Ignition of a Droplet of Composite Liquid Fuel in a Vortex Combustion Chamber

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Abstract. Experimental study results of a droplet ignition and combustion were obtained for coal-water slurry containing petrochemicals (CWSP) prepared from coal processing waste, low-grade coal and waste petroleum products. A comparative analysis of process characteristics were carried out in different conditions of fuel droplet interaction with heated air flow: droplet soars in air flow in a vortex combustion chamber, droplet soars in ascending air flow in a cone-shaped combustion chamber, and droplet is placed in a thermocouple junction and motionless in air flow. The size (initial radii) of CWSP droplet was varied in the range of 0.5–1.5 mm. The ignition delay time of fuel was determined by the intensity of the visible glow in the vicinity of the droplet during CWSP combustion. It was established (under similar conditions) that ignition delay time of CWSP droplets in the combustion chamber is lower in 2–3.5 times than similar characteristic in conditions of motionless droplet placed in a thermocouple junction. The average value of ignition delay time of CWSP droplet is 3–12 s in conditions of oxidizer temperature is 600–850 K. Obtained experimental results were explained by the influence of heat and mass transfer processes in the droplet vicinity on ignition characteristics in different conditions of CWSP droplet interaction with heated air flow. Experimental results are of interest for the development of combustion technology of promising fuel for thermal power engineering.

1. Introduction
According to the data of International Energy Agency [1, 2] and other expert organizations (for example, [3]), despite the development of green and renewable energy, the role of fossil fuels (oil, coal and natural gas) is dominant in the global energy balance. This trend will continue in the coming 20–25 years. Coal-fired power plants are considered to be the strongest polluters of the environment. However, the refusal of coal combustion for the near future cannot take place for a number of objective reasons. The reserves and availability of coal around the world make it an attractive energy source. For example, in 2014 approximately 41% of the electricity generated in the world was produced by coal burning [2]. Negative consequences of coal combustion are particularly noticeable in large cities and regions with developed mining and processing industries. It is known that the coal combustion leads to significant emissions of harmful gases (carbon dioxide, sulphur oxide, and nitrogen), volatile organic compounds, heavy metals, etc. Air, water and land pollution leads to increasing green-house effect, acid rain, deterioration of the atmosphere, etc. [4–6]. In addition to pollution from coal combustion emissions, there is another problem related to the coal industry. Coal washing plants generate coal waste. The quantity of waste according to rough estimates
is about 10–15% from the mass of the coal rock. Taking into account the world volume of coal mining, the amount of waste of coal enrichment is enormous therefore the problem of its utilization is relevant for the coal-mining regions.

One of the widespread technologies for coal enriching is flotation. It is based on the different ability of substances to wettability. According to flotation technology, the run-of-mine coal is washed with special reagents and then filtered. As a result of this process, a wet flotation waste is formed (called filter cake). Due to the imperfection of the technological process and equipment, the characteristics of the enriched raw material, filter cakes contain a rather large share of coal. Thus, during the enrichment, the fuel resource is lost.

Wet coal processing waste is called coal water slurry (CWS). Such slurry contains about 30–50% of water and small-sized 80–120 μm coal particles. Until recently, the characteristics of the ignition and combustion of CWS, prepared only on the basis of conditional coal dust, were investigated (for example, in [7, 8]). But in the last few years the idea was suggested [9, 10] for joint combustion of waste-derived coal water slurries and petrochemicals. In [9, 10] the characteristics of ignition and combustion of single CWS droplets were determined in conditions of motionless droplet placed in a holder (wire, thermocouple junction, etc.). The CWS prepared from wet flotation wastes, low-grade coal, petroleum component (waste industrial and automobile oils, heavy oil, oil-water emulsion) were studied [9, 10]. It has been established [11, 12] that the emissions of harmful gases in conditions of coal-water slurry combustion prepared from coal processing waste with an additive of oil (5–15% wt.) do not exceed similar characteristics of coal dust combustion.

In present paper for the development of theoretical base of CWS combustion technology, a comparative analysis were carried out for determination of ignition characteristics of CWS droplets with different component composition, size and interaction condition fuel droplet with heated air flow.

2. Experimental Details

2.1. Materials

CWS is a mixture of solid combustible component (coal), water, and liquid combustible component (oil). The composition of the CWS (components and its mass fraction) can vary considerably. It should be noted that the coal washing wastes (filter cakes) used in the study are already a slurry consisting of water and coal particles. The Tables 1, 2 show the properties of typical components that is used for CWS preparation. Filter cakes of nonbanking and gas coals contains 39.1% and 53% (respectively) of water in initial state.

| Sample                       | $W^a$, % | $A^d$, % | $V^d$, % | $Q^c,_{v}$, MJ/kg | $C^d$, % | $H^d$, % | $N^d$, % | $S^d$, % | $O^d$, % |
|------------------------------|----------|----------|----------|-------------------|---------|---------|---------|---------|---------|
| Filter cake of nonbaking coal | –        | 21.2     | 16.09    | 26.92             | 90.13   | 4.26    | 2.31    | 0.44    | 2.77    |
| Filter cake of gas coal      | –        | 33.82    | 43.11    | 22.16             | 75.12   | 4.64    | 0.02    | 0.23    | 19.99   |
| Lignite                      | 14.1     | 4.12     | 47.63    | 22.91             | 73.25   | 6.52    | 0.79    | 0.44    | 18.99   |
| Carbon residue of tire pyrolysis | 1.39 | 13.1     | 20.14    | 30.11             | 91.47   | 2.42    | 0.37    | 2.44    | 2.93    |

Note. $W^a$ – humidity of analytical sample in an air-dry state, %; $A^d$ – ash level, %; $V^d$ – volatiles in a dry ash-free state; $Q^c,_{v}$ – enthalpy of combustion of analytical sample, MJ/kg; $C^d$, $H^d$, $N^d$, $S^d$, $O^d$ – fraction of carbon, hydrogen, nitrogen, sulfur and oxygen in the sample (converted to a dry ash-free state), %.
Table 2. Characteristics of liquid combustible component of CWSP

| Sample                  | Density at 293 K, kg/m³ | Humidity, % | Ash level, % | Flash point, K | Ignition temperature, K | Combustion heat, MJ/kg |
|-------------------------|-------------------------|-------------|--------------|----------------|-------------------------|------------------------|
| Waste turbine oil       | 868                     | <0.01       | 0.03         | 448            | 466                     | 44.99                  |
| Heavy oil               | 1000                    | 6.12        | 4.06         | 438            | 513                     | 39.4                   |

2.2. Fuel preparation
The procedure of fuel preparation is described in detail in the papers [9, 10]. Homogenizer (MPW-302) was used to mix the fuel components. First, a water-oil emulsion was prepared and then the solid component (coal dust, crushed pyrolysis product of automobile tires) was added to the emulsion. All components were mixed during 8–10 minutes until a homogeneous suspension was obtained. If the filter cake is used as the main fuel component, the water-oil emulsion was prepared only in the case of drying of filter cake (which can occur during long-term storage). Otherwise, the fuel was prepared in one step by homogenizing the filter cake and the oil component.

2.3. Experimental setups
Three experimental setups and three experimental technics were used for studying ignition and combustion of CWSP droplets. The first method [9, 10] is based on the heating of single droplet placed on the junction of a low-inertia thermocouple. The ignition delay time and the burning time can be determined by both the temperature change in the droplet and by the video recording (by the intensity of the visible glow in the vicinity of the droplet). The combustion chamber was a hollow glass (quartz) channel in cylinder shape. Heated air flow was formed inside the channel. Temperature and velocity is controlled. The main equipment of the experimental setup, procedures for video recording of ignition and combustion characteristics, the measurement errors were described in [9, 10]. The second experimental method is based on the heating of single droplet injected into a cone-shaped combustion chamber. The characteristics of the ignition were determined from the intensity of the glow of the fuel sample (characteristic colour rendition by colour model RGB 255). RGB 255 corresponded to white colour, 0 – to black. It was assumed that the combustion of the sample corresponded to the range of the RGB model Threshold=220–255. Thus, the ignition delay time was determined as the time interval from the moment when the droplet was placed in the chamber until the Threshold parameter (in the region corresponding to the ignition) was 220 (on any part of the surface of the CWSP droplet). The characteristics of the experimental technique, combustion chamber, and measurement errors were described in [13].

The third experimental method is based on the heating of single droplet injected (by an automated coordinate device) into a vortex combustion chamber. It is made in the form of a cylinder with a diameter of 0.4 m and a height of 0.26 m. The temperature in the combustion chamber varied in the range of 600–850 K. The temperature was controlled by four type K thermocouples (temperature range 273–1373 K, error ± 3 K). The air flow, pumped by the air fan, was 72 m³/h. The characteristics of ignition and combustion processes of fuel droplet were investigated using high-speed video recording. The CWSP ignition time was determined by the intensity of the visible glow of the droplet during its combustion (identical as in the second experimental method).

3. Results and Discussion
It was established that the main stages of physical and chemical processes during the heating of CWSP of different compositions are the same in conditions of different experimental techniques. When droplet is placed in a thermocouple junction and motionless in air flow it is possible to determine in most detail the stages of ignition of composite liquid fuel by means of high-speed video registration and thermocouple measurements. When the droplet enters into the combustion chamber, the warming up of CWSP (especially the upper layers of droplet) takes place with intensive evaporation of moisture and combustible liquid. The surface of the droplet becomes porous. The process of coal thermal decomposition in the near-surface layer of droplet is intensified. When the fuel droplet moves in the
combustion chamber (including vortex), the effect of dispersing (or fragmentation) of the droplet can be enhanced due to intense interaction with swirling flows, and also due to contact with the walls of the combustion chamber.

The duration of the ignition stages differs (Fig. 1) for different conditions of fuel droplet interaction with heated air flow (different experimental techniques). The ignition of fuel droplet happens rapidly under heating in vortex combustion chamber, than in other cases (droplet soars in ascending air flow in a cone-shaped combustion chamber, droplet is placed in a thermocouple junction and motionless in air flow). It can be explained by the absence of heat outflow (to the holder), as well as additional heating from the radiation of the chamber walls. During the heating stage, the effect of the holder on the ignition characteristics of the fuel droplet can be quite significant, especially at temperatures close to the minimum ignition temperatures. However, in the case of high intensively physical and chemical processes (at high oxidizer temperature), the effect of heat exchange between the droplet and the holder significantly less affects to the ignition characteristics (Table 3).

It should be noted that the duration of ignition process of the slurry based on lignite with the addition of waste oil is higher than CWS without oil (Fig. 1). Obtained result can be explained by the properties of brown coal. Lignite is a reaction component and contains a large amount of volatiles, therefore, when a CWS droplet is heated, thermal decomposition of the organic mass, gas-phase and heterogeneous combustion of the fuel begins quickly and intensively (even at relatively low temperatures). When oil is added to the fuel, the mass fraction of coal is reduced and additional heat is spent to evaporate the liquid combustible component. Despite the increase in the duration of the ignition, the addition of oil to the suspension based on brown coal is advisable to increase the heat of fuel combustion. It is important to note that the use of oil in a suspension based on waste, on the contrary, can intensify fuel ignition.

![Figure 1](image_url)

**Figure 1.** Ignition delay time of CWS and CWSP in conditions of different experimental techniques (droplet parameters: $R_d \approx 0.5$ mm, $T_g \approx 700$ K, $V_g \approx 3$ m/s).
Table 3. Ignition delay time of CWSP (50% lignite, 39.5% water, 10% waste turbine oil, 0.5% plasticizer) in conditions of different experimental techniques and oxidizer temperature

| Oxidizer temperature, K | Thermocouple junction | Cone-shaped combustion chamber | Vortex combustion chamber |
|-------------------------|------------------------|-------------------------------|---------------------------|
| 600                     | 22                     | 15                            | 12                        |
| 700                     | 11                     | 8                             | 4                         |
| 850                     | 4.5                    | 4                             | 2                         |

The main economic advantage of CWSP in comparison with coal is the availability and low cost of raw materials for their preparation. Fig. 2 illustrates the characteristics of ignition of fuels, prepared from coal processing wastes, carbon residue of tire pyrolysis, and waste turbine oil or heavy oil. Stable ignition of droplets of such compositions takes place at the oxidizer temperature 670–900 K. Experiments have shown that the intensification of the CWSP ignition process at relatively low oxidizer temperature (less than 800 K) and reduction of the ignition delay time is possible if coal and coal-enrichment waste with a high content of volatiles, combustible liquids with low temperatures of flashpoints and ignition, low values of evaporation heat have been used as a components fuel.

![Figure 2](image)

**Figure 2.** Ignition delay time of CWSP based on different wastes (motionless droplet placed in a thermocouple junction, \(R_d\approx1.3\) mm, \(T_g\approx970\) K, \(V_g\approx2.5\) m/s).

4. Conclusion
A wide range of industrial waste can be used as components of composite fuels for combustion in industrial boilers. The use of waste derived fuels in thermal engineering is perspective from the point of view of waste disposal, reduction of dumping sites, and reduction of the cost of energy production. Fuels based on wet coal waste (filter cakes) can be effectively used in countries and regions with developed coal mining (China, Australia, India, and Russia). The analysis of characteristics and conditions of droplet ignition for fuel with different components presented in the paper shows the possibilities of industrial application of CWSP in power plants under for various combustion technologies including low-temperature ignition regime.
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