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The impact of cavitation-activated water on combustion dynamics and environmental characteristics of coal-water slurry fuel

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Abstract. Among the new coal technologies the burning of low-grade coal in the form of coal-water slurry fuel (CWSF) is of a great interest. The basis of CWSF is a highly concentrated coal-water slurry consisting of finely ground coal, water or other liquid and plasticizing agents. The development of CWSF technology is highly relevant for solving global problems of resource conservation and ecology. The study is dedicated to CWSF properties with respect to Kansk-Achinsk coal and water. This paper presents the results of the influence of CWSF's preliminary cavitation water treatment on the combustion dynamics of fuel, (including the features of the combustion temperature trends, delayed ignition time and time of complete combustion) and on its environmental characteristics. A rotary-type hydrodynamic oscillator at high angular velocity (10000 rpm) was used in supercavitation mode. It is shown that the technology of cavitation water treatment leads to a change in the dynamics of CWSF's combustion and to an additional decrease in NO_x emissions by 1.6 times, CO_2 by 1.3 times.

1. Introduction

Coal is an important energy and technological raw material, but it is characterized by the highest environmentally harmful emissions compared to other types of fossil fuels. More than half of SO_2 emissions, about 30% of NO, and ≈40% CO_2 emissions are produced by coal [1]. Therefore, the development and introduction of environmentally friendly technologies is important for the successful development of the coal industry. Fuel disperse systems technology, i.e. coal-water slurry fuel (CWSF), is considered to be the most environmentally friendly energy technology [2]. CWSF is safe at all stages of production and transportation [3]. It also allows to reduce the amount of harmful emissions into the atmosphere during combustion [4]. Additional measures can be introduced into the process of CWSF generation, which can significantly improve its burning characteristics and increase the purity of combustion in comparison with the original coal. The paper presents the results of the use of resource-saving cavitation technology for controlling the thermophysical and environmental characteristics of coal-water fuel applied to Kansk-Achinsk brown coal.

2. Experimental techniques

In this study we investigated a composite, a highly concentrated coal-water slurry based on Kansk-Achinsk brown coal (ash content equals 8%, humidity 20%) and distilled water.

The ignition delay time (τ_d), full combustion time (τ_c) and the nature of combustion (i.e. temperature profile) of fuel were studied using the method of high-speed video recording of the combustion process of a CWSF's droplet fixed on a ceramic rod in a muffle furnace at fixed oxidizer temperatures T_g, ºC. Systematic measurement errors ≈2% [5]. Concentrations of anthropogenic emissions from the combustion of CWSF (CO_2, CO, SO_2, NO_x) were measured on a "TEST" multi-component gas analyzer. The probe of the gas analyzer was being directed to a CWSF-sample (1.5 – 2.0 g) located on a metal grid in the center of a muffle furnace heated to 800 °C.

The study of the particle size distribution of the samples was performed on the analyzer 'CPS Disc Centrifuge Model DC 24000'. The device determines the particle size in the range from 10 nm to 50 microns.

2.1. Sample preparation

The initial coal was ground using an MBL-100 laboratory mill. The cavitation-activated water was obtained in a hydrodynamic rotary-type oscillator with a two-blade wedge-shaped impeller (cavitator wedge angle $\alpha = 60°$), engine power 1 kW, working chamber volume 10^{-4} m^3. Distilled water was treated at 20 °C for 5 minutes at a rotor speed of 10000 rpm in supercavitation mode.

Two types of coal-water slurry fuel compositions were produced and investigated. The first sample of CWSF (CWSF1) coal powder (75 g) and distilled water (75 ml) were mixed in a Waring 8010D blender for 3 minutes at a rotor speed of 10000 rpm. The second CWSF sample (CWSF2) was made of coal powder (75 g) and cavitation-activated distilled water (75 ml) mixed in a Waring 8010D blender for 3 minutes at a rotor speed of 10000 rpm.

3. Experimental results and discussion

3.1. Combustions dynamic

The properties of the dispersion medium, i.e. cavitation-activated water, in a coal-water slurry leads to a change in the dynamics of the combustion of a CWSF's drop. The ignition delay time increases as well as the time of complete combustion. The experimental data obtained are shown in figures 1–3.

The temperature dependence of τ_d and τ_c for CWSF2 is higher than the one for CWSF1. As for τ_d, its average value equals ≈8% (average experimental error ≈4%). As for τ_c, its temperature dependence equals ≈6%. The dependence of τ_d and τ_c on the size of the droplet for CWSF1 and CWSF2 is similar. Increase of droplet's size results in a larger increase of the ignition delay time and full combustion time for CWSF2 as compared to CWSF1.
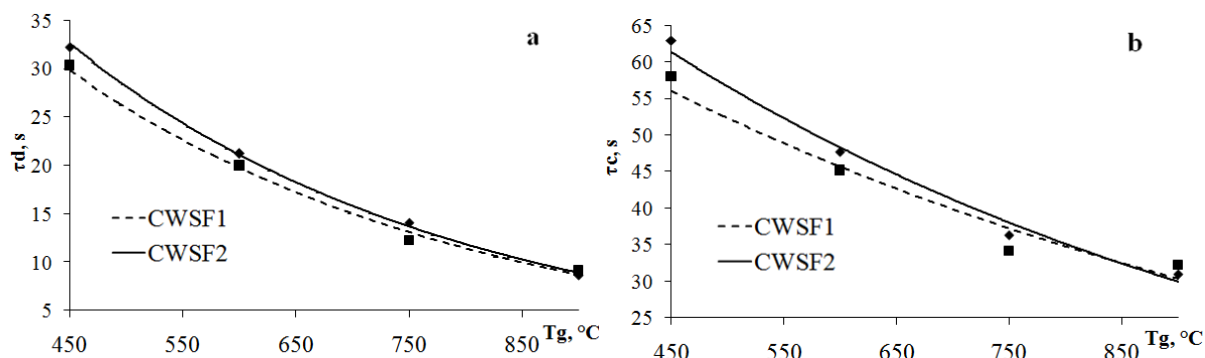

Figure 1. The dependence of the ignition delay time (a) and the time of complete combustion of the CWSF's drop (b) on the temperature of the furnace.
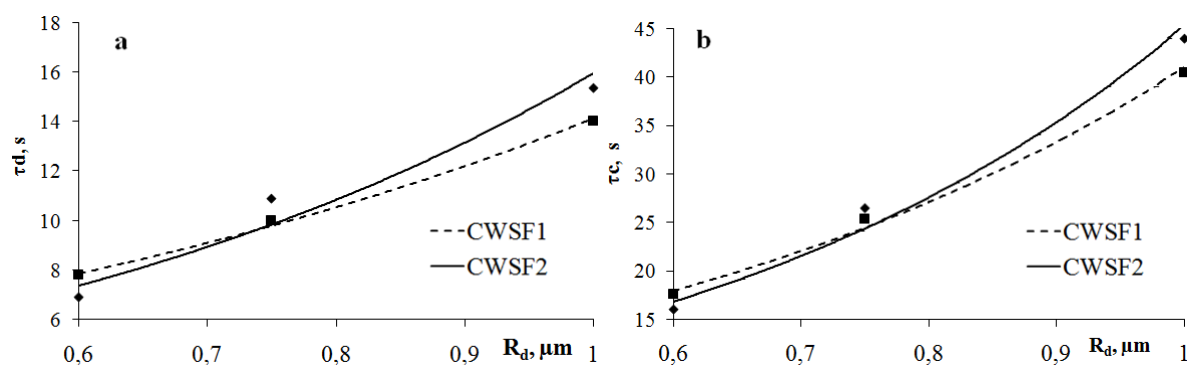
Figure 2. The dependence of the ignition delay time (a) and the time of CWSF's complete combustion (b) on the drop's size.
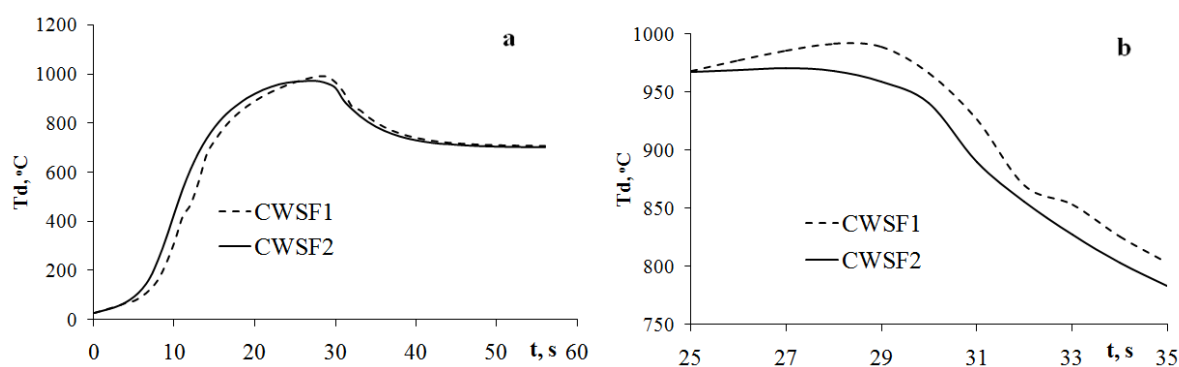

Figure 3. Temperature variation in the center of a CWSF's drop at furnace's temperature 700 °C (a), detail of the high-temperature combustion region of a CWSF's drop (b).

Ultrafine grinding in a blender is accompanied by a change in morphology of the coal's physical structure (e.g. pore size, surface area) and the structural-chemical structure (reduction of the molecular chains' length of the organic mass of coal (OMC) [6]). The XRP spectra of coal particles show decrease in the width of an amorphous halo attributed to OMC (figure 4a). The surface of coal particles with increased reactivity as well as adsorption (hydrophilic) centers (PAC) are formed.

The electronic state of the coal surface was studied by the EPR method (spectrometer SE / X-2544, Bruker) at temperature of 85 K. The EPR spectrum (figure 4) consists of a central intense line and side narrow peaks (hyperfine structure). The central peak is formed by a radical center, which is typical of carbon systems, and the hyperfine structure of the spectrum provides information about the surface. For CWSF1 and CWSF2 the hyperfine structure is different. In the EPR spectrum for CWSF2 the number and intensity of lines changes as a result of an increase in the degree of oxidation of the coal surface as compared to CWSF1 [7].
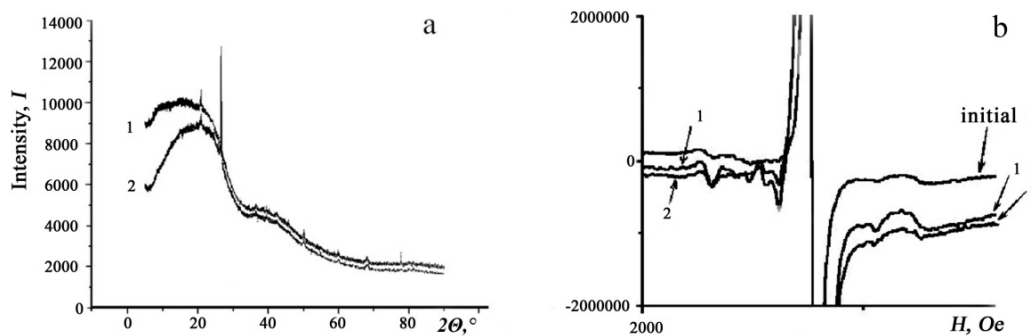
Figure 4. (a) RFA spectrum of coal: 1 – original coal, 2 – coal after grinding (without cavitation), (b) EPR spectra of the dispersed phase of initial water coal mixture (without cavitation dispersion), 1 – CWSF1, 2 – CWSF2.

In distilled water cavitation changes the surface tension, the pH value, the electrical flux and the oxygen concentration [8]. The cavitation-activated water contains H+ and OH- ions, H * and OH * radicals, decomposition products of hydrogen peroxide H_2O_2, and active water molecules. All of them can be additional sources of surface active centers (SAC). Clusters of water molecules and continuous monomolecular H_2O films form around the SAC due to H-bonds. As a result, there is an increase of bound water in CWSF2.

Due to hydrophobic properties of coal a significant part of micro- and mesopores is not filled with water. The reduction of surface tension contributes to the deep penetration of water into the pore space of coal and enables better filling-up of the meso- and macropores with moisture. Pore's shrinkage and breaking the cohesion of the porous structure can be introduced in order to prevent the maximum release of water from the filled porous space when heated. Indeed, according to thermogravimetric data obtained with the help of STA 449 C Netzsch, in the temperature range up to 160 °C the mass change of CWSF2 samples is 10% less than that of CWSF1. Thus, an increase in bound water in the porous part of the coal is probably one of the reasons for slowing down the ignition process and increasing the time of complete combustion of a CWSF2 drop. In addition, the radicals H*, OH*, active water molecules H_2O, decomposition products of H_2O_2, what present in cavitation-activated water, can influence the radial chain character of the combustion process of CWSF. As a result, there is a difference in the temperature trends of combustion of CWSF2 and CWSF1.

Turbulent micromixing of the composition of coal and water in a blender during the synthesis of CWSF allows to derive homogeneous mixtures containing particles of less than 50 microns above 60% of the total mass of the disperse phase. The coal ground in the mill and the disperse phases of the first coal-water suspension (CWSF1) and CWSF2 have a bimodal distribution. For coal powder the distribution peaks are 170 µm and 4.5 µm, for CWSF1 – 50 µm and 4 µm, for CWSF2 – 50 µm and 3.8 µm.
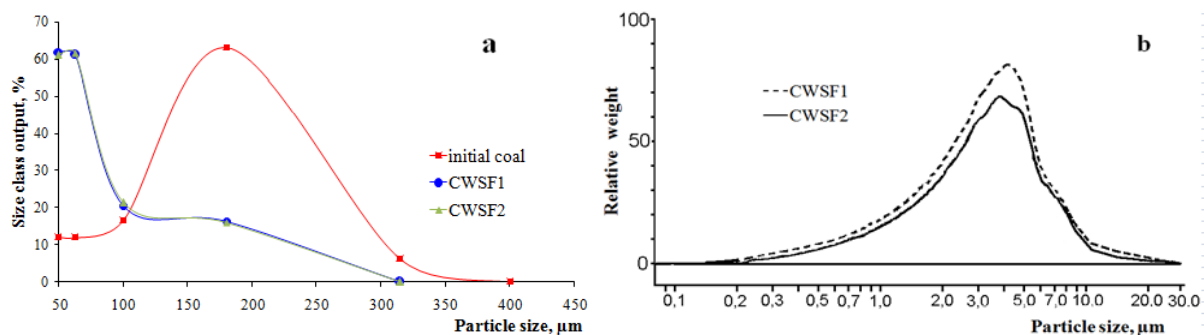

Figure 5. The particle size distribution of the CWSF and coal samples made on (a) sieves and (b) CPS Disc centrifuge.

This means that the cavitation water treatment of the disperse phase of CWSF does not lead to additional grinding of coal when dispersed in a blender. Therefore, the size of particles in a drop of CWSF1 and CWSF2 differ only within the experimental error. In equal drops of CWSF1 and CWSF2 the number of coal particles is the same. Since with an increase in the drop size the ignition delay time and the time of complete combustion for CWSF2 are longer than for CWSF1, this effect can only be explained by an increase in the amount of bound water in the coal particles of CWSF2.

3.2. Ecological characteristics

The average values of emissions of nitrogen oxides, sulfur, carbon in the process of burning fuel and coal are presented in tables 2–3 and in figure 6.

Table 1. Average values of emissions of oxides during CWSF combustion.

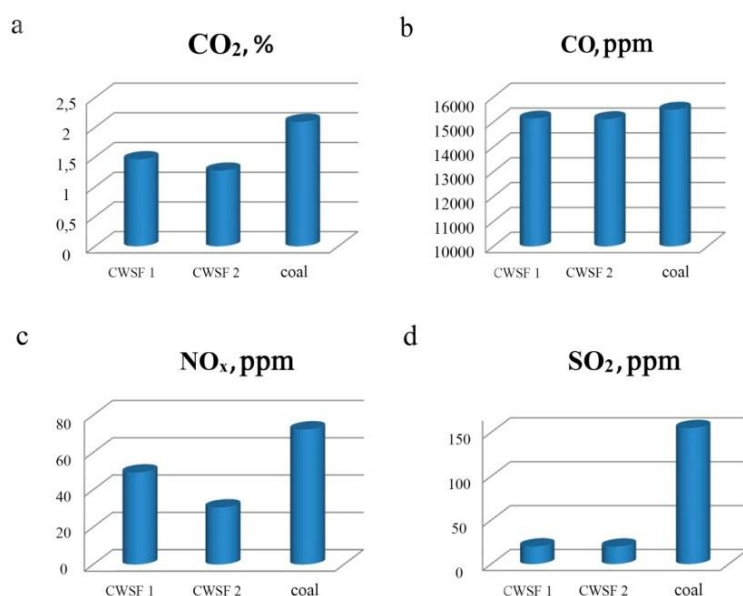|	NO_x ppm	SO_2 ppm	CO_2 %	CO ppm
CWSF1	49.32	20.15	1.46	15141.07
CWSF2	30.58	20.20	1.27	15121.95
COAL	72.38	155.00	2.09	15500.00

Figure 6. Average emissions of (a) carbon oxides CO_2; (b) carbon oxides CO; (c) nitrogen; (d) sulfur in the process of CWSF combustion.

As follows from the experimental data obtained, even small changes in the nature of the combustion of a CWSF2 droplet lead to significant reductions in NO_x emissions. The value of NO_x for CWSF2 in comparison with CWSF1 decreased by 1.6 times (table 1).

Among the possible causes of NO_x reduction is the increase in the time of complete combustion of CWSF2 and the change in the radial-chain character of combustion of CWSF2 due to the properties of cavitation-activated water.

The value of CO_2 emissions in CWSF2 in relation to CWSF1 decreased by 13% while CO emissions practically did not change. The preliminary cavitation water treatment of CWSF has not influenced the emissions of SO_2 either.

4. Conclusions

H* and OH* radicals, active water molecules H_2O, H_2O_2 decomposition products present in the cavitation-activated water can be triggers of chains in oxidizing reactions and take part in their development, i.e. affect the radial-chain nature of CWSF combustion.

Cavitation water treatment has an impact on the thermophysical properties of CWSF (e.g. ignition time delay τ_d, time of complete combustion τ_c of a drop, dependence of τ_d and τ_c on the size of a drop, nature of temperature trends of a drop).

The cavitation treatment reduces surface tension of water to promote more complete filling of meso- and macropores in the coal particles with moisture.

The increase in bound water in the porous part of coal is one of the reasons for slowing down the process of ignition and increasing the time of complete combustion of a drop.

The cavitation water treatment technology used in the experiment contributes to the reduction of the anthropogenic gases (NO_x, CO_2) during the combustion of CWSF.

For the implementation of modern environmental conditions for coal combustion, cavitation water treatment technology can be successfully implemented for synthesis of coal-water slurry fuel.

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