Study on the process of droplet formation when liquid flows out of a capillary

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Abstract. This article presents the theoretical background for the justification of the parameters of the rotating sprayer. Theoretical studies show that an increase in the rotation frequency of the disk at a constant air flow velocity leads to a minimum median mass diameter of the droplets. Therefore, when justifying the diameter of the sprayed droplets, it is necessary to consider the combination of the disk rotation speed and the axial velocity of the air flow. To obtain high-quality air-droplet flow, the initial speed of the main droplets discharged from the periphery of the spray disc should be less than the air velocity and rotational frequency. Pavlovskyi spray is recommended to be applied with in \( \omega=60…200 \text{ c}^{-1} \).

1. Introduction

For the purpose of timely and high-quality defoliation of cotton, preparation of fields for harvesting raw cotton, including cotton pickers, the President and the Cabinet of Ministers of the Republic of Uzbekistan pay great attention to the further development of cotton growing and the need for comprehensive mechanization and chemicalization, which increase labor productivity [1, 2]. The agronomic technique as defoliation allows to carry out harvesting by machines in a short time, to pick cotton of the best quality, to complete all autumn-winter work on time and to lay the foundation for next year's harvest. In addition, defoliation prevents mass reproduction of autumn generations of cotton pests, prevents fungal and bacterial diseases in cotton.

It was found that after defoliation, labor productivity increases, for example, manual picking of raw cotton by 15-20%. Timely and high-quality defoliation helps to accelerate the ripening and opening of bolls for 10-15 days, increase the...
productivity of cotton pickers by 10 ... 15%, increase the volume of machine harvesting of raw cotton up to 90%, increase the yield of first-class fiber by 4-5%, reduce cotton contamination - raw cotton by 1.5-2.0 times and moisture by 2-3 times, increases the yield of the first two varieties of raw cotton by 5-6 percent, which makes it possible to fully compensate for all defoliation costs and provide additional income [3, 4]. It should also be noted that the processing of cotton with pesticides on such vast areas (more than 2 million hectares) and in such large volumes (more than 9 million hectares due to repeated treatments) in a short time (10-15 days) is unthinkable without highly productive, reliable, economical and environmentally friendly technical means of mechanization [5-8].

The purpose of this study is to create a disk working body for the sprayer for the transition to the technological scheme of a low-volume method of spraying cotton.

2. Materials and Methods
In analytical studies of the process of spraying a working fluid by a rotating atomizer driven by an air flow, the theory of rotary atomizers and wind turbines was used on the basis of which analytical dependencies were obtained that determine the optimal monodisperse droplet sizes depending on the radius of the atomizer, specific liquid supply, rotational speed of the disk atomizer and other factors. Theoretical studies are carried out using the general laws of mechanics [9-14].

3. Results and Discussion
A diagram of the process of droplet formation during the outflow from a capillary of a liquid that does not wet its surface in the presence of a lateral air flow is shown in Figure 1 [9].

![Figure 1. Diagram of the process of formation of drops when blowing a capillary with a perpendicular air flow](image_url)

The liquid enters the capillary continuously at a constant flow rate q. As a result of the interaction of the gravitational force G and the surface tension force S,
approximately identical drops are formed at the lower end of the capillary, which should break off one after the other and fall down. At this moment, the air flow acts on the drop, i.e. there is a flow around the capillary diameter.

It is known that the aerodynamic force is determined by the following expression [10, 11]:

\[ F = C_A \frac{\pi d_2^2}{4} \frac{\rho_v u^2}{2} \]  \hspace{1cm} (1)

Due to the fact that the aerodynamic force \( F \) is a vector, it is convenient to use its projections of the rectangular coordinate axis. The origin of coordinates is taken at the center of gravity of the capillary, the X axis is directed in the direction of the air flow, the Z axis is to the side, and the Y axis is perpendicular to the XOZ plane (Fig. 2) [12].

Then, instead of equality (1), we obtain three equalities:

\[ A_x = C_x \frac{\pi d_2^2}{4} \frac{\rho_v u^3}{2} \]  \hspace{1cm} (2)

\[ A_y = C_y \frac{\pi d_2^2}{4} \frac{\rho_v u^2}{2} \]  \hspace{1cm} (3)

\[ A_z = C_z \frac{\pi d_2^2}{4} \frac{\rho_v u^2}{2} \]  \hspace{1cm} (4)

Figure 2. Air flow around a capillary with vectors of aerodynamic forces.

Let us assume that to obtain a directed air-droplet flow, the component \( A_x \) - the drag force must be significantly greater than the components \( A_y \) - the lifting force
and $A_x$ - the lateral mixing force of the aerodynamic force $A$. In this case, the aerodynamic force $A$ coincides with the direction of the flow, i.e. at the same time by the force of any resistance [13]:

$$A = A_x = C_x \frac{\pi d_t^2}{4} \frac{\rho u^2}{2}$$

(5)

The values of the drag coefficient are determined from the function $C_x=f(Re)$, where $Re$ – is the Reynolds number:

$$Re = \frac{ud_t}{v}$$

(6)

In further studies, when determining the dispersion of drops, we will consider the drag force for balls. Figure 3 shows a graphical dependence of the drag coefficient for a capillary $C_x=f(Re)$ at $d_t=const$.

The entire process of drip outflow can be divided into three parts: 1) the formation of a drop under conditions of quasi-stationary equilibrium of the forces acting on it; 2) droplet separation under conditions of disturbed equilibrium; 3) free fall of a detached drop.

As in the case of a droplet outflow in motionless air, let us assume that the diameter of a detached drop $d_t$ is determined by the equilibrium of forces acting on it, but we take into account the aerodynamic force $A$, i.e. accept $S^2=A^2+G^2$, where:

$$G = \frac{\pi d_t^2 \rho g}{6}$$ - the force of gravity, $S = 2\pi r\sigma$ - surface tension force.

Figure 3. Changing the coefficient of drag force
\[ C_x = f(\text{Re}) \] depending on the air flow rate \( U_0 \), at \( d_t = 80 \) to 200 μm and normal conditions \( (\nu=1.45 \times 10^{-5} \text{ m}^2/\text{s}, t=15^\circ, P=760 \text{ mm. rt. st.}) \) [14].

Equilibrium conditions:

\[ (2\pi r \sigma)^2 = \left( \frac{\pi d_t^3 \rho \nu}{6} \right)^2 + \left( \frac{\pi d_t^2 \rho_j U_0^2 c_x}{8} \right)^2 \]  

At critical flow rates, when, with an insignificant increase in the drop, the formation turns into a jet outflow, the diameter of the drop approaches the diameter of the capillary, and the expression for the surface tension force \( 2\pi r \sigma \) can be represented as \( \pi d_t \sigma \), while equality (7) takes the form of a biquadratic equation [15]:

\[ \pi d_t \sigma = \left( \left( \frac{\pi d_t^3 \rho \nu}{6} \right)^2 + \left( \frac{\pi d_t^2 \rho_j U_0^2 c_x}{8} \right)^2 \right)^{\frac{1}{2}} \]  

An analytical study of the process of droplet formation during the outflow of liquid from a capillary with the supply of a side air flow shows that with the help of a side air flow it is possible to increase the speed of a droplet formation and, consequently, improve the dispersion of the formed droplets.

Let us consider the process of monodisperse crushing of a liquid by a smooth rotating disk when it is blown by a coaxially lateral air flow.

A continuous stream of liquid is fed to the center of the rotating disk, which, due to centrifugal force, breaks off from the edge of the disk and breaks up into drops. The resulting droplets are characterized by a significantly greater monodispersity, at low flow rates within the first and second spray modes. With the supply of a lateral air flow, the picture changes somewhat, since an aerodynamic force is added (Figure 4).

The liquid enters the center of a smooth rotating disk and spreads out in the form of a thin film, wetting its entire surface. A liquid torus is formed at the edge of the disk. In places where the torus most easily loses its stability under the action of random perturbations, bulges appear that turn into appendages. These processes grow, stretch, and break away from the edge of the disk by centrifugal forces in the form of approximately equal basic droplets. Along with the main droplets, smaller satellite droplets are formed from the bridges between them [30]. This process is realized at very low liquid flow rates \( q \), with good wetting by the surface of the rotating disk. In the absence of air blowing of the disk, the size of the main droplets is determined from the condition of equality of the centrifugal force acting on the droplet \( B = \frac{\pi d_t^3}{6} \rho_j \omega^2 \) and surface tension forces \( S = \pi 2 r \sigma \) [16].
Figure 4. Diagram of the process of monodisperse liquid crushing with a rotating disk when blowing it with a coaxial-lateral air flow

When the disk is blown by an air flow, as in the case of the blown capillary considered above, the aerodynamic force $A$ is added to the forces $B$ and $S$ acting on the forming drop. The process of drop formation is divided into three parts, both during the drip outflow from the capillary and during centrifugal spraying: 1) formation of drops in terms of quasi-stationary equilibrium influencing forces; 2) the droplet from the periphery of a rotating disk; 3) free flight detached drops [14]. The process of droplet formation during centrifugal spraying is shown in Figure 5.

Figure 5. Diagram of the droplet formation process during centrifugal liquid atomization

After just drops the torn remains of the bulge, it grows due to the flow of liquid $q = \frac{qZ_1}{2\pi r}$, in terms of that because of the relative slowness of the process will be considered close to equilibrium ($Z_1$ - the average distance between adjacent places
a drop of education), \( Z = \lambda \). For a low-viscosity liquid at \( \frac{d_{\text{top}} \sigma \rho_j}{g} \gg 1 \), \( \lambda = 9a \) [15].

Figure 5, b shows the continuation of the drop formation process: the centrifugal B, the aerodynamic A, and the surface tension force S acting on the drop balance each other. In the future, the equilibrium is disturbed due to the inflow of liquid into the drop with a flow rate of \( q \). Due to this inflow, there is an excess force \( \rho_l = \tau r \omega^2 \) [16], which causes the acceleration of the movement of the drop relative to the disk (Figure 5, c.) in the radial direction \( \tau \) - the time of the start of separation).

When the drop moves in the radial direction, the bridge between the drop and the liquid torus narrows, the surface tension force S decreases, and the force that causes the drop to accelerate increases accordingly. The bridge breaks and splits into several satellite drops, and the main drop breaks off and moves freely in the lateral air flow (Figure 5, d).

When a drop is formed, the shape and size of the formed drop change rapidly, and the structure of the air flow around the drop changes accordingly. As in the case of a capillary, we can ignore this change and consider the process as corresponding to the stationary flow around a ball of diameter \( d \) by an undisturbed air flow having a velocity \( U \) determined by the equation (7).

![Figure 6](image_url)

**Figure 6.** Dependence of the median mass diameter \( d_t \) of droplets from \( U \) and \( \omega \) under different operating conditions of the sprayer.

The equilibrium condition in this case will be [16]:
$S^2 = B^2 + A^2$ or $S = \sqrt{A^2 + B^2}$

Substituting their values, we get the biquadratic equation

$$(2\pi r_1 \sigma)^2 = \left(\frac{\pi a_1^3}{6} \rho_f \rho \omega^2\right)^2 + \left(\frac{\pi a_1^3}{8} \rho \rho U^2 c_x^2\right)^2$$

at $2r_1 = d_r$

$$d_r^4 \left(\frac{1}{6} \rho_f \rho \omega^2\right)^2 + d_r^2 \left(\frac{1}{8} \rho \rho U^2 c_x^2\right)^2 - \sigma^2 = 0$$

The biquadratic equation (11) is similar to equation (8), only it has a centrifugal force instead of gravity. Solving the biquadratic equation will result in the following form [17]:

$$d_r = \frac{3}{4\sqrt{3}} \frac{\rho U^2 c_x}{\rho_f \rho \omega^2} \left[1 + \left(\frac{4\sqrt{2}}{3} \frac{\rho_f \rho \omega^2}{\rho U^2 c_x^2}\right)^4 \left(\frac{6\sigma}{\rho_f \rho \omega^2}\right)^2 \right] - 1$$

Figure 6 shows the dependence of the median mass diameter $d_t$ of droplets on the velocity $U$ of the air flow and the rotational speed $\omega$ of the disk sprayer under different operating conditions of the spray, calculated by the formulas (11 and 12).

The graph shows that an increase in the rotation frequency of the disk $\omega$ at a constant air flow velocity leads to a minimum median mass diameter of the droplets. Therefore, when justifying the diameter of the sprayed droplets, it is necessary to consider the combination of the disk rotation speed and the axial velocity of the air flow.

4. Conclusions
An analytical study of the droplet formation process when a liquid flow out of a capillary with the supply of a side air flow shows that with the help of a side air flow it is possible to increase the rate of droplet formation, therefore, to improve the dispersion of the formed droplets.

When justifying the diameter of the sprayed droplets, it is necessary to consider the combination of the rotational speed of the disk and the axial velocity of the air flow. To obtain a monodisperse spray with a diameter of the main droplets $d = 80-120$ microns, at an axial air flow velocity of the fan unit $U = 40-60$ m/s, the parameters of the disk atomizer and the propeller are linked with each other at the following values: disk radius $r = 65-85$ mm, the number of radial channels on the disk $n_p = 2-6$ pcs, the width of the radial channel $b_p = 3-4$ mm, the width of the
wind wheel blade $h = 6-10$ cm and the radius of the wind wheel $R_w = 14.0-16.0$ cm.
To obtain high-quality air-droplet flow, the initial speed of the main droplets discharged from the periphery of the spray disc should be less than the air velocity and rotational frequency. Pavlovskyi spray is recommended to be applied within $\omega = 60 \ldots 200$ $c^{-1}$.

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