HEAT EXCHANGE WITH DIFFERENT SCHEMES FOR INTRODUCING THE HEAT-EXCHANGE AGENT INTO A FURNACE

I. V. Zhdanovskaya, F. R. Shklyar,
A. Kh. Bokovikova and V. M. Malkin

UDC 536.3

The effect of the scheme for introducing the heat-exchange agent into a furnace for heat exchange in a selective nonisothermal gaseous medium is investigated taking into account the heat loss due to convection depending on the emissivity of the metal and the furnace lining.

Analysis of different schemes for introducing the heat-exchange agent into a furnace, beginning with the work described in [1], was of greatinterest to heat engineers. Computational and theoretical work, concerned with determining the advantage of one scheme over another, was based either on the gray model of a radiating gas or on an incomplete accounting of the selective properties of the gas [2-4], or on neglecting convection [5]. We have developed a model in which, together with a systematic accounting for the selective radiation of gases, the heat loss due to convection is also taken into account.

The physical statement of the problem is as follows. The working space of the furnace in the shape of a flat vertical slit consists of three gaseous zones with arbitrary thickness (Fig. 1). Fuel with air for combustion (or a heat-exchange agent) can be introduced into the zones in arbitrary ratios. Therefore, the heating system can be reproduced with the introduction of the heat-exchange agent under the refractory crown or by introducing it onto a heat-absorbing surface (metal) and so on.

The gas temperature in each zone is determined by the equations of heat balance

$$B_j Q_н^р = E_{rj} + q_{cj} + B_j V_\alpha c_g T_j,\ j = 1,\ 2,\ 3. \tag{1}$$

Here, it was assumed that the temperature of the gas leaving a zone is equal to the temperature of the gas remaining in the zone.

The resulting radiation E_r and convection q_c fluxes are functions of gas temperature T_j and the surface temperatures T_0 and T_4. In order to determine the temperature of the lining, we use the heat-transfer equations:

$$k(T_m - T_0) = E_{r0} + q_{c0}. \tag{2}$$

The temperature of the heat-absorbing surface is given. In this manner, the system of equations (1) and (2) comprises fourequations in four unknown temperatures T_1, T_2, T_3, T_0.

In order to calculate the resulting fluxes on the lining, the metal, and the gas volume zones, we will distinguish between the radiation from the gas and the walls, since the coefficient of absorption of radiation depends on its composition. Then, the specific resulting fluxes will be as follows:

on the lining

$$E_{r0} = \{[1 - a_{g0}(2l)](1 - A_4) - 1\}\alpha_1 E_{m_0} + E_{ef\,0}^{II} A_0 + E_{ef\,0}^{III} A_0 + E_{ef\,0}^{IV} A_0 + E_{ef\,0}^{V} A_0; \tag{3}$$

on the metal

$$E_{r4} = E_{ef4}^{I} A_4 + \{[1 - a_{g4}(2l)](1 - A_0) - 1\}\alpha_2 E_{m_4} + A_4[E_{ef4}^{III} + E_{ef4}^{IV} + E_{ef4}^{V}];$$

on the first gas zone

$$E_{r1} = E_{ef0}\, a_{g0/1}\left(\frac{T_1}{T_0}\right) + (1 - A_4) E_{ef\,4}^{I} \times$$

All-Union Scientific-Research Institute of Metallurgical Heat Technology, Sverdlovsk.
Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 39, No. 4, pp. 692-698, October, 1980. Original article submitted July 19, 1979.

 0022-0841/80/3904-1116$07.50 © 1981 Plenum Publishing Corporation

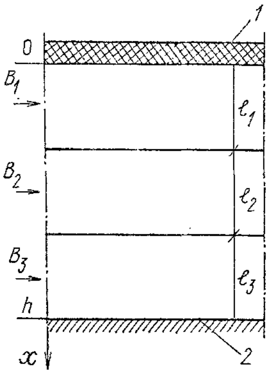

Fig. 1

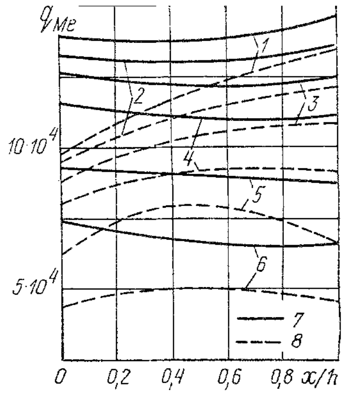

Fig. 2

Fig. 1. Computational scheme for a furnace, the gas volume in which is arbitrarily divided into three zones with temperature T_1, T_2, and T_3; 1) furnace lining; 2) heat-absorbing surface (metal).

Fig. 2. Values of the resulting heat fluxes on the metal as a function of the position of the flame in the absence of convection and heat losses through the lining for different emissivities of the metal (q_{Me}, W/m^2): 1) $A_4 = 1.0$; 2) 0.8; 3) 0.6; 4) 0.4; 5) 0.2; 6) 0.1; 7) $A_0 = 1.0$; 8) 0.6.

$$\times \frac{a_{g_0/123321}\left(\frac{T_1}{T_0}\right) - a_{g0/12332}\left(\frac{T_1}{T_0}\right)}{1 - a_{g0}(l)} + E_{ef_4}\left[a_{g4/321}\left(\frac{T_1}{T_4}\right)\right.$$

$$\left. - a_{g4/32}\left(\frac{T_1}{T_4}\right)\right] + (1 - A_0)E^{II}_{ef_0}\frac{a_{g4/3211}\left(\frac{T_1}{T_4}\right) - a_{g4/321}\left(\frac{T_1}{T_4}\right)}{1 - a_{g4}(l)}$$

$$+ (1 - A_0)E^{III}_{ef0}a_{g1/1} + (1 - A_4)E^{III}_{ef4}\frac{a_{g1/23321} - a_{g1/2332}}{1 - a_{g1/23}} - 2E_{g1}$$

$$+ (1 - A_0)E^{IV}_{ef0}\frac{a_{g3/211} - a_{g3/21}}{1 - a_{g3/21}} + (1 - A_4)E^{IV}_{ef4}(a_{g3/321} - a_{g3/32})$$

$$+ E_{g3}(a_{g3/21} - a_{g3/2}) + (1 - A_0)E^{V}_{ef0}\frac{a_{g2/11} - a_{g2/1}}{a_{g2/1}} + (1 - A_4)E^{V}_{ef4}\frac{a_{g2/3321} - a_{g2/332}}{1 - a_{g2/3}} + E_{g2}a_{g2/1}.$$

We obtain similar expressions for the remaining gas zones. Here, we denote:

$$\alpha_1 = [1 - (1 - a_{g0}(2l))(1 - A_0)(1 - A_4)]^{-1},$$

$$\alpha_2 = [1 - (1 - a_{g4}(2l))(1 - A_0)(1 - A_4)]^{-1},$$

$$E^{I}_{ef1} = [1 - a_{g0}(l)]\alpha_1 E_{m0},$$

$$E_{ef0} = E_{m0}\alpha_1,$$

$$E^{II}_{ef0} = [1 - a_{g4}(l)]\alpha_2 E_{4},$$

$$E_{ef4} = E_{m4}\alpha_2,$$

$$E^{III}_{ef0} = [1 + (1 - A_4)(1 - a_{g1/23321})]\alpha_3 E_{g1},$$

$$\alpha_3 = \left[1 - (1 - A_0)(1 - A_4)\frac{(1 - a_{g1/123})(1 - a_{g1/23321})}{1 - a_{g1/23}}\right]^{-1},$$

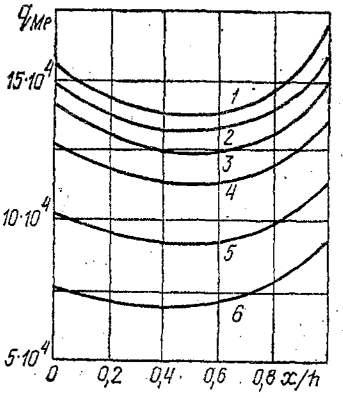

Fig. 3

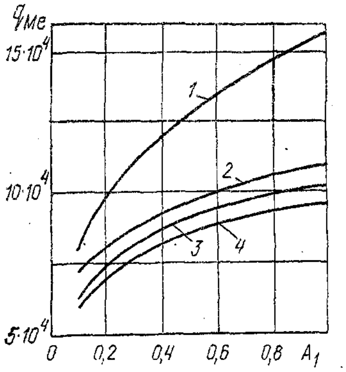

Fig. 4

Fig. 3. Values of the resulting heat fluxes to the metal as a function of the distance of the flame in the presence of convection and radiation and an adiabatic lining for different emissivities of the metal (q_{Me}, W/m^2): 1) $A_4 = 1.0$; 2) 0.8; 3) 0.6; 4) 0.4; 5) 0.2; 6) 0.1; $A_0 = 1.0$.

Fig. 4. Values of the resulting fluxes on the metal as a function of the change in the emissivity of the metal and the presence of convection and radiation and an adiabatic lining with different schemes for introducing the heat-exchange agent into the furnace (q_{Me}, W/m^2): 1) uniform distribution of gas temperature with height in the furnace; 2) flame at the metal; 3) at the lining; 4) flame in the middle.

$$E_{\text{ef}\,0}^{\text{IV}} = [(1 - a_{g3/21}) + (1 - A_4)(1 - a_{g3/321})]\,\alpha_4 E_{g3},$$

$$E_{\text{ef}\,4}^{\text{IV}} = [1 + (1 - A_0)(1 - a_{g3/21123})]\,\alpha_4 E_{g3},$$

$$\alpha_4 = \left[1 - (1 - A_0)(1 - A_4)\frac{(1 - a_{g3/321})(1 - a_{g3/21123})}{1 - a_{g3/21}}\right]^{-1},$$

$$E_{\text{ef}\,0}^{\text{V}} = [(1 - a_{g2/1}) + (1 - A_4)(1 - a_{g2/3321})]\,\alpha_5 E_{g2},$$

$$E_{\text{ef}\,4}^{\text{V}} = [(1 - a_{g2/3}) + (1 - A_0)(1 - a_{g2/1233})]\,\alpha_5 E_{g2},$$

$$\alpha_5 = \left[1 - (1 - A_0)(1 - A_4)\,\frac{1 - a_{g2/3321}}{1 - a_{g2/3}}\,\frac{1 - a_{g2/1123}}{1 - a_{g2/1}}\right]^{-1},$$

$$a_{gj/ikmnp} = \frac{\varepsilon_{gj}(T_j) + \varepsilon_{gi+k+m+n+p}(T_j) - \varepsilon_{gj+i+k+m+n+p}(T_j)}{\varepsilon_{gj}(T_j)}, \quad j = 1,\ 2,\ 3;$$

$$\varepsilon_{ga+b+c+\ldots}(T_j) = \varepsilon_g(T_j;\ l_{\text{ef}\,a} + l_{\text{ef}\,b} + l_{\text{ef}\,c} + \ldots),$$

$$a_{g0}(l) = a_{g0/123}, \quad a_{g0}(2l) = a_{g0/123321},$$

$$E_{mi} = A_i \sigma_0 T_i^4, \quad i = 0,\ 4,$$

$$E_{gj} = \varepsilon_{gj}\sigma_0 T_j^4, \quad j = 1,\ 2,\ 3.$$

Following the recommendations of Hottel [6], the absorbing ability for a single layer gas is computed as the emissivity of the gas at T_0 and for $l_{efa}(T_0/T_a)$ instead of l_{efa} and the result is multiplied by $(T_a/T_0)^{0.65}$ for carbon dioxide and by $(T_a/T_0)^{0.45}$ for water vapor. For a multilayer gas, instead of $l_{efa+b+c}$ we take $(l_{efa}/T_a + l_{efb}/T_b + l_{efc}/T_c)T_0$, as recommended in [7]:

TABLE 1. Coefficients of Convective Heat Transfer

Variant characteristics	Coeff. of convective heat transfer	
	to the metal	to the lining
Heat-exchange agent:		
at the metal	34,0	6,4
at the lining	3,5	34,0
in center of channel	3,5	6,4
Uniform distrib. of heat exchange across cross section	14,1	14,1

$$\alpha_{g_{0/abc}}\left(\frac{T_j}{T_0}\right)=\varepsilon_{CO_2}\left(T_0,\,T_0\left(\frac{l_{efa}}{T_a}+\frac{l_{efb}}{T_b}+\frac{l_{efc}}{T_c}\right)\right)\left(\frac{\bar{T}}{T_0}\right)^{0.65}+\varepsilon_{H_2O}\left(T_0,\,T_0\left(\frac{l_{efa}}{T_a}+\frac{l_{efb}}{T_b}+\frac{l_{efc}}{T_c}\right)\right)\left(\frac{\bar{T}}{T_0}\right)^{0.45},$$

where

$$\bar{T}=\frac{T_a l_{efa}+T_b l_{efb}+T_c l_{efc}}{l_{efa}+l_{efb}+l_{efc}}.$$

The quantities $\alpha_{g_4}(l)$ and $\alpha_{g_4}(2l)$ are computed using the same formulas, but the indices must be replaced as follows: 0 by 4; 1 by 3; 2 by 2; 3 by 1; and, 4 by 0.

The convective heat flux q_c is computed according to the formula

$$q_c=\alpha(T_w-T_g),$$

where T_g is the temperature of the gas layer bathing the corresponding wall with temperature T_w. The heat-transfer coefficient was computed according to the formula for the external flow [8]. In the case when the heat-exchange agent is not introduced along some surface, the heat-transfer coefficient was computed according to the formula for free convection. The overall resulting flux on the metal will be

$$q_{Me}=E_{r4}+q_{c4}.$$

The problem was programmed for solution on a computer. Below, we present an analysis of some of the computational results.

Figure 2 shows the resulting fluxes on the metal with a fuel input ($Q_H^p = 20.93$ kJ/m³, $V_\alpha = 7.7$ m³/m³) in the amounts 500 m³/h per meter of width of working space with height 1.5 m in different vertical zones (the heights of the zones are equal). The temperature of the heat-absorbing surface is 1000°C. Convection is taken as equal to zero; the emissivity for the furnace lining is unity, $k = 0$. From the figure, it is evident that when the flow occurs around the metal and for large emissivity for the metal ($A_4 > 0.6$), the heat transfer is greater than for other positions of the flame. However, with a low emissivity for the metal, when the flame is removed from it, the heat transfer increases. Similar results were obtained in [5] during analysis of the effect of different temperature distributions throughout the cross section of a heat-transfer channel.

This property of the heat transfer is explained by the selective properties of the gas, viz., the high absorbing capability relative to the characteristic radiation and the good transmission ability for radiation by the lining in the region of wavelengths in which the gas does not radiate. The presence of losses through the lining ($k \neq 0$) did not change the results qualitatively. The same figure shows the results of calculations for the same conditions examined above; for $A_0 = 0.6$, which approximately corresponds to the emissivity of a fireclay lining at working temperatures [9]. From the figure, it is evident that a decrease in the emissivity of the lining qualitatively changes the picture of heat exchange, widening the region of emissivity values for the metal at which heat transfer from the gas flow is greater if it bathes the metal and not the lining. In addition, it turned out that when the flame is introduced into the middle zone (for $A_4 \leq 0.3$), heat transfer to the metal is greater.

The results of the calculations taking into account convection are shown in Fig. 3, from which it is evident that when a metal with arbitrary emissivity is bathed by the flow, the heat transfer to the metal is greater than when the flow bathes the crown, while when the flow bathes the crown there results a higher heat transfer than when the flame is situated in the central part of the working space. The coefficient for convective heat transfer, corresponding to various choices, is shown in Table 1.

Figure 4 shows the resulting heat flux on the metal as a function of the emissivity of the heat-absorbing surface. It is evident from the figure that the best heat transfer occurs with uniform distribution of fuel throughout the three zones. The calculation presented under the conditions that the near-wall zones are absent, i.e., the temperature is constant as a function of height in the working space, gave practically the same result. Thus, from the variations compared, the best heat transfer is provided by a uniform introduction of the heat-exchange agent across the cross section of the furnace or with intense mixing of gases in order to equalize the temperature across the cross section. Similar results were obtained in [10] with the analysis of the problem of a gray gas with low optical density.

The model developed here permits finding the optimal distribution of fuel throughout the zones and their optimal thickness.

NOTATION

T, temperature; E_r, specific resulting radiative flux; q_c, convective heat flux density; q_{Me}, overall density of the resulting heat flux to the metal; ε, emissivity; a_{g_0}, absorbing capability of the gas relative to the radiation of the lining; a_{g_4}, same for the metal, $a_{g_0/a+b+c}$, absorbing ability of a layer of gas $a+b+c...$ relative to the radiation of the lining; $a_{gj/ikmnp}$, absorbing ability of the gas layer $i+k+m+n+p$ with radiation from layer j; A, emissivity of the walls; l_{ef}, effective length of a ray path; α, coefficient of convective heat transfer; k, heat-exchange coefficient from the internal surface of the lining with temperature T_0 in the medium with temperature T_m; B, fuel expenditure; Q_H^P, heat of combustion; V_α, volume of the combustion fuel products per 1 m^3 of gas; c_g, specific heat capacity of the gas; h, overall height of the channel; x, instantaneous height coordinate in the channel. The indices for the temperatures and heat fluxes are as follows: 0, lining; 4, metal; 1, 2, and 3, gas zones; m, media.

LITERATURE CITED

1. M. M. Éfros, "Enhancement of heat-exchange processes in the working space of gas furnaces and methods for improving them," Gasovaya Promy., No. 4, 39-45 (1966).
2. M. A. Denisov and A. Kh. Bokovikova, "Efficiency of heat exchange with different schemes for moving waste gas in the working chambers of furnaces," in: Metallurgical Heat Engineering [in Russian], No. 4, Metallurgiya, Moscow (1975), pp. 102-110.
3. S. I. Gertsyk, "Investigation of some problems of external heat exchange in plasma furnaces with nonuniform temperature fields," Author's Abstract of Candidate's Dissertation, Evening Metallurgical Institute, Moscow (1972).
4. A. E. Erinov and B. S. Soroka, Radiation Methods for Burning Gaseous Fuel in Heating Furnaces [in Russian], Tekhnika, Kiev (1970)
5. M. M. Mel'man, Yu. A. Popov, and A. S. Nevskii, "Effect of reflection by the lining on radiant heat exchange in a layer of nonisothermal selective gas," Izv. Sib. Otd. Akad. Nauk SSR, Ser. Tekh. Nauk, Issue 1, No. 3, 49-52 (1978).
6. V. H. MacAdam, Heat Transfer [Russian translation], Gostekhizdat, Moscow (1961).
7. S. L. Detkov and A. V. Vinogradov, "Heat transfer by radiation in a layer of CO_2 and H_2O gases and their mixtures," Izv. Akad. Nauk SSSR, Energ. Transport, No. 3, 139-144 (1969).
8. M. A. Mikheev and I. M. Mikheeva, Foundations of Heat Transfer [in Russian], Énergiya, Moscow (1973).
9. B. S. Mastryukov, N. P. Kuznetsova, and A. P. Shutov, "Investigation of the emissivity of industrial refractory materials," in: Radiative Heat Exchange in Industrial Furnaces [in Russian], Metallurgiya, Moscow (1975) (MISiS, Nauchn. Trudy No. 84), pp. 43-55.
10. V. N. Adrianov, Foundations of Radiation and Complex Heat Exchange [in Russian], Énergiya, Moscow (1972).