CERTAIN COMBUSTION CHARACTERISTICS OF FINE COAL-DUST FRACTIONS

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A study was made concerning the effect of various factors on the ignition and the combustion time of fine dust particles in anthracite and brown Nazarovsk coal.

Many reports have been published now, in this country and abroad, on the ignition and combustion of the coarse fractions in pulverized fuels.

In the course of studies conducted in recent years at the All-Union Heat-Engineering Institute, it has been possible to establish both qualitative and quantitative relations which determine the ignition and combustion time of dust particles in various grades of coal. A study has been made of the effect of degree of metamorphism of coal on the development of individual stages in the combustion of the coal dust. Data have been obtained for the calculation of coefficients of heat and mass transfer between coal-dust particles and the gas stream during combustion. The effect of various factors on the temperature of the dust particles during combustion has also been analyzed; this is very important for the correct estimation of the rates of various reactions in the mineral fraction of a fuel and for the analysis of the mechanism of sedimentation onto the heating surfaces. The studies were conducted mainly on coarse coal-dust fractions (150-1000 μ), which are of interest primarily from the point of view of cinder formation in boiler furnaces.

Because of certain procedural difficulties, much less effect has been devoted to the study of the ignition and the combustion of fine coal-dust fractions ($d < 100\ \mu$).

Meanwhile, it follows from the diffusion–kinetic theory of carbon combustion [1] that during the combustion of fine coal particles there may occur considerable qualitative changes in the process. We will present here the results of an experimental study concerning the ignition and combustion of 25-150 μ dust particles in anthracite and Nazarovsk brown coal.

The tests were performed in a gaseous medium containing 21-5% O_2, at a temperature of 1200-1800°K. The CO_2 concentration was varied, correspondingly from 0 to 16%. The test apparatus is shown schematically in Fig. 1.

High-speed photography was used in this study. Prior to testing, coal particles were pasted onto quartz filaments 15-25 μ in diameter and were measured in three directions. The reaction chamber 2, having been brought to the specified temperature, was moved to the particles by means of a spring mechanism. The travel time of the chamber here was less than 0.01 sec. The temperature and the composition of the gas remained almost the same throughout the ignition and combustion of the coal particles.

The heat carried off the coal particles by a quartz filament did not exceed, according to calculations, 5% of the total heat lost by the particles during combustion.

Experimental Results

The movie films shot during tests performed on Nazarovsk coal revealed no flame burning of volatiles above the surface of fine particles smaller than 150 μ, unlike the flame burning observed in [2] in the case of coarse particles of the same coal.

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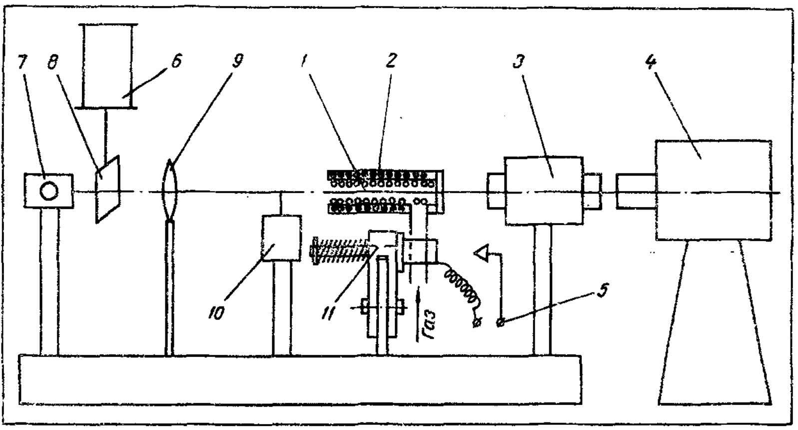

Fig. 1. Schematic diagram of the test apparatus: 1) coal particle; 2) reaction chamber; 3) microscope; 4) movie camera; 5) timer contact; 6) electromagnet; 7) lamp; 8) shutter; 9) lens; 10) micrometer table; 11) camera-positioning mechanism.

In trying to explain this peculiarity, one may naturally look in various directions for an answer.

For instance, one could surmise that the ignition time becomes too short for fine particles, that the volatiles have not enough time to separate during such a short period and thus burn together with the coke residue.

This hypothesis contradicts experimental data, however. Thus, for instance, it has been shown in the Badtsiokh tests [3] that at a gas stream temperature of $T_G = 1200°K$ the main mass of volatiles has enough time to separate from the fine coal dust within less than 0.05 sec. The ignition time of 100 μ Nazarovsk coal particles is approximately twice as long. This leads one to conclude that the rate at which coal-dust material is consumed at a gas temperature $T_G > 1200°K$ may be sufficiently high and should not cause the delayed separation and ignition of volatiles, at least not in the case of 100-150 μ particles.

It remains to surmise that, for some reason, particles smaller than $d = 150\ \mu$ cannot produce a flame front of volatiles separating from them and that their combustion spreads over the entire volume of the boundary layer. At this time, of course, the temperature in the reaction zone drops and the radiation intensity is reduced here to levels which cannot be picked up on the movie film.

The probable validity of this hypothesis seems to be confirmed by the following analysis.

According to studies conducted at the Institute [4], the flame burning time of volatiles during the ignition of larger than 150-200 μ dust particles of various coal grades does not depend on the temperature of the gaseous medium (at $T_G > 1200°K$), depends slightly on the oxygen content in the gas (within 21-10% O_2); and can be calculated by the formula:

$$\tau_{cv} = K_{cv} \cdot 0.49 \cdot 10^6 d^2 \text{ [sec]}, \tag{1}$$

where K_{cv} is an empirical factor having a specific value for each grade of coal.

Taking into account (1), we can determine the mean rate at which the main mass of volatiles leaves the surface of particles:

$$(\rho w_v)_s = \frac{\rho_d V^d}{2.93 \cdot 10^8 K_{cv}} \cdot \frac{1}{d} \left[\frac{\text{kg}}{\text{m}^2 \cdot \text{sec}}\right], \tag{2}$$

where ρ_d is the apparent density of dry coal, kg/m^3. The gaseous products of the thermal reaction approach the flame burning front of the volatiles at the following mean mass rate:

$$(\rho w_v)_f = (\rho w_v)_s \left(\frac{d}{d_f}\right)^2. \tag{3}$$

The rate of oxygen supply to the flame front of the volatiles, by diffusion, is

$$(\rho w_{O_2})_f = \frac{2 \cdot O_2 \cdot \rho_{O_2}}{100\, d_f} D_0 \left(\frac{T_G}{273}\right)^{n-1} \left[\frac{\text{kg}}{\text{m}^2 \cdot \text{sec}}\right]. \tag{4}$$

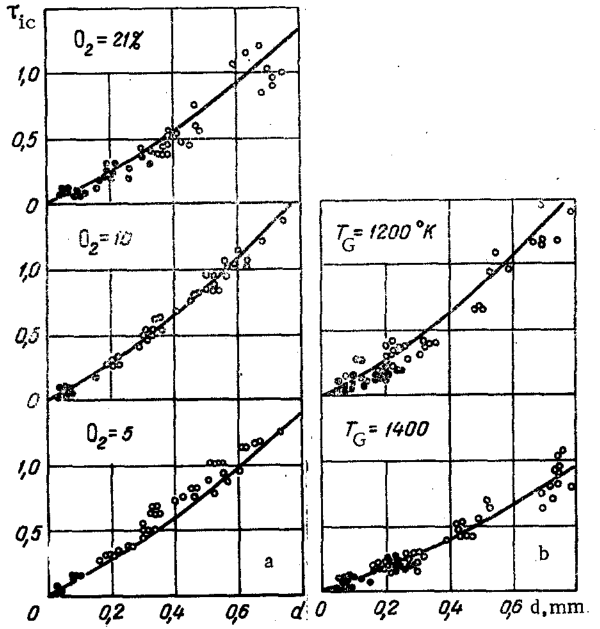

Fig. 2. Ignition time of coke residue in coal particles τ (sec) as a function of the particle size d (mm): a) anthracite, $T_G = 1600°C$; b) Nazarovsk coal, $O_2 = 21\%$. The curves have been plotted according to Eq. (6).

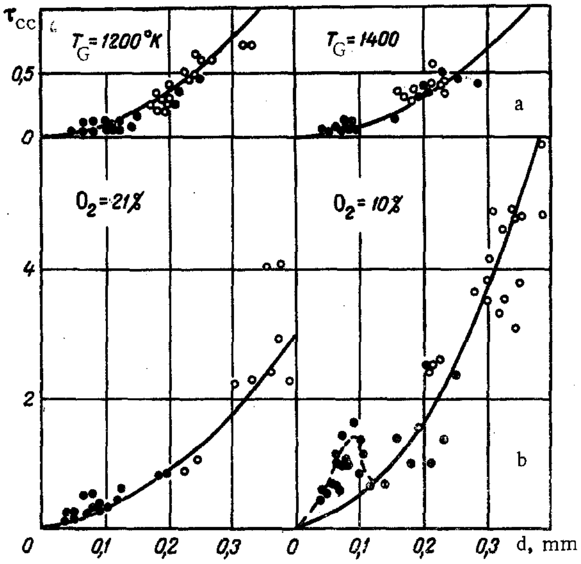

Fig. 3. Combustion time of coke residue in coal particles τ (sec), as a function of the particle size d (mm): a) Nazarovsk coal, $O_2 = 21\%$; b) anthracite, $T_G = 1600°K$. The curves have been plotted according to Eq. (7).

From (2), (3), (4), and stoichiometric considerations, we have

$$\frac{d_f}{d} = \frac{\rho_d V^d \cdot 100}{5.86 \cdot 10^8 K_{cv} \beta \cdot O_2 \cdot \rho_{O_2} D_0 \left(\frac{T_G}{273} \right)^{n-1}}. \qquad (5)$$

It follows from (5), in particular, that the relative size of the flame zone of the volatiles should not depend on the size of the particles.

The validity of this statement is supported by the results of experiments.

Considering relation (5), one can obtain from (2) and (3) the formula:

$$(\rho w_v)_f = K \cdot \frac{1}{d},$$

where K is a factor not dependent on the size of particles.

This last equation indicates that, as the size of coal particles decreases, the mass rate at which hot reagents are supplied per unit front surface of the flame of the volatiles will increase in inverse proportion to the particles size. By virtue of similarity between the diffusion and the heat-conduction processes, an equilibrium between the supply rate of reagents and the propagation rate of the flame is maintained until effects which are essentially physical in nature will limit the latter.

As the size of particles decreases, however, there must arrive a time when the rate of flame propagation becomes limited not by diffusion and heat conduction but by the rate of the chemical reactions; the combustion of volatiles then becomes kinetic and, as a result, they do not burn within the narrow flame front but spread over the volume of the boundary layer with an accompanying temperature drop in the combustion zone.

At given external conditions there should be a minimum radius of the flame of the volatiles at which flame burning is still possible. Such an assumption leads to several conclusions of practical interest.

In particular, by experimentally determining the minimum size of coal particles around which a flame of volatiles is still possible, we can estimate the rate of the chemical reaction in which the volatiles burn under any one set of conditions and we can determine the kinetic parameters of this process. Equation (5) may also be used for calculating the stoichiometric factor β in the combustion of volatiles and, consequently, for roughly estimating the composition of reagents in the combustion zone – which are usually unknown.

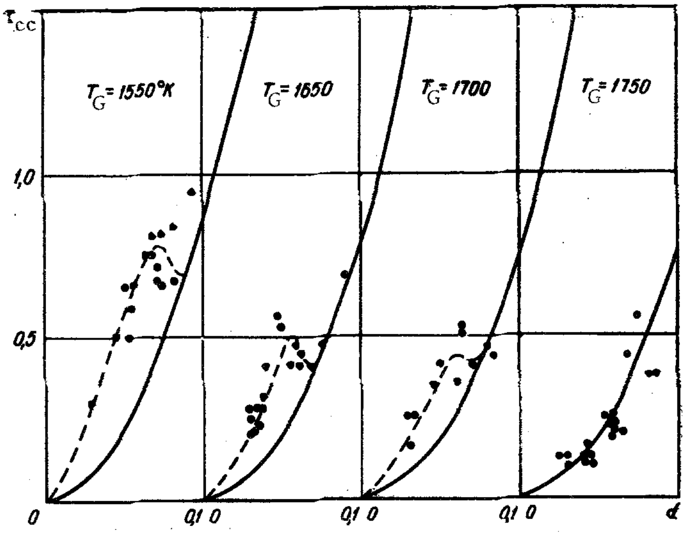

Fig. 4. Combustion time of fine anthracite particles τ (sec) as a function of their size d (mm). (O_2 = 5%).

Thus, during the ignition of Nazarovsk brown coal particles in air at a temperature $T_G = 1400°K$ the ratio of flame diameter to particle diameter is typically $d_f/d = 3.5$. According to [7], the diffusivity of oxygen during combustion in air may be taken as $D = 0.16 \cdot 10^{-4} (T_G/273)^{1.9}$ m²/sec. With these values inserted into Eq. (5), the value of the stoichiometric factor for the volatiles in Nazarovsk coal was found to be $\beta = 1.2$. This value corresponds most closely to the combustion of carbon monoxide, for which $\beta = 1.5$.

For hydrogen, as is well known, $\beta = 0.125$ and the stoichiometric factor for methane combustion is $\beta = 0.25$.

It follows from the test data that, as the oxygen concentration in a gaseous medium decreases and the flame temperature drops, the value of β increases and the flame of the volatiles becomes opaque with an accompanying precipitation of ash.

The test data pertaining to the ignition time are shown in Fig. 2 for the coke residue in Nazarovsk coal and anthracite dust particles at various temperatures of the gaseous medium with various oxygen concentrations. The black dots on the graphs represent test points which have been obtained for fine dust fractions, while the white points correspond to the test values obtained earlier for coarse dust fractions in a different experiment [2, 4].

The ignition time of coke residue in this case is defined as the length of time from the instant a cold particle enters the atmosphere of hot gases to the instant at which the temperature of its surface has stabilized, after which combustion begins. This ignition time is determined in various tests either by some color index or by the image density of a particle on the movie film.

The ignition time of coke residue includes the heating-up period of a particle till its volatiles begin to ignite, the combustion time of these volatiles, and the subsequent heating-up period of coke residue from the instant that the volatiles have burned out to the instant that the coke residue begins to burn quasisteadily.

Accordingly, we can write:

$$\tau_{ic} = \tau_{fv} + \tau_{cv} + \tau_{hc}.$$

When there is no flame burning of volatiles, the ignition of coke residue is treated as a single-stage process.

The curves in Fig. 2 have been plotted according to the equation which represents earlier test results with coarse coal-dust fractions [4]:

$$\tau_{ic} = K_{ic} \cdot 1.12 \cdot 10^{10} \frac{\rho_d d^{1.2}}{T_G^3} \left(\frac{21}{O_2} \right)^n \text{[sec]}. \tag{6}$$

At a gas temperature $T_G \geq 1400°K$ and an oxygen concentration within 5-21% O_2 the value of exponent n was found to be 0.15 for anthracite dust and 0.25-0.50 for coal dust rich in volatiles.

As can be seen in Fig. 2, there is a close agreement between test data which have been obtained in different experiments. The ignition time of coke residue in fine and coarse coal-dust fractions is adequately well described by a single expression. The absence of flame burning of volatiles above the fine particles in Nazarovsk coal had no effect on the length of the coke ignition time τ_{ic}.

It is to be noted that, as we proceeded to test the fine dust fractions, we did not note any increase in ignition time of coke residue in coal particles such as was observed by Katsnel'son and Marone [5, 6].

It may be supposed that the sharply increasing ignition time of $d < 150\text{-}200\ \mu$ coal particles in [5] and, under high pressures, also of larger particles, having $d = 300\text{-}400\ \mu$, in [6] was a consequence of the experimental conditions. For instance, in the experiments of [5] and [6] there was the possibility of a relatively cold gas stream forming in the center portion of the reaction chamber, which should have affected especially the fine particles.

Data pertaining to the combustion time of coal particles are shown in Figs. 3 and 4. The combustion time of coke residue τ_{cc} was counted on the movie film from the instant that the coke residue in a particle had completely ignited to the instant that its combustion was completed.

The white dots indicate test points which have been obtained earlier in a different experiment [2, 4].

The solid lines on the graph have been plotted according to the equation:

$$\tau_{cc} = K_{cc} \cdot 2.21 \cdot 10^8 \, \frac{100 - A_c^d}{100} \cdot \frac{\rho_c d^2}{T_G^{0.9} O_2} \text{ [sec]}. \tag{7}$$

This equation was derived from tests on coarse dust fractions in various grades of coal [4].

It is evident from the data shown here that the combustion of fine dust fractions in brown Nazarovsk coal follows the pattern which is characteristic of diffusive combustion at a relatively low temperature $T_G = 1200°K$. Another pattern is observed in the combustion of fine dust fractions in ASh anthracite. At a temperature $T_G = 1500°K$ and a 21% oxygen content in the gaseous medium the combustion of anthracite particles smaller than $100\ \mu$ was overtly kinetic in character. The temperature of particles differed little from the gas temperature. The ash did not melt and the combustion time of particles having $d = 50\text{-}60\ \mu$ was found even somewhat longer than the time of diffusive combustion of particles having $d = 200\ \mu$ in an identical gaseous medium.

It is noteworthy that the combustion of coarse ($d = 200\text{-}400\ \mu$) grade ASh anthracite particles becomes diffusive already at temperatures below $T_G = 1400°K$ as the size of particles decreases to $15\text{-}25\ \mu$. This paradox is only apparent, however, and can quite adequately be explained according to the thermal theory of combustion.

Bukhman has shown in [8] that, when made to burn diffusively, a coal particle will burn in this manner down to a very small size. At the same time, even larger particles will burn kinetically under identical external conditions, if the diffusion state has not been reached at the beginning of the combustion process. It can be seen in Fig. 4 that at low oxygen concentrations (5% O_2) the fine fractions of anthracite dust burn diffusively, if the initial temperature exceeds 1700-1750°K.

From this observation there follow several conclusions of practical importance.

The main mass of anthracite dust, after passing through a flame nucleus which in ASh anthracite burning boiler furnaces has a temperature of 1800-2000°K, must continue to burn diffusively.

On the other hand, coal-dust particles, which for any reason have not undergone this high-temperature treatment in a gaseous medium containing oxygen or which have passed through a flame nucleus in a gaseous zone not containing oxygen and then have been drawn into the flame tip where the temperature may be below 1700°K and the oxygen concentration may be less than 10% will burn kinetically at a slower rate and may be carried beyond the furnace chamber.

Such a situation may arise during a faulty diversion of air coming from the mill and containing fine dust fractions, during a disturbance of either furnace or boiler operation.

Here, evidently, one should look for the cause of the increased mechanical deficiencies in the combustion of dust in an anthracite furnace.

NOTATION

d	is the diameter of a particle, m;
T_G	is the temperature of gas stream;
τ_{cv}	is the time of flame burning of volatiles;
$(\rho w_V)_S$	is the mean mass rate of main volatiles fraction leaving a particle surface;
ρ	is the density;
V^d	is the volatiles content in dry mass, %;
$(\rho w_V)_f$	is the mean mass rate of gaseous products yielded by the thermal reaction;
d_f	is the diameter of the zone of volatiles in a flame;
$(\rho w_{O_2})_f$	is the rate of oxygen supply to flame front of volatiles;
ρ_{O_2}	is the density of oxygen;
D_0	is the diffusivity of oxygen;
β	is the stoichiometric factor;
τ_{ic}	is the ignition time of coke residue;
τ_{fv}	is the heating-up period before ignition of volatiles;
τ_{cc}	is the combustion time of coke residue;
K_{ic}, K_{cv}, K_{cc}	are the coefficients;
n	is an exponent;
A_c^d	is the ash content in the dry mass, %;
ρ_c	is the density of the coke.

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