Observations are made in [5] on the temperature of nepheline cake grains in the drum of a laboratory apparatus. The pyrometers were directed at the upper and lower edges of the layer surface. The source of irradiation was on the drum axis. The temperature radings were explicitly exaggerated. Computations we made do not have sufficient accuracy primarily because of the rough estimate for the mean time of exposure of particles in complicated motion. Nevertheless, it can be concluded that a noticeable, although not very substantial reduction in the heat flux is obtained.

NOTATION

a_0, effective thermal diffusivity coefficient, m^2/sec; $\bar{\varepsilon}$ and $\bar{a}$, reduced values of the emissivity and absorptivity of the furnace space; λ_e, effective heat-conduction coefficient, $W/(m \cdot K)$; c_m, specific heat of the body, $J/(kg \cdot K)$; ρ, body density taking account of its porosity, kg/m^3; T and T_e, actual and equivalent, from (4), temperatures of the furnace medium; T_0, body surface temperature, °K; Δ_m, depth of body heating from (1); Δ_*, characteristic dimension of the body being heated, m; τ and τ_0, running and total exposure time, sec; q, heat-flux density on the body surface, W/m^2; α_c, convective heat-transfer coefficient, $W/(m^2 \cdot K)$; $\varkappa$, $W \cdot sec^{1/2}/(m^2 \cdot K)$; $\sigma = 5.67 \cdot 10^{-8}$ $W/(m^2 \cdot K^4)$. $u = \tau/\tau_0$; $b = \sqrt[4]{\bar{\varepsilon}/\bar{a}}$; $\beta = T_0/(bT_e)$; $D = \sqrt{Fo}/Bo_e = \bar{\varepsilon}\sigma T_e^3 \sqrt{\tau_0}/(b\varkappa)$; $Fo = a_0\tau/\Delta_*^2$; $Bo_e = b\lambda_e/(\bar{\varepsilon}\sigma T_e^3 \Delta_*)$; $\theta = (T_0 - T_{0m})/(bT_e - T_{0m})$; $\beta_* \equiv \beta|_{T_{0m}}$; $\beta_0 \equiv \beta|_{T_{0max}}$.

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DETERMINATION OF GENERALIZED ANGULAR COEFFICIENTS WITH CONSIDERATION OF SELECTIVITY IN ABSORPTION BY THE MEDIUM

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Generalized angular coefficients are calculated with consideration of selectivity in absorption by the medium which consists of gaseous CO_2 and H_2O.

In many technological devices which use natural fuels as an energy source radiant heat exchange is determined to a significant degree by the radiating properties of the gases CO_2 and H_2O. As many studies [1-5] have shown, these gases emit and absorb radiation with significant selectivity. However, consideration of selectivity in heat-exchange calculations for a system of bodies is an extremely difficult problem, because of lack of knowledge of the dependence of the absorption coefficient of mixtures of these gases k on frequency ν and c due to problems of a purely computational character. As a rule, technical calculations employ a selective-gray approximation, dividing the entire spectrum of thermal radiation into absorbing and nonabsorbing bands. However, such a method leads to a significant increase in the volume of calculations due to the increase in the number of zonal equations. Below we will demonstrate how selective absorption of the gaseous medium can be considered by calculating generalized angular coefficients.

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In deriving the basic relationships we make use of the physical meaning of the angular coefficient. According to [6] the angular coefficient is the ratio of the portion of the radiant flux incident on the irradiated surface to the value of the hemispherical radiation of the surface.

We will assume the radiation to be isotropic, the absorbing medium, homogeneous, and the spectral density of the surface radiation $E^\lambda = \varepsilon^\lambda E_0^\lambda$, W/m^2, and the gas absorption coefficient k_λ, m^{-1} (m$^{-1}\cdot$atm^{-1}) known.

The amount of energy which a surface element dF_i radiates in all directions is:

$$dQ_{di}^\lambda = E_{\mathrm{ef},i}^\lambda \, dF_i = \varepsilon_i^\lambda E_0 dF_i. \tag{1}$$

Integrating over the entire spectrum, we obtain

$$dQ_{di} = \int_0^\infty \varepsilon_i^\lambda E_{0i}^\lambda d\lambda, \tag{2}$$

where

$$E_{0i}^\lambda d\lambda = \frac{c_1 \lambda^{-5} d\lambda}{\exp(c_2/\lambda T) - 1}.$$

In the case of a gray surface $(\varepsilon_i^\lambda = \varepsilon_i)$

$$dQ_{di} = \varepsilon_i \int_0^\infty E_{0i}^\lambda d\lambda dF_i = \varepsilon_i \sigma_0 T_i^4 \, dF_i. \tag{3}$$

The amount of energy incident on an element dF_k:

$$d^2 Q_{di,dk}^\lambda = \varepsilon_i^\lambda \frac{E_{0i}^\lambda}{\pi} \exp(-k_\lambda r) \cos\vartheta_i d\omega, \tag{4}$$

where $d\omega = dF_k \cos\vartheta_k / r^2$ is the element of solid angle over which the elementary area dF_k is visible from the center of the elementary area dF_i.

Thus,

$$d^2 Q_{di,dk} = \frac{1}{\pi r^2} \cos\vartheta_i \cos\vartheta_k \varepsilon_i^\lambda E_{0i}^\lambda \exp(-k_\lambda r) \, dF_i dF_k. \tag{5}$$

Integrating over the entire spectrum, we obtain

$$\begin{aligned} d^2 Q_{di,dk} &= \int_0^\infty \frac{1}{\pi r^2} \cos\vartheta_i \cos\vartheta_k \varepsilon_i^\lambda E_{0i}^\lambda \exp(-k_\lambda r) \, dF_i dF_k d\lambda = \\ &= \frac{1}{\pi r^2} \cos\vartheta_i \cos\vartheta_k dF_i dF_k \int_0^\infty \varepsilon_i^\lambda E_{0i}^\lambda \exp(-k_\lambda r) \, d\lambda. \end{aligned} \tag{6}$$

Thus:

$$\begin{aligned} \psi_{di,dk} &= \frac{d^2 Q_{di,dk}}{dQ_{di}} = \frac{\cos\vartheta_i \cos\vartheta_k}{\pi r^2} \, dF_k \times \\ &\times \frac{\int_0^\infty \varepsilon_i^\lambda E_{0i}^\lambda \exp(-k_\lambda r) \, d\lambda}{\int_0^\infty \varepsilon_i^\lambda E_{0i}^\lambda d\lambda}. \end{aligned} \tag{7}$$

For a gray surface

$$\psi_{di,dk} = \frac{\cos\vartheta_i \cos\vartheta_k}{\pi r^2 \sigma_0 T_i^4} dF_k \int_0^\infty E_{0i}^\lambda \exp(-k_\lambda r)\, d\lambda. \tag{8}$$

Similarly,

$$\psi_{di,k} = \frac{1}{\pi\sigma_0 T_i^4} \int_{F_k} \frac{\cos\vartheta_i \cos\vartheta_k}{r^2} \int_0^\infty E_{0i}^\lambda \exp(-k_\lambda r)\, d\lambda dF_k \tag{9}$$

and

$$\psi_{i,k} = \frac{1}{\pi F_i \sigma_0 T_i^4} \int_{F_i}\int_{F_k} \frac{\cos\vartheta_i \cos\vartheta_k}{r^2} \times \int_0^\infty E_{0i}^\lambda \exp(-k_\lambda r)\, d\lambda dF_i dF_k. \tag{10}$$

In the case of a gray gas ($k_\lambda = k$) the expressions for determination of generalized angular coefficients for cylindrical surfaces take on the form [7]

$$\psi_{di,k} = \frac{1}{\pi} \int_{-\pi/2}^{\pi/2} \int_{\beta_1}^{\beta_2} \exp(-kr) \cos\beta \cos^2\vartheta\, d\beta d\vartheta. \tag{11}$$

For a gray surface and a selectively absorbent gas

$$\psi_{di,k} = \frac{c_1}{\pi\sigma_0 T^4} \int_{0,75\cdot 10^{-6}}^{40\cdot 10^{-6}} \frac{\lambda^{-5}}{\exp(c_2/\lambda T) - 1} \times \int_{-\pi/2}^{\pi/2} \int_{\beta_1}^{\beta_2} \exp(-k_\lambda r) \cos\beta \cos^2\vartheta\, d\beta d\vartheta d\lambda. \tag{12}$$

Angular coefficients were calculated with Eq. (12) for the radiation from an elementary area onto a plane surface parallel to the area. In this case [8]

$$r = \frac{h}{\cos\beta \cos\vartheta}, \quad \beta_1 = -\pi/2, \; \beta_2 = \pi/2.$$

The distance between the areas h were chosen equal to 0.5 m. To approximate the dependence of the medium's absorption coefficient on wavelength the two-parameter model of Schack [1] and Penner [2], and the three-parameter model of Edwards [3] were used, and calculations were also performed for the gray model using the expressions of Mitor and Gurvich [9]. The net absorption coefficient of the medium was calculated with the expression

$$k_\lambda = k_{CO_2}^\lambda p_{CO_2} + k_{H_2O}^\lambda p_{H_2O}. \tag{13}$$

Characteristic gas absorption bands are presented in Tables 1 and 2. In constructing the tables, aside from the references cited above, data from [10] were used.

In the calculations using the technique of [1] for each gas outside the absorption band k_λ is equal to zero, while within the band it increases linearly from zero to k_λ at the midpoint of the band and then decreases linearly to zero.

For the case of the effective bandwidth approximation [2] in each absorption band $k_{CO_2}^\lambda$ and $k_{H_2O}^\lambda$ were defined as $\overline{\alpha}/\Delta\omega$, while outside (in nonabsorbing bands) $k_{H_2O}^\lambda$ and $k_{CO_2}^\lambda$ were equal to zero.

TABLE 1. Characteristic CO_2 Radiation Bands

Band number	Reference	Band, μm	Lower limit, cm^{-1}	Center, cm^{-1}	Upper limit, cm^{-1}	Δω vs T	Absorption coeff., [1]–k_λ, $m^{-1} \cdot atm^{-1}$, [2]$\bar{\alpha}$, $cm^{-2} \cdot atm^{-1}$
1	[1]	15	580	667	783		32
	[2, 3]	15	$667-\Delta\omega/2$	667	$667+\Delta\omega/2$	$\Delta\omega=300(T/273)^{1/2}$	$179{,}3\,\frac{300}{T}$
2	[3]	10,4	849	960	1013		
3	[3]	9,4	1013	1060	1141		
4	[1]	4,3	$\left[4{,}3-0{,}2\left(1+0{,}031\times\frac{T-273}{100}\right)\right]^{-1}\cdot 10^4$	2350	$\left[4{,}3+0{,}2\left(1+0{,}031\times\frac{T-273}{100}\right)\right]^{-1}\cdot 10^4$		$140+\frac{650\cdot 10^3}{T}$
	[2, 3]	4,3	$2350-\Delta\omega/2$	2350	$2350+\Delta\omega/2$	$\Delta\omega=49+396(0{,}001T)^{1/2}$	$2706\,\frac{300}{T}$
5	[1]	2,7	$\left[2{,}7-0{,}135\left(1+0{,}026\times\frac{T-273}{100}\right)\right]^{-1}\cdot 10^4$	3715	$\left[2{,}7+0{,}135\left(1+0{,}026\times\frac{T-273}{100}\right)\right]^{-1}\cdot 10^4$		$18\,\frac{273}{T}$
	[2, 3]	2,7	$3715-\Delta\omega/2$	3715	$3715+\Delta\omega/2$	$\Delta\omega=41+407(0{,}001T)^{1/2}$	179,3

TABLE 2. Characteristic H_2O Radiation Bands

Band number	Reference	Band, μm	Lower limit, cm^{-1}	Center, cm^{-1}	Upper limit, cm^{-1}	Δω vs T	Absorption coeff, [1]–k_λ, $m^{-1} \cdot atm^{-1}$, [2] $\bar{\alpha}$, $cm^{-2} \cdot atm^{-1}$
1	[1]	12	400	540	833		45
	[2, 3]	10	1000—Δω/2	1000	1000+Δω/2	$\Delta\omega=385(T/273)^{1/2}$	$64,2\frac{300}{T}$
2	[1]	6,65	1180	1500	2083		27
	[2, 3]	6,3	1600—Δω/2	1600	1600+Δω/2	$\Delta\omega=256[1+(T/273)]^{1/2}$	$192,5\frac{300}{T}$
3	[1]	2,75	3058	3636	4460		8
	[2, 3]	2,7	3750—Δω/2	3750	3750+Δω/2	$\Delta\omega=256[1+(T/273)]^{1/2}$	$138,7\frac{300}{T}$
4	[2]	1,5	6321	6666	6873		$20,59\frac{300}{T}$
	[3]	1,87	4620	5320	6200		
5	[3]	1,38	6200	7250	8100		

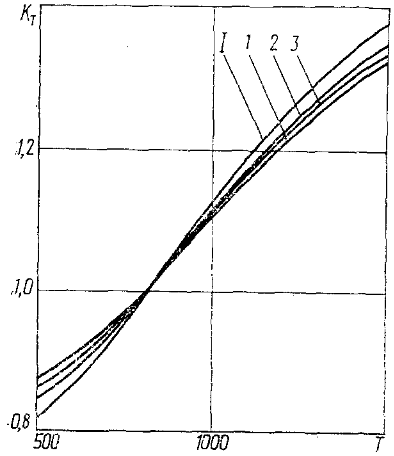

Fig. 1. Correction coefficient K_T vs temperature T, °C: 1) model of [1]; 2) [2]; 3) [3]; I) gray model.

TABLE 3. Generalized Angular Coefficients vs Pressure

p_{H_2O}, atm	Model	p_Σ, atm			
		0,1	0,2	0,4	1,0
0,1	[1]	0,374	0,306	0,294	0,288
	[2]	0,374	0,297	0,282	0,271
	[3]	0,356	0,286	0,278	0,264
	I*	0,382	0,351	0,324	0,279
0,2	[1]		0,289	0,268	0,256
	[2]		0,286	0,260	0,248
	[3]		0,274	0,259	0,249
	I		0,338	0,307	0,257
0,3	[1]			0,256	0,238
	[2]			0,250	0,236
	[3]			0,254	0,240
	I			0,292	0,237
0,4	[1]				0,226
	[2]				0,228
	[3]				0,294
	I				0,218

*I, gray model.

The three-parameter absorption model (see [3]) for the bands with oscillatory-rotational structure was considered in detail in [4]. For a complete description of absorption in the band three constants dependent on temperature alone were used. These constants can be found from the tables of [4] with the aid of the function φ, after which the tables are also used to determine the effective width of the band

$$\overline{A}_{\Delta\omega} = \int\limits_{\Delta\omega} (1 - \exp(-k_\omega r))\, d\omega. \tag{14}$$

Considering the absorption coefficient k_ω constant within the limits of the band, we obtain

$$\overline{A}_{\Delta\omega}(r) = (1 - \exp(-\overline{k}_{\Delta\omega} r))\, \Delta\omega,$$

whence

$$\overline{k}_{\Delta\omega} r = -\ln\left(1 - \frac{\overline{A}_{\Delta\omega}(r)}{\Delta\omega}\right). \tag{15}$$

For the purely rotational 10-μm H_2O band we find the absorption coefficient by Penner's method ($k_\lambda = \bar{\alpha}/\Delta\omega$).

To determine the generalized angular coefficients FORTRAN programs using Eqs. (13), (15) were written. Integrals were calculated by Simpson's rule [11]. The number of steps used for each variable was chosen such that the absolute error of the calculations did not exceed 0.005.

In order to produce this accuracy, 264 steps were required for the integration over wavelength, and eight steps in the integration over angle. The time required to calculate one coefficient on an ES-1022 computer with the two-parameter model was 10-15 min, with 40-50 min required for the three-parameter model.

The basic calculations was performed for T_0 = 800°C. To determine $\psi_{di,k}$ at other temperature graphs of the function $K_T = \psi_{di,k}(T)/\psi_{di,k}(T_0) = f(T)$ were constructed (Fig. 1).

It is evident that all the calculation methods produce a temperature dependence of the angular coefficients of the same character, while the absolute values differ by 3-5%. The least accurate dependence is given by Schack's method, which does not consider the change in absorption of H_2O with temperature.

Table 3 presents values of generalized angular coefficients for various values of total pressure $p_\Sigma = p_{CO_2} + p_{H_2O}$ and H_2O pressures calculated at T_0 = 800°C. It is obvious that for all calculation variants the values of the generalized angular coefficients decrease with increase in pressure of the absorbing gas; this is in complete agreement with the physical interpretation of thermal radiation absorption by gaseous media. At the same time, the absolute values of the coefficients vary by 10-20%, which can serve as an estimate of the accuracy of calculations by the gray model. Moreover, calculations with the most accurate three-parameter model produce a less intense dependence of the generalized angular coefficients on pressure than calculations by the other methods.

NOTATION

F, area, m^2; Q, quantity of energy radiated by elemental area in unit time, W; ε, emissivity; λ, wavelength, m; E_0^λ, spectral intensity of ideal blackbody radiation, W/m^3; σ_0 $5.67 \cdot 10^{-8}$, $W/(m^2 \cdot K^4)$; ϑ, angle between normal to area and direction of ray, rad; r, ray pathlength, m; ψ, generalized angular coefficient; $\pi \approx 3.141$; T, temperature, °K; p, pressure, N/m^2; $\bar{\alpha}$, absorption index, $m^{-2} \cdot atm^{-1}$; ω, wave number, m^{-1}; $\bar{A}$, effective bandwidth, cm^{-1}; K_T, dimensionless correction coefficient.

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