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Ignition of Different Grades of Coal by Laser Pulses in the Free-Running Mode

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Abstract

Laser ignition (λ = 1064 nm, τ_i = 120 μs) of the coal samples of different grades from the Kuznetsk coal basin was studied. Three consecutive stages of ignition were detected for all grades of coal. These stages are characterized by the threshold radiation energy densities $H_{cr}^{(1)}$, $H_{cr}^{(2)}$, $H_{cr}^{(3)}$ which are characteristic for each coal grade. It was established that the first stage involves surface heating and ignition of micro protrusions on coal particles. The duration of this stage does not exceed the time of the laser pulse. At the second stage, volatile substances are observed to evolve and ignite. The duration of combustion depends on the density of radiation energy. Ignition of the coke residue occurs at the third stage, upon reaching $H_{cr}^{(3)}$; burning time is 40–150 ms. It was demonstrated that the threshold value at the first stage varies only slightly for all coal grades. For bituminous coal, the second threshold decreases with an increase in coalification degree, while the third threshold increases. The second and the third thresholds for lignite are comparable with the values of $H_{cr}^{(2)}$ and $H_{cr}^{(3)}$ for low metamorphic bituminous coals. Experimental results allow us to conclude that ignition occurs at the first and the third stages according to the heterogeneous mechanism, while at the second stage it occurs according to a homogeneous mechanism.

Keywords: coal, laser ignition, combustion, coal dust

INTRODUCTION

The physical methods of coal dust ignition have not won a broad application yet. However, investigation of the laser ignition of coal will allow developing new economic and safe methods to ignite coal-based fuel.

Laser ignition of coal is studied using mainly neodymium and CO_2 lasers [1–8]. In [1], laser ignition (1064 nm, 150 μs, 740 mJ) of the suspensions composed of carbon particles, bituminous coal, and anthracite was studied. The kinetic characteristics of sample ignition were obtained, which allowed revealing two regions of glow. The first one, related to short-term glow, appears during the pulse, while the second, a broad one, lasts for 20–60 ms, with two maxima for bituminous coal and 20–30 ms with one maximum for carbon and anthracite.

The ignition of coal particles with the help of neodymium laser (1064 nm, 100 ms, 5 J) was studied in [2]. Three stages of the development of coal ignition process were distinguished. The first stage is connected with gas-dynamic processes arising during evaporation, flying-off and combustion of a coal particle, the second stage is characterized by the development of the exothermal decomposition reaction and the formation of the combustion centre; the third stage corresponds to self-maintaining combustion mode.

In [3], the ignition of 18 types of coal and petroleum coke with laser pulses (1064 nm, 150 μs, 1 J) was studied. Flame glow was recorded with the help of a photoelectric multiplier and a high-speed camera. The rate of flame propagation was recorded. A mechanism of flame propagation in the coal dust aerosol under laser radiation was proposed.

It was established in [4] that during the laser irradiation of coal particles the illuminated part is the first to ignite. Microasperities serve as the initiators of combustion. The ignition of a coal particle at a microasperity stimulates the development of thermochemical combustion reactions around this site. Combustion rapidly propagates over the whole irradiated part of the coal particle. Ignition process is thus recorded. The temperature of the coal particle is non-uniform during ignition; two maxima are observed. The first one is due to the release of volatile substances, while the second one is due to the combustion of coke and thermal glow of ash.

Theoretical studies of the mechanisms of solid fuel ignition with a powerful light field were described in [8–12].

A model of laser ignition (1064 nm, 5 ms) of coal was developed as described in [8]. It is assumed within the model that oxidation is initiated on the surface of coal particles as a result of laser action, and the volatile substances are released. The volatiles get mixed with the oxidizer. At the same time, the volatile substances absorb a part of the radiation, which results in heating the gas phase, and a chemical reaction starts to develop in the gas phase. Ignition of coal particles may occur either in the gas phase (homogeneous initiation) or the surface of the particle is initially ignited, and then the gas phase starts to burn (heterogeneous initiation). The theory of homogeneous and heterogeneous ignition of coal particles was developed in [9].

In [5], the occurrence of two mechanisms of laser ignition (homogeneous and heterogeneous) of coal samples was confirmed experimentally. The mechanism of ignition is considered in [13] to be dependent on coal grade.

It follows from the literature data mentioned herein that up to now there is no unambiguous notion of the mechanism of coal ignition and combustion. These processes seem to be dependent both on coal grade and on the parameters of laser radiation. Experiments that would allow to unambiguously allocate different stages of coal ignition and combustion under laser action are necessary.

In our previous works, we started investigation of the laser ignition of brown coal (B) and long-flame gas coal (DG) [14, 15]. A YAG:Nd^{3+} laser (1064 nm, 120 μs) was used for irradiation. It was discovered that the ignition and combustion of coal samples of both grades have three stages depending on the density of laser radiation energy. Each stage is characterized by a definite energy density.

The first stage is connected with the heating and glow of the sample surface under the action of laser radiation with energy density $H_{cr}^{(1)}$ = 0.4 J/cm^2 directly at the moment of a laser pulse. The second stage is characterized by the release and ignition of volatile substances, it is observed within the millisecond time range with an increase in energy density to $H_{cr}^{(2)} \geq 1$ J/cm^2. The flame is observed above the sample surface. At the third stage, the ignition of the coke residue and the escape of burning hot coal particles under the effect of the radiation with the energy density of $H_{cr}^{(3)} \sim 2–3$ J/cm^2 are observed. A vertical flame is seen above the sample [14, 15].

In the present work, we continued the studies of the laser ignition of coal from the Kuznetsk coal basin and studied the process characteristics depending on the stage of coal metamorphism.

EXPERIMENTAL

Coal samples from the Kuznetsk coal basin of different grades, B, DG, G, Zh, and K were used.

Coal samples were ground in a ball mill, and the fraction with particle size ≤63 μm was collected by sieving. The results of the technical analysis are shown in Table 1. The technical analysis of the G grade coal revealed high ash content (38.4 %), so demineralization by means of acid decomposition was carried out. The data for demineralized coal of G grade are shown in Table 1.

TABLE 1

Results of the technical analysis of coal samples

Coal grade	W^a, %	A^d, %	V^{daf}, %	C^{daf}, %
B	11.1	9.5	51.4	61
DG	4.0	4.6	40.2	79
G	6.2	1.6	40.9	81
Zh	1.2	4.8	34.1	88
K	1.0	4.9	21.2	90

Note. W^a – is humidity of the analytical sample, A^d is ash content of the analytical sample, V^{daf} is the yield of volatile substances; C^{daf} is carbon content in the analytical sample.

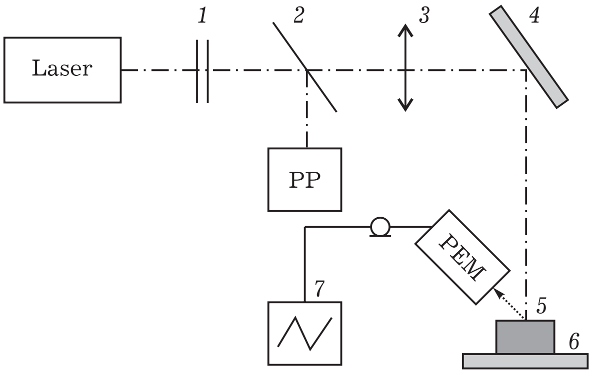

Fig. 1. Schematic of experimental set-up: *1* – neutral light filters, *2* – light-separating plate, *3* – focusing lens, *4* – sweep mirror, *5* – sample, *6* – massive base, *7* – oscillograph, laser is a pulsed YAG:Nd^{3+} laser, PD is pyroelectric detector, PEM is photoelectron multiplier.

TABLE 2

Threshold densities of radiation energy of coal ignition at different stages, J/cm^2

Coal grade	$H_{cr}^{(1)}$	$H_{cr}^{(2)}$	$H_{cr}^{(3)}$
B	0.47	1.75	2.6
DG	0.39	1.6	2.4
G	0.45	1.85	3.3
Zh	0.47	1.1	5.5
K	0.35	0.9	10.0

Experimental samples with the apparent density $\rho = 0.5$ g/cm^3 in the form of a weighted portion of 10 mg were placed in a copper cap 5 mm in diameter and 2 mm deep. A schematic of the experimental set-up is shown in Fig. 1.

Coal ignition was carried out with the help of sole pulses of radiation at the first harmonics ($\lambda = 1064$ nm) of the YAG:Nd^{3+} laser in the free-running mode. Pulse duration τ_i was 120 μs, the maximal energy in the pulse was 1 J. The radiation energy was regulated with the help of glass neutral optical filters with a known attenuation coefficient. For control, a part of the energy (8 %) was directed by a transparent glass plate onto an Ophir Photonics PE50BF-C pyroelectric detector (Israel). With the help of a focusing lens with a focal length $F = 25$ cm and a sweep mirror, the radiation was directed at the sample mounted on a massive base. The diameter of the laser spot on the sample was $d = 2.5$ mm. Sample glow was transformed with the help of a photoelectron multiplier Hamamatsu H-10707-21 (Japan) into the electric signal to be recorded with a LeCroy WY332A oscillograph (USA).

RESULTS AND DISCUSSION

Ignition thresholds of coal samples were studied. Ten samples of a specific coal grade were irradiated in series with a sole laser pulse with definite energy, and glow kinetics was recorded with the help of a photomultiplier. The probability of ignition was determined as $P = n/10$, where n is the number of flares recorded. Then radiation energy increased, and the experiment was repeated. Finally, a dependence of the probability of a flare on the density of laser radiation energy was obtained. The energy density H_{cr} corresponding to a 50 % probability of a flare to occur was taken as the ignition threshold.

With respect to the recorded kinetic curves for all coal grades under study, three thresholds H_{cr} could be distinguished, leading to different processes in the samples. The data on H_{cr} for all the studied samples are presented in Table 2.

To establish the effect of ash on the ignition threshold, the coal of G grade was studied similarly. As mentioned above, the ash content in it is 38.4 %. Laser ignition of the samples of initial coal of G grade gave threshold values close to those for demineralized samples. Correspondingly, the ash content in coal does not affect the threshold of laser ignition.

Oscillograms recorded with the photomultiplier and corresponding to flame glow on the coal of G grade for the probability $P = 0.5$ for three processes indicated above are shown in Fig. 2. Qualitatively similar frequency ratio curves and the corresponding glow kinetics were recorded also for other coal grades under investigation.

It was established that for all coal grades under study the duration of glow at the first stage is practically corresponding to the duration of the laser pulse (see Fig. 2, *a*). At the second state, the kinetics includes the first-stage glow and the glow within the millisecond time range (see Fig. 2, *b*). At the third stage, the glow kinetics includes the first two stages and the glow arising within approximately 10 ms after laser pulse action, with the duration of 40–150 ms for different coal grades (see Fig. 2, *c*).

For energy density corresponding to $H_{cr}^{(1)}$, a not very high flame is observed above the sample surface ($h \leq 1$ mm), while after the $H_{cr}^{(2)}$ value is achieved, the height is 3–5 mm. After the achieve-

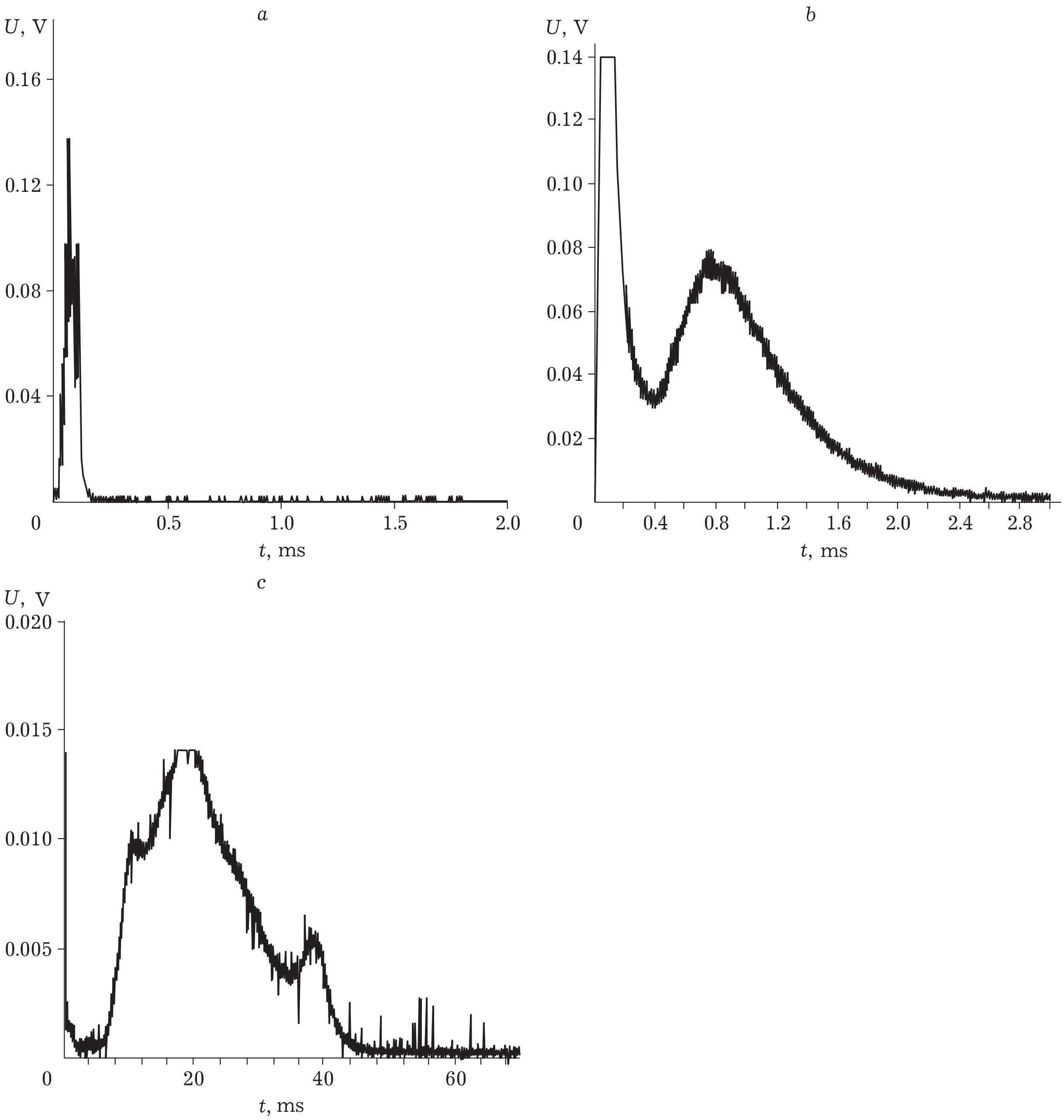

Fig. 2. Kinetics of flame glow for G grade coal, corresponding to three stages of ignition: $H_{cr}^{(1)}$ = 0.45 J/cm^2 (*a*), $H_{cr}^{(2)}$ = 1.85 J/cm^2 (*b*), $H_{cr}^{(3)}$ = 3.3 J/cm^2 (*c*).

ment of $H_{cr}^{(3)}$, a vertical flame up to 10 cm high is observed for all coal grades. Similar processes were observed by us earlier during the studies of the laser ignition of the B grade coal [15].

Dependences of the threshold radiation energy densities $H_{cr}^{(1)}$, $H_{cr}^{(2)}$, $H_{cr}^{(3)}$ for three stages of ignition on the degree of coalification, accompanied by an increase in the relative content of carbon in the sample (C^{daf}), are presented in Fig. 3. One can see in Fig. 3, *a* that almost constant values $H_{cr}^{(1)}$ = 0.35–0.47 J/cm^2 with great statistical straggling are observed with the change in coalification degree.

For coal (DG, G, Zh, K) with an increase in coalification degree, $H_{cr}^{(2)}$ values decrease (see Fig. 3, *b*), while $H_{cr}^{(3)}$ values increase (see Fig. 3, *c*). For brown coal, the values of threshold radiation energy densities for the second and the third stages are insignificantly different from the cor-

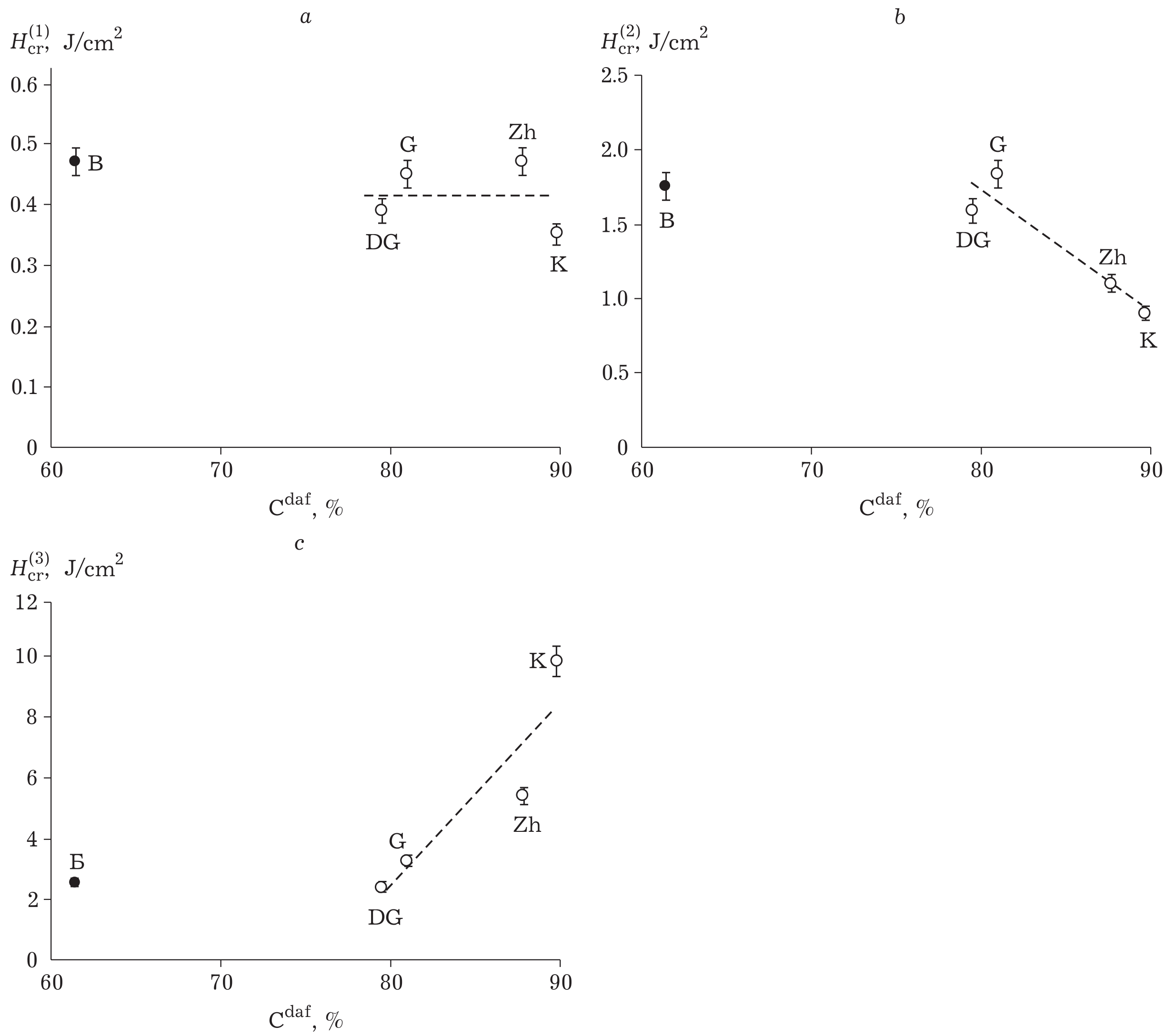

Fig. 3. Dependence of ignition thresholds $H_{cr}^{(1)}$ (*a*), $H_{cr}^{(2)}$ (*b*), $H_{cr}^{(3)}$ (*c*) on coalification degree for coal of different grades.

responding values for low-metamorphized coal of DG and G grades.

It is assumed that the particles of crushed coal may ignite either according to the heterogeneous mechanism (ignition of the surface, followed by the release and ignition of the gas-phase substances) or *via* the homogeneous mechanism (ignition of the released gas-phase substances followed by the ignition of the particle) [5, 8, 9, 13].

The former process corresponding to the energy density $H_{cr}^{(1)}$ was previously linked with particle surface heating by laser radiation [15]. Not very high (≤1 mm) flame observed above the surface is likely to be connected with the ignition of microasperities on coal particles as described in [4]. The temperature of heating at a given stage, measured by means of spectral pyrometry with time resolution, reaches 3200 K [15] and corresponds to surface temperature. The surface of a particle is cooled due to the convective and radiative processes. In addition, heat is conducted into the depth of the particle, which promotes its uniform heating. Model calculations described in [1] show that the process of temperature leveling depends on thermal physical parameters and the size of coal particles; in a general case, the time interval is 200–500 μs. The temperature of the particle drops. If the temperature of a particle after uniform heating is below the ignition point, then the glow of the particle attenuates after the radiation pulse (see Fig. 2, *a*).

With the achievement of the laser radiation energy density $H \sim H_{cr}^{(2)}$, a thermochemical reaction in the particle is initiated, which promotes the release and ignition of volatile substances. The spectral-kinetic measurements within the millisecond time range showed that at this stage under the action with energy density $H \geq 2$ J/cm^2 the glow of CO flame is observed, along with the excited H_2 and H_2O molecules, and thermal glow with the temperature of 2300 K [15].

These experiments do not give any information about the initial ignition temperature of the volatile substances. However, it may be assumed that the order of magnitude of this value is approximately equal to 2000 K, because additional heating as a result of the thermochemical reaction, measured in brown coal samples, gives the value ~2300 K [15].

So, at the stage under consideration ($H \sim H_{cr}^{(2)}$) the temperature of the particle surface is sufficient for the release, ignition and combustion of volatile substances in the gas phase. In this case, particle surface is a source of heat for the ignition of volatile substances or for the initiation of the reaction between the oxidizer and the volatiles in the gas phase. However, the surface itself does not burn. With this approach, the mechanism of combustion of the gas-phase substances may be considered homogeneous at this stage. After the volatiles get burnt out at $H \sim H_{cr}^{(2}$ within the millisecond time range, the flame dies away, and the particles do not ignite.

When the energy density of $H_{cr}^{(3)}$ is achieved, after ~10 ms, an increase in the intensity of glow is observed within the time range 40–150 ms (see Fig. 2, *c*). Combustion time is 40–150 ms for different coal grades. We suppose that this process is due to the initiation of chemical reactions in the coke residue after the release and combustion of volatile substances and, as a consequence, additional heating of coal particles. The flame temperature at this stage, measured previously by means of spectral pyrometry with time resolution for coal samples of B grade, was equal to 1800 K [15]. The mechanism of ignition may be considered heterogeneous at this stage of the investigation.

CONCLUSION

Under the laser action on the coal of B, DG, G, Zh, K grades with apparent density 0.5 g/cm^{3,} three ignition stages having the threshold nature were revealed. The first stage is connected with surface heating and the ignition of microasperities on coal particles. The second stage is characterized by the release and ignition of volatile substances. The third stage involves the ignition of the coke residue. Ignition thresholds for all coal grades at each stage were measured. The threshold at the first stage only weakly changes for all grades of coal within the sequence of metamorphism. For coal with an increase in coalification degree, the second threshold decreases while the third one increases. The second and the third thresholds for brown coal are only insignificantly different from those for low-metamorphism coal grades DG and G.

The duration of glow at the first stage coincides for all coal grades with the duration of the laser pulse (120 ms). the duration of coal glow at the second stage for $H = H_{cr}^{(2)}$ is 5–10 ms, while at the third stage it is 40–150 ms.

Experimental results allow concluding that ignition at the first and the third stages follows the heterogeneous mechanism, while at the second stage it follows the homogeneous mechanism.

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