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EVALUATION OF SPRAY CHARACTERISTICS AND PESTICIDE DISTRIBUTION USING CENTRIFUGAL NOZZLES UNDER LABORATORY CONDITIONS

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This scientific paper presents a comprehensive experimental study on the formation of the spray plume and the distribution of the working fluid by centrifugal nozzles under stationary laboratory bench conditions. The relevance of this study is driven by the strict requirements of modern agricultural production to increase the efficiency of plant protection product application while simultaneously minimizing environmental impact. Traditional field tests are often complicated by a number of uncontrolled meteorological factors (wind speed and direction, fluctuations in air temperature and humidity), which significantly reduces the reliability of determining the true performance characteristics of individual nozzles. To solve this problem, the authors applied a laboratory testing methodology using a specialized hydraulic bench manufactured in accordance with current standards, which made it possible to isolate and evaluate the influence of key technological parameters with high precision.

The object of the study is the processes of hydraulic liquid spraying by AM.03.SB and Ej.03 centrifugal nozzles. The subject of the study is defined as the regularities of changes in the coefficient of variation of the transverse distribution of the working fluid depending on the pressure in the pressure manifold and the height of the sprayer boom. During the experimental studies, the working pressure in the hydraulic system ranged from 0.1 to 0.3 MPa with a step of 0.1 MPa, and the boom installation height above the receiving surface varied from 0.30 to 0.50 m with a step of 0.05 m. The obtained arrays of experimental data were processed in the Wolfram Cloud environment, which made it possible to build adequate full second-order polynomial models. These models describe the nonlinear influence of the studied factors on the unevenness index (coefficient of variation) of fluid distribution across the working width.

Keywords: *spraying, centrifugal nozzles, pesticides, distribution uniformity, coefficient of variation, response surface, working pressure, boom height, laboratory test bench.*

Eq. 5. Fig. 4. Table. 1. Ref. 15.

1. Problem formulation

Despite significant advancements in precision agriculture and spray technology, achieving uniform pesticide application while minimizing environmental contamination remains a critical challenge [1]. Modern agricultural sprayers require high precision in droplet size distribution and spatial spray patterns to ensure biological efficacy and prevent off-target drift [2].

However, existing literature often lacks comprehensive empirical data on how specific operating parameters (such as working pressure and nozzle geometry) dynamically affect the spray characteristics and volumetric distribution under controlled bench test conditions. Traditional field evaluations are frequently hindered by variable environmental factors like wind speed and ambient temperature, making it difficult to isolate the true performance metrics of individual spray nozzles [3].

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Therefore, there is an urgent need for systematic bench testing and quantitative evaluation of spray nozzles to establish accurate correlations between operational modes and droplet metrics. This study addresses this gap by assessing the spray quality and distribution patterns of selected pesticide nozzles, providing a reliable methodological basis for optimizing agricultural spraying systems.

2. Analysis of recent research and publications

The operational efficiency and environmental safety of agricultural boom sprayers heavily depend on the precise regulation of structural and hydraulic parameters. Achieving a uniform volumetric distribution of the working fluid across the target area requires comprehensive optimization of equipment settings.

A significant body of recent research focuses on the stability, positioning, and height of the sprayer boom during operation. Advanced testing methodologies for automatic boom-height control systems demonstrate that maintaining a stable distance between the nozzles and the crop canopy is critical to prevent spatial distribution errors [4]. Sensor-based boom-height regulation mechanisms indicate that vertical deviations directly lead to uneven spray overlap and coverage irregularities on field crops [5]. Furthermore, quantitative analyses of vertical and horizontal oscillations in self-propelled boom sprayers prove that dynamic boom movements severely distort the transverse spray pattern [6]. Additionally, specialized boom posture adjustment and control systems have been developed to maintain stability across wide spray configurations [7].

In parallel, the interaction between working pressure and nozzle characteristics remains a central element of application technology. Physical models of operating pressure demonstrate that pressure fluctuations directly alter droplet size spectra and volumetric distribution from agricultural nozzles [2]. Evaluations of distinct nozzle types under varying pressure regimes highlight significant variations in spray angles and droplet velocities. Recent field and laboratory assessments establish that both nozzle geometry and liquid pressure dictate the extent of spray drift and coverage uniformity [1]. Adjustments in nozzle orifice sizes and working pressures modify droplet dynamics, confirming that proper pressure selection is vital for balancing biological efficacy and drift reduction. Finally, comprehensive state-of-the-art reviews on drop size measurement techniques emphasize that bench-testing protocols are indispensable for standardizing nozzle performance under simulated hydraulic conditions [8].

Despite these extensive findings, further targeted investigations are required to comprehensively assess specific nozzle configurations under distinct bench-testing regimes and combined pressure-height parameters.

3. The purpose of the article

The purpose of this research is to experimentally evaluate and optimize the spray characteristics and volumetric distribution patterns of pesticide spray nozzles under controlled bench test conditions, establishing precise empirical correlations between operational parameters and application quality.

4. Results and discussion

Research on the quality of pesticide atomization and the uniformity of their transverse distribution was carried out using a hydraulic test rig (Fig. 1) manufactured in accordance with the requirements of the standards [9].

The test rig operates as follows: the working fluid is pumped from the tank through the pressure manifold (2) to the test spray nozzles (1) using a centrifugal pump (QBX60), where it is atomized and hits the receiving surface (5), which is divided into sections by longitudinal partitions, from where the liquid flows through gutters into measuring cups (6).

The design of the test rig provides the capability to adjust the installation height of the boom above the receiving surface within the range of 0.15 to 1.0 m. The spacing of the spray nozzles on the boom is set at 50 cm with the possibility of increasing it to 100 cm. Control of the working pressure in the hydraulic circuit is carried out using a pressure gauge. Measuring cups with a capacity of at least 300 ml and a graduation interval of 1 ml are used to collect the liquid from the receiving surface. To ensure safety and comfortable working conditions for the operator, the receiving chamber of the rig is equipped with a protective barrier 300 mm high.

As part of the experiment, Rosa AM.03.SB (fig. 2a) centrifugal spray nozzles manufactured by Agromodul [10] with a rated flow rate of 1.2 l/min at a working pressure of 0.3 MPa, and Ej.03 (fig.2b) spray nozzles manufactured by ECOjet [11] with a flow rate of 1.18 l/min at a pressure of 0.3 MPa were investigated.

The program of experimental research on the test rig involves determining the following spray nozzle parameters: volumetric liquid flow rate, width and quality of the spray pattern, and the coefficient of variation of liquid distribution over the surface depending on the factors under study.

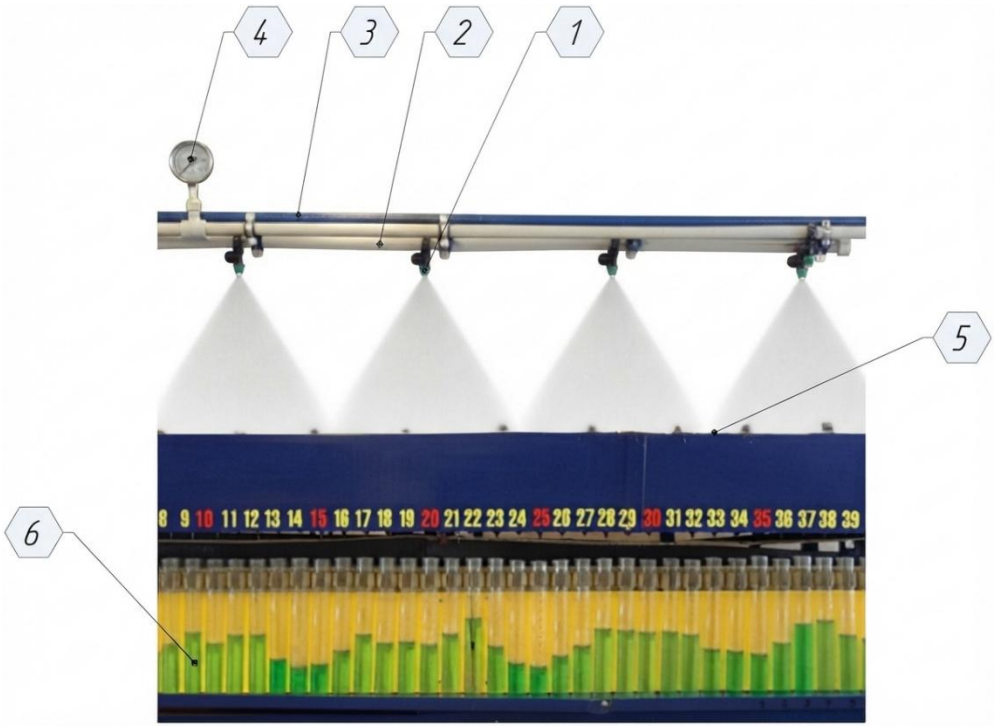


Fig. 1. General view of the test rig for studying spray nozzles: 1 – test spray nozzle; 2 – pressure manifold; 3 – boom; 4 – pressure gauge; 5 – receiving surface; 6 – measuring cups

Before testing the spray nozzles, they are thoroughly washed with water containing a detergent, and their technical condition is visually inspected for the absence of mechanical damage, corrosion of metal surfaces, and the integrity of the rubber seals.

The variable factors that have the greatest impact on the coefficient of variation of the transverse distribution were selected as follows [12, 13]: fluid pressure p, MPa, varied from 0.1 to 0.3 with a step of 0.1 MPa; boom height h, m, above the receiving surface ranged from 0.30 to 0.50 m with a step of 0.05 m.

The duration of the experiment was 1 minute and was controlled by a stopwatch. Each test was performed in triplicate. During the study, the temperature of the working fluid t, $°C$ used in the experiment was also determined and remained within $t = 17 - 18\ °C$. This indicator was measured using a thermometer.

a

b

Fig. 2. General view and components of centrifugal spray nozzles:
a – AM.03.SB; b – Ej.03;
1 – general view; 2 – bayonet cap; 3 – body; 4 – swirl core; 5 – gasket; 6 – rubber ring

The distribution of the sprayed liquid over the surface was determined by collecting water in measuring cups. The uniformity of the sprayed liquid distribution along the length was evaluated by the coefficient of variation [9]:

$$CV = \pm \frac{\sigma}{\bar{x}} \cdot 100, \tag{1}$$

where σ – is the standard deviation of the water volume in the measuring containers, ml; $\bar{x}$ – is the arithmetic mean of the volume in the measuring containers, ml.

$$\sigma = \pm \sqrt{\frac{\sum_{i=1}^{n} \left(x_i - \bar{x} \right)^2}{n-1}} \tag{2}$$

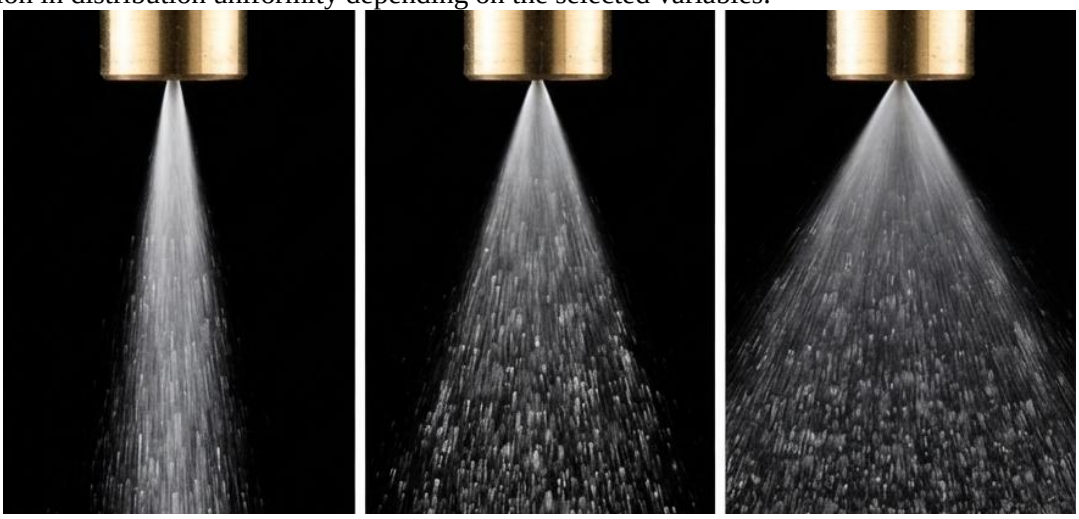
where x_i – is the volume of water in the *i*-th measuring container, ml; n – is the number of measuring containers between the axes of the outer spray nozzles.

$$\bar{x} = \frac{\sum_{1}^{n} x_i}{n} \tag{3}$$

The obtained array of experimental data was processed in the Wolfram Cloud environment [14], where second-order regression equations reflecting the influence of the studied variable factors on the quality of liquid atomization were obtained. These equations allow for a quantitative assessment of the variation in output parameters depending on the variation of input factors, as well as the determination of their optimal values.

The analysis of the spatial structure of the spray pattern based on Fig. 3 allows for a comprehensive assessment of the quality of spray pattern formation by the centrifugal nozzle depending on changes in operating pressure within the hydraulic system. At a low pressure of 0.3 MPa (Fig. 3, a), visual observation and analysis of the pattern geometry indicate instability in the film formation processes. The liquid film formed at the nozzle outlet has a deformed structure with a predominance of coarse droplets. This phenomenon is caused by insufficient kinetic energy of the flow to fully overcome surface tension and viscous friction forces, where internal nozzle surface roughness and micro-defects in the swirl generator geometry significantly affect the disintegration process. With an increase in operating pressure to 0.3 MPa (Fig. 3, c), the spatial structure of the spray pattern acquires stable parameters, forming a symmetrical thin-walled conical film at the nozzle exit that rapidly disintegrates into a stable spectrum of fine droplets due to intensive tangential flow swirling.

The experimental studies made it possible to determine the values of the coefficient of variation characterizing the uniformity of liquid distribution over the surface (Table 1). The research covers various combinations of the boom height h and operating pressure p, which provides a comprehensive assessment of the performance quality of the centrifugal nozzles under study. The conducted analysis reveals the patterns of variation in distribution uniformity depending on the selected variables.



a ***b*** ***c***

Fig. 3. Variation of the spray pattern shape depending on pressure p:
a – 0,1 MPa; b – 0,2 MPa; c – 0,3 MPa.

Table. 1.

Results of liquid distribution uniformity depending on the studied parameters

Pressure *p*, MPa		Boom height *h*, m				
		0,3	0,35	0,4	0,45	0,5
AM.03.SB	0,1	44,2	41,5	36,2	28,4	25,2
	0,2	22,1	16,5	11,2	8,6	7,7
	0,3	18,3	13	8,4	6,2	5,8
Ej.03	0,1	48,9	44,4	38,5	34,2	30,5
	0,2	24,2	18	12,4	9,3	8,6
	0,3	19,8	14,1	9,2	7,1	6,7

Based on the array of experimental data (Table 1) obtained during bench tests, an approximation was performed, yielding full second-order polynomial models for each of the nozzles:

$$CV_{AM.03.SB} = 198h^2 + 193h \cdot p - 276.8h + 950p^2 - 581p + 154 \quad (4)$$

$$CV_{Ej.03} = 340.95h^2 + 144h \cdot p - 378.76h + 1039p^2 - 612.5p + 179.58 \quad (5)$$

The primary objective of the mathematical processing stage is not merely model construction, but the identification of its extrema. For agricultural sprayers, achieving a minimal unevenness of working fluid distribution across the swath width is critically important, as it directly affects the quality of pesticide application. For the tested nozzles, the minimum value of the coefficient of variation is achieved at the following combination of factors within the experimental range:

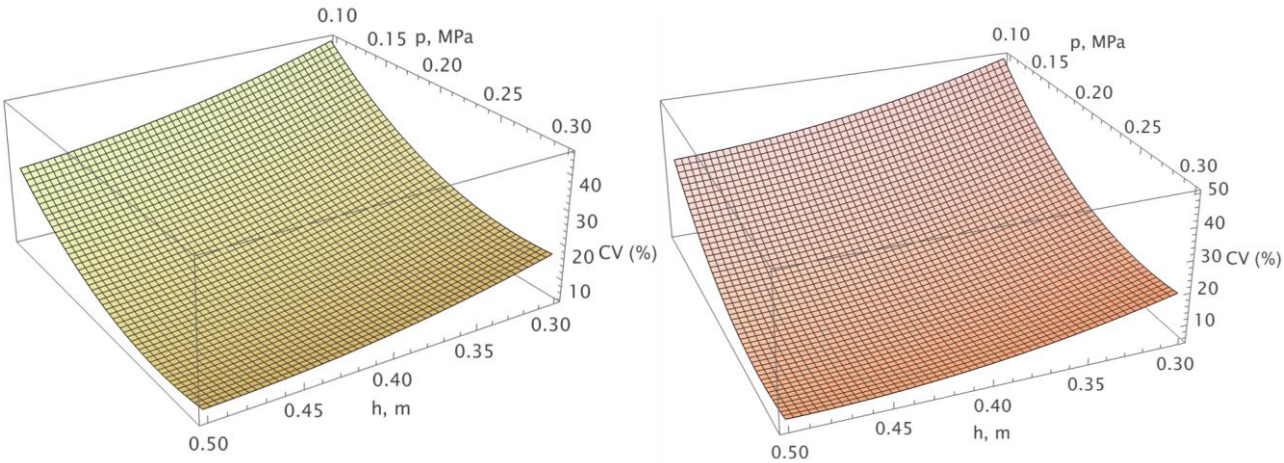
for the AM.03.SB nozzle $CV_{AM.03.SB} = 3{,}5\%$ at $p = 0{,}26$ MPa, $h = 0{,}5$ m;

for the Ej.03 nozzle $CV_{Ej.03} = 5{,}1\%$ при $p = 0{,}26$ MPa, $h = 0{,}5$ m.

The mathematical formalization of optimization criteria allowed for the construction of response surfaces (Fig. 4), which graphically depict the relationships between the studied hydraulic and structural factors.

The analysis of the obtained response surfaces indicates that both the working pressure and the nozzle installation height exert a non-linear, extremal effect on the atomization quality and the uniformity of transverse distribution.

At lower threshold pressure values (0,1 MPa), the kinetic energy imparted to the liquid film is insufficient to stabilize the disintegration process. This leads to an elevated coefficient of variation ($CV > 20\%$), primarily caused by the formation of coarse droplets and local under-dosing zones beneath the spray overlap areas. As the pressure increases to 0,3 MPa, the response surfaces demonstrate a clearly defined local minimum corresponding to the optimal operating zone. The intensification of the tangential liquid swirl inside the vortex chamber ensures the formation of a stable, thin-walled conical film that disintegrates uniformly.



a ***b***

Fig. 4. Dependence of the CV, % on the boom height h, m above the surface and liquid pressure p, MPa: a – AM.03.SB; b – Ej.03

The response surfaces also indicate that boundary values of the boom height ($h \le 0{,}3$ m) disrupt the

transverse overlap profile because adjacent spray patterns fail to merge properly, creating sharp peaks and troughs in the volumetric distribution profile. Conversely, excessive height ($h > 0,5$ m) increases the susceptibility of fine droplets to atmospheric drift, similarly degrading the fluid distribution uniformity metric. The curvature of the response surfaces confirms the synergistic interaction between pressure and height. The region of optimal distribution uniformity ($CV < 7\%$ for AM.03.SB and $CV < 8\%$ for Ej.03) is localized within a restricted coordinate matrix: working pressures ranging from 0,25 to 0,3 MPa at a boom height of 0,45 to 0,50 m.

5. Conclusion

Based on experimental studies and mathematical modeling in the Wolfram Cloud environment, adequate second-order polynomial regression models have been obtained, describing the dependence of the coefficient of variation (CV, %) of the transverse liquid distribution on the operating pressure and boom height for AM.03.SB and Ej.03 centrifugal nozzles. A non-linear extreme character of the influence of the studied factors was established, and it was proved that an operating pressure of 0.1 MPa is insufficient to stabilize the liquid disintegration process due to the formation of coarse droplets and under-application zones, whereas increasing the pressure to 0.3 MPa ensures the intensification of tangential turbulence and the formation of a stable conical spray plume.

According to agrotechnical requirements, the unevenness of the working liquid distribution across the working width should not exceed 20% [9, 15]. Experimental studies confirm that the nozzles ensure compliance with and exceedance of these regulatory indicators starting from an operating pressure of 0.2 MPa and a boom installation height of 0.35 m.

A comparative analysis of the tested nozzles reveals distinct hydrodynamic and operational features. AM.03.SB demonstrates a slightly higher potential for transverse uniformity within the optimal zone, achieving a minimum coefficient of variation below 7%, whereas Ej.03 provides stable distribution with $CV < 8\%$. At lower pressure thresholds (0.15–0.2 MPa), the Ej.03 nozzle exhibits a slightly higher sensitivity to pressure drops regarding droplet spectrum uniformity, whereas AM.03.SB maintains a more stable core of the spray pattern due to its internal swirl chamber design. Both nozzles achieve their peak performance within the identical narrow coordinate matrix (operating pressure of 0.25–0.30 MPa and boom height of 0.45–0.50 m).

Prospects for further research lie in the development of intelligent systems for automatic real-time regulation of sprayer operating modes, taking into account the unit's travel speed and crosswind velocity indicators based on the proposed mathematical models.

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ОЦІНКА ХАРАКТЕРИСТИК РОЗПИЛЕННЯ ТА РОЗПОДІЛУ ПЕСТИЦИДІВ ВІДЦЕНТРОВИМИ РОЗПИЛЮВАЧАМИ В ЛАБОРАТОРНИХ УМОВАХ

У представленій науковій роботі здійснено комплексне експериментальне дослідження процесів формування факела розпилення та розподілу робочої рідини відцентровими розпилювачами в умовах стаціонарного лабораторного стенда. Актуальність дослідження зумовлена сучасними вимогами аграрного виробництва щодо підвищення ефективності та рівномірності внесення засобів захисту рослин за одночасного зменшення непродуктивних втрат робочої рідини й мінімізації екологічного навантаження. Проведення традиційних польових випробувань істотно ускладнюється впливом швидкості та напрямку вітру, температури, вологості повітря й інших метеорологічних чинників, що знижує точність і відтворюваність результатів. Для усунення впливу цих факторів застосовано методологію лабораторних випробувань із використанням спеціалізованого гідравлічного стенда, який дав змогу ізолювати та з високою точністю оцінити ключові технологічні параметри процесу розпилення.

Об'єктом дослідження є процеси гідравлічного розпилення робочої рідини відцентровими розпилювачами типу AM.03.SB та Ej.03. Предметом дослідження визначено закономірності зміни коефіцієнта варіації поперечного розподілу рідини залежно від тиску в напірній магістралі та висоти розташування штанги над поверхнею. Робочий тиск змінювали в межах від 0,1 до 0,3 МПа з кроком 0,1 МПа, а висоту штанги – від 0,30 до 0,50 м з кроком 0,05 м. Такий діапазон факторів дозволив оцінити характер їх окремого та комплексного впливу на рівномірність поперечного розподілу робочої рідини.

Експериментальні дані оброблено в середовищі Wolfram Cloud із застосуванням методів математичної статистики та регресійного аналізу. Побудовано адекватні поліноміальні моделі другого порядку, які описують нелінійний вплив досліджуваних факторів на нерівномірність розподілу рідини по ширині захвату. Отримані залежності можуть бути використані для визначення раціональних режимів роботи розпилювачів, оптимізації висоти штанги й робочого тиску та підвищення якості технологічного процесу внесення засобів захисту рослин.

Ключові слова: *обприскування, відцентрові розпилювачі, пестициди, рівномірність розподілу, коефіцієнт варіації, поверхня відгуку, робочий тиск, висота штанги, лабораторний стенд, математичне моделювання*

Ф. 5. Рис. 4. Табл. 1. Літ. 15.

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