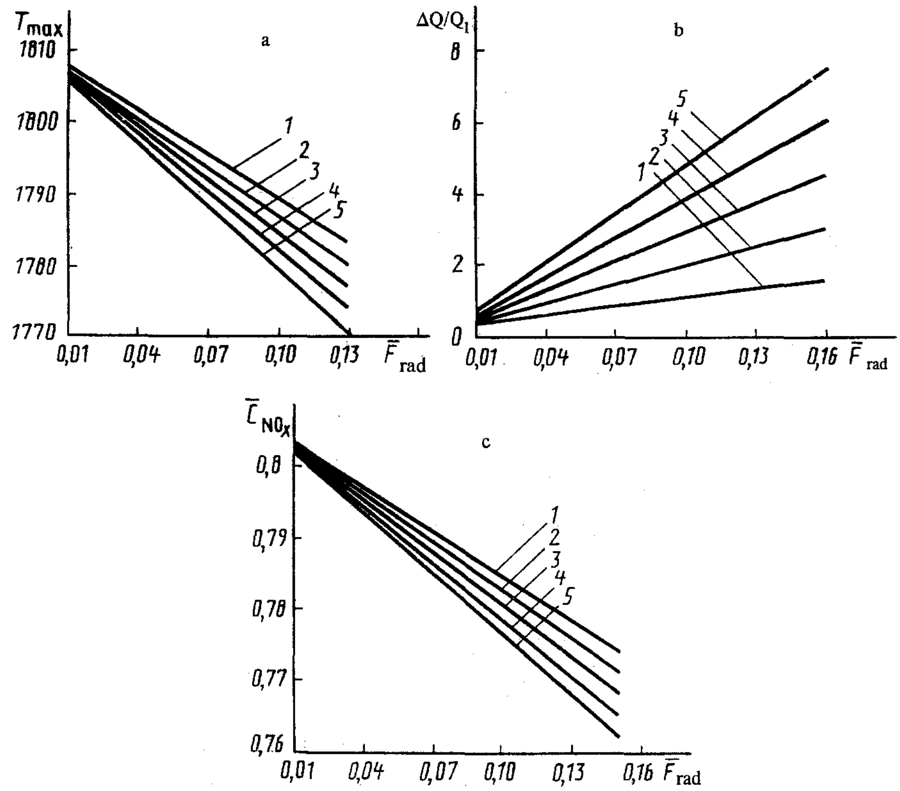

Fig. 1. Maximal temperature of the flame F_{max}, K (a), heat transfer enhancement in the furnace $\Delta Q/Q_1$, % (b), and relative concentration of nitrogen oxides C_{NO_x} (c) as functions of the relative surface area of the radiator F_{rad} and its emittance ϵ, W/(m^2·K): 1) ϵ = 0.65; 2) 0.735; 3) 0.82; 4) 0.905; 5) 0.99.

$$Q_{rad} = \frac{C_0 F_{rad}\left[\left(\frac{T_{rad}}{100}\right)^4 - \left(\frac{T_w}{100}\right)^4\right]}{\frac{1}{\varepsilon_1} + \frac{A_2}{\varepsilon_2}\left(\frac{1}{A_2} - 1\right) F_{rad}/F_w}. \tag{11}$$

Thus, on substituting into Eq. (9) the quantities Q_2 and Q_{rad} from Eqs. (10) and (11) we obtain an equation in one unknown T''_f. However, since the specific heat of the gases that governs their enthalpy H_2 is also a function of the unknown temperature T''_f, the problem is solved by the iteration method on a computer.

For solving the formulated problem, in conformity with the above-given methods we have worked out a program of calculation on a personal computer which permits one to obtain the maximal temperature of the flame, the heat absorption of the heating surfaces from the flame with a radiator and from the radiator proper, as well as variation in the relative concentration of nitrogen oxides depending on the relative surface area of the radiator and on its emittance ϵ.

The above relationships for the DE-25-14 GM boiler burning gaseous fuel are illustrated in Fig. 1.

NOTATION

T_{max}, maximal temperature of the flame, K; T_{rad}, temperature of the radiator surface, K; C_{NO}, C_{O_2}, C_{N_2}, concentrations of nitrogen oxides and oxygen in combustion products, and of molecular nitrogen, wt.%; R, universal gas constant, kJ/(kmol·K); T, temperature in the reaction zone, K; H, gas enthalpy, kJ/m^3. σ_0, Stefan-Boltzmann constant, W/(m^2·K^4); ϵ_f, emittance of the furnace medium; F, running area of the radiating heating surface, m^2; φ, heat efficiency of the screens; ψ, heat retentivity; F_w, surface area of the furnace walls, m^2; V_gC_g, mean total heat capacity of the combustion products, K; X_{max}, relative location of the temperature maximum in the course of the flame burnt-out expressed in fractions of a full length of the flame (furnace); T_f, gas temperature at the furnace exit, K; Bo, Boltzmann number; Q_1 and Q_2, heat absorption of the heating surfaces from the flame without and with a radiator, kJ/m^3; Q_f, usable heat release in the furnace, kJ/m^3; H_1 and H_2, gas enthalpies at the exit from the furnace without and with a radiator, kJ/m^3; M, parameter accounting for the temperature distribution along the furnace height; C_0, emittance of the black body, W/(m^2·K^4); T_w, temperature of the heat-absorbing surface, K; ϵ_1 and ϵ_2, thermal emission coefficients of the radiator and of the heat-absorbing surface, A_2, absorptivity of the heat-absorbing surface; B, fuel flow rate, m^2/sec.

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