Researches of two-phase stream by methods of registration of fluorescence of drops of liquid and Shadowgraph

O G Chelebyan, A Y Vasilyev, A A Sviridenkov and A A Loginova

Central Institute of Aviation Motors, Aviamotornaya 2, Moscow 111116, Russia

E-mail: ogchelebyan@ciam.ru

Abstract. In this paper, the fluorescent method is used in conjunction with the shadowgraph method to obtain the concentration distributions and droplet sizes in the spray. A beam of light from a pulsed laser, passing through a longitudinal or cross-section of a jet of atomized fuel, tinted with a fluorescent additive, oxyquinoline, partially scatters on droplets (Mie-scattering), while blue light with a wavelength $\lambda = 488$ nm excites fluorescence in the green range of the wavelength spectrum. A color image of the cross section of the fuel spray by a laser beam is recorded during scanning by a digital camera, the optical axis of which is directed at a right angle to the axis of the laser beam. Thus, at each point of the image of the spray cross section, fluorescence intensities are recorded, proportional to the volume concentration of the droplets and vertically polarized by the component scattered on the light drops with respect to the scattering plane (measurement). The ratio of fluorescence intensity to Mie scattering intensity is proportional to the diameter of the fuel droplets averaged over the Sauter.

1. Introduction
Reducing emissions of pollutants from liquid fuel fired combustion chambers is becoming an increasingly serious problem for industries facing the need to comply with new and upcoming environmental restrictions and regulations. An important condition for meeting these requirements, as well as a critical problem in the development of advanced liquid combustion chambers and high-pressure fuel injectors, is a detailed understanding of the process of mixing fuel with air, droplet size and velocity distribution, and fuel density distribution pattern encountered in high-pressure combustion chambers.

Until recently, the actual flow fields in the combustion chamber were not available for highly sensitive and specific optical sensing methods. The emission characteristics of the combustion chambers of power plants are largely determined by the quality of atomization of fuel injectors. Improving the mixing of fuel with air can reduce NOx emissions, increase the efficiency of the combustion chamber, reduce its size, the instability of combustion, and increase the service life of engines.

The smaller the size of the droplets, the shorter the time of their evaporation, as the total surface of the droplets increases, which accelerates heat transfer. However, on the other hand, very small droplets follow the flow. As a result, the penetration of sprayed droplets into the gas stream may decrease, which will make it difficult to obtain a homogeneous fuel-air mixture. Based on theoretical
calculations and experimental work, various researchers recommend optimal values of the average Sauter diameter of the SMD 15-25 μm.

In addition to the average diameter, the maximum droplet size is also important. Large drops reduce spraying and increase fuel penetration, causing irrigation of the combustion chamber walls. To illustrate the droplet size effect, it is easy to calculate that a droplet with a diameter of 40 μm has a fuel mass of eight times the surplus mass of 20 μm droplets and by the time the 20 μm droplets have completely evaporated, the large droplet will still have a diameter of ~ 38 μm.

Therefore, it is important not only to create front-line devices that provide the necessary parameters of the air-fuel mixture, but also to have means of controlling both time-averaged distributions of concentrations and sizes of droplets, and their pulsation values at each point of the combustible mixture. The most modern and informative method for determining these parameters is currently the method based on the fluorescence of a laser-excited dye added to a liquid, or the natural fluorescence of a fuel (kerosene). Together with the measurement of Mie scattering of laser radiation, the method allows to obtain quantitative values of the concentration and size of droplets of sprayed fuel.

Shadowgraph is the only method that can be used to characterize droplets and liquid filaments of arbitrary shape. However, the shadow method, like the PDA method, can only be used in optically dilute aerosols, since the light illuminates both the focused and non-focused drops, and the light rays pass through the entire spray cone before entering the recording chamber. In addition, more complex image processing is required to distinguish between droplets that are in focus and droplets that are out of focus in order to obtain accurate droplet size. While PDA devices use high-power lasers with a continuous wave of radiation, it is advisable to use pulsed lasers that can provide uniform stray light for a shadow image, or use cameras with a very short exposure time.

The fluid mechanics first quantitatively determined the concentration of the LIF method and apparently were applied by Owen in 1976, which measured the concentration and velocity of two coaxial jets flowing into space with a sudden expansion [1]. The LIF / Mie method for determining size droplets has been used in a variety of studies since the study by Yee et al., First published in 1993, in which diesel fuel spraying was studied [2]. The droplets under investigation are spherical. Molecular absorption inside the droplets should be taken into account. The cubic and square dependence of the droplet diameter on the optical signals of LIF and Mie scattering, respectively, should be observed. The dye concentration and laser power remain constant during the experiment. The optical signal LIF is proportional to the power of the laser and at the time of the experiment it does not saturate. The evaporation rates of the fluorescent dye and the liquid medium should be close. Also consider the effects of multiple light scattering and minimize oscillations of the Mie scattering signal.

Research have shown that the use of continuous exciting laser radiation leads to incorrect measurement results near the nozzle, due to secondary scattering on droplets, as well as the presence of non-spherical droplets and liquid ligaments formed at the initial stage of the breakup of fuel film. The use of non-stationary radiation source helps to reduce measurement errors. The paper notes that the contribution of the intensity of scattered light is very difficult to predict, and the observed tendency can change depending on the viewing angle, the transparency of the optical medium, the size of the droplets, their distribution, etc. To calibrate the intensity ratios LIF / Mie SMD data from PDA measurements were used at each measurement point.

In [4] 0.02 g rhodamine 6G dissolved 200 ml of ethanol. This solution was mixed with 4 liters of gasoline and used for experiments. The concentration of rhodamine used (5 mg / l of gasoline) was selected from the literature as the lowest. About 300 images were taken at each time point and averaged over the ensemble after subtracting the background to obtain the final Mie image and fluorescence. The area size of 1 × 1 mm corresponded to 300 × 300 pixels in the images. It is worth emphasizing that, although the uncertainty in the PLIF diameter versus diameter introduces some uncertainty in the calibration factor and, consequently, in SMD, the PLIF method is a quantitative technique, and as such, the PLIF images give the SMD number at any point in the spray. For the standard deviation of the average value of 33%, the error of these measurements, based on a 95%
confidence level, is ± 20%. However, in areas close to the nozzle the assumption of the dependence of PLIF on the diameter is violated due to the presence of ligaments and, therefore, the data in this area will not be accurate. This is, in fact, a limitation of all the methods described in the literature.

Studies of the characteristics of a fuel atomized by a centrifugal nozzle were carried out jointly by the methods of light scattering at small angles and PLIF in [5]. To calibrate the fluorescent method we simultaneously measured the sizes and concentration of droplets in the same cross section of the spray jet of a well-studied (standard) pressure nozzle using the method of light scattering at small angles. The mean values of the Mie intensities of the scattered light and the fluorescent light emission with the surface and volume concentration of the droplets, respectively, were determined from the mean concentrations and droplet sizes in this spray section. These values were used later in the research.

To obtain the concentration distributions and droplet sizes along the radius of the studied cross section of the centrifugal nozzle flame, the Abel transformations of the concentration and droplet size distributions measured along the chords in this cross section by scattering light at small angles were performed. The distributions obtained by the two measurement methods agree satisfactorily with the exception of the region of large concentration gradients in the central part of the spray. This discrepancy may be due to errors that occur during the Abel transform of experimental data representing insufficiently smooth functions.

In the present work, we measured the characteristics of a spray jet of a pneumatic nozzle [6] using the shadow method and the method of recording light on fluorescent kerosene droplets (TS-1) with oxyquinoline dye and irradiated with continuously working laser.

2. Results of investigation

Measurements of the characteristics of the shadow method were carried out at a distance of 30 mm from the nozzle. The droplet speeds, sizes and fuel consumption were measured through the cross section of the spray. Fuel consumption was 1 g / s, air rate 15 g / s.

Figure 1 shows the distribution of the longitudinal component of the velocity of the fuel droplets.

![Figure 1. Distribution of the longitudinal velocity component.](image)

As can be seen from the graph of velocity distribution at a distance of 30 mm to the nozzle on the axis of the spray there is an intense recirculation flow, the speed of which reaches 55% of the maximum velocity of the direct flow.

The distribution of the volume flow through the cross section of the spray cone is shown in figure 2.
Knowing the velocity distribution of the droplets and their volume flow through the cross sections of the spray, it is possible to determine the volume concentration of the droplets.

With the same operating parameters of the nozzle, measurements of Mie scattering and fluorescence of fuel droplets were carried out. A beam of light from a laser, passing through a longitudinal or transverse (horizontal) cross section of a jet of sprayed fuel tinted with a fluorescent oxyquinoline additive, partially scatters on droplets (Mi-scattering), while blue light with a wavelength $\lambda = 488$ nm excites fluorescence in the green range of the length spectrum waves. A color image of the cross section of the fuel spray by a laser beam is recorded during scanning by a digital photo or video camera, the optical axis of which is directed at a right angle to the axis of the laser beam. Thus, at each point of the image of the spray cross section, the fluorescence intensities $I_F$ and the vertically polarized component $I_S$ Mie of the light scattered on the drops with respect to the scattering plane (measurement) are recorded. Information from a video camera is transfer to a computer. The values $D_{32} = K <D^3> / <D^2>$ for $D_{32} > 10 \mu m$ are calculated from the equations for the intensities of scattered light

$$I_S = \alpha <D^2>N I_0 = 2 \alpha C_s I_\delta$$
$$I_F = \beta <D^3>N I_0 = 3 \beta C_V I_\delta$$

Therein $N$ is the numerical concentration of droplets; $\alpha$ and $\beta$ are constants determined experimentally; $I_\delta$ is the intensity of the incident light; $C_s$ and $C_V$ – surface and volume concentration of droplets. Hence, the expressions for the diameter of $D_{32}$ drops, averaged over Sauter, and their $C_V$ concentration are: $D_{32} \sim I_F / I_S$, $C_V \sim I_F$. The constants $\alpha$ and $\beta$ were determined by comparing the maximum values in the distributions of fuel concentration and droplet sizes at this point, obtained by Shadowgraph and fluorescence. An example of the obtained distributions is shown in figure 3.
Figure 3. The distribution of the droplets fuel concentration in the cross section of the spray (red curve-Shadowgraph, violet – fluorescence).

Since the proportion of the volume occupied by the sprayed droplets at the exit of the pneumatic nozzle is equal to the ratio of fuel and air rate divided by their density ratio, the average volume concentration of fuel is equal to $C_{v\text{mean}} = G_f / (G_a \times \rho_f / \rho_a)$. In experiments, this value was measured directly and turned out to be equal to $C_{v\text{mean}} = 1.0 \times 10^{-4}$. The characteristics of the spray pattern were measured at a distance of 30 mm from the nozzle. At this distance, the width of the spray is approximately two times larger than directly near the nozzle. Consequently, the average volume concentration of fuel droplets at this distance is approximately $2.5 \times 10^{-5}$. Measured as a mean is equal to $3.6 \times 10^{-5}$, mean-mean value $2.4 \times 10^{-5}$. As can be seen from the figure above, there is a satisfactory agreement of the distributions in the left part of the figure. In the right part of the figure, the width of the spray, measured by the fluorescence method, turned out to be less than that measured by the shadowgraph method. Note also that, when processing the color image of the spray, it was not detected the real fluorescence intensity in the inner area of the spray pattern. This appearance was observed in [3] and is associated with the phenomena of secondary scattering of light by fluorescence. To obtain realistic results, an adjustment was made to the intensity of the fluorescent light. Figure 4 shows the intensities of the green component of the scattered light before and after the adjustment.
Figure 4. Fluorescence intensity before-and-after updating.

Figure 5 shows the size distribution of droplets in the cross section of the atomization spray. As can be seen from the figure, the difference in droplet sizes in the center of the spray exceeds 100% of the measured local values, although the trend in size distributions is the same.

Figure 5. The distribution of the size of fuel droplets Sauter-average in the cross section of the spray (red curve-Shadowgraph, violet – fluorescence).

With a transverse arrangement of a laser sheet, non-uniform distribution of the concentration of fuel droplets in the circumferential direction can be obtained. An example of such a distribution is shown in figure 6.
As can be seen from the figure 6 in spray, there is an area with low fuel content. Details of procedure non-uniform calculation are described in [5].

3. Conclusion

A study of the characteristics of spraying fuel in a spray behind a pneumatic nozzle using shadowgraph and fluorescence of droplets of sprayed fuel showed that, despite the informative and high rate production of experimental results, the use of fluorescence requires particularly careful experimentation. This is primarily due to the secondary scattering of light from fluorescent droplets in the spray. It is also necessary to use the minimum concentration of the fluorescent dye to maintain the cubic dependence of the fluorescence intensity on the diameter of the liquid droplets.

References

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