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Simultaneous ignition of several droplets of coal–water slurry containing petrochemicals in oxidizer flow

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ABSTRACT

This paper examines ignition features of coal–water slurry containing petrochemicals (CWSP). Fuel slurry composition is based on a filter cake (typical processing waste) of coal (grade K), water, scavenged turbine oil, and plasticizer. The novelty of this paper is that it indicates a joint influence of several droplets on the CWSP ignition characteristics in an oxidizer flow (air). Its temperature and velocity vary in the range of 400–1200 K and 0.5–5 m/s. These ranges are chosen so as to yield optimal results that can be used in various fuel technologies and waste recycling. The study examines the cases of two, three, four, and five droplets. It is considered that droplets are arranged differently relative to each other (in parallel, in series, and in rhomb) in the oxidizer flow. The distances between droplets are also different; here, they vary from 0.5 mm to 1.5 mm. The diameter of each droplet is about 1 mm. The study specifies the ignition delay time for CWSP. Special facilities, such as high-speed cameras, cross-correlation systems, a hollow glass cylinder (representing a combustion chamber), are used to monitor the basic parameters of ignition. Tema Automotive and Actual Flow software allow processing of the experimental results. Experiments demonstrate that the local sources of heterogeneous combustion are formed when CWSP droplets are burning. Such formation is characterized by some features, since droplets are spaced differently in the group relative to the oxidizer flow. Finally, the paper discusses the joint influence of neighboring droplets on the conditions and characteristics of their sustainable combustion.

1. Introduction

Recycling of typical organic energy resources, e.g., coal and oil, is accompanied by the generation of waste such as oil sludge and cakes. The volume of this waste is from 8% to 15% of energy production volume, depending on deposits, processing technologies, and production rate [1–6]. For example, China produced 1.84 billion tons of coal and lignite in 2015. At the same time, almost 162 million tons of cakes were formed there [5,6]. For Russia, the United States, Japan, and India, these numbers are also quite large [1–6]. These issues are of particular interest in Russia, since most of this waste is stored outdoors there.

Cakes and oil sludge pose a great danger to the environment. Although a part of this waste is disposed of, the bulk of waste is not recycled at all. To date, the world has accumulated more than 1 billion tons of sludge [3–6]. Moreover, various industries produce annually tens of millions of tons of liquid combustible waste (e.g., scavenged motor, turbine, transformer, and compressor oil, etc.).

To date, it has become clear that further disposal or open storage of cakes, sludge, and waste flammable liquids is becoming impossible. In particular, it was discussed at a conference on climate change held in Paris in December 2015. It is necessary to take measures at an international level to recycle both new waste and waste accumulated over the past decade. Failure to take measures to eliminate such waste can lead to an environmental disaster. A striking example is air pollution in China's major cities that is now at a level ten times greater than the maximum allowable concentration (as of January, 2016). This is mainly caused by the operation of coal processing and coal burning plants which emit coal dust into the atmosphere. One of the current trends is energy efficient and environmentally friendly recycling of coal and oil waste for preparing coal–water slurry (CWS) and coal–water slurry containing petrochemicals (CWSP) [7–12]. Such slurries can be burned in power industry, as well as in car engines instead of diesel.

It is assumed that the fuel compositions of CWS and CWSP should be burned in the form of aerosol streams in power plants [7–12]. Unfortunately, there are virtually no reliable experimental data on the conditions and characteristics of ignition and combustion of such slurries as an aerosol. This state of affairs can be explained by the lack of appropriate experimental methods that allow one to record high-speed processes during the combustion of aerosol fuels. Another reason is a high complexity of these processes, especially when examining the factors that affect ignition and combustion characteristics. Moreover, a large number of components with different properties must be considered. In particular, the following components can be used for preparing

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Nomenclature

C_{o2}	Dimensionless oxidant concentration
L_x	Longitudinal distance between droplets, m
L_y	Transverse distance between droplets, m
R_d	Droplet radius, m
T	Temperature, K
T_d	Droplet temperature, K
T_g	Oxidizer flow temperature, K
V_g	Oxidizer flow velocity, m/s

Greek symbols

τ	Time, s
τ_d	Ignition delay time, s

CWS and CWSP: low-quality coal dust, coal and oil refining waste, wastewater, scavenged oil, and various flammable liquids.

A famous theory of ignition of CWS and CWSP (e.g., [13–19]) is based on the experimental results for individual droplets or particles. Note that both terms are used in the literature, depending on the moisture content. There is a quite large group of experimental methods, for example, described in references [20–25]. Currently, the most widely used method proposes to hang CWS or CWSP droplets on a low-inertia thermocouple junction, ceramic filament, metal wire, or another small holder [20,21]. This approach allows for temperature control of a fuel droplet at all reaction stages: from inert heating till heterogeneous carbon burning.

Modern software (e.g., Ansys, Fluent, CWF, and Matlab) for mathematical simulation allow the use of the experimental models of heat and mass transfer, phase transformations, and chemical reactions of CWS and CWSP [17–19] only for individual droplets or particles (to the best of the authors knowledge). In such circumstances, it is almost impossible to take into account the joint influence of several fuel droplets or particles on the conditions and characteristics of their combustion. This effect is most likely to be crucial for droplets in the oxidizer flow. For example, experiments [26] demonstrated that the droplets moving first affect significantly the heat transfer conditions of the following droplets. In the case of CWS and CWSP, mass transfer in gas plays an important role in addition to heat transfer.

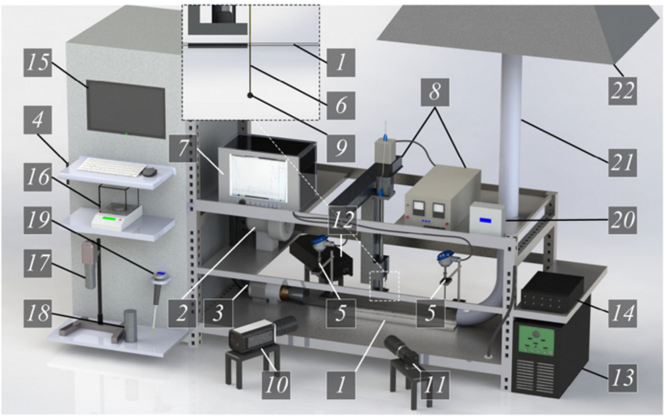

Fig. 1. Schematic of the experimental setup [23]: *1*—hollow glass cylinder; *2*—air fan; *3*—heater; *4*—remote control; *5*—thermocouples; *6*—tip (or low-inertia thermocouple); *7*—recorder; *8*—minirobotic arm; *9*—CWSP droplet; *10*—high-speed video camera; *11*—cross-correlation camera; *12*—laser; *13*—laser generator; *14*—laser and cross-correlation camera synchronizer; *15*—computer; *16*—analytical balance; *17*—homogenizer; *18*—vessel with CWSP; *19*—electronic dispenser; *20*—gas analyzer; *21*—ductwork; *22*—ventilation.

Table 1
Results of technical analysis of filter cake based on bituminous coal.

Sample	Mass fraction, %			Enthalpy of oxidation, MJ/kg
	Humidity	Ash	Volatiles	
Dry filter cake based on bituminous coal	–	26.46	23.08	24.83

The approach proposed in papers [20,21] indicated that neighboring CWSP droplets influence their ignition conditions and characteristics in the oxidizer flow. According to this approach, droplets are hung in the oxidizer flow at a controlled mode and velocity. It is thus possible to monitor the relative position and distances between droplets, as the oxidizer flow moves in different directions. It is advisable to examine the most typical droplets' arrangements in the oxidizer flow. This study will demonstrate how this factor influences fuel ignition characteristics. Also, it will help to make recommendations for optimizing fuel spray (flow rate, droplets' sizes, their concentration, location, and distances between them) into the combustion chamber.

The objective of this paper is to study experimentally the ignition characteristics of several CWSP droplets in the heated oxidizer flow.

2. Experimental methods

Fig. 1 shows a schematic of an experimental setup. The main recording equipment and droplets' generation tools are similar to those used in experiments [23–25].

Low-inertia thermocouple junctions were used as a holder (feature *6*) (type-S, temperature measurement range is 273–1873 K, systematic error is ±1 K, inertia is less than 1 s). This allows investigation of the ignition conditions and characteristics of single and several (two, three, four, and five) CWSP droplets in a heated air flow. In experiments [23–25], metal wires and ceramic threads with appropriate configurations were used in addition to these junctions. Studies [23–25] revealed that the holder influences significantly ignition characteristics at relatively low temperatures of ignition (up to 800 K). Times were minimal in the case of using a thermocouple junction, maximal—when using a metal wire. At temperatures over 800 K, the main ignition characteristics were similar for all three types of holders. The differences did not exceed 5–7%.

This study examines one of the most common [24,25] fuel compositions of CWSP. It is based on waste from coal processing and coal refining (filter cake), and scavenged oil (turbine oil). A dry filter cake based on bituminous coal was supplied from the enrichment factory "Severnaya" of the Kemerovo region, Russian Federation. A filter-cake is a waste product of coal flotation. The size of a coal particle in filter cakes is 80–100 μm. Tables 1–3 present the results of technical and elemental analysis of filter cake [24,25].

Scavenged turbine oil is used as a liquid fuel component of CWSP (see Table 4). A plasticizer is added to the fuel composition (see Table 5), as in experiments [24,25]. This enhances the long-term preservation of a stable structure of CWSP. The relative mass concentrations of the components are assumed as follows: 89.5% of a wet filter cake, 10% of waste turbine oil, 0.5% of a plasticizer.

Methods for preparation of CWSP compositions, as well as for analysis of its viscosity and stability, are similar to those described in references [24,25]. The following two technologies of preparing CWS and CWSP are the most widely used in scientific research and industrial

Table 2
Results of elemental analysis of filter cake based on bituminous coal.

Sample	Mass fraction converted to a dry ash-free state, %				
	C	H	N	S	O
Dry filter cake based on bituminous coal	87.20	5.09	2.05	1.022	4.46