USE OF MOBILE PIPELINE WITH SELF-REGULATED WATER OUTLETS FOR FURROW IRRIGATION

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Surface irrigation is one of the most common irrigation methods, but it has its own significant drawbacks. A mobile pipeline for furrow irrigation from closed irrigation network was designed and its parameters were proved in order to improve furrow irrigation. The mobile pipeline consists of plastic pipes based on 10 pairs of spring skis connected in the middle by a flexible connection. It is known that water flow into the furrow decreases along the pipeline due to pressure losses along the length of the pipeline. It was proposed to use water outlets ensuring uniform supply of water to each furrow by the presence of the butterfly valve in housing of the water outlet in the mobile pipeline. In order to ensure sustainable valve position, an equation was derived and values of the area of the upper and bottom parts of the valve were obtained. According to the pipeline field test results, water distribution uniformity coefficient through the outlets was 0.98, at a flow rate of 1.0–3.0 $l \cdot s^{-1}$ and hydraulic slopes along the pipeline of 0.001–0.005.

water flow, uniformity of irrigation, mechanization, pipe, butterfly valve

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INTRODUCTION

Irrigated land worldwide is one of the main factors for the stability of agricultural production and ensuring the food security. Irrigated land, constituting less than 20% of arable land, produces more than 40% of crop production (Bruinsma, 2003).

Surface irrigation nowadays is one of the most common irrigation methods, as it has several advantages: low power consumption; simplicity, and high reliability in operation; weak dependence on wind speed; low capital investment in the construction of the irrigation network. However, surface methods have significant drawbacks: low level of mechanization, irrigation efficiency does not exceed 50–70%; significant losses due to surface fault and depth filtration; uneven irrigation (Heermann et al., 1990). Agronomic requirements imposed on the surface irrigation system are the following: uneven supply of water in furrows should not exceed ± 10% of a given norm of watering; simultaneous operation of all pipelines; crop damages should not exceed 0.2%; soil erosion at the joints and pipe irrigation water outlets is not allowed; operation area of 5–30 ha (with different configurations); length of irrigation furrows 100–600 m, depth of 13–16 cm.

Recently developed technologies and facilities partially correct the shortcomings of the traditional surface irrigation, hindering its development. Primarily this includes designed precision layout of field surface using laser equipment (Jat et al., 2006), new ways of irrigated furrow formation (Schwankl et al., 1992; Yonts, 2007), as well as proved technologies and irrigation regimes that enable uniform moisture along the furrow length (Ampas, 1998; Nasseri, 2013). Development of technological schemes of irrigation provides the parameters such as furrow length, water flow to the furrow, irrigation duration according to the given calculated rate with the width of the irrigation's front and the value of head in the irrigation network (Santos, 1996; Horst et al. 2005; Holzapfel et al., 2010). For quality irrigation on a well-designed field, it is necessary to use technical means for supplying water to the field, allowing productivity increase, reducing the seepage loss, ensuring even flow of water in the furrows, and reducing the cost of labour and resources.

Flexible pipes, semi-rigid collapsible pipelines, rigid collapsible steel and aluminum pipes are currently available (Walker, 1989; Zerihun et al., 2001; Nasseri, 2013). However, all these mechanisms are time consuming to assemble and service; and the diameter of the water outlet holes along the length cannot be regulated to change the flow of water to the furrow. To improve the technology of furrow irrigation, there was a need to propose a mobile pipeline enabling a uniform flow of water in furrows, regardless of the total pressure in the network and the slope along the pipeline, and to reduce the cost of labour and resources.

To achieve this purpose, the following tasks must be resolved: to develop a mathematical model of the impact of water flow on the valve turnouts ensuring equal flow of water to furrows; to substantiate the structural and technological scheme and parameters of the irrigation pipe with regulated discharge outlets; to study the influence of the parameters and operating modes of the irrigation pipeline of the quality indicators.

MATERIAL AND METHODS

Mobile irrigation pipes (rigid and flexible) may be used in the planned areas with a hydraulic slope of more than 0.003 in the longitudinal and transverse watering.

For irrigation of crops in the pipeline is provided with two series of outlets: at the bottom by each 70 cm and by 45 cm at the top. Changing of the position to top-bottom if the support of clamps are loosening and installing plugs, that allows us to adjust the distance between the discharge outlets to 45, 70, 90, 135, 140, 180, and 210 cm. Outlets are installed in the lower part of the tube, which promotes quick emptying of the pipeline after water supply.

The length of the pipeline depends on the distance between hydrants closed irrigation network. In this embodiment, the distance between hydrants is 50 m. The choice of pipe diameter depends on the length of the pipeline and conditions of water flow supply. In order to adjust water flow into the furrow, the designed self-regulating outlets are used.

The theoretical work was based on the provisions of law and methods of fluid dynamics using mathematics. In laboratory experiments the theory of hydrodynamic similarity with the Newton's number as the general criterion of hydrodynamic similarity was used.

Investigations were performed in accordance with applicable standards in laboratory and field conditions based on conventional techniques using the theory of mathematical planning and processing of experimental data.

Theoretical substantiation of the design parameters of the pipeline

As given above, we have developed a mobile pipeline consisting of two plastic pipes connected by ameliorative cloth and clamps, based on (through the brackets) spring skis the length of which exceeds two aisles of furrows, several series of water outlets along the length of irrigation pipe, a manometer installed to monitor the pressure, and a connecting bend (Kokurin et al., 2008). One end of the spring ski is rigidly fixed to the bracket, and the other one is placed freely (Fig. 1). Two rows of water outlets are made along the length of pipeline at an angle of 180º through 0.70 and 0.45 m, respectively, while the unused row of holes is closed with plugs. Water is supplied from a hydrant of the closed irrigation network through the connecting bend. Length and diameter of the pipeline are justified depending on the feed network parameters.

The technological process of irrigation using a mobile pipeline is as follows. A tractor moves the irrigation pipe using a rope from one position (irrigated) to another (to be irrigated). For this purpose, the front end of irrigation pipeline is connected to the hydrant via a flexible hose by a clamp. After filling the pipeline with water, its mass increases 7–10 times, and the pipe rests on furrow ridges.

At the end of irrigation of this position, hydrant was shut; flexible connection was removed and secured on irrigation piping.

During this time, irrigation pipe started to be empty, the load on the spring ski decreased and it straightened, raising the irrigation pipe above the soil surface. Irrigation pipeline moved to a new position with the help of the tractor.

Spring ski is a constant cross-section leaf with a constant radius of curvature along the entire length, with one clamped and one sliding supports (Fig. 2).

Based on the condition that the maximum load on the spring ski should correspond to the value of the static spring deflection (Parhilovsky, 1978)

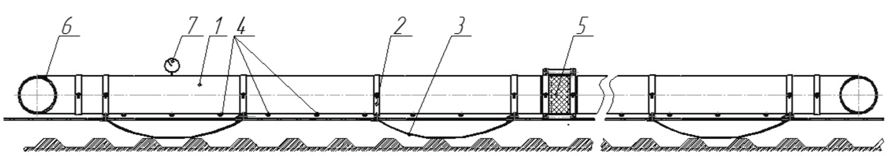

Fig. 1. Layout of irrigation piping

1 = pipe, 2 = clamp, 3 = spring ski, 4 = water outlet, 5 = flexible connection, 6 = connecting bend, 7 = gauge

$$P_T = \frac{4E_y b_0 a_0^3 f}{l_r^3 \delta_P} \quad (1)$$

where:
P_T = applied load (N)
l_r = spring length (m)
E_y = modulus of elasticity (MPa)
b_0 = spring width (m)
a_0 = spring thickness (m)
f = value of static deflection
δ_p = deflection magnification (δ_p = 1)

Total number of spring skis that provide pipeline lift and lowering (P a r h i l o v s k y, 1978)

$$n_p = \frac{\sum Q}{P_T} \quad (2)$$

where:
$\sum Q$ = total load on the spring skis (N)
n_p = number of spring skis in the pipeline

In order to ensure a uniform supply of water to the furrow, and in view of pressure head losses along the length of the water pipe, water outlets are mounted in pipe structure with the butterfly valve of a trough shape (G r u d i e v, V y s o c h k i n a, 2009).

The butterfly valve of a trough shape, consisting of two platforms ($S_в$ and $S_н$), is mounted on the axis in the housing of the water outlet (Fig. 3). Upper platform $S_в$ is in the housing part 1 of the pipeline, and the lower one is in pipeline 2 of the irrigation piping water outlet.

At the time of water supply into the pipeline, water outlet valves are rotated (Position I) and shut the water outlet openings under the action of the pressure force F_1.

After filling the pipeline with water under the action of pressure force on the bottom of valve F_2, simultaneous opening of the water outlet openings (Position II) takes place, wherein the angle of valve inclination depends on the water flow rate.

The water flow through the water outlet depends on cross-sectional area and the flow head (L i k h i, 1995; R a i n k i n a, 2005):

$$Q_i = \mu_p \omega \sqrt{2gH_u} \quad (3)$$

where:
Q_i = water flow through i-th outlet (m^3·s^{-1})
μ_p = flow coefficient through outlet
ω = cross-sectional area (m^2)
g = acceleration of gravity (m·s^{-2})
H_u = flow head (m)

Preliminary measurements of the flow rate in the pipeline at the working model have shown that the flow regime is turbulent (R >> 2400). Taking into account the rapid increase in the velocity modulus from 0 to V_{max}, it is possible to substitute the actual speed at every point of flow interaction with the valve by its average speed $\overline{V_i}$.

The butterfly valve of the water outlet takes the operating position with equal moments of forces acting on the top and the bottom valve. Along with the rule of moments we used the law of conservation of energy, and its particular case in hydrodynamics – the Bernoulli equation.

Based on the condition of equality of the outlet flow $Q_i = Q_{i-1}$, after equating flows, after transformations (L i k h i, 1995; R a i n k i n a, 2005) we obtain:

$$\sqrt{2gH_{ui}} = \left(1 - \frac{S_н \cos\alpha}{S_в}\right)\sqrt{2gH_{ui} + \frac{\overline{V}_{i-1}^{\,2}}{2{,}38}} \quad (4)$$

where:
H_{ui} = pressure head of the flow through the i-th outlet (m)
$S_в$ = area of the top valve platform (m^2)
$S_н$ = area of the bottom valve platform (m^2)
α = angle by which the valve has to decline (allowing forecasting the flow section of the outlet and the flow of water into the furrow)

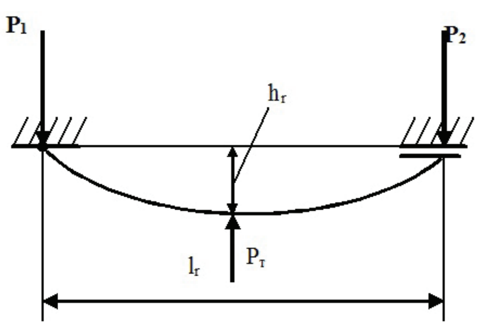

Fig. 2. Calculation scheme of spring ski

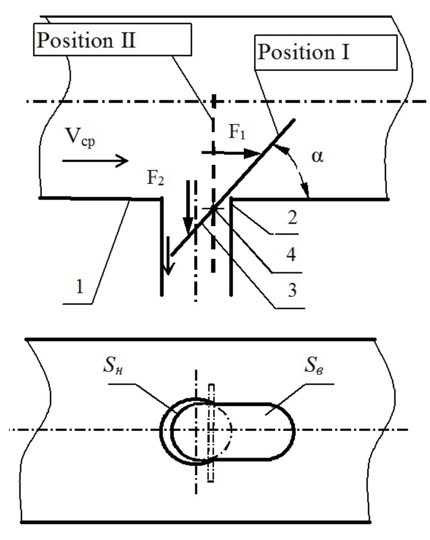

Fig. 3. Scheme and photo of a self-regulating water outlet design
1 = pipeline, 2 = water outlet pipe, 3 = butterfly valve, 4 = axis

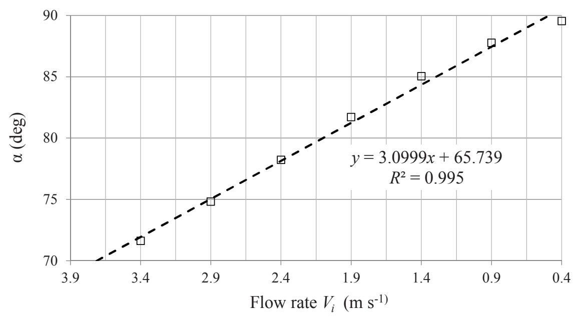

Fig. 4. Dependence of valve angle of inclination on the flow rate

Thus, the equality of outlet flow depends on the area ratio of the upper and lower valves, flow pressure head, flow rate of fluid in the outlet area, and valve inclination angle. Angle α depends on the speed of fluid flow $\alpha = f(V_i)$ (Fig. 4).

A prerequisite for sustainable outlet valve position is the equality of moments applied to its upper and lower parts, $M_в = M_н$.

When determining the forces acting on the body by the water flow, generally used equations expressing the law of change of momentum are differential equations of Navier-Stokes and Reynolds (Altschul, 1977). Then the moment of force acting on the upper and bottom parts of the valve is determined as follows:

$$M_в = F_{i\alpha} l_в \sin\alpha \tag{5}$$

$$M_н = F_{iн} l_н \cos\alpha \tag{6}$$

The area of the bottom part of the valve is limited by the outlet diameter.

Taking into account equations (4,5,6) and given that the sectional area of the water outlet may be defined as a circular area (diameter equal to the diameter of the passage section), and equating the moments acting on the upper (eq.5) and bottom (eq.6) parts of the valve, after transformation the upper valve part area is:

$$S_в = S_н \sqrt{\frac{2\left(\left(1+k^2\right)gH_и + \frac{2}{3}gl_H \sin\alpha + \frac{k(n+1-i)\overline{V}_n}{1{,}19}\cdot\sqrt{2gH_и} + \frac{(n+1-i)^2\overline{V}_n^2}{2{,}38}\right)\beta\ ctg\alpha}{(n+1-i)\overline{V}_n^2}} \tag{7}$$

where:

ß = coefficient taking into account the configuration of the valve

Since the relationship between the mean flow rates at the outlets is recurrent, the resulting expression is valid for any sequence number of the outlet.

Laboratory experiments

The theory of hydrodynamic similarity (Bertram, 2011) was used in laboratory experiments. The water flow rate and the flow rate along the pipeline were measured by ultrasonic flow meter (industrial ultrasonic flow meter «Vzljot PR», association «Vzljot», St. Petersburg, Russian Federation). To measure the flow and flow rate in the pipeline, flow meter sensors were mounted before and after each outlet (Fig. 5) alternately in ascending order. By changing the pressure in the pipeline, controlling reading on the gauge, measured parameters were indicated on the flow meter display with the selected dimension and display period.

The experiment results revealed that when water is supplied to the irrigation pipeline, the water outlet openings are completely shut under the influence of pressure force F_1.

When flow rate is steady, water flow rate at the beginning of the pipeline is greater than at its end, and the valve tends to close the initial water outlet hole to a greater extent than the next ones, depending on the distribution of water pressure along the length of the pipeline (Fig. 6).

Equality of the outlet flow depends on the area ratio of the upper and bottom valves, flow pressure head, flow rate of fluid in the outlet area, and valve inclination angle $\alpha_1 < \alpha_2 < \alpha_3$.

Field tests were conducted in the Stavropol Territory, Russian Federation, in 2008–2009 during furrow irrigation of corn. The furrows were located crosswise of piping arrangement and hydrants line. Irrigated land with well levelled surface was chosen, irrigation furrows were 200 m, and hydraulic slope was from 0.003 to 0.01.

The distance between hydrants was 110 m, hydrant diameter was 320 mm. The maximum capacity of the hydrant of the closed irrigation network was 210 l·s^{-1}, the flow into the furrow was up to 3.0 l·s^{-1}.

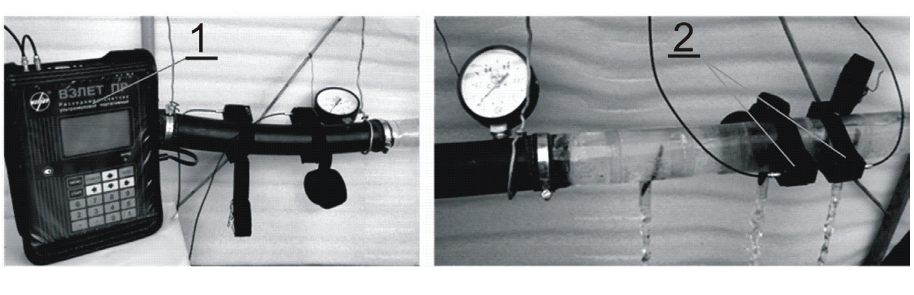

Fig. 5. Experimental mount to determine the flow of water by outlets 1 = ultrasonic flow meter, 2 = flow meter sensors

Table 1. Water pressure in the pipeline at a total flow rate of 140 l s^{-1}

On the length section of pipeline (m)	Water pressure in the pipe (m of water column)	
	with a slope of i = 0.001	with a slope of i = 0.005
10	6.02	6.00
20	5.40	5.10
30	4.75	4.43
40	4.30	3.94
50	4.05	3.61

The outlet diameter (30 mm) was selected based on the maximum flow to a furrow through the last water outlet; water flow through the outlet was adjusted from 1.0 to 3.0 l·s^{-1}. The area of the upper part of the valve was $7.54 \cdot 10^{-3}$ m^2, of the bottom one $5.77 \cdot 10^{-3}$ m^2.

Studies were carried out at a total flow rate of the water in the pipe 100, 140, 180 l·s^{-1} at hydraulic slopes 0.001 and 0.005.

RESULTS

The head loss by the length of the pipe was determined along the pipeline on a hydraulic slope from 0.001 to 0.005 at total water flow rate of 140 l·s^{-1} (Table 1). Head loss along the pipeline increased with slope decreasing.

Water flow in a furrow was measured through the water outlet holes and self-regulated water outlets. Deviation of water flow along the length of irrigation pipeline was ± 0.02 l·s^{-1}, with a total flow rate of 140 l·s^{-1}, which meets the agronomical requirements. A change in the slope of the field along the pipeline did not affect the flow at outlets – flow remained constant. This suggests that the design of the water outlets operates through internal hydraulic processes, regardless of the slope along the pipeline. Hydraulic processes are based on interdependent speed fluid flows affecting butterfly valves of outlets (Fig. 7).

It has been determined that the butterfly valve of the outlets damps flow energy in the pipeline, reducing the energy of the jet fed into the furrow, thereby decreasing the depth and diameter of the plunge basin in the water discharge area (Fig. 8).

The total water pressure drop along the pipeline was 4.4 m. Generated water pressure at hydrant of water column of 5.4 m ensured the total flow of 140 l·s^{-1}. The coefficient of land use of irrigated area with the furrow length of 200 m was 0.96.

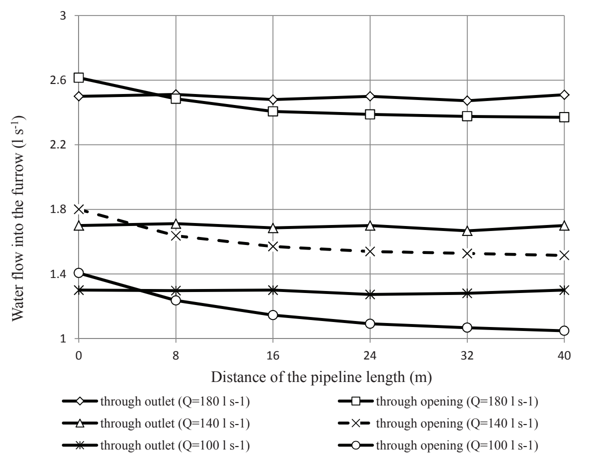

Fig. 7. Water flow in the furrow along the pipeline with a slope of 0.005

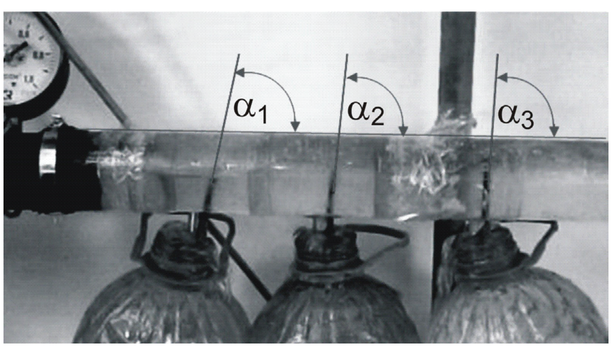

Fig. 6. Position of the water outlet valve in the steady flow of water in the pipeline

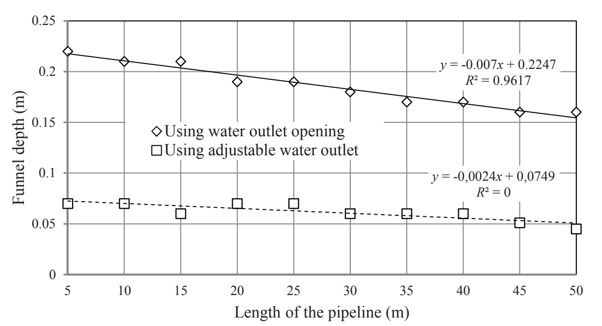

Fig. 8. Depth of plunge basin in water discharge area

DISCUSSION

Pipelines for furrow irrigation currently have turnouts outlet with constant flow rate (Walker, 2003) or different diameter along the length of the pipeline (Enciso, Peries, 2005).

Outfalls of constant cross-section do not provide the same flow along the length of the pipeline due to pressure losses (Bertram, 2011). Choice of different water outlets diameters is connected to the complexity of the calculations. With a constant cross-section it is not possible to change the water flow quickly under varying soil climatic conditions.

In many countries, various surface irrigation design of ground irrigation pipes is used. Most pipelines are equipped with automatic control sensors (Walker, 1989; Sharma, Sharma, 2008). Using pipes with risers-water outlets and electronic control unit irrigation worsens conditions for unimpeded cultivation of row crops and increases the cost of labour and funds for the building of irrigation networks.

Using the laws of hydrodynamics, we have determined the size of the dampers (Kokurin et al., 2008; Grudiev, Vysochkina, 2009) providing self-regulating of the water flow along the pipe, regardless of the slope along the pipeline and created pressure on the network.

It was established that the use of pipelines for supplying water to furrows can increase the coefficient of water use, but it does not provide a uniform feeding of water in furrows. The regularities of the movement of water in the pipe in view of mode - turbulence in the hydraulically smooth pipes, allows estimating the head loss along the pipe in continuous distribution of water in furrows, depending on the length and diameter of the pipe, slope and water head in the hydrants.

CONCLUSION

When watering crops, it is necessary to provide greater water flow than it is set on the hydrant water pressure considering head losses along the pipeline equal to water flow through all the outlets, and reduction of erosive flow rate at the exit from outlets.

The designed parameters of water outflow were proved to reduce the rate of water discharge and define flow. Taking into account flow equality in each outlet, the dependence of valve angle on the flow rate along the length of the pipeline was deduced. Taking into account the conditions for sustainable position of outlet's valve, i.e. equality of moments applied to the upper and bottom parts of the valve, the sizes of the upper and bottom parts of the valve were determined. The mathematical model of the impact of fluid flow on the valve turnouts ensured uniform water flow in furrows and justified the design parameters of water outlets with a diameter of 30 mm, equipped with butterfly valves, the upper part ($7.54 \cdot 10^{-3}$ m^2) of which located in the cavity of the pipeline, and the lower one ($5.77 \cdot 10^{-3}$ m^2) located in the overflow tube, blocking the flow area depending on the pressure, and the expiration of providing water supply to the furrow with a coefficient of uniformity of 0.98 at a flow rate of 1.0–3.0 l·s^{-1} and with the slopes along the pipeline 0.001–0.005.

It was found that the coefficient of land use of irrigated area with furrows length of 200 m located according the transverse pattern of location for the pipeline operation from the closed irrigation network was 0.96, which does not exceed the statutory value.

It was established that the butterfly valve of water outlet reduces the energy of flow in the pipeline, reducing the energy of the jet supplied to the furrow, and as a result the depth of the erosion craterwill be reduced by half, as well as its diameter.

The use of irrigation piping with adjustable outlets can improve the efficiency of water use by 12%, uniformity of water flow into the furrows by 9%, greatly facilitating the work of irrigators, and allows reducing the cost of manual labour.

The designed irrigation pipeline with self-regulating outfalls can be used for irrigation of cultivated crops in furrows at any cross slope areas (within tolerance) with equal flow dosing into a furrow.

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REFERENCES

Altschul AD (ed.) (1977): Sample calculations for hydraulics. Stroyizdat, Moscow. (Russian Federation)

Ampas V (1998): Optimum application efficiency of furrow irrigation. Geotechnical Scientific Issues, 9, 4–12. (in Greek)

Bertram V (2011): Practical ship hydrodynamics. Butterworth-Heinemann, Oxford.

Bruinsma J (2003): World agriculture: towards 2015/2030 – An FAO perspective. FAO, Rome.

Enciso J, Peries X (2005): Using flexible pipe (poly-pipe) with surface irrigation. Texas Cooperative Extension. Fact Sheet No. L-5469.4.

Grudiev GV, Vysochkina LI (2009): Outfall irrigation conduit. Pat. 89923 Russian Federation, the IPC A01G 25/02. Compilation, 36, 3.

Heermann DF, Wallender WW, Bos MG (1990): Irrigation efficiency and uniformity. Management of farm irrigation systems. American Society of Agricultural Engineers, St Joseph.

Holzapfel EA, Leiva C, Mariño MA, Paredes J, Arumi JL, Billib M (2010): Furrow irrigation management and design criteria using efficiency parameters and simulation models. Chilean Journal of Agricultural Research, 70, 287–296.

Horst MG, Shamutalov SS, Pereira LS, Gonçalves JM (2005): Field assessment of the water saving potential with furrow irrigation in Fergana, Aral Sea basin. Agricultural Water Management, 77, 210–231.

Jat ML, Chandna P, Gupta R, Sharma SK, Gill MA (2006): Laser land leveling: a precursor technology for resource conservation. Rice-Wheat Consortium Technical Bulletin Series 7, New Delhi.

Kokurin IS, Vysochkina LI, Nosov KN, Nosov AK, Grudiev GV (2008): Mobile irrigation pipeline-loop. Pat. 2347360 Russian Federation, the IPC A01G 25/00. Bulletin 6, 5.

Likhi SK (1995): Hydraulics: laboratory manual. Wiley Eastern Limited, New Delhi.

Nasseri A (2013): Furrow irrigation: some experimental experiences. LAP LAMBERT Academic Publishing, Saarbrücken.

Parhilovsky IG (1978): Automotive leafy springs. Mechanical Engineering, Moscow. (in Russian)

Rainkina LN (2005): Hydromechanics. Study guide on solving problems. Russian State University of Oil and Gas, Moscow.

Santos FL (1996): Evaluation and adoption of irrigation technologies. I. Management-design curves for furrow and level basin systems. Agricultural Systems, 52, 317–329.

Schwankl LJ, Hanson BR, Panoras A (1992): Furrow torpedoes improve irrigation water advance. California Agriculture, 46, 15–17.

Sharma RK, Sharma TK (2008): Irrigation engineering. New Delhi.

Walker WR (1989): Guidelines for designing and evaluating surface irrigation systems. FAO, Rome.

Walker WR (2003): Surface irrigation simulation, evaluation and design. Utah State University, Logan.

Yonts CD (2007): Firming irrigation furrows to improve irrigation performance. NebGuide. The Board of Regents of the University of Nebraska, Lincoln.

Zerihun D, Sanchez A, Farrell-Poe KL (2001): Analysis and design of furrow irrigation systems. Journal of Irrigation and Drainage Engineering, 127, 161–169.

LIST OF ABBREVIATIONS:

P_T = applied load (N), l_r = spring length (m), E_y = modulus of elasticity (MPa), b_0 = spring width (m), a_0 = spring thickness (m), f = value of static deflection, δ_p = deflection magnification, n_p = number of spring skis in pipeline, ΣQ = total load on spring skis (N), Q_i = water flow through the i-th outlet ($m^3 \cdot s^{-1}$), μ_p = flow coefficient through outlet, ω = cross-sectional area (m^2), g = acceleration of gravity ($m \cdot s^{-2}$), H_u = flow head (m), H_{ui} = pressure head of flow through the i-th outlet (m), $S_в$ = area of top valve platform (m^2), $S_н$ = area of bottom valve platform (m^2), α = angle by which valve has to decline, allowing forecasting flow section of outlet (deg), F_1 = pressure force on upper parts of valve (N), F_2 = pressure force on bottom parts of valve (N), $\overline{V_i}$ = average speed ($m \cdot s^{-1}$), M_B = moment of force acting on upper parts of valve (N·m), M_H = moment of force acting on bottom parts of valve (N·m), b = coefficient taking into account configuration of valve, k = rate coefficient (equal to flow coefficient), V_{n} = average flow rate at the i-th outlet zone ($m \cdot s^{-1}$),$F_{i\alpha}$ = normal pressure force on upper parts of valve at the i-th outlet (N),F_{iH} = normal pressure force on bottom parts of valve at the i-th outlet (N), l_B = length of upper part of valve (m), l_H = length of bottom part of valve (m).

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