Ignition of Slurry Fuels Based on Coal Processing Waste and Petroleum Products

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Annotation: The work present the results of experimental investigation of necessary conditions and integral characteristics of stable ignition of slurry fuels, prepared on the base of typical coal and oil processing wastes. The main attention is paid for analysis of differences of ignition of coal-water slurries containing petrochemicals received from filter cakes of different bituminous coals (nonbanking, coking, low-caking, fat, flame, gas coals). Ignition delay times, minimum (threshold) temperatures of steady ignition are established, the heat of combustion is determined for such waste-derived fuels. Conclusions about the effect of the properties of the components on the characteristics of the ignition are made.

Key words: ignition, coal water slurry containing petrochemicals, coal processing waste, waste oil.

INTRODUCTION

In accordance with an expert forecast [1–4], the coal in the coming decades will continue to hold the leading positions in the world energy balance. Coal, as before, is one of the most accessible and widespread fuel resources for many regions of the world. According to the report of the International Energy Agency [1, 2], almost 41%

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of global electricity in 2013 was produced by coal combustion. In 2014–2016 years similar indicators increased to 46%. Unfortunately, the processes mining, processing and use of coal in industry have a very strong impact on the natural environment. In particular, during coal washing a large amount of wastes is generated. These wastes are formed in the amount of hundreds of millions of tons annually and stored in dumps and storage ponds, which, in turn, entails the loss of useful lands and environmental pollution.

At present, the most serious concern is the effect of coal combustion at thermal power plants. Emissions of nitrogen, sulfur and carbon oxides, and fly ash extremely adversely affect the condition of the soil, water bodies and the atmosphere. This, in turn, leads to serious violations of human health. According to the current findings of the world scientific community (for example, [5–8]), atmosphere pollution by industrial emissions is the cause of increased morbidity in large cities; in the areas of coal mining and combustion, soil and water contamination with heavy metals [9]; emissions of coal-fired power plants cause global acid rain fallout [10]. Since coal combustion entails global processes of changing the biosphere and human health, the searching for the methods to reduce the anthropogenic impact of coal processing and coal combustion causes reasonable interest.

One of the approach, which allows large-scale utilization of industrial combustible wastes (such as coal flotation residues, unclaimed petroleum products) as well low-grade coals is the development, preparation and combustion of composite liquid fuels (in the literature such fuels are often called coal water slurries (CWS)

[11–13] and coal water slurries containing petrochemicals (CWSP) [14, 15]). The development of technologies of CWS and CWSP contributes not only to the utilization of waste, the expansion of the fuel raw materials base, but also to reduce emissions of hazardous heavy oxides (in comparison with traditional high-temperature coal dust combustion). The studies [16–19] illustrate the ecological advantages of slurry fuel combustion, which are primarily due to reduced combustion temperatures, as well as the ability of water vapor to absorb sulfur and nitrogen oxides.

Using combustible flotation enrichment wastes as a component of CWS and CWSP is of particular interest from the point of view of economic, ecological and energy aspects. Such wastes are called filter cakes and are typical for regions with a developed coal mining industry. After coal washing plant filter cake represent the ready-made CWS – a mixture water (40–50 wt.%), coal particles (with average size not more than 200 μm) and particles of non-combustible mineral constituents.

In order to develop efficient technologies of waste-derived fuels combustion, in the present paper the processes of ignition and combustion of single droplets of CWSP, based on coal and oil processing wastes, are investigated.

EXPERIMENTAL DETAILS

Experimental setup and procedure. In this study an experimental technique based on fixing a single fuel drop on a miniature junction of a fast-response thermocouple was used. This method is widely used for studying ignition and combustion of CWSP [15] and CWS [12] droplets. The processes of heating, ignition

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and burning of single fuel droplets were investigated using means of high-speed video recording, software Tema Automotive, panoramic optical method Particle Image Velocimetry [15]. Figure 1 illustrates a schematic diagram of experimental setup, which we used for investigation of CWSP droplets ignition and combustion.

A CWSP droplet, fixed on a thermocouple junction (R-type, range 273–1873 K, systematic error ± 1 K, inertia no more than 0.1 s, junction diameter 0.1 mm)), was placed into a combustion chamber (hollow cylinder 1 m long and 0.1 m in diameter, made of quartz glass with specialized holes to insert thermocouples and fuel droplets as well as for high-speed video recording). Initial radius of CWSP droplets was about 1 mm. The temperature in the combustion chamber was varied from 600 to 1000 K and the oxidizer flow velocity, from 0.5 to 3 m/s.

The following parameters were recordered: temperature (T_g) and velocity (V_g) of air flow at flowing around the fuel droplet; temperature (T_d) on the interface thermocouple junction / fuel slurry, that is at the center of the droplet; initial size (average radius R_d) of droplet; ignition delay time (τ_d), combustion time (τ_b) and time of complete burnout ($\tau_c=\tau_d+\tau_b$). The τ_d parameter represents the time from the moment of injecting the droplet into the cylinder till the starting time of coke burning (we verified the simultaneous implementation of the inequality $T_d{\geq}T_g$ and achieving the change rate T_d of not less than 10 K/s [15]). The τ_b parameter is the time from the moment of heterogeneous ignition of coke residue till its complete burnout (characterized by the value of T_d deviation from the established value (with $\tau{\to}\infty$) of no more than $0.05T_d{}^{\max}$ ($T_d{}^{\max}$ is the maximum temperature of a droplet in the course

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of combustion)). Taking into account the video recording rate of 10^3 frames per second, the systematic errors in determining the values τ_d, τ_b and τ_c did not exceed 0.5 ms. The methods of system and random error evaluation in these experiments were similar to those described in reference [15]. Each series of experiments consisted of at least 10 tests under identical conditions. This provided a satisfactory reproducibility of the experimental results.

Components of fuel slurries. In this study we used filter cakes of different grades (coking, flame, gas, non-baking, low-caking and fat) as the basis of investigated fuel slurries. Filter cake is a wet (mass water share varies for different filter-cakes in the range of 40–60%) waste formed in the process of coal enrichment by flotation. As part of the technological process, coal is washed with a surfactant solution and then screened into separate fractions. Water used for washing the rock is fed into special tanks, where coal particles are deposited. Coal-water slurry is pumped out and sent to belt press filters to force out water. A wet residue (mixture of water, coal particles and mineral component) is known as a filter cake. The size of the solid particles of filter cake is about 100 μm. Tables 1–2 presents the results obtained from the proximate and elemental analysis of the used filter cakes.

Liquid petroleum product was the second component of CWSP. In this study we used mainly waste and unclaimed products of petroleum origin. Main properties of these components are presented in Table 3. The mass fraction of liquid combustible component in prepared slurries was varied in the range of 5–15% by weight.

In accordance with the required proportions, the fuel components were previously weighted by the means of the systems ViBRA HT 84RCE. Homogenizer MPW-302 was used for preparation of fuel slurries. The duration of mixing the components in the working glass (capacity is 0.25 l) was about 8–10 min to obtain a homogeneous fuel.

RESULTS AND DISCUSSION

For droplets of composite fuels of different compositions, the physical process of ignition and subsequent combustion has a common basis, but it can have distinctive features depending on the properties and mass fraction of the components. The main stages of CWSP droplet ignition are following: the inert heating of the sample, the evaporation of moisture from the subsurface layer (water and a liquid non-flammable component), the thermal decomposition of the organic part of coal in a subsurface droplet layer, the mixture of combustible gases with the oxidizer, the ignition of the gas-vapor mixture, the heating up of carbon, its heterogeneous ignition and subsequent combustion. Figure 2 shows the temperature change in the center of droplets during heating. The section of the curve with a monotonous increase in temperature to the value of the oxidizer temperature corresponds, basically, to the endothermic stages (evaporation of liquid components, thermal decomposition of coal). The section of the curve at which the temperature at the center of the drop sharply increases and begins to exceed the temperature of the external gaseous medium corresponds to the ignition and combustion of the coke residue. It can also be noted that when the fuel is heated, the effects of microexplosions inside and on the

surface of the droplets, dispersion of solid particles, effervescence of the liquid fuel component can occur.

In accordance with the study [15], the heat of combustion CWSP is additive to the heat of combustion of each component in accordance with its mass fraction in the CWSP composition. The results of calculating the heat of combustion of CWSP prepared on the basis of filter cakes of different grades and waste compressor oil are presented in Table 4. As can be seen from the Table 4, the heat of combustion of fuel with the addition of liquid combustible product significantly exceeds the heat of combustion of the wet filter cakes (Table 2), since petroleum products have a high calorific value, exceeds a similar parameter even of coals with high metamorphism grade. Certainly, with increasing oil product mass fraction in CWSP composition, the heat of CWSP combustion will increase. However, a significant increase (from 20% and more) of petroleum component mass fraction is not a justified step in terms of ecology, since the anthropogenic emissions will increase significantly at burning CWSP with a high share of oil product [19, 20].

Table 5 and Figures 2–4 illustrate the ignition characteristics of studied waste-derived slurries of different component compositions. Analysis of the experimental results allows to make the following conclusion: the properties of the solid combustible component, which determine the processes of ignition and combustion of suspensions, are ash content, humidity and volatiles. As experiments have shown, the use of filter cakes with sufficiently low ash content and a high volatile content (for example, filter cake of coking coal) is promising in order to reduce the costs of

initiating CWSP combustion. Therefore, characteristics such as the delay time and the limit temperature of ignition for fuels prepared on the basis of such components are minimal (Table 5, Figure 3). At the same time, the use of components with high ash content, which for some filter cakes (for example, of low-caking and fat coals) is about 50%, will lead to an increase in the costs of initiating the CWSP combustion. In particular, the relatively low initial moisture content and a large amount of volatiles in the ashless part of the filter cakes of low-caking and fat coal will not contribute to improving the ignition characteristics, since a large number of mineral constituents in the fuel will suppress the ignition process. The use of components with lower ash content and higher volatile content in the fuel will promote ignition at lower temperatures of the external gas environment (Table 5).

It should be noted that when choosing a cake filter with a high humidity (more than 50%) as the basis for fuel, a significant increase in the inertia of the CWSP ignition is expected. Evaporation of water is the most energy-intensive (vaporization heat is about 2 MJ / kg) process in the studied system. In addition, as the proportion of water increases, the share of combustible mass decreases. Water vapor in the vicinity of the droplet and in the pores of the near-surface layer hinders the evaporation of the liquid combustible product and the thermal decomposition of the organic mass of the coal and slows the heating of the fuel. Therefore, with an increase in the water fraction in the suspension, a considerable increase in the delay time of the ignition of the CWSP droplets was observed.

In the first approximation, the curves in Figure 3 also illustrate sufficiently close ignition delay times for the CWSP compositions obtained from waste from enrichment of coals of different grades. However, for more ash fuels with less volatile the large ignition delay was noticed. With the temperature increase, the physicochemical transformations on the surface and in deep layers of the CWSP droplet are intensified (evaporation of moisture and petroleum component, volatilization, oxidation of coal thermal decomposition products and petroleum vapors in the gas phase, heating and heterogeneous ignition of carbon). Therefore, the temperature increase in the combustion chamber in the range 880–1000 K led to a decrease in the duration of the initiation of combustion of the coke residue by 25–40%. It should also be noted that with increasing temperature of the external heating medium and a decrease of the droplet size, the differences in the ignition delay become less noticeable for CWSP with different component compositions.

Figure 4 shows the dependences of the delay times on the ignition of droplets on the basis of the wet coal enrichment waste on the oxidant temperature when using different types of liquid combustible component. It can be seen from Figure 4 that the ignition delay times for the CWSP with different combustible liquids are close enough in the first approximation. The differences are most noticeable in the region of relatively low temperatures (720–820 K) of hot air (Figure 4). As experiments have shown, suspensions based on waste automobile and turbine oils are characterized by lower values of ignition delay times compared to CWSP with heavy oil additive. Oils, as compared to fuel oil, are more volatile petroleum products; they

evaporate more easily and ignite at lower oxidizer temperatures. Therefore, the difference in ignition delay times for suspensions with the addition of turbine oil and CWSP with heavy oil is quite significant (Figure 4) – in the range of the oxidizer temperature 720–950 K it was 3–6 s. Ignition of CWSP at lower temperatures of the gaseous medium is promoted by liquid combustible components with low values of flash and ignition temperatures and evaporation heat (Figure 5). This conclusion is especially important for suspensions derived from coal-enrichment wastes that are sufficiently ash and contain a smaller amount of volatile substances compared to coal dust, the heat of combustion of which can significantly accelerate the heating and ignition of the coke residue. It is important to note that the use of additives of liquid petroleum products in the CWS based on coal dust (especially brown coal) may lead to an increase in inertia and limit temperatures of ignition, but in all cases the use of oils or some other petroleum products (with a high calorific value) will increase the calorific value of prepared fuel slurry.

The obtained experimental data expand the ideas of the ignition processes of promising CWSP compositions based on coal and oil processing waste. The results illustrate the possibilities of using a wide range of available components to prepare CWSP, as well as unifying the utilization technology for various waste oils and coal processing waste by their combustion as part of CWSP.

CONCLUSIONS

1.   It is possible to involve a large group of coal processing wastes, unclaimed petroleum products, and waste oils to energy as a component of fuel slurries.

2.   For a wide industrial use, additives that intensify the ignition and increase the heat of combustion of filter cakes are necessary (waste oils). It is also likely to be used in mixtures with other solid combustible components (less inert and ash).

3.   All the considered liquid combustible components increase the heat of combustion and the combustion temperature of the fuel slurry. Waste turbine, transformer, automobile, compressor oil contribute to a decrease in temperature and delay time of CWSP ignition.

4.   The results illustrate the possibilities for reducing the temperature of heating air for CWSP ignition, which, in turn, will reduce the heat stress of some sections of the technological process and prolong the service life of the equipment. In addition, it allows reducing the need for gas and oil for combustion chamber heating (CWSP is promising as the main and startup fuel).

The obtained experimental results are of interest for the development of advanced combustion technologies for composite liquid fuels of various component compositions and the creation of adequate physical and mathematical models for their ignition and subsequent combustion.

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Table 1. Properties of filter cakes (after drying)

Sample	Proximate analysis			Elemental analysis, % daf		
	Ash, %	Volatiles, % daf	High heat value, MJ/kg	Carbon, %	Hydrogen, %	(oxigen+ nitrogen+ sulfur), %
1	26.46	23.08	24.83	87.20	5.090	7.53
2	36.99	41.47	19.24	73.27	4.904	21.83
3	33.82	43.11	22.16	75.12	4.638	20.24
4	50.89	30.16	15.23	87.47	5.039	7.36
5	21.20	16.09	26.92	90.13	4.255	5.52
6	57.67	45.24	20.9	73.16	4.999	21.84

Note: 1 – filter cake of coking coal; 2 – filter cake of flame coal; 3 – filter cake of gas coal; 4 – filter cake of low-caking coal; 5 – filter cake of non-baking coal; 6 – filter cake of fat coal.

Table 2. Properties of wet filter cakes (in initial state)

Sample	Mass fraction of water, %	Heat value, MJ/kg
filter cake of coking coal	43.5	14.03
filter cake of flame coal	56.8	8.31
filter cake of gas coal	53.0	10.41
filter cake of low-caking coal	37.9	9.46
filter cake of non-baking coal	39.1	16.42

filter cake of fat coal	37.9				12.91

Table 3. Properties of liquid combustible components

Component	Density at 293 K, kg/m^3	Moisture, %	Ash, %	Flash temperature, K	Ignition temperature, K	Heat value, MJ/kg
Waste automobile oil	871	0.28	0.78	405	491	44.1
Waste turbine oil	868	–	0.03	448	466	45.1
Waste transformer oil	877	–	–	421	442	44.9
Waste compressor oil	887	–	0.023	458	502	45.2
Oil-water emulsion	794	0.04	0.006	313	330	45.5
Fuel oil	1000	6.12	4.06	438	513	39.4

Table 4. Combustion heat of CWSP (90% wet filter cake, 10% waste compressor oil)

Filter cake of non-baking coal	Filter cake of coking coal	Filter cake of fat coal	Filter cake of gas coal	Filter cake of low-caking coal	Filter cake of flame
19.29	17.15	16.14	13.89	13.03	11.99

Table 5. Limit (minimum) temperatures of stable ignition of CWSP droplets (90% wet filter cake, 10% waste turbine oil) at $R_d \approx 1$ mm, $V_g \approx 2$ m/s

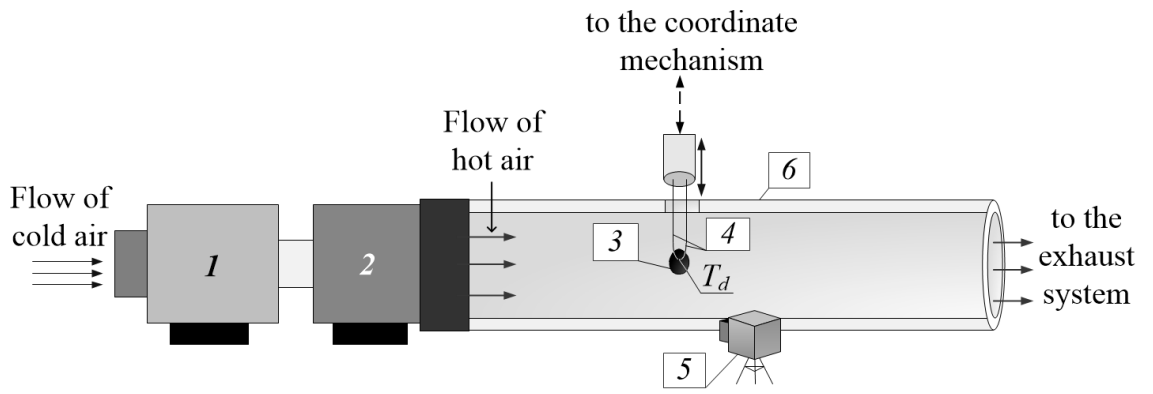| Filter cake of coking coal	Filter cake of low-caking coal	Filter cake of non-baking coal	Filter cake of flame coal	Filter cake of gas coal	Filter cake of fat coal
840 K	900 K	860 K	780 K	845 K	800 K

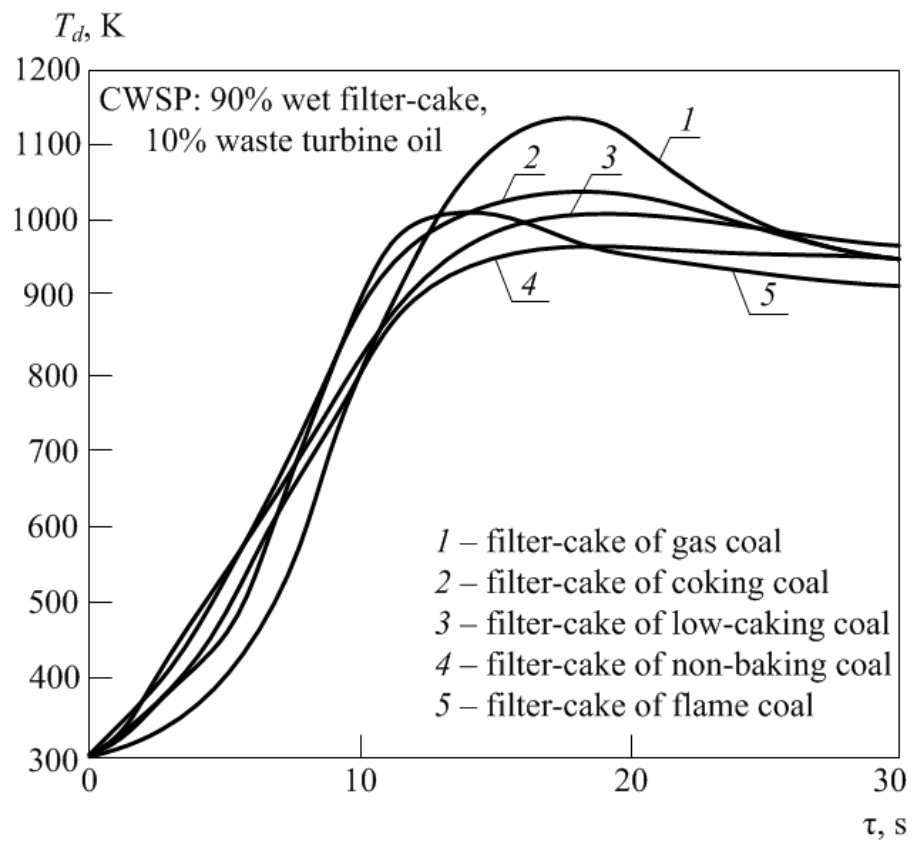**Fig. 1.** Vershinina K.Yu., Lyrshchikov S.Yu., Strizhak P.A.

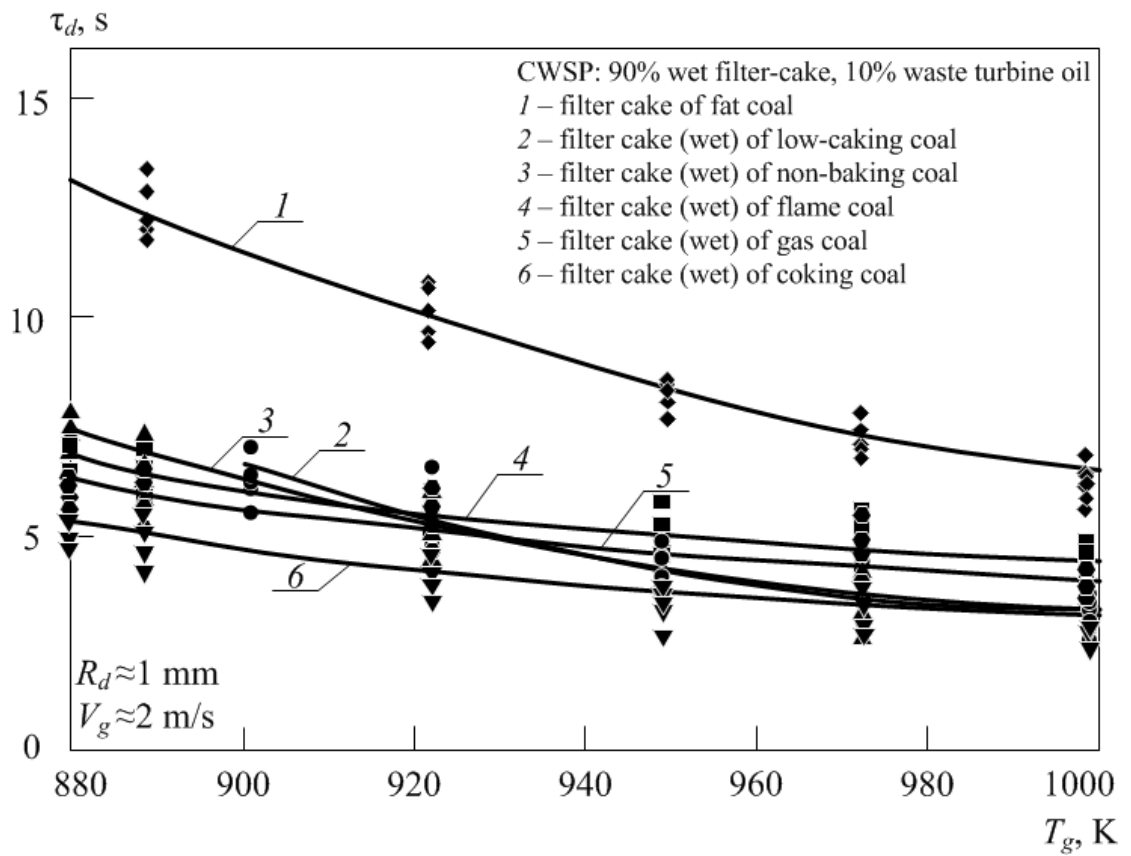**Fig. 2.** Vershinina K.Yu., Lyrshchikov S.Yu., Strizhak P.A.

Fig. 3. Vershinina K.Yu., Lyrshchikov S.Yu., Strizhak P.A.
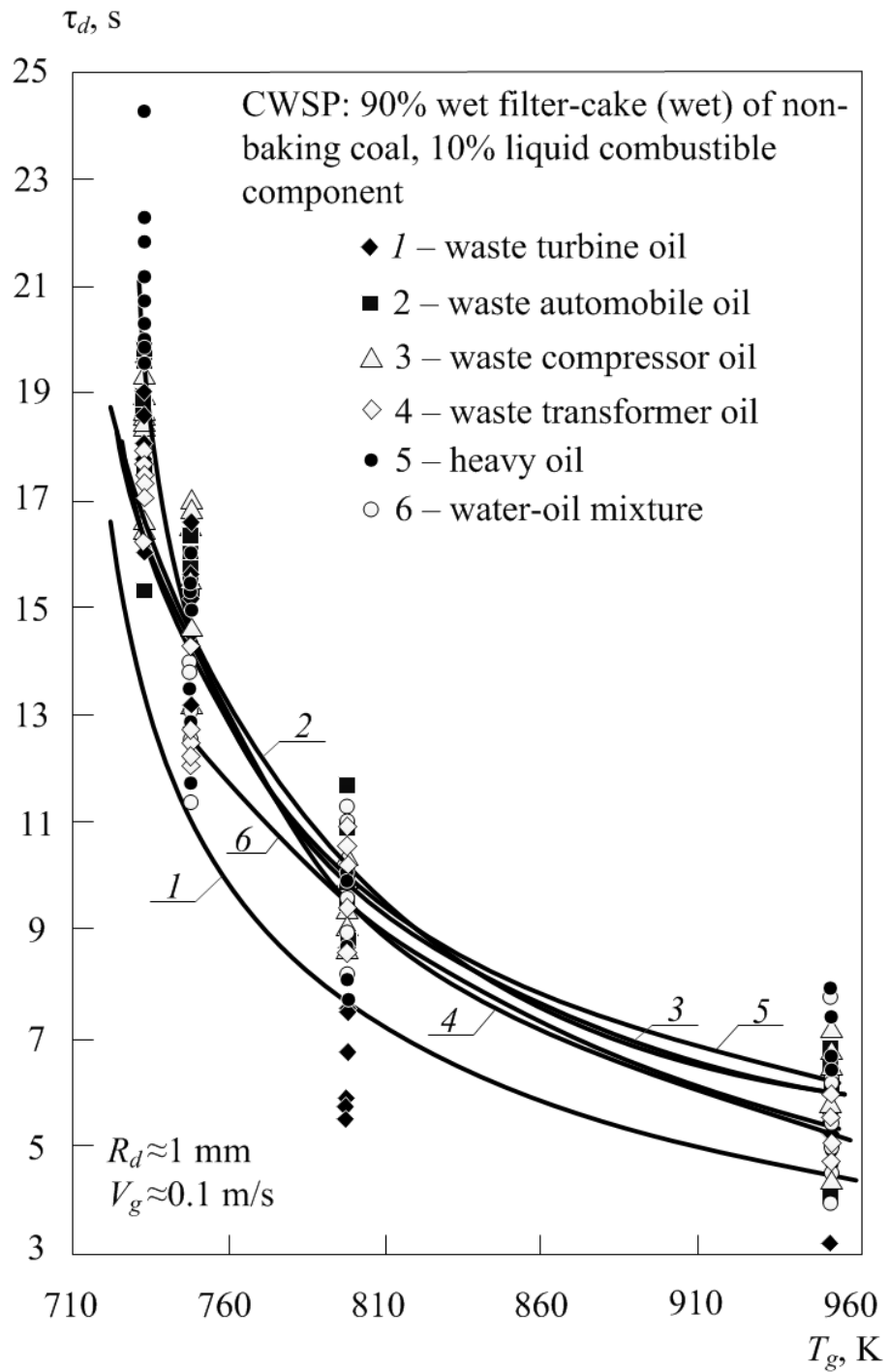
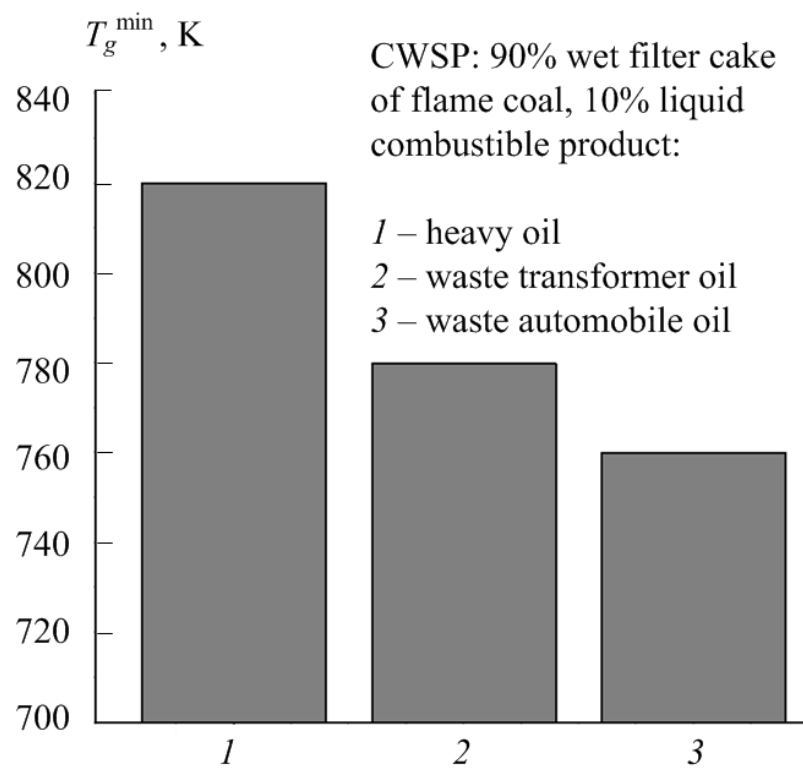**Fig. 4.** Vershinina K.Yu., Lyrshchikov S.Yu., Strizhak P.A.

Fig. 5. Vershinina K.Yu., Lyrshchikov S.Yu., Strizhak P.A.

Fig. 1. Scheme of experimental setup: *1* – air fan; *2* – air heater; *3* – fuel droplet; *4* – low-inertia thermocouple; *5* – video camera; *6* – hollow quartz cylinder [15].

Fig. 2. Temperature trends at the center of the CWSP droplet based on different filter-cakes (R_d≈1mm, T_g≈900 K, V_g≈1.5 m/s).

Fig. 3. Dependence of ignition delay of CWSP droplets on oxidant temperature at varying the grade of coal flotation waste.

Fig. 4. Dependence of ignition delay of CWSP droplets on oxidant temperature at varying the type of liquid fuel component.

Fig. 5. Limit temperatures of ignition of CWSP droplets (R_d≈1 mm) based on filter cake of flame coal.

Nomenclature

R_d – initial radius of droplet, mm;

T_d – temperature at the center of CWSP droplet, K;

T_g^{min} – minimum oxidizer temperature required for stable ignition of CWSP, K;

V_g – velocity of oxidizer flow, m/s;

τ – time, s;

τ_b – time of burning, s;

τ_c – time of complete burnout, s;

τ_d – ignition delay time, s.