Experimental research of flow characteristics of coaxially atomized coal-water fuel

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Abstract. Results of experimental studies of characteristics of coal-water fuel (CWF) stream in the process of its coaxial spraying in aerodynamic furnace simulator of a power boiler are presented in this paper. Mechanism of CWF atomization was researched at the following component ratios: 50% of coal and 50% of water. Coal fraction was 200 microns and less. Studies were conducted at pressures of 0.2 MPa (CWF) and 0.18 MPa (air). Visualization of CWF spray cone structure and assessment of the flow quality were made in the plane perpendicular to the axis of the cone on three segments. Geometrical parameters and velocities of CWF droplets in the process of spraying were established. Characteristic areas of CWF spray cone, which are formed in the process of atomization, were selected according to the obtained experimental results. Values of Weber number were calculated for corresponding velocities of CWF droplets. Characteristic stages of droplets breakup of the sprayed CWF were identified, and process conditions were formulated.

1. Introduction
Annual rise of prices for fuel and energy resources is the reason for creation and development of new fuel technologies for power engineering and industry [1]. Alternative and renewable energy sources partially compensate for the need of cheap and affordable energy [2], but, as a rule, this is not enough. World reserves of steam coal are prerequisites for the development and implementation of new environmentally promising and energy-efficient fuels for production of heat and electricity [3, 4]. Previous studies [5] allow concluding that the most promising type of fuel for power engineering is coal-water fuel (CWF). Currently operating thermal power plants are known to use CWF as boiler-furnace fuel [6]. As a rule, CWF is a mixture of water and fine coal with or without plasticizer [7]. It was previously established [8] that the main parameters determining CWF are its rheological properties (viscosity, density, and sedimentation stability). These characteristics are unstable and depend on coal grade, its concentration in the composition of CWF, method of treatment, as well as the type of plasticizer [9]. It was determined that rheological properties of CWF largely depend on porosity of coal particles, which contributes to an increase of coal humidity ratio, resulting in an increase of CWF viscosity [10].

It is known that quality of CWF spraying significantly affects efficiency of its combustion [11]. Therefore, a more complete disclosure of CWF droplets breakup mechanisms during the spraying process is an urgent problem.
2. Experimental setup

2.1. Materials
Coal from the Krasnoyarsk mine (Kemerovo region) was used to prepare the slurry fuel. The coal was sifted through a sieve with a mesh size of $200 \times 10^{-6}$ m after grinding. The obtained material was mixed in a ceramic drum with a volume of 3 liters with water and grinding bodies for one hour at a mass ratio of balls and coal 1:1. Lignosulfonate was used as a plasticizer in an amount of 1% by weight of coal. Such parameters of slurry fuel preparation were selected based on the results of previous studies [12].

2.2. Experimental test bench
Studies of the dynamics of slurry fuel droplets in the flow are based on experimental results. The test bench for the study of the flow structure of the sprayed slurry fuel and the mechanisms of droplet breakup at different parameters is presented in Fig. 1. Coaxial atomization of the slurry fuel is carried out by means of a spraying device (nozzle) with an internal mixing chamber located in the aerodynamic simulator of the boiler furnace. The studied fuel composition is supplied by NDP15 pump with a pneumatic drive from the reserve tank with a capacity of $3 \times 10^3$ m$^3$. The volume of the slurry fuel was $2 \times 10^3$ m$^3$ for the experiment. The air pumped by the compressor is used as a spraying agent. The flow of the sprayed mixture is illuminated by a light sheet created by Vlite-200 laser. Recording of the spray cone structure and its components (fuel droplets) is carried out by Bobcat IGV-B2020 high-speed cross-correlation camera. It is possible to install the camera in several positions (A, B, C) for registering different parts of the spray cone. Simultaneous operation of the laser and camera is carried out by the synchronization unit SP-2.0 PS.

![Figure 1](image)

**Figure 1.** Experimental setup a – general view; b – principal model. 1 – nozzle, 2 – aerodynamic simulator of the furnace, 3 – diaphragm pump with pneumatic drive of NDP 15 series, 4 – CWF tank, 5 – Becker compressor, 6 – Beamtech Vlite-200 laser, 7 – high-speed camera, 8 – PC, 9 – waste CWF collection tank A, B, C – possible camera positions.

Experimental studies were performed at the following pressure values of the slurry fuel and air: 0.2 MPa/0.18 MPa. The air pressure was set at 0.02 MPa less in order to avoid "choke" the fuel by air in the nozzle due to the significant viscosity of the latter. The mass flow rate of slurry fuel and air was $37 \times 10^{-3}$ and $16 \times 10^{-3}$ kg/s, respectively. The gas-to-liquid ratio was 0.4. The camera and laser are located at a distance of 0.5 m from the axis of the spray cone. The results obtained (droplet size)
during the atomization of slurry fuel processed in the vector editor. We number was analyzed as a criterion characterizing the mechanism of droplet breakup in the flow in accordance with [13, 14]:

$$We = \frac{\rho \cdot D \cdot w^2}{\sigma},$$

here $\rho$ is the density of slurry fuel, kg/m$^3$; $D$ is the characteristic size (diameter of slurry fuel droplet), m; $w$ is the velocity of slurry fuel droplets, m/s; and $\sigma$ is the surface tension coefficient, kg/s$^2$.

The studies were performed under the following conditions and assumptions:
- the effect of rotation of the slurry fuel droplets during the spraying process was not taken into account for We number estimation;
- the droplet size was taken as the characteristic size;
- the values of surface tension coefficient of the suspension ranged from 0.05 to 0.07 kg/s$^2$;
- during the experiment, the value of the surface tension coefficient of the suspension was 0.06 kg/s$^2$ (water/coal ratio – 50%/50%);
- external factors were not taken into account – pressure and temperature inside the aerodynamic simulator of the furnace (normal conditions);
- thermal preparation of the slurry fuel was not carried out.
- digital tracer imaging was performed using a single cross-correlation camera.

2.3. Atomization method

The outlet diameter of the nozzle is 2*10$^{-3}$ m, which allows studying the process of fuel atomization with solid particles with a size of up to 1*10$^{-3}$ m in the composition. The diameters of the inlet holes of the suspension fuel and air are 8*10$^{-3}$ m and 4*10$^{-3}$ m, respectively. Nozzle length is 70*10$^{-3}$ m, mixing chamber length is 9*10$^{-3}$ m.

2.4. Recording method

The estimation of the droplet velocity was carried out using the non-contact method of velocity measurement in flows – PIV (Particle Image Velocimetry) – the method of digital tracer visualization. Table 1 shows the characteristics of the laser and the camera.

| Table 1. Characteristics of the equipment |
|-------------------------------------------|
| **Vlite-200 Laser** | **Value** | **Bobcat IGV-B2020 Camera** | **Value** |
| Wavelength, nm | 532 | Resolution, pixels | 2048x2048 |
| Repetition rate, Hz | 1-15 | Maximum resolution, pixels | 2056x2060 |
| Pulse energy, mJ | 200 | Sensor | KAI-04022, CCD |
| Energy stability | ≤ 2% | Sensor format | 4/3" optical |
| Pulse width, ns | 6-8 | Standard frame rate, MHz/fps | 40/16 |
| Divergence, mrad | ≤ 3 | Overclocked frame rate, MHz/fps | 50/20 |
| Pointing stability, μrad | ≤ 50 | Balance | Analog and digital |
| Beam diameter, mm | 7 | Shutter speed, sec (normal) | From 1/100000 to 1/16 |
| Data delay, ns | ≤ 1 | Double inter-frame trigger, nanoseconds | 200 |
| Spectral purity | ≥ 99.8% | Vibration, Hz | (20-200) XYZ |

A Nikon lens with a focal length of 50 mm and a viewing angle of 46° was used for recording. Experimental study of slurry fuel atomization was performed using ActualFlow software. Processing of the images was performed in the same software. A standard cross-correlation method was used to
determine velocity of the slurry fuel droplets. The calculation was carried out by the method of direct convolution calculation in order to avoid undesirable effects inherent in Fourier transform (in particular, the systematic error in determining the displacement of particles).

3. Results and discussion

Figure 2a shows image typical for a stable spray cone. Slurry fuel spray time at a pressure ratio of 0.2 MPa/0.18 MPa was 120 s. Length of the research area along the spray cone axis was 0.17 m.

![Image](image.png)

| Name             | Minimum, m/s | Maximum, m/s | %    | Number of droplets |
|------------------|--------------|--------------|------|--------------------|
| Velocity range 1 | 0            | 8            | 81.6 | 65642              |
| Velocity range 2 | 8            | 34           | 18.2 | 14608              |
| Velocity range 3 | 34           | 40.41        | 0.3  | 214                |

*Figure 2. Flow structure and parameters at pressure of slurry fuel and air of 0.2 MPa/0.18 MPa*

- a) image of the spray cone; b) edited image of the spray cone with three zones; c) velocity distribution along the spray cone.

It was established that in the process of coaxial atomization a spray cone is formed with pronounced zones - core of the flow, middle and outer zones (Fig. 2b). Their length – L and width – S (in the widest section perpendicular to the axis of the torch) were: core of the flow – L up to 0.08 m, S up to 0.01 m (marked with a red line); middle zone – L up to 0.13 m, S up to 0.02 m (marked with a blue line); the outer zone – L up to 0.17 m, S up to 0.05 m (marked with a green line). Three characteristic velocity ranges of droplets in the stream were selected: from 0 to 8 m/s, from 8 to 32 m/s, and from 32-40.03 m/s. Fig. 2c shows qualitative distribution of slurry fuel droplets in the process of coaxial spraying. It was established that droplets with maximum velocities from 32–40.03 m/s (velocity range 3) are distributed throughout the study area (Fig. 2c, marked with red symbols). Moreover, their number varies from 214 to 492, which is no more than 1% of the total number of recorded particles. The second range is characterized by droplets, whose speeds vary from 8 to 32 m/s in an amount close to 15,000 (18% of the total number of recorded particles (Fig. 2c, marked with green symbols). The greatest amount (up to 70,200, almost 82% of the total number of recorded particles; are distributed over the yellow background) of droplets of the sprayed slurry fuel have velocities of up to 8 m/s.
The process of coaxial spraying of coal-water fuel is accompanied by the breakup of droplets [15]. It can be assumed that solid components separated from the liquid phase during breakup, which have a lower coefficient of friction relative to air possess the highest velocity (34 m/s and more) [16].

Fig. 3 shows dependence of We criterion on velocity. Dependence of We number on droplets velocities of various sizes makes it possible to isolate the maximum (critical) values of We criterion in the researched area and to characterize some stages of the breakup of slurry fuel droplets. It can be concluded that a significant 13.4% of droplets of the sprayed slurry fuel are destroyed by the principle of vibration breakup during the experiment (We criterion varies in the range from 1,500 to 6,300). 4.2% of the droplets undergo breakup by the “parachute” type (We criterion values range from 6300 to 7800). A significant part of droplets – 78.2% - undergoes catastrophic breakup (We=7800 and more). Breakup of droplets does not occur in the range of We from 0 to 1500.

![Figure 3. Dependence of We number on droplets velocities.](image)

**Conclusion**

Experimental studies of the flow structure of the sprayed slurry fuel in the composition with a plasticizer (lignosulfonate) depending on pressure were conducted. Distribution of droplets by velocity, their number and size was performed for the first time. Analysis of droplets distribution by velocity allows drawing several conclusions: the largest number of particles have velocities of up to 8 m/s; proportion of droplets with speeds of 32 m/s and more does not exceed 1% of the total; significant number of droplets have speeds from 8 to 32 m/s.

Thus, according to the results of experimental studies of the flow structure, the following values of We criterion can be formulated for some stages of breakup of the sprayed CWF droplets:

- from 1500 to 6300 - vibratory breakup of CWF droplets;
- from 6300 to 7800 - breakup of CWF droplets by the "parachute" type;
- from 7800 and higher - catastrophic breakup of CWF drops.

Experimentally obtained values of We number for the characteristic stages of CWF droplets breakup in the process of coaxial spraying can be used for mathematical and physical modeling of CWF atomization process in the furnaces of power boilers, which will allow for prognostic estimates of the aerodynamic characteristics of the designed and existing units.

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