Journal of Engineering Physics and Thermophysics, Vol. 68, No. 2, 1995

COMBUSTION KINETICS OF COAL DUST

A. V. Sal'nikov, B. S. Repič,
P. T. Radulovič, and L. L. Jovanovič

UDC 536.46:62-661

A method for determining parameters that are important for the combustion kinetics of coal dust is developed. Values of these parameters for six types of lignite are obtained from experimental results on combustion of coal dust in a laboratory furnace.

Experimental Setup. In experiments carried out in a 15 kW laboratory furnace (LF) (Fig. 1) samples of coal dust (CD) of six types of Yugoslavian lignites from three main coal fields, namely, Kolubara, Kostalac, and Kosovo, were burned.

The LF is a setup for investigating the combustion of the three groups of CD particles under conditions similar to those occurring in real boiler furnaces. The LF is vertical and the flow of the fuel and combustion products is upward. Its main characteristics are the flow rate (0-4 kg/h), the average velocity of flue gases (3 m/sec), the maximum temperature of the flue gases (1373 K), and the height of the furnace (4 m) [1].

In the LF one can vary the parameters of the fuel (type, milling finness, and consumption) and the inlet gas (composition, temperature, flow rate, and velocity) and the temperature of the walls of the furnace.

Processing of Experimental Data. An experimental series was conducted under almost identical conditions. In all the experiments "medium" coal of fine dispersion $R_{90} = 50\%$ (the residue on a 90 μm sieve) was used. The residual moisture was 8% for all coals except Kolubara lignites (12%). The other main parameters remained constant during all the experiments: $T_a = 438$ K (the inlet temperature of the coal-air mixture), $\lambda = 1.25$ (excess air), and $v_{ps} = 3$ m/sec (the average combustion temperature in the furnace).

In the experiments we determined the content of unburned residues in solid specimens from the *LF*. The ash contents determined at different levels of the furnace are used to calculate the degree of combustion:

$$\mathrm{STS} = (A_i^s - A_0^s)\, 10^4/(A_i^s\, (100 - A_0^s))\,, \tag{1}$$

where A_0^s (%) is the ash content in the coal (dry); A_i^s (%) is the ash content in a solid specimen (%).

These data are used to plot diagrams of the degree of combustion of the CD versus the level in the furnace at which a CD particle occurs. Temperatures determined at various heights in the furnace are used for graphic representation of the temperature distribution as a function of the level in the furnace for each type of coal separately (for example, Tamnava lignite, Fig. 2).

In terms of the relations of the level and residence time of a particle in the furnace (Fig. 2), the curves of the degree of combustion of CD versus the level of occurrence of a particle in the furnace (Fig. 3, Tamnava lignite) are reduced to curves of the degree of combustion versus the combustion time (Fig. 4).

The combustion constants of the coke reside are calculated from similarity with the conditions in boiler furnaces. The following quantities were used in the calculation: the distance from the furnace inlet L (m), the residence time τ (sec), the temperature at the various levels in the furnace T (K), the degree of combustion STS, the time derivative of the degree of combustion $d\mathrm{STS}/d\tau$ (1/sec); the reaction rate k_g^m determined by the law of reacting masses [2]:

$$k_g^m = (d\mathrm{STS}/d\tau)/(1 - \mathrm{STS})\,, \tag{2}$$

Institute of Nuclear Research Vinča, Laboratory of Heat Engineering and Power, Belgrade, Yugoslavia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 68, No. 2, pp. 258-262, March-April, 1995. Original article submitted September 21, 1992.

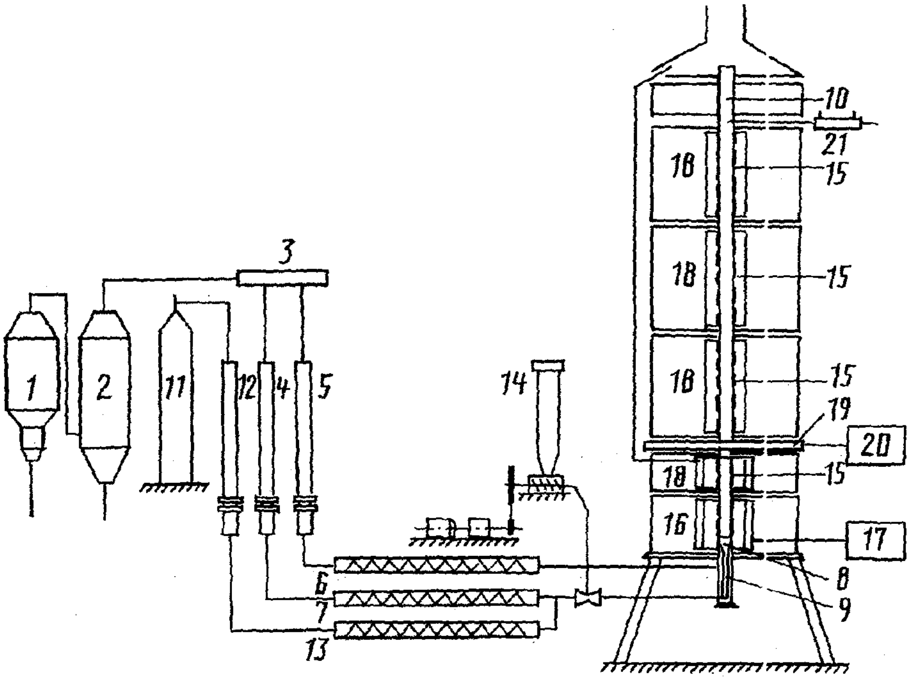
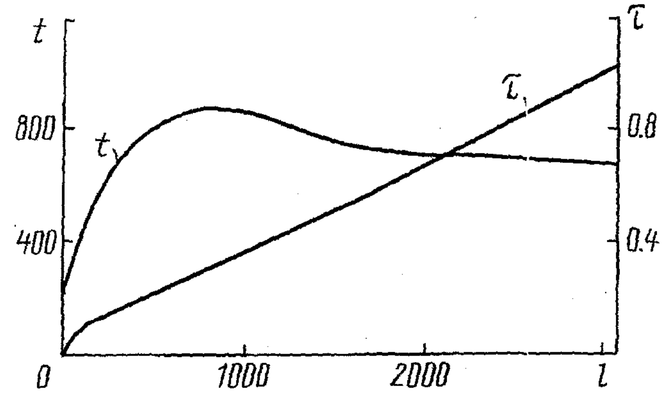


Fig. 1. Experimental laboratory furnace: 1, 2) air driers; 3, 4, 5) separator of the flow air; 6, 7) heaters of the air; 8, 9) burner; 10) exhaust stack; 11, 12, 13) inlet and heater of nitrogen; 14) batcher with hopper; 15) electric heaters; 16, 17) air refrigerator; 18) heat insulation; 19) sampling probe; 20) filter, condenser, rotameter, and vacuum pump; 21) thermocouple with shield.



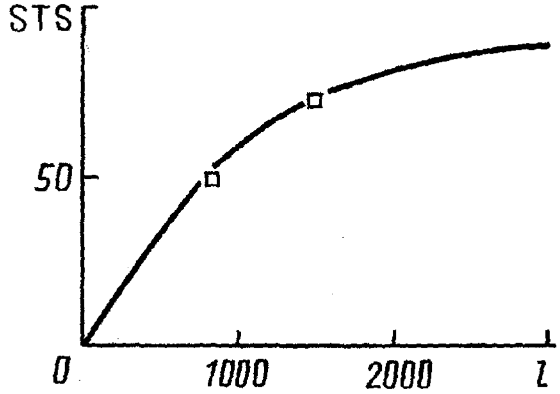


Fig. 2. Temperature distribution over the height of the furnace. t, °C; τ, sec; l, mm.

Fig. 3. Distribution of the degree of combustion of CD over the height of the furnace. STS, %.

and the total combustion area S_{gi} (m^2).

The ratio of the surface area of one particle to the total surface area of polydisperse dust is

$$S_g = S_k \left\{ n \int\limits_0^a \left| \frac{\varphi(x)}{\varphi_k} \right| \left| \frac{\rho_k}{\rho(x)} \right| \left| \exp\left(-\frac{x}{x_k}\right)^n \left(\frac{x}{x_k}\right)^{n-2} \right| d\left(\frac{x}{x_k}\right) \right\}, \tag{3}$$

where

$$S_k = \varphi_k \frac{6}{x_k \rho_k}. \tag{4}$$

From the assumption that $\phi(x)/\phi_k = \text{const} \simeq 1$ and $\rho_k/\rho(x) = \text{const} \simeq 1$, it follows that

$$S_g = S_k n \psi(n), \tag{5}$$

where

$$\psi(n) \int_0^{\alpha} \exp\left(-\frac{x}{x_k}\right)^n \left(\frac{x}{x_k}\right)^{n-2} d\left(\frac{x}{x_k}\right). \tag{6}$$

The total combustion surface area of polydisperse dust is determined from the expression

$$S_g = \varphi_k \psi(n)\, 6n/(x_k \rho_k), \quad x_k = d_k, \tag{7}$$

taken from [3], where the value of ϕ_k is taken from [2]. The characteristic density ρ_k is defined by

$$\rho_k = \rho G_0/(\varepsilon - 1), \quad G_0 = 1 - W_{0\text{sr}} - A_{0\text{sr}}. \tag{8}$$

The bulk densities ρ of the test coal dusts are evaluated by averaging experimental data. Porosities of CD ε are given in [4], and $\psi(n)$, in [3]. The average moisture contents $W_{0\,sr}$ and the average ash contents $A_{0\text{sr}}$ are obtained by averaging measurements.

Let the particle size remain constant during the whole combustion process and the total reaction area depend on the degree of combustion in the following way:

$$S_i = S/(1 - \text{STS}_i). \tag{9}$$

The specific reaction rate (the reaction rate based on the specific surface area of the particles) is defined by the equation

$$k_g^s = k_g^m/S_g, \tag{10}$$

and the reaction rate of oxygen is defined by the expression

$$k_s^{O_2} = k_g^s/\beta \quad (\text{kg}/(\text{m}^2\cdot\text{sec})), \tag{11}$$

where $\beta = 0.75$ for combustion of C and CO on the surface of a particle.

The concentration of O_2 in the flue gases is calculated by

$$C_{O_2} = (\lambda - \text{STS})\, C_{O_2}^0\, v^0 T_0/(v_g T) \quad (\text{kg}/\text{m}^3). \tag{12}$$

The concentration of O_2 in the air $C_{O_2}^0$ is 0.3 kg of O_2/m^3 of air (0.98 bar, 273 K). It is assumed that the values of $C_{O_2}^0 v^0/v_g$ and excess air $\lambda = 1.25$ remain constant over the whole length (height) of the furnace and that $T_0 =$ 273 K.

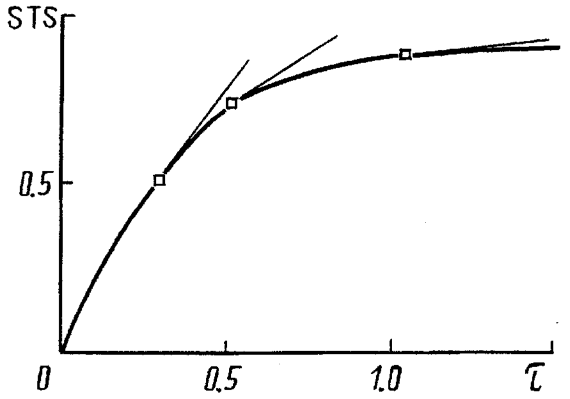
The fictitious rate constant of combustion including diffusion and kinetic resistances is defined by the expression

$$k_p = k_s^{O_2}/C_{O_2} \quad (\text{m}/\text{sec}), \tag{13}$$

and the diffusion mass transfer coefficient is defined by the expression

$$\alpha_d = \text{Nu}_d^{O_2} D_T/d_{\text{sr}} \quad (\text{m}/\text{sec}). \tag{14}$$

For a low relative velocity of a particle and the gas, Nu is written as



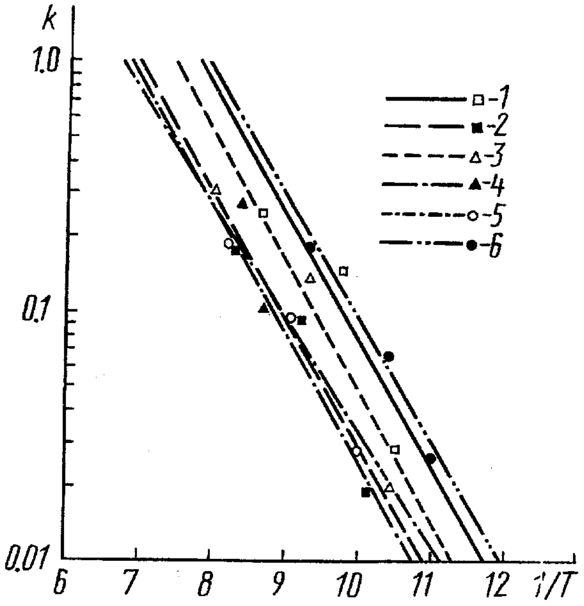


Fig. 4. Plot of the degree of combustion of CD versus the residence time in the furnace.

Fig. 5. Plot of the reaction rate constant versus the temperature: CD of lignite from the fields Tamnava (1), Field D (2), Čirikovac (3), Drmno (4), Belačevac (5), Dobro Selo (6). k, m/sec; $1/T$, 1/10 K.

$$\mathrm{Nu}_d^{O_2} = 2 + 0.16\,\mathrm{Re}^{2/3} \tag{15}$$

and the turbulent diffusion coefficient is

$$D_T = D_0\,(T/T_0)^m \quad (\mathrm{m}^2/\mathrm{sec}), \tag{16}$$

where $D_0 = 18\cdot 10^{-6}$ m^2/sec and $m = 1.75$ [2]. As is shown in [3], the average particle diameter of CD is determined by

$$d_{\mathrm{sr}} = d_k\varphi\,(n) = d_k\Gamma\,(1/n + 1),$$

where

$$d_k = 147.7\cdot 10^{-6} \ \mathrm{m} \quad (\text{for } R_{90} = 50\ \%), \quad d_k = 362.4\cdot 10^{-6} \ \mathrm{m} \quad (\text{for } R_{90} = 70\ \%). \tag{17}$$

We calculate the kinetic mass transfer coefficient

$$\alpha_k = 1/(1/k_p - 1/\alpha_d) \quad (\mathrm{m/sec}), \tag{18}$$

the ratio of the external area to the total surface area of a particle

$$S_{sp}/S_{uk} = S_{g0}/(S_{g0} + 85.5\,\rho_k). \tag{19}$$

and the rate constant of combustion

$$k = \alpha_k S_{sp}/S_{uk} \quad (\mathrm{m/sec}). \tag{20}$$

Results and Discussion. The calculated rate constants of combustion at the various levels in the furnace are expressed in a semilogarithmic coordinate system (Fig. 5), where the abscissa is $1/T$ and the ordinate is ln k. Let the Arrhenius law be expressed by

TABLE 1. Values of k_0 and E of Pulverized Yugoslavian Lignites

Coal field	k_0 (m/sec)	E (kJ/kmole)
Tamnava (Kolubara)	9000	97100
Field "D" (Kolubara)	8900	95400
Čirikovac (Kostolac)	7000	98200
Drmno (Kostolac)	5500	99500
Belačevac (Kosovo)	4500	97100
Dobro Selo (Kosovo)	9500	95200

$$k = k_0 \exp(-E/RT)\,, \tag{21}$$

i.e.,

$$\ln k = \ln k_0 - (E/RT)\,. \tag{22}$$

The intersection points of the straight lines with the ordinate give numerical values of the pre-exponential term k_0. The activation energies E for any type of coal are obtained by multiplying the slope of the corresponding straight line by the universal gas constant R. In Table 1 the evaluated quantities are given as an exameple. They agree well with the corresponding results of other authors. For example, for brown coal from the CIS $k_0 = 7.72 \cdot 10^3$ m/sec and $E = 9.82 \cdot 10^4$ kJ/kmole [5].

Conclusion. The assumptions made here have affected the accuracy of the results. Substantial differences in k_0 (by about 50%) and possible deviations of E result from temperature variations. The values of the activation energy are close (the scatter is less than 5%) and agree well with the corresponding data of other authors. The results appear satisfactory both qualitatively and quantitatively. They are the first data of this kind on Yugoslavian lignites. The combustion rate constant is used to calculate the combustion time, to design boiler furnaces [5], and for mathematical modeling of combustion of coal dust.

REFERENCES

1. B. S. Repič, M. M. Stanušič, and A. V. Sal'nikov, IBK-ITE-783, Institute of Nuclear Sciences Vinča, Belgrade (1989).
2. D. I. Khzmalyan and Ya. A. Kagan, Theory of Combustion and Furnace Devices [in Russian], Moscow (1976).
3. M. A. Field, D. W. Gill, B. B. Morgan, and Hawksley, Combustion of Pulverized Coal, B. C. U. R. A., Leatherhead (1967).
4. P. T. Radulovič et al., IBK-ITE-361, Institute of Nuclear Research Vinča, Belgrade (1982).
5. Handbook of Heat Engineering [in Russian], Moscow (1976).