Quality estimation of the nozzle spray by measuring the brightness of the reflected light

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Abstract. This paper presents the results of the laboratory and numerical experiments performed to measure the sizes of transparent liquid droplets sprayed in air. The results of the laboratory experiments were mainly obtained using the Glare Point Technique (GPT) which gave information about the droplet size and the brightness of the light reflected by drops. The relationship between the brightness of the light reflected from the surface of droplets and their sizes was analyzed. Theoretically, the brightness of light scattered by a single spherical drop is proportional to the drop surface area and, accordingly, to the square of the drop diameter. It has been observed experimentally and verified numerically that the theoretical dependence obtained is relevant only for the brightest droplets because of nonuniform illumination. The results of the numerical experiments with a random sample of drops indicated the dependence of the total brightness of reflected light on the effective droplet size. It is shown that, for a fixed total volume, the total brightness of light reflected by drops is proportional to the droplet Sauter mean diameter.

1. Introduction
Knowledge of the droplet size distribution in sprays produced by various spray devices is very important for the design and optimization of these devices. The part of the atomizing device responsible for the formation of the spray is usually the nozzle. To measure the size of droplets and their distributions in space created by nozzles, optical methods are widely applied [1, 2, 3]. In particular, using the Glare Point Technique (GPT) [4], researchers obtain information about the size, velocity and position of transparent liquid droplets in space [5]. The study of such characteristics as the average speed, the average droplet size, the droplet Sauter mean diameter, the spray angle, and the flow rate is of great significance for manufacturing and quality control of nozzles. Estimation of the average droplet size, the droplet Sauter mean diameter and the spray angle by applying optical methods with laser illumination of the droplet stream and information on the brightness distribution of reflected light can also be useful. Visual observation of the spray of a particular nozzle gives a lot of information of non-quantitative character, on the basis of which the operator can draw a subjective conclusion about the nozzle operation. At the same time, information about the amount of light scattered by the spray stream is objective and quite reliable to quantitative assessment.

According to the Mie scattering theory [1], the brightness of light scattered by transparent liquid drops is proportional to their surface area and for spherical drops to the squares of the droplet diameters. Thus, if we assume that the brightness of the incident light is the same for all drops, that is, all drops are uniformly illuminated, then the brightness of the light scattered by drops can be used to
judge then relative sizes, and after calibration, then absolute sizes. However, in laboratory experiments and, moreover, under production conditions, it is difficult to achieve uniform illumination of the fluid flow. Therefore, we investigate here the quantitative dependence of the brightness of the reflected light on the droplet size, both for individual droplets of different sizes and for the ensembles of droplets with different droplet size distributions under nonuniform illumination.

2. Laboratory and numerical experiments

2.1. Laboratory-experiments (measurement of droplet sizes and reflected light brightness)

Experimental layout is shown in figure 1. The nozzle (1) forms a spray (2) consisting of droplets of a clear liquid (distilled water was used). The laser (3) with a short (10 ns) flash of light, deployed in the form of a plane (4) with a thickness of about 1.5 mm parallel to the direction of the spray propagation, illuminates a certain section of the spray. The CCD camera (5), synchronized with a laser, records images of drops as objects with pairs of glare points (6).

![Figure 1](image1.png)

**Figure 1.** Scheme of the GPT measurements. 1 – nozzle, 2 – spray, 3 – laser, 4 – laser beam, 5 – CCD camera, 6 – GPT primitive images of droplets.

In figure 2 (a), a snapshot of spray (the nozzle is located on the middle-top) is presented with the rectangle sectors in which the droplet diameters were measured by the GPT method. Typical GPT images from a CCD camera are shown in figure 2 (b). Paired points (glares) are the images of individual spherical droplets, the sizes of which are obtained at some distance between the glares on the droplets (typical size of 20 pm). In this case, the brightness of the light reflected by this drop is recorded. Thus, it is possible to obtain the dependence of the brightness of the reflected light on the droplet size.

![Figure 2](image2.png)

**Figure 2.** View of the spray at different magnifications: a) general view of the spray of the nozzle against the background of the coordinate target, the rectangle marks areas 33, 34, 35, where the droplet sizes were measured by the GPT method; b) Images of droplets: GPT images.
Further, the measured diameters were compared with the brightness of the droplets. Figure 3 shows the dependence of the brightness of light reflected by a drop on the size of the drops. All the set of droplet sizes obtained in this way is divided into intervals of ± 2.5 pm. The dots mark the average brightness values for the drops, and the bars are the standards deviations within the size interval.

![Figure 3](image.png)

**Figure 3.** Dependence of the brightness of the light reflected by droplets versus their diameters.

From figure 3 it is apparent that the spread in brightness is very large. This means that it is impossible to judge about its size by the brightness of an individual drop. Apparently, such a spread arises due to the nonuniform light illuminating the drops. To check this, as well as to establish other regularities, several numerical experiments have been carried out.

2.2. *Numerical experiments*

Numerical experiments were carried out to obtain the dependence of the brightness of the reflected light on the droplet size under nonuniform illumination conditions. The software product Wolfram Mathematica was used to perform numerical experiments. Also, some assumptions were made due to the data of laboratory experiments. Since in the laboratory experiment and under production conditions, the fluid flow is usually illuminated by laser light, which has an brightness distribution inside the beam similar to the Gaussian distribution, then in the numerical experiment the reflection of light from the particles falling into the light beam was simulated. The light brightness distribution corresponding to the Gaussian distribution with standard deviation was $\sigma = 1$. Figure 4 illustrates changes in the brightness of the droplets depending on the size and distance to the maximum illumination at $z = 0$. The light brightness change interval is limited by $3\sigma$. This means that the probability that a random variable will take a value that deviates from the mathematical expectation by more than three standard deviations does not exceed 0.28%, i.e., it is negligible.

To simulate random samples of droplets by analyzing their size, the Maxwell distribution was used (histogram is given in figure 5a). This distribution qualitatively repeats the characteristic shape of the size distributions of distilled water droplets in the flare of two nozzles of different designs obtained in laboratory experiments (see figure 5 (b)).

As a result, a picture of the distribution of the reflected light brightness has been obtained depending on the droplet dimensionless radius (see figure 6). As can be seen from figure 6, for the brightest particles, that is, those that fall into the most illuminated area, the brightness distribution of the reflected light is found with respect to parabolic dependence. For the rest of the particles, the scatter of brightness values is too large to obtain any dependence on the sizes of individual droplets.
Figure 4. Light brightness profile $I(z)$. The dots show drops of different sizes randomly distributed over $z$, the brightness is determined by the size and distance to the center.

Figure 5. Histograms of the random ensemble of drops with Maxwell distribution of sizes (a) and real distributions (b) (labels “O” and “P” correspond to measurements (with different nozzle types).

Figure 6. Simulated droplet brightness of reflected light versus droplet sizes (radius $R$ is given in units of $\sigma$).
However, if the total amount of all particles remains constant for different particle size distributions, then for such ensembles of particles it is possible to obtain some dependence of the average size values on the total brightness of the reflected light.

Figure 7. Ensembles of droplets with the same total volume: a) ensembles of the same particle sizes; b) the same ensembles of particles, but with a Maxwell distribution of sizes within the ensemble.

If the distributions of particles shown in figure 7 vary under the illumination conditions from figure 4, then there is an inversely proportional dependence of the total brightness of the light reflected by the particles, both for the Sauter mean diameter of ensembles of particles with a Maxwell distribution and for the average diameter of ensembles of particles of the same size shown in figure 8.

Figure 8. Total brightness of the reflected light $\Sigma I$ versus the Sauter mean radius (in units of $\sigma$): red points are given for ensembles with the same sizes (see distributions in figure 7 (a)); blue points are given for ensembles with Maxwell distribution of sizes (see distributions in figure 7 (b)).

Conclusions
The experimental measurements and numerical simulations carried out in this study confirm that the nonuniform illumination does not allow one to unambiguously relate the size and brightness of an individual droplet. The analysis of a sufficient set of statistical data for a fixed total volume of the sprayed liquid showed that the integral brightness of an ensemble of droplets changes inversely with
the droplet size. This dependence is retained for the Sauter mean radius in the case of the ensemble of droplets distributed by sizes. Thus, it can be assumed that measurements of the total brightness of light reflected by the stream of a particular nozzle will provide simple quantitative information about the differences in the spray of nozzles both in laboratory experiments and under similar production conditions. In particular, having received the light brightness value for a reference nozzle, one can compare the group of nozzles with the reference one using this brightness value.

Acknowledgments
This applied work is supported by the Russian Foundation for Basic Research under project No. 19-08-00574.

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