Investigating characteristics of diesel fuel spray in a perspective burner

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Abstract. Gas-droplet flow at diesel fuel spraying by superheated steam jet has been experimentally investigated in this work with the use of interferometric method (IPI). Data on the dispersed composition of the steam-fuel jet have been obtained in a wide range of operating parameters (steam and fuel flow rates) corresponding to the area of stable operation of the burner. Dependences of droplet sizes in the flow on the regime parameters have been established.

Introduction
Developing methods for creating dispersed gas-liquid flows with specified parameters is an important scientific and technical task. Gas-droplet flows are widely used in various fields: medicine, energy, etc. One of the important trends in the use of such flows is the combustion of liquid hydrocarbon fuels. The efficiency of combustion and emission of harmful combustion products largely depends on the characteristics of the liquid fuel spray, which determines the intensity of the interphase exchange and the composition of the fuel mixture. Understanding the patterns of fuel atomization is necessary to control the combustion process, used in a wide range of industrial technologies. The development of new efficient and environmentally safe methods of fuel combustion with spraying requires a detailed study of spray devices, i.e. nozzles, using laboratory modeling. Obtaining detailed information about the structure and dispersed composition of the gas-droplet fuel jet using modern optical methods (SP, IPI) [1-2] is important for optimizing the equipment and the combustion process as a whole.

One of the promising devices for fuel combustion is a burner developed by the staff of IT SB RAS [3]. This burner uses superheated steam for fuel atomization. Its distinctive feature is the lack of contact between the fuel and the surface of the spray nozzle, which prevents from possible coking of surfaces and subsequent failures in operation. In order to find the optimal operating parameters for the creation and subsequent ignition of the gas-droplet flow, there is a need in a detailed experimental study of the characteristics of fuel atomization by the nozzle used in this burner.

Experimental setup and technique
In this paper, the atomization of liquid hydrocarbons by a jet of superheated steam in a direct-flow burner (without combustion) is studied by the example of diesel fuel. This type of fuel, as the most common and widely used liquid fuel, is chosen to investigate the base characteristics of the spray unit.

The process of atomization and combustion of liquid fuels is as follows (Fig. 1-a). The steam flows out of the nozzle (diameter of 0.5 mm) in the form of a jet. Liquid fuel flows freely into its base and interacts with the steam jet to form a finely dispersed gas-droplet flow. At the same time, superheated water vapor increases the temperature of fuel droplets, thereby improving the mixture formation and fostering its stable ignition. Along with this, in the combustion zone there is a steam gasification of the
thermal decomposition products of the fuel, which, as in the case of evaporative burners [4], improves the combustion characteristics of liquid hydrocarbons. To reduce toxic emissions and increase the completeness of fuel combustion, it is important to ensure high uniformity of the gas flow, the smallest possible fragmentation of fuel, and high stability of the torch.

Figure 1. (a) Scheme of the experimental burner: cylindrical housing – 1, steam atomizer – 2, air supply holes – 3, steam line – 4, fuel feed tube – 5, chamfer – 6, nozzle – 7, fuel receiver – 8, torch – 9, steam-fuel jet – 10, recirculation zone – 11; (b) Regime map of the burner ($T_s=250^\circ$C): I – flame blowout; II – zone of “ecological” stable combustion; III – flame with a high content of CO in combustion products (> 500 ppm); “+” – regimes studied with IPI.

Preliminary studies [5] of this burner design (Fig. 1-b) allowed determining the conditions for stable combustion of diesel fuel. The investigation concerned the regimes in the range of steam flow rate $F_v$ corresponding to the working range of the metering water pump and to the performance of laboratory electric steam generator, required to superheat the steam to a predetermined temperature ($T_s = 550^\circ$C). The limits of variation of fuel flow rate $F_f$ corresponded to the permissible power of the burner in laboratory measurements ($\gamma = F_v/F_f$ is the relative mass flow rate of steam). The temperature of superheated steam in the experiments was set constant $T_s = (250\pm 10)^\circ$C, since it had been previously found that a further increase in the degree of steam superheating (at $T_s > 250^\circ$C) did not affect the combustion process. Depending on $F_v$ and $T_s$ values, steam pressure ranged from 3 to 11 bar, and steam overheating $T_f - T_s$ reached 100$^\circ$C ($T_s$ – saturated steam temperature).

In accordance with the data obtained for combustion modes, this paper studies characteristics of fuel dispersion without combustion in the same range of fuel and steam flow rates (their values are shown in Fig. 1-b with symbol “+”). The measurements were carried out in the flow region 10, shown in Fig. 1-a, where the dispersed fuel evaporated intensively and mixed with water vapor.

The characteristics of liquid fuel spraying by a steam jet were studied by a non-contact optical method for diagnosing flows, namely an interferometric method for determining droplet diameters (IPI) [1, 6-7]. The method is based on the registration of defocused droplet images, illuminated by a laser sheet. According to the scattering theory [6-7], the light reflected and two times refracted by the spherical surface of the droplet creates interference fringes in the droplet images. Their frequency directly depends on the droplet diameter. Fig. 2 shows an example of an image obtained using the IPI method. Digital analysis of the obtained images allows determining the position and size of the droplets suspended in the stream. This method serves to measure particles with sizes from 10 microns.
Figure 2. The inverted images of the investigated droplets obtained by the IPI method.

To conduct the experiments, the “Polis” measuring complex was used. It includes: CCD camera ImperX B4820-M (resolution 4904×3280 pixels, shooting frequency of 3.2 Hz, and minimum inter-frame delay of 200 ns) and a Nikon macro lens with a focal length of 105 mm. To compress the image in one direction, an optical compression unit specially designed for the lens was used. A pulsed laser Nd:YAG QuantelEVG (wavelength – 532 nm, pulse energy – up to 145 MJ, and pulse duration – 10 ns) was used as a light source.

In digital processing, the ActualFlow software with IPI Kit package was used to implement the following algorithms:
- Image search algorithm. When searching for images, the scales corresponding to the size of the droplet image are selected by applying a continuous wavelet transform to the image, and the intensity maxima on the resulting image correspond to the position of the images. To eliminate failures, the algorithm includes a step of the found image filtering by the following parameters: the average brightness of the image; the brightness of the image relative to the background; and the distance between the maximums (elimination of multiple operations of the algorithm in one image).
- Frequency calculation algorithm. The frequency of interference fringes in the image is determined by the maximum in the amplitude Fourier spectrum, built over the contour along the image of the drop.
- Algorithm for screening images. In this algorithm, the following filters are used: screening of images located on the image border; screening by the signal/noise ratio; screening by the minimum and maximum distance between the interference fringes.
- Calibration algorithm. This algorithm is used to convert the frequency of interference fringes in identified images into the droplet size. Input parameters are refractive indices of environment (air) and atomized liquid (fuel); laser radiation wavelength; the size of one pixel of the camera matrix; as well as the defocus distance and optical magnification obtained from preliminary calibrations of the optical system.

Results
For each mode under study, a series of 100 images was obtained. The processing took into account the total distribution of particles in all images, normalized by the total number of identified particles. As a result of IPI-image processing, detailed information has been obtained on the disperse composition in the measuring area of the gas-droplet flow when diesel fuel is sprayed by a high-speed flow of superheated steam depending on the operating parameters (fuel flow rate and steam flow rate and temperature).

It is shown that the predominant particle size in all studied regimes is in the range of 10-20 µm (Fig. 3), which is a sufficient condition for efficient fuel combustion [7] and indicates the advantages of the method used for dispersing liquid fuel.
Figure 3. Results of digital processing of IPI data: (a) dependence of disperse composition of diesel fuel spray on fuel flow rate \( (F_f) \), \( F_f = 0.8 \) kg/h; (b) dependence of disperse composition of diesel fuel spray on vapour flow rate \( (F_v) \), \( F_v = 1.4 \) kg/h, \( T_s = 250 \) °C.

\( (n_i \) – number of droplets with sizes of the \( i \)-th range in the \( j \)-th image, \( N \) – total number of droplets identified by the algorithm in the \( j \)-th image, \( j = 1…100) \)

With changes in fuel flow rate in the studied range (at a fixed steam flow rate) droplet sizes do not change (Fig. 3-a). Therefore, flameout and high CO content in combustion products observed in certain modes (Fig. 1-b) are not related to the disperse composition of the spray.

With an increase in steam flow rate from 0.8 to 1.2 kg/h at constant fuel flow rate (1.4 kg/h), there is a slight decrease in the share of identified droplets of predominant size (10-20 µm) and an increase in the number of larger droplets (Fig. 3-b). Due to a high flow rate the time of phase interaction decreases and less fuel evaporates, respectively.

Conclusion
In this work, using the interferometric method for determining the droplet diameter, the gas-droplet flow has been experimentally studied at diesel fuel spraying by a jet of superheated water vapor in a straight-flow burner (without combustion). In a wide range of operating parameters corresponding to different combustion modes, size distributions of fuel droplets have been obtained. The characteristic size of the identified droplets in all studied regimes is shown to be 10-20 µm, which is sufficient for efficient combustion of liquid fuel. It has been revealed that the modes of flameout with high content of CO in the combustion products are not associated with the disperse composition of the spray, but are caused by fuel to oxidizer ratio that is non-optimal for combustion. The obtained experimental data are in demand for numerical calculations of the combustion processes of dispersed liquid hydrocarbons.

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