

the medium. The calculation for three variants of the specified temperatures T and T_0 is presented in Table 1. It can be seen that with an overall difference of 200°K between temperatures of the gas and of the heating surface, the temperature of the lining is only 8°K lower than the gas temperature. The divergence of the temperatures with gray and antigray spectra of the medium was $5\text{--}6^\circ\text{K}$. The found solution is 2°K lower than the one obtained by the method known in the literature.

NOTATION

a_1, a_2, a_3 , absorptivities of the volume relative to the incident flux with black spectrum with single, twofold, threefold, ... passages of the rays through the volume; $\epsilon_1, \epsilon_2, \epsilon_3, \dots$, degrees of blackness of the volume under the same conditions; α_T , degree of blackness of the furnace space; K , a magnitude proportional to it; A , absorptivity (degree of blackness) of the surface; $R = 1 - A$; B , intermediate magnitude; F , surface area, m^2 ; N_{ik} , coefficient with the sense of the probability that a quantum of energy emitted by zone i will reach zone k directly or after multiple reflections and will be absorbed in this zone; c , interpolation coefficient; T , temperature, $^\circ\text{K}$; Q_p , power of the resulting heat flux, W ; q_p , its density, W/m^2 ; $\sigma = 5.67 \cdot 10^{-8} \text{ W}/(\text{m}^2 \cdot ^\circ\text{K})$; φ , slope from lining to lining regardless of the energy absorption by the medium (approximately). Subscripts: 0 , heating surface; $*$, lining; V , volume of the medium.

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SPECTRAL COMPOSITION OF THE EMISSION OF A NONISOTHERMAL STREAM OF COMBUSTION PRODUCTS

A. G. Blokh, Yu. A. Zhuravlev,
and I. V. Spichak

UDC 536.3

The influence of the temperature and carbon dioxide concentration profiles on the spectral composition of the emission of a stream of combustion products is considered.

The investigation of the temperature fields of gas streams in the working chambers of internally fired furnaces and the fireboxes of boiler plants has great importance for the choice of rational operating and construction parameters assuring the best conditions for heat transfer to the surfaces being heated. The possibilities of determining temperature fields in the volume of a medium on the basis of spectral intensities of incident radiation measured at different wavelengths have been revealed in recent years [1-5].

As is known, the spectral radiation field is the result of the emission and absorption of the medium and the surrounding surfaces and depends on the fields of temperatures and concentration of the emitting components. This results in the possibility of connecting the intensities of spectral emission with the temperature distribution along the viewing line

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of the measuring instrument. Mathematically this problem comes down to obtaining integral equations of emission, one equation for each wavelength at which the spectral emission intensity is measured. An analysis of the system of integral equations thus obtained, with values of the spectral intensity of the incident radiation known from experiment, allows one to judge the temperature profile along the viewing line of the radiation receiver.

The advantages of this approach: 1) interaction between the measuring instrument and the test object is absent; 2) the need for an outside source of electromagnetic radiation is eliminated; 3) the measurements can be made from any remote point; 4) instruments with a low resolution are needed for measuring the spectral emission [5].

The possibilities of this method were discussed in [3-5] in application to fire-engineering apparatus. A comparison of the methods of iterative transformation (inversion) was made in [3]. It was shown that the use of the iteration method does not require profiles of simple shape, while the departure of the calculated temperatures along the viewing line from experimentally measured values does not exceed 5%. Questions of the determination of, besides the temperature profiles, the profiles of concentration of the emitting components were additionally considered in [4, 5]. The influence of the emission of the back boundary of the system is investigated and the possibilities of using the usual optimization methods to solve problems of spectral inversion are studied.

The influence of the temperature and carbon dioxide concentration profiles on the spectral composition of the emission of combustion products is investigated in the present work in application to the conditions of power furnaces, the main temperature decrease over the width of which takes place in a boundary layer with a thickness of 0.5-1.5 m [6]. Equations are offered for determining the gas temperature at different distances from the wall on the basis of emission intensities measured in different sections of the spectrum. These questions have special importance in the solution of problems of reducing the slagging of furnace screens, the search for possibilities of further intensification of heat transfer through improvement of the aerodynamics of the gases, etc.

The possibility of determining the temperature profile along the viewing line of a narrow-angle radiation receiver is due to the fact that, in the absence of radiation-scattering components in the investigated medium, the change in spectral intensity along an elementary path length of the beam depends uniquely on the local values of the coefficient of absorption and temperature of the medium. A solution of the transfer equation

$$\frac{dI_{\lambda}(x)}{dx} = \alpha_{\lambda}(x)[I_{0,\lambda}(x) - I_{\lambda}(x)], \quad (1)$$

written for the case of an emitting and absorbing medium, allows one to determine the radiation intensity at the boundary of the medium,

$$I_{\lambda}(0) = \int_0^L I_{0,\lambda}(x) \alpha_{\lambda}(x) \exp\left[-\int_0^x \alpha_{\lambda}(x) dx\right] dx + \exp\left[-\int_0^L \alpha_{\lambda}(x) dx\right] [I_{0,\lambda}(T_w) e_w + I_{ref}]. \quad (2)$$

The first term on the right side of Eq. (2) allows for the emission of the medium and the second term allows for the effective emission of the back wall. On the basis of the tasks of the present work (the investigation of the spectral composition of the emission of a furnace medium to determine the temperature profiles in the volume of the gas), the choice of radiation wavelengths, and hence of the spectral optical density of the medium,

was made so as to observe the condition $\exp\left[-\int_0^L \alpha_{\lambda}(x) dx\right] < 0.01$. In investigating the character of the temperature variation in the boundary layer of furnace gases the quantity L was taken as far less than the cross-sectional size of the furnace. Then various sections of the boundary layer of gas make the main contribution to the emission intensity, while the influence of the emission of the main part of the high-temperature core of the gas stream and the opposite wall is negligibly small.

The emission intensity of a stream of combustion products was determined from the equation

$$I_{\lambda}(0) = \int_0^L I_{0,\lambda}(x) \alpha_{\lambda}(x) \exp\left[-\int_0^x \alpha_{\lambda}(x) dx\right] dx. \quad (3)$$

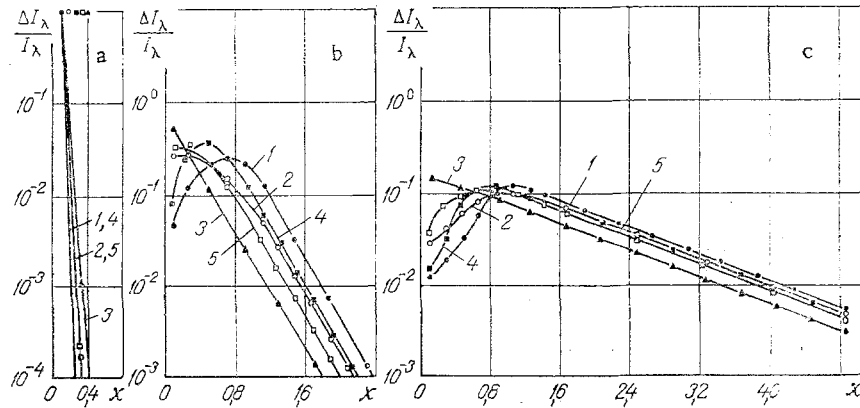


Fig. 1. Relative contributions of individual gas layers 0.2 m thick to the emission intensity of a furnace medium for triangular [1) $\Delta T = 500^\circ\text{K}$; 2) 300°K ; 3) 0°K] and parabolic [4) $\Delta T = 500^\circ\text{K}$; 5) 300°K] temperature profiles with $T_c = 1500^\circ\text{K}$ at wavelengths of a) $4.273 \mu\text{m}$; b) $4.566 \mu\text{m}$; c) $4.651 \mu\text{m}$. x , m.

For the numerical solution of Eq. (3) the gas volume was divided into m layers with a thickness $\Delta L = L/m$. The values of the coefficient of absorption $\alpha_{\lambda, i}$ of the medium at the temperature of the middle of a layer was determined on the basis of tabular values of the spectral coefficients of absorption $\alpha_{\lambda}^{\text{STP}}$ [7] from the relation

$$\alpha_{\lambda, i} = \alpha_{\lambda}^{\text{STP}} \rho_i \frac{273}{T_i} \quad (4)$$

The main calculations were made in application to the products of combustion of natural gas ($P_{\text{CO}_2} = 0.089 \text{ atm}$) for triangular (linear) temperature profiles described by a broken line,

$$T_t = \begin{cases} T_c - \Delta T(1-x) & \text{at } 0 \text{ m} \leq x \leq 1 \text{ m}, \\ T_c & \text{at } 1 \text{ m} \leq x \leq 5 \text{ m}, \end{cases} \quad (5)$$

and parabolic temperature profiles,

$$T_p = \begin{cases} T_0 + \Delta T(2x - x^2) & \text{at } 0 \text{ m} \leq x \leq 1 \text{ m}, \\ T_c & \text{at } 1 \text{ m} \leq x \leq 5 \text{ m}. \end{cases} \quad (6)$$

The results of a calculation for the right-hand branch of the $4.3 \mu\text{m}$ CO_2 absorption band (emission wavelength interval from 4.273 to $5.10 \mu\text{m}$) are presented below. The choice of this band for investigating temperature profiles in furnace chambers is due to the rather wide range of variation of the coefficient of absorption, as well as the absence of overlapping emission bands of other gases. In particular, this eliminates the influence of water vapor, the concentration of which can vary quite considerably, depending on the pulverization system and moisture content of the coal, when solid fuel is burned. The rather flat character (compared with the left-hand branch of the $4.3\text{-}\mu\text{m}$ band) of the variation of the coefficient of absorption of carbon dioxide in the wavelength interval from 4.273 to $5.10 \mu\text{m}$, which makes it possible to use instruments with a resolution of about $0.02 \mu\text{m}$ to measure the spectral emission intensity, should also be mentioned.

Distributions of the relative contributions of individual gas layers 0.2 m thick to the emission intensity of a furnace medium for parabolic and triangular temperature profiles at different wavelengths are presented in Fig. 1. It is seen that for a spectral interval with a high value of the coefficient of absorption ($\lambda = 4.273 \mu\text{m}$, $\alpha_{\lambda}^{\text{STP}} = 2116 \text{ m}^{-1}$) the relative contribution of the emission of the second gas layer (from 0.2 to 0.4 m) does not exceed 0.001 of the emission intensity at the given wavelength for the different temperature profiles (Fig. 1a).

As the optical density decreases (Fig. 1b and c), the maximum of the relative contribution shifts toward the core of the stream for profiles with a temperature drop in the boundary layer. Here the larger the temperature drop $\Delta T = T_c - T_0$, the farther the maximum of the relative contributions is located from the wall. For an equal temperature drop the parabolic profile yields a larger relative contribution of gas layers closer to the receiver

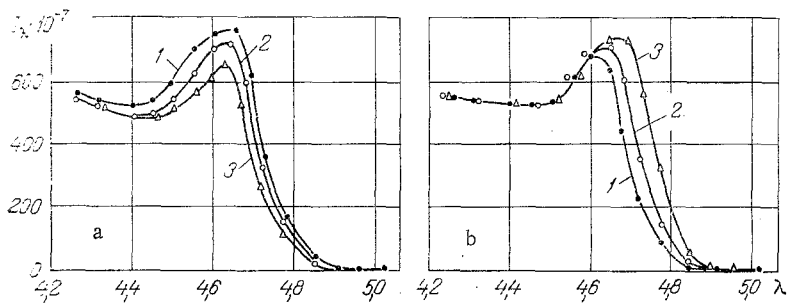


Fig. 2. Spectral emission intensity I_λ ($W/(m^3 \cdot sr)$) as a function of wavelength λ (μm) for a triangular temperature profile ($T_c = 1500^\circ K$; $\Delta T = 300^\circ K$) for different thicknesses of the boundary layer (a): 1) 0.5 m; 2) 1.0 m; 3) 2.0 m, and total thickness of the emitting volume (b): 1) 3.0 m; 2) 5.0 m; 3) 11.0 m.

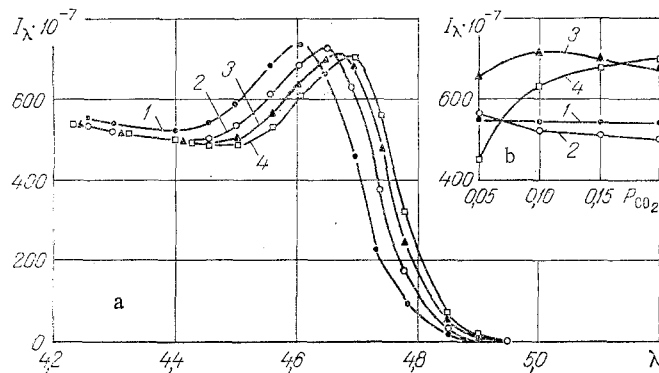


Fig. 3. Spectral emission intensity I_λ ($W/(m^3 \cdot sr)$) as a function of wavelength λ (μm) for a triangular temperature profile ($T_c = 1500^\circ K$ and $\Delta T = 300^\circ K$) at different carbon dioxide partial pressures P_{CO_2} (a): 1) 0.05 atm; 2) 0.10; 3) 0.15; 4) 0.20 atm; b) spectral emission intensities I_λ for wavelengths of 4.273 μm (1), 4.494 (2), 4.651 (3), and 4.695 μm (4) as functions of the carbon dioxide partial pressure P_{CO_2} in a layer of combustion products 5 m thick for a triangular temperature profile with $T_c = 1500^\circ K$ and $\Delta T = 300^\circ K$.

than the triangular profile. Naturally, at all wavelengths the maximum of the relative contribution cannot be located beyond the start of the high-temperature core with a constant temperature. The thickness of the boundary layer of a furnace medium has considerable influence on the magnitude and character of the spectral emission intensity distribution (Fig. 2a).

The results obtained indicate the possibility of obtaining information about the temperature profile in the volume of a nonisothermic emitting and absorbing medium with known radiative characteristics using values of the spectral emission intensity measured at different wavelengths. It must be noted, however, that in determining temperature profiles in industrial fire-engineering apparatus by measuring and analyzing spectral emission intensities one must keep in mind the possibility of the distorting influence of the emission of gas layers lying beyond the stream core or the back wall. The size of such a contribution is particularly significant in the wings of bands. The calculations showed (Fig. 2b) that as the thickness of the gas stream increases from 3 to 10 m the upper limit of the wavelength range within which one must measure the spectral emission intensity increases from 4.60 to 4.68 μm .

The magnitude of the spectral emission intensity by wavelengths is determined not only by the level and character of the distribution of temperatures in the volume of the gas but

TABLE 1. Values of the Spectral Emission Intensity of a Stream of Products of Combustion of Natural Gas with a Stream Core Temperature $T_c = 1500^\circ\text{K}$ for Different Temperature Drops ΔT in the Boundary Layer and Wavelengths λ for Triangular (numerator) and Parabolic (denominator) Temperature Profiles; $I_\lambda \cdot 10^7$, $\text{W}/(\text{m}^3 \cdot \text{sr})$

$\lambda, \mu\text{m}$	$\Delta T, ^\circ\text{K}$			
	0	300	500	700
4,273	991	548	309	134
	$\frac{991}{991}$	$\frac{548}{558}$	$\frac{309}{320}$	$\frac{134}{142}$
4,566	837	619	550	509
	$\frac{837}{837}$	$\frac{619}{663}$	$\frac{550}{608}$	$\frac{509}{574}$
4,651	785	716	712	709
	$\frac{785}{785}$	$\frac{716}{733}$	$\frac{712}{727}$	$\frac{709}{724}$

also by the concentration of the emitting and absorbing component, the influence of which on the emission intensity of a layer of finite thickness can be different for different wavelengths (for a gas stream 5 m thick with $T_c = 1500^\circ\text{K}$ and $\Delta T = 300^\circ\text{K}$ (see Fig. 3)).

Thus, for the optically dense part of the spectrum an emissivity close to unity (0.98) is reached at a small distance from the wall (0.20 m), even for $P_{\text{CO}_2} = 0.05$ atm, and a further increase in carbon dioxide concentration only slightly decreases this distance, and hence the effective emission temperature. The emission intensity remains practically unchanged in this case (curve 1 in Fig. 3b), retaining a tendency to decrease, however, especially for a large temperature gradient in the boundary layer.

For a wavelength with a somewhat smaller coefficient of absorption ($\lambda = 4.494 \mu\text{m}$, $\alpha_\lambda^{\text{STP}} = 662.9 \text{ m}^{-1}$) the contribution of the emission of layers farther from the wall with a high temperature will be larger. In this case an increase in the CO_2 concentration results in greater screening of the high-temperature emission of the stream core and, as a consequence, a decrease in the emission intensity (curve 2 in Fig. 3b).

With a further decrease in the spectral coefficient of absorption (with an increase in λ for the P branch of the $4.3 \mu\text{m}$ CO_2 emission band) the total emissivity of the emitting volume becomes considerably less than unity. Therefore, with an increase in the CO_2 partial pressure one first observes a prevailing influence of the increase in the total emissivity of the emitting volume, which is expressed in an increase in emission intensity, and then, after the emissivity of the volume approaches unity, the increase in the emissivity of the cooler boundary layers of gas begins to play the dominant role, which is expressed in a decrease in emission intensity. The variation of the emission intensity as a function of the concentration of the emitting and absorbing component has an extremal character as a whole (curve 3 in Fig. 3b).

At rather low values of the spectral coefficient of absorption ($\lambda = 4.695 \mu\text{m}$, $\alpha_\lambda^{\text{STP}} = 22.16 \text{ m}^{-1}$) an increase in P_{CO_2} results in an increase in the spectral emission intensity, which is due to the increase in the total emissivity of the stream.

The results obtained indicate the different amounts of influence of the temperature drop in the boundary layer on the spectral emission intensity at different wavelengths (Table 1). For example, an increase in the temperature drop with a constant stream core temperature considerably lowers the spectral emission intensity in the optically dense section of the spectrum ($\lambda = 4.273 \mu\text{m}$, $\alpha_\lambda^{\text{STP}} = 2116 \text{ m}^{-1}$) and hardly affects the spectral emission intensity for a wavelength with a low coefficient of absorption ($\lambda = 4.651 \mu\text{m}$, $\alpha_\lambda^{\text{STP}} = 52.12 \text{ m}^{-1}$).

The influence of the type of temperature profile (parabolic or triangular) on the spectral emission intensity is displayed to the highest degree for large temperature drops in the boundary layer and especially for moderate values ($\alpha_\lambda^{\text{STP}} = 228.9 \text{ m}^{-1}$, $\lambda = 4.566 \mu\text{m}$) of the coefficient of absorption (see Table 1).

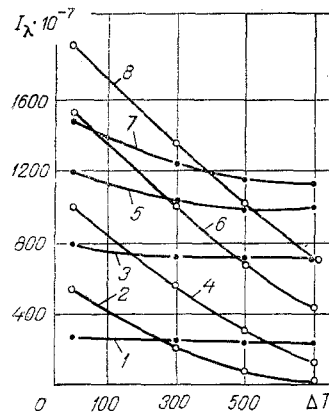


Fig. 4. Spectral emission intensities I_λ ($W/(m^3 \cdot sr)$) as functions of the temperature drop ΔT ($^\circ K$) in the boundary layer for a triangular temperature profile for wavelengths of $4.273 \mu m$ (2, 4, 6, 8) and $4.651 \mu m$ (1, 3, 5, 7) and different values of T_0 : 1, 2) $1200^\circ K$; 3, 4) 1500 ; 5, 6) 1800 ; 7, 8) $2000^\circ K$.

TABLE 2. Values of the Spectral Emission Intensity of a Stream of Products of Combustion of Natural Gas for Different Temperature Drops ΔT in the Boundary Layer and Gas Temperatures T_0 near the Wall for Wavelengths of $4.273 \mu m$ (numerator) and $4.651 \mu m$ (denominator)

$T_0, ^\circ K$	$\Delta T, ^\circ K$		
	0	300	500
1000	299	305	309
	133	454	712
1200	538	548	—
	265	716	—
1500	991	1006	1017
	785	1024	1152

An analysis of the results obtained showed that the gas temperature in the stream core (for a constant ΔT) has a considerable influence on the spectral emission intensity for all wavelengths (Fig. 4). Here the emission intensity in an optically dense section of the spectrum (at $\lambda = 4.273 \mu m$, for example) can be higher or lower than the emission intensity in optically less dense sections of the spectrum (at $\lambda = 4.651 \mu m$, for example), depending on the temperature in the stream core and the temperature drop in the boundary layer.

As seen from the results obtained (see Table 2), the emission intensity in the optically dense section of the spectrum ($\lambda = 4.273 \mu m$) is determined mainly by the gas temperature T_0 near the wall, while the emission intensity at $4.651 \mu m$ depends to a considerable extent on the stream core temperature. The possibility of estimating these temperatures follows from this. On the basis of Planck's law the value of the temperature near the stream boundary can be determined approximately from the equation

$$T_0 = \frac{C_2}{\lambda \ln [(C_1 \lambda^{-5} / I_\lambda) + 1]} \quad (7)$$

TABLE 3. Variation (in %) of Calculated (from Eqs. (8)-(11)) Gas Temperature at Different Distances x from a Screen with a 5% Change in the Spectral Emission Intensity for the Wavelengths λ ($T_c = 1500^\circ\text{K}$, $\Delta T = 300^\circ\text{K}$)

x, m	$\lambda, \mu\text{m}$				
	4,273	4,525	4,566	4,608	4,651
0	0,5	—	—	—	—
0,5	1,9	4,5	—	—	—
1,0	—	0,4	1,5	4,9	—
1,5	0,7	0,7	0,7	1,4	2,5

Substituting the value of I_λ ($\lambda = 4.273 \mu\text{m}$) = $0.548 \cdot 10^{10}$ W/($\text{m}^3 \cdot \text{sr}$), calculated for a triangular temperature profile with $T_0 = 1200^\circ\text{K}$ and $\Delta T = 300^\circ\text{K}$, into Eq. (7), we obtain $T_0 = 1207^\circ\text{K}$, which is essentially the effective emission temperature of the surface layer of gas (~ 0.20 m). The error of such a determination of the gas temperature near the wall will increase with an increase in the temperature drop in the boundary layer.

It does not seem possible to use the indicated approach to determine the gas temperature at different distances from a screen. Therefore, in the present work it is proposed to determine the values of these temperatures on the basis of regression equations obtained by treating, by the method of least squares, a considerable number of data on the spectral composition of emission for different temperature profiles.

The values of the temperature in a stream of products of combustion of natural gas (0.089 atm) at distances of 0, 0.5, 1.0, and 1.5 m from a screen can be determined from the relations

$$T_0 = 645,1 + 1103,1I_{\lambda_1} - 220,6I_{\lambda_1}^2; \quad (8)$$

$$T_{0,5} = 742,5 + 121,2I_{\lambda_1} + 806,4I_{\lambda_2} + 2082,4I_{\lambda_2}^2 - 1845,9I_{\lambda_1} I_{\lambda_2}; \quad (9)$$

$$T_{1,0} = 893,0 - 642,7I_{\lambda_2} + 2062,6I_{\lambda_3} - 790,6I_{\lambda_4} + 441,4I_{\lambda_2}^2 - 5277,6I_{\lambda_2} I_{\lambda_3} + 5014,3I_{\lambda_2} I_{\lambda_4}; \quad (10)$$

$$T_{1,5} = 746,2 - 590,7I_{\lambda_2} + 2779,7I_{\lambda_4} - 1060,0I_{\lambda_5} + 175,4I_{\lambda_2}^2 + 2557,3I_{\lambda_5}^2 - 1088,9I_{\lambda_2} I_{\lambda_4} + 1557,2I_{\lambda_2} I_{\lambda_5} - 3454,8I_{\lambda_4} I_{\lambda_5}. \quad (11)$$

An analysis of the results obtained shows that with greater distance between the screen and the point at which the gas temperature must be determined, the amount of information required for this increases, that is, one must measure the spectral emission intensities at more and more wavelengths.

Equations (8)-(11) describe, with an error of 2-4%, the numerical temperature dependences of the spectral emission intensities at the indicated points obtained by calculation. The above analysis showed that the presence of a systematic error of 5% in the measurement of spectral emission intensities (for infrared spectrometers the error in measuring the emission intensity at wavelengths of 4.0-4.7 μm will not exceed this value) results in an additional error not exceeding 3% in determining the temperature profile for $T_c = 1500^\circ\text{K}$. The influence of the random error in measuring the spectral emission intensity is manifested to the greatest extent for wavelengths making the largest contribution to the emission of the gas layer in which the temperature is determined (Table 3).

The advantage of the proposed approach over the well-known approach of [4, 5] consists in the possibility of expressing the unknown temperatures in explicit form through the experimentally measured spectral emission intensities. This permits a direct determination of the temperatures of a nonisothermal stream of combustion products without resorting to computers.

NOTATION

$I_{0,\lambda}(x)$, emission intensity of an absolutely blackbody at the temperature of the medium at the point x, W/($\text{m}^3 \cdot \text{sr}$); $I_\lambda(x)$, emission intensity along the OX axis at a distance x from the boundary of the medium, W/($\text{m}^3 \cdot \text{sr}$); $\alpha_\lambda(x)$, volumetric coefficient of absorption of the medium, m^{-1} ; ϵ , emissivity; p_i , partial pressure of the emitting gas component in the i-th layer, atm; T_i , temperature of the i-th layer of the gas volume, $^\circ\text{K}$; T_0 , temperature at the boundary of the gas volume at the point of contact with the wall, $^\circ\text{K}$; T_c , gas temperature

in the stream core, °K; λ , wavelength, μm ; $C_1 = 1.19088 \cdot 10^{-16}$, constant in Planck's law, $(\text{W} \cdot \text{m}^2)/\text{sr}$; $C_2 = 1.4388 \cdot 10^{-2}$, constant in Planck's law, $\text{m} \cdot \text{°K}$; L , thickness of gas stream, m ; $\Delta T = T_c - T_0$, temperature drop in the boundary layer of gas, °K; $I_{\lambda_1}, I_{\lambda_2}, I_{\lambda_3}, I_{\lambda_4}, I_{\lambda_5}$, spectral emission intensities measured at wavelengths of 4.273, 4.525, 4.566, 4.608, and 4.651 μm , respectively, $10^{10} \text{ W}/(\text{m}^3 \cdot \text{sr})$. Indices: STP, standard conditions ($P_{\text{CO}_2} = 1 \text{ atm}$ and $T = 273 \text{°K}$); w , boundary surface (wall); ref , reflected radiation.

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DESIGN OF INSTALLATION FOR DRYING BY A GAS CONTAINING HYGROSCOPIC PARTICLES

V. K. Maskaev and A. P. Baskakov

UDC 66.047

A method is given for designing drying installations where a suspension of finely dispersed hygroscopic particles in air is used as the drying agent.

One way to intensify convective drying is to increase the volumetric heat capacity of the gaseous agent by introducing finely dispersed solid particles into it. A method of designing such installations published in [1] contemplates the use of a drying agent containing nonhygroscopic particles and presumes that their moisture content equals zero at any stage of this process. In practice such a condition is satisfied either at high temperatures or when the particles are absolutely nonhygroscopic. Ignoring the influence of the moisture adsorbed by the particles of drying agent can result in appreciable errors in the calculation. There also exist a number of processes of complex drying when solid particles contained in the gas stream are dried simultaneously with the primary object (material). The use of capillary-porous colloidal bodies as the finely dispersed particles is also advantageous for the reason that their hygroscopicity increases as well as their mass capacity, i.e., the drying capacity of the agent.

We allow for the presence of hygroscopic moisture in the particles of the agent in designing a drying installation, which in general consists of an air chamber (mixer), an air heater for heating the gas suspension, and the dryer proper. We assume that heat losses are absent; the mass flow rate of absolutely dry air is constant; the hygroscopic particles have small sizes and the establishment of their equilibrium parameters and those of the air takes place rather rapidly; the heat capacities c_p , c_a , and c_w do not vary.

S. M. Kirov Ural Polytechnic Institute, Sverdlovsk. Translated from *Inzhenerno-Fizicheskii Zhurnal*, Vol. 43, No. 2, pp. 258-265, August, 1982. Original article submitted June 1, 1981.