INFLUENCE OF THE SHAPE OF SOARING PARTICLE BASED ON COAL-WATER SLURRY CONTAINING PETROCHEMICALS ON IGNITION CHARACTERISTICS

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This paper examines the laws of stable ignition of organic coal-water slurry containing petrochemicals (CWSP). CWSP is based on the filter cake of coal and scavenge oil. The experiments are performed for individual CWSP particles soaring in a special setup. The temperature and velocity of an oxidizer flow are varied between 500–1200 K, and 0.5–3 m/s. The dimensions (longitudinal and transverse) of particles range are from 0.5 mm to 5 mm. The study indicates how the shape of a fuel particle (sphere, ellipsoid, and polyhedron) influences its ignition characteristics (delay time, minimum temperature, modes, stages). Based on the experimental results, the paper explains why the surface configuration of particles influences the conditions of heat transfer with an oxidizer. The results obtained for soaring particles are compared with the results for fixed CWSP particles having different surface configurations (sphere, ellipsoid, and polyhedron). In general, the study may contribute to the expansion of the fuel resource base. The experimental data may be used for the development of the technologies of burning CWSP prepared by recycling traditional fuels. As a result of this study, several recommendations for the practical application of research results are made.

Keywords: *coal-water slurry, petrochemicals, particle, sphere, ellipsoid, polyhedron, ignition delay time.*

1. Introduction

Nowadays, much attention is paid to the creation of fuels with great environmental, economic and energy prospects. From this perspective, it is noteworthy to consider coal-water slurry (CWS) [1–3] and coal-water slurry containing petrochemicals (CWSP) [4–6]. They are produced by recycling coal, oil and low-grade raw materials. The development of the technologies of energy efficient and environmentally friendly combustion of CWS and CWSP will contribute to the recycling of numerous waste, such as turbine, transformer, motor, castor, and compressor scavenge oils, petroleum deposits, sludge, oil-water emulsions, low-grade oil and coal, filter cakes of coal processing, carbon residue after processing car tires, and others. The use of coal can grow by several times by 2020 [7–9]. As a consequence, waste volumes will also increase significantly. At present, the amount of such waste is considerable in countries such as Russia, China, Japan, and the United States. Thus, the issues of recycling coal and oil waste are becoming topical there. For many regions of Siberia (Russia) these issues are already of current interest. According to experts, many regions of Russia, China, Japan and other countries can be supplied with heat and electric power only through efficient burning of CWS or CWSP based on coal and oil waste.

The broad recycling (in industrial scale) of the wastes listed above for preparing CWS and CWSP is limited. This is due to the fact that there is a very few data on the laws of their combustion. Moreover, low-grade coal and coal wastes require a lot of energy to initiate combustion.

They are characterized by a high content of sulfur and nitrogen oxides in combustion products, as well as by large mechanical and chemical incomplete combustion. It is possible to minimize these disadvantages by mixing low-grade coal and coal waste with water (i.e., to prepare CWS and CWSP). Certainly, it is not sufficient to justify the feasibility of recycling such wastes for producing composite fuel only by theoretical conclusions. It is thus necessary to obtain experimental data on the integral characteristics of ignition and combustion of CWS and CWSP.

The idea of using CWS instead of petroleum products received active dissemination in China, Japan, Sweden, Germany, the United States and some other countries in the early 70s of the last century (during the global oil crisis). In recent years, China and Japan have demonstrated a great interest in studying CWS. In particular, there are several research centers in China working on this research direction. If in 2001 China produced and consumed annually over 2 million tons of CWS, in 2006 it was about 15 million tons. This amount is sufficient for producing 10–12 gigawatts of electricity [7–9]. By 2020, China plans to reach a record value in the production of CWS, namely 100 million tons per year [7–9]. A significant number of corresponding studies in China once again proves the importance of the development of technologies for CWS applications (e.g., recent publications in periodicals [10–12]).

Japan has also made a significant contribution to the development and application of CWS (in particular, [13]). The demonstration projects of 80s are currently implemented in industry. CWS has found its application mainly in steam boilers with a capacity of 20–600 MW. At present, about 800 thousand tons of CWS is annually burned on the territory of this country. A large part of coal-water compositions is delivered to Japan from China. Only a small amount of CWS is prepared on its own facilities (by traditional cavitation technology to produce a highly concentrated suspension).

In Russia, the first burst of research on the development of coal-water technologies was in the 50s of the last century (during the USSR). It was caused by the growing problem of recycling fine coal sludge, which has appeared in a large amount with the rapid development of hydraulic mining and hydraulic transportation of coal, as well as with cleaning of coal by liquids. Research teams in Russia revealed the prospects of this direction in the near future. Therefore, they continued to develop the technologies of preparing and using CWS. As a result, they obtained a world class results in the last 20–25 years [14–16].

The most common way for the experimental study of burning CWS or CWSP droplets (particles) is to hang them in a low-inertia thermocouple junction, ceramic filament or metal wire [5, 6, 17, 18]. The main advantage of this method is the possibility to monitor the temperature on the surface of the fuel particle, at its center or in a thin superficial layer. This allows defining burning stages: inert heating, evaporation of water from the droplet (particle), yield and combustion of volatiles from coal; carbon burning. Also, this allows detecting the moment, when phase transformations and chemical reactions are completed. The main limiting factor in the use of this method is a heat flow from the surface to the center of the fuel particle and then to a holder (i.e., the element on which the particle is attached). The study [19] has experimentally proved that this factor can significantly affect the integral characteristics of ignition (delay times, modes, stages). This factor constrains the application of research results in practice. The study [19] proposes an approach, where CWSP particles are soaring in the oxidizer flow without using holders. This approach is quite promising, since it can be used for various compositions of CWS and CWSP having a wide range of basic components: liquid combustible substances, water and solid combustible substrate.

The experiments [5, 6] indicated that the most important factor in combustion initiation is heat transfer of CWSP droplets (particles) with an oxidizer. A major parameter along with the particle size of fuel and the temperature and velocity of the oxidizer is the particle’s surface configuration. The studies [5, 6] revealed that irregularly shaped particles (substantially different from spherical) are characterized by the minimum ignition lag. This result is due to the enhancing of heat transfer of the particle with the oxidizer, and is very important for application use. It is, therefore, of interest to study the effect of various particle shapes without a holder, i.e. when a particle is soaring in the oxidizer flow as in the approach [19].

The aim of this study is to determine experimentally how the shape of soaring CWSP particles influences on the integral ignition characteristics.

2. Experimental setup and procedure

The setup and procedure of experimental studies are similar to those presented in the paper [19]. The facility is based on a special combustion chamber made of quartz glass with conical input and output [19]. A supercharger and a heater can vary the temperature and velocity in the combustion chamber within the range: 500–1200 K and 0.5–3 m/s, respectively. Two thermocouples of type K (temperature measurement range is 273–1373 K, bias is ± 3 K, lag is no more than 3 s) are used to monitor the oxidizer temperature. The oxidizer velocity is detected by introducing special tracers and by applying optical flow visualization techniques [5, 6]. The deviation of oxidizer temperatures is no more than 5 K, of velocities – no more than 0.1 m/s.

Unlike the experiments [19], in this study, we use a dispenser with special tips for generating the particles (droplets) of CWSP. The dispenser has several operating modes, which allow setting instantaneous flow rate, the feed rate of the composition, and etc. Special tips enable the particles of three different shapes: sphere, ellipsoid and irregularly shaped polyhedron (see fig. 1). Note that here we assume that a particle with several (usually 5–7) pronounced vertices and edges is an irregularly shaped polyhedron.

The average particle sizes are varied between 0.5–5 mm. For sphere the characteristic dimension for calculation is a diameter D_d. For ellipsoid two maximum dimensions a_d and b_d are used for computing: $D_d=(a_d+b_d)/2$. For polyhedron four dimensions are used a_d, b_d, c_d and e_d: $D_d=(a_d+b_d+c_d+e_d)/4$. The maximum error in determining the particle size is 3 %.

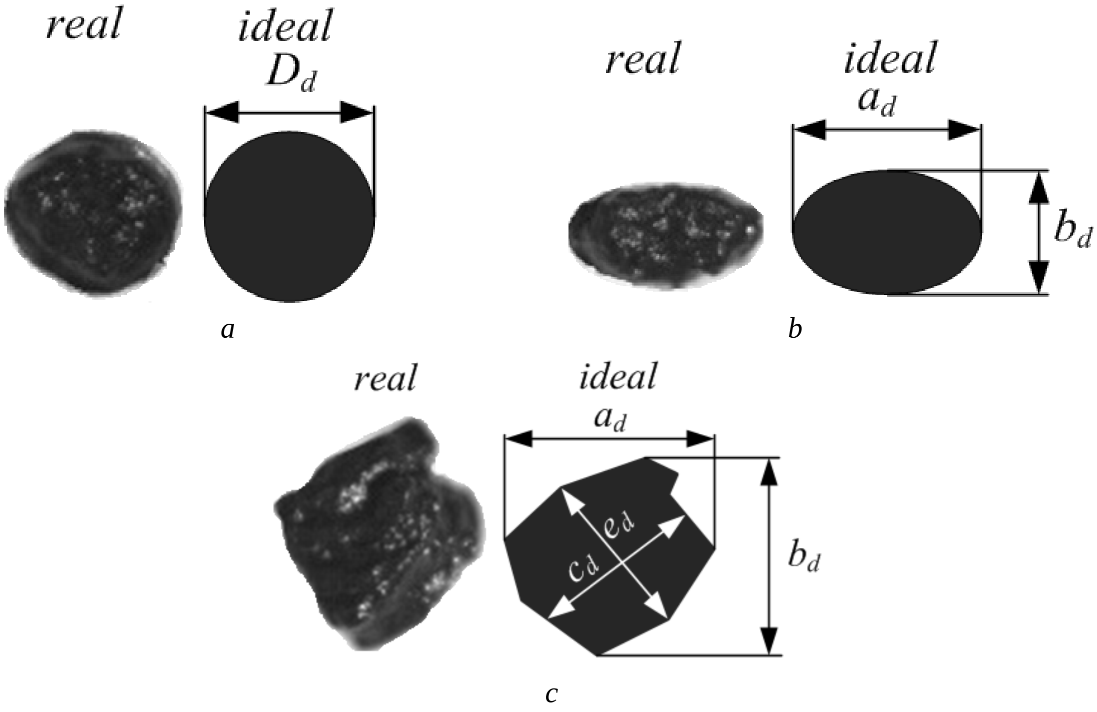


Figure 1. Video frames and ideal analogues of spherical (*a*), ellipsoid (*b*) and polyhedral (*c*) CWSP particles

In this study, CWSP is prepared using a homogenizer MPW-324, as in [19]. In the first stage, an oil-water emulsion is prepared taking into account the relative mass concentrations of oil and a plasticizer. The components are weighted on an analytical balance ViBRA HT 84RCE. After that, they are added to a container of the homogenizer (capacity is 0.25 l), where they are mixed. The duration of mixing the emulsion components is 3 minutes. Then, coal particles are introduced to the container with the emulsion (in accordance with the desired relative mass concentration). The duration of mixing the components is 10 minutes. The main components of CWSP are: a filter cake of coal of grade K (tab. 1, 2), scavenge motor oil (tab. 2), a plasticizer (tab. 3) and distilled water. A filter cake is a byproduct of coal cleaning, whereby coal is washed by water with surfactants. The water used for washing coal is fed into special tanks, where carbon particles are precipitated. The coal-water slurry is pumped and passed through press filters for water extraction. A moist residue (a mixture of water and coal) is a filter cake. The average size of coal dust particles in the filter cake is no more than 100 μm. Tab. 4 gives the concentrations of the CWSP components used for investigation.

Table 1. Characteristics of filter cake of grade K in the initial state

Sample	Proportion of dry substance – coal waste, %	Q^a_s, MJ/kg
Filter cake (wet) of coal of grade K, coal washing plant Severnaya, Kemerovo region	56.5	14.03

Table 2. Characteristics of combustible components of CWSP

Parameter	Combustible component	
	Filter cake K	Scavenge motor oil
Ash content, %	26.46	0.78
Moisture content, %	–	0.28
Devolatilisation V^{daf}, %	23.08	–
Highest calorific value $Q^a_{s,V}$, kcal/kg	5930	10509
Flash temperature, K	–	405
Ignition temperature, K	–	491

Table 3. Main characteristics of a plasticizer Neolas

Parameter	Value
Appearance	Transparent liquid
Content of surfactants, %	25
Solution pH	6.5
Density at 293 K, kg/m^3	954

Table 4. CWSP composition (relative mass concentrations of components)

Coal component, %	Liquid fuel component, %	Water, %	Plasticizer, %
Filter cake K	Scavenge motor oil		
50.5	10	39	0.5

A CWSP particle is introduced into the combustion chamber with the help of an automated coordinate mechanism. The particle is released to the chamber by a special element. A schematic diagram of such element is depicted in the paper [19]. In contrast to experiments [19], here the element is modified, namely, the pusher is rearranged and reconfigured to provide the conditions for releasing the particles of various shapes.

As in experiments [19], the ignition delay times (τ_d) of CWSP particles are calculated. For this purpose, a digital RGB model and special Tema Automotive software are used. The parameter τ_d represents the time from introducing the particle to the channel *1* till its ignition, i.e. when the following conditions are fulfilled simultaneously: $T_d > T_g$ and $dT_d/d\tau > 10$ K/s. The systematic error in determining the times τ_d does not exceed 0.5 ms. The techniques for evaluating the errors in determining basic parameters are similar to those described in references [5, 6, 19]. In particular, studies [5, 6, 19] indicate that it is appropriate to use the digital RGB model and special Tema Automotive software for accurate recording of sustainable ignition of CWSP (fig. 2).

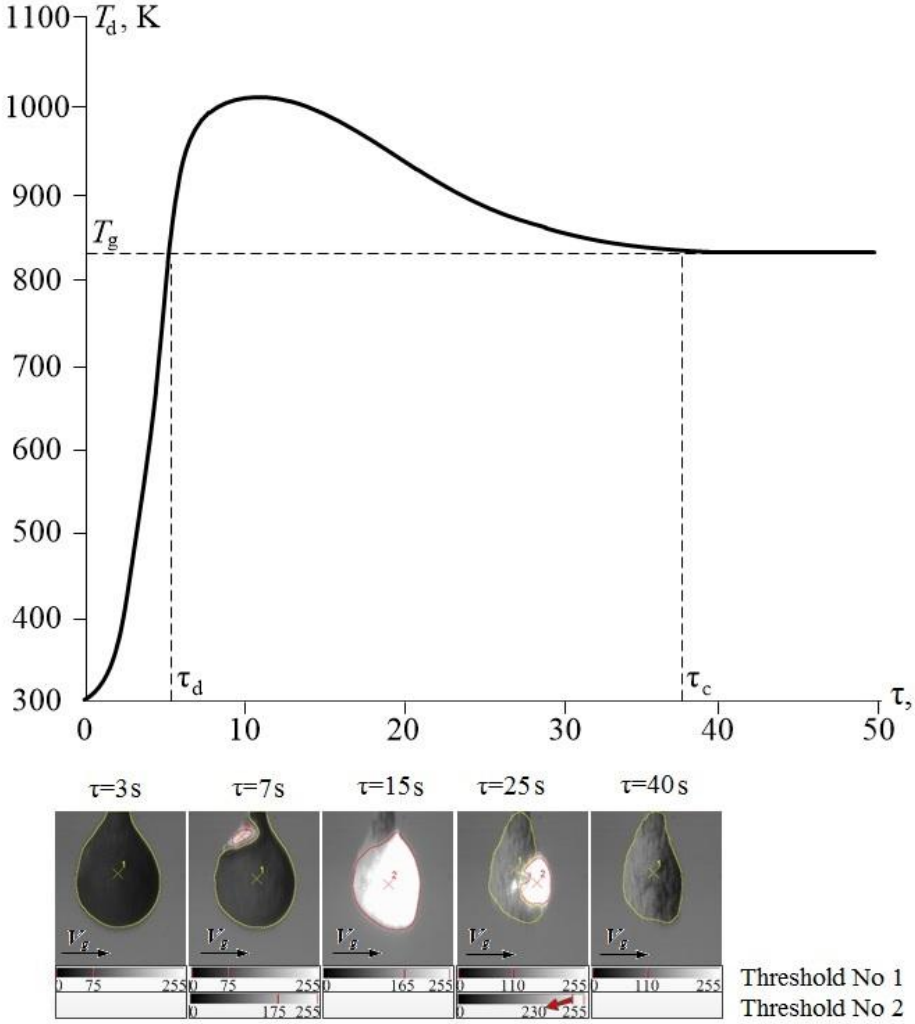


Figure 2. Trend [5, 6] of temperature change of a CWSP particle (on thermocouple junction) with illustration of procedure of selecting the ignition criteria at R_d≈0.8 mm, T_g≈830 K, V_g≈5 m/s

A color gradient is set according to the conditions, under which a fuel particle is burning. According to the RGB color model, 255 correspond to white color, 0 – to black. It is assumed that a glow during the combustion of the sample corresponds to the RGB range between 220–255 [5, 6]. Also, unlike experiments [19], here, special diaphragms and a high-temperature thermal imager Testo 885 are additionally applied for investigating the ignition features of particles of different shapes. These devices allow scaling video frames and determining the particle temperature (T_d) during its heating in the oxidizer flow, regardless of its location in the combustion chamber.

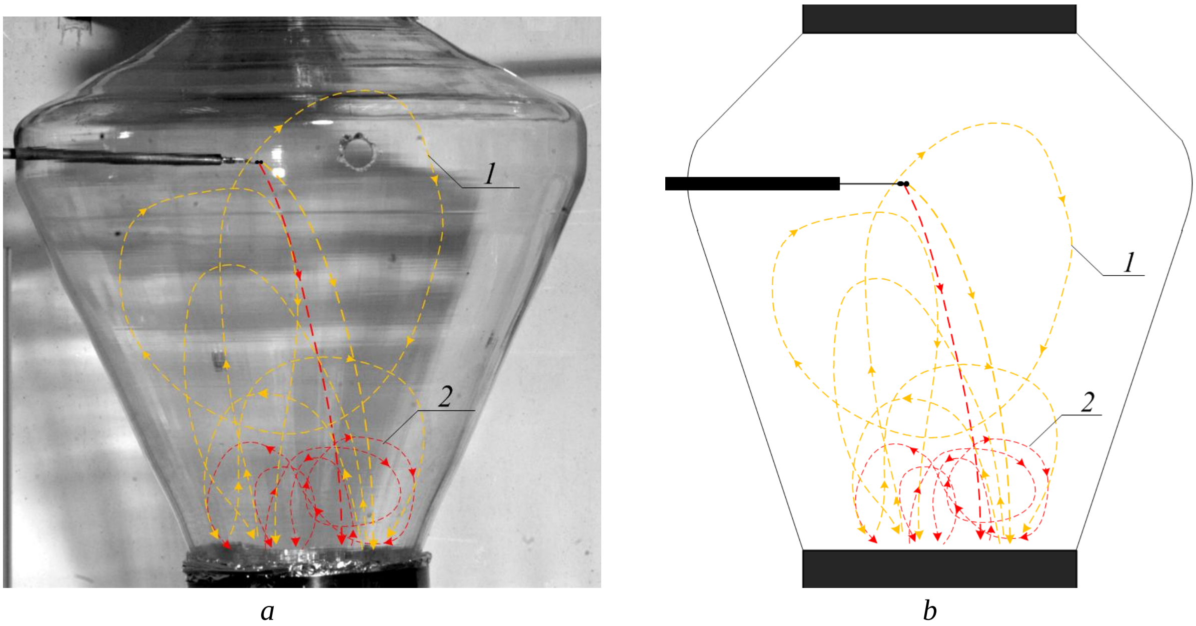
3. Results and discussion

Fig. 3 illustrates the typical tracks (trajectories) of the CWSP particles moving (soaring) in the combustion chamber developed for the experiments.

The experiments distinguished four ignition modes in the combustion chamber. They differ in the trajectories of CWSP particles:

1) a particle separates from the tip of the coordinate mechanism, moves to the bottom of the chamber under gravity, deposits on a grid (leveling the oxidizer flow) and is ignited by direct contact with the grid (this mode is typical for large particles which are originally relatively heavy);
2) a particle is placed to the combustion chamber, where it is entrained by the oxidizer flow to the upper part and touches the upper distribution grid; after several such contacts it is ignited (this mode is typical for small droplets);
3) a particle is placed into the combustion chamber, where it is soaring along the axis of symmetry in the central part, then it is ignited;
4) a particle is soaring along the side wall of the combustion chamber, then it is ignited.

As in experiments [19], here we may identify two stable modes of soaring fuel particles: in the central part of the chamber and in the wall side.



a *b*

Figure 3. Typical trajectories (*a, b* – photo and scheme of combustion chamber) of CWSP particles of different shapes (*1* – ellipsoid, polyhedron, *2* – sphere) during ignition

Video recordings of the experiments demonstrate that the shape of a CWSP particle may significantly affect its trajectory in the combustion chamber (fig. 3). Spherical particles are characterized by relatively small (in longitudinal and transverse dimensions) displacement areas in the combustion chamber. It can be seen in fig. 3 that they are located near the bottom of the chamber (where the oxidizer flow enters the chamber). Ellipsoidal and polyhedral particles are characterized by considerably larger (by several times) displacement areas. Video recordings show that these particles tend to be twisted by the flow. Consequently, a rotational component is added to linear velocity. As a result, the particle gains an additional impulse and accelerates. Therefore, the trajectories of the particles of such shapes are significantly larger compare to spheres. Obviously, a spherical particle can also rotate about its center of mass during the motion in the combustion chamber. But in this case, rotation rate is several times lower than for an ellipsoid or a polyhedron due to less aerodynamic drag.

The rotational motion of ellipsoidal and polyhedral particles (with respect to their own center of mass) is likely to be one of the main reasons for their more intensive ignition compared to spherical particles. The relative velocities of the particle and the oxidizer flow increase. In particular, fig. 4 and 5 show that ignition delay times τ_d may differ by almost 25–35 % depending on particle shape. In accordance with modern concepts of heat transfer of gases and bodies with different surface configurations, we may conclude that a polyhedron is characterized by maximum drag coefficients compared to a sphere. An ellipsoid is characterized by the average value of the drag coefficient relative to a sphere and a polyhedron. As a consequence, when aerodynamic drag enhances, friction and inertia increases. Heat transfer with the oxidizer intensifies. As a result, the typical durations of the ignition stages discussed above decrease, as well as ignition delay times τ_d.

The combustion chamber provides uneven temperature distribution (the maximum temperature is at the bottom, the minimum – near side walls). The temperature difference reaches 30–40 K in the longitudinal coordinate, and 20 K in transverse (similar to experiments [19]). Since spherical particles are soaring at the bottom of the chamber (where the oxidizer flow enters the chamber), one would expect minimum times τ_d. However, fig. 4 and 5 illustrate a determining role of the convective component of heat transfer, as well as a significant contribution of intensive rotational motion of ellipsoidal and polyhedral particles. It can be concluded that irregularly shaped particles ignite at lower oxidizer temperatures and shorter times τ_d.

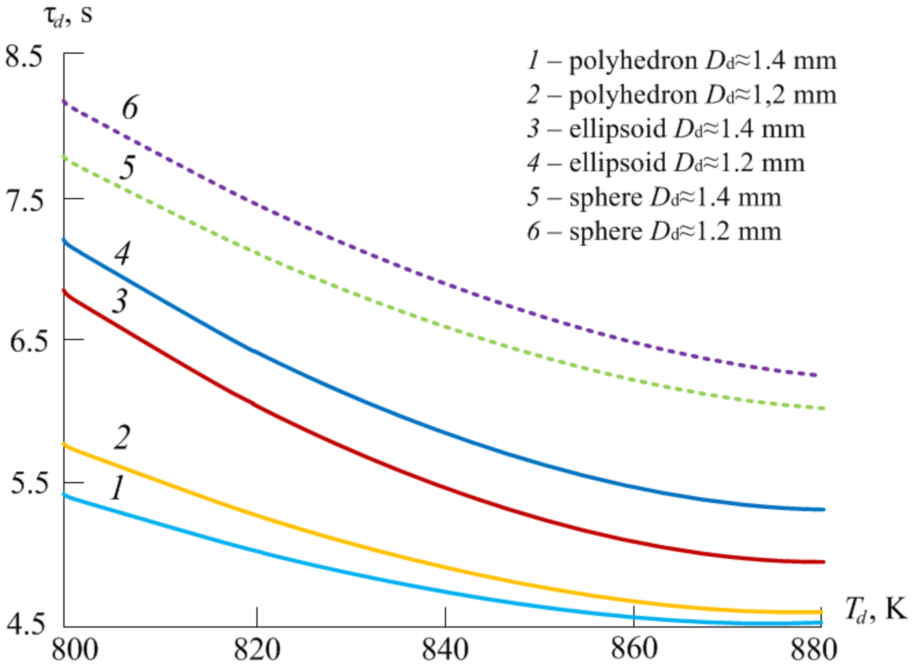


Figure 4. Ignition delay times of CWSP particle depending on the oxidizer temperature

It is rather difficult to detect the times of complete combustion of fuel particles in the setup developed for this study (unlike experiments with fixed particles [5, 6]). This is due to the fact that after ignition, a particle moves along the trajectory near the side wall of the chamber. When reactive particles touch the walls of the chamber, they are dispersed. This process leads to the formation of a large group of small particles and their intensive combustion. Nevertheless, based on the results of the experiments conducted as in [5, 6], we may suggest that most of the time of complete combustion are ignition delay times. Thus, as can be seen in fig. 4 and 5, a role of particle shape decreases with increasing temperature.

It can be noted from fig. 5 that the ignition delay times of particles with various surface configurations are different in the whole range of changing size D_d. Thus, we can conclude about the generality of this pattern. It should also be noted that the smaller the particle, the more spherical it is. This implies for of all shape configurations. One may therefore predict the convergence of times τ_d with decreasing D_d. However, the experiments did not confirm this effect. Most likely, this is due to the rotation of particles during the motion in the oxidizer flow. In the case of the CWSP particles fixed on a thermocouple junction, this effect (convergence of times τ_d with decreasing D_d) is clearly seen (fig. 6).

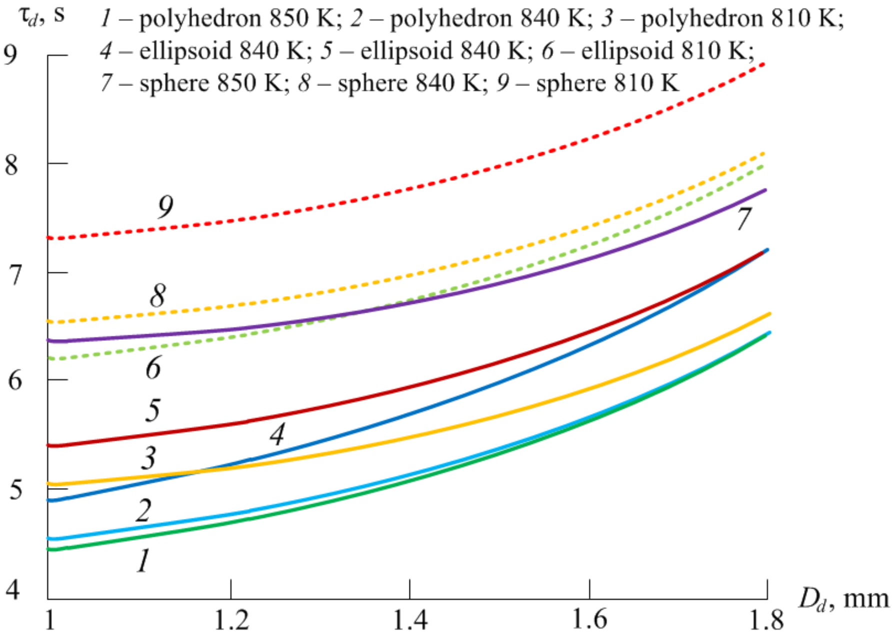


Figure 5. Ignition delay times of CWSP particle depending on its size

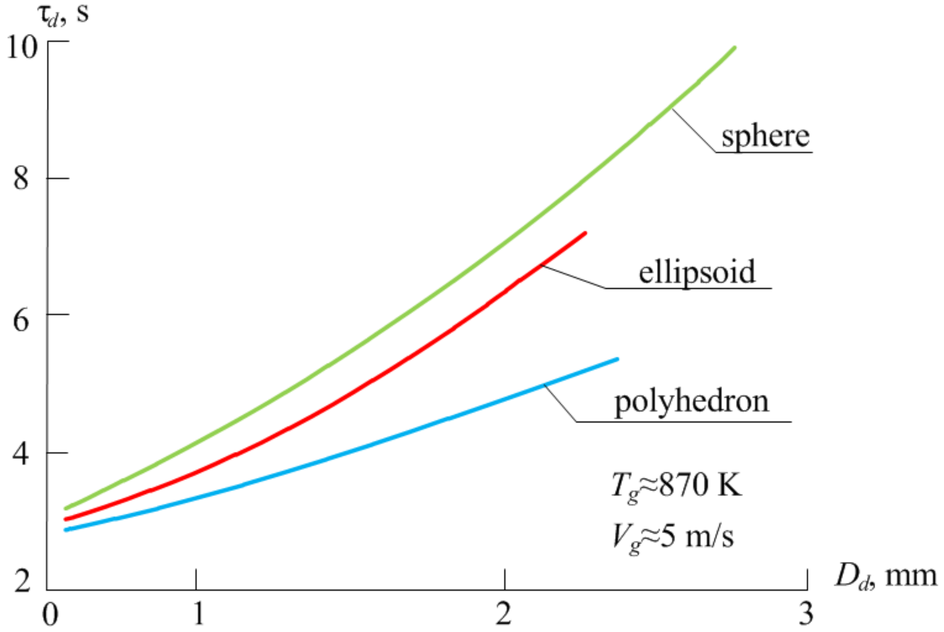
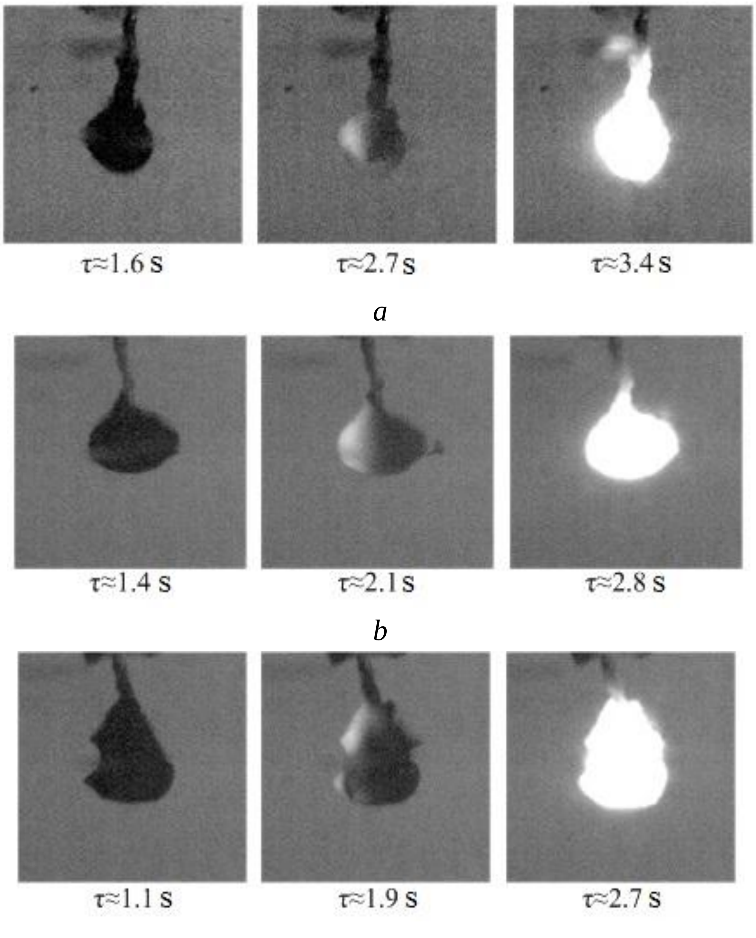


Figure 6. Ignition delay times of the CWSP particle fixed on thermocouple junction depending on the oxidizer temperature [5, 6]

Experiments [5, 6] revealed that the shortest ignition delay times are typical for polyhedral CWSP particles. This is caused by a noticeable intensification of convective flows in a thin superficial layer. In the case of irregularly shaped particles (polyhedral), its interaction with the oxidizer is more complicated. When the oxidizer flow meets protrusions on the particle surface (vertices of the polyhedron), it is divided substantially evenly. The oxidizer velocities increase significantly near such protrusions. This is caused by the formation of local vortices (turbulence). The latter are blown by the flow from the frontal part to the track. This leads to the fact gas velocities in the track are higher for an irregular polyhedron then for a sphere and an ellipsoid (with identical sizes). Therefore, the droplet is heated-up faster due to the intense formation of vortices in the front and their growth in the wake of the particle. More intense heat transfer with the flow is typical for irregularly shaped particles (with surface roughness and porosity). Several ignition zones are formed on the particle's surface. Fig. 7 shows the typical images of experiments [5, 6], where we can see the emergence of several local ignition zones for the polyhedral particle and a combustion front for the sphere and the ellipsoid.



a

b

c

Figure 7. The emergence of heterogeneous combustion front on the protrusions of the CWSP particle (*a* – sphere, *b* – ellipsoid, *c* – polyhedron) fixed on thermocouple junction [5, 6]

Video recordings of experiments [5, 6] have shown that the influence of fuel particle shape is particularly noticeable at the initial stage of combustion. The conditions of the spread of the combustion front and the completion of combustion are almost identical for different shapes. The combustion front of carbon is emerged under significantly different conditions and characteristics depending on shape configuration. For all of the experiments, the combustion front is formed from the side of the oncoming oxidizer flow. This is due to the relevant characteristics of flowing around the particle. In the case of the sphere, such front is usually located on the axis of particle's symmetry. For the ellipsoid, ignition zone is shifted relative to the axis of symmetry in the direction of one of the lateral vertices. In the experiments with the irregular polyhedron, the combustion front is formed in the region with the largest protrusions (vertices) of the polyhedron from the side of the oncoming flow. It does not matter what is the position of protrusions (top, bottom or near the symmetry axis). In this case, the durations of the characteristic stages of combustion are minimal. As a result, the ignition delay times of irregular polyhedral particles are minimum compared to that for spherical and ellipsoidal particles (fig. 6).

Let us mention an important feature indicating how the shape of the CWSP particle influences its ignition characteristics. This feature has been revealed during additional experiments with soaring particles. The influence of particle shape on times τ_d enhances, when the proportion of volatiles in CWSP increases. We have conducted experiments with the CWSP based on brown coal, similar to that described in the paper [19]. It has been found that polyhedral particles ignite substantially faster than spheres or ellipsoids. This is due to the fact that polyhedral particles are rapidly dispersed during rotation in the oxidizer flow. This is caused by the yielding of volatiles and moisture from their superficial layer.

A comparison of the obtained experimental results and experimental data [5, 6, 19] allow us to make some recommendations for the development of modern technologies of burning CWS and CWSP in power plants and other facilities. These recommendations will help to improve the efficiency of combustion initiation:

– to minimize the consumption of resources in the combustion of coal-water slurry, it is advisable to use special devices (e.g., sieves or grids on spray nozzles) for generating irregularly shaped particles of CWS and CWSP (for a wide range of oxidizer temperatures and velocities relative to fuel particles);

– it is also advisable to increase the velocity of CWSP particles to enhance their surface deformation (the transformation of a sphere into an ellipsoid and more complex shapes due to the growth of aerodynamic forces);

– it is advisable to use carbon components for preparing CWS and CWSP (e.g., brown coal, the products of its processing, coal mixtures including brown coal), which ensure dispersion with a high probability. In this case, irregularly shaped particles are formed spontaneously (dispersion takes place and, accordingly, the fragments detached from the main body ignite);

– it is advisable to increase the viscosity of suspensions (for example, by increasing the proportion of liquid fuel components or coal). The additional experiments have demonstrated that even if to inject CWSP particles with high viscosity by a laboratory dispenser [5, 6], their surface will substantially deform (particles will not be spherical);

– it is advisable to add coal mixtures to CWSP. Then, the structure of a fuel suspension will be substantially uniform. This leads to surface deformation, irregularly shaped particles, and the intensification of ignition;

– surface deformation of a particle ensures stable ignition at low temperatures (compare to spheres).

The experimental study specifies the ignition laws of CWSP particles having different surface configurations. This knowledge may expand current understanding of the ignition of coal-water slurry compositions. It can be useful for the development of relevant heat and mass transfer models (in particular, [20–22]) in terms of phase changes and chemical reactions.

The study revealed that irregularly shaped particles react more intensively even at lower oxidizer temperatures. The temperatures for ellipsoids and polyhedrons are 20–30 K lower than for spheres in the combustion chamber. This leads to the conclusion that the effect of particle shape should be used for the development of low-temperature (limit or threshold) ignition [23, 24]. We may also predict its great potential for power engineering, since the main difficulty is usually in ignition and subsequent incomplete combustion due to relatively low temperatures.

Conclusion

This paper expands the findings of the study [19] on the ignition of coal-water slurry particles soaring in the oxidizer medium. The coal-water slurry is prepared by recycling coal and oil. The conditions provided in the experiments are very close to real boilers in power plants.

The study points out that integral ignition characteristics are different for fuel particles with various surface configurations. This indicates that this issue has a big perspective for ignition optimization. Another issue is to minimize the expenditure of resources when burning CWSP in power plants. For this purpose it is advisable to use special devices (e.g., sieves or grids on sprayers) for generating irregularly shaped particles (having maximum aerodynamic drag).

Acknowledgement

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Nomenclature

a_d, b_d, c_d, e_d – maximum linear dimensions of fuel particle with different surface configurations, [m]
D_d – average particle size, [m]
$Q^a_{s,V}$ – highest calorific value, [kcal/kg]
R_d – radius of fuel particle, [m]
T_d – temperature at the center of particle, [K]
T_g – oxidizer temperature, [K]
V_g – oxidizer velocity, [ms^{-1}]
τ – time, [s]
τ_c – time of complete combustion of particle, [s]
τ_d – ignition delay time of particle, [s]

References

[1] Zasypkin, I. M., *et al.*, Systems of ignition and combustion stabilization for water-coal fuel, *Thermal Science*, *16* (2012), 4, pp. 1229-1238

[2] Wilczyńska-Michalik, W., *et al.*, Composition of coal combustion by-products: The importance of combustion technology, *Fuel Processing Technology*, *124* (2014), pp. 35-43

[3] Murko, V. I., *et al.*, Investigation of the spraying mechanism and combustion of the suspended coal fuel, *Thermal Science*, *19* (2015), 1, pp. 243-251

[4] Jianzhong, L., *et al.*, Pilot-scale investigation on slurrying, combustion, and slagging characteristics of coal slurry fuel prepared using industrial waste liquid, *Applied Energy*, *115* (2014), pp. 309-319

[5] Glushkov, D. O., *et al.*, Influence of organic coal-water fuel composition on the characteristics of sustainable droplet ignition, *Fuel Processing Technology*, *143* (2016), pp. 60-68

[6] Glushkov, D. O., *et al.*, Minimum temperatures for sustainable ignition of coal water slurry containing petrochemicals, *Applied Thermal Engineering*, *96* (2016), pp. 534-546

[7] Kontorovich, A. E., *et al.*, Long-term and medium-term scenarios and factors in world energy perspectives for the 21st century, *Russian Geology and Geophysics*, *55* (2014), 5-6, pp. 534-43

[8] *Coal Information*, International Energy Agency, Luxembourg, 2015

[9] *BP Statistical Review of World Energy*, BP, London, England, 2015

[10] Zhao, H., *et al.*, Breakup and atomization of a round coal water slurry jet by an annular air jet, *Chemical Engineering Science*, *78* (2012), pp. 63-74

[11] Tu, Y., *et al.*, Method for evaluating packing condition of particles in coal water slurry, *Powder Technology*, *281* (2015), pp. 121-128

[12] He, Q., *et al.*, The utilization of sewage sludge by blending with coal water slurry, *Fuel*, *159* (2015), pp. 40-44

[13] Umar, D. F., *et al.*, Effect of dispersing and stabilizing additives on rheological characteristics of the upgraded brown coal water mixture, *Fuel Processing Technology*, *90* (2009), 4, pp. 611-615

[14] Khodakov, G. S., *et al.*, Coal-slurry fuel, *Solid Fuel Chemistry*, *39* (2005), 6, pp. 12-27

[15] Khodakov, G. S., Coal-water suspensions in power engineering, *Thermal Engineering*, *54* (2007), 1, pp. 36-47

[16] Red'Kina, N. I., *et al.*, Coal fuel slurry for internal combustion engines, *Solid Fuel Chemistry*, *47* (2013), 5, pp. 306-314

[17] Gajewski, W., *et al.*, Analysis of cyclic combustion of solid fuels, *Fuel*, *88* (2009), 2, pp. 221-34

[18] Kijo-Kleczkowska, A., Combustion of coal-water suspensions, *Fuel*, *90* (2011) 2, pp. 865-77

[19] Valiullin, T.R., *et al.*, Low temperature combustion of organic coal-water fuel droplets containing petrochemicals while soaring in a combustion chamber model, *Thermal Science*, Online First. 10.2298/TSCI151215221V

[20] Kuznetsov, G. V., *et al.*, Numerical simulation of ignition of particles of a coal–water fuel, *Combustion, Explosion and Shock Waves*, *51* (2015), 4, pp. 409-415

[21] Syrodoy, S. V., *et al.*, The influence of heat transfer conditions on the parameters characterizing the ignition of coal-water slurry particles, *Thermal Engineering*, 62 (2015), 10, pp. 703-707

[22] Belošević, S., *et al.*, Numerical prediction of processes for clean and efficient combustion of pulverized coal in power plants, *Applied Thermal Engineering*, 74 (2015) 102-110

[23] Glushkov, D. O., *et al.*, Numerical research of heat and mass transfer during low-temperature ignition of a coal particle, *Thermal Science*, *19* (2015), 1, pp. 285–294