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THE STUDIES OF WATER FLOW CHARACTERISTICS IN THE WATER CONDUCTING BELT OF WIDE-COVERAGE SPRINKLING MACHINES

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ABSTRACT
The optimization of sprinkler water pipe parameters allows to reduce the metal consumption and machine cost, save water resources and electricity significantly. The aim of the research is to develop a scientifically grounded method for the hydraulic calculation of the water-conducting belt of wide-coverage sprinklers, which allows to determine its optimal parameters and justify the arrangement of sprinkling devices. The theoretical studies of water movement with a variable flow rate along a pipeline length made it possible to obtain the dependencies describing flow characteristics, pressure losses and flow changes taking into account the discreteness, i.e. the number of taps for sprinklers per unit of length. Experimental studies of discreteness parameter values make it possible to confirm the validity of the calculation technique application. Using the presented technique, the watering belt of the Kuban-LK1M sprinkling machine (CASCADE) was optimized, the nomenclature row of sprinkler devices was designed and introduced into production (Saratov, LLC "Meliorative machines" - FSEI HE SSAU named after N.I. Vavilov). The comparison of experimental study results with those calculated by the proposed method gives a good agreement and confirms the reliability of the obtained dependences.

Keywords: Water flow, wide-coverage, sprinkling machines

INTRODUCTION

In recent years, the task of new generation of sprinkling equipment introduction with higher technical and economic indicators, resource-saving irrigation technology and the production of machines, the reduction of material consumption and cost becomes more urgent.

A design improvement is directly related to the optimization of the machine water-supply belt, the precisely selected parameters of which will allow to reduce the material consumption and increase a sprinkler efficiency (Isaev A.P. 1973).

The optimization criteria for the water-conducting belt of the machine are the following ones: a pipeline diameter, the length and the diameter of pipeline sections with its variable cross-section, the distance between sprinklers and the cross-section area of a nozzle.

The motion of liquid with the change of mass along a path was first considered in the works by I. Hinds (1926) and H. Favre (1993). Subsequently, their theoretical studies were applied to the hydraulic calculation of irrigation pipes for drop irrigation in (Keller J., Karmeli D. 1975.;Keller J., Karmeli D. 1974;Keller J., Hanks R. 1972;Solomon K., Keller J. 1978;Bresler El. 1978;Greulich H., Kleinschroth A. 1977;Journal of the Irrigation and Drainage Division. 1975
). However, in all studies, during the determination of pressure losses along the length, the Hazen-Williams formula (Hazen A. & Williams G.S. 1920) was used, which gives significant errors in the calculations at a continuous fluid sampling.

2. METHODOLOGY OF RESEARCH

2.1 Theoretical studies of the processes in pipelines

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Let us consider the differential equation of liquid steady-state motion with variable mass in a constant-section pipeline with a sampling rate obtained by prof. I.M. Konovalov in his works (I.M. Konovalov. 1937):

$$\frac{1}{g}\int\frac{(1-a_1)V}{\omega}dQ_1-\frac{1}{g}\int\frac{(1-a_2)V}{\omega}dQ_2+\frac{V^2}{2g}+\frac{P}{\gamma}+z+h_f=c, \quad (1)$$

where: a_1 and a_2 are the coefficients of attachment and detachment of the fluid mass; V is the average flow velocity; Q_1 and Q_2 - the rate of connection and detachment, respectively; ω is the area of the flow live section; P is the hydrodynamic pressure; z is the specific potential energy of the position in the section under consideration; γ is the volumetric weight of liquid (water); h_f is the loss of flow specific energy due to the friction between the sections considered; g is the acceleration of gravity.

The coefficients of attachment and detachment are defined as follows:

$$a_1=V_1/V; \quad a_2=V_2/V, \quad (2\text{-}3)$$

where: V_1 and V_2 – are the projections to the axis of flow attachment and detachment rate.

The flow rate of liquid (water) in any arbitrary section of a sprinkler water-conducting belt is expressed by the following equation:

$$Q=Q_0+\int_0^x dQ_1-\int_0^x dQ_2, \quad (4)$$

where Q_0 and Q – the flow in the initial section and in an arbitrary section of the flow, respectively.

Having differentiated the equation and having transformed it, we get the following expression:

$$\frac{\alpha_0(1-a_1)Q}{g\omega^2}\frac{dQ_1}{dx}-\frac{\alpha_0(1-a_2)Q}{g\omega^2}\frac{dQ_2}{dx}+\frac{\alpha_0 Q}{g\omega}\frac{d}{dx}\left(\frac{Q}{\omega}\right)+\frac{d}{dx}\left(\frac{P}{\gamma}+z\right)+\frac{d}{dx}(h_f)=0, \quad (5)$$

Here $V=Q/\omega$. (6)

The amount of frictional losses during the movement of water at a variable flow rate can be determined from the following equation:

$$\frac{d}{dx}(h_f)=\frac{Q^2}{\omega^2C^2R} \quad (7)$$

Where C is Chezy coefficient; R is the hydraulic radius.

Since the differential equation will have the following form for the pipelines with a constant diameter and perforation ω =const and $K^2=\omega^2C^2R$:

$$\frac{\alpha_0(a_2-2)Q}{g\omega^2}\left(\frac{\partial Q_2}{\partial H}\frac{dH}{dx}+\frac{\partial Q_2}{\partial\omega_0''}\frac{d\omega_0''}{dx}\right)+\frac{dH}{dx}-i+\frac{Q^2}{K^2}=0 \quad (8)$$

where K is the expense characteristic.

The equation of the piezometric line:

$$\frac{dH}{dx}=\frac{i-\frac{Q^2}{K^2}-\frac{\alpha_0(a_2-2)Q}{g\omega^2}\frac{d\omega_0''}{dx}\frac{\partial Q_2}{\partial\omega_0''}}{1+\frac{\alpha_0(a_2-2)Q}{g\omega^2}\frac{\partial Q_2}{\partial H}}, \quad (9)$$

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In order to simplify the expression, we introduce the value A:

$$A = \frac{\alpha_0(a_2 - 2)}{g\omega^2} \tag{10}$$

The coefficient α_0 determines the ratio of the actual amount of movement of water mass to the amount of motion determined by average speed. According to the scholar G.A. Petrov (1964), the introduction of the coefficient α_0 in practical calculations is inexpedient because of its small deviation from unity.

For a uniform detachment rate, i.e. for the branch uniformly located along the water-conducting belt of sprinkling devices q_2=const, $\omega_0^{//}\neq$const

$$\frac{dH}{dx} = i - \frac{Q^2}{K^2} - AQ\,q, \tag{11}$$

where q is the specific detachment rate.

An important condition is the provision of a uniform distribution of water flow along a pipeline, i.e. the obtaining of equal jets from all branches of sprinkling devices. Let's perform the integration with a uniform disconnection of the flow rate.

$$dH = idx - \frac{Q^2}{K^2}dx - AQ\,dQ_2, \tag{12}$$

In the case of a uniform disconnection of water flow rate in any section along the length of a water-conducting belt, the flow rate will be expressed by the following dependence:

$$Q=Q_0 - qx, \tag{13}$$

where Q_0 is the flow in the initial section;

Then, taking into account that $dQ_2=-qdx$, we obtain the equation of the piezometric line for the given case in the differential form:

$$dH = idx - \frac{1}{K^2}\left(Q_0^2 - 2Q_0qx + q^2x^2\right)dx - A\left(Q_0q - q^2x\right)dx, \tag{14}$$

After the transformations, we obtain the expression to determine the piezometric pressure in the cross-section x of the water-conducting belt with the outlets for sprinklers:

$$H_P = H_1 + ix - \left(Q^2 + QQ_x + \frac{Q_x^2}{3}\right)\frac{x}{K^2} - A\left(QQ_x + \frac{Q_x^2}{2}\right), \tag{15}$$

where H_P and H_1- the piezometric pressure in the cross-section x of the pipeline with the outlets and the piezometric pressure at the beginning of this section, respectively; Q and Q_x – the water flow in an arbitrary section of a water-conducting belt and the detachment rate along the length x, respectively.

$$H_P = \frac{P_x}{\gamma}; \quad H_1 = \frac{P_1}{\gamma}, \tag{16 – 17}$$

For a final cross-section of the water-conducting belt section with the taps along its length, $x=\ell$:

$$Q=Q_{TP} \text{ and } Q_x=Q_n., \tag{18}$$

where Q_{TP} and Q_n– transit and travel consumption, respectively.

The equation takes the following form:

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$$H_P = H_1 + i\ell - \left(Q_{тр}^2 + Q_{TP}Q_n + \frac{Q_n^2}{3}\right)\frac{\ell}{K^2} - A\left(Q_{тр}Q_n + \frac{Q_n^2}{2}\right), \quad (19)$$

Its application will allow to determine the piezometric pressure in the final section of a sprinkler water-conducting belt.

The change of the piezometric pressure is determined from the following expression:

$$h_P = H_1 - H_P + i\ell, \text{ i.e.} \quad (20)$$

$$h_P = \left(Q_{тр}^2 + Q_{TP}Q_n + \frac{Q_n^2}{3}\right)\frac{\ell}{K^2} + A\left(Q_{тр}Q_n + \frac{Q_n^2}{2}\right), \quad (21)$$

The absolute value of the piezometric water pressure recovery depends on the intensity of flow disconnection, which is explained by the transfer of kinetic energy into the potential one during the selection of water along a water-conducting belt length.

The uniformity condition for the irrigation of the whole area can be represented as follows

$$\frac{q}{\pi r^2} = \frac{Q_0}{\pi R_M^2}, \quad (22)$$

Where q is water flow, which ensures a uniform watering of the circle with the radius r, i.e. the detachment rate; Q_0 – total, summary consumption of the machine; R_M - the machine radius (the length of the watering belt).

Hence, the following expression can be obtained:

$$q = Q_0\frac{r^2}{R_M^2}, \quad (23)$$

The water flow through an arbitrary section of the water supply pipeline:

$$Q = Q_0 - \frac{Q_0}{R_M^2}r^2, \quad (24)$$

Since for each modification of the sprinkler Q_0=const and R=const, we obtain the following expression after differentiation:

$$dQ = \frac{2Q_0}{R_M^2}rdr, \quad (25)$$

After the integration from 0 to r, the expression becomes the following one:

$$H = ir - \frac{1}{K^2}\left(Q_0^2 r - \frac{2Q_0^2}{3R_M^2}r^3 + \frac{Q_0^2}{5R_M^2}r^5\right) + A\left(\frac{Q_0^2}{R_M^2}r^2 - \frac{Q_0^2}{2R_M^4}r^4\right), \quad (26)$$

The total pressure loss along the entire length of a sprinkler water-supply belt is determined at $r=R_M$.

For i=0, we obtain the following:

$$H_n = 0{,}533\frac{Q_0^2 R_M}{K^2} - 0{,}5AQ_0^2, \quad (27)$$

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The value of pressure loss during a discrete sampling can be expressed in terms of pressure loss value at a uniform water sampling and the discreteness parameter k_{∂}' by A.A. Fedorets (Fedorets A.A. 1976):

$$h_{тр.\ дискр} = h_{тр.\ равн}\left(1+1{,}7\left(\frac{\ell_{отв}}{\ell}\right)^{1{,}04}\right), \tag{28}$$

where $\ell_{отв}$ is the distance between the taps for the sprinklers.

Taking into account Dupuy's formula for the loss of pressure on friction, we determine the pressure loss at discrete selection of water in the water-supply belt with the taps for sprinklers:

$$h_g = \left(Q_{TP}^2 + Q_{TP}Q_n + \frac{Q_n^2}{3}\right)\frac{\ell}{K^2} \bullet \left(1 + 1{,}7\left(\frac{\ell_{отв}}{\ell}\right)^{1{,}04}\right) + A\left(Q_{TP}Q_n + \frac{Q_n^2}{2}\right) \tag{29}$$

The uniformity of irrigation by a sprinkling machine is ensured by a sediment layer equality:

$$h_{oc} = \frac{Q_M}{\pi R_M^2}, \tag{30}$$

where Q_M is the total consumption of a machine; R_M is the irrigation radius equal to the machine length.

For any sprinkler installed on a machine's water-supply belt, the precipitation layer will be equal to the flow rate ratio for an irrigation ring area:

$$h_{oc} = \frac{q_a}{\pi(r_1^2 - r_2^2)}, \tag{31}$$

where q_a is the flow rate of a sprinkler, r1 and r2 - the outer and the inner radius of the irrigation ring, respectively.

Hence:

$$q_a = \frac{Q_M}{R_M^2}\left(r_1^2 - r_2^2\right), \tag{32}$$

The flow rate of a sprinkler can also be expressed in terms of flow through a hole:

$$q_a = \mu\omega_0\sqrt{2gH}, \tag{33}$$

where μ is the flow coefficient; ω_0 is the cross-sectional area of the nozzle, H is the pressure at a sprinkler entrance.

After conversion, the nozzle section makes the following:

$$\omega_0 = 0{,}225\frac{Q_M(r_1^2 - r_2^2)}{R_M^2\mu\sqrt{H}}, \tag{34}$$

The characteristics Q_M and R_M for this modification of a sprinkler are constant ones, the pressure at a sprinkler entrance is variable depending on the pressure of a machine entrance.

Since the flow in the sections of a pipeline along the length decreases, it is advisable to choose a pipeline of variable cross-section for a water-conducting belt if it is necessary to install a console, which will also allow to reduce a structure cost.

The proposed simple dependence allows you to choose a water-conducting belt diameter or a sprinkler console:

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$$d = d_0 \sqrt[5]{\frac{\lambda_П}{\lambda_0}\left(1 - \frac{Q_n}{Q_n + q_{тр}} \frac{r^2}{R_M^2}\right)^2}, \tag{35}$$

where d_0 is the diameter in the initial section of a pipeline, λ_n/λ_0 is the ratio of hydraulic friction coefficients in an arbitrary section λ_n and in the initial section of the pipeline λ_0; Q_n is the flow, taken along the entire length of the water-supply belt, $q_{тр}$ is the flow of the end sprinkler.

The determination of pressure losses in the water pipe is performed under the condition i = 0, taking into account the sampling discreteness:

$$\Delta H_x = Q_M^2\left(1 + 1{,}7\left(\frac{\ell_{отв}}{\ell}\right)^{1{,}04}\right)\left(1 - 0{,}666\frac{r^2}{R_M^2} + 0{,}2\frac{r^4}{R_M^4}\right) -$$

$$- AQ_M^2\left(\frac{r^2}{R_M^2} - 0{,}5\frac{r^4}{R_M^4}\right), \tag{36}$$

2.2 Process modeling in the water-supply belt

On the basis of the proposed theory, the flow characteristics in the water-conducting belt of a sprinkler were simulated, with the console of a variable diameter, with a terminal sprinkler.

Conditions: the total length of the sprinkler makes 527 m with the console of 27 m; the irrigated area makes 87.2 hectares; the length of the pipeline with 159 mm in diameter (the internal diameter of 153 mm) makes L_M = 420 m; the section in the form of 80 m pipe with the internal diameter of 147.2 mm and the console length of 27 m -96 mm. The distance between the branches for sprinklers makes ℓ_{sv} = 1.45 m. The irrigation norm is h = 40 mm. The geodetic pressure Hg = 4.5 m; the pressure at the last branch makes 2 m. The speed of the last support V_{po} = 0.31 m / min.

Calculation results: the flow rate Q_M = 57.72 l/s is required for a sprinkler operation. Total pressure losses in the waterway make Σh_{tr} = 24.9 m. The required pressure of a sprinkler hydrant makes H = 31.4 m. The diameter of sprinkler nozzle varied along the length from 2.5 to 12 mm. Dependences of the change in pressure, flow and transit flow along the length of the pipeline are shown on Figures 1-3.

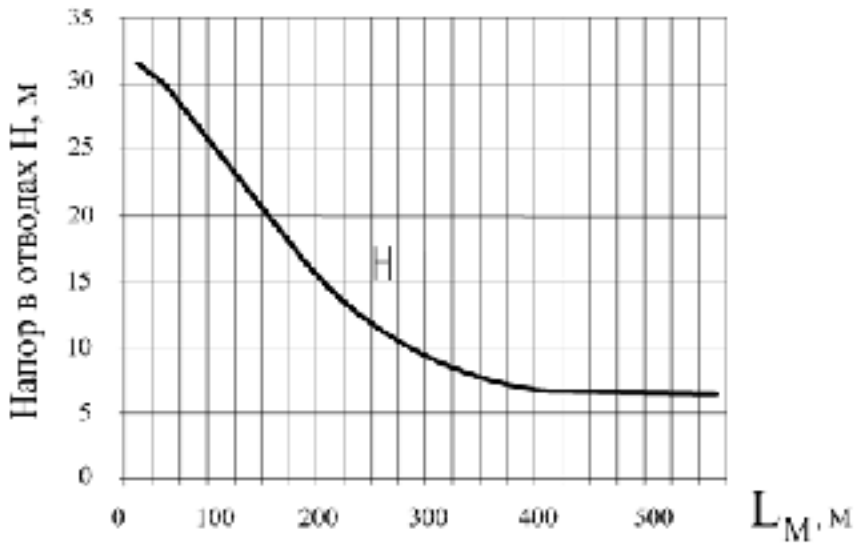

Fig 1. Pressure change along pipeline length

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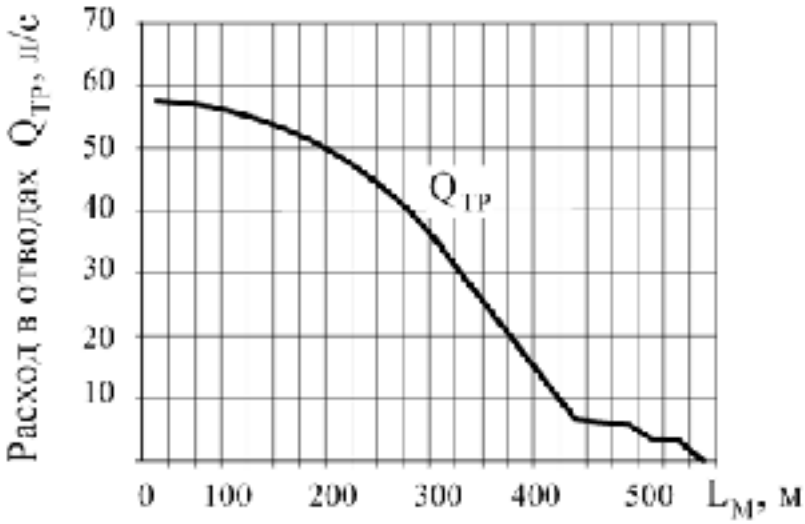

Fig 2. Transient flow along pipeline length

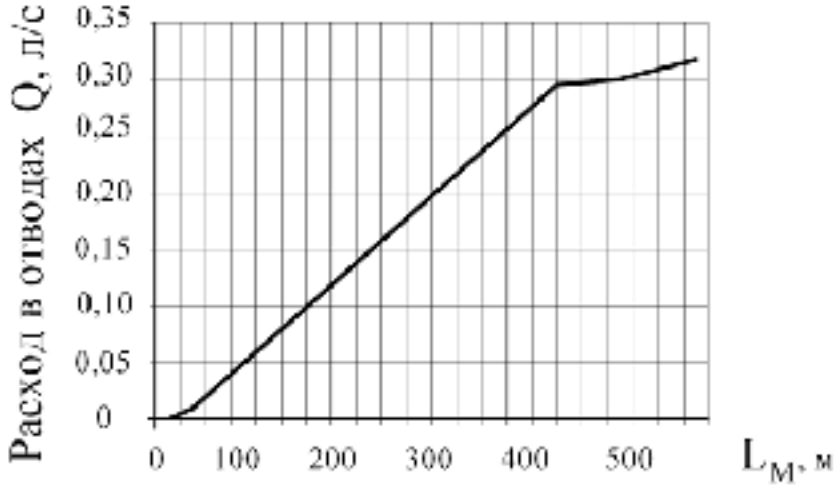

Fig 3. Consumption change along a pipeline length

2.3 Experimental studies of processes

In order to confirm the theoretical studies of the discreteness parameter application, the experimental studies were carried out based on the theory of similarity and dimensions.

The criterion equation looked like this:

$$\lambda = f\left(\frac{\Delta}{R},\ \mathrm{Re},\right) \tag{37}$$

where Re – the Reynolds number; $\frac{\Delta}{R}$ – a relative roughness of walls.

In order to conduct experimental studies, the pipes with the diameter of 16; 20; 25; 30.0; 48.0; 60 mm were used the length of which made 2 - 6 m. The distances between holes: 0,125; 0.25; 0.5; 1.0; 2.0 m; Hole diameters: 1.0; 1.5; 3.0; 5.0 mm. The water pressure in a pipeline varied from 0.06 to 0.35 MPa, while the Reynolds numbers varied between 1000 and 100,000.

Hydraulic friction ratio.

The conducted studies show that when the flow of water flows in perforated pipelines the value of hydraulic friction ratio is greater than at a uniform motion; at that this difference increases with the increase of selection intensity along the length.

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At high Reynolds numbers, the value of the hydraulic friction coefficient in pipelines with taps is approximately equal to the value of the hydraulic friction coefficient at a uniform motion of water $\lambda_n \approx \lambda_0$, i.e. the sampling of water does not affect the amount of pressure loss (Figure 4).

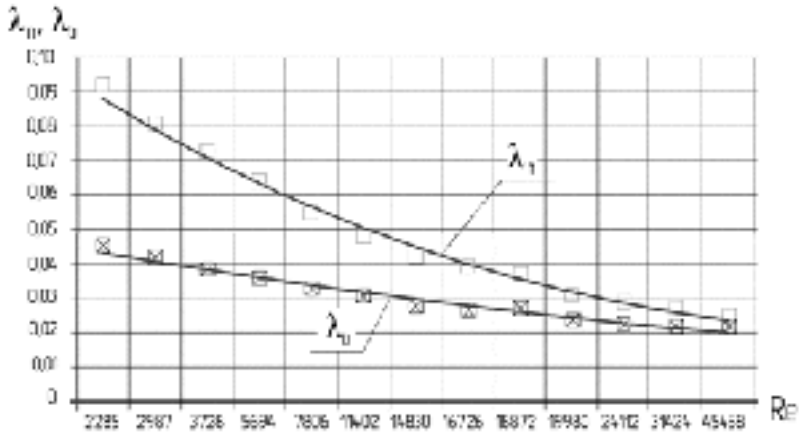

Fig 4. The changes of hydraulic friction ratio in pipelines with the outlets and with a uniform movement of water from the Reynolds number: $\lambda_n=0{,}098e^{-0{,}11Re}$ $R^2=0{,}98$; $\lambda_0=0{,}046e^{-0{,}06Re}$ $R^2=0{,}97$.

The ratio λ_n/λ_0 varies from 2.2 to 1.2 on average depending on the Reynolds number (Figure 5).

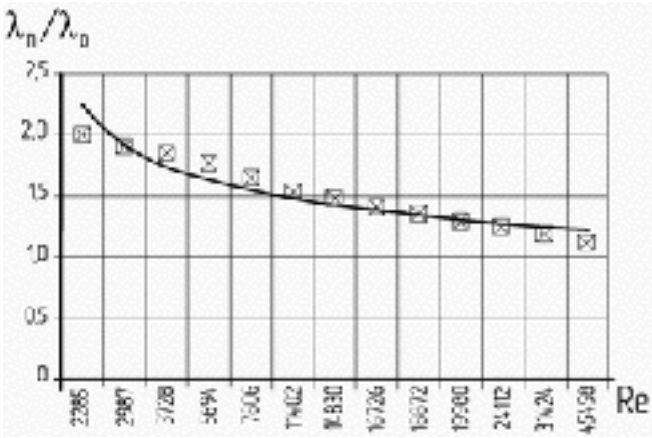

Fig 5. The dependence of λ_n/λ_0 ratio on Re: $\lambda_n/\lambda_0=2{,}26Re^{-0{,}23}$, $R^2=0{,}889$

The coefficient of water mass detachment along the pipeline.

In order to clarify the water detachment coefficient a2, the studies were carried out, the results of which showed the independence of the main flow velocity ratio and the rate of jet outflow from hole diameter (Figure 6). The obtained results show that the coefficient of flow detachment is within the limits of $0{,}66<a_2<0{,}87$.

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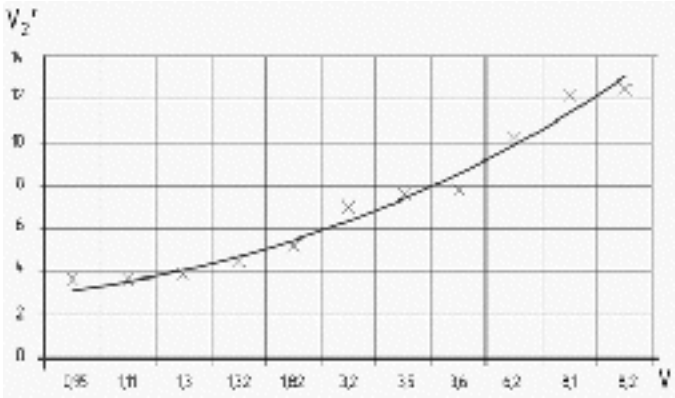

Fig 6. The ratio of the main stream velocity V and the velocity of the jet outflow V_2': $V_2'=2{,}78\ e^{0{,}14V}$ $R^2=0{,}97$

Discreteness parameter

The experimental studies were carried out on pipes with the diameter d: 16; 20; 30.0; 48.0; 63 mm, the length of 6 m, divided into 1 m sections with the hole diameter d_{OTV}: 1, 3, 5, 10, 14 mm. The distances between the holes $\ell_{отв}$ make 0,25; 0,5; 1,0 m. The water pressure in the pipeline varied from 0.06 to 0.35 MPa. The pressure losses in the sections were measured by piezometers (pressure gauges at the pressures from 0.2 MPa), set after each 1m. The track and transit flow was determined by a volumetric method. The track flow on the measured area was collected by the means of gutters (Figure 7).

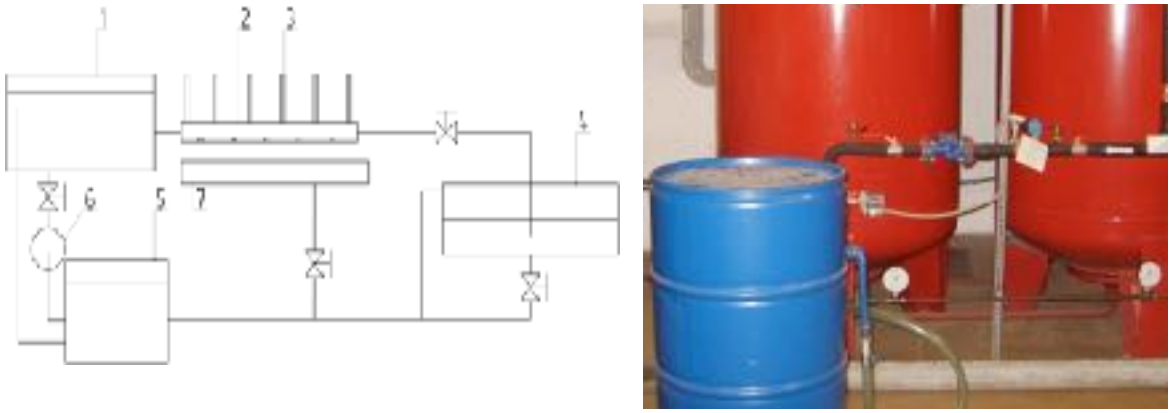

Fig 7. Laboratory unit: 1 - pressure tank, 2 - replaceable perforated tubes, 3 - piezometers; 4 - measuring tank; 5 - drain tank; 6 - pump

3. RESULTS

The main results of the performed studies are presented in Table 1.

Table 1. The results of experimental studies

$\ell_{отв}$, m	Q_n, l/s	d , mm	d ОТВ, mm	$Q_{тр}$, l/s	Re	Experimental h_∂	Calculated h_∂	% deviations
	7,8	48	10	39	14257	1,4	1,42	1,4
	31,6	60	20	151,6	17821	1,9	1,88	1,0
0,25	1,9	60	5	12,2	1852	0,8	0,76	5
	20	60	16	98	15621	1,6	1,55	3,1

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	5	60	8	40,3	22101	1,3	1,28	1,5
	3,9	48	10	17,2	13556	0,9	0,95	5,5
	15,6	60	20	62,4	14267	1,5	1,56	4
0,5	0,96	60	5	5,6	19885	0,6	0,63	5
	10	60	16	160,2	17523	1,9	1,88	1
	2,4	60	8	12,6	18665	0,8	0,84	5
1	1,9	48	5	9,5	13557	0,6	0,63	5
	7,8	60	20	31,2	16425	1,1	1,06	3,6
1	0,48	60	5	2,4	13823	0,4	0,42	5
	5	60	16	20,1	14558	0,9	0,91	1,1
	1,2	60	8	27,2	17533	1,2	1,25	4,1

The comparison of the calculated and the experimental values shows a good agreement of the results.

4. DISCUSSION

The experimental check of the water flow parameter numerical values confirmed the validity of the application for the equation calculation of the pipeline belt of sprinkling wide-coverage machines with a uniformly distributed distribution along the water pipe axis, taking into account the introduction of the discreteness parameter in them, which takes into account the number and the arrangement of the branches for the sprinklers.

On the basis of the presented technique they designed a nomenclature series of sprinklers and manufactured the wide-coverage sprinkler of circular motion "Kuban-LK1M" (CASCADE) in FSBEI HE Saratov SAU (Figure 8).

Fig 8. The wide-coverage sprinkler "Kuban-LK1M" (CASCADE)

5. SUMMARY

The theoretical studies of water movement with a variable flow rate along the length of a water-supply belt made it possible to obtain the dependences describing the flow characteristics in the presence of both uniform and uneven installation of drainage systems for sprinklers, pressure losses and flow changes, taking into account the discreteness parameter which considers the number of bends per unit of length.

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They determined the dependences of the nozzle cross-section area of a sprinkler to ensure the uniformity of irrigation along a pipeline length. Based on the dependencies, they performed the calculation of a sprinkler water-conducting belt with variable diameter, with a console.
The comparison of field study results with the calculated ones gives a good agreement and indicates the correctness of the proposed methodology and the reliability of the obtained dependences.

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