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HEAT AND MASS TRANSFER IN FLUIDIZED-BED FURNACES IN COMBUSTION OF A COAL-WATER MIXTURE

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The possibility in principle of burning highly ballasted fuel, including irrigated fuel, is considered. The permissible limits of the ash content and the moisture content are determined. The process of the thermal interaction between a drop of a coal-water mixture (CWM) and a fluidized bed is analyzed. Calculations of the distribution of volatiles and moisture in the fluidized bed in one-sided introduction of the CWM are performed. The combustion of a CWM in a boiler furnace confirmed the practical possibility and expediency of recovering irrigated fuel waste of coal cleaning by this method.

One of the fundamental problems of modern power engineering is judicious and environmentally safe use of fuel. A noticeable reduction in the quality of burnt coal is observed at thermal power stations. This is due to the mining of deposits that are characterized by a high ballast content. A changeover to using low-grade coal on the basis of traditional methods of preparation and combustion presents serious difficulties. A constant increase in the ash content of the fuel and a decrease in the heat of its combustion impair the efficiency and reliability of equipment operation: slagging and drift of heat transfer surfaces is observed; in a number of cases, their abrasive wear is intensified; the wear of the units for fuel supply, of the coal pulverization system, and for hydraulic ash disposal is enhanced; the operation of the ash collectors is impaired. Furthermore, the temperature in the flame cone lowered, which results in a retarded process of combustion, decreased intensity of fluxing along the flame length, and increased combustible losses.

The sharp reduction in the quality of mined coal has led to a considerable increase in the volumes of coal cleaning. High dispersion, irrigation, and the ensuing problems of transportation and recovery of cleaning waste, the content of combustibles in which does not exceed 25–50%, call for new approaches to organizing the combustion of this fuel. Combustion of coal cleaning waste in furnaces with a low-temperature (800–900°C) fluidized bed seems more efficient [1]. Here it is also possible to use coal washing waste in the form of a pumped coal-water mixture (CWM) with a 40–50% moisture content. Here, sufficiently reliable transportation through a pipeline is ensured for an operating moisture content of 30 to 50% for the majority of coal types.

The possibility in principle of independent – with no additional preliminary illumination – combustion of a fuel in a furnace is governed by the excess of the heat of fuel combustion over all the occurring heat losses in the boiler. We consider how much the heat of combustion of the fuel changes in its irrigation to the highest of the indicated moisture contents (50%). In this case, 1 kg of the fuel as-received (the CWM) will contain 0.5 kg of moisture-free coal and 0.5 kg of water. Of this total CWM as-received (1 kg), the coal proper will provide a positive portion of the heat of combustion, equal to $0.5Q_i^d$, and a negative portion – removal of the heat expended on water evaporation at a rate of 1 MJ/kg of fuel (here 2 MJ/kg is the heat of evaporation of 1 kg of water at normal pressure rounded off to units). Thus, the heat of combustion of the CWM will be determined as $(0.5Q_i^d - 1)$ MJ/kg and will be, for example, $0.5 \cdot 20 - 1 = 9$ MJ/kg for a CWM of power-generating coals with a rather common heat of combustion of 20 MJ/kg. This magnitude of the heat of combustion, which is similar to the heat of combustion of firewood and peat, is quite acceptable for ensuring operation of, for example, boiler furnaces. Thus, when the technological conditions for burning a CWM are met (optimum excess air, uniform composition of the CWM) such a high moisture content of it (up to 50%) is not, in fact, an obstacle to a normal furnace process with a positive thermal effect.

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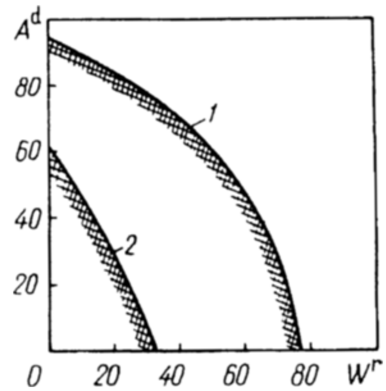


Fig. 1. Permissible values of the moisture content and ash content of a fuel burned in a fluidized bed. The heat of combustion of the combustible matter of the fuel is 31.4 MJ/kg. $\alpha = 1.2$; $q_3 = 5\%$; $q_4 = 5\%$; q_5: 1) 3%, 2) 40. A^d, W^r, %.

For a more accurate determination of the possibility of independent combustion of CWM in a furnace, we should also take into account both the ballast content of the fuel (its ash content A^r) and concrete magnitudes of the heat loss by the boiler. Figure 1 gives results of these calculations, i.e., a nomogram, for a fuel with a heat of combustion of the combustible matter of 31.4 MJ/kg and for different heat losses into the ambient medium, which makes it possible to use this nomogram not only for boilers with good insulation, operating at nominal load, but also for pilot plants and cases of boiler operation with a partial load, when the relative magnitude of the heat losses into the ambient medium through the barrier increases.

The technology of fluidized-bed combustion, apart from the possibility of recovering low-grade coals (including sludges of various sorts—cleaning waste), is also appealing because of the fact that it ensures the binding of toxic products of combustion or prevents their formation in the process of combustion itself [1, 2]. Of importance, too, is the possibility of realizing no-waste technology since the ash produced in fluidized-bed combustion contains less than 5% combustibles, which satisfies the requirements for using it in the production of building materials.

In studying the processes that occur in the fluidized-bed combustion of a CWM we should take into account both the thermal and mechanical interactions of a drop with the fluidized bed. One of the fundamental problems of fuel combustion under these conditions is a decrease in the losses with mechanical incompleteness of combustion q_4 with removal. Taking into account the small-fraction composition of coal washing waste, we could expect that the portion of ash removal a_{rem} in fluidized-bed combustion of a CWM will be much higher than in coal combustion. However, results of experiments showed that under approximately the same conditions a_{rem} differs slightly for the combustion of Kizelov coal and a CWM of sludge of Kizelov coal. Of interest is the extremum dependence of the portion of ash removal on the fluidized-bed temperature obtained in the combustion of a CWM. The minimum a_{rem} occurs for a fluidized-bed temperature ($t_{fl.b}$) of 890–910°C. Decrease in $t_{fl.b}$ (for a constant velocity of the gases in the installation) to 730°C leads to an increase in the portion of ash removal to about 50% or more.

Experiments performed with the aim of studying special features of the interaction between a CWM and the material of the fluidized bed, showed that when a CWM drop is incident on the bed asymmetric breakup of it occurs: a large piece with a volume of 50% of the initial volume and numerous smaller fragments are usually produced. The size of the large piece depends on the bed temperature and the moisture content of the drop. The influence of the temperature manifests itself in two ways. On the one hand, acceleration of the drying of the surface leads to formation of a crust that prevents the drop from breaking up, and on the other, overintensification of the process of evaporation increases the probability of the drop breaking up due to the increase in the pressure in it. The data obtained make it possible to explain the extremum character of the dependence $a_{rem}(t_{fl.b})$. For a moisture content of 50%, the mixture processes decreased viscosity and for relatively low fluidized-bed temperatures, the drop is broken up into small fragments since the drying of the surface is retarded. As the fluidized-bed temperature is increased to 900°C, the crust on the drop surface forms more rapidly, and here growth of the sizes of the remaining pieces is observed. As the temperature is increased further, the drying process becomes overintensified and water vapor breaks up rupture the drop. A major portion of the initial drop changes into small fragments, which provides an increase in the number of particcles removed from the bed. The density of the agglomerates is practically independent of the fluidized-bed temperature and is governed by the CWM moisture content. As the moisture content grows, the density of the residue decreases and for CWMs with a moisture content of 30, 40, and 50% it is, respectively, 790, 700, and 650 kg/m^3. In all the cases, the collected agglomerates have a strongly developed porous structure and are of sufficient strength.

Experiments on studying changes in the fractional composition of the bed showed that when a CWM is supplied to the layer the bed particles become larger at the expense of adhered coal fines. Owing to this, up to 52% of the ash introduced with the fuel is retained in the bed.

As has been mentioned above, when a CWM is supplied to the bed agglomerates (drops) form whose sizes can attain 30 mm or more. In this connection, it is of interest to study the processes occurring in a drop of large diameter in heating it. Investigating the processes that occur in a drop of a CWM in its combustion directly in the fluidized bed is a very difficult problem. Study of the combustion of a quiescent drop in a special furnace, on the other hand, gives a rather comprehensive idea of the evolution of the drop in combustion and makes it possible to obtain data for calculating the processes that occur in the fluidized-bed combustion of a CWM.

Experiments on studying the change in the temperature of the surface layers and the center of a drop with a 25% moisture content, performed in a muffle furnace, showed that in the initial stage, there is heating of the drop, primarily of its surface layers, to the point of boiling water. Next, the moisture begins to evaporate from the drop volume. From the theory of drying it is known that the entire drying process can be divided into two periods – the period of a constant rate of drying and that of a decreasing rate of drying. The critical moisture content that corresponds to the first period going over to the second period is determined experimentally for different materials. The experiments showed that the volume of the moist core of a CWM drop (in the moist core, $t = \text{const}$) and, hence, the mass of the evaporated moisture decrease at a constant rate. The exception is the internal region 3–5 mm in radius, where the rate of drying slows down. This makes it possible to infer that no less than 95% of the moisture is evaporated in the period of a constant rate of drying.

Experiments on determining the decrease in the mass of a drop in heating it also showed the presence of a period of constant drying rate, whose duration is 150–160 sec. This magnitude is in good agreement with the duration determined from the thermogram of heating a drop. Measuring the rate of decrease of the mass of an air-dry "drop" (in this case, the entire decrease in the mass can, with a certain degree of approximation, be attributed to the escape of volatiles since the moisture content does not exceed 2%) showed that the velocity of volatile escape depends on the heating time for the drop and attains its largest magnitude approximately in the middle of the process of visible combustion of volatiles; the velocity of volatile escape increases with increasing volatile content in the initial coal.

In experiments of G. N. Delyagin, V. V. Isaev, and others [3, 4], where the heating of small-diameter (below 1 mm) drops was studied, it was assumed and confirmed by experiment that the temperature over the drop cross section is practically the same. As the size of the drop increases, the assumption of its isothermality becomes invalid. Indeed, we noticed a significant temperature gradient over the drop cross section. While the temperature of the surface layers of the drop had already attained 600–650°C, its center had a temperature of 100°C. In this case, moisture evaporation from the internal regions of the drop and volatile escape are observed simultaneously. The experiments showed that the duration of the processes of moisture evaporation and volatile escape is governed by the size of the particles of the initial coal and the drop diameter rather than by the type of coal in question, and it turned out to be proportional to $d_{\text{dr}}^{1.8}$ whereas volatile escape is retarded as compared to this process in an air-dry "drop" by approximately a factor of 1.5.

The obtained experimental data on drop heating in a muffle furnace give a rather comprehensive idea of the special features and regularities of the processes in the drop. In going over to fluidized-bed combustion of a CWM, we should take into account the differences in the conditions of heating a CWM drop in the fluidized bed and the muffle furnace. Approximate evolution of the heating time for the drop usung the Bi number (the thermal conductivity of air-dry coal and coal with a moisture content of 25% was determined under laboratory conditions by the method of a regular regime and was, respectively, 0.14 and 0.60 $W/m \cdot K$, and the heat-transfer coefficient

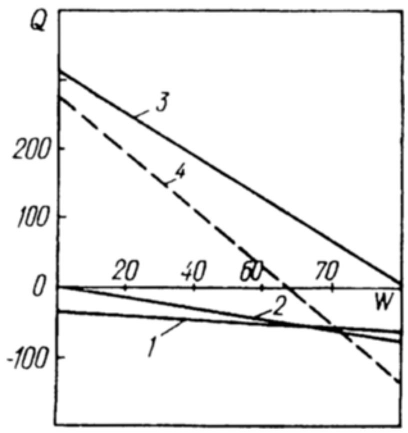


Fig. 2. Heat balance of a CWM drop: $A^d = 50\%$; $V^{daf} = 40\%$; $d_{dr} = 36$ mm; 1) heating of the drop; 2) moisture evaporation (expenditure of heat); 3) combustion of the carbon residue (heat release); 4) total expenditure of heat. Q, kJ; W, %.

in the fluidized bed was estimated by the formula of S. S. Zabrodskii [5] and was equal to 446 $W/m^2 \cdot K$) shows that the heating of the drop in the fluidized bed is more rapid by approximately a factor of 1.5 than in the muffle furnace. In the experiments, the duration of volatile escape in the fluidized bed was found to be reduced by approximately a factor of 1.7 as compared to that in the muffle furnace. The data obtained made it possible to calculate the a change in $t_{fl.b}$ in supplying the CWM drop to the bed from the balance of the heat expended on drop heating and moisture evaporation and the heat released in the bed in the combustion of volatiles. The results of the calculation are in satisfactory agreement with experiment.

In fluidized-bed combustion of a fuel, a major portion of the air is supplied via an air-distributing grating rather than a burner (as in flame combustion). Therefore, for high-quality combustion of the fuel, uniform distribution of it over the cross section of the bed is required. It is governed by the design of the atomizing burner and by the dispensing of the fuel by the fluidized bed itself. It is evident that long-burning-out coke particles are distributed over the fluidized-bed cross section more uniformly than volatiles since a considerable amount of time passes between the supply of the initial drop to the bed and the beginning of the combustion of the carbon residue, which can turn out to be sufficient for uniform distribution of it over the bed cross section. Therefore the quality of fluidized-bed combustion of a CWM will be governed mainly by the distribution of volatiles.

Experiments on studying the processes of heating, moisture evaporation, and volatile escape from a CWM drop showed that escape of volatiles from a moist drop is retarded by approximately a factor of 1.5 as compared to an air-dry "drop." Since a CWM drop when hitting the fluidized bed is simultaneously involved in two parallel processes, namely, it travels over the furnace cross section due to the mixing of the bed material and it releases volatiles upon heating and evaporation of a portion of the moisture, it is evident that retardation of volatile escape enhances the uniformity of the distribution of combustibles over the furnace cross section owing to the intense mixing of particles. From the viewpoint of practical combustion of a CWM, of interest is the influence of the uniformity of the volatile distribution on the temperature in the furnace. In this case, for calculations we should also know the moisture distribution over the furnace cross section since, in CWM combustion, the expenditure of heat on heating and moisture evaporation is very considerable (Fig. 2).

We consider the evolution of a single drop that hits a fluidized bed with a temperature of 850–950°C. From the moment of introduction to the instant τ_h, the surface layers of the drop are heated, after which moisture evaporation begins. The duration of this process is determined by the time τ_{ev}, and most of the moisture evaporates in the period of a constant rate of drying. Some time after the beginning of the evaporation but prior to the moment of its completion, volatiles begin to escape (at the instant τ_{ign}). The duration of volatile escape is τ_v. We note that the velocity of volatile escape, as the experiments with the air-dry "drop" showed, depends on the heating time for the drop. However, to simplify calculations, as a first approximation we take the velocity of volatile escape to be constant. The combustion of the carbon residue, which has practically no effect on the uniformity of the combustible distribution in the bed, is not considered in the problem.

Thus, if a set of drop-particles is isolated in the fluidized bed, one group of them that contains drops that stay in the installation for a time that does not exceed τ_h is heated to the equilibrium temperature; a second group – with a time of stay from τ_h to τ_{ign} – is dried; a third group – with a time of stay from τ_{ign} + τ_{h+ev} – is dried and is rid of volatiles; in a fourth group – with a time of staying in the bed from τ_{h+ev} to τ_{ign+v} – the volatile escape ceases; a fifth group consists of just the carbon residue.

For calculating the distribution of volatiles and moisture along the furnace length, we should find the local distribution of the particles in ages. The basic method for finding the age distribution function is a tracer method that consists in recording the curves of the response $C(\tau)$ to concentration disturbances from a tagged substance – a tracer – at the inlet to the system [6].

For finding the distribution of volatiles and moisture along the length of the fluidized bed when the fuel is supplied from a boiler front, we considered an unsteady-state diffusion equation that describes the mixing of tracer particles in the fluidized bed under the assumption that tracer concentrations are constant over the furnace width. Furthermore, we took into account that the mixing of the particles is much more intense in the vertical direction than in the horizontal [6]. With account taken of these comments, the equation will be written as

$$\frac{\partial C}{\partial \tau} = D_{hor} \frac{\partial^2 C}{\partial x^2} - \frac{C}{T}, \tag{1}$$

where the last term characterizes uniform removal of the particles along the furnace length; D_{hor} is the effective diffusion coefficient in the horizontal direction. We reduce Eq. (1) to the dimensionless form

$$\frac{\partial C}{\partial \Theta} = \frac{\partial^2 C}{\partial \xi^2} - \frac{C}{\Theta_0}. \tag{2}$$

Here $\xi = x/l$; $\Theta = \tau D_{hor}/l^2$; $\Theta_0 = TD_{hor}/l^2$.

Using the Fourier method, we find the solution to this equation under the following initial and boundary conditions:

$$\begin{gathered} \tau = 0 \quad C = \frac{1}{\delta\xi} \quad 0 \le \xi \le \delta\xi\,; \quad C = 0 \quad \xi > \delta\xi\,; \\ \tau > 0 \quad \xi = 0;\, 1 \quad \frac{\partial C}{\partial \xi} = 0\,, \end{gathered} \tag{3}$$

where δ is the relative layer length occupied by the tracer when $\tau = 0$.

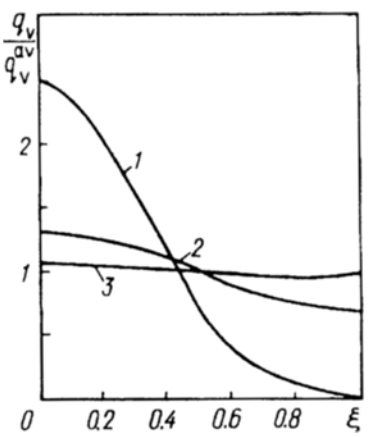
The solution of Eq. (2) for $\delta\xi \to 0$ will be expressed by the following formula [7]:

$$C(\Theta, \xi) = e^{-\Theta/\Theta_0} + 2 \sum_{k=1}^{\infty} \exp\left[-\frac{\Theta}{\Theta_0}(\pi^2 k^2 \Theta_0 + 1)\right] \cos(\pi k \xi). \tag{4}$$

Knowing the tracer concentration, we can easily determine the local differential function $I(\xi, \Theta)$ of the age distribution of the particles in the region of the dimensionless time Θ [6]:

$$I(\xi, \Theta) = \frac{C(\Theta, \xi)}{\int_0^{\infty} c(\Theta, \xi)\, d\Theta}. \tag{5}$$

Hence we can find the distribution of volatiles and moisture along the furnace length. The mass flux density of the water vapor j_{fl} and the volatiles j_v is calculated by the formulas



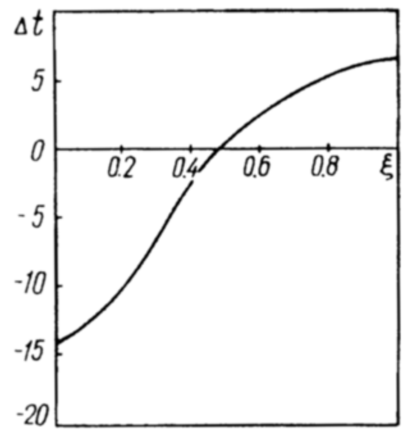


Fig. 3. Volatile distribution along the furnace length for different sizes of CWM drops. Fuel: a CWM of sludge of Kizelov coal, $W^r = 30\%$. $l = 2$ m; $H_0 = 0.3$ m; $B_f = 800$ kg/h; d_{dr}, mm: 1) 3, 2) 5, 3) 10.

Fig. 4. Distribution of the deviation of the fluidized- bed temperature Δt along the furnace length. Fuel: a CWM of sludge of Kizelov coal, $W^r = 30\%$; $l = 2$ m; $H_0 = 0.3$ m; $B_f = 800$ kg/h; $d_{dr} = 10$ mm. Δt, °C.

$$j_{fl}(\xi) = \frac{BW^r}{100} \frac{\Phi(\xi, \Theta_h + \Theta_{ev}) - \Phi(\xi, \Theta_h)}{\int_0^1 [\Phi(\xi, \Theta_h + \Theta_{ev}) - \Phi(\xi, \Theta_h)]\, d\xi}, \tag{6}$$

$$j_v(\xi) = \frac{B(100 - W^r)(100 - A^d)V^{daf}}{10^6} \frac{\Phi(\xi, \Theta_{ign} + \Theta_v - \Phi(\xi, \Theta_{ign})}{\int_0^1 [\Phi(\xi, \Theta_{ign} + \Theta_v) - \Phi(\xi, \Theta_{ign})]\, d\xi}. \tag{7}$$

Here Θ_h, Θ_{ev}, Θ_{ign}, and Θ_v are, respectively, the dimensionless times of the drop heating, moisture evaporation, beginning of volatile ignition, and volatile escape.

We consider the influence of the distribution of volatiles and moisture on the isothermality of the fluidized bed. Taking the distribution of the carbon residue to be uniform, we obtain that at the point for which the mass fluxes of the volatiles and the water are equal to their averages over the cross section the temperature will be equal to the temperature average over the furnace cross section. For excess volatiles, the bed temperature will grow and it will decrease when the moisture is in excess. We find the distribution along the furnace length of the deviation of the fluidized bed temperature Δt from the average $t_{fl.b}$ in the furnace. It will be the solution to the equation

$$\lambda \frac{d^2 \Delta t}{dx^2} + q_l = 0 \tag{8}$$

under the boundary conditions $d\Delta t/dx = 0$ at $x = 0, l$. Here q_l is the strength of the internal heat sources.

Results of the calculations are presented in Figs. 3 and 4. As Fig. 3 shows, an increase in the CWM drop size enhances the uniformity of the volatile distribution along the furnace length (Fig. 3). However, we should note that in the region of the introduction of the CWM (Fig. 4), a pronounced zone of lowered temperatures is observed; the region of elevated temperatures is less pronounced.

Thus, in fluidized-bed combustion of a CWM, the uniformity of the distribution of combustibles and correspondingly the uniformity of the temperature field of the fluidized bed are enhanced as compared to the combustion of coal due to retardation of volatile escape but there is the risk of freezing the region adjacent to the point of introduction of the CWM. To prevent this unwanted phenomenon, a uniform distribution of the CWM over the cross section of the bed should be organized. This is attained using a coarse atomizing burner that consists of a fuel-supplying channel and an air-conveying tube with a slot attachment (for increasing the velocity of atomizing air) under the channel. To protect the burner from the action of high temperatures, it is placed in a water-cooled chamber. A model investigation of the distribution of a CWM over the bed cross section in supplying it through a coarse atomizing burner showed that a more uniform CWM distribution is obtained for a rectangular shape of the fuel channel since, in this case, the CWM is distributed more uniformly over the fuel channel width, owing to which the ratio of the flow rates of the air and the CWM remains constant over the entire width of the plane jet discharging from the fuel channel. The experiments showed that the distribution uniformity increases as the moisture content of the CWM drops increases. With allowance for the data obtained, experimental-industrial combustion of a CWM with a moisture content of up to 34% was performed together with the Institute of Environmental Protection (Perm') in a reconstructed DKVR-4-13 boiler with a fluidized-bed furnace ($t_{fl.b} = 85^oC$). Stable operation of the boiler (the area of the bed was 2.7 m^2) was provided by a single coarse atomizing burner with a capacity of 1400 kg/h. The boiler bore a full load in the tests.

The results of the work performed show that combustion of a coal-water suspension is possible in a fluidized-bed furnace and the analysis made enables us to select the number of points for introducing the fuel with allowance for the maximum difference in temperatures over the bed cross section that is permissible in each case. This temperature difference can be governed by both the conditions of sludging (attaining the temperature of ash softening) and the conditions of the reduction of the formation of nitrogen oxides in the process of combustion and binding of sulfur. It was shown by the results of the investigation that no fine atomization of the CWM is required; throwing large drops of the fuel onto the bed surface is preferable.

To completely solve the problem of creating fluidized-bed furnaces with the aim of burning a CWM, we should accumulate further data of an industrial experiment, especially for large-size furnaces, and improve the unit for fuel introduction by creating an atomizing burner that produces the minimum amount of small drops in fuel atomization.

NOTATION

A^d, A^r, ash content for the moisture-free fuel and the fuel as-received; a_{rem}, portion of ash removal; B_f, fuel flow rate; Bu, Biot number; C, concentration; D_{hor}, effective diffusion coefficient in the horizontal direction; d_{dr}, drop diameter; H_0, height of the granular-material layer; l, furnace length; Q_i^d, Q_i^r, heat of combustion referred to the moisture-free fuel and the fuel as-received; q_3, q_4, heat losses from chemical incompleteness of combustion and mechanical incompleteness of combustion; q_5, heat losses via the external barrier; $t_{fl.b}$, fluidized-bed temperature; V^{daf}, content of volatiles referred to the dry-and-ash-free fuel; W^r, moisture content of the fuel as-received; α, excess-air coefficient; λ, thermal conductivity; τ_{ign}, time of the beginning of ignition; τ_h, τ_{ev}, τ_v, duration of the processes of heating, moisture evaporation, and volatile escape.

REFERENCES

1. V. A. Borodulya and L. M. Vinogradov, Fluidized-Bed Combustion of Solid Fuel [in Russian], Minsk (1980).
2. K. E. Makhorin and P. A. Khinkis, Fluidized-Bed Combustion of Fuel [in Russian], Kiev (1989).
3. V. V. Isaev and G. N. Delyagin, Khim. Tverd. Topliva, No. 1, 138-141 (1978).
4. G. N. Delyagin, Kinetics and Aerodynamics of the Processes of Fuel Combustion [in Russian], Moscow (1969), pp. 111-127.
5. S. S. Zabrodskii, Inzh.-Fiz. Zh., 1, No. 4, 22-30 (1958).
6. I. P. Mukhilenov, B. S. Sazhin, and V. F. Frolov (eds.), Calculations of Fluidized-Bed Apparatuses: Handbook [in Russian], Leningrad (1986).
7. A. N. Tikhonov and A. A. Samarskii, Equations of Mathematical Physics [in Russian], Moscow (1966).