Investigating the gas-droplet flow generated by a pneumatic nozzle for a coal-water slurry

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Abstract. The paper studies a promising method of spraying, based on the interaction of cumulative and near-wall jets with the impinging liquid and the Coanda effect. The measurements are based on shadow photography (SP) and interferometric method (IPI). In a wide range of performance parameters data have been obtained on the disperse composition of a gas-droplet flow at water spray by a special pneumatic atomizer intended for coal-water fuel. The dependences of droplet sizes on the flow rate of liquid and spraying air have been found.

1. Introduction
Currently, one of the most important areas in coal energy is the use of low-grade (substandard) coals and coal-enrichment wastes as fuel. A promising way to dispose of low-quality coal waste with high energy and environmental indicators is the combustion of coal in the form of coal-water slurry [1]. Combustion of such fuel requires spraying in the combustion chamber using pneumatic nozzles. Laboratory modeling to obtain detailed information about the structure and dispersed composition of the two-phase flow created by the nozzles is an important step in the creation and optimization of equipment for spraying and combustion of slurry fuel.

The perspective method of coal-water slurry spraying, developed by the researchers of IT SB RAS [2, 3], is based on the interaction of cumulative and near-wall jets created by the nozzle with the impinging liquid. In order to find the optimal operating parameters (atomizing air and liquid flow rates) for the creation and subsequent ignition of the gas-droplet flow, a detailed experimental study of the fuel atomization characteristics is necessary.

2. Experimental setup and technique
In this paper, the atomization by a pneumatic nozzle developed for coal-water fuel is studied using water as a test liquid. The specificity of liquid dispersion is as follows. A gas jet flowing out of a conical slit nozzle forms a converging jet gas stream outside the nozzle. As a result, flow along the nozzle axis in the forward direction and a high-speed return jet of the cumulative type are formed. The liquid is supplied through the central pipe under pressure. Due to the Coanda effect, the fluid flow is deflected to the walls of the diffuser nozzle and spreads along with them as a thin layer. High-speed return gas jet leads to dispersion of the liquid jet. The return flow of gas after collision with the liquid changes its direction to the opposite, spread along the walls of the diffuser and accelerates the flow of liquid. As a result of the interaction of gas and liquid flows at the outlet of the diffuser, a homogeneous fine gas-droplet flow is formed (Fig. 1). Previously [4], the characteristic angle of the jet opening varying within the range of 20°–25° was determined.
Figure 1. Gas-droplet flow generated by a pneumatic nozzle for coal-water slurry.

In the experiments, the regimes at the initial air overpressure in the annular gas chamber of the injector were studied within the range of $P_0 = 1.0-4.0$ bar (volume air flow $G = 80-100$ m$^3$/h). The pressure was regulated by a valve and controlled by a standard pressure gauge. The liquid was supplied by a pump (flow rate $F_w = 20-80$ g/s), and the flow control was carried out by means of a rotating vane flowmeter. The selected flow ranges of the carrier phase and liquid corresponded to the operation modes of the injector on a real boiler [3].

To study the characteristics of the liquid spray with a pneumatic nozzle, non-contact optical methods of flow diagnostics were used: the method of shadow photography (SP) [5] and the interferometric method for determining the droplet diameters (IPI) [6]. Figure 2-a shows the measuring areas (35x24 mm): on the axis of the jet and on the periphery.

The SP method is based on the registration of a shadow photo of an object with a refractive index different from that of the environment. In this case, behind the object under study (relative to the camera), there is a diffuse light source with a uniform spatial distribution of intensity. Digital analysis of the shadow image allows determining the position and boundary of the object. Figure 2-b shows a characteristic shadow photo of the gas-droplet flow processed using special algorithms, where the identified particles are marked with markers. The IPI method is based on the registration of defocused droplet images, illuminated by a laser sheet. According to the Mie theory of scattering [6], the light reflected and two times refracted by the spherical surface of the droplet creates interference fringes in the images of droplets. Their frequency directly depends on the droplet diameter. Digital analysis of the obtained images allows determining the position and size of the droplets suspended in the stream. This method allows measuring particles with sizes from 10 microns.

To conduct experiments by the SP method, the “Polis” measuring complex was used. It includes the following components: CCD camera ImperX B4820-M (resolution 4904x3280 pixels, shooting frequency of 3.2 Hz, and minimum inter-frame delay of 200 ns) and a macro lens Tamron SP AF with a focal length of 180 mm, which ensured measurements with a good spatial resolution (magnification 1:1). As a light source, a background screen with a rhodamine-based fluorescent coating was used. It was pre-illuminated by a defocused beam of a pulsed Nd:YAG QuantelEVG laser (wavelength – 532 nm, pulse energy – up to 145 MJ, and pulse duration – 10 ns). To increase the contrast of shadow
photography, a threshold light filter (560 nm) was used. Its bandwidth corresponded to the wavelength of light re-emitted by rhodamine.

The implementation of the IPI method also required the measuring complex “Polis”, which includes the following parts: CCD camera ImperX B4820-M and a Nikon macro lens with a focal length of 105 mm. With the aim of increasing the method resolution and registration of individual particles in a dense gas-droplet stream, the images of drops decreased in one direction using an optical compression block specifically designed for the used lens. A pulsed laser Nd:YAG QuantelEVG was used as a light source.

The ActualFlow software with packages SP Kit and IPI Kit was used for digital processing.

3. Results

Shadow photos of the gas-droplet jet in different regions were obtained (Fig. 2-a). Figure 3 shows typical shadow images of the jet at different distances from the nozzle (in areas 1, 2 and 3, Fig. 2-a). It should be noted that near the axis the flow is dense and optically translucent, which prevents from using SP and IPI methods for the study. Therefore, the dispersed composition was investigated on the jet periphery (region 4, Fig. 2-a).

As a result of image processing in the measuring area, information on the dispersed composition of liquid droplets at different modes was obtained. Figure 4 presents distributions of the relative number of droplets by size depending on air overpressure $P_0$ in the nozzle at a constant flow rate $F_w$ (Fig. 4-a) and on flow rate at constant $P_0$ (Fig. 4-b,c). Data on fractions smaller than 10 µm are not available because the used systems do not allow recording particles with such dimensions.

Analysis of the results shows that an increase in pressure increases the relative number of small droplets (10-20 microns), i.e., the increasing dynamic effects of the flow on the liquid increase the
efficiency of fragmentation. At that, an increase in the flow rate leads to an increase in the relative number of larger drops.

4. Conclusion
With the use of modern optical methods, data have been obtained on the dispersed composition of the gas-droplet flow at water spraying through a pneumatic nozzle at different operating parameters, corresponding to the stable operation of the burner under study. The predominant droplet size at the periphery of the jet in the studied regimes was within the range of 10-20 µm. It is shown that the increase in air flow rate leads to a decrease in the proportion of large drops, i.e. an increase in the dynamic effect on the liquid increases the efficiency of fragmentation. At the same time, an increase in fluid flow rate leads to an increase in the proportion of large drops. The obtained results allow predicting the dispersion efficiency and optimizing the operating parameters.

The obtained experimental data may be used for numerical calculations of the combustion of pulverized fuel slurries.

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