THEORETICAL AND EXPERIMENTAL FOUNDATIONS FOR RESOURCE-EFFICIENT OPTIMIZATION OF SPRINKLER IRRIGATION USING A LOW-PRESSURE DEFLECTOR NOZZLE UNDER ARID CLIMATE CONDITIONS

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ABSTRACT. This study presents the theoretical and experimental foundations for the resource-efficient optimization of sprinkler irrigation using a low-pressure deflector nozzle under arid climate conditions. Particular attention is given to water droplet motion, droplet formation mechanisms, and evaporation losses, considering aerodynamic drag and the influence of external environmental factors.

Water droplet motion was described using differential equations based on Newton’s second law, while droplet diameter was evaluated as a function of outlet velocity, nozzle orifice diameter, surface tension, and fluid density. Evaporation and wind drift losses were analyzed as functions of air temperature, relative humidity, wind velocity, and droplet size, allowing assessment of their combined impact on irrigation efficiency.

Theoretical predictions were validated through laboratory and laboratory–field experiments. The results confirmed stable water discharge within the low-pressure operating range and the formation of aerodynamically stable droplets with diameters of 1.0–1.4 mm. This droplet size range was identified as optimal for limiting evaporation and wind drift losses, with the relative reduction in evaporation exceeding 50% under optimal operating conditions. Irrigation uniformity was evaluated using the Christiansen coefficient, which reached high values, demonstrating compliance with agrotechnical requirements.

Overall, the obtained results indicate that the proposed low-pressure deflector sprinkler nozzle provides an effective water- and energy-efficient solution for reducing evaporation losses and improving the performance of sprinkler irrigation systems operating in arid and semi-arid regions.

Keywords: low-pressure sprinkler irrigation; deflector nozzle; water droplets; evaporation losses; wind drift; irrigation uniformity; Christiansen coefficient; arid climate; resource-efficient irrigation.

1. INTRODUCTION.

The limited availability of water resources and the expansion of arid climate regions necessitate the development of resource-efficient irrigation technologies in agriculture. According to international studies, the largest share of global water consumption is attributed to agriculture, and improving irrigation efficiency in arid and semi-arid regions plays a decisive role in mitigating water scarcity [1,2].

In conventional high-pressure sprinkler irrigation systems, excessive fragmentation of the droplet spectrum leads to increased wind drift and evaporation losses, resulting in a significant reduction in irrigation efficiency [3,4]. In addition, high operating pressures increase the energy consumption of pumping units and raise the operational costs of irrigation systems. Previous studies indicate that low-pressure sprinkler irrigation systems provide greater potential for stabilizing droplet diameter and achieving a more uniform distribution of water over the field surface [5].

In recent years, low-pressure sprinkler irrigation devices based on deflector nozzles have been widely investigated due to their ability to reduce wind drift and evaporation losses while lowering energy consumption. In such nozzles, the water flow is redistributed over the deflector surface, forming relatively large and aerodynamically stable droplets, which leads to a reduction in wind-induced drift and evaporation losses [6]. However, most existing studies focus primarily on experimental investigations, while comprehensive theoretical and experimental justification of droplet motion, environmental effects, and hydraulic characteristics remains insufficiently addressed.

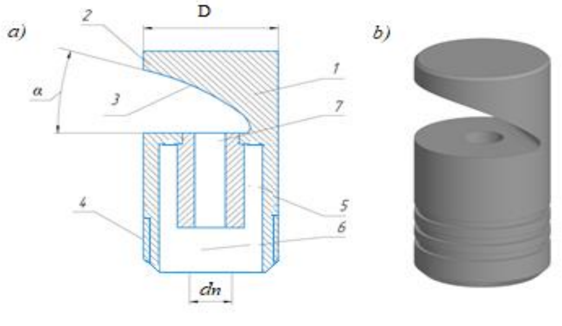
In the authors’ previous works, the trajectory of water droplets and the influence of environmental factors on the sprinkler irrigation process were theoretically analyzed [7,8], and several structural solutions for deflector nozzles were investigated [9]. The present study represents a logical continuation of these works and aims to provide a comprehensive evaluation of the operating process of a low-pressure deflector sprinkler nozzle under arid climate conditions using a resource-efficient approach.

The objective of this study is to develop a theoretical model of a low-pressure deflector sprinkler nozzle that accounts for droplet motion, droplet formation, and evaporation losses, and to validate the model using laboratory and field experimental results. The findings of this study are of practical importance for improving sprinkler irrigation systems designed for efficient water and energy use under arid climate conditions.

2. MATERIALS AND METHODS

2.1. Design and Operating Principle of the Device.

The proposed low-pressure deflector sprinkler nozzle is designed to generate stable and aerodynamically relatively large droplets by redistributing the water flow over the deflector surface. The device is equipped with a replaceable regulating orifice nozzle, which allows control of water discharge, outlet velocity, and droplet spectrum through technological parameters (Figure 1).

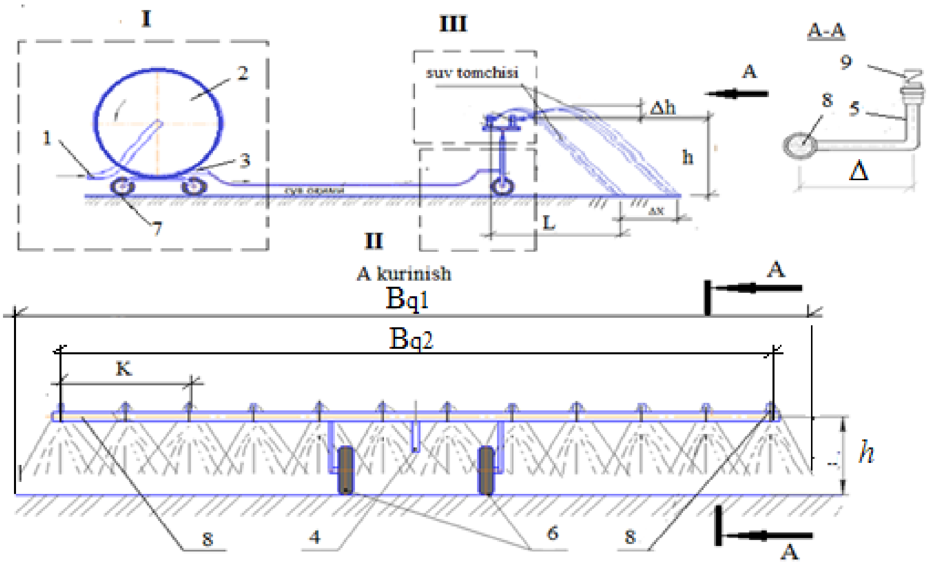


1 — base; 2 — deflector; 3 — screened flow reflector; 4 — connecting section; 5 — central channel; 6 — converging section (confuser); 7 — orifice nozzle.

Figure 1. General view of a low-pressure deflector nozzle equipped with a replaceable regulating orifice nozzle.

The main structural components of the nozzle include the housing, deflector, screened flow reflector, central channel, converging section, and orifice nozzle. The experimental prototype was equipped with deflectors having different inclination angles and interchangeable orifice nozzles with variable diameters, which enabled a comprehensive assessment of the influence of flow parameters.

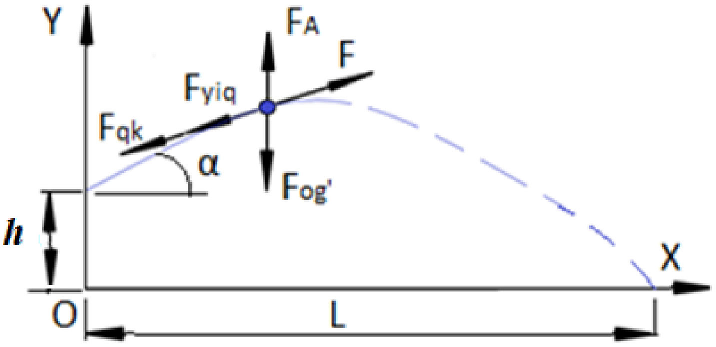
The device operates as part of a drum–hose sprinkler irrigation system. The irrigation process is carried out under low operating pressure, which reduces the energy consumption of pumping units and ensures stable droplet distribution (Figure 2).



1 — water supply pipeline; 2 — drum; 3 — hose retraction mechanism; 4 — flexible hose; 5 — outlet pipeline; 6 — sprinkler unit wheel; 7 — drive unit chassis; 8 — sprinkler boom; 9 — sprinkler nozzle**.**

Figure 2. Technological scheme of a low-pressure sprinkler irrigation system operating over the field surface.

2.2. Theoretical Background and Water Droplet Motion Model. During the sprinkler irrigation process, the motion of a water droplet is primarily governed by the combined action of gravitational force and aerodynamic drag. The flight distance and trajectory of the droplet are determined by the irrigation height, initial outlet velocity, droplet diameter, and ambient environmental conditions (Figure 3).



h — irrigation height; L — flight distance of the water droplet.

Figure 3. Main forces acting on a water droplet during the sprinkler irrigation process.

The motion of a water droplet in the Cartesian coordinate system is described by the following differential equations [10,11]:

$$m\frac{d^2x}{dt^2} = -F_d cos\theta, \qquad (1)$$

$$m\frac{d^2y}{dt^2} = -mg - F_d sin\theta, \qquad (2)$$

where **m** — mass of the water droplet; **g** — acceleration due to gravity; **θ** — direction angle of the droplet velocity. The aerodynamic drag force is determined by the following expression:

$$F_d = \frac{1}{2} C_d \ \rho_a \, \mathrm{A} \, \vartheta_d^2 \ , \qquad (3)$$

where C_d — aerodynamic drag coefficient; ρ_a — air density; A — projected cross-sectional area of the droplet; ϑ_d — droplet velocity.

Based on this model, it was established that the flight distance of a water droplet depends on the initial outlet velocity ϑ_0, the droplet diameter, and the sprinkler height. The calculated results were subsequently compared with the data obtained from laboratory and laboratory–field experiments.

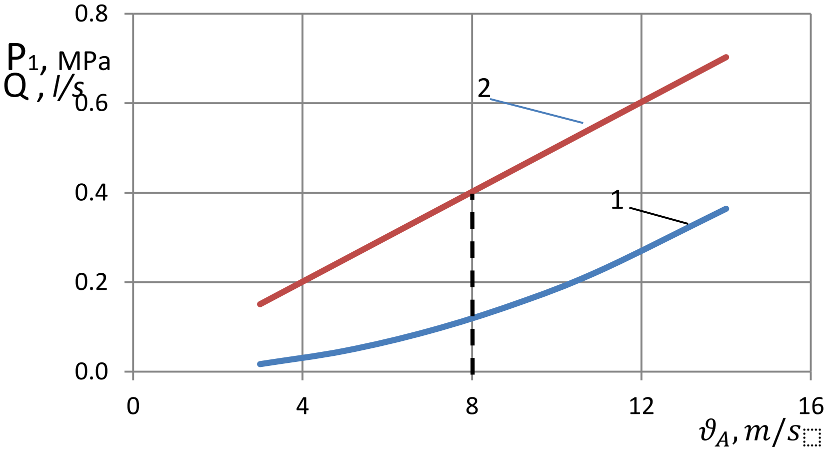
2.3. Hydraulic model of the deflector nozzle. In the deflector nozzle, the water flow rate varies depending on the diameter of the perforated nozzle and the inlet pressure. The water discharge from the nozzle was evaluated using the following expression:

$$Q = \mu A_n \sqrt{2gH}, \qquad (4)$$

where A_n— cross-sectional area of the perforated nozzle; **H** — inlet pressure head; **μ** — discharge coefficient.
The outlet velocity of the water flow was determined using the following expression:

$$\vartheta_0 = \frac{Q}{A_n}. \qquad (5)$$

These relationships were used to evaluate the stable variation characteristics of the water flow rate and outlet velocity in the low-pressure operating range (Figure 4).



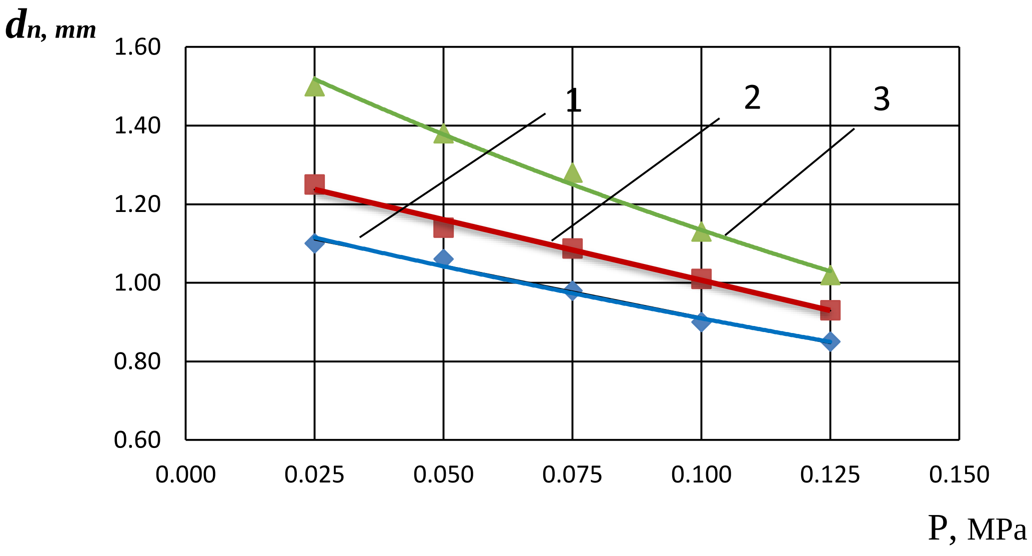
1 — dependence of water flow velocity in the deflector nozzle on the pipeline pressure; 2 — dependence of water flow velocity in the deflector nozzle on the water flow rate.

Figure 4. Dependence of the water flow velocity in the deflector nozzle on pressure and water flow rate.

2.4. Droplet formation. As a result of the breakup of the water flow on the deflector surface, the size of the generated droplets mainly depends on the outlet velocity and the diameter of the perforated nozzle. The droplet diameter was expressed by the following general functional relationship [12]:

$$d_s = f(\vartheta_0, d_n, \sigma, \rho), \qquad (6)$$

where ϑ_0 — flow velocity; d_n — diameter of the perforated nozzle; **σ** — surface tension***; ρ*** — liquid density.
In this study, the parameter **D** was considered as a structural external dimension of the nozzle and was not regarded as a factor directly influencing the droplet formation process. The theoretical values of the droplet diameter were evaluated as functions of the perforated nozzle diameter d_n and the outlet velocity (Figure 5).



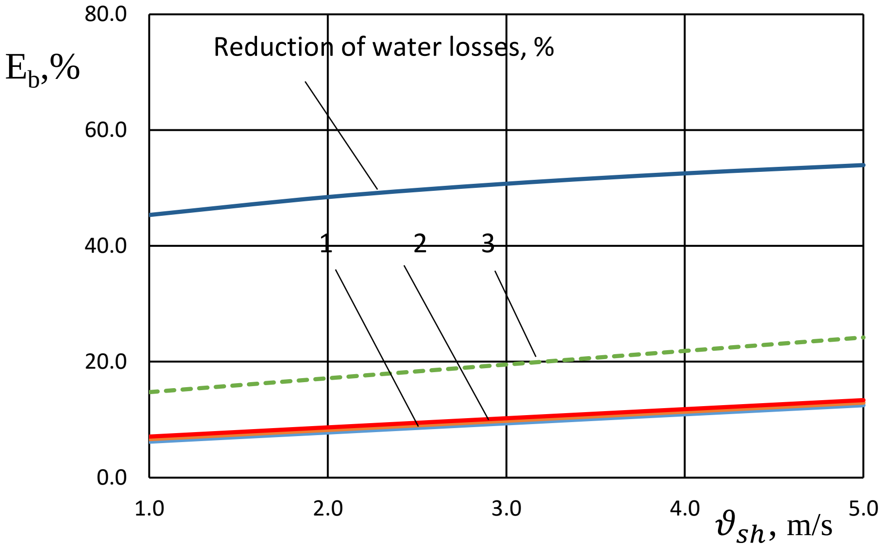
1-d_n = 4 mm; 2-d_n = 6 mm; 3-d_n = 8 mm

Figure 5. Dependence of the diameter of water droplets formed in the deflector nozzle on the water pressure in the nozzle tube.

2.5. Evaluation of droplet evaporation. During the flight of a water droplet, evaporation depends on the parameters of the surrounding environment, primarily air temperature ***t***, relative humidity W, wind velocity ϑ_{sh}, and droplet diameter ϑ_{sh}. Droplet evaporation and wind-induced losses were evaluated using the following functional relationship [13–16]:

$$E_b = f(t, W, \vartheta_{sh}, d_s). \qquad (7)$$

This relationship was used to assess the possibility of reducing evaporation and wind-induced losses by optimally selecting the droplet size and outlet operating regime of the deflector nozzle.

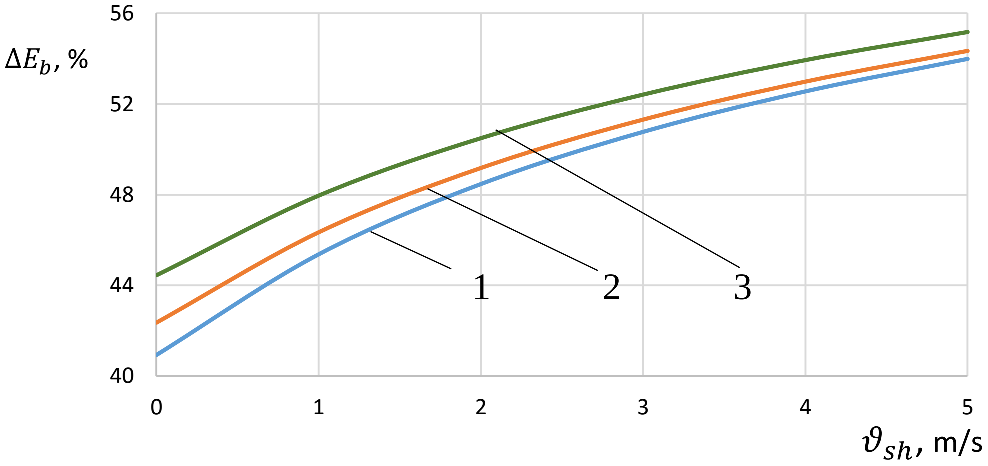


1-ϑ_0 =6 m/s, *h*=0,7 m; 2- ϑ_0 =8 m/s, *h*=0,7 m; 3- ϑ_0 =12 m/s, *h*=0,7 m;

Figure 6. Dependence of water droplet evaporation losses on wind velocity

According to the calculation results, an increase in wind velocity leads to a significant rise in droplet evaporation losses (Figure 6). However, for relatively large droplets formed by the low-pressure deflector nozzle (d_s **≥ 1.0 mm**), evaporation losses remain within a limited range.

By optimally selecting the outlet operating regime and structural parameters, including the outlet velocity (ϑ_0), the diameter of the perforated nozzle (d_n) and the deflector inclination angle (**α**), evaporation and wind-induced losses can be further reduced (Figure 7). This confirms that the deflector nozzle enables water application under a resource-efficient operating mode in arid climate conditions.



1-ϑ_0= 3 m/s; 2-ϑ_0=5 m/s; 3-ϑ_0= 8 m/s

Figure 7. Reduction of water droplet evaporation under different technological and structural parameters.

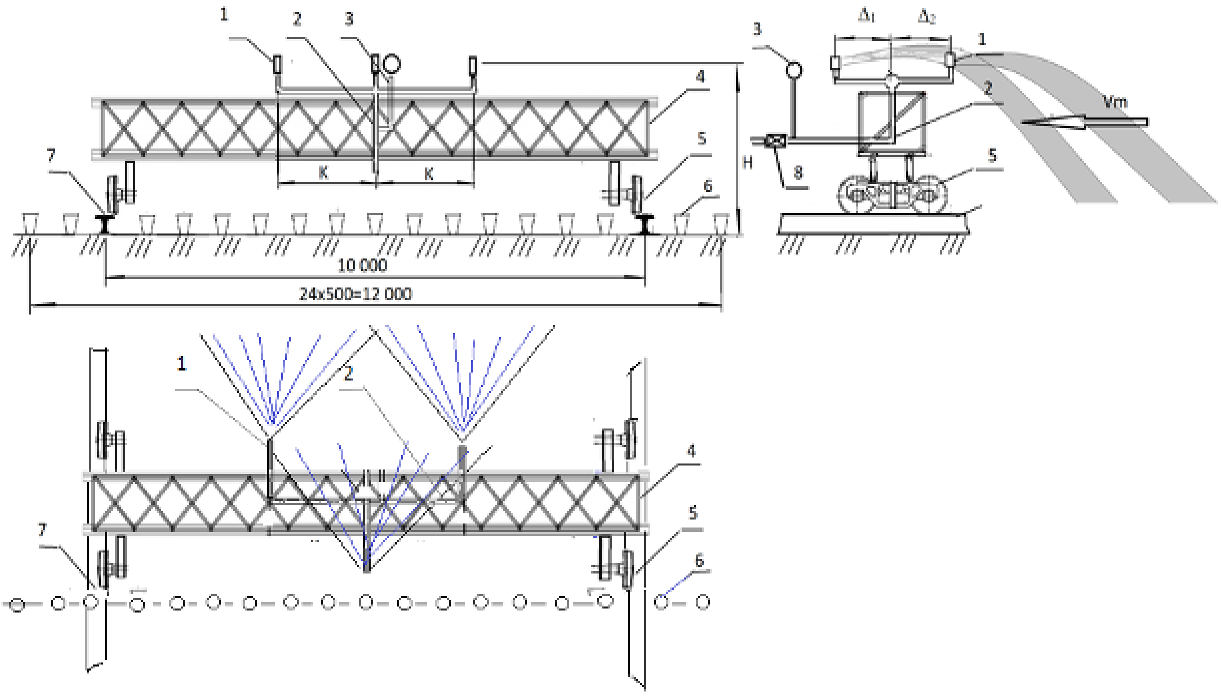
The theoretical calculation results of the main hydraulic and droplet parameters of the deflector nozzle are presented in **Table 1**.

Table 1. Theoretically calculated hydraulic and droplet parameters of the deflector nozzle.

Calculation conditions: P=0.12 MPa; ϑ_0 =8 m/s; ϑ_m=0.02 m/s; h=0.70 m; α=25°

No.	Perforated nozzle diameter dn, mm	Flow thickness on deflector δ, mm	Water flow rate Q, L/s	Average sprinkler intensity Iavg, mm/min	Maximum flight distance Lmax, m	Theoretical droplet diameter d_s, mm
1	4	< 1.68	0.43	0.62	4.6	1.4–1.6
2	6	< 1.32	0.43	0.64	4.8	1.2–1.4
3	8	< 1.19	0.43	0.65	5.0	1.0–1.2

2.6. Experimental setup and measurement methods. Laboratory and laboratory–field experiments were conducted using a specialized experimental test stand as well as a full-scale reel–hose sprinkler irrigation machine (Figure 8). During the experiments, the operating pressure, the diameter of the perforated nozzle, and the deflector inclination angle were systematically varied.



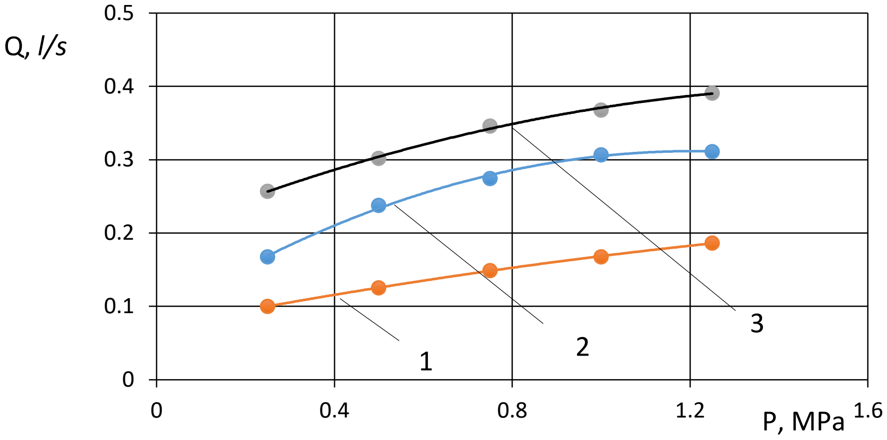
1 — sprinkler nozzle; 2 — water supply pipe; 3 — pressure gauge; 4 — test stand trolley; 5 — trolley wheel; 6 — rain gauges; 7 — rails.

Figure 8. Laboratory–field test stand designed for testing a moving sprinkler irrigation system.

Irrigation uniformity was evaluated using the Christiansen coefficient. The spatial distribution of water droplets was determined using rain gauges, and the water depth distribution curve (epure) and frequency distribution were constructed [17,18].

3. RESULTS

3.1. Dependence of water flow rate on operating pressure. Based on the theoretical hydraulic model, the dependence of the water flow rate on the operating pressure of the deflector nozzle was analyzed. The calculation results showed that the water flow rate exhibits a stable increasing trend within the low-pressure range (P = 0.04–0.12 MPa) (Figure 9).



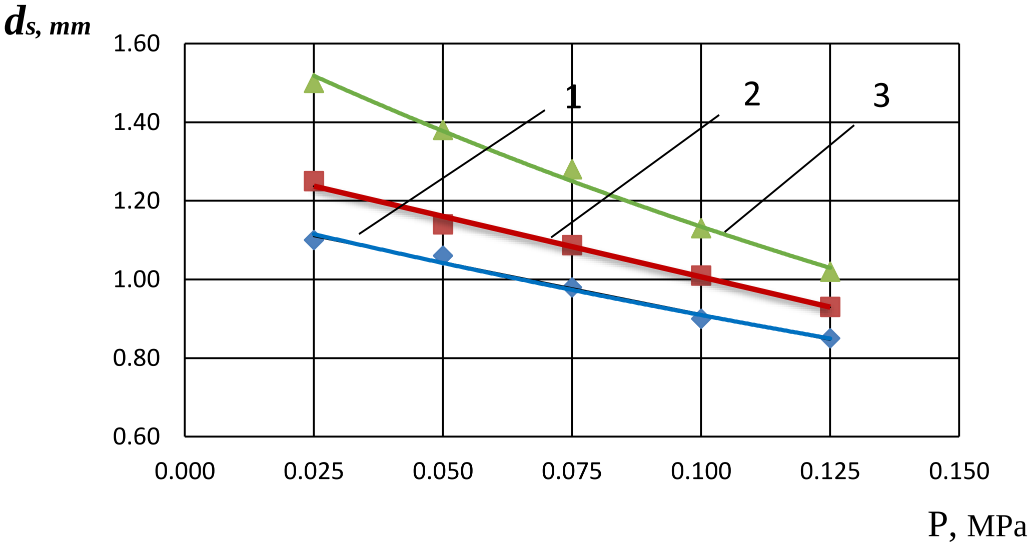
1-d_n = 4 mm; 2-d_n = 6 mm; 3-d_n = 8 mm

$t = 41{,}9^oC, \quad W = 19\%, \quad \alpha = 25^0$

Figure 9. Dependence of the water flow rate on the operating pressure of the deflector nozzle.

It was found that even with changes in the diameter of the perforated nozzle, the overall water flow rate remains relatively stable without abrupt variations. This indicates that the deflector geometry and outlet operating regime ensure a stable redistribution of the water flow. The obtained results confirm that the low-pressure deflector nozzle operates under an energy-efficient regime.

3.2. Dependence of droplet diameter on operating pressure. Based on the theoretical droplet formation model, the dependence of the water droplet diameter on the operating pressure was evaluated. According to the calculation results, an increase in operating pressure leads to an increase in the outlet velocity, accompanied by a decreasing trend in droplet diameter (Figure 10).



1-d_n = 4 mm; 2-d_n = 6 mm; 3-d_n = 8 mm

Figure 10. Dependence of the diameter of water droplets formed in the deflector nozzle on the operating pressure.

The majority of the droplet diameters were formed within the range of 1.0–1.4 mm, which was identified as optimal for ensuring aerodynamic stability of the droplets and limiting wind drift and evaporation losses. The results indicate that the droplet diameter is primarily governed by the perforated nozzle diameter d_n and the outlet velocity ϑ_0.

The majority of the droplet diameters were formed within the range of 1.0–1.4 mm, which was identified as optimal for ensuring aerodynamic stability and limiting wind drift and evaporation losses. The obtained results indicate that the droplet diameter is mainly determined by the diameter of the perforated nozzle and the outlet velocity.

The analysis shows that evaporation losses of water droplets increase significantly with increasing wind velocity. According to the data presented in Figure 6, when the wind velocity ϑ_{sh} increases from 1 to 5 m/s, evaporation losses range from 6–12% under low operating conditions, 15–23% under medium operating conditions, and 45–55%

under high-intensity operating conditions. This behavior is explained by the intensification of convective mass transfer under stronger wind conditions.

The results shown in Figure 7 indicate that, with optimal selection of the deflector nozzle parameters, evaporation losses can be substantially reduced. At a wind velocity of ϑ_{sh}=5 m/s, the relative reduction in evaporation losses ΔE_b reaches 53–56%, whereas at near-zero wind conditions this value is approximately 41–44%.

3.3. Comparison of theoretical and experimental results. The results of laboratory and laboratory–field experiments were compared with the theoretical calculations. The experimentally measured water flow rate and average sprinkler intensity were close to the theoretically predicted values, with the differences remaining within the limits of measurement accuracy and the influence of external environmental factors.

The main hydraulic and droplet parameters determined through theoretical calculations are presented in Table 1. According to the experimental results, the majority of droplet diameters were recorded within the range of 1.0–1.1 mm, which confirms that the developed theoretical model adequately describes the droplet formation process.

3.4. Irrigation uniformity and field results. Based on the field test results, the distribution of water droplets over the field surface was analyzed. The water depth distribution curve (epure) and frequency distribution demonstrated a high degree of irrigation uniformity (Figure 11).

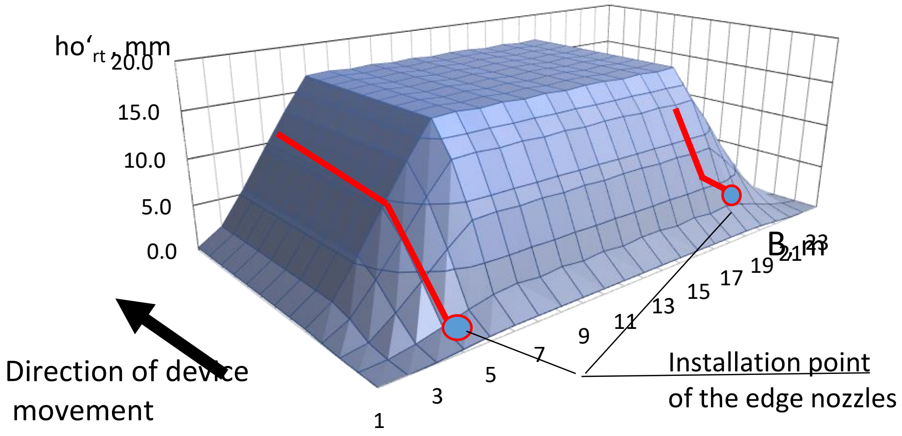


Figure 11. Water depth distribution curve produced by the device in a single pass.

The irrigation uniformity coefficient calculated using the Christiansen method was CU = 97.6%. This value exceeds agrotechnical requirements and confirms that the deflector nozzle is capable of providing high irrigation quality even under low-pressure operating conditions.

3.5. General assessment of the results. The obtained results indicate that the low-pressure deflector sprinkler nozzle is capable of stable control of the water flow rate, formation of droplet diameters within an optimal range, and ensuring high irrigation uniformity. The agreement between the theoretical calculations and experimental tests confirms the reliability of the developed model.

4. DISCUSSION

4.1. Agreement between theoretical and experimental results. The obtained results confirm the adequacy of the theoretical model developed for the deflector sprinkler nozzle. A good agreement was observed between the theoretical predictions and experimental data regarding the dependence of water flow rate on operating pressure as well as the decreasing trend of droplet diameter with increasing pressure. This indicates that the mechanism of stable redistribution of the water flow over the deflector surface in the low-pressure nozzle has been correctly modeled.

The droplet diameter range of 1.0–1.4 mm identified in the theoretical analysis was confirmed by experimental results. This range is considered optimal for ensuring aerodynamic stability of droplets and limiting wind drift and evaporation losses. In addition, this range was found to be suitable for maintaining irrigation quality and meeting current agro technical requirements.

The obtained results demonstrate that relatively large droplets formed by the low-pressure deflector nozzle ($d_s \geq 1.0$ mm) play a key role in limiting evaporation losses. Due to the reduced surface-to-volume ratio of larger droplets, evaporation intensity decreases, and even at wind velocities up to 5 m/s, evaporation losses remain within acceptable limits.

Furthermore, the results confirm that evaporation losses can be reduced by more than 50% through optimization of the outlet velocity, nozzle diameter, and deflector inclination angle. This confirms that the low-pressure deflector sprinkler system provides a resource-efficient and effective solution for irrigation under arid climate conditions.

4.2. Technological advantages of low-pressure operation. The study results demonstrate that operation of the deflector nozzle at low working pressures (0.04–0.12 MPa) provides several technological advantages. In particular, the stability of the water flow rate reduces the energy load on pumping units and increases the overall energy efficiency of the irrigation system.

Compared with conventional high-pressure sprinkler devices, excessive droplet atomization is not observed in low-pressure deflector nozzles. This is a decisive factor in limiting evaporation and wind drift losses under arid climate conditions. As a result, water use efficiency is improved and the stability of the irrigation process is ensured.

4.3. Irrigation uniformity and practical significance. The high irrigation uniformity coefficient recorded during field tests (CU = 97.6%) indicates that the deflector nozzle is ready for practical application. The water depth distribution curve and frequency distribution confirm that a large proportion of the irrigated area is effectively watered.

These results demonstrate that integration of the deflector nozzle into reel–hose sprinkler irrigation machines allows modernization of existing irrigation systems without major capital reconstruction. This technical solution is of particular practical importance for regions with limited water resources and arid climatic conditions.

5. CONCLUSION.

The present study developed and validated a theoretical model describing water droplet motion, droplet formation, and hydraulic processes in a low-pressure deflector sprinkler nozzle. The model enabled quantitative evaluation of the relationships between water flow rate, droplet diameter, flight distance, and the key structural and technological parameters of the nozzle.

Theoretical calculations and experimental investigations confirmed stable water discharge within the low-pressure operating range and the formation of droplets with diameters of 1.0–1.4 mm. This droplet size range was identified as optimal for limiting evaporation and wind drift losses under arid climate conditions. Depending on wind velocity and operating regime, the relative reduction in evaporation losses exceeded 50%, demonstrating the effectiveness of droplet size stabilization achieved by the deflector nozzle.

Field experiments demonstrated a high level of irrigation uniformity that fully satisfies agrotechnical requirements. Overall, the obtained results indicate that the proposed low-pressure deflector sprinkler system provides a water- and energy-efficient, stable, and practically applicable solution for sprinkler irrigation under arid and semi-arid climate conditions.

REFERENCES

1. FAO. *Water for Sustainable Food and Agriculture.* Food and Agriculture Organization of the United Nations, Rome, Italy, 2017.
2. Dukhovny, V.A., Sokolov, V.I. Water management in Central Asia under conditions of climate change. *Water Resources Management*, 2018, 32, pp. 331–344. https://doi.org/10.1007/s11269-017-1842-5
3. Playán, E., Mateos, L. Modernization and optimization of irrigation systems to increase water productivity. *Agricultural Water Management*, 2006, 80(1–3), pp. 100–116. https://doi.org/10.1016/j.agwat.2005.07.007
4. Tarjuelo, J.M., Ortega, J.F., Montero, J., de Juan, J.A. Uniformity and efficiency of sprinkler irrigation in semi-arid areas. *Irrigation Science*, 2015, 33, pp. 23–38. https://doi.org/10.1007/s00271-014-0445-6

5. DeBoer, D.W., Monnens, M.J. Low-pressure sprinkler irrigation systems: design and performance. *Applied Engineering in Agriculture*, 2001, 17(3), pp. 343–348. https://doi.org/10.13031/2013.6467
6. Salvador, R., Martínez-Cob, A. Evaporation and wind drift losses in sprinkler irrigation systems. *Agricultural Water Management*, 2013, 120, pp. 37–47. https://doi.org/10.1016/j.agwat.2012.12.015
7. Khudayarov, Z.J., Khalilov, R., Gorlova, I., Mirzakhodjaev, Sh., Mambetsheripova, A. Mathematical model of water drop trajectory in artificial rainfall. In: *Proceedings of the IV International Scientific Conference “Construction Mechanics, Hydraulics and Water Resources Engineering”*, Tashkent, Uzbekistan, 2022, Vol. 365, Article No. 04011. https://doi.org/10.1051/e3sconf/202236504011
8. Khudayarov, Z.J., Khalilov, R., Mirzakhodjaev, Sh., Nurmukhamedov, B., Mamasov, Sh. Theoretical study of the influence of the changing environment on the rainfall irrigation process. In: *Proceedings of the International Scientific and Practical Conference “Environmental Risks and Safety in Mechanical Engineering”*, Rostov-on-Don, Russia, 2023, Vol. 376, Article No. 02013. https://doi.org/10.1051/e3sconf/202337602013
9. Khudayarov, Z.J., Mirzakhodjaev, Sh., Khalilov, R., Nurmukhamedov, B., Mamasov, Sh. Deflector nozzles of rain irrigation machines. In: *Proceedings of the VIII International Conference on Advanced Agritechnologies, Environmental Engineering and Sustainable Development*, Krasnoyarsk, Russia, 2023, Vol. 390, Article No. 01033. https://doi.org/10.1051/e3sconf/202339001033
10. Çengel, Y.A., Cimbala, J.M. *Fluid Mechanics: Fundamentals and Applications.* 3rd ed., McGraw-Hill Education, New York, USA, 2018, 1024 p. (Chapter: External Flow over Spheres and Cylinders).
11. Crowe, C.T., Sommerfeld, M., Tsuji, Y. *Multiphase Flows with Droplets and Particles.* 2nd ed., CRC Press, Boca Raton, FL, USA, 2012, 544 p. https://doi.org/10.1201/b11255
12. Lefebvre, A.H., McDonell, V.G. *Atomization and Sprays.* 2nd ed., CRC Press, Boca Raton, FL, USA, 2017, 365 p. https://doi.org/10.1201/9781315120911
13. Playán, E., Salvador, R., Faci, J.M., Zapata, N. Day and night wind drift and evaporation losses in sprinkler irrigation. *Agricultural Water Management*, 2005, 76(3), pp. 139–159.
14. Allen, R.G., Pereira, L.S., Raes, D., Smith, M. *Crop Evapotranspiration.* FAO Irrigation and Drainage Paper No. 56, FAO, Rome, Italy, 1998.
15. Ranz, W.E., Marshall, W.R. Evaporation from drops. *Chemical Engineering Progress*, 1952, 48(3), pp. 141–146.
16. Christiansen, J.E. Irrigation by sprinkling. *University of California Agricultural Experiment Station Bulletin*, 1942, No. 670.
17. Merriam, J.L., Keller, J. *Farm Irrigation System Evaluation.* Utah State University, Logan, USA, 1978.