relaxation-time interval; α, the weight coefficient; H, the height of the cavity; L, the width of the cavity; φ, the angle formed between the vertical and the side surface of the trapezoidal cavity; n, the coordinate of the orthogonal surface; ψ, the stream function; Gr, the Grashof number; Pr, the Prandtl number; Nu, the Nusselt number; Ra, the Rayleigh number; g, the acceleration of free fall; g_{y_i}, the projection of g onto the y_i axis; g_i, the covariant component of the vector g.

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RELATIONSHIP BETWEEN THE COEFFICIENT OF MASS TRANSFER AND LOCAL EFFICIENCY FOR VAPOR (GAS)–LIQUID SYSTEMS

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UDC 66.048.37

Using typical mathematical vapor and liquid models, we demonstrate analytically that the structure of the liquid flow in two-phase systems has no effect on the volumetric coefficient of mass transfer.

As we calculate the number of contact devices in rectification and absorption columns, the process of mass transfer is described by equations linking the efficiency of the plate with the parameters of the vapor–liquid flow model [1-3]. The magnitude of the local efficiency included in these equations, in its physical sense, characterizes the kinetics of mass transfer and it is determined in various ways [4-8]. The local efficiency is determined in [4, 5] from the equation which links this quantity with the number of transfer units, which, in its own turn, is calculated on the basis of a two-film mass-transfer model which involves the utilization of empirical relationships for the coefficients of mass transfer in the vapor and liquid phases. For purposes of calculating the local efficiency, the theoretical and experimental liquid-concentration profiles are compared in [6] over the length of the plate during the mass-transfer process (adsorption), while regime and technological parameters for an operational rectification column are used in [7, 8]. The algorithm used to calculate the local efficiency makes provision for reducing to a minimum the mean-square error in the theoretical and experimental concentration profiles [6] or to find the optimum magnitudes of the local component efficiency in such a manner that the theoretical and actual

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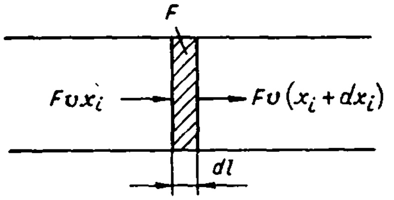

Fig. 1

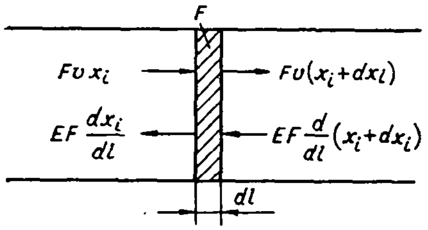

Fig. 2

Fig. 1. Lengthwise distribution of liquid piston flow.

Fig. 2. Lengthwise distribution of liquid flow for the diffusion model.

number of plates coincides with the known regime and operating parameters at the top, at the bottom, and in the influx of the column, as well as to find the parameters of the liquid flow structure model plates that have been installed. Such an approach relieves the researcher from routine experimentation on the determination of the mass-transfer coefficients for the vapor and liquid phases, as well as from the statistical processing of this information into criterial equations [4, 5].

However, the literature contains no equations which link the volumetric coefficient of mass transfer and the local efficiency for two-phase systems described by various mathematical flow-structure models. We are aware of descriptions for one of the phases, which is essentially unreliable, since the vapor (gas)–liquid system is closed.

For purposes of comparison, in this article we present equations which relate the volumetric coefficient of mass transfer and the local efficiency for one of the phases (liquid) or for two phases (vapor–liquid) of two-phase systems.

For the single phase we examined:

A. Complete Mixing Model. From the material balance for the steady state $L(x_{in} - x_{out}) - K_{0x}V(x_{out} - x^*) = 0$ we obtain

$$\frac{x_{in} - x^*}{x_{out} - x^*} = [1 - \eta_{0x}]^{-1} = 1 + K_{0x}\tau$$

or

$$\eta_{0x} = \frac{K_{0x}\tau}{1 + K_{0x}\tau}. \qquad (1)$$

B. Ideal Expulsion Model. For the element $d\ell$ (Fig. 1) the material balance of the liquid flow has the form $Fvx_i - Fv(x_i + dx_i) - K_{0x}Fd\ell(x_i - x^*) = 0$, from which

$$-Fv\frac{\partial x_i}{dl} = K_{0x}F(x_i - x^*)$$

or in dimensionless form

$$\frac{d(x_i - x^*)}{x_i - x^*} = -K_{0x}\tau dZ. \qquad (2)$$

The general solution of the equation

$$\ln(x_i - x^*) = -K_{0x}\tau Z + A$$

for the boundary conditions $Z = 1$, $x_i = x_{out}$.

The solution of Eq. (2) with boundary conditions has the form

$$\frac{x_i - x^*}{x_{out} - x^*} = \exp K_{0x}\tau(1 - Z)$$

or

$$\frac{x_{in} - x^*}{x_{out} - x^*} = \exp K_{0x}\tau, \ 1 - \eta_{0x} = \exp(-K_{0x}\tau). \qquad (3)$$

C. Diffusion Model. For the element $d\ell$ (Fig. 2) we have

$$EF\frac{d}{dl}(x_i+dx_i)+Fvx_i-EF\frac{dx_i}{dl}-Fv(x_i+dx_i)-K_{0x}Fdl(x_i-x^*)=0,$$

from which

$$\frac{d^2(x_i-x^*)}{dZ^2}-\mathrm{Pe}\frac{d(x_i-x^*)}{dZ}=\mathrm{Pe}\,K_{0x}\tau(x_i-x^*). \tag{4}$$

With the boundary conditions

$$Z=0,\ \frac{d(x_i-x^*)}{dZ}=\mathrm{Pe}(x_i-x_{\mathrm{in}}),$$
$$Z=1,\ \frac{d(x_i-x^*)}{dZ}=0 \tag{5}$$

the roots of the characteristic equation (4)

$$q^2-\mathrm{Pe}\,q-\mathrm{Pe}\,K_{0x}\tau q=0,$$
$$q_{1,2}=(\mathrm{Pe}\pm\sqrt{\mathrm{Pe}^2+4\,\mathrm{Pe}\,K_{0x}\tau})/2,$$
$$q_1=\alpha+\mathrm{Pe},\ q_2=-\alpha,$$

where

$$\alpha=\frac{\mathrm{Pe}}{2}\left(\sqrt{1+\frac{4K_{0x}\tau}{\mathrm{Pe}}}-1\right).$$

The general solution of Eq. (4): $x_i - x^* = A_1\exp(q_1Z) + A_2\exp(q_2Z)$, and consequently

$$\frac{d(x_i-x^*)}{dZ}=A_1q_1\exp(q_1Z)+A_2q_2\exp(q_2Z).$$

From boundary condition (5) we have: $A_1q_1 + A_2q_2 = \mathrm{Pe}(A_1 + A_2 - x_{\mathrm{in}})$, $A_1q_1\exp(q_1) + A_2q_2 \times \exp(q_2) = 0$. The solution of Eq. (4) with boundary conditions (5)

$$\frac{x_{\mathrm{in}}-x^*}{x_{\mathrm{out}}-x^*}=\frac{(\alpha+\mathrm{Pe})\exp\alpha+\alpha\exp-(\alpha+\mathrm{Pe})}{2\alpha+\mathrm{Pe}}=\frac{1}{1-\eta_{0x}}. \tag{6}$$

We examine the mass-transfer process (rectification) for two phases under the following assumptions: 1) the equilibrium line within the limits of the plate is linear in nature; 2) the local efficiency within the limits of the plate is a constant quantity; 3) the vapor reaching the plate is completely mixed through the height of the liquid layer.

A. The Complete Mixing Model for Both the Liquid and the Vapor. The equations of material balance for the steady state: for the liquid, $L(x_{\mathrm{in}} - x_{\mathrm{out}}) - K_{0x}V(x_{\mathrm{out}} - y_{\mathrm{out}}/m) = 0$; for the vapor, $G(y_{\mathrm{in}} - y_{\mathrm{out}}) + K_{0x}V(x_{\mathrm{out}} - y_{\mathrm{out}})/m) = 0$.

As a result of the solution of these equations, we obtain

$$x_{\mathrm{out}}=\frac{\left(1+\frac{K_{0x}\tau}{\lambda}\right)x_{\mathrm{in}}+\frac{K_{0x}\tau}{m}y_{\mathrm{in}}}{1+K_{0x}\tau+K_{0x}\tau/\lambda}, \tag{7}$$

$$y_{\mathrm{out}}=\frac{\varphi K_{0x}\tau x_{\mathrm{in}}+(1+K_{0x}\tau)y_{\mathrm{in}}}{1+K_{0x}\tau+K_{0x}\tau/\lambda}, \tag{8}$$

where $\varphi = L/G$, $\tau = V/L$, $\lambda = mG/L$.

From the determination of the magnitude of the vapor local efficiency we have

$$y_{\mathrm{out}}-y_{\mathrm{in}}=\eta_{0y}(mx_{\mathrm{out}}-y_{\mathrm{in}}). \tag{9}$$

Having substituted expressions (7) and (8) into this equation, we obtain

$$\eta_{0y}=\frac{K_{0x}\tau}{\lambda+K_{0x}\tau}\,. \tag{10}$$

From the determination of the liquid-phase local efficiency we have

$$x_{\text{in}}-x_{\text{out}}=\eta_{0x}\left(x_{\text{in}}-\frac{y_{\text{out}}}{m}\right). \tag{11}$$

Having substituted expressions (7) and (8) into this equation, we obtain

$$\eta_{0x}=\frac{K_{0x}\tau}{1+K_{0x}\tau}\,. \tag{12}$$

The relationship between η_{0y} and η_{0x} has the form

$$\eta_{0y}=\left(\frac{1+K_{0x}\tau}{\lambda+K_{0x}\tau}\right)\eta_{0x}. \tag{13}$$

Let us analogously calculate the volumetric mass-transfer coefficient K_{0y} for the vapor phase. The equations of material balance for the liquid and vapor phases are written in the following form:

$$(x_{\text{in}}-x_{\text{out}})-K_{0y}\tau\varphi'(mx_{\text{out}}-y_{\text{in}})=0,$$
$$(y_{\text{in}}-y_{\text{out}})+K_{0y}\tau'(mx_{\text{out}}-y_{\text{in}})=0,$$

where $\varphi' = G/L$, $\tau' = V/G$.

As a result of the solution of this system of equations, we obtain:

$$y_{\text{out}}=\frac{K_{0y}\tau' m x_{\text{in}}+(1-K_{0y}\tau'+K_{0y}\tau'\varphi' m)\,y_{\text{in}}}{1+K_{0y}\tau'\varphi' m}\,, \tag{14}$$

$$x_{\text{out}}=\frac{x_{\text{in}}+K_{0y}\tau'\varphi' y_{\text{in}}}{1+K_{0y}\tau'\varphi' m}\,. \tag{15}$$

Having substituted these expressions into Eqs. (9) and (11), we obtain

$$\eta_{0y}=K_{0y}\tau', \tag{16}$$

$$\eta_{0x}=\frac{\lambda K_{0y}\tau'}{1+K_{0y}\tau'\lambda-K_{0y}\tau'}\,. \tag{17}$$

B. Ideal Expulsion Model for the Liquid and the Model of Complete Mixing for the Vapor.

The liquid concentration with consideration of assumption 2) is determined on the basis of formula (3) from the equations of material balance for the element $d\ell$ (Fig. 1):

$$\left(x_{\text{in}}-\frac{y_{\text{out}}}{m}\right)-(\exp K_{0x}\tau)\left(x_{\text{out}}-\frac{y_{\text{out}}}{m}\right)=0.$$

The equation of material balance for the vapor is written in the form:

$$(y_{\text{in}}-y_{\text{out}})+K_{0x}\tau\varphi\left(x_{\text{out}}-\frac{y_{\text{out}}}{m}\right)=0.$$

As a result of the solution of the system of equations, we obtain

$$x_{\text{out}}=\frac{m\left(1+\frac{K_{0x}\tau}{\lambda}\right)x_{\text{in}}-(1-\exp K_{0x}\tau)\,y_{\text{in}}}{K_{0x}\tau\varphi+m\exp K_{0x}\tau}\,, \tag{18}$$

$$y_{\text{out}}=\frac{m\,[K_{0x}\tau\varphi x_{\text{in}}+(\exp K_{0x}\tau)]\,y_{\text{in}}}{K_{0x}\tau\varphi+m\exp K_{0x}\tau}\,. \tag{19}$$

Having substituted these expressions into Eqs. (9) and (11), we obtain

$$\eta_{0y}=\frac{K_{0x}\tau}{\lambda+K_{0x}\tau}\,, \tag{20}$$

$$\eta_{0x} = \frac{\exp K_{0x}\tau - 1}{\exp K_{0x}\tau}. \tag{21}$$

Let us carry out analogous calculations for the volumetric mass-transfer coefficient K_{0y} for the vapor phase. The equations of material balance for the liquid and vapor phases are written in the following form:

$$\left(x_{\text{in}} - \frac{y_{\text{in}}}{m}\right) - (\exp K_{0y}\tau'\lambda)\left(x_{\text{out}} - \frac{y_{\text{in}}}{m}\right) = 0,$$

$$(y_{\text{in}} - y_{\text{out}}) + K_{0y}\tau'(mx_{\text{out}} - y_{\text{in}}) = 0.$$

As a result of the solution of this system of equations, we obtain the equations which relate the input and output concentrations of both the vapor and the liquid

$$x_{\text{out}} = \frac{x_{\text{in}} - (1 - \exp K_{0y}\tau'\lambda)\, y_{\text{in}}/m}{\exp(K_{0y}\tau'\lambda)}, \tag{22}$$

$$y_{\text{out}} = \frac{K_{0y}\tau' m x_{\text{in}} + [\exp(K_{0y}\tau'\lambda) - K_{0y}\tau']\, y_{\text{in}}}{\exp(K_{0y}\tau'\lambda)}. \tag{23}$$

Having substituted these expressions into Eqs. (9) and (11), we obtain

$$\eta_{0y} = K_{0y}\tau', \tag{24}$$

$$\eta_{0x} = \frac{\exp(K_{0y}\tau'\lambda) - 1}{\exp(K_{0y}\tau'\lambda) - K_{0y}\tau'}. \tag{25}$$

C. Diffusion Model for the Liquid, and the Complete Mixing Model for the Vapor. The concentration of the liquid, with consideration of assumption 2), is determined on the basis of formula (6) from the equations of material balance for the element dℓ (Fig. 2):

$$\left(x_{\text{in}} - \frac{y_{\text{out}}}{m}\right) - T\left(x_{\text{out}} - \frac{y_{\text{out}}}{m}\right) = 0.$$

The equation of material balance for the vapor:

$$(y_{\text{in}} - y_{\text{out}}) + K_{0x}\tau\varphi\left(x_{\text{out}} - \frac{y_{\text{out}}}{m}\right) = 0.$$

As a result of the solution of this system of equations, we obtain

$$x_{\text{out}} = \frac{m\left(1 + \frac{K_{0x}\tau}{\lambda}\right) x_{\text{in}} - (1 - T)\, y_{\text{in}}}{K_{0x}\tau\varphi + mT}, \tag{26}$$

$$y_{\text{out}} = \frac{[K_{0x}\tau\varphi x_{\text{in}} + T\tau y_{\text{in}}]m}{K_{0x}\tau\varphi + mT}, \tag{27}$$

where

$$T = \frac{(\alpha + \text{Pe})\exp\alpha + \alpha\exp - (\alpha + \text{Pe})}{2\alpha + \text{Pe}}.$$

Having substituted these expressions into Eqs. (9) and (11), we obtain

$$\eta_{0y} = \frac{K_{0x}\tau}{\lambda + K_{0x}\tau}, \tag{28}$$

$$\eta_{0x} = \frac{T - 1}{T}. \tag{29}$$

Analogous calculations for the volumetric coefficient of mass transfer K_{0y} for the vapor phase as a result of the solution of the system of equations for the vapor and liquid phases enabled us to obtain the following relationships between the input and output concentrations, as well as between the local efficiency and the volumetric coefficient of mass transfer:

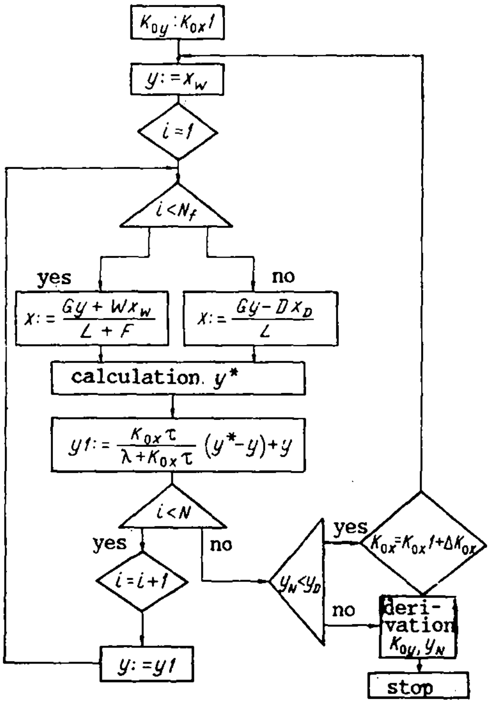

Fig. 3. Algorithm for calculation of volumetric mass-transfer coefficient with consideration of effective output data in the rectification process.

$$x_{\text{out}} = \frac{x_{\text{in}} - (1 - T')\frac{y_{\text{in}}}{m}}{T'}, \tag{30}$$

$$y_{\text{out}} = \frac{K_{0y}\tau' m x_{\text{in}} + (T' - K_{0y}\tau') y_{\text{in}}}{T'}, \tag{31}$$

$$\eta_{0y} = K_{0y}\tau', \tag{32}$$

$$\eta_{0x} = \frac{T' - 1}{T' - K_{0y}\tau'}, \tag{33}$$

where

$$T' = \frac{(\alpha' + \mathrm{Pe}) \exp \alpha' + \alpha' \exp - (\alpha' + \mathrm{Pe})}{2\alpha' + \mathrm{Pe}};$$

$$\alpha' = \frac{\mathrm{Pe}}{2}\left(\sqrt{1 + \frac{K_{0y}\tau'\lambda}{\mathrm{Pe}}} - 1\right).$$

The foregoing allows us to draw the conclusion that the magnitude of the local efficiency for the vapor phase is independent of the form of the liquid flow structure model, and consequently, also independent of the plate design in the mass-exchange equipment, but it is dependent on the physical—chemical properties of the separated mixture and the operating regimes of the equipment, uniquely defining the kinetics of mass transfer.

Thus, by replacing the local efficiency by the volumetric coefficient of mass transfer, we can determine the efficiency of the contact installation for various models of the liquid flow structure or we can determine the relationship between the input and output concentrations of the vapor at the plate under the condition of complete mixing of the vapor in the interplate space.

I. Model of Complete Liquid Mixing:

$$y_{\text{out}} = \frac{K_{0x}\tau}{\lambda + K_{0x}\tau}(m x_{\text{in}} - y_{\text{in}}) + y_{\text{in}} \quad \text{or} \quad y_{\text{in}} = K_{0y}\tau' (m x_{\text{in}} - y_{\text{in}}) + y_{\text{in}}.$$

II. Model of Ideal Expulsion. Under the boundary conditions $z = 1$, $x_i = x_{\text{out}}$

$$y_{\text{out}} = \frac{\exp\left[\lambda K_{0x}\tau/(\lambda + K_{0x}\tau\right] - 1}{\lambda}(mx_{\text{in}} - y_{\text{in}}) + y_{\text{in}}$$

or

$$y_{\text{out}} = \frac{\exp(\lambda K_{0y}\tau') - 1}{\lambda}(mx_{\text{in}} - y_{\text{in}}) + y_{\text{in}}.$$

III. Diffusion Model. Under the boundary conditions

$$Z = 0,\ dx_i/dz = \mathrm{Pe}\,(x_i - x_{\text{in}});$$
$$Z = 1,\ dx_i/dz = 0$$

$$y_{\text{out}} = \frac{K_{0x}\tau}{\lambda + K_{0x}\tau}\left\{\frac{1 - \exp\left[1 - (\alpha + \mathrm{Pe})\right]}{(\alpha + \mathrm{Pe})\left(1 + \dfrac{\alpha + \mathrm{Pe}}{\alpha}\right)} + \frac{\exp(\alpha) - 1}{\alpha\left(1 + \dfrac{\alpha}{\alpha + \mathrm{Pe}}\right)}\right\}(mx_{\text{in}} - y_{\text{in}}) + y_{\text{in}}.$$

IV. Combination Model.

$$y_{\text{out}} = \eta_{\text{py comb}}(mx_{\text{in}} - y_{\text{in}}) + y_{\text{in}}.$$

Figure 3 shows the algorithm for the calculation of the volumetric coefficient of mass transfer for binary mixtures, with consideration given to the data of the effective output [7]. As an example, we used the model of complete mixing both for the vapor and the liquid (1).

Thus, from these results we can draw the conclusion that the relationship between the local efficiency with respect to the vapor and the volumetric coefficient of mass transfer remains constant [see, formulas (10), (20), (28) and (16), (24), (32)], i.e., the difference in the structure of the liquid model, characterizing the design of the plate, in no way affects the kinetics of mass transfer which is uniquely defined by the local efficiency of the vapor in terms of the volumetric coefficient of mass transfer. Moreover, these investigations have enabled us to determine the volumetric coefficient of mass transfer for any system of separable mixtures, wherein consideration is given to the data of the effective output (using the rectification process as the example), without resorting to empirical relationships such as those derived under certain boundary conditions [4, 5].

The analysis of the relationship between the efficiency of the plate (η_{py}) for the case of ideal liquid expulsion and total vapor mixing

$$\eta_{\text{py}} = \frac{\exp\left(\dfrac{\lambda K_{0x}\tau}{\lambda + K_{0x}\tau}\right) - 1}{\lambda}$$

demonstrated that as $\lambda \to 0$ (at the top of the column) $\eta_{0y} \to 1$ and $\eta_{\text{py}} = \eta_{0y} = 1$, while when $1 < \lambda < 1$ (the bottom of the column) $\eta_{0y} < 1$ and $\eta_{\text{py}} < 1$. This analysis shows that the structure of the liquid flow, dependent on the design of the plate, significantly affects the efficiency of separation, particularly in the upper portion of the column, whereas in the opinion of the majority of researchers, the structure of the liquid flow to the top of the column ($\lambda \to 0$) has little influence on the effectiveness of separation. It became possible to draw this conclusion due to the derived relationship between the local efficiency, the diffusion potential factor, and the volumetric coefficient of mass transfer.

The algorithm shown in Fig. 3 was used to calculate the volumetric coefficient of mass transfer for an acetone–water system which effectively yielded phenol–acetone. As a result of computer calculations in which provision was made for the assumptions regarding the constancy of the mass-transfer coefficient through the height of the rectification column it was found that $K_{0x} = 1800$ kmol/(m$^3\cdot$h).

NOTATION

E, the coefficient of reverse mixing, m^2/sec; F, the cross-sectional area of the flow, m^2; L, G, the flow rate of the liquid (reflux), vapor (gas), kmole/h; m, the tangent to the angle of inclination of the equilibrium line ($m = dy/dx$); Pe, the Péclet number ($\mathrm{Pe} = v\ell/E$);

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 ($\lambda = mG/L$); 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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UDC 621.181.016

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 $R_{1000}^{init} = 40\text{-}70\%$, $R_{5000}^{init} = 10\text{-}40\%$, 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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