and heating surface; δ_0, thickness of nonboiling liquid film; Θ, wetting angle; λ, thermal conductivity of liquid; ρ'', vapor density; σ, surface tension; P, surface porosity of wick.

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MIXING OF A FINE-GRAINED MATERIAL AND INTERNAL HEAT TRANSFER IN THE FURNACE OF A BOILER WITH A FLUIDIZED BED

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Results are presented from measurements and calculations of the temperature fields in the furnace of a boiler with a fluidized bed.

The use of a fluidized bed for the low-temperature combustion of fuels in the bed is promising compared to traditional methods of fuel combustion [1]. Introduction of this method in boiler technology is meeting several problems, some of which are related to inadequate knowledge of how to calculate temperature fields in the furnace boilers.

The empirical data in the literature [2, 3] on measuring the diffusion coefficient and diffusivity of a fluidized bed in the horizontal direction has been generalized for a free fluidized bed. There has not been enough study of problems of heat and mass transfer in fluidized beds constrained by tube bundles (boiler furnace analog), and the empirical formulas in [4, 5] require empirical verification in commercial-scale units. Thus, this work is devoted to study of the laws of heat and mass transfer in boiler furnaces with a fluidized bed.

The tests were conducted in a KPV-KS-5.7-14-180 experimental boiler with a fluidized-bed-equipped furnace. The experimental boiler was built at the heat and electric power plant of the scientific-industrial group of the I. I. Polzunov Central Scientific-Research, Planning, and Design Institute of Boilers and Turbines. Figure 1 shows the cross section of the boiler. The dimensions of the furnace in plan are 1.925 × 1.5 m. The upper zone of the bed, 380 mm from the cover, is constrained by the 28-mm-diameter tubes of the plant economizer. The side walls are shielded by the tubes. A more detailed description of the boiler can be found in [6].

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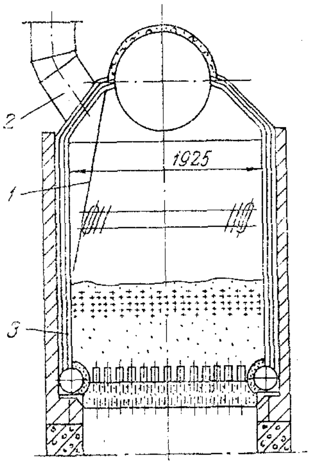

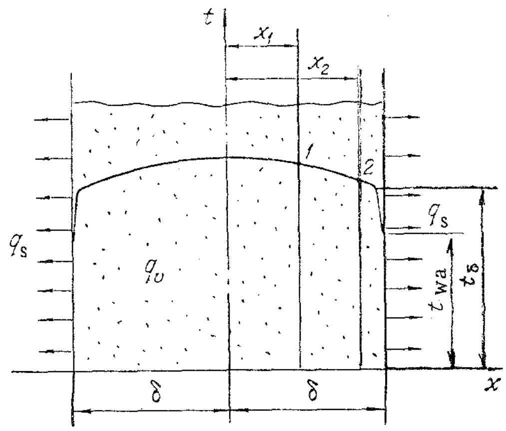

Fig. 1 Fig. 2

Fig. 1. Cross section of furnace of KPV-KS-5.7-14-180 boiler: 1) baffle; 2) safety valve; 3) shielded lateral heating surfaces.

Fig. 2. Heat conduction in a fluidized bed with internal heat sources.

Since the mixing of a fine-grained material and internal heat transfer in units with a constrained fluidized bed can be described with a diffusion model [4], here we have determined the diffusion coefficient, diffusivity, and thermal conductivity of the fluidized bed in the horizontal direction.

The values of the coefficient D_{ef}^{h} were found by the transient-regime method from the solution of Fick's equation for an infinite field with the initial and boundary conditions:

$$\frac{\partial c}{\partial \tau} = D_{ef}^{h} \frac{d^2 c}{\partial x^2}, \quad c(x,\ 0) = 0; \ c(\infty,\ \tau) = 0. \tag{1}$$

In the presence of an instantaneous source of tagged particles of power Q_0, the solution of Eq. (1) has the form [7]

$$c = \frac{Q_0}{2\sqrt{\pi D_{ef}^{h} \tau}} \exp\left(-\frac{x^2}{4 D_{ef}^{h} \tau}\right). \tag{2}$$

Having written the expression for c for two values of x and then having divided and taken the logorithm of the resulting expressions, we finally obtain

$$D_{ef}^{h} = \frac{x_2^2 - x_1^2}{4\tau \ln \frac{c_1}{c_2}}. \tag{3}$$

In accordance with the measurement method, a batch of tagged particles was quickly introduced into the boiler furnace through the safety-valve branch pipe. A baffle was installed on the left side wall under the valve to ensure uniform and directional entry of the particles (Fig. 1). The bed material in the tests was fireclay with particles of 1.94 mm. As tagged particles, we used coal and silica gel 2.24 and 3.14 mm in size, respectively. Samples were taken at different moments of time at two points 1000 and 1600 mm from the site of introduction of the tagged particles. When silica gel was used as the tagged particles, the concentration of the impurity in the samples was determined visually. In the case of coal, the concentration was calculated and was determined through chemical analysis of the samples. The initial bed height was 670, 500, and 320 mm, which corresponds to the situation whereby all of the economizer tubes, some of the tubes, and none of the tubes are immersed in the unfluidized bed. It is known [4] that the diffusivity of constrained fluidized beds is an order greater in the vertical direction than in the horizontal. This allowed us to make the test conditions closely approach the initial conditions (1). Since the impurity concentration is completely equalized after 60-180 sec and it takes 15-45 sec to take a sample, the impurity concentration was adequate under these conditions to perform an analysis, and the effect of the baffle could be ignored. The accuracy of the measurement of D_{ef}^{h} by the above method in the furnace was 20%.

The values of the coefficient λ_{ef}^{h} were determined from solution of the steady-state equation of heat conduction with uniformly distributed internal heat sources of constant power (Fig. 2)

$$\frac{d^2t}{dx^2} + \frac{q_v}{\lambda_{ef}^{h}} = 0 \tag{4}$$

with the boundary conditions

$$x = 0 \quad \frac{dt}{dx} = 0;$$
$$x = \pm\delta \quad -\lambda_{ef}^{h}\frac{dt}{dx} = \alpha_{fb.sur}(t_{core} - t_{wa}). \tag{5}$$

Considering that the heat-transfer resistance in the fluidized bed is concentrated a short distance from the heat-transfer surface R_α [8] when $1/\alpha_{fb.sur} >> R_\alpha/\lambda_{ef}^{h}$, it may be assumed that the temperature of the bed several millimeters from the wall is equal to the temperature of the core of the bed. Then the expression for the temperature field for this problem has a form similar to the equation of the temperature field of a uniform plate with internal heat sources [9]:

$$t = t_{wa} + \frac{q_v\delta}{\alpha_{fb.sur}} + \frac{q_v}{2\lambda_{ef}^{h}}(\delta^2 - x^2). \tag{6}$$

Writing the temperature at two points 1 and 2 (Fig. 2) and subtracting one expression from the other, we obtain the expression for λ_{ef}^{h}:

$$\lambda_{ef}^{h} = \frac{q_v(x_2^2 - x_1^2)}{2(t_1 - t_2)}. \tag{7}$$

In the tests, the role of the heat sources was played by the natural-gas combustion products, leaving the combustion chamber at 400-500°C and subsequently filtering evenly through the bed of fine-grained material. Heat flow in the horizontal direction was generated by the removal of heat by the shielded lateral heating surfaces (Fig. 1).

The values of the coefficient a_{ef}^{h} were determined by conversion of the resulting values of λ_{ef}^{h}: $a_{ef}^{h} = \lambda_{ef}^{h}/\rho_{fb}c_p$. The density of the fluidized bed was measured. The accuracy of measurement of the coefficient λ_{ef}^{h} by the above method was 18%, while the accuracy for a_{ef}^{h} was 22%. The assumption that $t_\delta = t_{core}$ lowered the accuracy of the measurements by only 1%.

The test results are shown in Table 1. The last column shows values of the coefficient a_{ef}^{h} calculated by the formula presented earlier in [10]:

$$a_{ef}^{h} = [2.11 + 1.35W - 0.25n + 1.14d_p - 0.26\sin\alpha - 0.2S_{1,2}/d_{tu} + (-1)^k \cdot 0.27] \cdot 0.45(5F_{un} + 1) \cdot 10^{-4}. \tag{8}$$

Equation (8) was obtained in a factorial experiment in which the top part of the bed 200 mm from the gas-distributing grate was constrained by a tube bundle with the parameters d_{tu} = 18-36 mm and $S_{1,2}/d_{tu}$ = 2-4. It is strictly valid only for the conditions under which it was derived. However, it was necessary to check the feasibility of using this equation to evaluate a_{ef}^{h}, as well as to check the degree of the effect of the cross-sectional area of the unit on a_{ef}^{h} – since the values of the other factors were within the ranges investigated earlier.

It is apparent from the table that the experimental values of the coefficients D_{ef}^{h} and a_{ef}^{h} and the calculated values of a_{ef}^{h} agree satisfactorily with each other. It can be concluded from this that Eq. (8) by and large correctly accounts for the effect of the main factors and can be used to evaluate a_{ef}^{h} in designing similar units. It should also be noted from comparison of the experimental and theoretical values that the cross-sectional area of the tube-constrained bed, as that of a free bed [11], determines D_{ef}^{h} and a_{ef}^{h}. Evidently, the mechanism of heat and mass transfer in a fluidized bed in the horizontal direction is considerably more complex than the mechanism proposed by O. M. Todes [3]. According to Todes, the factor determining D_{ef}^{h} and a_{ef}^{h} is the bed height.

Using the above results, we calculate the temperature field in the fluidized-bed-equipped furnace with introduction of the fuel by the scheme shown in Fig. 3. The fuel (solid particles) is fed constantly and evenly over the entire left lateral surface of the fluidized bed. The fuel is instantaneously heated to the temperature of the bed at the site of its introduction. The water-cooled heating surfaces are located uniformly in the volume of the bed.

TABLE 1. Experimental and Theoretical Values of the Transfer Coefficients

No. of test	H_0, mm	W	Exptl. values			Calc.
			D^h_{ef}, m²/sec	a^h_{ef}, m²/sec	λ^h_{ef}, W/m·K	a^h_{ef}, m²/sec
1	670	1,54	0,0011			0,0021
2	670	2,28	0,0041	0,0036	4700	0,0034
3	500	1,20	0,0023			0,0018
4	500	2,28	0,0032	0,0034	4300	0,0034
5	320	2,36	0,0054			

Since combustion air is fed into the furnace uniformly over the bed cross section and always with an excess $\alpha_{exc} > 1$, we will divide the fuel combustion region into two zones. In the first (I) zone, the concentration of fuel will be greater than the mean concentration calculated from the heat-release rate of the bed. The power of the sources from fuel combustion in the zone is a constant value, determined by the quantity of air introduced for combustion. In the second zone (II), the concentration of fuel is below the mean value, and the combustion rate is directly proportional to the fuel concentration. The bed temperature corresponds to the calculated value at the point where the concentration equals the mean value. The temperature field was calculated separately for each zone.

Allowing for the heat sources and sinks in zone I, the heat-balance equation is written in the form

$$\lambda^h_{ef}\frac{d^2t}{dx^2} + q_v - \varphi(t - t_0) = 0. \tag{9}$$

The boundary conditions:

$$x = 0 \quad \lambda^h_{ef}\frac{dt}{dx} = q_g; \quad x = l_1 \quad t = t_{bd} \tag{10}$$

Having divided all of the terms of Eq. (9) by λ^h_{ef} and changing over to the dimensionless variables $\eta_1 = x/l_1$; $\vartheta = (t - t_0)/(t_{ad} - t_0)$, we rewrite Eqs. (9) and (10) in the form

$$\frac{d^2\vartheta}{d\eta_1^2} - A\vartheta + q_v^g = 0, \tag{11}$$

the boundary conditions:

$$\eta_1 = 0 \quad \frac{d\vartheta}{d\eta_1} = M; \quad \eta_1 = 1 \quad \vartheta = \vartheta_{bd}. \tag{12}$$

Here

$$A = \frac{l_1^2\varphi}{\lambda^h_{ef}}; \quad q_v^g = \frac{q_v l_1^2}{\lambda^h_{ef}(t_{ad} - t_0)}; \quad M = \frac{q_g l_1}{\lambda^h_{ef}(t_{ad} - t_0)}.$$

The general solution of Eq. (11), with allowance for boundary conditions (12), has the form [12]

$$\vartheta = C_1 \exp \sqrt{A}\,\eta_1 + C_2 \exp - \sqrt{A}\,\eta_1 + \frac{q_v^g}{A}. \tag{13}$$

The constants C_1 and C_2 have the following values:

$$C_1 = C_2 + \frac{M}{\sqrt{A}}; \quad C_2 = \frac{\vartheta_{bd} - \frac{q_v^g}{A} - \frac{M}{\sqrt{A}}\exp\sqrt{A}}{\exp\sqrt{A} - \exp - \sqrt{A}}. \tag{14}$$

Before proceeding to the calculation of the temperature field in zone II, we will calculate the change in fuel concentration. The mass balance equation for this zone, with the boundary conditions, is written thus:

$$D^h_{ef}\frac{d^2\varepsilon}{dx^2} - \frac{\varepsilon}{\tau_f} = 0, \tag{15}$$

the boundary conditions:

$$x = 0 \quad \varepsilon = \varepsilon_{av};\ x = l_2 \quad \frac{d\varepsilon}{dx} = 0. \tag{16}$$

Again using dimensionless variables, we obtain

$$\frac{d^2\mu}{d\eta_2^2} - B\mu = 0, \tag{17}$$

the boundary **conditions:**

$$\eta_2 = 0 \quad \mu = \mu_{av};\ \eta_2 = 1 \quad \frac{d\mu}{d\eta_2} = 0. \tag{18}$$

Here, having introduced the notation $\eta_2 = x/l_2$, $\mu = \varepsilon/\varepsilon_0$, $\mu_{av} = \varepsilon_{av}/\varepsilon_0$, $B = l_2^2/\tau_f D_{ef}^h$, we obtain the solution of Eq. (17), with boundary conditions, in the form [12]

$$\mu = C_3 \exp \sqrt{B}\,\eta_2 + C_4 \exp - \sqrt{B}\,\eta_2. \tag{19}$$

Here

$$C_3 = \frac{\mu_{av} \exp - \sqrt{B}}{\exp \sqrt{B} + \exp - \sqrt{B}};\ C_4 = \frac{\mu_{av} \exp \sqrt{B}}{\exp \sqrt{B} + \exp - \sqrt{B}}.$$

Now let us proceed to calculate the temperature field in zone II. The heat balance equation, with boundary conditions, is written thus:

$$\lambda_{ef}^h \frac{d^2t}{dx^2} + \frac{Q_l^w \varepsilon}{\tau_f} - \varphi(t - t_0) = 0, \tag{20}$$

the boundary conditions:

$$x = 0 \quad t = t_{bd};\ x = l_2 \quad \lambda_{ef}^h \frac{dt}{dx} = -q_s. \tag{21}$$

Using the dimensionless variables adopted earlier, we obtain

$$\frac{d^2\vartheta}{d\eta_2^2} + A_1\vartheta + B_1\mu = 0, \tag{22}$$

the boundary conditions:

$$\eta_2 = 0 \quad \vartheta = \vartheta_{bd};\ \eta_2 = 1 \quad \frac{d\vartheta}{d\eta_2} = -N. \tag{23}$$

We additionally designate:

$$A_1 = \frac{l_2\varphi}{\lambda_{ef}^h};\ B_1 = \frac{Q_l^w l_2^2 \varepsilon_0}{\lambda_{ef}^h \tau_f (t_{ad} - t_0)};\quad N = \frac{q_s l_2}{\lambda_{ef}^h (t_{ad} - t_0)}.$$

Solving Eq. (22) with boundary conditions (23), we obtain

$$\vartheta = C_5 \exp \sqrt{A_1}\,\eta_2 + C_6 \exp - \sqrt{A_1}\,\eta_2 + \frac{\beta}{B_1 - A_1} \exp \sqrt{B_1}\,\eta_2 + \frac{\gamma}{B_1 - A_1} \exp - \sqrt{B_1}\,\eta_2. \tag{24}$$

Here

$$C_5 = \vartheta_{bd} - C_6 - \frac{\beta + \gamma}{B_1 - A_1};\ \beta = -\frac{B_1\mu_{av} \exp - \sqrt{B}}{\exp \sqrt{B} + \exp - \sqrt{B}};$$

$$\gamma = -\frac{B_1\mu_{av} \exp \sqrt{B}}{\exp \sqrt{B} + \exp - \sqrt{B}};\ C_6 = \frac{\vartheta_{bd} \exp \sqrt{A_1}}{\exp \sqrt{A_1} + \exp - \sqrt{A_1}} +$$

$$+ \frac{N}{\sqrt{A_1}(\exp \sqrt{A_1} + \exp - \sqrt{A_1})} + \frac{\sqrt{B_1}(\beta \exp \sqrt{B_1} - \gamma \exp - \sqrt{B_1})}{\sqrt{A_1}(B_1 - A_1)} -$$

$$- \frac{(\beta + \gamma) \exp \sqrt{A_1}}{(B_1 - A_1)(\exp \sqrt{A_1} + \exp - \sqrt{A_1})}.$$

The results of this analysis were used to calculate the temperature field in the furnace of a boiler with parameters corresponding to the experimental KPV-KS-5.5-14-180 boiler. The fuel delivery and removal scheme was as shown in Fig. 2. Particles of fireclay with $d_p = 1.5$

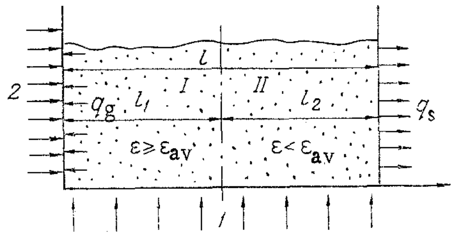

Fig. 3

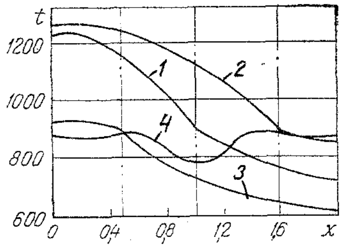

Fig. 4

Fig. 3. Scheme of calculation of the temperature gradients in a boiler furnace with a fluidized bed: 1) delivery of air for fluidization; 2) fuel introduction.

Fig. 4. Change in temperature of bed t (°C) along the furnace x (m): 1, 2) combustion of carbon particles without soot with excess-air coefficients: 1) $\alpha_{exc} = 2$; 2) $\alpha_{exc} = 1.25$; 3) combustion of brown coal yielding 20% volatile matter with $\alpha_{exc} = 1.25$; 4) temperature profile in furnace of boiler KPV-KS-5.7-14-180 in the combustion of Irsha—Borodin coal.

mm were introduced into the furnace, which measured 2 × 1.5 m in plan. The number of fluidizations W = 4 and bed height H = 1 m. The heat-release rate from the combustion surface was $3.0 \cdot 10^6$ kcal/m^2·h ($3.48 \cdot 10^3$ kW/m^2). The colorific value of the fuel was 5000 kcal/kg. We took a design temperature of 900°C for the bed, this currently being the most suitable level for low-temperature fuel combustion in a fluidized bed. The fuel concentration for these conditions $\varepsilon_{av} = 0.166$ kg/m^3. The cooling water in the heating surfaces and the air supplied to the furnace for combustion and fluidization collect 50% of the heat liberated in the burning of the fuel. The shielded surfaces located in the bed take up 5% of the heat liberated. The value of the coefficient a^h_{ef} calculated from Eq. (8) was 0.0063 m^2/sec. We took 100 sec for the time of combustion of the fuel particles. It was assumed in the calculations that all of the oxygen which passed through the zone I was used in combustion.

The results of the calculations and experiments are shown in Fig. 4. It can be seen from the figure that the temperature gradients 0.4 m from the furnace wall in the fluidized bed may reach 100°C. Similar gradients were recorded in tests on the boiler in burning Irsha—Borodin coal fed into the furnace from the front under the tube bundle along two fuel-supply lines.

Thus, in designing boilers with a fluidized bed, the fuel supply zone should be limited to a single feeder, due to temperature-gradient considerations. However, this makes it mandatory that the temperature and concentration fields of fluidized-bed-equipped boiler furnaces be calculated.

NOTATION

a^h_{ef}, thermal conductivity in the horizontal direction; c, running concentration of tagged particles; c_p, heat capacity of the bed material; D^h_{ef}, diffusion coefficient in the horizontal direction; d_p, diameter of bed particles; d_{tu}, diameter of tubes in tube bundle; H_0, H, initial height of stationary bed and height of fluidized bed; F_{un}, cross-sectional area of unit; k = 0 or 1 for an unstaggered or staggered bundle; n, degree of dispersion of particles; q_g, q_s, heat flux at left side wall, equivalent to the heat flux due to instantaneous heating of the fuel at the site of introduction and to the shielded heating surfaces, respectively; Q_0, q_v, power of instantaneous heat (mass) source and internal sources; Q^W_l, lowest working heat value of the fuel; S_1, S_2, longitudinal and transverse intervals in the tube bundle; t, t_{bd}, t_0, t_{ad}, t_{core}, t_{wa}, temperature of bed, calculated temperature of the bed, air under the grate, and the water in the tube bundle, the adiabatic fuel-combustion temperature, the temperature of the bed core, and the temperature of the wall of shielded heating surfaces, respectively; W, number of fluidizations; x, coordinate; α, angle between direction of propagation of heat flow and the tubes in the tube bundle; α_{exc}, excess-air coefficient; $\alpha_{fb.sur}$, coefficient of heat transfer from the fluidized bed to the heating surfaces; δ, thickness of fluidized bed; ε, ε_0, ε_{av}, running concentration of fuel, at site of introduction, and calculated value; ϑ_{bd}, calculated dimensionless temperature of bed; λ^h_{ef}, thermal conductivity in the horizontal direction; ρ_{fb}, density of the fluidized bed; τ, τ_f, running time and time of fuel combustion; φ, coefficient accounting for removal of heat by the air supplied for fluidization and the water in the tube bundle.

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EXPERIMENTAL STUDY OF STEAM CONDENSATION ON A BED OF DISPERSED MATERIAL

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UDC 536.423.4

Results are presented from an experimental study of heat exchange in the condensation of water vapor on a bed of solid dispersed material.

The process of vapor condensation on dispersed material is used in various engineering apparatus, especially in the construction industry. Preliminary heating of concrete mixtures before forming has been empolyed in recent years in making structural elements. Analysis of the efficiency of this method shows that it is best to use steam to continuously heat the mixture at the site of formation of the element. However, it is nearly impossible to precisely design equipment for such heating due to a lack of theoretical and empirical data in the literature on heat transfer in vapor condensation on a flow of a dispersed solid material [1].

Examination of the results of studies of vapor condensation on liquid streams [2, 3] shows that the complexity and multifaceted nature of the physical phenomena realized in the mixing of vapor with a liquid phase do not allow an analytical solution or a solution, by numerical methods, of the system of differential equations which describes the course of the process in a first approximation. In connection with this, there remains only direct experiment as a recourse for determining the main factors affecting the rate of vapor condensation on a dispersed material and the relationship between these factors.

As the first step, we studied the condensation of steam during its interaction with a stationary bed of a dispersed solid. Preliminary analysis of the course of the process showed

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