Laser diagnostics of the spray cone characteristics in centrifugal sprayer

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Abstract. The results of the experimental determination of dispersity and spatial distribution of droplets in the spray torch of the centrifugal sprayer are presented. The laser complex for spray diagnostic equipped with devices for laser diagnostics of aerosol systems is described. The parametric analysis is carried out, according to its results, the criterion relations for the maximum diameter of the particles in the spray torch of the centrifugal sprayer are presented.

1. Introduction
The problem of liquid atomization is relevant to ensure reliable combustion of fuel mixtures in internal combustion engines and in the combustion chambers of rocket engines. In powder metallurgy, these issues have been actively studied since the middle of the last century, and now have become particularly relevant in connection with the increasing requirements for the particle size of the final powder product [1, 2].

To determine the main characteristics of droplets (dispersity, spatial structure) in the spray cone of a centrifugal sprayer, the use of non-contact optical methods is the best, in particular, the method of small-angle scattering indicatrix and the method of spectral transparency. The methods have some advantages, including the minimum amount of necessary prior information, the ability to measure the parameters of the droplets in the spray cone and determine their distribution function by size, as well as the spatial distribution of the concentration of the drops [3-7].

The study of the dispersed parameters of aerosol polydisperse media requires appropriate sets of equipment that face the strict requirements of experiments in laboratory and production conditions.

This paper presents the results of experimental determination of dispersity and spatial distribution of droplets in the spray cone of the centrifugal sprayer. The laser complex for spray diagnostic equipped with setups for laser diagnostics of aerosol systems is described. According to the results of experimental studies, the parametric analysis for the maximum diameter of the particles in the spray cone of the centrifugal sprayer was carried out.

2. Laser diagnostic complex for the study of the main characteristics of the spray cone in the centrifugal sprayer
Experimental studying of the structure and dispersity of droplets in the spray cone of a centrifugal sprayer was carried out on a laser diagnostic complex [9, 10]. The laser complex for spray diagnostic consists of devices for determination of the dispersion of droplets (figure 1) and for determination of the concentration of droplets in the spray cone (figure 2). Air and water supply systems are not shown in the diagrams.
To determine the disperse composition of droplets in the atomization of co-current flow gas testing on the laser complex for spray diagnostic, the method of measuring the angular scattering phase function of the laser radiation was used (figure 1). The examined sprayer 1 is mounted on a tripod, mounted on a massive frame 2. The probing laser beam 4 is directed horizontally into the measuring volume 5, located on the axis of symmetry of the spray cone 3. The radiation scattered in the measuring volume 5 is recorded by the receiving system 6, which is placed on the console 7. The console 7 is hinged on the frame 2 with the possibility of rotation in a vertical plane with the help of a bearing. The rotation of the console 7 at an angle $\theta = \pm 10^\circ$ relatively to the direction of the probing radiation is carried out by a tripod 8 with a micrometric screw, which allows to measure the indicatrix in this range of scattering angles. With the help of an additional laser beam 9, the distance $l_1$ is fixed on the measuring scale 10, located at a distance $l_2 = 2180$ mm from the center of the measuring volume 5. The scattering angle is determined by the ratio: $\theta = \arctg \left( l_1 / l_2 \right)$. More complete description of the setup for determination of the dispersed composition of droplets in the spray cone can be found in [5, 10].

Determination of the spatial distribution of the concentration of droplets in the aerosol was carried out on the laser complex for spray diagnostic using the spectral transparency method (figure 2). After starting the laser radiation source 4, the electric motor 11 is switched on. The rotating reflector 12, mounted coaxially with the laser beam, performs a radial laser beam scanning of a plane perpendicular to the axis of symmetry of the sprayer. With the help of an optical two-lens system 13, a parallel scan of the plane of the section of the spray cone 3 and the arrival of the laser beam to the receiver 14 is carried out. With the help of the oscilloscope 15 and the computer 16, the distribution of the laser radiation intensity in the cross-section of the measuring volume is recorded. A more complete description of the setup for determination of the spatial distribution of droplets in the spray cone can be found in [8, 9].

An integrated approach to determine the disperity of droplets and their spatial distribution in the spray cone allows obtaining all the main characteristics of the sprayer under study.

3. The results of the experimental studies of the main characteristics of the spray cone in the centrifugal sprayer.

Spraying of model liquids was carried out using a centrifugal sprayer with the varying flow rate of the model liquid and air at the inlet to the sprayer. The scheme of the centrifugal sprayer is shown in figure 3. The injection sprayer consists of twisting of the camera 1, the input tangential channels 2 and outlet sprayer 3. Figure 4 shows a photo of the spray cone of the investigated centrifugal sprayer.
The characteristics of the centrifugal sprayer are determined by the following geometric parameters: \( R_0 \), the twisting interval (the distance from the axis of symmetry of the centrifugal sprayer to the axis of the input channel); \( R_{ca} \), the radius of the twisting chamber; \( r_{in} \), the radius of the input channel; \( r_c \), the radius of the nozzle; \( n \), the number of input channels. The geometrical parameters of the sprayer are presented in table 1.

The liquid is introduced into the centrifugal sprayer tangentially, whereby the flow is twisted. At the exit of the liquid from the nozzle, the flowing jet is dispersed into droplets that scatter along the rectilinear rays that make up the angle \( \alpha \) with the axis of the centrifugal sprayer (the root angle of the spray cone). The value \( \alpha \) is determined by the values of the axial \( u \) and tangential \( w \) components of the velocity vector \( \vec{u} \) in the output section of the nozzle \( \alpha = \arctg\left(\frac{w}{u}\right) \).

| Parameter | Value |
|-----------|-------|
| \( n \)   | 3     |
| \( r_{in} \) (mm) | 0.45 |
| \( r_c \) (mm)   | 0.8   |
| \( R_{ca} \) (mm) | 1.32 |
| \( R_0 \) (mm)   | 0.87  |
| \( \alpha \) (deg) | 40.9 |

The pressure drop varied in the range \( \Delta p = (0.002 \div 0.8) \) MPa. In the experiments, we measured the liquid flow rate \( G \), a pressure drop \( \Delta p \) and angle of spray \( \alpha \). The relative measurement error \( G \) was 1%, the pressure drop 1%, the spray angle of 2.5% (with a confidence probability of 95%). The results of the experimental studies have shown that the values of the pressure drop \( \Delta p > 0.15 \) MPa, spray angle can be determined by Abramovich–Klyachko formulas [11] with an error of \( (5 \div 6)\% \). At \( \Delta p < 0.15 \) MPa error increases to \( (50 \div 80)\% \).

The processing of the measurement results for the dispersity of droplets in the spray cone was carried out in the framework of models of monodisperse and polydisperse droplets [5, 10]. The measured radius of monodisperse drops was \( r = 24.8 \) µm (figure 5, curve 1). A closer correspondence between the calculated and experimental scattering indicatrices was obtained for the model of polydisperse drops (figure 5, curve 2). The distribution function obtained as a result of the experimental data processing is shown in figures 6. The modal radius of drops \( r_0 = 3.5 \) µm. The mass median radius of drops \( r_{43} = 27.2 \) µm. Note that the value of \( r_{43} \) is in good agreement with the radius of monodisperse drops \( r = 24.8 \) µm.
The spectral transparency method was used to determine the spatial distribution of droplets in the spray cone in centrifugal sprayer [8, 9]. The method is based on the measurement of the spectral transmittance of the laser scanning of the chords of the spray cone in its different sections, followed by the solution of the corresponding inverse problem.

Processing of the results was carried out in automatic mode separately for each section of the spray cone and was reduced to the calculation of the distribution of the optical density of the torch along the chords. The results of measurements showed that the concentration of droplets in the spray cone of the centrifugal sprayer is uneven both in the radial coordinate and in the length of the cone figure 7. In figure 7, the concentration of droplets in the spray cone of the centrifugal sprayer \( C(r) \) is normalized to the maximum value \( C(r)_{\text{max}} \). The value for the current radial coordinate is shown in dimensionless form \( \mathcal{C} = r/R \), where \( R \) is the radius of the spray boundary in the investigated section. The distance from the beginning of the spray cone of the sprayer to the position of the investigated cross-section all along the length of the spray cone of the sprayer: \( z \).

4. Parametric analysis of the results of the experimental studies of the dispersity of droplets in the spray cone in the centrifugal sprayer

To estimate the dispersed composition of droplets in the spray cone in the centrifugal sprayer, the criteria relations, obtained by processing the results of measuring the size of droplets by the method of small angles of the laser radiation scattering indicatrix were used.

In accordance with the theory of dimensions, the criterion equation for determining the size of

Figure 5. The calculated and experimental (points) scattering phase functions.

Figure 6. The function of droplet size distribution.

Figure 7. The radial distribution of the concentration of drops in the different sections of the spray cone in the centrifugal sprayer.
droplets in the spray cone in centrifugal sprayer can be represented as:

\[ \frac{D}{\delta} = f(\frac{\rho_g}{\rho}, \frac{\mu_g}{\mu}, \text{Re}, \text{Oh}) \]  

(1)

where \( D \) is a certain average droplet diameter; \( \delta \), the thickness of the liquid resulting from a centrifugal sprayer; \( \rho_g, \rho \) is the density of the gas and liquid phases; \( \mu_g, \mu \), coefficient of dynamic viscosity of gas and liquid.

The first two criteria of similarity (simplex) according to (1) characterize the physical properties of liquid and gas; \( \text{Re} = \frac{\rho_g \mu \delta}{\mu_g} \), Reynolds number for the liquid film; \( \text{Oh} = \frac{\rho_g \sigma \delta}{\mu_g^2} \), Ohnesorge number. Where \( u \) is the velocity of the liquid from the nozzle of the sprayer, \( \sigma \) is the surface tension of the liquid. Values \( \delta, u \) was determined according to the theory of Abramovich-Klyachko [11].

Analysis of the experimental data showed that the value of simplices \( (\frac{\rho_g}{\rho}) \) and \( (\frac{\mu_g}{\mu}) \) relatively weakly affect the dispersion of droplets in the spray cone. Therefore, the criterion for estimating the dispersion of droplets is simplified: \( \frac{D}{\delta} = f(\text{Re}, \text{Oh}) \).

Analysis of the results of the experiments together with the known approximation formulas allowed to recommend the following criterion:

\[ \frac{D_{\text{max}}}{\delta} = \left(67 + 3.7 \times 10^{-3} \text{Oh}\right) / \text{Re}^{0.7}, \]  

(2)

where \( D_{\text{max}} \) is the maximum diameter of the drops (corresponds to ordinate 0.95 on the integral curve of the mass distribution function of the drops by size). The graphs of dependence (2) are shown in figure 8.

The ratio (2) is performed in the following ranges of similarity criteria: \( \text{Re} = (120 \div 1200), \text{Oh} = (7000 \div 69000) \).

5. Conclusion

- A new scheme of the laser diagnostic complex for determining the main characteristics of the spray cone in the centrifugal sprayer is present.

- The data of the size of droplets in the spray cone of the centrifugal sprayer in the framework of mono- and polydisperse models is obtained. The value of the average mass-radius of drops (polydisperse model) correlates with the radius of monodisperse drops.

- By the generalization of the results of measurement in dispersion of the droplets of the spray cone in the centrifugal sprayer, an approximating formula for the dependence of maximum droplet size on the determining similarity criteria of Reynolds and Ohnesorge was obtained.

![Figure 8. The dependence of \( \frac{D_{\text{max}}}{\delta} \) on the criteria values Re and Oh.](image-url)
Acknowledgments
This study was supported by the Russian Science Foundation (Project No. 15-19-10014).

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