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# RESULTS OF STUDIES ON THE INFLUENCE OF KEY PARAMETERS ON THE TRANSVERSE UNIFORMITY OF WORKING FLUID DISTRIBUTION BY A BOOM SPRAYER

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*Ensuring uniform transverse distribution of spray liquid during crop protection treatments is a key factor determining the effectiveness of pesticide application and reducing losses of active ingredients. Non-uniform application leads to untreated zones and local overdosing, which negatively affects both crop yield and environmental safety. This article presents the results of experimental research on the influence of boom height and operating pressure in the supply line on the uniformity of spray distribution when using flat-fan nozzles.*

*The experiments were conducted on a test bench manufactured in accordance with relevant standards (ISO) for evaluating distribution uniformity. Boom height was varied within the range of 0,15-0,9 m, while the operating pressure was adjusted between 0,2 and 0,6 MPa. The collected data were processed using the least squares method, with determination of mean values, variances, standard deviations, and coefficients of variation. Regression models were developed in the Wolfram Mathematica environment, and corresponding response surface plots were generated to identify optimal operating zones for the sprayer.*

*The experimental results showed that at boom heights below 0,4 m, the coefficient of variation reached 30-75%, exceeding agronomic requirements several times. Increasing the height to approximately 0,6 m significantly reduced distribution non-uniformity for all pressure levels studied. Using the constructed response surfaces, optimal combinations of parameters that provide the highest level of spray uniformity were identified.*

*Practical recommendations were formulated for field application: a boom height of 0,7-0,8 m is advisable at 0,2 MPa; 0,5-0,7 m at 0,3 MPa; and approximately 0,5 m at 0,6 MPa. The findings can be used to improve spraying guidelines and enhance the efficiency of pesticide application. The article also outlines prospects for future research aimed at further optimization of structural and operational parameters of boom sprayers.*

***Key words:*** *spraying, boom sprayer, distribution uniformity, coefficient of variation, nozzle, pressure, boom height, response surface, pesticides.*

***Eq. 5. Fig. 3. Table. 1. Ref. 16.***

## 1. Problem formulation

Diseases of cultivated plants, pest infestations, and weed contamination of crop stands are among the major biotic stress factors that significantly reduce the potential productivity of agricultural crops. According to various estimates, yield losses caused by these harmful organisms may reach 30% or more, even when high-yielding varieties and hybrids are used [1].

To mitigate the negative impact of pests, pathogens, and weeds, modern agricultural production widely employs chemical plant protection agents – pesticides, which include fungicides, herbicides, insecticides, and other specialized formulations. Chemical crop protection is performed using several technological methods such as spraying, dusting, seed dressing, soil fumigation, and the application of toxic baits.

Despite the diversity of protection methods, spraying remains the most common and universal technology, ensuring the application of pesticide working solutions onto plant surfaces or soil in the form of fine droplets [2].


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Today, both in Ukraine and worldwide, pesticide solutions are predominantly applied using field boom sprayers equipped with flat-fan slit nozzles, with application rates ranging from 75 to 300 L/ha and active ingredient concentrations of 0,1-2 L/ha [2, 3].

One of the essential agrotechnical requirements for the operation of boom sprayers is achieving uniform distribution of the working fluid across the boom width. The coefficient of variation of distribution uniformity must not exceed ±12% [3], as it directly influences pesticide efficiency, minimizes chemical overuse, and ensures the environmental safety of the application process.

## 2. Analysis of recent research and publications

In recent years, the improvement of pesticide and herbicide application efficiency has become increasingly important due to stricter environmental regulations, rising pesticide costs, and the need for precise target spraying. Numerous studies focus on the influence of nozzle design, operating pressure, boom height, and travel speed [4] on droplet size, spray coverage, and uniformity.

Studies [5, 6] demonstrate that nozzle type (flat-fan, air-induction, twin-jet) significantly determines droplet spectra and drift potential, directly affecting herbicide performance in cereal crops. Research [7] further indicates that air-induction nozzles effectively reduce drift but may lower coverage on lower canopy layers due to larger droplet formation.

The effect of pressure and boom height has been extensively evaluated. Authors [8-10] showed that variations in boom height of even 10-15 cm can considerably affect spray overlap and distribution uniformity. Found [11] that increasing pressure produces finer droplets but simultaneously increases wind-drift risk.

Research [12, 13] focus on spray-pattern modeling, digital analysis of droplet formation, and high-speed imaging to assess coverage distribution. These authors highlight that modern twin-fan and new-generation air-induction nozzles improve herbicide application efficiency in windy conditions.

Most studies indicate that improving the uniformity of crosswise distribution of spray liquid by a boom sprayer is achievable only through the comprehensive coordination of nozzle design, operating pressure, travel speed, and boom height. At the same time, it remains insufficiently understood which combinations of these parameters provide the optimal uniformity of liquid distribution when using flat-fan nozzles, which justifies the need for further experimental research in this area.

## 3. The purpose of the article

The aim of our study was to investigate the influence of constant parameters and to determine the optimal values of the examined parameters at which the highest uniformity of spray liquid distribution can be achieved.

## 4. Results and discussion

Spraying a working fluid onto a target surface is an extremely complex and multifactorial process that is not always amenable to precise prediction. It involves several interrelated phenomena – the liquid exiting the nozzle under a specific operating pressure breaks into droplets of varying sizes and shapes, these droplets acquire kinetic energy, which determines their trajectory, simultaneously, they are subjected to air resistance, gravity, and turbulence, which alter their speed and direction. As a result, the droplets are transported away from the nozzle and deposit onto the surface of plants or soil, forming a coverage layer that must be uniform to ensure the effective action of pesticides, herbicides, or other agrochemicals.

Given the complexity and inherent unpredictability of these processes, an important criterion for evaluating the performance of a sprayer is the degree of surface coverage by droplets $M$ (1). This indicator allows for a quantitative assessment of the uniformity of spray application and its compliance with technological standards. Mathematical models and equations are used to determine this parameter, taking into account nozzle characteristics, operating pressure, travel speed, and the physical properties of the spray liquid.

$$M = \frac{100\pi}{4f_0}(d_1^2 \cdot n_1 + d_2^2 \cdot n_2 + ... + d_n^2 \cdot n_n) = \frac{25\pi}{f_0}\sum_{i=1}^{n} d_i^2 \cdot n_i, \%, \quad (1)$$

where $d_i$ – diameter of droplets or traces, μm; $n_i$ – number of droplets of the $i$-th size; $f_0$ – area of the surface under study, μm².

As previously noted, flat-fan nozzles have become the most widely used on modern boom sprayers. They provide a characteristic, patterned distribution of spray liquid across the working width, which typically follows a triangular function or a shape closely resembling it. This spray pattern geometry contributes to relatively uniform coverage of the target surface, enhancing the effectiveness of pesticide and herbicide application.

Figure 1 illustrates a schematic representation of a typical spray distribution profile, showing that the maximum flow occurs at the center of the spray fan, gradually decreasing towards the edges and forming a distinct triangular or nearly triangular profile.

The nozzles mounted on the boom of a field sprayer at a fixed spacing (typical spacing is 0,5 m) create overlapping spray patterns across the transverse direction. This interaction of neighboring spray fans plays a crucial role in achieving a uniform transverse distribution of the spray liquid on the soil or plant surface. Ideally, the individual flat-fan spray patterns should overlap in such a way that the resulting application profile across the spray width meets agronomic requirements as closely as possible.

Since flat-fan nozzles typically generate a spray distribution that approximates a triangular pattern, it is assumed that this distribution is symmetrical relative to the nozzle's longitudinal axis. Under this assumption, the spray fans of adjacent nozzles intersect within the vertical-transverse plane and form a combined distribution pattern that can ensure satisfactory coverage uniformity. This condition can only be achieved at a certain optimal boom height, where the overlap between spray patterns is sufficient but not excessive.

The described principle is illustrated geometrically in Fig. 2, which shows the overlap of adjacent spray fans and the formation of the overall liquid distribution profile.

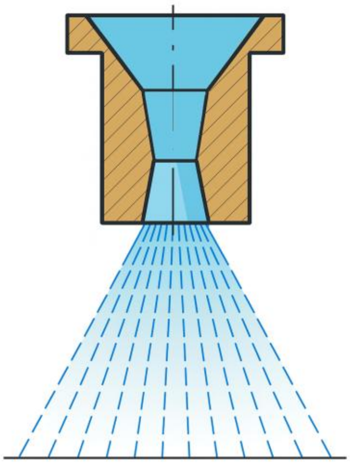

***Fig. 1. Liquid discharge from a flat-fan nozzle***

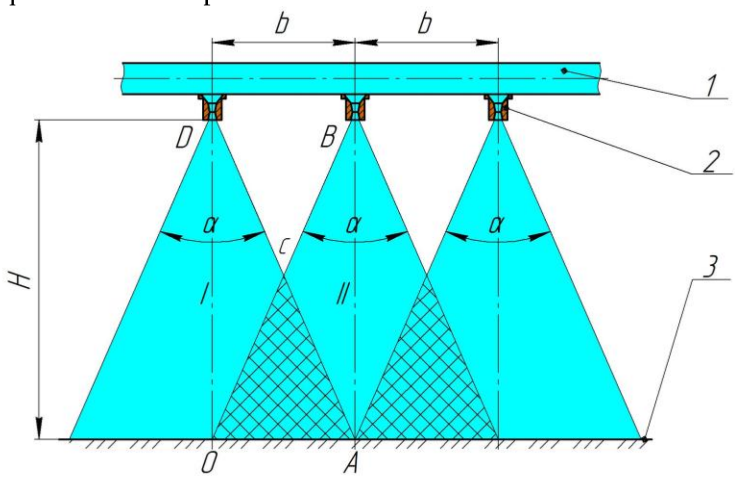


***Fig. 2. Diagram of spray pattern interaction: 1 – boom; 2 – nozzle; 3 – treated surface***

The conditions for ensuring uniform application of liquid onto the treated surface can be reduced to proving the equality of triangles *OCA* (the «double» zone) and *DCB* (the «empty» zone). The figure *ODBA* is a rectangle; therefore, *OA* = *DB* = *b*, and *OD* = *AB* = *H*. The equality of triangles *OAC* and *CDB* occurs when the overlap of adjacent spray patterns is such that the right boundary line *DA* of nozzle *I* reaches point *A* of nozzle *II*, while the left boundary line *OB* of nozzle *II* intersects the axis of symmetry of the spray pattern of nozzle *I* at point *O*. In this case, point *C* is the intersection of diagonals *AD* and *OB*. Thus, triangles *OCA* and *CDB* are equal, and this equality occurs only if:

$$H = \frac{OA}{(tg\alpha / 2)} = \frac{b}{(tg\alpha / 2)} \tag{2}$$

Raising the boom with the nozzles above the value $H = \frac{b}{(tg\alpha / 2)}$, or lowering it below this value, shifts point *A* in both cases away from the axis of symmetry *AB* and disrupts the equality of the triangles. According to test results, the spray angle $\alpha \approx 83 - 84°$. Assuming it equal to $\frac{\pi}{2}$, we obtain

$$H = \frac{b}{tg45°} \text{ or } H = b \tag{3}$$

In other words, as a first approximation, this satisfies the allowable variation in surface coverage uniformity that occurs when the boom height is equal to the spacing between the nozzles.

To determine the influence of the boom height above the treated surface, as well as the pressure in the supply line, comprehensive bench-scale experimental studies were carried out. The experiments were conducted using a test bench manufactured in accordance with the requirements of the relevant standard [14] for assessing the transverse distribution uniformity of spray solutions. A 4-meter boom equipped with eight flat-fan nozzles, spaced at a fixed distance from each other, was rigidly mounted on the bench frame.

During the tests, each nozzle produced a spray pattern that, upon reaching the bench surface, was divided by specially installed ribs simulating individual transverse coverage zones. The liquid collected in each zone subsequently drained into separate graduated cylinders, which enabled precise measurement of the discharge volume and the resulting distribution profile.

During the experimental investigations, the height of the boom with the nozzles was adjusted across a wide range of values – 0,15; 0,2; 0,25; 0,4; 0,5; 0,6; 0,7; 0,8 and 0,9 m. This selection of heights made it possible to thoroughly analyze the pattern of changes in transverse liquid distribution both within and beyond the recommended agronomic parameters. At each height setting, experiments were conducted under three operating pressures in the supply line: 0,2, 0,3 and 0,6 MPa, which enabled evaluating the influence of both hydraulic operating conditions and the geometric positioning of the boom.

Each experimental mode was repeated three times to ensure statistical reliability. The liquid volume readings in the graduated cylinders were taken with an accuracy of 0,5 graduation units (0.5 ml), providing sufficient resolution for subsequent mathematical processing. The collected data were analyzed using the method of least squares [15]: for each test series, the arithmetic mean, variance, standard deviation, and coefficient of variation were calculated. The coefficient of variation $\delta$ (4) served as a generalized indicator of the uniformity of the transverse distribution of the spray liquid.

$$\delta = 100 \times \frac{s}{\bar{x}} \quad (4)$$

where $s$ – standard deviation, representing the dispersion of discharge values relative to the mean; $\bar{x}$ – arithmetic mean value of the liquid collected in all measuring zones; by reducing the coefficient of variation $\delta \to \min$, the uniformity of liquid distribution improves

The statistical analysis of the experimental results was performed using Wolfram Cloud [16]. To evaluate the influence of boom height, operating pressure, and other fixed parameters on the uniformity of the transverse liquid distribution, a set of built-in analytical tools was utilized.

In particular, the LinearModelFit function was used to construct regression equations describing the relationships between the studied factors and the quality indicators of spray distribution – specifically, the coefficient of variation. These models enabled assessment of the significance of individual factors as well as their interactions.

The FindMaximum and FindMinimum functions were applied to identify optimal combinations of factors that yield the best (i.e., minimal) values of distribution non-uniformity, as well as to determine the boundaries of operating conditions in which the parameters exceed allowable technological limits.

The Plot3D function enabled construction of response surfaces illustrating the spatial dependence of the coefficient of variation on two primary factors. This made it possible to locate the optimal operating zones of the sprayer, where the highest uniformity of liquid distribution is achieved.

As a result of the experimental study, numerical values of the transverse distribution uniformity of the spray liquid were obtained, expressed through the coefficient of variation $\delta$ (Table 1). The collected data cover a wide range of boom heights *h* and operating pressure *p* levels, allowing for a comprehensive assessment of how these parameters influence the quality of spray application.

***Table 1***

***Coefficient of variation of liquid distribution non-uniformity depending on boom height and supply line pressure***

| Boom height *h*, m | Coefficient of variation $\delta$ of non-uniformity (%) at spraying pressure *p*, MPa | | |
|---|---|---|---|
| | 0,2 | 0,3 | 0,6 |
| 0,15 | 81,2 | 79,3 | 71,1 |
| 0,20 | 62,0 | 53,3 | 47,9 |
| 0,25 | 41,8 | 35,8 | 31,6 |
| 0,30 | 29,1 | 23,2 | 23,9 |
| 0,40 | 17,9 | 16,0 | 11,9 |
| 0,50 | 14,8 | 10,2 | 7,1 |
| 0,60 | 11,9 | 6,7 | 8,5 |
| 0,70 | 9,7 | 8,5 | 12,4 |
| 0,80 | 8,1 | 12,1 | 14,2 |
| 0,90 | 10,5 | 14,7 | 15,8 |

The analysis of these results makes it possible to trace the patterns in the variation of distribution uniformity in response to the studied factors.

As a result of statistical processing of the experimental data in Wolfram Mathematica, a regression equation (5) was constructed describing the dependence of the coefficient of variation of the transverse spray distribution on the studied parameters. The equation was obtained in a decoded form, allowing direct interpretation of the influence of each factor – boom height *h*, operating pressure *p*, and their interaction – on the uniformity of liquid application.

$$\delta = 131{,}09 - 350{,}25h - 81{,}93p + 254{,}62h^2 + 55{,}16p^2 + 56{,}56h \cdot p \qquad (5)$$

For a more visual representation and comprehensive interpretation of the experimental results, three-dimensional response surfaces were constructed (Fig. 3).

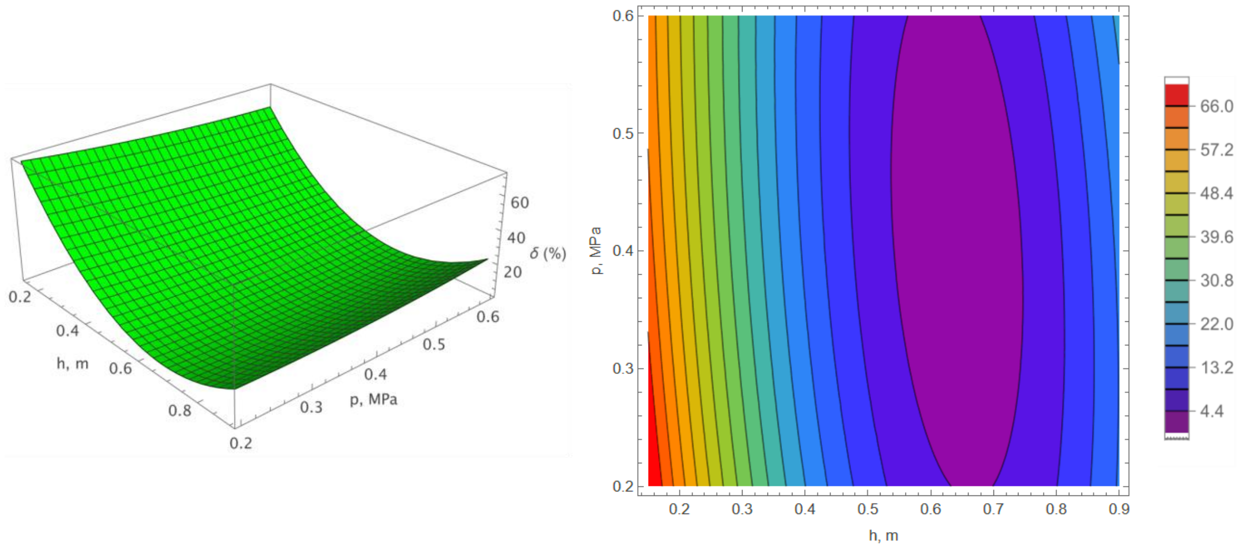


***Fig. 3. Dependence of the coefficient of variation $\delta$ on boom height h and supply line pressure p***

The results of the study indicate that, regardless of the operating pressure in the supply line, at low boom heights (up to 0,4 m), the coefficient of variation of non-uniformity $\delta$ is extremely high, ranging from 30% to 75%. These values exceed the agronomic requirements several times, indicating insufficient spray fan overlap and significant unevenness in the application of the spray liquid on the target surface.

As the boom height increases to 0,6 m, a substantial reduction in the variation of the non-uniformity coefficient is observed across the entire range of tested operating pressures. In this case, the level of liquid distribution non-uniformity approaches the technologically acceptable range and meets agronomic standards. These results demonstrate the existence of an optimal boom height at which sufficient fan overlap is achieved, ensuring stable and uniform coverage of the surface with the spray liquid.

Based on the experimental results and subsequent analysis, practical recommendations can be formulated regarding the optimal adjustment of the sprayer boom height depending on the operating pressure in the supply line, to ensure uniform application of pesticide solutions:

- at an operating pressure of 0,2 MPa, it is recommended to set the boom at a height of 0,7-0,8 m, which provides sufficient spray fan overlap and minimizes uneven distribution of the liquid;
- when the pressure is increased to 0,3 MPa, the optimal boom height is 0,5-0,7 m, which compensates for the higher liquid exit velocity and maintains stable coverage uniformity;
- at a spraying pressure of 0,6 MPa, the boom should be positioned at approximately 0,5 m, ensuring acceptable distribution quality.
- Following these recommendations allows for the optimization of the spraying process, increases the efficiency of pesticide application, and reduces technological losses of the spray solution.

## 5. Conclusion

The conducted research has demonstrated that the transverse uniformity of working fluid distribution by a boom sprayer is significantly influenced by two primary operational parameters – boom height and spraying pressure in the supply line. Experimental results confirmed that inadequate boom height (below 0,4 m) leads to excessively high non-uniformity levels, with the coefficient of variation reaching 30-75%, which far exceeds agronomic standards. Increasing the boom height to 0,6 m consistently reduced the variation across all tested pressure levels (0,2, 0,3, and 0,6 MPa), bringing the uniformity parameters closer to technological requirements.

Regression modelling and response surface analysis enabled the identification of optimal working zones where satisfactory uniformity can be achieved. The results also indicated that the relationship between height, pressure, and liquid distribution is nonlinear and requires coordinated adjustment of these parameters to obtain the desired application quality. The practical recommendations formulated in this study provide clear guidance for operators regarding the optimal boom height under different spraying pressures, thereby enhancing the efficiency of pesticide application and minimizing both chemical losses and negative environmental effects.

Overall, the obtained results form a solid foundation for further improvement of pesticide application technologies aimed at increasing efficiency, reducing environmental impact, and enhancing the performance of modern boom sprayers.

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**РЕЗУЛЬТАТИ ДОСЛІДЖЕНЬ ВПЛИВУ ОСНОВНИХ ПАРАМЕТРІВ НА РІВНОМІРНІСТЬ ПОПЕРЕЧНОГО РОЗПОДІЛУ РОБОЧОЇ РІДИНИ ШТАНГОВИМ ОБПРИСКУВАЧЕМ**

*Забезпечення рівномірного поперечного розподілу робочої рідини під час хімічного захисту рослин є одним із ключових чинників ефективності застосування пестицидів та зниження втрат діючих речовин. Нерівномірність внесення робочих розчинів призводить до утворення недооброблених зон та локальних перевитрат, що впливає як на врожайність, так і на екологічну безпеку. У статті представлено результати експериментальних досліджень впливу висоти штанги обприскувача та тиску в напірній магістралі на рівномірність внесення робочої рідини з використання щілинних плоскофакельних розпилювачів.*

*Дослідження проводилися на стенді, виготовленому відповідно до положень ДСТУ щодо оцінювання рівномірності розподілу. Висоту штанги варіювали в діапазоні 0,15-0,9 м, а тиск – у межах 0,2-0,6 МПа. Зібрані дані оброблено методом найменших квадратів із визначенням середніх значень подачі, дисперсій, середньоквадратичних відхилень та коефіцієнтів варіації. Побудовано регресійні моделі в середовищі Wolfram Mathematica та відповідні поверхні відгуку для визначення оптимальних зон роботи обприскувача.*

*Експериментальні результати показали, що при висотах штанги до 0,4 м коефіцієнт варіації досягає 30-75%, що у кілька разів перевищує агротехнічні вимоги. Зі збільшенням висоти до 0,6 м нерівномірність розподілу знижується до допустимого рівня для всіх досліджуваних тисків. На основі побудованих поверхонь відгуку визначено оптимальні комбінації параметрів, за яких забезпечується найкраща рівномірність нанесення рідини.*

*Практичні рекомендації включають оптимальні висоти штанги залежно від тиску: 0,7-0,8 м при 0,2 МПа; 0,5-0,7 м при 0,3 МПа; близько 0,5 м при 0,6 МПа. Результати дослідження можуть бути використані для вдосконалення технологічних карт обприскування та підвищення ефективності внесення засобів захисту рослин. Окреслено перспективи подальших досліджень, спрямованих на оптимізацію конструктивних та технологічних параметрів штангових обприскувачів.*

***Ключові слова:*** *обприскування, штанговий обприскувач, рівномірність розподілу, коефіцієнт варіації, розпилювач; тиск, висота штанги, поверхня відгуку, пестициди.*

***Ф. 5. Рис. 3. Табл. 1. Літ. 16.***

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