LOW TEMPERATURE COMBUSTION OF ORGANIC COAL-WATER FUEL DROPLETS CONTAINING PETROCHEMICALS WHILE SOARING IN A COMBUSTION CHAMBER MODEL

by

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The paper examines the integral characteristics (minimum temperature, ignition delay times) of stable combustion initiation of organic coal-water fuel droplets (initial radius is 0.3-1.5 mm) in the oxidizer flow (the temperature and velocity varied in ranges 500-900 K, 0.5-3 m/s). The main components of organic coal-water fuel were: brown coal particles, filter-cakes obtained in coal processing, waste engine, and turbine oils. The different modes of soaring and ignition of organic coal-water fuel have been established. The conditions have been set under which it is possible to implement the sustainable soaring and ignition of organic coal-water fuel droplets. We have compared the ignition characteristics with those defined in the traditional approach (based on placing the droplets on a low-inertia thermocouple junction into the combustion chamber). The paper shows the scale of the influence of heat sink over the thermocouple junction on ignition inertia. An original technique for releasing organic coal-water fuel droplets to the combustion chamber was proposed and tested. The limitations of this technique and the prospects of experimental results for the optimization of energy equipment operation were also formulated.

Key words: *organic coal-water fuel, droplet, soaring, low-temperature combustion, combustion chamber model*

Introduction

At present, quite a large group of countries (for example, China, Japan, Russia, USA, and others) has increased interest in the use of alternative fuels (based on coal-water technologies) instead of traditional (coal, fuel oil) for various power plants. In particular, the number of research papers has increased significantly in the field of creation and application of coal-water fuel (CWF) in large and small power industries [1-8]. The interest in using CWF in the energy sector is due to reasonable (quite substantial) benefits, including:

- the possibility of involving various low-grade fuels (*e. g.,* high-ash coal) and liquid flammable substances (waste oil, oil-water emulsion), the raw material base of which is constantly replenished [9-11],
- the improvement of the environmental performance of boiler plants on emissions (*e. g.* SO_x and NO_x content in flue gases) compared to the burning of traditional fuels (especially coal), and
- the improvement of economic performance of heat and electricity production through the use of cheaper source of fuel.

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As the main CWF components, there are used fine coal (particle size is 100-150 μm or less) and water. Over the past 10-15 years, coal-water slurry containing petrochemicals (organic CWF – OCWF) has begun to be considered as promising CWF. The OCWF contains various liquid petrochemicals in addition to a solid fuel base and water [9-11]. The use of various liquid petrochemicals (oils, oil-water emulsion, and other) for creating OCWF allows, on the one hand, improve the properties of fuel coal-water compositions (in particular, increase the heat of combustion, increase the duration of segmental stability conservation) and, on the other hand, utilize safely (with improved environmental and economic performance) materials such as, for example, waste motor, turbine, transformer and other oils.

For the effective use of CWF and OCWF in real thermal power plants, it is advisable to carry out preliminarily relevant investigations in the laboratory to identify the main characteristics of the ignition and combustion of certain fuel compositions. The CWF and OCWF are burned in the chamber furnaces of boiler plants, when fuel is sprayed through nozzles. Thus, it is appropriate to conduct model tests, while feeding fuel in air jet into the combustion chamber or ensure a soaring mode in the oxidizer flow. The traditional and most common approach for defining ignition and combustion characteristics is based on suspending fuel droplets at the low-inertia thermocouple junction, wires or non-combustible (usually ceramic) filaments [12-16]. One of the major drawbacks of this method is the presence of heat sink over the thermocouple junction, wire or a ceramic filament [12-16]. This phenomenon imposes certain constraints (restrictions) in modelling heat and mass transfer processes, and often do not allow matching adequately the physical model of fuel combustion in a boiler and the mathematical model used for describing such processes, for example in [17-20].

Therefore, it is advisable to create experimental methods for determining ignition characteristics of CWF and OCWF in the laboratory, as close as possible to the processes occurring in real power plants. In this case, as a promising direction, it can be considered the determining of the ignition characteristics of individual fuel droplets during soaring (often, it is used a special term *fluidized bed*) in the combustion chamber. Moreover, first of all, it is necessary to examine low-temperature (below 1000 K) ignition modes [21-23], which can significantly reduce the times of switching energy equipment to specified operating modes.

The purpose of the present study is to determine experimentally the integral characteristics of low-temperature ignition of coal-water slurry droplets containing petrochemicals during their soaring in the combustion chamber model.

Experimental set-up and procedure

Authors have determined the integral characteristics of OCWF ignition on experimental set-up (fig. 1) in the combustion chamber (fig. 2) made of optically transparent quartz glass. We calculated the geometric parameters of the combustion chamber under the following set conditions: OCWF droplet size is from 0.3 to 1.5 mm (spherical coefficient is 0.73), the maximum height of droplet displacement along the vertical axis – 120 mm (defined by performance limitations of a high-speed camera at a given resolution and duration of recording), droplet characteristics (density, ash content, *etc.*) were defined by OCWF component composition. The calculation of geometric dimensions of the chamber was performed by the method of determining the soaring of a single droplet (particle), for which it is assumed the equality of aerodynamic drag forces of a particle and gravitational forces in the oxidizer upstream. The calculation was performed using an empirical Todes relationship [24]:

$$\mathrm{Re} = \frac{\mathrm{Ar}}{18 + 0.61\sqrt{\mathrm{Ar}}}$$

Two technological holes 11 mm in diameter were drilled in the combustion chamber. The holes were used for inserting a OCWF droplet, as well as for measuring the air temperature by a chromel-alumel thermocouple (temperature measurement range is 273-1373 K, systematic error is ±3 K, the inertia is not more than 3 seconds). Using a blower and a heater, the temperature and velocity in the combustion chamber varied in ranges: 500-900 K and 0.5-3 m/s, respectively. At the lower and upper parts of the combustion chamber, distribution grids were mounted made of stainless steel with a mesh size of 0.5 × 0.5 mm. These grids are intended for averaging (levelling) the oxidizer velocity over the cross section of the combustion chamber.

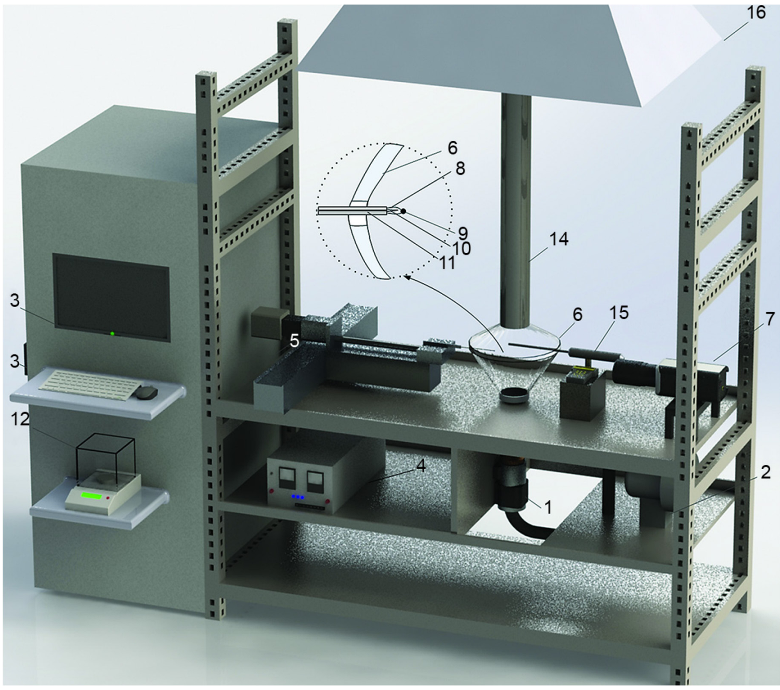

Figure 1. Scheme of experimental set-up
1 – air heater, 2 – blower, 3 – remote control, 4 – power supply and control of positioning mechanism, 5 – positioning mechanism, 6 – combustion chamber, 7 – high-speed video camera, 8 – ni-chrome filament, 9 – fuel composition droplet, 10 – cutting element, 11 – hollow metal rods, 12 – balance, 13 – personal computer, 14 – thermally insulated corrugated channel, 15 – digital temperature meter (complete with chromel-alumel thermocouple), 16 – exhaust ventilation

The OCWF compositions were prepared using a MPW-324 homogenizer. At the first stage, an oil-water emulsion was prepared (taking into account the relative mass concentration of oil and a plasticizer). The components were added to the container (capacity is 0.25 L) of the homogenizer for mixing (after pre-weighing by an analytical balance ViBRA HT 84RCE). The duration of mixing emulsion components was 3 minutes. Carbon particles were then injected to the homogenizer container with the emulsion (in accordance with the desired relative mass concentration). The duration of mixing the components was 10 minutes.

To study the processes of soaring and ignition of OCWF droplets, the following procedures were performed. With the help of a frequency regulator, the necessary air flow of air that passed through the blower and the heater was set, and entered to the combustion chamber (fig. 2). At proper air flow and temperature, the soaring rates of fuel particles in the oxidizer flow (in the combustion chamber) were monitored. The experimentally obtained values of soaring rate

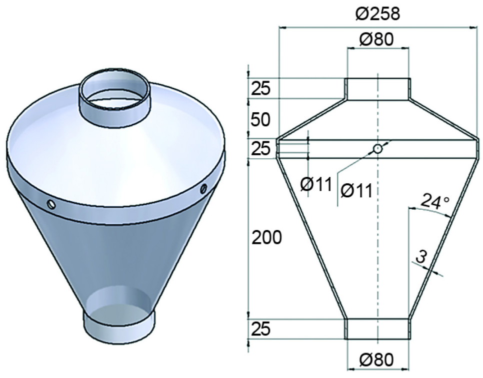

Figure 2. Developed combustion chamber made of quartz heat resistant glass
(*internal dimensions in mm*)

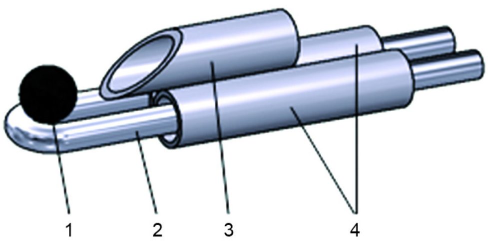

Figure 3. Scheme of dropping an OCWF droplet in the combustion chamber
1 – the OCWF droplet, 2 – ni-chrome filament, 3 – cutting element, 4 – metal hollow rods

were on the average from 0.03 to 0.1 m/s, for example, for particles with a radius 0.4-0.7 mm at the output from the lower cylindrical part of the combustion chamber.

An OCWF droplet was introduced into the combustion chamber using the automated positioning mechanism, which allows reciprocating motion in the horizontal plane from the outer wall of the combustion chamber to the axis of its symmetry with variable pitch and speed. The droplet was introduced to the chamber (and dropped) with the help of a specialized element, a scheme of which is shown in fig. 3.

The operation of the element illustrated in fig. 3 was as follows. An OCWF droplet (1) (single-channel dispenser Finnpipette Novus was used) of a given size (radius varied between 0.3-1.5 mm) was placed on a ni-chrome filament (2) (diameter is 0.3 mm) extending inside two parallel hollow stainless steel tubes (4). When the movable platform of the positioning mechanism moved towards the combustion chamber, the ni-chrome filament was stretched and moved in the opposite direction (from the combustion chamber). The OCWF droplet clung by a cutting element (3) and collided with the filament into the combustion chamber. The time during which the droplet entered the combustion chamber and detached from the ni-chrome filament was on the average 1 second.

Further, the slurry droplet began to move toward the bottom distribution grid. At the same time, the droplet lost weight intensively. This is associated with the evaporation of liq–uid combustible and non-combustible components. The droplet transformed into a solid po–rous particle. When the patricle reached the weight corresponding to soaring mode, it began to move along rather complex trajectory to the upper part of the combustion chamber (and, conversely, to the lower part, being twisted by the oxidizer flow). Upon reaching the required surface temperature, the particle ignited with intense light, which was recorded by a high-speed video camera.

The integral ignition characteristics on OCWF samples was studied, and its' composition is given in tab. 1. As solid combustible components, low-metamorphosed coals (brown coal grade "B2") was used together with and high-ash processed (enrichment) products of coking coals – filter cake of coal grade "K" (Keck "K"). The characteristics of OCWF components are presented in tab. 2. As a plasticizer, a specialized wetting agent "Neolas" was used (tab. 3).

Investigation recorded the following parameters during the experiments: the air (oxidizer) temperature, T_g, and velocity, V_g, at the input to the combustion chamber, *i. e.* at its bottom cylindrical part; size (radius R_d) and mass (m_d) of a fuel composition droplet; the time

Table 1. The studied OCWF compositions

Number of composition	Relative mass concentration of solid components [%]		Relative mass concentration of liquid combustible components [%]		Relative mass concentration of water [%]	Relative mass concentration of a plasticizer
	Coal "B2"	Keck "K"	Engine oil	Turbine oil		
1	50	–	10	–	39.5	0.5
2	50	–	–	10	39.5	0.5
3	–	50.5	10		39	0.5
4	–	50.5		10	39	0.5

Table 2. Features of OCWF combustible components

Parameter	Combustible component			
	Coal "B2"	Keck "K"	Engine oil	Turbine oil
Ash [%]	4.12	26.46	0.78	0.03
Humidity [%]	14.11	0	0.28	<0.01
Devolatilization, V^{daf} [%]	47.63	23.08	–	–
Highest calorific value, $Q^a_{s,V}$, [kcalkg^{-1}]	5472	5930	10509	10745
Flash temperature [K]	–	–	405	448
Ignition temperature [K]	–	–	491	466

Table 3. Main features of the plasticizer "Neolas"

Parameter	Value
Appearance	Colorless liquid
Content of surfactants [%]	25
Solution pH	6.5
Density at 293 K [kgm^{-3}]	954

of introducing the droplet to the chamber till dropping (τ_m); ignition delay time (τ_d). To monitor the time τ_d, specialized Tema Automotive software algorithms were used, which allow determining characteristic colour rendition – the intensity of fuel sample glow (during ignition and combustion) – with continuous object tracking. In particular, with a monochrome black and white high-speed video camera and Tema Automotive software, a gradient colour was set in the observed area that corresponds to the conditions, under which the fuel sample burns: the colour model RGB 255 corresponds to a white colour, 0 – black. It was assumed that glow during combustion corresponds to the range of RGB 220-255, similar as in experiments [15, 16].

The possibility of applying this approach was set in the comparison of experimental studies on determining the ignition delay times of a single OCWF droplet suspended on the thermocouple junction and the data obtained using the specialized Tema Automotive software [15]. The ignition criterion of droplets was simultaneous fulfilment of inequality $T_d > T_g$ and reaching temperature T_d change rate in the droplet centre not less than 10 K/s.

Results and discussion

During the combustion of OCWF droplets, for the conditions of soaring, quite complex fuel particle's trajectories (after the evaporation of combustible and non-combustible components from the droplet subsurface layer) were observed (fig. 4).

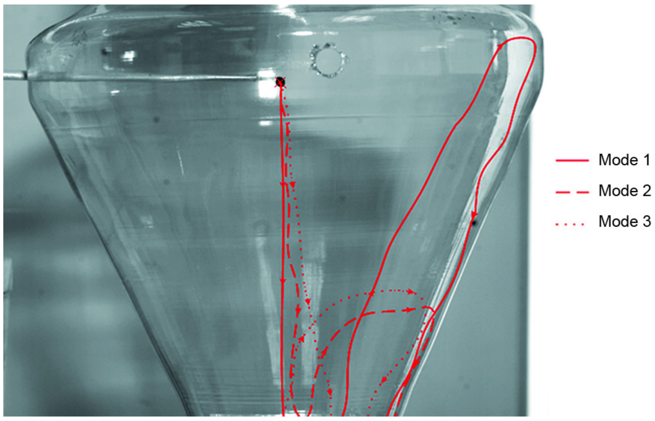

Figure 4. Videogram of experiment with a OCWF droplet (1st composition), when it soared in the combustion chamber during ignition (after post-processing in Tema Automotive) for conditions $R_d \approx 0.5$ mm, $T_g \approx 840$ K, and $V_g \approx 1.5$ m/s

After the OCWF droplet detached from the ni-chrome filament, when it was cut by the specialized cutting element (fig. 4), it began to move under gravity along the axis of symmetry of the chamber to the bottom distribution grid. At that time, there was quite intense evaporation of liquid non--flammable (water) and flammable (oil) components, as well as the thermal decomposition of the organic portion of coal in the subsurface layer of the OCWF droplet. The latter in this condition can be considered as the particle. The processes specified contribute to the rapid decrease in the particle mass, and some decrease in its size. When the particle reached the minimum mass corresponding to transition conditions to a suspended state, it began to soar in the oxidizer flow (it moved from the bottom part of the chamber to the top and contrariwise) with the intensive heating of coal and the release of volatile substances from it. The particle moved up to the upper part of the chamber, as a rule, along a curved path (fig. 4). In most cases, the particle moved to the peripheral parts of the chamber and along generatrix near the wall of a bottom truncated cone. Droplets with small radius (0.3-0.7 mm) soared in the upper part of the combustion chamber close to the aperture plane for inputting a thermocouple. Larger droplets (0.7-1.5 mm) soared in the lower part of the combustion chamber.

When volatiles were released and the OCWF solid particle was heated up, coke residue was ignited, and its intensive heterogeneous combustion occurred (accompanied by a clearly visible glow, the recording of which allowed calculating ignition delay times τ_d).

As the main parameter characterizing the integral ignition characteristics the ignition delay time of OCWF droplets was selected. The choice of this parameter is due to the fact that it allows developing the physical and mathematical models of burning fuel in real power plants (and optimizing the operation of the latter) on the basis of the known thermophysical characteristics of the used components and their relative concentrations in the droplet.

The experimental results on determining the ignition delay times of OCWF (figs. 5-7) showed a significant difference as among various compositions, so for different hydrodynamic conditions of the location of fuel in the combustion chamber (the numbers of curves in the figures correspond to the compositions listed in tab. 1). The essential difference was detected in determining the ignition delay time for the stationary position of the OCWF droplet (in the case, when it is placed on the thermocouple junction) and for the conditions of the soaring mode.

Under the conditions of the soaring mode of the droplet, a decrease in ignition delay times observed and compared to that, when the fuel droplet is placed on the low-inertia thermocouple junction at comparable component compositions, oxidizer initial temperatures, and original droplet diameter. On the average, the reduction of ignition delay time (when comparing these modes) was from 0.5 to 4 seconds. Essential role is played by the oxidizer initial temperature and fuel droplet initial size. The lower the oxidizer initial temperature and greater fuel droplet initial diameter, the more significant is the difference between ignition delay times. In this case, the optimum parameters for ignition are provided under the conditions of fuel droplet

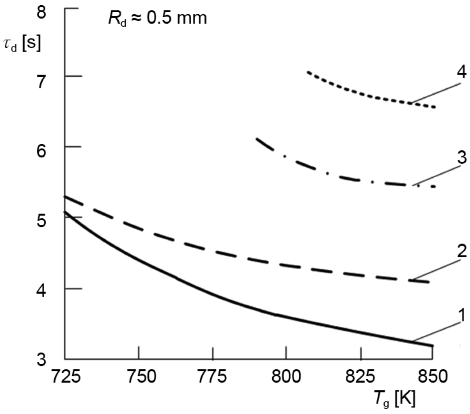

Figure 5. Ignition delay times of OCWF droplets depending on the oxidizer temperature during soaring in the combustion chamber

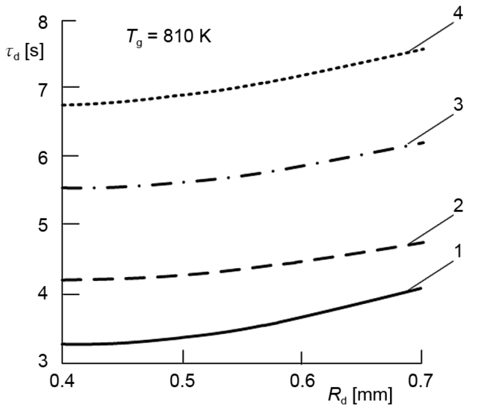

Figure 6. Ignition delay times of OCWF droplets depending on their size during soaring in the combustion chamber

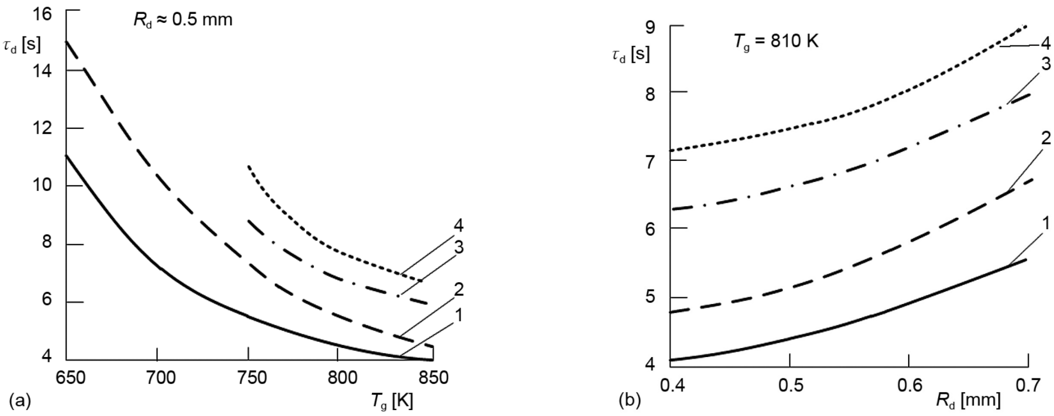

Figure 7. Ignition delay times of OCWF on the low-inertia thermocouple junction (type S, temperature measurement range is 273-1873 K, systematic error is ±1 K, inertia is not more than 1 second, diameter of junction is about 0.1 second) depending on T_g (a) and R_d (b)

soaring. Due to more intense heat and mass transfer during flowing around the fuel droplet by the oxidizer, the droplet dries rapidly (turns into a particle), heats up with the release of volatiles and heterogeneous combustion on the particle surface begins.

Thus, when the OCWF droplet is placed on the low-inertia thermocouple junction, it is not possible to obtain reliable data (we may talk only about estimated values) on the effect of thermophysical fuel characteristics on the parameters of ignition and combustion.

Under experimental conditions, it was implemented low-temperature (up to 1000 K) ignition [21-23] of OCWF droplets. For different component composition, the limits (minimum) ignition temperatures were significantly different. The highest initial ignition temperature (about 800 K) was characteristic for the compositions based on a cake. This is primarily due to the higher ash of cake "K" (tab. 2) and a higher degree of coalification of coal source ("R"), from which cake was obtained. These parameters greatly affect the thermophysical characteristics of the fuel particle (increasing heat capacity with increasing ash content), which in turn determines the intensity of heating up the fuel particle and thus the yield of volatiles (tab. 2), as well as the presence in coke residue of flammable substances (mainly carbon) available for burning.

A noticeable effect on the ignition delay time has a type of the liquid fuel component of OCWF. For example, the use of turbine oil increases the ignition delay time by about 1 second (as compared to engine oil) for the respective solid combustible components of the OCWF droplet. Most likely, this is due to the fact that waste motor oil contains large amounts of low-boiling components having a lower heat of vaporization. This, in turn, allows heating up more intense the fuel particle from the peripheral areas to the centre with less heat for the evaporation of liquid combustible and non-combustible components.

The results of experimental data on the low-temperature ignition of the OCWF droplet on the thermocouple and during soaring show that a significant impact on ignition delay time has the initial oxidizer temperature. In both cases of low-temperature ignition, a similar trend was detected – the growth of the initial oxidizer temperature of the oxidizer from the minimum (650 K) to the maximum value (900 K) investigated in this paper, which contributes to the non-linear reduction of ignition delay time. This can be most clearly seen in the experimental studies conducted on the low-inertia thermocouple junction. It is not so significant for soaring conditions, since under the conditions when the droplet soared in the cone, we observed some (rather limited) divergence of the temperature in different points of the combustion chamber (in the direction to the central axis of symmetry, as well as in the radial direction). The greatest difference was 30-40 K in the direction of the central axis (in radial, not more than 20 K). As previously shown in fig. 4, the motion of the droplet in the chamber is characterized by rather complex trajectory. Moreover, in most cases it was parietal motion. When the droplet moved down under gravity after being released, and then, when it moved up (soaring) after the evaporation of OCWF liquid components, some change in the oxidizer temperature occurred, and, respectively, in the heating rate of the droplet. The change of the latter with the slowdown in the upper wall region of the cylindrical part (inner diameter is 258 mm) of the combustion chamber was noticeable at relatively low initial oxidizer temperatures.

An initial droplet size of OCWF has significant impact on ignition delay time. Under other identical conditions (the oxidizer temperature, composition, and rate), an increase in the initial droplet size contributes to a significant increase in ignition delay time. However, this trend is not so much pronounced in the case of the soaring mode of the droplet (figs. 5 and 6 for compositions 1 and 2). This indicates that in solving the problem of optimizing the combustion of fuel based on OCWF in a real power plant, it is possible to change (optimize) significantly the basic design parameters of a spray nozzle by setting the required diameter of fuel droplets and controlling the oxidizer flow rate. This problem is rather urgent, because its solution will increase the service life of a burner (by optimizing the grinding characteristics of the solid fuel component of OCWF) and allow choosing the desired ratio of oxidizer excess in the furnace of a power plant, which will essentially influence the chemical and mechanical incomplete combustion of fuel.

One of the most promising (and still unsolved) problems for the developed experimental set-up shown in fig. 1 is impossibility at this stage to organize the collection of burnt fuel droplets (the basic problem related to the fact that after the fuel droplet is burnt, remaining ash, when it touches chamber walls, falls into a large group of pieces and carried away from the chamber). Furthermore, it is necessary to provide the collection of ash in order to set the amount of residual fuel components in the fuel particle. Their amount will also allow setting the desired (optimum) size of fuel droplets, and together with the assessment of the impact of the initial droplet size on ignition delay time, it will allow determining the size of the solid flammable component of CWF and OCWF sufficient for complete combustion. It will also be possible to perform analysis for incomplete burning of fuel under different conditions of soaring in the combustion chamber.

Conclusions

The experimental values of the integral ignition characteristics (delay time) of OCWF fuel droplets during soaring (as compared with stationary location of droplets) correspond to the processes occurring in real power plants. Comparison of the experimental results obtained at the location of the droplet on the low-inertia thermocouple junction and under conditions of soaring showed that for the stationary arrangement of the fuel droplet, there exists heat sink over a thermocouple, whereby, ignition delay times are increased by an average 0.5-4 seconds at comparable experimental conditions: temperature and oxidizer flow rate, as well as fuel component composition.

The proposed approach to the study of integral ignition characteristics of OCWF fuel droplets during soaring in the model combustion chamber can be implemented for a variety of compounds with a wide range of content of the main components of OCWF and CWF – liquid combustibles, water, and solid fuel base.

In order to expand controlled experimental parameters characterizing the combustion modes of fuel droplets, it is necessary to provide an opportunity to capture and collect burnt fuel particles in order to determine the characteristic incomplete combustion. This allows, on the one hand, establishing the maximum diameters of fuel droplets that can be used in actual power plants, and, on the other hand, making additional boundary conditions in the developed physical and mathematical models.

Acknowledgment

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Nomenclature

Ar – Archimedes number $[= (2R_d)^3 g\rho(\rho_d - \rho_g)/\mu_g^2]$, [–]
g – acceleration of gravity, $[m^2s^{-1}]$
m_d – droplet mass, [kg]
$Q^a_{s,V}$ – highest calorific value, $[kcalkg^{-1}]$
R_d – fuel droplet radius, [m]
Re – Reynolds number $(V_g 2R_d/\nu_g)$, [–]
T_d – temperature in the center of a fuel droplet, [K]
T_g – oxidizer temperature, [K]
V^{daf} – yield of volatiles, [%]
V_g – oxidizer velocity, $[ms^{-1}]$

Greek symbols

μ_g – dynamic viscosity of gas environment, [Pa·s]
ν_g – kinematic viscosity of gas environment, $[m^2s^{-1}]$
ρ_d – density of a fuel droplet, $[kgm^{-3}]$
ρ_g – density of gas environment, $[kgm^{-3}]$
τ_d – ignition delay time of fuel droplet, [s]
τ_m – time of introducing a droplet into a combustion chamber before dropping, [s]

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