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METHODOLOGICAL APPROACHES TO JUSTIFICATION OF KINEMATIC PARAMETERS OF VOLUMETRIC SPRAYERS

I.S. Kruk[1], T.P Kot[1], O.V. Gordeenko[2], A. Marczuk[*3], W. Romaniuk[4], K. Gałuszko[5]

[1] Belorussian State Agro-technical University, Belarus
[2] Belorussian State University of Agriculture, Belarus
[3] Department of Agricultural and Transport Machines, University of Life Science in Lublin Poland
[4] Institute of Technology and Life Sciences, Warsaw Branch, Poland
[5] Faculty of Military Medicine, Medical University of Lodz, Poland
[*] *Contact details: ul. Beskidzka, 70, 20-869 Lublin, e-mail: andrzej.marczuk@up.lublin.pl*

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ABSTRACT

The objective of the research is to justify kinematic parameters of volumetric sprayers in order to improve the efficiency of delivery of the process solutions of pesticides onto the objects of treatment. Theoretical research was carried out on the basis of the laws of aerodynamics and mechanics. The results of the theoretical research formed the foundation for the justification of the scheme of a relative position and the main parameters of the air and hydraulic systems of volumetric sprayers.

Introduction

Plant protection against pests, diseases and weeds is one of the main elements of modern technologies of agricultural crops cultivation. Field sprayers play a main role in the means of mechanization. The analysis of the traditional field sprayers reveals a number of disadvantages. The main of them is irregular plant treatment by volume. From the portion of the process solution which gets on a plant, 80% accumulates on the top layer, less than 10% on the lower layer, the reverse side of the leaves and stems remains practically non-treated, while they are the main zone of pests and pathogens location (Степук и др. 1998; Radkowski and Kuboń, 2012).

Compulsory delivery of drops of pesticides to treated objects by airstream is the most effective of all known methods of volumetric treatment of crops (Литвинова, 1998). Thus, the justification of kinematic and structural parameters of sprayers, working on this principle (Figure 1), is an important issue.

a) b) c)

Figure 1. Volumetric sprayer (a,b) and the principle of its operation (c)

Objective and area of operation

The objective of the research was to justify the kinematic parameters of volumetric sprayers in order to improve the efficiency of delivery of process solutions of pesticides onto the treated objects.

Realization of this purpose provides for the theoretical research to justify the kinematic parameters and a relative position of air distributional and hydraulic systems of the volumetric sprayers.

Main part

The efficiency of the volumetric sprayer operation is determined by consistency of the air and hydraulic systems' operation. During the atomization of liquid by atomizers, droplets form a spray. In the spray some droplets fly at some angle α_c from the vertical line to the right, others go to the left, the trajectory of the rest is approaching the vertical line. The angle α_c is variable, as every droplet flies in its path.

Let us consider the basic motions of droplets in interaction with air stream: 1) the deviation of the droplets at an angle α_c from the vertical line to the right, 2) the deviation of the droplets at an angle α_c from the vertical line to the left; 3) the motion of the droplets vertically down. It is known that it is theoretically not possible to determine the nature of the motion of droplets like any other material bodies placed in the air stream because it is impossible to consider all factors. Thus, the problem is simplified.

Let us have a directed air stream which is characterized by velocity v_a, the angle β' between the direction of velocity and the horizontal plane and mass of the liquid droplet m_d moving with a velocity v_d at an angle γ_0 to the air stream and at an angle α_c from the vertical line (Figure 2a).

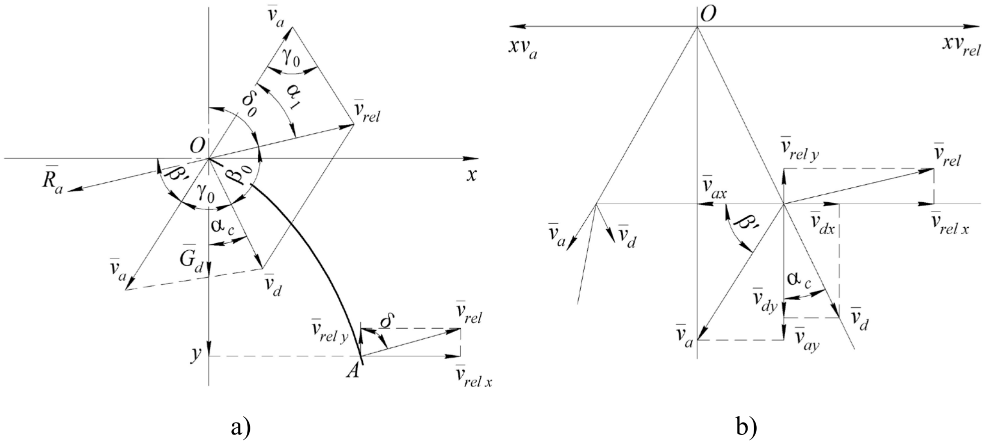

Figure 2. Calculations (the droplet moves at an angle α_c from the vertical line to the right): the trajectory of relative (a) and general (b) motion of the droplet in the air stream

The relative velocity is determined upon the velocity triangle

$$v_{rel} = \sqrt{v_a^2 + v_d^2 - 2v_a v_d \cos\gamma_0} \tag{1}$$

The relative velocity v_{rel} and the direction v_a forms angle α_1

$$\sin\alpha_1 = \frac{v_d \sin\gamma_0}{v_{rel}} \tag{2}$$

Acceleration imparted to the droplet by air stream in the turbulent regime is determined by the formula (Гладков (Gladkov, 1991):

$$a_{R_a} = \frac{k_r \rho_a S_d v_{rel}^2}{m_d} = k_w v_{rel}^2 \tag{3}$$

where:

k_r – is the coefficient of air resistance,

S_d – section of droplets (the area of the projection of the droplet on the plane which is perpendicular is the middle to the direction of droplet motion), (m^2)

$k_w = \dfrac{k_r \rho_a S_d}{m_d}$ – coefficient of windage.

Let us consider the relative motion of the droplet in the air stream in the movable coordinate system which is shifted by a parallel motion with a stream (Figure 2a). We denote the components of velocity of the droplet relative motion v_{rel} at the point *A* to the trajectory of the relative motion of *OA* – $v_{rel\,x}$, $v_{rel\,y}$, and the velocity components of the air stream – v_{ax}, v_{ay}. Then

$$v_{ax} = v_a \cos\beta', \qquad v_{ay} = v_a \sin\beta' \tag{4}$$

The angle α_c showing a deviation of the general velocity from the vertical line is determined by the formula:

$$\mathrm{tg}\alpha_c = \frac{v_{dx}}{v_{dy}} = \frac{v_{rel\,x} - v_a \cos\beta'}{v_a \sin\beta' - v_{rel\,y}}. \tag{5}$$

where:

v_{dx}, v_{dy} – are the components of general velocity v_d, related to the fixed coordinate axes (Figure 2,b), (m·s^{-1})

$$v_{dx} = v_{rel\,x} - v_{ax}, \qquad v_{dy} = v_{ay} - v_{rel\,y} \tag{6}$$

At the beginning of the motion $v_{rel} = v_a$, then

$$R_a = m_d k_w v_a^2 \tag{7}$$

It follows from Figure 3 that

$$\mathrm{tg}\alpha_{c_0} = \frac{R_{ax}}{m_d g + R_{ay}} = \frac{R_a \cos\beta}{m_d g + R_a \sin\beta} = \frac{k_w v_a^2 \cos\beta}{g + k_w v_a^2 \sin\beta} \tag{8}$$

where:

R_{ax}, R_{ay} – are the components of air stream resistance, (N).

g – is free fall acceleration, (m·s^{-1}).

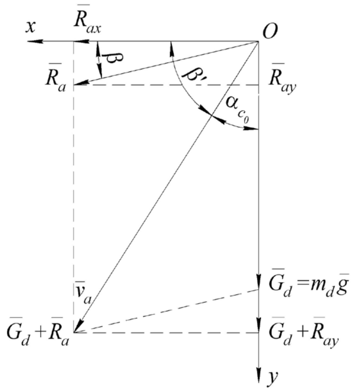

Figure 3. The velocity deviation from the vertical line when $v_{rel} = v_a$

Relative velocity approaches a vertical line, when $v_{rel\,y} \to v_{rel\ crit}$ (a relative critical velocity) and $v_{rel\,x} \to 0$

$$\mathrm{tg}\alpha_{c\,crit} = \frac{-v_a \cos\beta'}{v_a \sin\beta' - v_{rel\ crit}} = \frac{-k_w v_a^2 \cos\beta'}{k_w v_a^2 \sin\beta' - g}. \tag{9}$$

The obtained formulas show that the deviation of the droplet motion from the vertical line varies with the coefficient of windage of the droplet k_w, air stream velocity v_a and angle change α_c.

By the second option (deviation from the vertical line to the left), in the formula (9) the minus sign changes to the plus one, and the formula becomes

$$\mathrm{tg}\alpha_{c\,crit} = \frac{v_a \cos\beta'}{v_a \sin\beta' - v_{rel\ crit}} = \frac{k_w v_a^2 \cos\beta'}{k_w v_a^2 \sin\beta' - g}. \tag{10}$$

The third option, when the droplet flies straight down, $(\mathrm{tg}\alpha_c = 0)$ is possible when the coefficient of windage of the droplet is $k_w = 0$; the air stream velocity is $v_a = 0$; $\beta' = 90°$ so the direction of the air stream and the motion of the droplet are the same.

Theoretical investigations concerning the influence of the directed air stream on the individual droplets moving at different trajectories are the basis for the justification of the required angle of spray of the hydraulic atomizer. All the droplets flying out of atomizers must be caught by the air stream, so the angle of spray of the atomizer must be coordinated with the angle of the air stream distribution to create conditions for the delivery of droplets by the directed air stream and their regular distribution on the objects of treatment.

If we consider the interaction between the directed air stream and the air-droplet stream generated during the atomization of the process solution by the hydraulic atomizers but not separate drops, such parameters as coefficient of windage and the mass of the droplets can be neglected. Due to a significant difference in the air and fluid densities a droplet stream should be considered as the air stream. When usual correlations of the atomized fluid mass to air mass are considered their relation is about a thousand (Абрамович, 1976). It follows that the fundamental parameters affected by the interaction of streams are the magnitude and direction of the air stream velocity, droplet stream velocity, relative position of the streams. To ensure a delivery of the droplets to the object of treatment by the air stream it is necessary to change the velocity of the air stream. At the moment of meeting of air-droplet and air streams the velocity of the latter must be significantly greater than the velocity of the air-droplet stream. Therefore, the direction of drops movement will change in the direction of the air stream. A finally formed integrated stream should be uniform for regular distribution of the process solution droplets throughout the volume of the plants. It requires that at the moment of meeting of the streams the air stream must be uniform, indissoluble (Степук and Кот, 2005). We define the distance over which such kind of stream is formed. There are three zones of the flow of air through the exhaust nozzles of the air distribution system: the first zone consists of the motion of the independent streams, the second one is transitional (streams converging occurs and boundary layers mix and therefore there is the smoothing of the velocity field) and the third zone is (a combined motion of streams resembling the flow from the solid slot with a regular velocity field).

Distance h_1 corresponding to the area of the double overlapping of air distribution sprays is determined by the formula:

$$h_1 = \frac{b_1 - 0{,}5d_h}{\mathrm{tg}\gamma}, \tag{11}$$

where

b_1 – is the axes distance between outlet holes of the air distribution hoses, (m)

d_h – is the diameter of the outlet hole, (m)

γ – is the angle of the lateral expansion of the air stream, (deg)

We can observe the same by the flow of the processing liquid from hydraulic atomizers but relative to quantitative distribution of the processing liquid. One cannot speak about the uniformity of the velocity field because every droplet moves along its own trajectory with its own speed in the spray. Therefore, the main criterion that should be observed for the formation of the integrated air-droplet stream is an interflow of the sprays of the adjacent atomizers (Литвинова, 1999).

The distance h_2 at which this interflow occurs corresponds to the second transitional zone and is determined by the formula:

$$h_2 = \frac{0{,}5b_2}{\mathrm{tg}\frac{\alpha_s}{2}}, \tag{12}$$

where:

b_2 – is the axes distance between the atomizers, (m)

α_s – is the angle at the top of the spray of the atomizer, (deg)

It is necessary to determine the average velocity and direction when forming the single air-droplet stream. It is advisable to send them at an angle to each other by external blending of the streams. To find the direction and velocity of the blending streams it is necessary to construct a parallelogram at the vectors of their kinetic momentum. Its diagonal E will determine the direction of blending streams. As the distance from the flow plane increases the mass of the streams increases and velocity decreases. Since between mass m and velocity v there is a simple inverse relationship, the kinetic momentum in all sections of the streams will be constant and equal to the initial kinetic momentum, that is mv (Кот, 2005).

The magnitude of the resultant E is determined by the formula:

$$E = m_{as} v_{a_0} \cos\beta + m_{ads} v_{d_0} \cos\theta, \tag{13}$$

where:

m_{as} – is the mass of air stream, (kg)

m_{ads} – is the mass of the air-droplet stream, (kg)

v_{d_0} – is the velocity of the droplet escape from the atomizer, ($m \cdot s^{-1}$)

β – is the angle of the deviation of the air stream from the vertical line, (deg)

θ – is the angle of the deviation of the air-droplet stream from the vertical line, (deg)

Then the average velocity of the integrated stream (the final) is determined by the formula:

$$v_{aver} = \frac{m_{as} v_{a_0} \cos\beta + m_{ads} v_{d_0} \cos\theta}{m_{as} + m_{ads}}. \tag{14}$$

Mass of the air stream is determined by the formula:

$$m_{as} = \rho_f Q_h n_h t, \tag{15}$$

where

Q_h – is the air discharge in one outlet hole, (m^{-3})

n_h – is the number of outlet holes, (pcs)

t – is time, (s)

The air discharge in one outlet hole is determined by the formula:

$$Q_h = \mu \frac{\pi d_h^2}{4} v_{a_0}. \tag{16}$$

The mass of the air-droplet stream (in the initial section it can be regarded as a liquid one) is determined by the formula:

$$m_{ads} = \rho_f Q_f n t, \tag{17}$$

where:

ρ_f – is the density of the processing liquid, ($kg \cdot m^{-3}$)

Q_f – is the flowrate through the atomizer, ($m \cdot s^{-3}$)

n – is the number of atomizers, (pcs)

After the necessary transformations we get:

$$v_{aver} = \frac{\rho_a \mu \frac{\pi d_h^2}{4} v_{a_0}^2 n_h \cos\beta + \rho_f Q_f n v_{d_0} \cos\theta}{\rho_a \mu \frac{\pi d_h^2}{4} v_{a_0} n_h + \rho_f Q_f n}, \tag{18}$$

where:

v_{a_0} – is the initial velocity of the air flow from the outlet holes, ($m \cdot s^{-1}$).

The integrated air-droplet stream before meeting with a vegetative layer overcomes a certain distance y_1. The stream velocity at the entrance in the vegetative layer is determined by the formula:

$$v_{y_1} = \frac{0{,}48 v_{aver}}{\frac{a y_1}{d_h} + 0{,}145}, \tag{19}$$

where:

y_1 – is the distance from the zone of the integrated stream formation to the entrance in the vegetative layer, (m).

Formula (19) is valid under ideal conditions, in real conditions external factors should be taken into consideration. Firstly, you should consider the influence of the natural wind on the air-droplet stream. Secondly, convective currents influence the dynamics of the stream. They appear due to the presence of various types of surfaces on the way of the stream (in our case it is the earth's surface and plants), the temperature of which differs from the temperature of the air stream. Therefore the formula (19) can be represented in the following form:

$$v_{y_1} = \sqrt{\left(\frac{0{,}73 g y_1 (t_s - t_{at})}{v_{aver} T_{at} \cos\alpha}\right)^2 + \left(\frac{0{,}48 v_{aver}}{\frac{a y_1}{d_h \cos\alpha} + 0{,}145}\right)^2}, \tag{20}$$

where:

t_s – is the temperature on the stream axis, (deg. C)

t_{at} – is the ambient temperature, (deg. C)

T_{at} – is the absolute ambient temperature, (deg. abs.)

α – is the angle of the deviation of the integrated stream direction from rectilinear motion, (deg)

It is necessary to ensure that the effect of movement and rotation of the plant leaves by the integrated stream treats the plants uniformly with pesticides. For this purpose it is necessary to know the maximum and minimum effective force impact on plants. In this case it is maximum permissible velocity of stream entry in the vegetative layer $v_{\max_{per}}$ which does not damage the plants, and the minimum velocity which ensures the effect of turning leaves in the lower zone of the vegetation layer $v_{\min_{eff}}$. On this basis we can express the required velocity of the stream entry onto the vegetative layer (Лысов, 1983):

$$v_{y_1} = \frac{v_{y_2}}{e^{-\xi(y - y_1)}} = \frac{v_{y_2}}{e^{-\xi \Delta D}}, \tag{21}$$

where:

v_{y_2} – is the stream velocity in the lower zone of vegetation layer, (m·s^{-1}),

ξ – is the permeability coefficient, (m^{-1}),

ΔD – is the thickness of the vegetation layer, (m).

The following conditions should be carried out: $v_{y_2} > v_{\min_{eff}}$, $v_{y_1} \le v_{\max_{per}}$. In addition to avoid destruction of droplets of the processing liquid the velocity of the entry of the integrated air-droplet stream onto the vegetative layer must be greater than the velocity of natural wind ($v_{y_2} > v_{wind}$).

Taking into consideration the formula (21), the relation (18) takes the form (Литвинова, 2000):

$$v_{aver} = \sqrt{\frac{\left(\frac{ay_1}{d_h \cos\alpha} + 0{,}145\right)^2}{0{,}46}\left(\left(\frac{v_{y_2}}{e^{-\xi\Delta D}}\right)^2 + \sqrt{\left(\frac{v_{y_2}}{e^{-\xi\Delta D}}\right)^4 - \frac{47{,}16 y_1^2 \left(t_s - t_{at}\right)^2}{\left(\left(\frac{ay_1}{d_h \cos\alpha} + 0{,}145\right)^2 T_{at}^2 \cos^2\alpha\right)}}\right)}. \quad (22)$$

Knowing the final velocity of the integrated air-droplet stream it is possible to determine the initial velocity of the flow of air from the outlet holes of the air distribution hoses (Кот, 2002):

$$v_0 = 0{,}5 v_{aver} + 0{,}5\sqrt{v_{aver}^2 + \frac{4\rho_f Q_f n\left|v_{d_0}\cos\theta - v_{aver}\right|}{\rho_a \mu \frac{\pi d_h^2}{4} n_h \cos\beta}}. \quad (23)$$

Knowing the initial velocity of the air flow from the holes, it is possible to calculate parameters of the air distribution hoses of the volumetric sprayers.

Summary

The results of the theoretical research carried out to justify the kinematic parameters and relative arrangement of the air distributional and hydraulic systems of volumetric sprayers are shown in the article. The mechanism of interaction of directed air stream generated by the air-distributional system with an air-droplet stream generated during the atomization of the processing liquid by hydraulic atomizers at their outer mixing has been presented. Mathematical relationships for determination of the required initial velocity of the air stream, including the interaction of the processed object and parameters of the air distributional and hydraulic systems are provided.

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METODOLOGICZNE PODEJŚCIA PRZY UZASADNIENIU PARAMETRÓW KINEMATYCZNYCH OPRYSKIWACZY OBJĘTOŚCIOWYCH

Streszczenie. Celem pracy było uzasadnienie parametrów kinematycznych opryskiwaczy objętościowych w celu poprawy skuteczności dostarczania roztworów procesowych zawierających pestycydy na opryskiwane obiekty. Badania teoretyczne przeprowadzono na podstawie praw aerodynamiki i mechaniki. Wyniki badań teoretycznych przyczyniły się do sformułowania podstawy dla uzasadnienia schematu odpowiedniego ułożenia i głównych parametrów systemów powietrznych i hydraulicznych opryskiwaczy objętościowych.

Słowa kluczowe: opryskiwanie, system powietrzny, system hydrauliczny, strumień powietrze-kropla, atomizery