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Study on coal ignition by CO_2-laser

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Abstract. The ignition temperature of solid fuel is an important characteristic that affects both the energy and environmental characteristics of the combustion process. In this paper, the results of a study on ignition and combustion of brown and bituminous coal samples using laser ignition setup and thermogravimetric analyzer. Characteristic temperatures were determined for samples in the heat flux density range 90-150 W/cm^2 and at heating rates in range 10-30 ° C / min respectively. It was found that the characteristic temperatures obtained by laser ignition are 1.5-2 times higher than the temperatures obtained by means of thermogravimetry.

Tags: *ignition, solid fuel, coal, thermogravimetry, TG–analysis, ignition temperature, CO_2-laser*

1. Introduction

Solid fuel is one of the main sources of energy in the world nowadays [1]. At the same time, coal-fired power plants are one of the main sources of greenhouse gases [2], sulfur oxides and nitrogen emissions [3], as well as solid particles emissions into the atmosphere [3]. Reducing the temperature in the reaction zone is an effective way to increase the efficiency of fuel burning technologies and to reduce emissions of nitrogen oxides [4]. However, decreasing of temperature significantly reduces the rate of chemical reactions. In this case, detailed information about the laws of the ignition process is needed to ensure sufficient combustion completeness.

At present, a lot of works in scientific literature are devoted to the study of the features of ignition processes for individual particles of coal [5] and coal dust in the flow [6]. In most works ignition of fuel is achieved by means of its conductive [7] or convective [8] heating. This leads to the need for using

empirically obtained heat transfer coefficients values to determine the heat flow supplied to the sample. This in turn leads to a significant uncertainty in heat flux values. Meanwhile, in modern pulverized-coal power boilers the main mechanism of heat transfer is radiation [9]. Articles which are devoted to the study of ignition processes with radiant fuel heating are presented in literature in much less numbers. Data on studies of the ignition of coal dust clouds with various dispersity are presented in [9-11] with radiant heating at varying radiation intensity. Similar studies for fixed single particle are presented in [12-15]. In all these works, lasers of pulsed action were used as a source of radiation. It substantially differs from the conditions of actual equipment where the radiation flux is constant. Articles which were devoted to the investigation of the coal ignition by a constant radiant flux are not represented in the literature.

Another widely used method for studying fuel ignition characteristics is non-isothermal thermogravimetric analysis. Despite mentioned before drawback, TG analysis allows us to obtain reliable results on the kinetics of reactions with a small instrumental error and good repeatability using standard analytical equipment. This causes a large number of articles devoted to the study on the coal ignition characteristics of various origin in the literature [16-19]. There are several methods based on TG curves for determining ignition temperature. The most widely used methods are the intersection of tangent lines [16] and the achievement of a preset reaction rate [17].

In this article, the results of an investigation on ignition delay times dependence and the characteristic temperatures of the surface of two grade coal samples by the laser radiation flux in an atmospheric air environment are presented. Also, study on the coal powder ignition in the chamber of a TG analyzer was carried out. The dependences of these parameters on time and radiation intensity were determined.

2 Experimental section

2.1 Material characterization

As experimental samples, T grade bituminous coal and 2B grade brown coal powders of Kuznetsk and Cansk-Achinsk deposits, respectively, with a particle size of less than 80 μm were used. The original coal was ground using a ball mill and sieved through a sieve with 80 μm mesh size. The proximate analysis of the samples was carried out in accordance with the corresponding standards. Ultimate analysis was carried out using an elemental composition analyzer Euro EA 3000. The results of the investigated fuel analysis are given in Table 1.

Table 1

For experiments on laser ignition of fuels, the initial powders of 0.5 g were compressed with a force of 2.5 tons into tablets with a diameter of 10 mm and a height of approximately 5 mm.

2.2. Experimental setup for ignition of sample

Fuel ignition process was carried out using the apparatus which is based CO_2-laser of continuous action with a wavelength of 10.6 microns and a maximum power of 200 W (fig. 1). The flat end surface of the samples was visually monitored for the absence of pores, cavities and cracks.

Figure 1

The tested sample (6) of coal was attached to the holder (8). When the shutter (4) was opened, the radiation was focused by a sodium chloride lens (5) to the sample of coal (6). Signals from photodiodes (7) were transmitted via the L-card E-14-440 (9) ADC, written to a personal computer (10) and then processed using the LGraph2 software application. The ignition delay time t_{ign} was defined as timing difference determined by the time between signal changes of the photodiodes (7), one of which recorded the occurrence of flame on the flat end surface of the sample.

The surface temperature of the fuel sample during the heating process was recorded using a Jade J530 SB thermal imaging camera at a frequency of 50 Hz in the temperature range 373-1800 ° C. The thermal imaging data and the photodiode parameters were synchronized by a characteristic click produced by shutter opening. It corresponds to the start of coal sample heating.

The power of the laser radiation heat flux on the coal sample was measured with a thermoelectric sensor Ophir FL400A (3). A maximum value of the radiation power at the center of the laser beam was determined through a diaphragm 2 mm in diameter.

2.3 Thermogravimetric analysis

Thermogravimetric analysis of coal samples was carried out using a synchronous thermal analyzer Netzsch STA Jupiter F3. The study was carried out at three heating rates – 10, 20, 30 °C/min – in the temperature range 50-1000 °C/min in air. The volumetric air flow for all measurements was 240 ml/ min (the purge flow rate of argon was 10 ml/min). The weight of the samples was set to 25-30 mg to ensure the absence of diffusion effects during experiments.

The ignition temperature was determined using two techniques described in [18]:

1. Achieving 1 wt.%/min speed.
2. The intersection of the tangent lines to the TG-curves at the beginning of the process and at the point with the maximum rate of mass loss.

3 Results and discussion

3.1 Ignition delay time

The dependence of the ignition delay times of solid fuel samples on the radiation flux density obtained using radiant heating setup is shown in fig.2.

Figure 2

According to the figure, it is clear that the ignition delay times for T-grade coal are 1.5-2 times higher than for brown coal 2B. While increasing radiation heat flux density from 90W/cm^2 to 150 W/cm^2 the relative difference between the ignition delay times decreases. This is due to both lower activation energy of the brown coal oxidation reaction and to lower thermal conductivity of brown coal [20].

The experimental dependences obtained were approximated by a power-law function by equation of the following form:

$$t_{ign} = A \cdot q^{-B}$$

here t_{ign} - delay time of solid fuel ignition, s; q - heat flux density, W/m^2; A, B – approximation constants.

Approximation constant values and the determination coefficient R^2 for experimental data is given in table 2.

Table 2

3.2 Ignition by radiation flux

Figure 3 shows the synchronized frames of video and thermal imaging that correspond to the main stages of the ignition using the example of a T-grade coal sample.

Figure 3

The results of thermal imaging for fuel samples at the time corresponding to the ignition of the samples are shown in fig. 4. Based on the presented in fig. 4 data analysis, the characteristic surface temperatures for fuel samples were obtained at the time corresponding to the ignition of the fuel. The surface temperature values are shown in Table 3.

Figure 4

Table 3

The experimental dependences of the maximum and average temperatures of surface on time at heat flux density 112.5 W/cm^2 are shown in fig. 5 and 6 respectively.

Figure 5

Figure 6

It is seen that the process of heating and ignition of fuels can be divided into two stages: intensive heating and stable combustion. In this case, the average cross-sectional area and the maximum temperature of ignition of bituminous and brown coal are approximately same.

The slope of the temperature curves in the first stage is mainly dependent on thermal conductivity of solid fuel samples. In this case, the average temperature of the sample surface is most indicative – fig. 6. From the slope of the curves, the

conclusion could be made that the heat capacity of bituminous coal is slightly higher than that of brown coal.

The slope for the second stage is related to two factors - the rate and the thermal effect of the exothermic reaction. Since values of the coal carbon oxidation heat are approximately same for both samples, the differences are explained, first of all, by different values of the activation energy and the kinetics of carbon oxidation.

3.3 Results of thermogravimetric analysis

Figure 7 shows the TG curves of the samples studied.

Figure 7

Two peaks can be observed on the DTG-graphs: the first in the temperature range 50-250 ° C (associated with the removal of moisture from the sample) and the second in the range 250-650 ° C for T-grade coal and 250-1050 ° C for 2B-brown coal. It is associated with the burning out of bound carbon. Therefore, to determine the ignition temperature, the temperature range of the second stage was taken into account. The rate of oxidation of 2B-grade brown coal is significantly higher than that of T-grade coal. It may be seen by the maximum value of the mass loss rate (fig. 7c and 7d).

3.4 Ignition by thermogravimetric analysis

Based on the thermal analysis data, the ignition temperatures of T-grade coal samples and 2B-grade coal samples were determined by the two methods described in 2.3. These temperatures are given in table 4.

Based on the data from table 4, it can be concluded that the ignition temperature of coal is determined by the first method (415-350 ° C), is significantly higher than the temperature determined by the second method (304-313 ° C). This is true for brown coal, although the difference between the corresponding temperatures is less significant.

At the same time, a comparison of these data with the results for radiant flux ignition shows that the temperatures determined by thermogravimetry are significantly lower. This is due to a much lower heat losses compared to TG-

chamber. This is also could be explained by the peculiarities of the experimental procedure, in which the entire volume of the investigated coal was heated simultaneously in a TG analyzer. Meanwhile under laser ignition only the flat end surface of the sample was heated. This causes both a lower degree of conversion for reacting substance, and some impulsivity of the laser ignition results due to ejected fuel particles.

4 Conclusion

Studies on T-grade and 2B-grade coal ignition via laser ignition setup with radiation heating in range of heat flux density 90-150 W/cm^2 and using TG-analyzer with a heating rates 10, 20 and 30 °C. The ignition delay times for fuel samples, as well as the sample surface temperatures at that moment were determined. Based on the thermal analysis results ignition temperatures of the fuels were determined by applying two methods. It was determined that the ignition temperature of the samples for bituminous and brown coals, which were determined by the laser ignition system, is in the range of 640-680 °C. Determined by TG analysis temperatures were in the range 300-415 ° C for bituminous coal and in range 250-300 ° C for brown coal. Such a significant difference between the results obtained by these methods could be caused by the difference between thermal loss values for different experiments.

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Table 1 – Proximate and ultimate analysis of coal

Coal sample	Proximate analysis, wt. %				Ultimate analysis, wt. %				
	M	A	V	FC	C	H	N	S	O
T-grade	3	21	20	66	68	4	3	<1	4
2B-grade	7	16	32	45	50	4	2	<1	28

Table 2 – Approximation constant and determination coefficient values.

Coal sample	A	B	R2
T-grade coal	9,61e12	-5,083	0,991
2B-grade coal	2,20E+10	-3,895	0,958

Table 3 – Sample surface temperatures at the moment of ignition.

Coal sample	T-grade	2B-grade
Maximal surface temperature, °C	1038	1066
Average surface temperature, °C	644	677

Table 4 – Ignition temperatures for studied fuels.

Coal sample	Method 1, °C			Method 2, °C		
	10 K/min	20 K/min	30 K/min	10 K/min	20 K/min	30 K/min
T-grade	415	360	350	304	313	310
2B-grade	300	280	290	270	276	250

Figure 1. A.G. Korotkikh

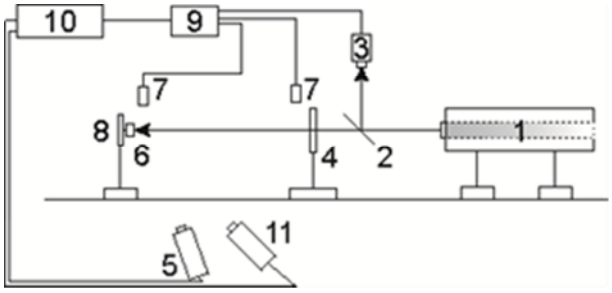

Fig. 1. Pattern of CO_2-laser based experimental setup: 1 – CO_2-laser; 2 – semitransparent mirror; 3 – radiation power measurer; 4 – shutter; 5 – lens; 6 – coal samples; 7 – photodiode; 8 – sample holder; 9 – ADC; 10 – PC; 11 – thermal-imaging camera.

Figure 2. A.G. Korotkikh

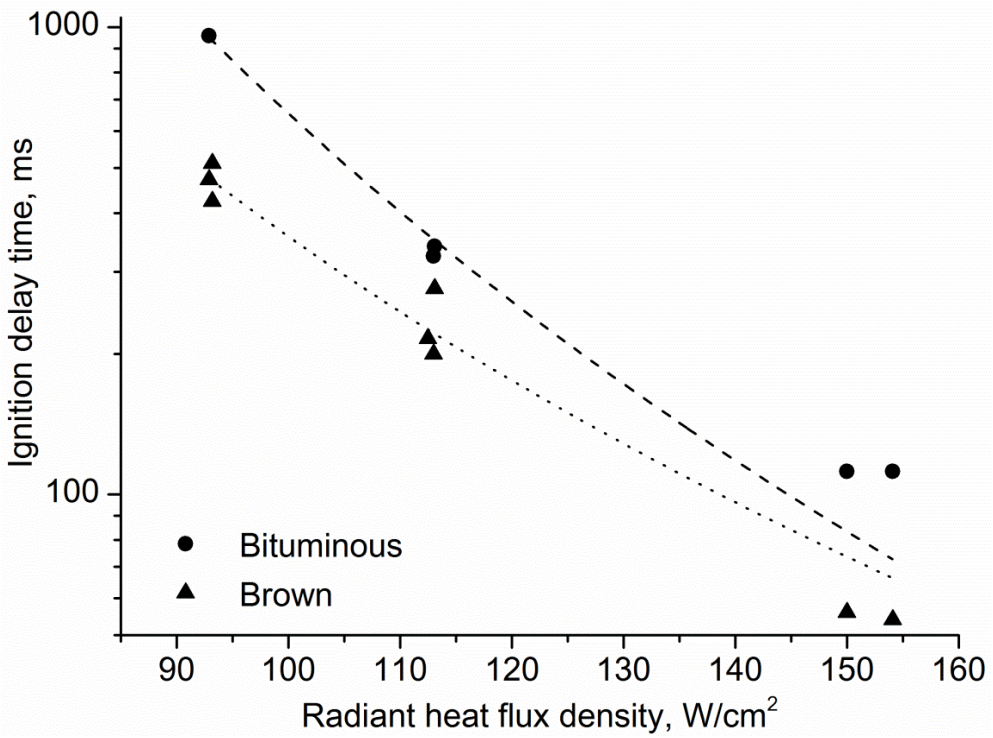

Fig.2 – Solid fuel ignition delay time dependences on laser heat flux density.

Figure 3. A.G. Korotkikh

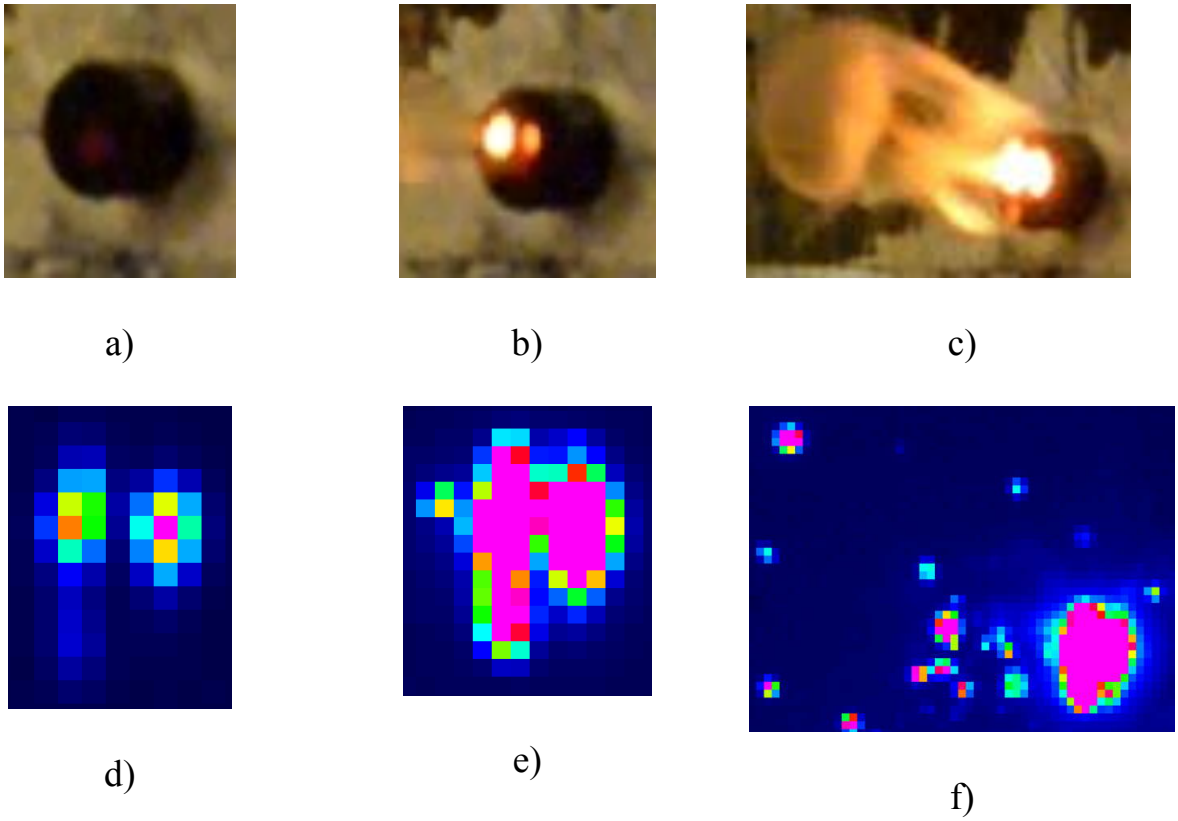

Fig.3 – Synchronized by time cadres of video-imaging and thermal-imaging for main stages of sample ignition on the example of T-grade bituminous coal: a, d – beginning of experiment; b, e – heating stage; c, f – moment of ignition.

Figure 4. A.G. Korotkikh

a) b)

Fig. 4 – Thermal-imaging cadres at the moment of sample ignition at heat flux density value 112,5 W/cm^2: a – T-grade bituminous coal; b – 2B-grade brown coal.

Figure 5. A.G. Korotkikh

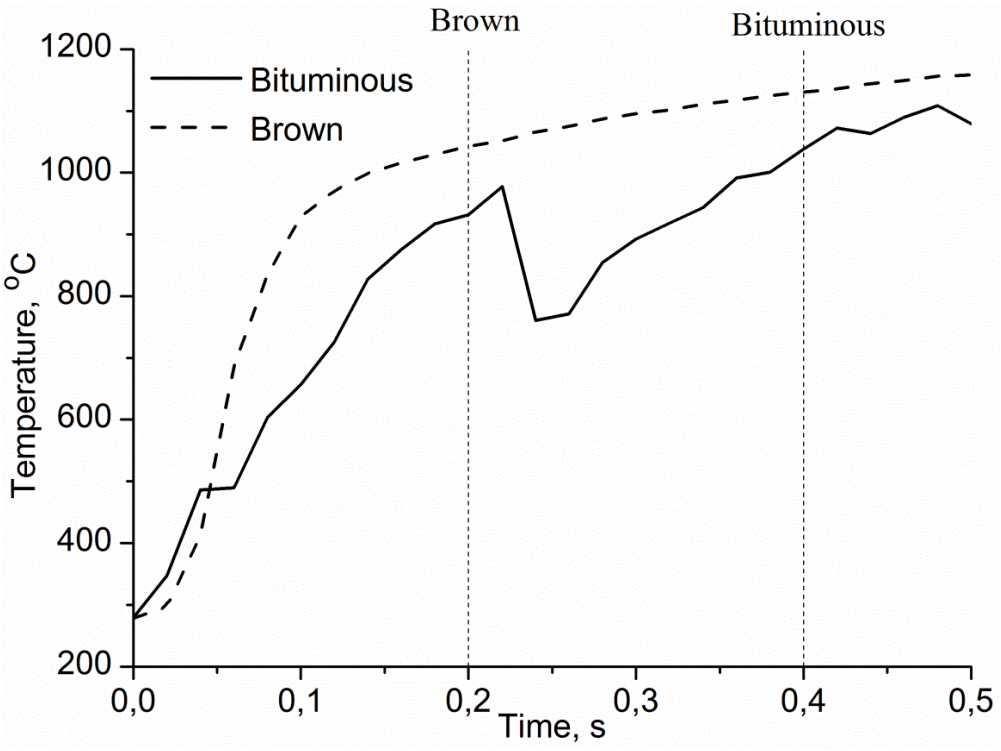

Fig. 5 – Dependence of maximal sample surface temperature on time.

Figure 6. A.G. Korotkikh

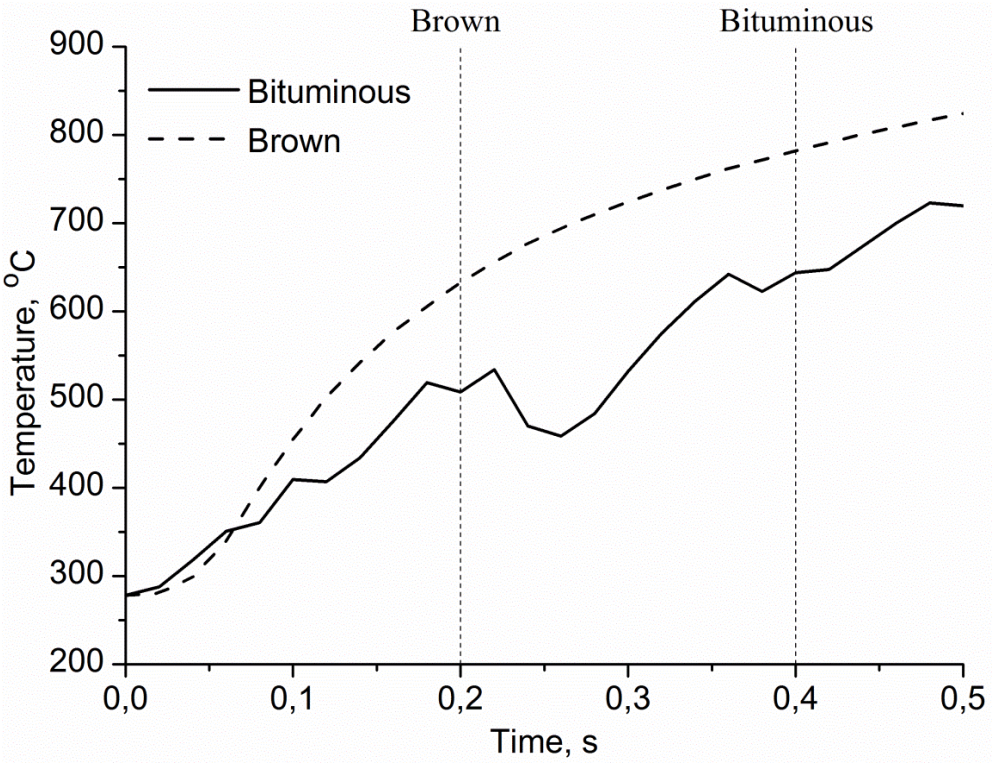

Fig. 6 – Dependence of average sample surface temperature on time.

Figure 7. A.G. Korotkikh

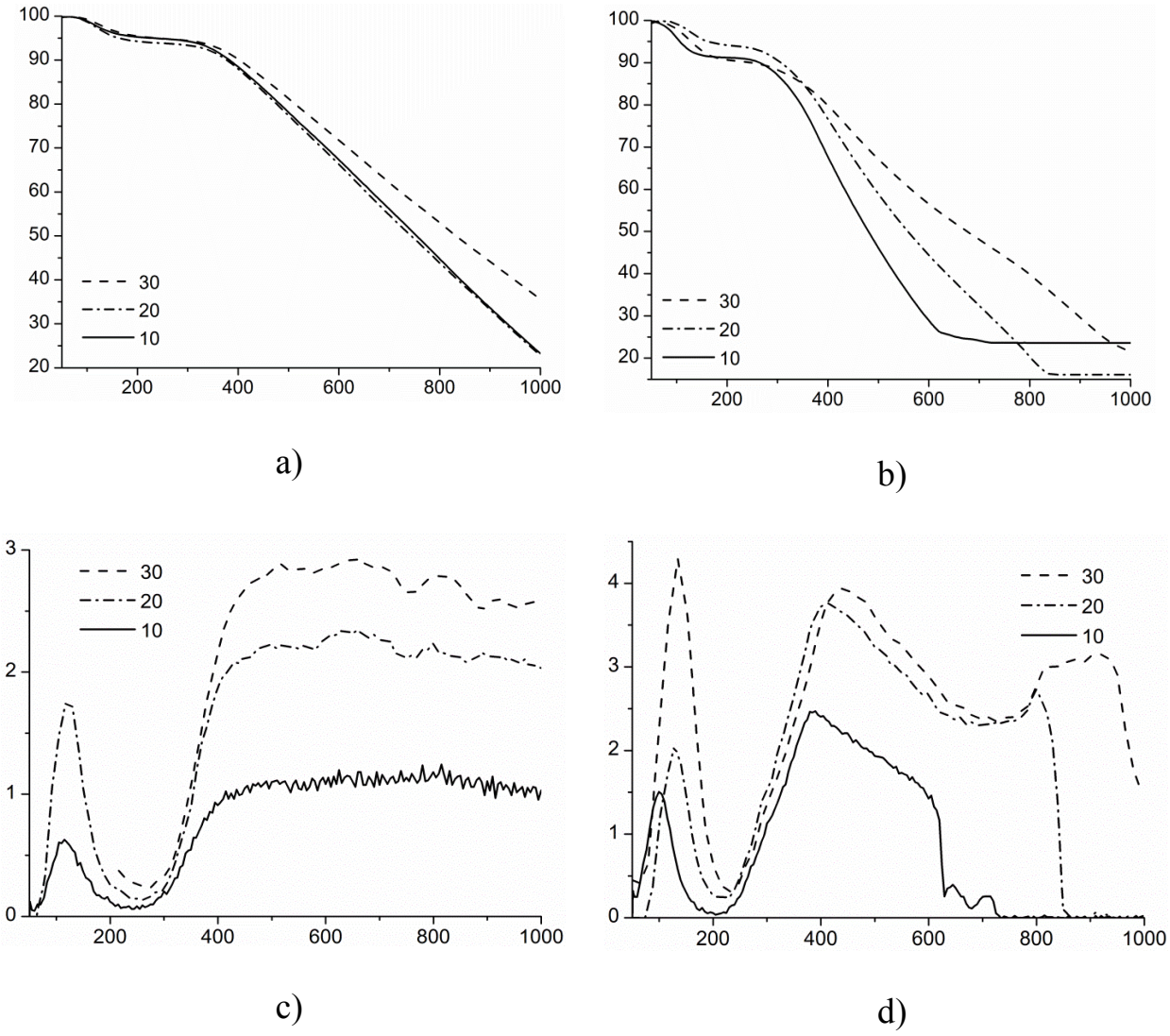

Fig. 7 – Sample mass (wt. %) dependence on ambient temperature (°C): a – TG-curve for T-grade coal; b – TG-curve for 2B-grade coal; c – DTG-curve for T-grade coal; d – DTG-curve for 2B-grade coal.

Figure caption

Fig. 1. Pattern of CO2-laser based experimental setup: 1 – CO2-laser; 2 – semitransparent mirror; 3 – radiation power measurer; 4 – shutter; 5 – lens; 6 – coal samples; 7 – photodiode; 8 – sample holder; 9 – ADC; 10 – PC; 11 – thermal-imaging camera.

Fig.2 – Solid fuel ignition delay time dependences on laser heat flux density.

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Fig. 4 – Thermal-imaging cadres at the moment of sample ignition at heat flux density value 112,5 W/cm2: a – T-grade bituminous coal; b – 2B-grade brown coal.

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Fig. 6 – Dependence of average sample surface temperature on time.

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