THE DYNAMIC ANALYSIS OF A SMALL FLUIDIZED BED COMBUSTOR

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The dynamic characteristics of a small fluidized bed combustor for coal were examined analytically and experimentally.

Introduction. In recent years great interest has been shown in the use of the fluidized bed technique in the process of combustion, and particularly for the combustion of coal. Investigations, carried out in England under the auspices of the National Coal Board, led to a preliminary project with boiler units, with a fine fluidized (boiling) bed (atmospheric and with combustion under pressure) [1]. Most of the data were obtained from investigations under stationary conditions. There was comparatively little investigation of dynamic aspects of such systems.

We [2] carried out experiments on mixing in a cold boiling bed, of diameter 1.6 m; these experiments enabled us to select suitable spacings between the coal feeds in a furnace of industrial dimensions. A generalized dynamic model, of general response, was selected for a boiler of industrial dimensions, with combustion at atmospheric pressure, although up till now none of the results of these investigations have been published [3]. In a previous paper [4] we considered a simple dynamic model of a thick combustor with a boiling bed under pressure, but no experimental data were obtained to check the model. The object of the work described here was to develop an analogous semi-empirical model for a small combustor, at atmospheric pressure, with a fluidized bed, based on the normally accepted behavior of a boiling bed, and comparison of this with the previous experimental data on the response of the temperature of the bed and of the output water to changes in the heat supply, with use of the technique of correlation analysis.

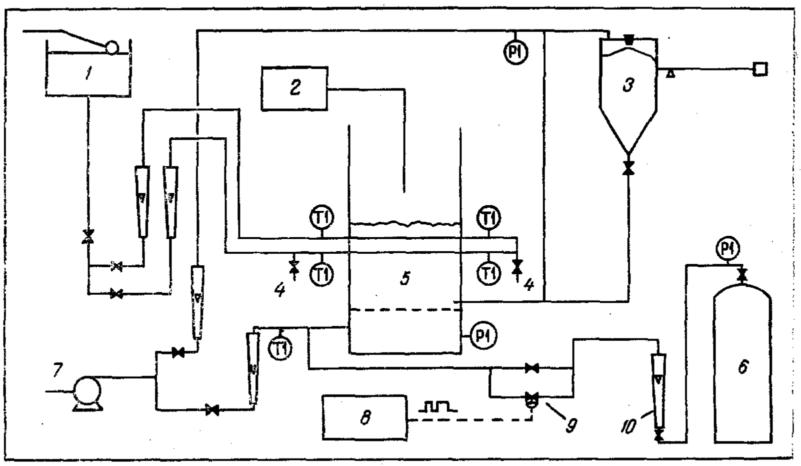

Fig. 1. Line diagram of apparatus: 1) water; 2) gas analysis unit; 3) coal; 4) drain; 5) combustor; 6) propane; 7) air; 8) PRBS signal generator; 9) solenoid valve; 10) needle valve.

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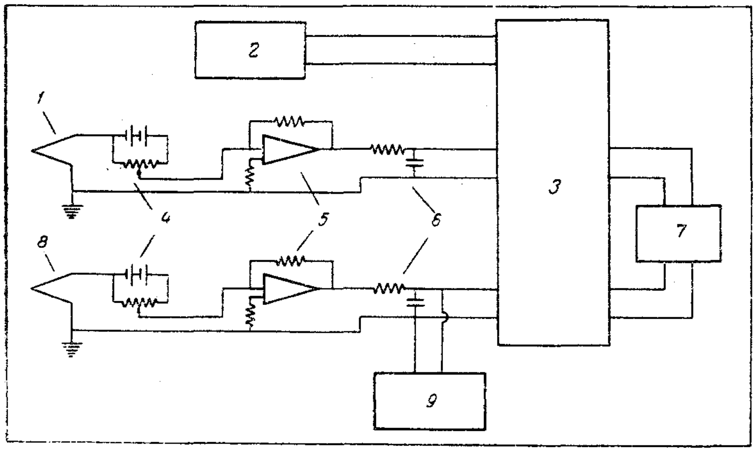

Fig. 2. Signal recording equipment: 1) water stream thermocouple; 2) PRBS generator; 3) tape recorder; 4) potentiometers; 5) amplifiers; 6) filters; 7) oscilloscope; 8) bed thermocouple; 9) pen recorder.

Experimental Apparatus. Figure 1 shows a diagram of the apparatus with an experimental combustor. This had a cross-section of 250 × 250 mm, and was 950 mm tall. The gas-distributing lattice consisted of a stainless steel plate, 6.4 mm thick, with 0.8 mm diameter openings; the spacing was 13 mm and the arrangement triangular. Air was fed into the lattice chamber through a tube 89 mm in diameter; propane could be injected into this. Crushed coal (a 3200 μm fraction) was fed into the lower part of the bed by a screw feed with an electric driving gear. The boiling bed consisted mainly of ash (the particle size was of the order of 500 μm), and was about 215 mm tall. The height of the bed could be maintained by the overflow of ash through a baffle. A water-cooled tube, made of stainless steel, and of internal diameter 9.6 mm, passed twice through the bed at a height of 160 mm above the lattice. Thermocouples were fitted into the inlet and outlet water.

The bed temperature was monitored at five different points. The temperature of the exit gases was measured at a height of 340 mm above the lattice (i.e. about 125 mm above the surface of the bed), and samples were taken at this level for measurement of the O_2, CO, and CO_2 contents of the gas.

The coal feed could be adjusted by the number of revolutions of the feed motor, and the coal consumption was determined from the change in weight of the bunker (by measurement of the displacement of a balance arm) after a definite time. Gas and water consumptions were measured by combination rotameters. It was difficult to make fine adjustments to the fuel supply by means of the coal feed, so that, for dynamic investigations, the heat supply was maintained by a possibly more stable and variable pulsed injection of propane into the flow of air to the boiling bed, before the gas distribution lattice.

Figure 2 shows an electrical diagram of the scheme for dynamic analysis. Potentiometers were used to ensure the reliability of the counterelectromotive force, so that the signals from the thermocouples in the bed and in the water had only an alternating component. These signals were amplified and filtered before being recorded on magnetophonic tape. The PRBS generator, which controlled the propane feed channel, consisted of a six-step shift recorder, giving a succession of 63 bits, controlling the synchronizing pulses, which could be adjusted within the range 1.5 to 20 sec.

Stationary Regime. The mass of the bed in the combustor was about 11 kg. The air consumption (25.8 kg/hour) was sufficient to maintain fluidization of the bed, with a fluidity number of the order 4, at 800°C. The fuel consumption was 2.3 to 2.6 kg/hour and the heat consumption was distributed approximately as follows: 1) 40% as the physical heat of the waste gases; 2) 30% as the change in enthalpy of the stream of cooling water; 3) 30% as the heat loss through the walls of the chamber, radiation from the surface of the bed, incomplete combustion, and the enthalpy of the discharged ash. These losses were determined as the difference between the heat added and that consumed under the headings 1) and 2).

Stationary Model. Figure 3 shows the mass consumptions and temperatures of the streams entering the bed and leaving it. Having drawn up a thermal balance, we could construct a steady state model. The heat supply is equal to the product of the fuel consumption f and the gross heat of combustion λ.

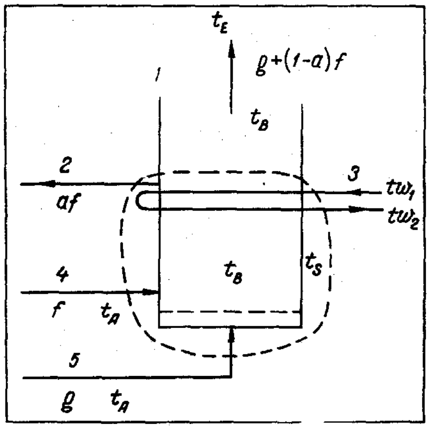

Fig. 3. Schematic diagram of combustor: 1) flue gas; 2) ash; 3) water; 4) coal; 5) air.

The heat consumption may be considered as the sum of five components: a) the physical heat of the gases; b) the heat transferred to the water stream; c) direct radiation from the surface of the bed; d) heat loss through the walls; e) the physical heat of the ash withdrawn.

Then we can write the two following equations:

$$f\lambda = \sum_{i=1}^{4} m_i h_i - wc_W(tw_2 - tw_1) + A_R \varepsilon\sigma(\hat{t}_B^4 - \hat{t}_E^4) \tag{1}$$

$$+ (k/x) A_W (t_B - t_S) + afc_{PA}(t_B - t_A),$$

$$wc_W(tw_2 - tw_1) = U_D A (tw_2 - tw_1)/\ln \frac{t_B - tw_1}{t_B - tw_2}, \tag{2}$$

where

$$h_i = a_i(\hat{t}_B - \hat{t}_A) + \frac{b_i}{2}(\hat{t}_B^2 - \hat{t}_A^2) - \frac{c_i}{3}(\hat{t}_B^3 - t_A^3);$$

a_i, b_i, and c_i are experimental constants [5]; i refers to the components O_2, N_2, CO_2, and H_2O. The overall coefficient of heat transfer from the bed to the water U_D was determined as a function of the rate of permeation of air into the bed U_0, and was calculated from the empirical equation:

$$U_D = 214\,U_0 + 1055 \text{ kJ/h} \cdot \text{m}^2 \, ^\circ\text{C}$$

where $0.26 < U_0 < 0.5$ m/sec and $150 < w < 260$ kg/h. Thus U_D will depend on the temperature, just as the temperature level depends on the permeation rate. These two equations are inexplicit functions of the temperatures t_B and tw_2; they are best solved by the integration method of Newton and Rafson.

The stationary model gave a realistic prediction for t_B and tw_2, for the given regime of the parameters f, g, w, t_A, tw_1, and t_S, and showed that the loss of heat in the ash was negligibly small [6]. The inclusion of some of these data in the dynamic model was justifiable. The object was to predict how the bed and the water stream would respond, under typical hydrodynamic and temperature conditions, to a change in the fuel supply. Unfortunately, as mentioned above, technical difficulties made it impossible to vary the coal feed, while the pulse f, strictly speaking, referred to a mixture of coal and combustible gas.

Dynamic Model. Having considered the various kinetic processes, we arrive at the following assumptions for a nonstationary regime:

1) Transfer to the bed of the thermal disturbance, arising from the supply of additional combustible gas, will be accompanied by some delay.

2) This gas will burn with a velocity depending on the presence of oxygen, and the heat will probably be evolved close to the gas distribution lattice.

3) There will be a rapid heat exchange between the gas and the particles, which will lead to some local overheating of the material.

4) This material will move from the bulky layer primarily under the action of the gas bubbles rising through the layer.

5) The heat, reaching the walls of the tube, is transferred to the stream of water. The resulting change in water temperature at the outlet is determined by the resistance to heat transfer from the bed to the water, and by the accumulation of heat in the water stream.

Since measurement of the distribution of temperature in the bed, under stationary conditions at 800°C gave a scatter of values of approximately ±4°C, in spite of the high rate of heat evolution, there is evidently a basis for assuming that the bed mixes very intensively, and the case is similar to that of a directly heated vessel with full mixing. However, the additional heat is distributed between various outlets — the material of the bed, the walls of the chamber, the fluidizing gas, the tubing, and the water.

The intensity of the change in heat flow in refractory walls, associated with a change in the bed temperature, will not be great owing to their low thermal conductivity, and will therefore scarcely appear as a response to the bed temperature.

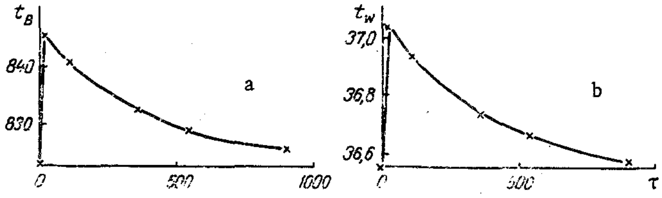

Fig. 4. Predicted bed response a) at $\tau_B = 400$ sec; b) predicted water response at $\tau_W = 400$ sec.

Combining the thermal capacity of the water and of the tube, we obtain:

$$Q_B \frac{dt_B}{d\theta} = f\lambda - \{g + (1-a) f\} c_{PM} (t_B - t_A) - wc_W (tw_2 - tw_1)$$

$$- A_R \varepsilon\sigma (\hat{t}_B^4 - \hat{t}_E^4) - (k/x) A_W (t_B - t_S), \tag{3}$$

$$Q_W \frac{dtw_2}{d\theta} = U_D A (tw_2 - tw_1)/\ln \left\{ \frac{t_B - tw_1}{t_B - tw_2} \right\} - wc_W (tw_2 - tw_1). \tag{4}$$

Here f is the perturbation function, t_B and tw_2 are dependent variables (functions of the time θ), and all the other terms are taken as constants. These equations can be solved numerically for a pulsed input pulse, giving the response of the temperature of the bed t_B and of the water tw_2. Table 4 (a and b) gives typical calculation results, for a bed temperature of 825°C and a water consumption of 260 kg/hour.

Experimental Results. The combustor had nonlinear characteristics owing to the influence of mixing of the particles and to radiation losses. Accordingly, in order to simplify the analysis at the limits of linear response, we used only small perturbations in an experiment to determine the dynamic response. The technique of correlation analysis was found very useful for this, since it enabled us to exclude strong signal noise, which arose inevitably in the boiling bed in the combustor. However one experimental difficulty remained, namely that there was only a very weak response by the temperature of the outlet water. To obtain greater variations in water temperature it would have been convenient to use larger perturbations, but this would have led to problems in nonlinearity.

For investigation of the dynamic response of the bed, with achievement of a quasistationary state, pseudorandom binary succession (PRBS) signals were made to act on the solenoidal valve controlling the

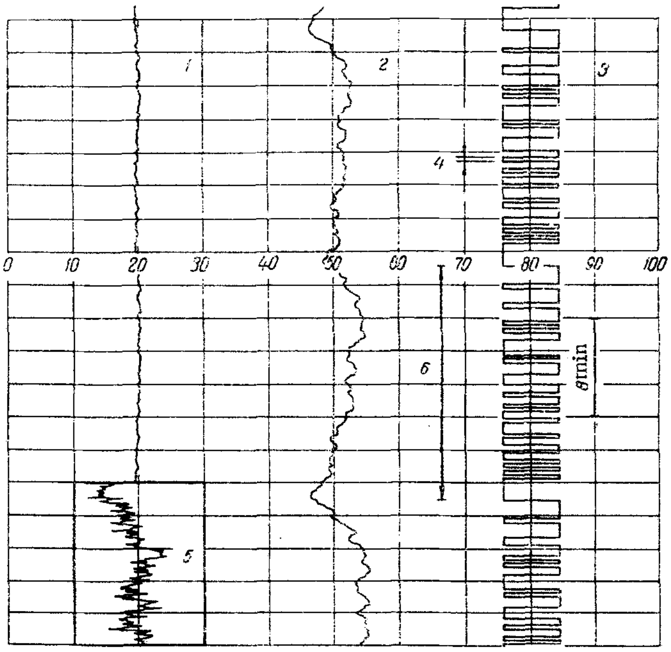

Fig. 5. Pen recorder diagram: 1) temperature of water; 2) temperature of bed; 3) pseudofluidized sequence; 4) length of clock pulse; 5) amplified signal; 6) sequence length of pulses.

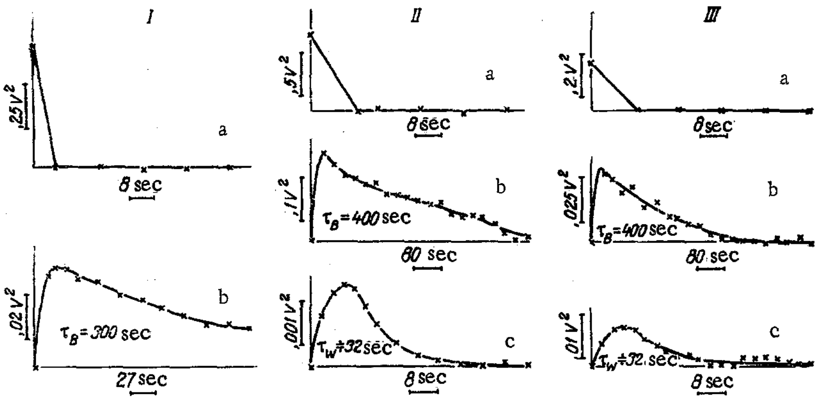

Fig. 6. Correlation functions: a) autocorrelation of PRBS; b) cross correlation of PRBS/bed temperature; c) cross correlation of PRBS /water temperature. For I, a) N = 2048, $\Delta\tau$ = 0.8 sec; b) N = 2048, $\Delta\tau$ = 8/3 sec; clock pulse 7.2 sec. For II, a) N = 4096, $\Delta\tau$ = 0.8 sec; b) N = 1024, $\Delta\tau$ = 8 sec; c) N = 4096; $\Delta\tau$ = 0.8 sec; clock pulse 17.6 sec. For III, a) N = 4096; $\Delta\tau$ = 0.8 sec; b) N = 1024; $\Delta\tau$ = 8 sec; c) N = 8196; $\Delta\tau$ = 0.8 sec; clock pulse 16.8 sec.

feed of combustible gas. The length of the synchronizing pulse was selected to correspond to the time constant [7]. With the aid of the dynamic model we obtained similar responses for the temperatures of the bed and of the water. It was therefore thought that one and the same pulse length would be suitable for estimating the time constants of both the bed and the water. However, the experimental results showed that the response of the water was characterized by a much shorter time constant than was the response of the bed. Therefore, the width of the autocorrelation for investigation of the response of the bed would be too great for the response of the water. This would inevitably lead to a broadening of the recorded response, which would distort the true response of the water temperature. The use of a shorter pulse, of lower energy, would lead to a further deterioration in the signal to noise ratio.

The thermal response of the bed was registered by a thermocouple, located at a height of about 50 mm above the grid, or in some experiments at the level of the water-cooled tube. Another thermocouple, located in the outlet water stream, registered the response of the water temperature. The signals from the thermocouples were amplified and fed into two channels of a magnetophone, while the PRBS signal was simultaneously fed into the third (Fig. 2). It was necessary to screen all the leads carefully, so as to avoid pick-up.

The ratio between the values of the heat supplied by combustion of coal and gas were selected such that the temperature fluctuations had an amplitude of 10°C. All the other components of the heat supply were maintained as constant as possible during a run of experiments (in order to avoid drift and impairment of analysis). In each experiment we recorded 360 m of tape; an experiment lasted for about 3 hours. Figure 5 shows a typical diagram, consisting of synchronous records in the three channels.

Analysis of Data. The data were analyzed by feeding the signals recorded on tape into a Hewlett Packard 3721A correlator, at a speed more than eight times the recording speed. The tape was "played back" to find the optimum data: we determined the root mean square deviation, the frequency of sampling, and the number of points taken in realization, and then the best correlogram was selected.

Figure 6, I, a shows autocorrelation for the PRBS signal, with a 7.2 sec pulse. Such a sequence was of insufficient length to obtain the "tail" of the response of the bed, but it showed that the time constant of the bed was about 300 sec (Fig. 6, I, b). Another, longer sequence (17.6 sec synchronizing pulse, Fig. 6, II, a) gave a better result (Fig. 6, II, b). A very similar response of the bed (Fig. 6, III, b) was obtained in another experiment with a 16.8 sec synchronizing pulse (Fig. 6, III, a). This confirmed that the time constant of the bed was about 400 sec, i.e. it was equal to the value calculated from the model (Fig. 4). However it is obvious, from Fig. 6, II, c and Fig. 6, III, c, that the response of the water temperature was clearly not of the first order and had a prevailing time constant of less than 30 sec, i.e. it differed from the value predicted by the model (Fig. 4b). The full results have been given [6].

Interpretation of Responses. There was very good agreement between the calculated time constant of the bed and the experimental values obtained in dynamic experiments (compare Fig. 4a, with Fig. 6, II, b and 6, III, b. On the other hand, the calculated response of the temperature of the exit water was greater than that measured by the correlation method, by more than an order of magnitude. Thus the effective time constant was found to be close to 10 sec, instead of the 30 sec deduced from Fig. 6, II, c and 6, III, c, when experiments were carried out with short clock pulses [6]. With such short clock pulses as 1.25 sec, from which we could obtain only poor response curves (owing to the above mentioned noise problem), the nature of the response was such that it was doubtful whether it was possible to characterize it by a simple time constant, as a system of the first order. Under some circumstances the response was obviously fluctuating. This provided a basis for supposing that pulsations in the gas feed gave a clearly defined picture of the circulation. The use of baffles, on both sides of the water-cooled tube, to restrain the possible circulation of particles, impaired the mixing of the bed and led to a more sharply defined wave-like response, the timing of which altered only slightly.

We can evidently suppose that the small time-constant of the response of the water temperature could be explained by one or two basic reasons:

1) Gas pulsations produced a change in the coefficient of heat exchange with the tube, either because of some increase in the velocity of gas permeation, or owing to a change in the nature of the combustion ("explosive" combustion of the gas was observed under the experimental conditions).

2) The mixing of the bed was not so ideal as assumed in the model. In this case combustion of the gas could have given rise to local superheating of the material above or below the bed and, by the passage of superheated particles close to the tube, affected the temperature head in the heat exchange between the bed and the tube.

The object of the experiments with baffles, which were closely fitted in the tubes, was to check the second alternative. The response altered little, in spite of the evident change in the local mixing of particles. From the increase in the heat transfer coefficient, when additional feed pulses of gas were used, it is clear that the bed was in that region of pseudofluidization where the heat transfer coefficient increased with the rate of gas permeation. However, the increase in the linear velocity amounted to only about 1% of the basic value, which could be neglected. A more important factor might have been the known explosive character of the combustion of gas under the experimental conditions. The pressure pulsations, generated by the explosive combustion, may have affected the circulation of the particles, and in particular the concentration of particles at the heat exchange surface, thus increasing the heat transfer coefficient [8]. It therefore appears that the test signal not only altered the intensity of heat evolution in the bed, but directly affected the response of the water temperature by improving contact between the water and the bed. In a subsequent theoretical "experiment" we disturbed the heat transfer coefficient U_D, but kept the fuel feed constant. The response of the model directly followed the disturbance, and the rapid character of the response, found experimentally, most probably reflected this and was associated with hysteresis. This hysteresis must have been produced by conditions which allowed the gas to penetrate to the bed and burn, and was also related to the flow rate of the water in the tube. In all the cumulative effect was expressed by a hysteresis time of about 5 sec.

The data from some experiments, in particular when there were baffles in the bed, evidently reflected the response obtainable with some particular type of circulation, which became established in the bed. The fact that these wave-like responses developed rather for water than for the bed can probably be explained on the assumption that the tube effectively added up what was going on over a large region at the given level of the bed, while at the same time the thermocouple, measuring the bed temperature, registered only the more localized effects (although the typical scatter of the values of the bed temperature amounted only to ±4°C). In this there was the additional possibility of superposition of the observed responses of the water stream temperature on the the "long period" response, similar in its extent to the response of the bed temperature. With the existing form of experimental apparatus we were unable to check this possibility, since, in order to obtain greater sensitivity, it would have been necessary to carry out a coarser quantization and then, owing to the high noise level in the signal, it would not have been possible to carry out a correlation analysis with a small number of samples. The diagrams obtained were less distinct.

We would like to thank J. J. Henderson, of the Faculty of Electronics and Electrical Engineering of Birmingham University, for his advice and assistance in this work.

NOTATION

a	is the mass fraction of ash in coal;
A	is the tube surface area in the bed, m^2;

A_R	is the radiating bed surface area, m^2;
A_W	is the effective wall area for conductive losses, m^2;
a_i, b_i, c_i	are the constants in molar enthalpy expression;
C_{PA}	is the specific heat of ash, kJ/kg°C;
C_{PM}	is the mean specific heat of exhuast gas, kJ/kg°C;
C_W	is the specific heat of water, kJ/kg°C;
f	is the fuel feedrate, kg/h;
g	is the air feedrate, kg/h;
h_i	is the molar enthalpies of exhaust gas constituents, kJ/kg mole;
H(t)	is the impulse response of the system;
i	is the suffix referring to exhaust gas constituents N_2, O_2, CO_2, or H_2O;
k	is the thermal conductivity of refractory walls, kJ/hm °C;
m_i	is the molar flow rates of exhaust gas constituents, kg moles/h;
N	is the number of samples;
q	is the number of sequence;
Q_B	is the thermal capacity of the bed, kJ/°C;
Q_W	is the thermal capacity of the tubes and water, kJ/°C;
t_A	is the ambient temperature (Λ notation signifies absolute temperature °K), °C;
t_B	is the bed temperature (Λ signifies absolute temperature °K), °C;
t_E	is the mean temperature of extractor hood (Λ signifies absolute temperature °K), °C;
t_S	is the mean temperature of combustor surface, °C;
t_{W_1}	is the water temperature entering the combustor, °C;
t_{W_2}	is the water temperature leaving the combustor, °C;
U_D	is the overall heat transfer coefficient to the tube, kJ/h^2m^2deg;
U_0	is the bed superficial air velocity (at bed temperature);
w	is the water mass flowrate, kg/h;
x	is the thickness of refractory walls, m;
ε	is the emissivity of bed surface and extractor hood;
λ	is the gross calorific value of coal, kJ/kg;
σ	is the Stefan—Boltzmann constant = $20.6 \cdot 10^{-8}$, $kJ/hm^2\,°K^4$;
τ_B	is the bed response time constant, sec;
τ_W	is the water response time constant, sec;
$\Delta\tau$	is the sampling interval, sec;
τ	is the time, sec.

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