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SRAYING WITH ROsá CENTRIFUGAL ATOMIZERS

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Part 2. Atomization of Pesticides

The present state of the arts of chemical plant protection is recognized by the experts [1] from the All-Russian Research Institute of Plant Protection (GNU VIZR) as following: "Pesticide chemistry has advanced far into the 21st century, but the agricultural technologies by which these pesticides are currently sprayed, got stuck in the 19th century." These experts ground their claims on facts that droplets having biologically optimal size of 80-350 μm does not exceed 10 % of the total amount in spraying and losses for evaporation of droplets of 10-80 μm in size are accrued with droplets of 350-2000 μm, which slip off the leaves onto the ground; for these reasons, the norms of pesticide application are twice or thrice overrated.

The ROsá centrifugal atomizers bring agricultural technology of atomization to the level of the 21st century.

We would like to offer the readers of the journal the insights into the methods by which the improvements in pesticide spraying have been achieved.

1. Jet atomization.

To date, there is no universally accepted and scientifically grounded concept of the mechanism of fluid atomization. Disintegration of a spray of fluid (or a film) into droplets is attributed to emergence of waves of capillary origin on the surface, to stream turbulence, cavitation, and the effects caused by environmental factors. The most prevalent idea is about the wave mechanism of fluid thread breaking up, which is based on the solution by B. Rayleigh (1878) to the problem of instability of a cylindrical thread of non-viscous fluid in vacuum. If the wavelength in the thread is 4.5 times greater than its diameter, the thread breaks up into droplets. By analogy, the problem of the breaking up of a stream and a cylindrical film in gaseous medium has been solved in [2]. However, the ideas suggested by V. Ya. Natanzon (1938) that the flow turbulence might be a cause of jet atomization did not receive further development.

The experimental data on atomization of various jets were summarized by L.A. Vitman [3]. Fig. 1 shows the modes of oscillations and the time intervals τ before breaking up of the water jet into droplets depending on the velocity U. The length of the stretched liquid ligament $L = \tau \cdot U$ $L = \tau \cdot U$ can be reduced only due to decreasing the diameter or increasing the velocity. If the velocity exceeds 10 m/s, a stream is atomized into droplets without oscillations; this can be explained only by the endogenous structural properties of the stream.

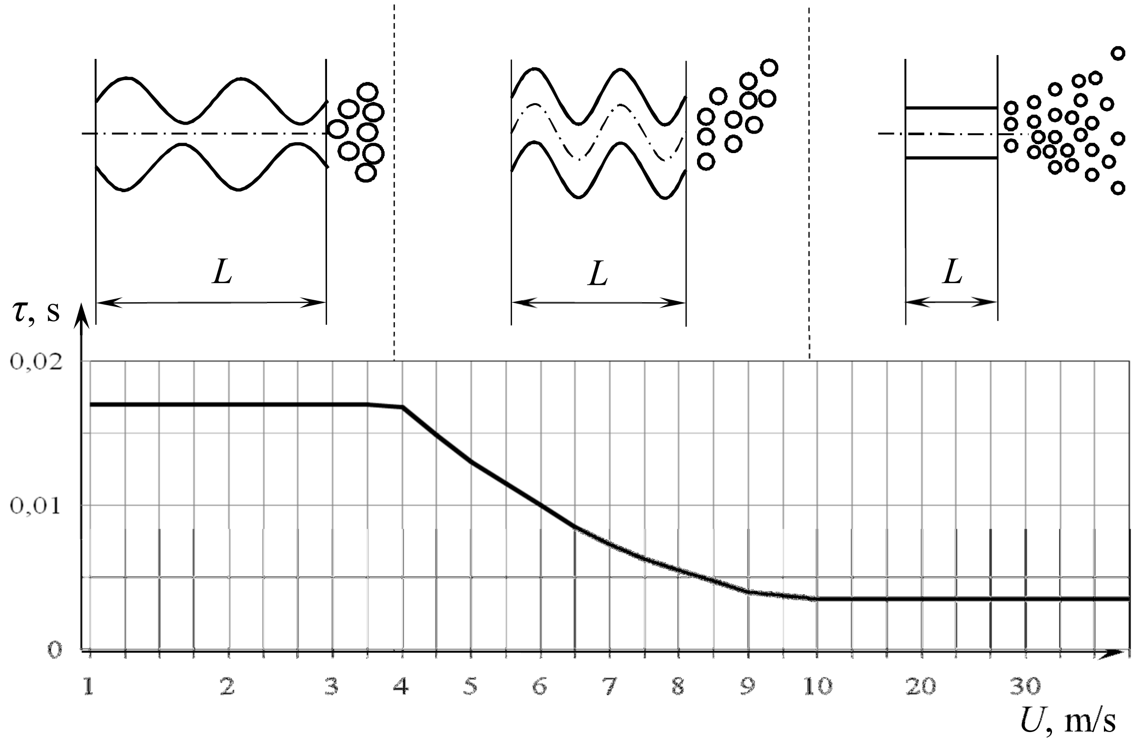


Fig. 1. Time intervals and a water jet pattern with a diameter of 0.51 mm before breaking up.

Thus, at a velocity of U = 4 m/s, the jet will break up into droplets over the time interval τ = 0.017 s and the length of an unbroken liquid ligament is L = 0.068 m. As the velocity increases up to U > 10 m/s, the time interval shortens to 0.003 s with L = 0.03 m.

The volumetric flow rate of the fluid ejected from the atomizer is given by:

$$Q = \mu f \sqrt{\frac{2\Delta P}{\rho}}, \tag{1}$$

where μ = 0.6 – 0.8 is the coefficient of the fluid flow rate; f is the cross sectional area of the nozzle orifice; ΔP is the differential pressure; ρ is the fluid density.

Droplet sizes are usually determined experimentally by manufacturers and specified in the advertising materials of the companies. The jet atomization process can be realized only at very high relative velocities of the fluid flow.

2. Centrifugal atomization

Successful application of the centrifugal atomization process in a V-2 rocket engine triggered off extensive research into this process. Due to the swirling motion imparted to the fluid in the swirl chamber, it is feasible to control spray pattern angles and droplet sizes.

G.N. Abramovich, (1949) proposed a theory of a centrifugal atomizer for the ideal (inviscid) fluid. According to the law of conservation of angular momentum for the flow of fluid,

$$W \cdot r = const, \tag{2}$$

we obtain the circumferential velocity W; and from the equation of energy conservation we can get the differential pressure:

$$\Delta P = \frac{\rho}{2}(W^2 + U^2). \qquad (3)$$

An increase in the rotational velocity of the fluid towards the axis is accompanied with a decrease in the pressure and forming a conical depression with a gas vortex in it. From the equations (2) and (3) we can determine the coefficient of fluid flow rates, the thickness of the film in the nozzle orifice, and the spray angle.

However, with viscous fluids, the design characteristics of the atomizer cannot be verified experimentally. The rotational velocity of a viscous fluid varies according to the law

$$W \cdot r^n = c, \qquad (4)$$

where $n \approx 0.8$ refers to the atomizers. As suggested in [2], a loss of the initial angular momentum should be corrected for the fluid friction against the walls, though it is known that the friction manifests itself only in the near-wall layer of the fluid.

The methods of calculations of a centrifugal atomizer for a viscous fluid proposed in the investigations [4] are based on the novel concept of the structure of a swirling flow (Fig. 2).

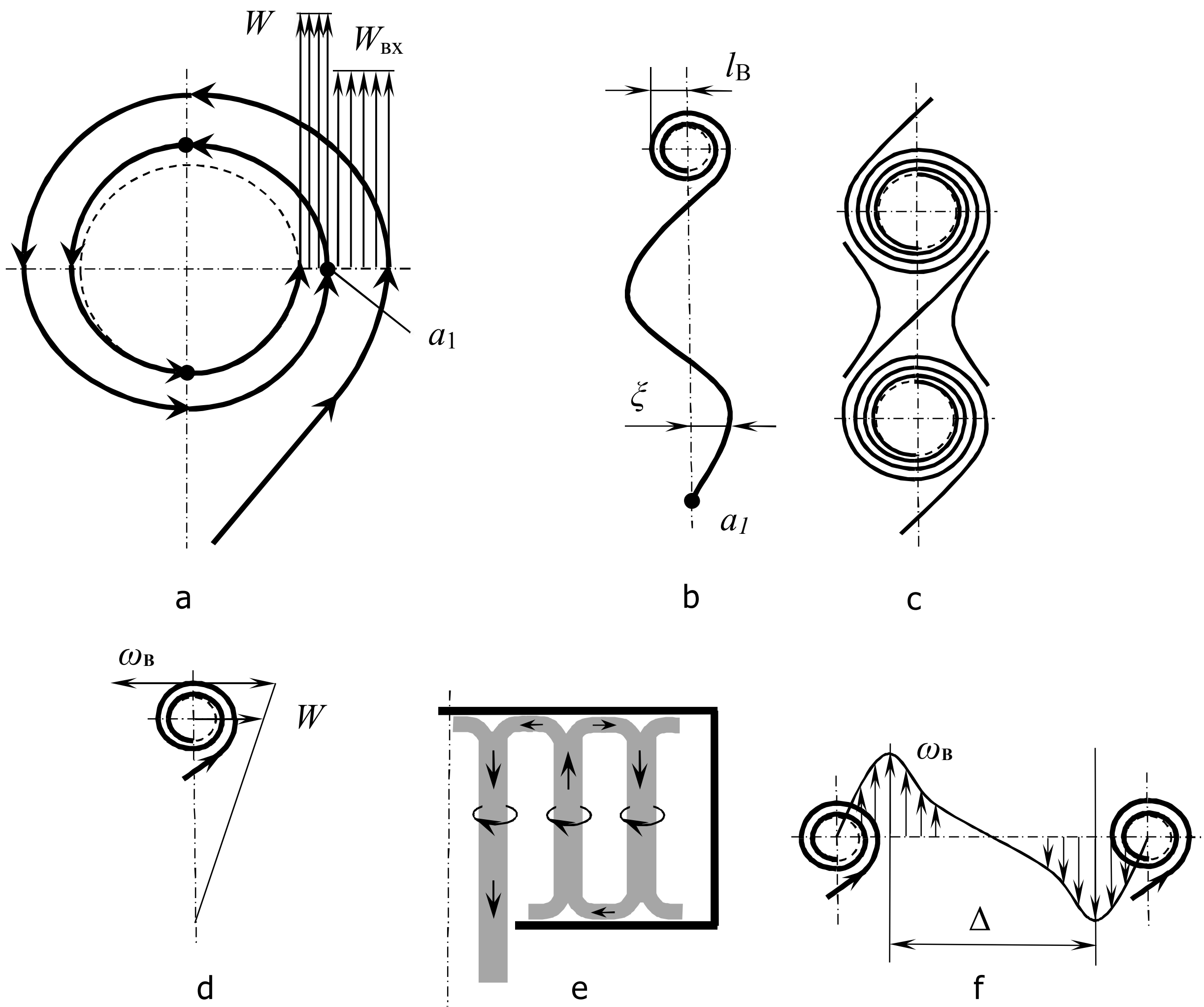
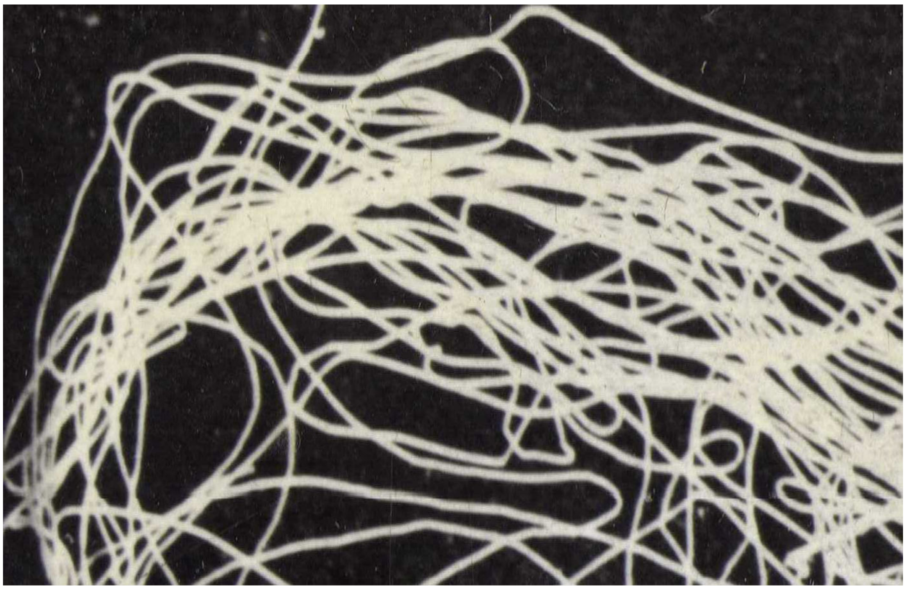


Fig. 2. Schematic illustration of forming vortex threads by the swirling flow: a – the swirling flow; b – the dividing boundary; c, d, e – vortices in the swirl chamber; f – for assessment of effective viscosity.

If the peripheral helix loop is swirling at the velocity of W_{BX} and the internal helix loop which co-flows towards the point a_1 at the velocity $W > W_{BX}$ (Fig. 2, a), the contact surfaces of these two loops are subjected to induced oscillation (Fig. 2, b) with the amplitude of ξ (the Helmholtz instability). When the oscillation amplitude reaches its critical value, the vortex threads with the radius l_B intertwine with each other and merge into coherent kinematic formations (Fig. 2, c).

When the rotation velocity reaches the value ω_B that is equal to the velocity W of the translational motion (Fig. 2, d), the threads are subjected to the influence of the radial differential pressure and shift closer to the axis of the swirling flow. In the swirl chamber, the ends the vortex threads move near the walls (Fig. 2, e), and the fluid drains down from the threads into the near-wall layers.

In contrast to conventional belief of flow turbulence (a state of chaos), we recognize the swirling flow as pseudoturbulent (a seemingly chaotic condition), wherein the vortex filaments or threads ("rollers") are generated. The generation of vortex threads by the swirling flow has been confirmed experimentally [5]. In the swirling flow of tin emerging from the nozzle orifice, the vortex filaments separated from each other and had practically the same diameter (Fig. 3). Before solidification, the tin threads twisted, as evidenced by the crystal alignments on their surfaces.



a

b

Fig. 3. General view of vortex threads:
a – a tangle of vortex threads; b – individual vortex threads (x 500).

The rotational motion of vortex threads is sustained due to the normal stress in the swirling flow of fluid:

$$\tau_{\mathrm{T}} = 2\mu_{\mathrm{T}} \left|\frac{\partial V}{\partial r}\right|;$$

where μ_{T} is the effective viscosity, V is the radial velocity of the thread motion towards the axis.

Friction between the vortex threads is:

$$\tau = \mu \frac{2\omega_B}{\Delta}; \tag{5}$$

where μ is the molecular dynamic viscosity, ω_B is the maximum rotational velocity of an individual thread, and Δ is the diameter of the line (Fig. 2, f).

With the equality of τ_{T} and τ, it follows that the effective viscosity is

$$\mu_{\mathrm{T}} \sim \mu \frac{2\omega_B}{\Delta} \frac{1}{\left|\frac{\partial V}{\partial r}\right|}. \tag{6}$$

Thus, the radial velocity of the swirling flow is a crucial factor for the rotational motion of the vortex threads. Velocity pulsations in the moving fluid flow, which are measured by thermal anemometers, represent the fluid velocities in the vortex threads.

In accordance with [6], the fluctuations of the circumferential velocity in the swirl chamber increase toward the axis $\omega_{\mathrm{B}} \sim \frac{1}{r}$, while the magnitudes of pulsations decrease, Δ ~ r. If we assume that the fluid flow rate is a constant value, $V \cdot 2\pi r h = const$, $V \sim \frac{1}{r}$, $\left|\frac{dV}{dr}\right| \sim \frac{1}{r^2}$, where h is the height of the chamber, then we get $\mu_\tau \sim const \cdot \mu$.

The calculation techniques devised in [4] are intended for the vortex chamber design with a swirling flow having a constant effective viscosity. The swirling flow was conditionally broken up into an actual vortex (U = 0) and a vortex generating region (a source) with $U \neq 0$, for both of them the equations for conservation of angular momentum for the rotational velocity are written as:

$$\rho V \frac{d}{rdr} W = \mu_\tau \frac{d}{dr} \frac{d}{rdr} W, \tag{7}$$

and the equation for conservation of mass in the vortex is:

$$\frac{d}{dr} rV = 0, \tag{8}$$

while that for the vortex generator region is:

$$\frac{d}{dr} rV + \frac{\partial U}{\partial x} = 0, \tag{9}$$

Upon integration of Eq. (8), we obtain the radial velocity $V = -|V_{\mathrm{K}}| \frac{R_{\mathrm{K}}}{r}$, and from Eq. (7) we get the experimentally known exponent law for the circumferential velocity in the vortex:

$$W r^{1-k} = const, \tag{10}$$

where R_{K} is a radius of initial swirling, V_{K} is a corresponding radial velocity, and $k = \frac{\rho |V_{\mathrm{K}}| R_{\mathrm{K}}}{\mu_{\mathrm{T}}}$ is the effective Reynolds number.

Equation (4), (10) disclose the reasons for decreasing the angular momentum in a viscous liquid in comparison to that in an ideal fluid. The same is true for the mean motion energy.

The part of losses of the angular momentum and energy accumulates in the vortex threads.

For the ideal fluid, $\mu_{\mathrm{T}} = 0$ and Eq. (7) is simplified to $\frac{d}{rdr} rW = 0$ by the known solution of Eq. (2), which fully corresponds to Eq. (10) with k = 2.

For a solid body, with $\mu_\tau \Longrightarrow \infty$, from Eq. (7) we get

$$\frac{d}{dr} \frac{d}{rd\square} rW = 0, \tag{11}$$

with the solution of $W = const \cdot r$, and that correlates to Eq. (10) with k = 0.

We have defined the boundary values of the effective Reynolds number for the swirling flow with k = 0 ÷ 2 and the relationships between the value k and a fluid flow rate, the molecular viscosity of the fluid and dimensions of a swirling flow [4].

In the region of generation of vortices (near the source), the radial and circumferential velocities decrease due to emergence of the axial velocity [4].

The distribution of the rotational velocity in Eq. (10) is fundamentally different from the distribution for the ideal fluid in Eq. (2) accepted by G.N. Abramovich in the calculation technique for centrifugal atomizers.

Provided the distribution of velocities in the swirling flow is known, we can determine the pressure, the flow rate coefficient, the spray angle, and the thickness of the film in the nozzle orifice. All the dimensions in the vortex chamber are calculated using the technique developed for the viscous fluid. A swirl chamber design is considered optimal if the pressure losses for friction in the flow are minimal.

3. The vortex "begets" a drop

A fluid film in the nozzle orifice of the centrifugal atomizer consists of the vortex threads. Reduction of static pressure in areas of the maximum speed in vortex threads leads to deformation of the film surface by the pressure of the medium wherein the liquid is sprayed and also by capillary pressure. Fluctuations of the film surface before its disintegration are not incidental, but they are stipulated by the rotational motion of the fluid and the surface tension forces of the vortex threads (Fig. 4).

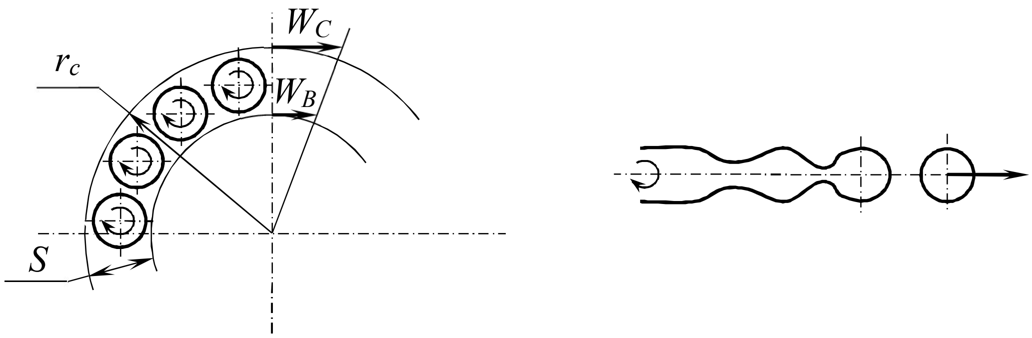


Fig. 4. Schematic representation of disintegration of a film and a vortex thread: W_C – the rotational velocity at the radius of the nozzle orifice, W_B – the rotational velocity at the radius of the gaseous vortex; S is the thickness of the fluid film in the nozzle orifice.

The internal energy per unit of length of the vortex threads whose core rotates with a nearly constant angular velocity:

$$E_{\text{в}} = \frac{I\omega_{\text{в}}^2}{2} = \frac{\rho\omega_{\text{в}}^2}{2}\int_0^{l_{\text{в}}} r^2 2\pi r dr \approx \frac{\rho\omega_{\text{в}}^2 \pi l_{\text{в}}^4}{4}, \tag{12}$$

where I is the moment of inertia, and $\omega_B = \frac{W_c - W_B}{S}$ is the angular velocity of a vortex thread in the film.

The work for displacement of vortex threads per unit thickness of the film is expressed as:

$$E_{\text{тр}} = F_{\text{тр}} l_{\text{в}} \cdot 2S \sim \mu \frac{W_{\text{c}} - W_{\text{в}}}{S} \cdot \frac{S}{\Delta} l_{\text{в}} \cdot 2S, \tag{13}$$

where $F_{\text{тр}}$ is the frictional force of the unit length of a vortex thread.

If we assume that the diameter of the vortex thread determines the most probable (median) diameter of droplets and if we take the particles resulting from the vortex thread disintegration as $b = \chi \cdot 2l_{\text{в}}$, where χ is the flow contraction ratio that depends on the mode of disintegration, then from the equality of the volumes of a cylinder and a droplet we will get $d_m = \sqrt[3]{12\chi \cdot l_{\text{В}}}$. Using a tentative distribution of velocities in the film $W_c - W_B \approx W_{\text{c}} \frac{S}{r_c}$, from the equality of the energies $E_{\text{В}} = E_{\text{тр}}$ we obtain the formula for the median diameter of droplets

$$\frac{d_m}{S} = C \left(\frac{SW_c}{\nu} \right)^{-\frac{1}{3}}$$

where $C = \left(\frac{9\square}{\pi} \frac{l_{\text{В}}}{\Delta} \right)^{\frac{1}{3}}$.

Substituting S and W_c with the geometric characteristics of the swirl chamber, we obtain [7] the formula for the volume mean diameter of the droplets:

$$\frac{d_{30}}{2r_c} = \frac{15}{A^{0,9} B^{0,7} 10^{0,7k}}$$

where $A = \frac{\pi r_c R_k}{m f_{\text{вх}}}, B = \frac{\pi h R_k}{m f_{\text{вх}}}$, $m f_{\text{вх}}$ is the area of the input channels.

Each vortex thread generated by the flow constitutes an element of the flow structure and "begets" a droplet. The quest to obtain a desired droplet size at a minimum fluid pressure is commonplace. The concept put forward by V.Ya. Natanzon was found to be tenable and received further development for a swirling flow.

4. Optimized hydrodynamic efficiency of the swirl chamber

Atomizers can be compared by the quality of dispersion they produce and the specific energy consumption required for the atomization.

The dispersity resulted from the atomization is evaluated in terms of the mean volume diameter of droplets in the spray pattern $d_{30} = \sqrt[3]{\frac{\sum_{i=1}^{n} n_i d_i^3}{n}}$, the volume median diameter $D_{V0.5}$, which subdivides the volume of the atomized fluid into two equal parts, and the mean volume-surface diameter (the Sauter mean diameter, SMD) $d_{32} = \frac{\sum_{i=1}^{n} n_i d^3}{\sum_{i=1}^{n} n_i d^2}$, where n_i is the number of droplets having diameter i, and n is the total number of droplets. Dispersion characteristics are also identified by the droplet sizes (diameters) prevailing in 10 % and 90 % contents of the total volume of droplets produced.

The surface area of droplets in a polydispersed spray pattern is defined as:

$$S = \pi \sum n_i d_i^2 = \pi d_{32}^2 \cdot n,$$

where $n = \frac{6Q}{\pi d_{32}^3}$ is the number of droplets.

A decrease in the mean surface-volume diameter d_{32} of droplets entails an increase in the droplet quantity in the atomized fluid, i.e. $n \sim \frac{1}{d_{32}^3}$. So, the total surface area of droplets $S \sim \frac{1}{d_{32}}$ increases as well.

The rate of specific energy e required for obtaining a unit surface area of atomized fluid is a measure of excellence of atomization methods and adequacy of atomizer parameters. Since the energy expenditure is expressed as $N = P \cdot Q$, J / s, then

$$e = \frac{N}{S} = \frac{P \cdot d_{32}}{6}.$$

The advantages of the centrifugal atomization realized in a swirl chamber of optimal configuration and dimensions have been proved by comparing the spray dispersity characteristics attained with various atomizers (Table 1): the ROsá centrifugal atomizer R.03.0.6 (Agromodul, Dnepropetrovsk, Ukraine), the centrifugal atomizer N.059.010 (GSKB Lviv, Ukraine), the flat spray nozzles LU 120-02 and IDK 120-015 (Lechler GmbH, Germany), the rotary disc atomizer ("Zarya" Company, Russia).

Table 1

Spray dispersion characteristics in atomizers

Parameters	Types of Atomizers				
	Centrifugal		Flat nozzle		Rotary disc
	R.03.0.6	H.059.010	LU 120-02	IDK 120-015	
Pressure, MPa	0,30	0,3	0,30	0,30	0,02
Capacity, L/min	0,63	0,72	0,78	0,60	3,0
Droplet sizes (μm)					
d_{30}	85	184	132	173	166
d_{32}	115	235	164	282	228
Droplet VMD, %					
$D_{V0.1}$	70	152	88	137	157
$D_{V0.5}$	131	271	183	367	267
$D_{V0.9}$	238	420	314	839	330

The spray dispersity characteristics in the H.059.010 centrifugal atomizer are at the same level as those in the slit-type and rotary disk atomizers. In comparison to the H.059.010 model, the volume-median diameter ($D_{V0.5}$) of droplets in the R.03.0.6 atomizer is half less.

Owing to the optimization of the configuration and dimensions of the swirl chamber, the rate of specific energy for the centrifugal atomization was decreased from 12.0 J/m^2 in H.059.010 to 5.8 J/m^2 in R.03.0.6.

Table 2 shows the spray dispersion characteristics in the ROsá atomizer, R.03.06, as a function of pressure at a distance of 0.5 m from the atomizer nozzle.

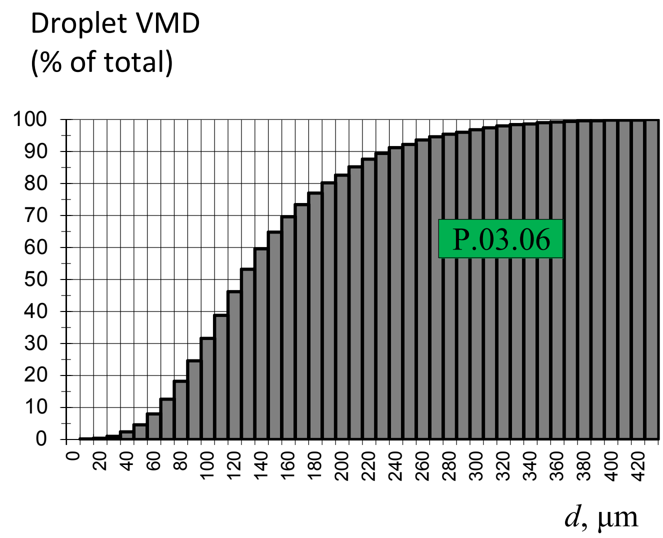
Table 2

Spray dispersion characteristics

Parameters	Atomizer R.03.06			
Pressure, MPa	0,1	0,2	0,3	0,4
Capacity, L/min	0,35	0,50	0,63	0,77
Droplet sizes (μm)				
d_{30}	151	99	84	74
d_{32}	216	137	115	94
Droplet VMD, %				
$D_{V0.1}$	135	86	70	60
$D_{V0.5}$	254	157	131	108
$D_{V0.9}$	408	271	238	164
$D_{V0.9}$	527	377	347	232
Rate of specific energy e, J/m^2	3,6	4,6	5,8	6,3

As evident from Tables 1 and 2, the centrifugal atomizer at a pressure of 0.1 MPa ensures the quality of dispersion comparable to that attained with the flat fan atomizer at a pressure of 0.3 MPa.

Fig. 5 shows the integral characteristics of spray dispersion in the R.03.0.6 centrifugal atomizer and their comparison to relevant data for the IDK 120-015 injector flat spray nozzle, as obtained by Lechler GmbH; all the measurements were taken at a distance of 0.5 m from the nozzle orifice and at a pressure of 0.3 MPa.



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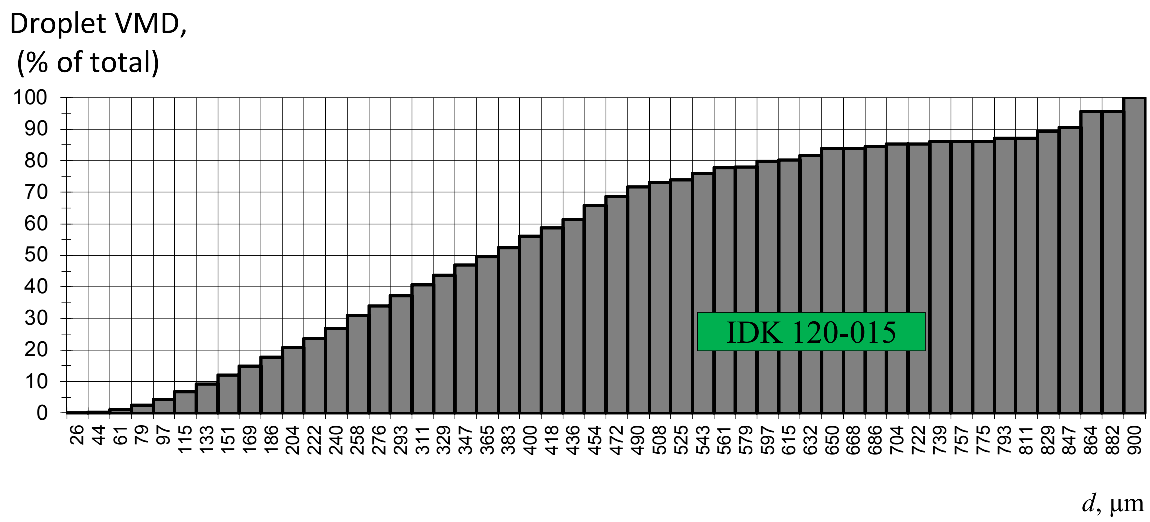

b

Fig. 5. Integral characteristics of volume median distribution of droplets in the atomizers: a - R.03.0.6; b - IDK 120-015.

In spraying, the ROsá centrifugal atomizer ensures a volume median distribution of atomized droplets within the range from 80 µm to 350 µm in size, which are considered [1] to be biologically optimal at the level of 86%, while up to 80 microns - 13%.

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