DROPLET SIZE DISPERSION IN THE SPRAY CONE OF JET - SWIRL ATOMIZERS

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Abstract

The burning process in the combustion engines strongly depends on the quality of atomization; hence the microstructure of the atomized fuel is an important factor for designers. Jet-swirl atomizers spray fuel into a wide cone of directions, as quite small droplets, which ensures effective burning. In some applications (e.g. turbine engines) it is important to guarantee that a certain portion of mass of the fuel is atomized in droplets of diameters lower to a fixed critical value D_k. This can be done by creating a quasi-monodispersive distribution of small droplets. The paper presents the results of experimental and statistical investigations into the microstructure of aerosols, with particular interest in the relative standard deviation of droplets diameters d and its relations with the mass portion of droplets of diameters greater the critical value D_k. Diagram of flow through a jet-swirl atomizer with swirling grooves, relative radius is the ratio of radius at which measurements were made, to the spray cone radius, log-normal distribution fitted to a typical experimental data set and the corresponding mass distribution, log-normal distribution fitted to a typical experimental data set and the corresponding mass distribution, Dependence of the mass carried by droplets are illustrated in the paper.

Keywords: *relative standard deviation, dispersion of the droplets' spectrum, aerosol microstructure*

1. Introduction

Fuel injection is crucial for turbine engines, as the whole burning process depends on the quality of atomization. However, the drop size spectrum of the sprayed fuel is the worst-known parameter of such engines. To ensure effective burning, fuel should be atomized in all directions as possibly small droplets. One of the solutions to achieve this goal is a jet-swirl atomizer [1], which is a functional combination of both jet and swirl atomizers. Despite being unique from other atomizing devices, it is sometimes classified as a swirl atomizer [2].

Under operating conditions typical of jet-swirl atomizers, two jets of the same liquid, or different liquids, interact. One flows as an inner, unswirled axial jet; the other jet has an external, annular (helicoidal) swirled flow. With two different liquids, a function of the mixer is also performed by the jet-swirl atomizer. The interaction of both jets is very important as it enables the features of jet and swirl atomizers to join, affecting the value of the parameters of the atomized jet [3, 4]. This makes it possible to obtain the uniform atomizing distribution necessary for all the devices - including, among others, energy appliances [5] - in which very good heat and mass exchange between droplets of an atomized liquid and the surrounding medium is required.

2. Design of jet-swirl atomizers

Various design variants of jet-swirl atomizers are widely represented on paper [6]. Owing to a simple production process for atomizer parts and easy change of flow parameters, with proper part selection, the jet-swirl atomizer with swirling grooves has the greatest number of practical applications [6].

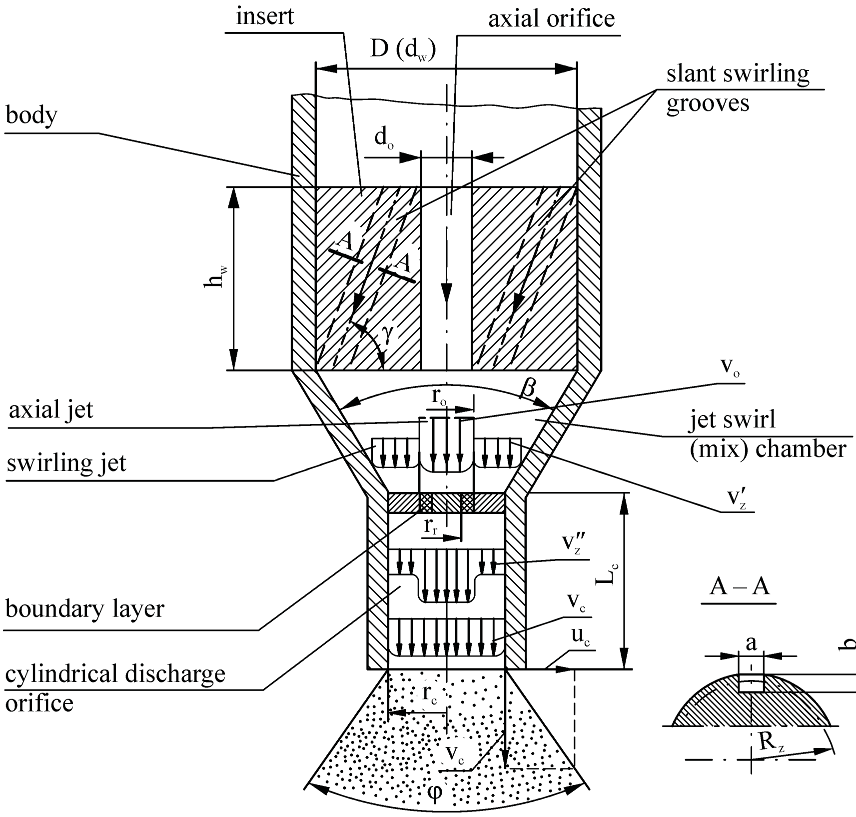


Fig. 1. Diagram of flow through a jet-swirl atomizer with swirling grooves

The cross-section of each groove is characterized by dimensions a and b – Fig. 1 [6]. In the outlet orifice of an atomizer some kinetic energy is transferred from the axial jet to the swirling one, because velocity v_o is bigger than the axial velocity component v''_z of the swirling jet. Within the discharge orifice the motion consists of free vortex and axial flow. Inside the discharge orifice in the boundary layer (Fig. 1) – the zone of jets interaction – kinetic energy is transmitted between the swirling external ring and the core, which does not swirl. Axial components of both velocities become equalized and the axial jet gains some peripheral velocity at the cost of the energy of rotation of the swirling jet. The phenomena proceeding in the boundary layer not only causes an exchange of momentum and energy, but it also mixes both jets.

2. Measurements of droplets

In order to evaluate the influence of each geometric parameter, characterizing orifices of the jet-swirl atomizer with swirling grooves on macro- and microscopic parameters of the atomized jet, 18 versions of different bodies and 19 versions of inserts of this atomizer were made. The dimensions of each of the elements are given in paper [6].

Geometric parameters of bodies of the investigated design variants of the jet-swirl atomizers are as follow:

- inner diameter of the body D = 20.05 mm,
- diameter of the discharge orifice d_c varied from 1.50 mm to 5.20 mm,
- length of the discharge orifice L_c from 2.00 to 6.00 mm,
- height of body part cooperating with the insert h_k from 5.30 to 30.10 mm,
- angle of flare of the swirl chamber β from 60° to 120°.

Geometric parameters of inserts of the investigated design variants of the jet-swirl atomizers are as follow:

- outer diameter of the insert d_w varied from 19.45 to 20.00 mm,
- height of the insert h_w from 5.25 to 30.05 mm,
- diameter of the axial orifice d_o from 2.00 to 2.10 mm,
- number of swirling grooves n from 2 to 6,
- angle of inclination of swirling grooves γ from 10° to 25°,
- width of swirling grooves a from 1.45 to 2.50 mm,
- depth of swirling grooves b in the inlet cross-section from 1.24 to 3.56 mm,
- depth of swirling grooves b in the outlet cross-section from 0.58 to2.46 mm.

To analyse the influence of the geometry of an atomizer on the microstructure of the atomized liquid a geometric factor K'_g comprising all the above mentioned parameters was introduced. Assuming hyperbolic peripheral velocity distribution in the discharge orifice of a jet-swirl atomizer with an insert with swirling grooves, this factor – in accordance with [6] after transformations – is given by the following relation:

$$K'_g = \frac{4 d_w nab(d_w - b)\sin\gamma}{\left(\pi d_o^2 + 4nab\right)^2} \cdot \frac{\pi d_c^4 L_c}{D^4 h_k \sin\dfrac{\beta}{2}}. \tag{1}$$

Drop sizes were measured using a droplet spectrum analyzer AWK briefly described in paper [7]. Up to 10 000 droplets per second in the interval 0.5 ÷ 3000 μm can be counted. The analyzer consists of a probe with a photoelectric converter. Two photodiodes in the converter detect light signals created by droplets moving through the measuring zone and produce corresponding electric signal. The falling droplets were counted and divided into fifteen classes depending on their diameter (the maximal size D_{max}≈700 μm).

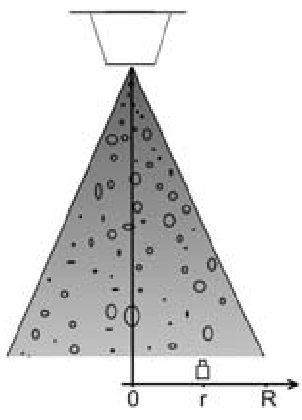


Fig. 2. Relative radius r/R is the ratio of radius r at which measurements were made, to the spray cone radius R

Although this method is very effective it has one disadvantage. The uncertainty level obtained while counting droplets smaller than about 30 μm is quite high. To have the full view of the drop size spectrum a further insight into this interval is needed. This can be done using the diffraction method widely described in papers [8, 9, 10 and 11].

A laser beam shining through falling droplets creates a diffraction pattern, which provides us with information about average linear diameter of droplets and standard deviation of its distribution.

Measurements were conducted at a fixed liquid delivery in a flat fragment of the spray cone as a function of relative radius *r/R*, where *R* is the radius of the spray cone at a certain height *h* (Fig. 2). The experiment was repeated for ten values of the parameter *r/R*.

In order to evaluate the influence of geometry of an atomizer on the drop size spectrum, the measurements were conducted on 27 pairs (i.e. body and insert). Each pair was investigated under three pressures of atomized liquid Δp (0.20 MPa, 0.50 MPa and 0.90 MPa).

3. Distribution fitting

The experimental data was approximated with lognormal distribution for each value of the relative radius. Relation (2) is the probability density function for this distribution for $D > 0$:

$$f(D;\mu,\sigma) = \frac{1}{\sqrt{2\pi}\cdot\sigma D}\exp\left(-\frac{(\ln D-\mu)^2}{2\sigma^2}\right). \quad (2)$$

The diameter of a droplet D is the random variable, whereas μ and σ are the mean and standard deviation of the variable's logarithm. These two parameters were calculated using the maximum likelihood estimation method. The log-normal distribution is a good approximation of the experimentally-obtained drop size spectrum [12].

The probability density function $f(D;\mu,\sigma)$ can be used as a tool to estimate many parameters, which are essential to evaluate the quality of atomization and to conduct calculations connected with appliances of the produced aerosol. One of the parameters characterising the average droplets size is the modal diameter D_m, which is the value for which function $f(D;\mu,\sigma)$ reaches its maximum (i.e. the most often diameter of droplets). Its dependence on the geometric factor K'_g, relative radius *r/R* and pressure Δp of the jet-swirl atomizer is discussed in paper [13].

The histogram representing the number of droplets of certain sizes and the fitted log-normal distribution is shown in figure 3, as well as the distribution of mass carried by those droplets.

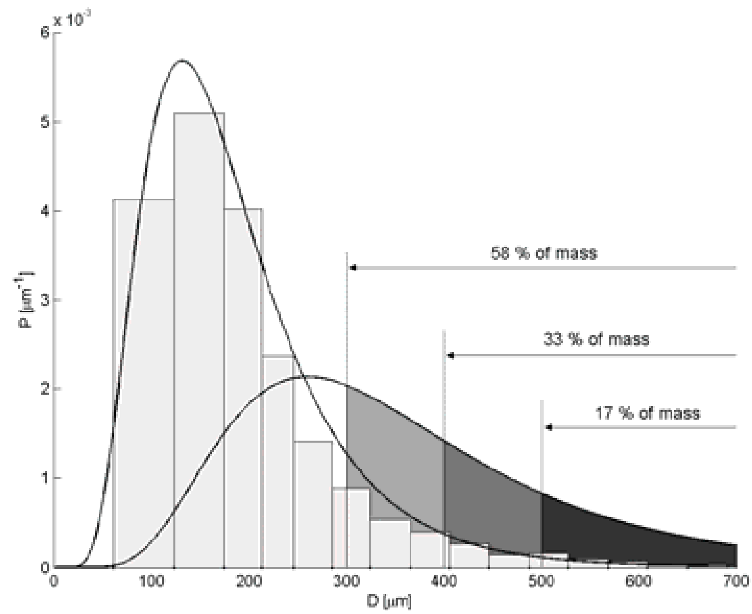


Fig. 3. Log-normal distribution $f(D;\mu,\sigma)$ fitted to a typical experimental data set (histogram) and the corresponding mass distribution

An important role in the combustion process is played by the biggest droplets. Since the volume of droplets is proportional to a cube of their diameter, a small number of the biggest droplets may carry a considerable amount of mass. Figure 3 provides information about the percentage of mass carried by droplets of diameters *D* greater than certain values (300 µm, 400 µm, and 500 µm) for a typical experimental data set. Big droplets require much more time to evaporate completely than small ones, and hence they burn longer. This is particularly important in turbofans. To propel the turbine the fuel must burn in a short combustion chamber. Too big droplets partially burn in the discharge nozzle or even outside the engine. This last case is especially adverse, since not only it raises the consumption of fuel, but also heats the air behind the engine decreasing the thermodynamic efficiency. For this reason the designers of the combustion chambers need to know the mass portion of droplets greater than a certain critical value D_k.

4. The relative standard deviation

Two parameters of the sprayed liquid, the mean diameter D_e and the standard deviation of droplets diameter are said to be crucial for designers of combustion engines. The first provides information about the average size of droplets, while the second is a measure of its dispersion. For a few design variants of atomizers the mean diameter D_e is much smaller than for others. The standard deviation of the droplets diameter spectrum reaches its minimum for the same design variants. This feature makes them very interesting, as a quasi-monodispersive distribution of droplets sizes was obtained. The increase of liquid pressure results in a decrease of the droplets size and their dispersion.

To examine the monodispersivity of various distributions the relative standard deviation *d* was introduced (equation 3):

$$d = \frac{\sqrt{V(D)}}{E(D)}, \tag{3}$$

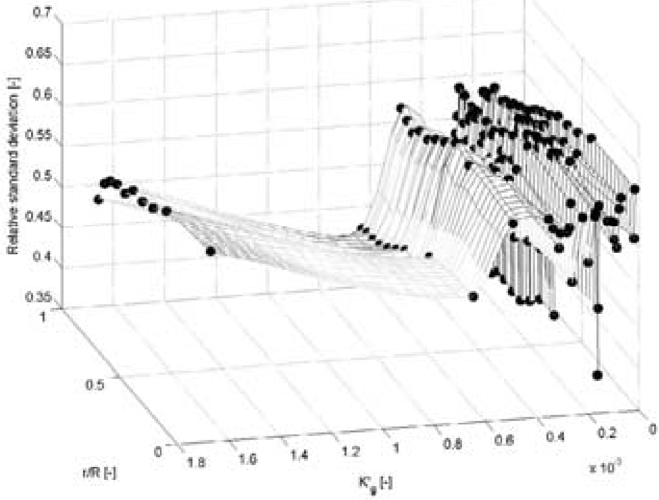
where $\sqrt{V(D)}$ is the standard deviation of the drop size spectrum and $E(D)$ is its expected value. In case of a lognormal distribution relation 3 takes form (4):

$$d = \sqrt{e^{\sigma^2} - 1}. \tag{4}$$

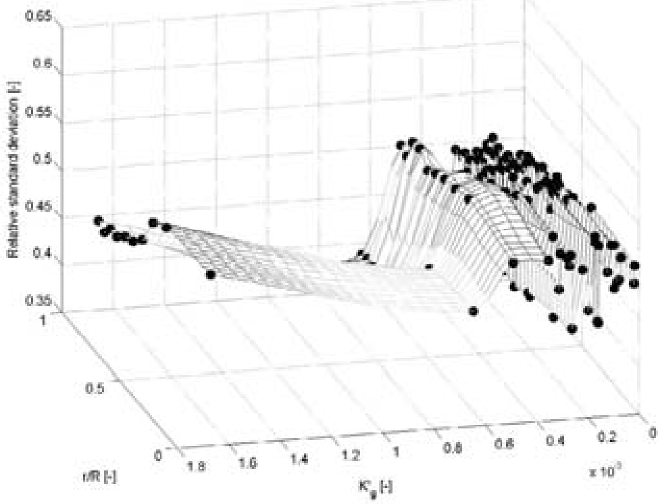
The dependences of the relative standard deviation *d*, the relative radius *r/R*, and the geometric factor K'_g for three values of pressure are presented in figure 4.

Figure 5 provides the information about the percentage of mass carried by droplets of diameters *D* greater than certain values (300 µm, 400 µm and 500 µm) as a function of the relative standard deviation *d*. The mass portion for pressure 0.20 MPa is represented by white markers, while for pressure 0.50 MPa and 0.90 MPa it is symbolized by grey and black ones respectively. This dependence is increasing, which means that low values of the relative standard deviation correspond with smaller size and low number of the biggest droplets. In other words, to ensure effective combustion a quasi-monodispersive droplets size spectrum is needed. Consequently designers should pay attention to the relative standard deviation, which is a measure of monodispersivity. In figure 4 three parameters, $d(300\mu m, 10\%)$ $d(400\mu m, 10\%)$, and $d(500\mu m, 10\%)$ were marked. They indicate values, which must be obtained by the relative standard deviation, to ensure that not more than 10% of mass of the atomized liquid is carried by droplets of diameters greater than 300 µm, 400 µm and 500 µm respectively. For example, to guarantee that the mass portion carried by droplets smaller than 500 µm is greater than 90% the relative standard deviation *d* must be smaller than $d_{500}(10\%)$, i.e. $d \le 0.465$. Similarly, the value $d_{400}(10\%)$ is equal to 0.425, while $d(300\mu m, 10\%) = 0.380$.

a) $\Delta p = 0.20$ MPa



b) $\Delta p = 0.50$ MPa



c) $\Delta p = 0.90$ MPa

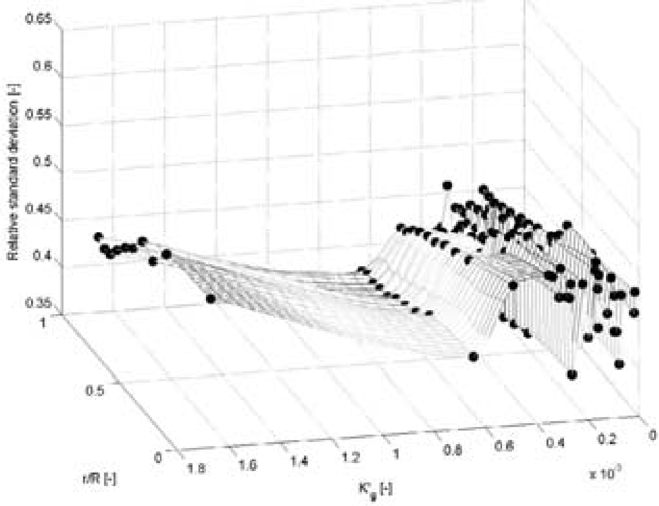


Fig. 4. Log-normal distribution $f(D; \mu, \sigma)$ fitted to a typical experimental data set (histogram) and the corresponding mass distribution

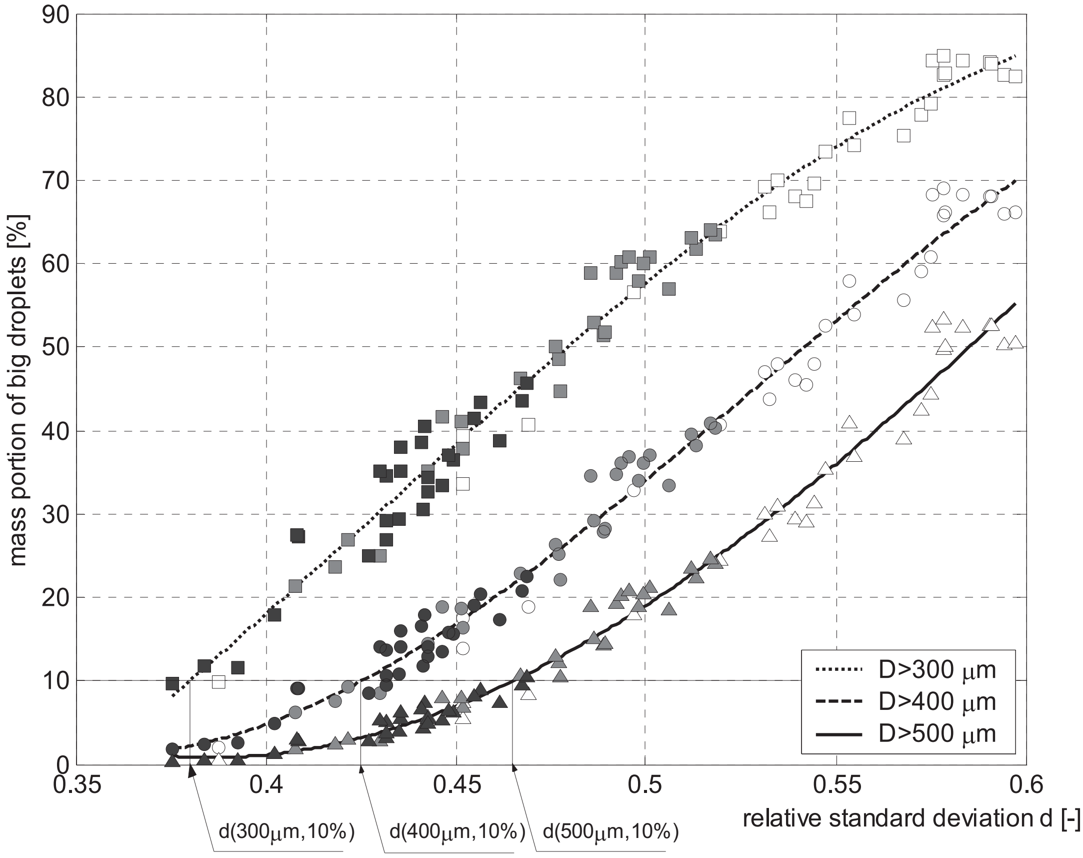


Fig. 5. Dependence of the mass carried by droplets, whose diameter is greater than 300 μm, 400 μm, and 500 μm respectively on the relative standard deviation d

Figures 4 and 5 show, that the increase of pressure reduces the relative standard deviation. It also results in a higher liquid delivery and initial velocity of droplets. The white markers, which represent the lowest pressure, concentrate near the top-right corner of plot 5 whereas the black ones symbolizing the highest pressure are located near the bottom-left one. Consequently, the mass portion of the biggest droplets is strongly dependent on the pressure.

The dependence of relative standard deviation d on the position in the spray cone, which is determined by the relative radius, is much weaker than its dependence on the geometry of an atomizer described by the K'_g factor. These variations seem to be a result of the degree of interaction of the inner unswirled jet and the outer swirling one.

5. Conclusions

The droplet size dispersion described by the relative standard deviation d is a crucial parameter to estimate the mass portion of droplets bigger than a certain value, which is particularly important in turbine engines. The results of experimental research, shown in figure 5, give designers a criterion to decide, whether a given jet-swirl atomizer working at a certain pressure is adequate for the intended application.

The designers of the combustion chambers of turbine engines are able to estimate the maximal droplets diameter D_k , which would evaporate and burn completely in the flame-tube. The decrease in the portion of mass of the injected fuel carried by the biggest droplets ($D>D_k$) can be achieved in two ways: by creating a quasi-monodispersive aerosol of the mean droplets diameter $D_e<<D_k$ and low relative standard deviation d (e.g. $d<0.2$) or by creating a drop size spectrum of a negative skewness.

Bibliography

[1] Prywer, J., Orzechowski, Z., Leszczyński, Z., *Rozpylacz strumieniowo-wirowy,* Patent nr 44304, Urząd Patentowy, Warszawa, 1988.

[2] Lefebvre, A. H., *Atomization and Sprays*, Hemisphere Publishing Co., New York – Washington Philadelphia – London, 1989.

[3] Orzechowski, Z., Prywer, J., *Rozpylanie cieczy w urządzeniach energetycznych*, WNT, Warszawa, 1994.

[4] Bayvel, L., Orzechowski, Z., *Liquid atomization*, Taylor and Francis, Washington, 1993.

[5] Sirignano, W., *Fluid Dynamics and Transport of Droplets and Sprays*, Cambridge University Press, 1999.

[6] Prywer, J., *Wpływ parametrów konstrukcyjnych rozpylaczy strumieniowo-wirowych na ich właściwości*, Zeszyty Naukowe Politechniki Łódzkiej nr 916, seria Rozprawy Naukowe, zeszyt no 317, Łódź, 2003.

[7] Prywer, J., *Zautomatyzowane urządzenie do eksperymentalnego badania rozpylaczy otwartych* Metrologia i Systemy Pomiarowe, Warszawa, no. 5, pp. 95 – 108, 1990.

[8] Opara, T., *Test stands for measuring the average diameter of the fuel aerosol drops by diffraction method,* Optica Applicata, Vol. XXXI, no. 1, Wrocław, 2001.

[9] Opara, T., *Diffraction methods of drop size measurement in polidispersive media,* Optica Applicata, Vol. XXXI, no. 1, Wrocław, 2001.

[10] Opara, T., *Diffraction measurement methods of sizes of drops in quasi-monodispersive aerosol,* Optica Applicata, Vol. XXX, no. 4, Wrocław, 2000.

[11] Opara, T., *Metrologiczne aspekty badania zjawisk zachodzących w stożku rozpylania wtryskiwaczy turbinowych silników lotniczych,* WAT, Warszawa 1996.

[12] Kiciński, W., *Statistical model for noisy data selection*, Proceedings of SPIE on Fluctuation and Noise 2005, vol. 5846, pp. 63-69.

[13] Prywer, J., Opara, T., Opara, K., *Drop size distribution in the spray cone of jet-swirl atomizers,* Silniki Spalinowe, Combustions Engines, 2007 - SC2 - 059 (P07 - C059), Mixture Formation, Ignition & Combustion, pp. 135 - 141, 2007.