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RESULTS OF EXPERIMENTAL STUDIES OF JET NOZZLES FOR THE APPLICATION OF LIQUID MINERAL FERTILIZERS

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The efficiency of applying liquid mineral fertilizers is largely determined by the uniformity of their transverse distribution, which depends on the design and operating parameters of jet-type sprayers. This study presents the results of comprehensive experimental research on the influence of working pressure, boom height, and the diameter of the adjustable throttle orifice on the coefficient of variation (CV) of liquid distribution during the application of mineral fertilizer solutions. The tests were conducted on a hydraulic bench using RD.05.SD5-b nozzles and a combined nozzle equipped with interchangeable throttles. Using the Box–Behnken design method, statistically significant second-order regression models were developed, and their adequacy was confirmed by the Fisher criterion. Response surface analysis showed that increasing the pressure and boom height, as well as reducing the throttle orifice diameter, leads to a decrease in the coefficient of variation and improves the uniformity of liquid distribution. The minimum CV values – 18.9% for the RD.05.SD5-b nozzle and 16.8% for the combined nozzle – were achieved under optimal combinations of the studied factors. The obtained results confirm the practical importance of optimizing nozzle geometry and accurately adjusting operating modes to increase fertilizer application efficiency and reduce environmental risks. The developed models can be used for engineering calculations, sprayer calibration, and further improvement of jet-type sprayer designs. Future research should focus on validating the results under field conditions and assessing the influence of the physicochemical properties of fertilizers, temperature fluctuations, and boom dynamics on distribution quality. These results form a scientific foundation for the development of adaptive control systems for precision fertilizer application in modern agricultural technologies.

Key words: *liquid mineral fertilizers, UAN, jet sprayer, coefficient of variation, hydraulic sprayer, pressure, boom height, throttle diameter, distribution uniformity, parameter optimization.*
Eq. 2. Fig. 3. Table. 1. Ref. 16.

1. Problem formulation

Improving the efficiency of mineral fertilizer use is one of the key challenges in advancing modern agricultural production technologies. Achieving high fertilizer use efficiency not only increases crop yields but also supports sustainable farming practices by reducing nutrient losses and minimizing environmental pollution.

Among modern application systems, urea–ammonium nitrate (UAN) solutions have become increasingly popular due to their liquid form, which allows precise dosing, automation of processes, and accurate delivery to the target zone. However, the agronomic efficiency of UAN is determined not only by its physicochemical properties but also by the technical performance of the liquid application system, particularly the design and operation of stream jet spray nozzles [1].

Stream jet applicators (also referred to as streaming nozzles or jet-type fertilizer tips) are designed to apply liquid fertilizers in the form of coherent jets rather than fine sprays. This approach minimizes foliar contact, reduces the risk of leaf burn, and improves the placement of nutrients near the root zone. Nevertheless, the uniformity of distribution across the applicator's working width remains a critical factor influencing fertilizer use efficiency. Variations in jet flow rates may cause uneven fertilizer application, leading to localized over- or under-application, nutrient imbalance, and uneven crop growth.

A key parameter for assessing liquid distribution quality in such systems is the coefficient of variation (CV), which quantifies the degree of non-uniformity in fertilizer delivery along the boom width [2]. Lower CV

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values indicate uniform distribution, while higher CV values reflect increased irregularity. Maintaining CV within the acceptable range is essential for ensuring accurate and efficient fertilizer placement.

Therefore, identifying the relationships between the coefficient of variation and key operational factors an important scientific and practical task. Establishing these dependencies enables the optimization of operating regimes for stream jet applicators, ensuring high accuracy of fertilizer application under varying field conditions. The results of such studies form a foundation for developing improved applicator designs and operational guidelines aimed at enhancing the precision, environmental safety, and economic efficiency of liquid fertilizer technologies.

2. Analysis of recent research and publications

The issue of ensuring uniform transverse distribution of working fluid by sprayers during the application of agrochemicals, particularly liquid mineral fertilizers, is one of the key aspects of modern research in precision agriculture technologies. As noted in [3, 4], the efficiency of fertilizer use largely depends on the accuracy of dosage and the stability of fluid distribution along the working width of the sprayer. Any deviation from uniformity leads to inefficient fertilizer use, reduced nitrogen utilization efficiency, and local areas of nutrient deficiency or excess, which ultimately negatively affects crop yield and environmental safety.

Among the main factors determining the uniformity of fluid distribution, researchers highlight the design features of jet nozzles, the shape and stability of the spray pattern, the supply pressure, boom height, and the overlap angle between spray fans [5, 6]. Particular attention is paid to the influence of the nozzle geometry and outlet orifice shape on the hydrodynamic structure of the jet, which, in turn, determines the quality of transverse liquid distribution on the working surface.

Comprehensive studies conducted in [7, 8] have shown that the coefficient of variation (CV) of the liquid distribution significantly depends on the type of nozzle (single-jet or dual-jet), liquid flow rate, and operating pressure. At low pressure levels, larger droplets are formed, causing the spray fan to lose uniformity and increasing distribution irregularity. Conversely, excessive pressure leads to turbulence and instability of the jet structure, also resulting in higher coefficients of variation.

According to the findings of [9, 10], the optimal operating mode of the spraying system is achieved by harmonizing the structural parameters of the jet nozzle with the hydraulic characteristics of the liquid delivery system. This ensures stable pressure, uniform distribution, and effective overlap of adjacent spray fans – all of which are crucial for improving agrochemical application efficiency and minimizing nutrient losses to the environment.

3. The purpose of the article

Despite the considerable number of scientific studies devoted to the topic, the operation of stream type jet nozzles during the application of urea–ammonium nitrate (UAN) solutions remains insufficiently investigated. Existing literature lacks systematic laboratory experiments that comprehensively account for the influence of operating pressure, boom height, and design parameters of nozzle on the uniformity of transverse liquid distribution. This gap highlights the relevance and necessity of conducting detailed bench-scale experiments aimed at identifying the regularities in the variation of the coefficient of variation (CV) of the liquid's transverse distribution under different operating conditions.

4. Results and discussion

The experimental studies on the uniformity of liquid distribution were carried out under controlled laboratory conditions in accordance with the requirements of standard [11]. For this purpose, a specialized hydraulic test bench was used (Fig. 1), which provided the ability to simulate the operating parameters of a sprayer under various technological modes.

The hydraulic test bench (Fig. 1) is structurally designed to ensure precise simulation of the operating conditions of sprayer nozzles under laboratory settings. It consists of a worktable divided by partition ribs into parallel channels, each 0.1 m wide, which serve to collect the liquid distributed by the nozzle. At the end of each channel, there is a block of graduated measuring cylinders 1 used for collecting and quantifying the liquid volume from each section, thereby allowing for the assessment of the uniformity of transverse fluid distribution.

A pump unit (not shown in the figure) delivers the working liquid through a system of pipelines 3 to the nozzles 7 mounted on the boom. The supply pressure is maintained at the level recommended by the manufacturer for each tested nozzle type and is continuously monitored using a pressure gauge 4 to ensure experimental consistency.

The boom structure is installed above the ribbed working surface of the table and is designed with adjustable height settings, enabling experiments at different nozzle-to-surface distances. The boom is also equipped with clamping devices that make it possible to fix the installation angle of the nozzle according to specific experimental requirements, such as varying spray patterns or flow directions.

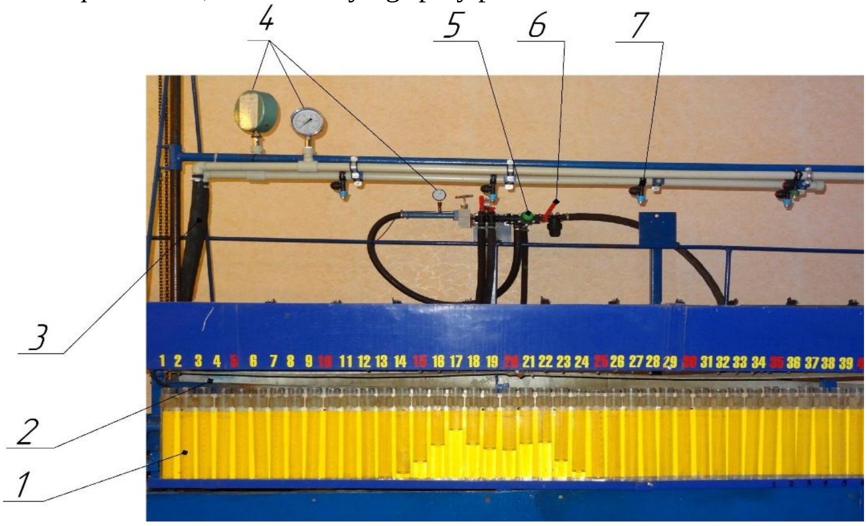

Fig. 1. Hydraulic test bench: 1 – measuring cylinders; 2 – trough; 3 – pipelines; 4 – pressure gauges; 5 – pressure regulator; 6 – flow direction control lever; 7 – nozzle (sprayer).

In the experimental studies, the following jet-type nozzles were utilized: the RD.05.SD5-b model (Fig. 2a) [12], equipped with interchangeable throttles, and a designed combined nozzle (Fig. 2b) [13]. Both types of nozzles were mounted on the boom of the hydraulic test bench at an interval of 0.5 m between adjacent nozzles, which corresponds to the standard spacing used in field sprayer configurations.

Fig. 2. Jet nozzles: a – RD.05.SD5-b; b – combined type

The working fluid used during the experiments was clean water, maintaining an average temperature of 17 °C, which ensured stable viscosity and reproducibility of the results. Each nozzle was tested under identical operating conditions to evaluate and compare their performance characteristics.

Based on the analysis of scientific publications [3–10], the factors that exert the greatest influence on the transverse distribution of liquid during spraying were identified, which served as the basis for designing the experimental program. These studies consistently emphasize that the operating pressure, the height of the sprayer boom above the target surface, and the geometry of the nozzle's internal flow channel, including the use of interchangeable throttle inserts, are among the most critical parameters affecting spray pattern stability, droplet distribution, and overall uniformity.

Considering these findings, the experimental design incorporated three primary factors:

- working pressure (*p*, MPa) – a key hydraulic parameter that determines jet velocity, spray fan formation, and droplet size distribution. Variations in pressure allow the assessment of how the spray structure changes under low, medium, and high operational loads.

Boom height above the measuring table (*h*, m) – a parameter that significantly influences the degree of spray fan overlap between adjacent nozzles. Adjusting the height makes it possible to evaluate the sensitivity of each nozzle type to changes in installation geometry, which is crucial for maintaining stable distribution under real field conditions.

Interchangeable throttle inserts (*d*, mm) – structural elements of the nozzle that modify the liquid flow rate and jet shape. Their inclusion in the experiment makes it possible to determine how different internal configurations affect the uniformity of liquid distribution and the resulting coefficient of variation (CV).

The ranges of variation for each factor were established in accordance with the methodological recommendations presented in [3, 4], ensuring consistency with commonly used operating modes for sprayers applying liquid mineral fertilizers. The selected parameter ranges are summarized in Table 1, which served as the foundation for planning the series of laboratory tests.

Table 1

Factors and ranges of variation

Symbol	Factor	Factor levels			Variation interval
		-1	0	+1	
X_1	Pressure p, MPa	0,2	0,25	0,3	0,05
X_2	Boom height h, m	0,5	0,7	0,9	0,9
X_3	Throttle diameter d, mm	1,0	1,5	2,0	0,5

To process and interpret the experimental results, the Box–Behnken design method [14] was applied. The adequacy of the developed mathematical model was verified using the Fisher F-test [15], the verification was performed at a 5% significance level (α = 0,05), corresponding to a confidence probability of 0,95. The calculations showed that for the RD.05.SD5-b nozzle, the obtained value was F = 102,8, while for the combined nozzle, it was F = 137,8, indicating that the constructed models are statistically adequate and correctly describe the experimental process.

Further statistical processing of the collected data resulted in the development of second-order regression equations (1) and (2), which quantitatively characterize the influence of the main operational factors –working pressure, boom height, and throttle diameter – on the output parameter of the process. These equations allow not only the assessment of how the response variable changes with variations in individual factors but also the determination of optimal factor combinations that ensure minimal coefficient of variation and improved uniformity of liquid distribution.

All computational procedures, including model construction and response surface visualization, were carried out in the Wolfram Cloud software environment [16].

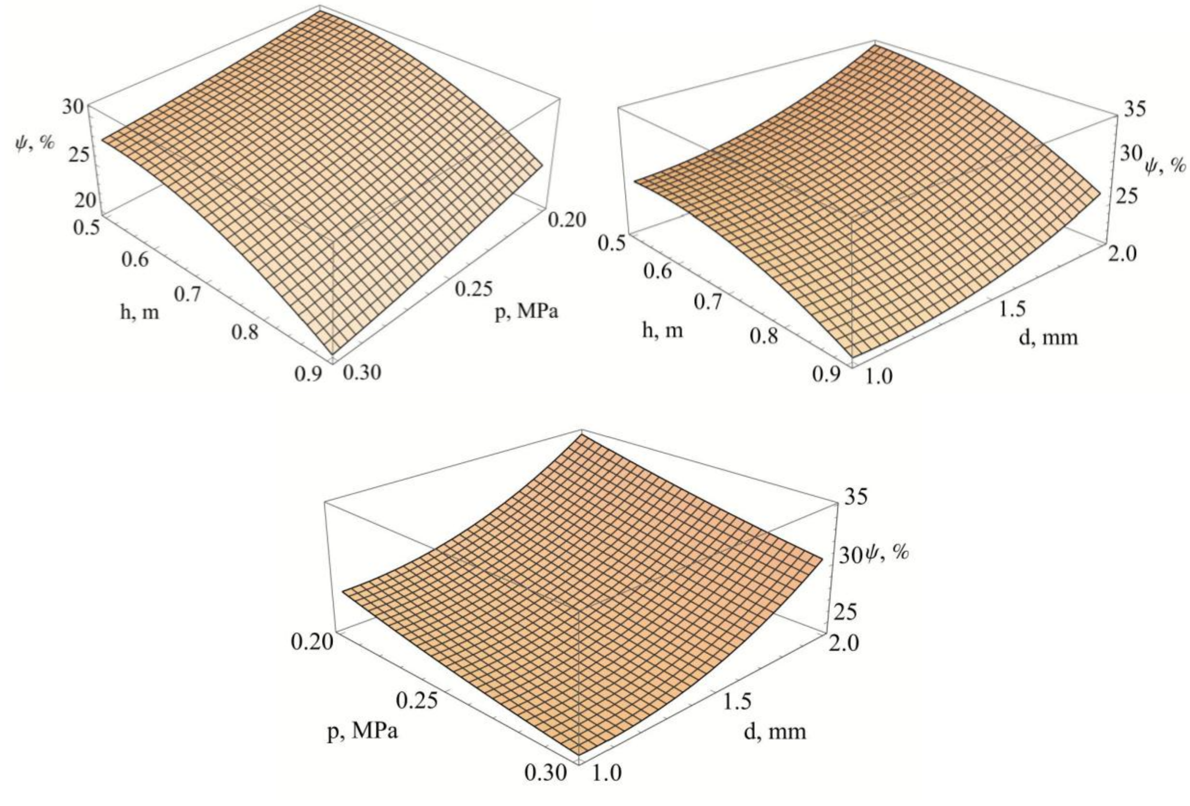

Fig. 3. Dependence of the coefficient of variation of the transverse liquid distribution ψ on pressure p, boom height h and throttle diameter d for the RD.05.SD5-b nozzle

The regression equations in the decoded form have the following structure:
– for the RD.05.SD5-b nozzle

$$\psi = 21,92 + 7,18 \cdot d^2 - 47,98 \cdot h^2 + 67,11 \cdot h - 30,83 \cdot p \cdot h - -7,07 \cdot d - 6,83 \cdot h \cdot d - 11,66 \cdot p \cdot d - 54,36 \cdot p + 108,88 \cdot p^2 \quad (1)$$

– for the combined nozzle

$$\psi = 56,77 + 8,91 \cdot d^2 - 33,02 \cdot h^2 + 42,79 \cdot h - 59,9 \cdot p \cdot h - -14,65 \cdot d - 6,75 \cdot h \cdot d - 5,9 \cdot p \cdot d - 191,3 \cdot p + 401,6 \cdot p^2 \quad (2)$$

For a clearer visualization and deeper interpretation of the experimental results, a series of response surface plots was constructed, as shown in Fig. 3, 4. These graphical models provide a comprehensive representation of how the primary operational and structural factors – namely, the working pressure (*p*), the height of the boom above the target surface (*h*), and the diameter of the throttle orifice (*d*) – influence the uniformity of liquid distribution, expressed through the coefficient of variation (ψ).

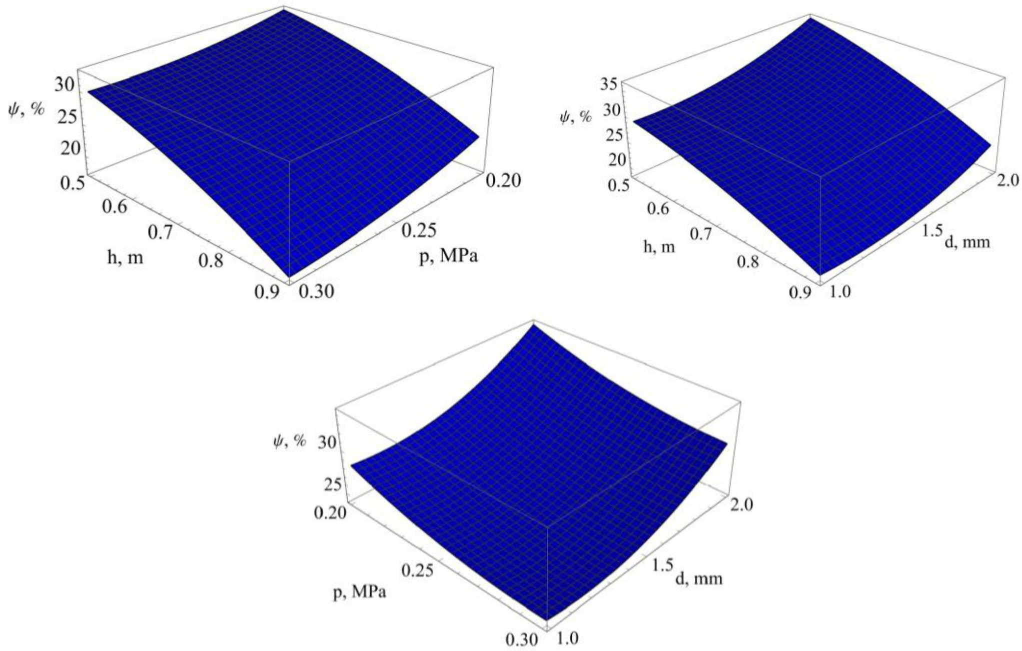

Fig. 3. Dependence of the coefficient of variation of the transverse liquid distribution ψ on pressure p, boom height h and throttle diameter d for the combine type nozzle

The response surfaces clearly demonstrate that all factors involved in the experimental study are statistically significant for both the baseline RD.05.SD5-b nozzle and the combined nozzle design. The optimization parameter – the coefficient of variation ($\psi \to 0$), which characterizes the uniformity of liquid distribution over the surface – decreases in a favorable direction, indicating an improvement in application quality.

The study revealed the following patterns of factor influence. Increasing the boom height ($h \to 0,9$) leads to a reduction in the coefficient of variation due to decreased excessive overlap between adjacent spray patterns and the formation of a more stable coverage profile. An increase in operating pressure ($p \to 0,3$) produces a similar positive effect: by reducing the average droplet size and increasing spray density, a more uniform liquid application is achieved.

At the same time, decreasing the diameter of the adjustable orifice ($d \to 0,1$) also contributes to lowering the coefficient of variation. This is associated with the formation of finer droplets that provide more homogeneous surface coverage.

The minimum values of the coefficient of variation were achieved under the following combinations of the studied factors:

- for the RD.05.SD5-b nozzle, the lowest CV value of 18.9% was obtained at the optimal operating parameters, namely: working pressure of *p* = 0,3 MPa, boom height of *h* = 0,9 m, and throttle orifice diameter of *d* = 1,16 mm. Under these conditions, the spray pattern formed by the nozzle demonstrated the highest degree of distribution uniformity, indicating stable jet formation and balanced overlap between adjacent spray streams.

For the combined nozzle, an even lower CV value of 16.8% was recorded when operating at a working pressure of p = 0,3 MPa, a boom height of h = 0,9 m, and a throttle orifice diameter of d = 1,2 mm. This result reflects the advantages of the improved internal geometry and the use of interchangeable throttles, which ensure more controlled liquid flow and enhanced redistribution across the working width.

5. Conclusion

The conducted experimental studies have confirmed the significant influence of operating pressure, boom height, and throttle orifice diameter on the uniformity of transverse liquid distribution when applying liquid mineral fertilizers using stream-type jet nozzles. The obtained regression models for both the RD.05.SD5-b nozzle and the combined nozzle design were found to be statistically adequate and reliably describe the relationship between the selected factors and the coefficient of variation of liquid distribution. The response surface analysis demonstrated that increasing the boom height and operating pressure, as well as reducing the throttle diameter, contributes to a decrease in the coefficient of variation, thereby improving the uniformity of application. The minimum CV values – 18.9% for the RD.05.SD5-b nozzle and 16.8% for the combined nozzle – were achieved under specific optimal combinations of pressure, height, and throttle diameter, confirming the efficiency of the proposed design and operational improvements.

The results substantiate the practical importance of optimizing jet nozzle parameters to enhance the precision and economic effectiveness of liquid fertilizer application systems. The developed mathematical models can be used to guide the selection of operating modes for sprayers applying mineral fertilizer solutions and serve as a basis for further engineering improvements to nozzle geometry and hydraulic characteristics.

Prospects for further research include expanding the scope of experimental studies to real field conditions in order to validate laboratory findings under variable agronomic environments. Additional attention should be given to evaluating the influence of mineral fertilizer physicochemical properties, temperature fluctuations, and dynamic boom behavior on distribution uniformity. Further development of combined nozzle designs, including modifications to internal flow channels and multi-jet configurations, may contribute to additional improvements in spray pattern stability and overall application efficiency.

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РЕЗУЛЬТАТИ ЕКСПЕРИМЕНТАЛЬНИХ ДОСЛІДЖЕНЬ СТРУМЕНЕВИХ РОЗБРИЗКУВАЧІВ ДЛЯ ВНЕСЕННЯ РІДКИХ МІНЕРАЛЬНИХ ДОБРИВ

Ефективність внесення рідких мінеральних добрив значною мірою визначається рівномірністю їх поперечного розподілу, що залежить від конструктивних та режимних параметрів струменевих розбризкувачів. У роботі наведено результати комплексних експериментальних досліджень впливу робочого тиску, висоти штанги та діаметру отвору змінного дроселя на коефіцієнт варіації (CV) розподілу рідини під час внесення розчинів мінеральних добрив. Випробування проводилися на гідравлічному стенді з використанням розпилювачів RD.05.SD5-b та комбінованого з змінними дроселями. За методом Бокса-Бенкена побудовано статистично значущі регресійні моделі другого порядку, адекватність яких підтверджено критерієм Фішера. Аналіз поверхонь відгуку показав, що підвищення тиску та висоти штанги, а також зменшення діаметра дросельного отвору забезпечують зменшення коефіцієнта варіації та покращують рівномірність розподілу рідини. Мінімальні значення CV – 18,9% для RD.05.SD5-b та 16,8% для комбінованого розбризкувача – досягатимуться за оптимальних комбінацій досліджуваних факторів. Отримані результати підтверджують практичну значущість оптимізації геометрії розпилювачів і точного налаштування режимів роботи для підвищення ефективності внесення добрив та зниження екологічних ризиків. Розроблені моделі можуть бути використані для інженерних розрахунків, калібрування обприскувачів та подальшого вдосконалення конструкцій струменевих розбризкувачів. Перспективами досліджень є перевірка результатів у польових умовах і оцінювання впливу фізико-хімічних властивостей мінеральних, температурних коливань та динаміки штанги на якість розподілу. Ці результати формують наукову основу для розробки адаптивних систем керування для точного внесення добрив у сучасних сільськогосподарських технологіях.

Ключові слова: *рідкі мінеральні добрива, КАС, струменевий розбризкувач, коефіцієнт варіації, гідравлічний обприскувач, тиск, висота штанги, діаметр дроселя, рівномірність розподілу, оптимізація параметрів.*

Ф. 2. Рис. 3. Табл. 1. Літ. 16.

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