v, the velocity of the liquid flow, m/sec; V, the liquid volume, m^3; W, F, D, the flow rates of the vat residue, feed, and the distillate, kmole/h; x_i, x_{in}, x_{out}, x_W, x^*, the concentrations of the liquid in the i-th section, the inlet and outlet of the flow from the cell, the vat residue, the equilibrium concentration, kmole/kmole; y_{in}, y_{out}, y_N, y_D, y^*, the concentrations of the vapor at the inlet and outlet of the cell, of the N-th plate, in the distillate, and the equilibrium concentration, kmole/kmole; K_{0x}, K_{0y}, the volumetric coefficient of mass transfer, kmole/($m^3 \cdot$h); Z, the dimensionless length of the liquid path; τ, τ', the average stay times of the liquid and the vapor on the plate, sec; λ, the diffusion potential factor (λ = mG/L); η_{ox}, η_{oy}, the local efficiencies of the liquid and the vapor (gas); $\eta_{py\ com}$, the efficiency of the vapor (gas) for the combination model.

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CALCULATING THE RADIATIVE EXCHANGE OF HEAT IN MEDIA CONSISTING OF NONISOTHERMAL COMPONENTS

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We have analyzed the combustion of a coarsely dispersed fuel under low-temperature conditions to ascertain the influence exerted on the radiative exchange of heat by nonignited fuel particles. The calculations are compared against experimental results.

There is presently evident a trend in both domestic and worldwide power generation of utilizing lower-quality lignite coals for fuel, involving an elevated output of ash, a higher moisture content, slag formation, and a diminished heat of combustion. In this connection, in furnaces with solid slag removal, an effort is made to arrange the combustion of such fuels with a coarser fractional composition and at a reduced heating-medium temperature level. For example, in furnaces with a circulating boiling layer and in low-temperature vortex furnaces the fractional composition of the fuel is characterized by R_{1000}^{init} = 40-70%, R_{5000}^{init} = 10-40%, while the temperature in the combustion zone is 1100-1400 K. In view of the coarse dispersion of the fuel supplied to the furnace chamber with a virtually operational moisture content and burned at a reduced process temperature level, unlike the case of high-temperature combustion, the heating medium consists not only of gases, ash, and coke particles, whose temperatures are close to each other, but it also consists of a considerable

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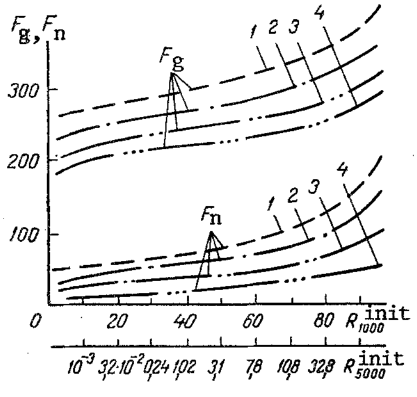

Fig. 1

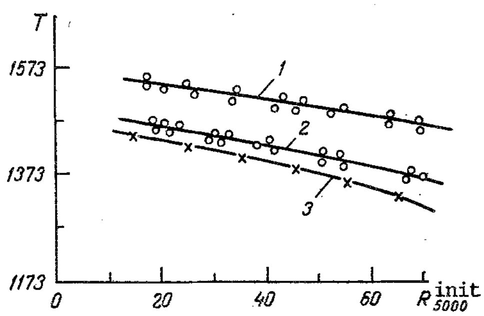

Fig. 2

Fig. 1. The lateral cross-sectional area F_g (the sum of the coke-residue particles and the volatile-yield particles) and the area F_n of the nonburning Irsh-Borodinskii coal particles as functions of the fractional composition with a fuel flow rate of 20 kg/sec, as well as of various process temperature levels: 1) 1420 K; 2) 1470; 3) 1520; 4) 1570. F_g, F_n, m²; $R_{1000}{}^{init}$, $R_{5000}{}^{init}$, %.

Fig. 2. Experimental maximum (1) and midvolume (2) temperatures in the vortex zone of a BKZ-420-140-9 furnace boiler, as well as the theoretical effective temperature of the heating medium (3) when T_1 = 1500 K as a function of the fractional composition of the Irsh-Borodinskii coal. T, K.

quantity of particles which release volatile substances at a considerably lower surface temperature, as well as nonburning heated particles whose surface temperature is even lower than the temperature of the furnace walls. Thus, for example, as shown in Fig. 1, in the combustion of unbroken Irsh-Borodinskii coal in a low-temperature vortex (LTV) E-420-140 boiler furnace (model BKZ-420-140-9), the fraction of the transverse cross-sectional area of all of the particles during the release of the volatile materials from the overall total may be as high as 30%, and as much as 20% in the case of the nonburning particles.

Thus, any given volume of the heating medium in furnaces in which solid fuels are burned consists of gases at a volume-averaged temperature $\bar{T}_g{}^V$, of particles which release volatile substances at an average temperature $\bar{T}_v{}^F$ over their lateral cross-sectional surface area F_v, particles of the coke residue with F_c and $\bar{T}_c{}^F$, particles of the volatile ash with F_A and $\bar{T}_A{}^F$, and the heating nonburning particles with F_n and $\bar{T}_n{}^F$. The optical thickness of the heating medium in this case is

$$\tau^i_{h.m} = \tau^i_g + \tau^i_c + \tau^i_A + \tau^i_v + \tau^i_n, \tag{1}$$

where i = o is the optical damping thickness, s is the scattering thickness, and a is the absorption thickness.

Let us assume that the optical thickness of the heating medium must be divided into n "isothermal" components with respect to the temperature T_j:

$$\tau^i_\Sigma = \sum_{j=1}^{n} \tau^i_j. \tag{2}$$

There exists the concept of the effective temperature of an actual nonisothermal layer, by which is meant that temperature $T_{h.m.}$ of a hypothetical isothermal layer at which the spectral radiation intensity of the layer becomes equal to the spectral radiation intensity of the actual nonisothermal layer [1]:

$$T^4_{h.m} = \frac{2}{1 - \exp(-2\tau_{h.m})} \int_0^{\tau_{h.m}} T^4(\tau)\, e^{-2(\tau_{h.m} - \tau)}\, d\tau. \tag{3}$$

Here it is assumed that at all points τ the temperature of the medium, i.e., the term $\tau_{h.m}$, is $T(\tau)$, and that it is identical for all components. In this case the intrinsic radiation of the heating medium is

$$q_{h.m} = (1 - e^{-2\tau_{h.m}})\,\sigma_0 T^4_{h.m} = \varepsilon_{h.m}\sigma_0 T^4_{h.m}\,. \tag{4}$$

In the case of a multicomponent heating medium we have to refine the concept of effective temperature and effective emissivity for the heating medium, with consideration of the considerable nonisothermicity of its components.

Based on the concepts of set intersection and the mathematical model for the effective emissivity of the given volume, we obtain an expression for the contribution made by each j-th component to the overall effective emissivity of the heating medium:

$$\varepsilon''_j = \varepsilon_j + \sum_{r=1}^{n} (-r)^{r-1} \frac{1}{r} \sum_{P=1}^{r} \prod_j \{C^r_n(\varepsilon)\}, \tag{5}$$

where $\sum_{P=1}^{r} \prod_j \{C^r_n(\varepsilon)\}$ is the sum of the emissivity products composed of a combination of r components of n components, one of which must necessarily be j:

$$\varepsilon_j = 1 - \exp(-2\tau^i_j); \tag{6}$$

$$\varepsilon_{h.m} = (1 - \exp(-2\tau_{h.m})) = \sum_{j=1}^{n} \varepsilon''_j. \tag{7}$$

Then, proceeding from the fact that

$$q_{h.m} = \sigma_0 \sum_{j=1}^{n} \varepsilon''_j T^4_j = \varepsilon_{h.m}\sigma_0 T^4_{h.m}, \tag{8}$$

we derive an expression for the effective temperature of the multicomponent heating medium in the form

$$T^4_{h.m} = \frac{1}{\varepsilon_{h.m}} \sum_{j=1}^{n} \varepsilon''_j T^4_j\,, \tag{9}$$

where in accordance with (3),

$$T^4_j = \frac{2}{1 - \exp(-2\tau_j)} \int_0^{\tau_j} T^4_j(\tau)\, e^{-2(\tau_j - \tau)} d\tau. \tag{10}$$

Analysis of Eqs. (5) and (6) leads to two important conclusions.

1. The effective temperature of the heating medium is significantly reduced, all other conditions being equal, with the coarsening of the fractional composition of the fuel fed into the furnace, as a consequence of the increased content in the heating medium of low-temperature components (Fig. 2). An analogous effect is observed with an increase in the moisture content of the fuel. This can be regarded as one way of evening out the temperature fields of the heating medium and the density fields of the incident radiation, by separating the influx of coarser fuel fractions into the zone of assumed maximum temperatures.

2. The method of measuring local heating-medium temperatures, currently in vogue in coal-dust furnaces, by means of a suction pyrometer, does not yield a uniquely defined concept with regard to the temperature field of the heating medium in LTV furnaces burning coarsely dispersed fuel. This method can yield data only on the temperature field of the mixture of the gas component and the particles of the volatile ash, whose numerical values may differ significantly from the temperature-field values of the heating medium in various zones of the furnace chamber.

In connection with the fact that in the calculations of the exchange of heat in the furnaces the unknown and the given quantities are the temperature of the heating medium at the outlet from the furnace chamber, i.e., the temperature of the gas-component mixture with the entrainment particles consisting primarily of volatile ash, it is of interest to obtain an expression which relates explicitly $T_{h.m}$ and the temperature of this mixture which we will denote T_1:

$$T^4_{h.m} = T^4_1 (\bar{\varepsilon}_{h.m}/\varepsilon_{h.m}), \tag{11}$$

where

$$\bar{\varepsilon}_{h.m} = \sum_{j=1}^{n} \varepsilon''_j (T_j/T_1)^4 = \sum_{j=1}^{n} \varepsilon''_j t^4_j, \tag{12}$$

and then

$$q_{h.m} = \bar{\varepsilon}_{h.m}\sigma_0 T^4_1 = \varepsilon_{h.m}\sigma_0 T^4_{h.m}. \tag{13}$$

This approach allows us to calculate the exchange of heat through radiation within the furnace on the basis of experimental data relative to t_j, obtained on an installation which simulates the conditions of particle reactions in the furnace chamber through measurement of the particle-surface temperature and that of the gas medium.*

Having analyzed the contribution of heat components of the n-component heating medium to the density of the incident $q_{j-w}{}^{inc}$, the reverse $q_{j-w}{}^{rev}$, and the resultant $q_{w-j}{}^{res}$ radiations, we obtain the following expressions:

$$q^{inc''}_{j-w} = k_j q^{inc}_{j-w} - k_{j_0} q_w, \tag{14}$$

$$q^{rev''}_{w-j} = k_j q^{rev}_{w-j} - k_{j_0} q_w, \quad \bar{a}_{w-h.m} = a_w + a_{h.m} - a_w a_{h.m}, \tag{15}$$

$$q^{res''}_{w-j} = -q^{res''}_{j-w} = k_j q^{res}_{w-j}, \tag{16}$$

$$k_j = \bar{a}_{w-j}/\bar{a}_{w-h.m} \quad \bar{a}_{w-j} = a_w + a''_j - a_w a''_j,$$

$$k_{j_0} = (a_{h.m} - a''_j)/(a_{h.m}\bar{a}_{w-h.m}), \quad a_{h.m} = \sum_{j=1}^{n} a''_j,$$

$$q^{inc}_{j-w} = \frac{q_j + (1 - a''_j) q_w}{\bar{a}_{w-j}}, \quad q^{rev}_{w-j} = \frac{q_w + (1 - a_w) q_j}{\bar{a}_{w-j}},$$

$$q^{res}_{w-j} = -q^{res}_{j-w} = (a_w q_j - a''_j q_w)/\bar{a}_{w-j},$$

$$q_w = \varepsilon_w \sigma_0 T^4_w, \quad q_j = \varepsilon''_j \sigma_0 T^4_j.$$

In this case

$$q^{inc}_{h.m-w} = \sum_{j=1}^{n} q^{inc''}_{j-w}, \quad q^{rev}_{w-h.m} = \sum_{j=1}^{n} q^{rev''}_{w-j};$$

$$q^{res}_{w-h.m} = -q^{res}_{h.m-w} = \sum_{j=1}^{n} q^{res''}_{w-j}.$$

Here a_w and ε_w are the absorptivity and emissivity of the external layer of the heating surface; a_j'' is the contribution of the j-th component to the absorptivity of the heating medium, determined analogously by means of Eqs. (5)-(7), where $a_{h.m} = 1 - \exp(-2\tau^a_{h.m})$; $a_j = 1 - \exp(-2\tau^a_j)$; q_w is the density of the intrinsic radiation of the heating surface.

By means of Eqs. (14)-(16) we can analyze the effectiveness of the heat exchange for each component with the heating surfaces:

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*In these calculations we made use of the data obtained at the Kalinin Polytechnic Institute in Leningrad by A. P. Dudukalov for Irsh-Borodinskii and Azeiskii lignite.

$$\psi_{w-j} = q^{res''}_{w-j}/q^{inc''}_{j-w}, \quad q^{res}_{w-h.m} = \sum_{j-1}^{n} \psi_{w-j} q^{inc''}_{j-w}, \tag{17}$$

$$\psi_j'' = q^{res''}_{w-j}/q^{inc}_{h.m-w}, \quad \psi = \sum_{j-1}^{n} \psi_j''. \tag{18}$$

Here ψ is the coefficient of thermal efficiency (CTE) of the heating surfaces (HS) on interaction with the multicomponent heating medium; ψ_{w-j} is the CTE of the heating surface on interaction with the j-th component of the n-component heating medium; ψ_j'' is the contribution to the CTE of the interaction of the j-th component with the HS.

It follows from (17) and (18) that ψ_{w-j} and ψ_j'', on interaction of all of the nonburning particles with the HS, are negative quantities, since $T_w > \bar{T}_n^F$. Thus, the low-temperature components reduce the density of the resulting radiation of the heating medium—HS system both as a result of the screening out of the high-temperature radiation (incident and reflected) and as a consequence of the excess flow of energy to components from the HS when $T_w > \bar{T}_j^F$.

In the case of an LTV furnace, based on experimental data, it is enough to divide the optical thickness of the heating medium into three nonisothermal components: $\tau_{h.m} = \tau_1 + \tau_2 + \tau_3$, $\tau_1 = \tau_g^a + \tau_A^a + \tau_c + \tau_n^s + \tau_v^s$, $\tau_2 = \tau_v^a$, $\tau_3 = \tau_n^a$, $T_1 = \bar{T}_g^V = \bar{T}_A^F = \bar{T}_c^F$, $T_2 = \bar{T}_v^F$, $\bar{T}_3 = \bar{T}_n^F$. Then, for the contribution of each of the components to the effective emissivity of the heating medium, in accordance with (5), we obtain the expression

$$\varepsilon_1'' = \varepsilon_1 - (\varepsilon_1\varepsilon_2 + \varepsilon_1\varepsilon_3)/2 + \varepsilon_1\varepsilon_2\varepsilon_3/3. \tag{19}$$

In analogy with (19), we determine ε_2'' and ε_3''.

The coarse dispersion of the solid phase in LTV furnaces (the average fractional parameters of diffraction are considerably greater than 100) allows us to introduce the following assumptions into the calculations: 1) to refer all of the optical thicknesses of the heating-medium scattering components to the first term, since the incident radiation scattered by the large-scale particles consists primarily of the diffraction portion and can be defined as penetrating radiation [2]; 2) to regard the constant numerical value of the Schuster criterion as independent of the physical properties of the particles.

In accordance with the findings of [1-3] under the conditions of LTV combustion, we can assume values for Schuster criterion of $S_c \approx 0.6$ and, consequently,

$$\begin{aligned} \tau^s_{j,i} &= 1,\ 2\,(F_{j,i}/V_i)\,L_i, \\ \tau^a_{j,i} &= 0.8\,(F_{j,i}/V_i)\,L_i, \\ \tau_{j,i} &= 2.0\,(F_{j,i}/V_i)\,L_i, \end{aligned} \tag{20}$$

where V_i is the volume of the i-th zone, m³; L_i is the effective thickness of the radiation layer of the i-th zone, m; $F_{j,i}$ is the lateral cross-sectional area of the particles of the j-th component in the i-th zone.

The optical thickness of the gas component of the heating medium is determined from the familiar relationships found in [4]. The optical thickness of all of the particles making up the volatile ash can be determined from the recommendations found in [1]:

$$\tau^a_{Ai} = \frac{0.015}{\sqrt[3]{\bar{x}_{32}^{A2}}} \sqrt{T_{1,i}} \left[1 - \frac{b_2}{1 + b_1 (\mu_{Ai} L_i)^{-2}}\right] \mu_{Ai} L_i. \tag{21}$$

Here the mass concentration of the ash $\mu_{Ai} = M_{Ai}/V_i$; the average dimension of the ash particles for Irsh-Borodinskii and Azeiskii coals in LTV combustion is $\bar{x}_{32}^A = (40\text{-}45)\cdot 10^{-6}$ m.

Working with the experimental data of A. P. Dudukalov demonstrated that in the case of LTV combustion of Irsh-Borodinskii coal, in first approximation, we can obtain

$$\bar{\varepsilon}_{h.m} = \varepsilon_1'' + \varepsilon_2'' 0.316 + \varepsilon_3'' 0.017. \tag{22}$$

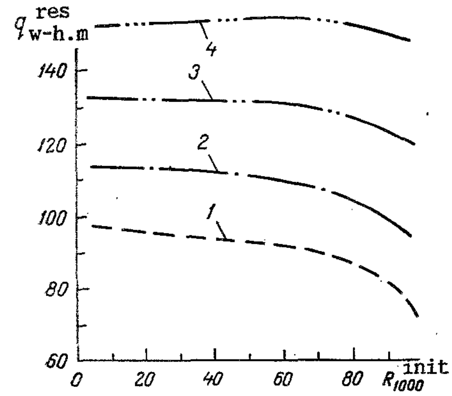

Fig. 3. Density of resulting heating-surface radiation as a function of the fractional composition of the fuel for an effective radiation-layer thickness L = 1.45 m, with the values of 1-4 the same as in Fig. 1. $q_{w-h.m}^{res}$, kW/m².

Applying these considerations to the multicomponent heating medium, we obtain expressions for the reduced emissivity of the furnace chamber and the CTE:

$$q_{w-h.m}^{res} = \varepsilon_h \psi \sigma_0 T_{h.m}^4,$$
$$\varepsilon_h = \varepsilon_{h.m}/(a_{h.m} + (1 - a_{h.m})\psi), \tag{23}$$
$$\psi = \frac{1 - b^4 a_{h.m}/\varepsilon_{h.m}}{1/\varepsilon_w + b^4/\varepsilon_{h.m} - b^4 a_{h.m}/\varepsilon_{h.m}}.$$

Here $a_{h.m} = 1 - \exp(-2\tau^a_{h.m})$ is the absorptivity of the heating medium, $\tau^a_{h.m} = \tau^a_g + \tau^a_c + \tau^a_v + \tau^a_n + \tau^a_A$; $b = T_w/T_{h.m}$ is the characteristic of the temperature discontinuity across the boundary between the HS and the heating medium.

It is important to note that for all $t_j = 1$ and $a_{h.m} = \varepsilon_{h.m}$ these formulas correspond to the expressions for ψ and ε_h obtained for coal-dust furnaces in [1, 3].

In using this model for calculating the radiation exchange of heat in LTV furnaces we find that the fundamental assumptions are: 1) uniformity of distribution in the solid phase of the heating medium through the volume of the furnace zones; 2) the nature of the distortion caused by the particles with respect to the field of the incident radiation is independent of the particle surface temperature; 3) the optical thickness of the heating medium is independent of the form of the temperature field in that zone.

The validity of these assumptions when using this model is governed both by the specific features of LTV combustion and by the theoretical concepts relating to the distortion of the incident radiation field by the large-scale particles.

Calculations of the radiative heat exchange on the basis of the method described here, performed for LTV combustion of Irsh-Borodinskii lignite in the BKZ-420-140-9 furnace boiler, show that the density of the resulting HS radiation depends significantly on the fractional composition of the fuel (Fig. 3). The optimum grinding fineness of this coal, from the standpoint of heat-exchange intensification within the furnace, is found in the range R_{5000}^{init} = 8-17%. It is important to point out that as the temperature level of combustion increases the screening effect of the low-temperature components of the heating medium on the density of the resulting HS radiation is leveled off, conversely increasing when the combustion temperature level is reduced.

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