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Influence of the outlet system parameters of a horizontal bulb pump unit on its performance characteristics

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Abstract

Results of an extensive experimental study conducted in eighties at the former Leningrad Polytechnic Institute are revised and analysed in context of some further research. The optimum length of straight outlet tubes with diffuser of circular cross-section and the outlet/inlet cross-sectional area ratio are established. The optimum geometrical features of cranked type outlet tubes and the outlet tubes with diffuser cross-section transition from circular to square and rectangular ones are determined. Finally, the influence of the outlet conjunction channel slope on the pumping station efficiency is studied in detail.

Nomenclature

B	–	width of open inlet pump chamber
D	–	capsule diameter
D_1	–	impeller diameter

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F	–	cross-sectional area
H	–	head
h_{ch}	–	outlet channel depth
K_Q	–	discharge coefficient
K_H	–	head coefficient
L	–	length of the outlet system
l	–	length
l_0	–	discharge nozzle inlet cone length
$\bar{l}$	–	mixing length
m	–	conjunction slope ratio, $m = \tan\gamma$
n	–	rotation speed
Q	–	discharge
R	–	radius
t	–	blade cascade pitch
T	–	outlet system type
V	–	velocity
V_z, V_n, V_r	–	axial, peripheral and radial velocity components
V_{zmax}	–	maximum value of axial water velocity

Greek symbols

α	–	swirl angle of water
α_{uz}	–	corner peripheral angle swirl of water
α_{rz}	–	radial swirl angle of water
β	–	diffuser axis slope angle
γ	–	conjunction slope angle (Fig.2)
η	–	efficiency
θ	–	opening angle of the diffuser

Subscripts and superscripts

0	–	discharge nozzle inlet cone (Fig.2)
K	–	capsule, also the interim discharge nozzle segment (Fig.2)
D	–	discharge nozzle outlet diffuser
V	–	horizontal outlet apron (Fig.2)
C	–	sloping conjunction (outlet apron) (Fig.2)
u	–	peripheral
z	–	axial
r	–	radial
Q	–	discharge
H	–	head

Keywords: Pumping station; Bulb pump; Pump outlet system; Conjunction channel; Hydraulic laboratory; Performance tests; Design optimisation

1 Introduction

In connection with increased capacity of hydropower plants, increased requirements on the effectiveness of individual elements of the flow pathway and in particular, on the outlet (draft) tubes of power plants with horizontal bulb units, are ever more common. For low-pressure hydropower installations with horizontal units the outlet tube construction accounts up to 30% of the cost of the civil works [1–2]

Outlet tube, being one of the main elements of the feeder tract, largely determines the technical and economic parameters of a pumping stations as well [3]. It is designed for the following technological functions:

1. Conversion of kinetic flow energy into the pressure energy with minimum hydraulic losses in the outlet tube.
2. Formation of the flow pattern at the exit of a pump impeller.
3. Overflow and lock-up device of a pumping station.

To perform these functions the most effective elements of the outlet system are determined: adjustable guide vanes, the outlet stay vanes, discharge diffuser and the transition channel between the diffuser and the outlet channel. On the basis of analysis of the energy loss distribution in the flow path of hydraulic machines it is known that great power losses occur in the outlet tubes [4–6]. On the other hand, the level of hydraulic losses in the elements of the feeder tract largely determines the energy performance of a low-pressure pumping station with horizontal bulb unit.

The analysis of the ways to improve axial flow pumps shows that the possibility of increasing efficiency by improving the system impeller blades and that of the straightening guide vanes is a challenging task [4,7]. At the same time outlet tubes, in which intense flow separation and irreversible losses of energy occur, show considerable potential for increasing the efficiency of horizontal capsular (bulb) units [4].

The relatively large velocity head of the impeller axial pump and expansion of the flow in the outlet (discharge) tube cause the largest hydraulic energy loss. The influence of outflow device on the maximum efficiency point at the axial pump discharge characteristics has been also established [8]. The size and shape of the outlet tube show a significant influence on the performance characteristics of a pump unit. In some cases, the increase in the overall size of the outlet tube is accompanied by an increase in capital investments for construction and assembly work on the pump power plant building with a horizontal capsule unit. Hence, there exists an optimum variant of the outlet tube, in which the estimated expenditure of the pumping station will be minimal.

Investigations [18–19] show that the form of the downstream apron and its slope angle affect substantially velocity distribution in the exit section of the draft tube, which results in the change of efficiency and capacity of the turbine. The influence of conjunction slope ratio behind the draft tube on the turbine efficiency was investigated. The conjunction slope varied from m = 1:5 to m = 1:2. The estimation of energy efficiency has shown that with conjunction slope higher than m = 1:2, the efficiency tends to decrease. However, the investigations of a hydraulic unit model of Cherepovetskaya hydropower plant [20] have shown that the reversed conjunction slope of less than m = 1:4 does not influence the flow pattern in the afterbay.

Layout solutions with rectilinear configuration of the feeder tract have found the widest application in the tidal power plants (TPP) and hydropower plants (HPP) with bulb units, as such a configuration reduces flow resistance in the hydraulic generating set flow path. Reduction of hydraulic losses can be also achieved by providing optimum flow conditions at the inlet of the diffuser [5,9–14]. In some cases, outlet tubes with small uplift deflection of the diffuser can be used; this reduces the amount of excavation and concrete work on the underground part of the plant building [15]. In this connection two types of outlet tubes have been investigated – a straight and a bent one. Figure 1 shows a pumping station block model with a horizontal bulb unit.

2 Statement of the problem

2.1 Optimization task

The study was conducted in order to develop a computer model to optimize parameters of the outlet tubes of large pumping stations with horizontal capsular units. This model is a part of the general method of optimizing the parameters of pumping stations of water supply systems. To construct the model for optimizing the shape of the outlet tube the main parameters were identified. Their optimization should be carried out jointly [1]. Both the type of the outlet tube and geometrical parameters are to be taken under consideration. Geometrical parameters include the length of the outlet tube elements (l_0, l_K, l_D, l_V) and the opening angle of the outlet tube elements (θ_0, θ_K, θ_D). Geometrical parameters are shown in Fig. 2. The parameters of the outlet channel conjunction include l_V, l_C, γ or l_V and m for straight outlet systems. The alternative conjunction with

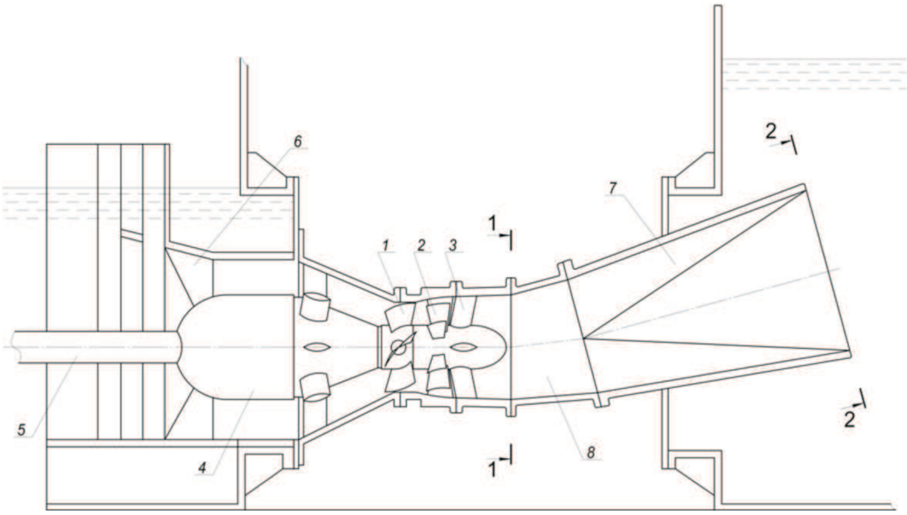


Figure 1: A pumping station model with a horizontal bulb unit: 1 – impeller, 2 – straightening guide vanes, 3 – stay vanes, 4 – streamlined capsule, 5 – shaft housing, 6 – closed water-supply chamber, 7 – outlet tube diffuser, 8 – elbow. Measuring sections (section 1–1) and outlet (section 2–2).

the outlet channel is shown by a dashed line and is determined by the diffuser axis slope angle β.

With selected geometrical parameters and the type of the outlet tube the cross-sectional area variation along the length, F, is uniquely determined. These parameters enable complete mathematical description of the outlet tube.

2.2 Experimental setup and models of outlet tubes

Studies of the performance and hydraulic characteristics of the pump station block model with an impeller diameter $D_1 = 0.35$ m were performed at a special stand in the laboratory of the Department of Water Power Utilisation of the Leningrad Polytechnical Institute [16], Fig. 3.

The pumping station model encompasses a horizontal bulb unit with the impeller blade system OP-6 and $D_1 = 0.35$ m diameter. In experimental installation the guide vane apparatus is placed behind the impeller. It provides for decrease of the flow vorticity in the outlet system in a wide range of operation modes. The guide vane cascade consists of twelve vanes of variable thickness. It allows to block the water flow. The cascade density equal $l/t = 1.1$ has been assumed.

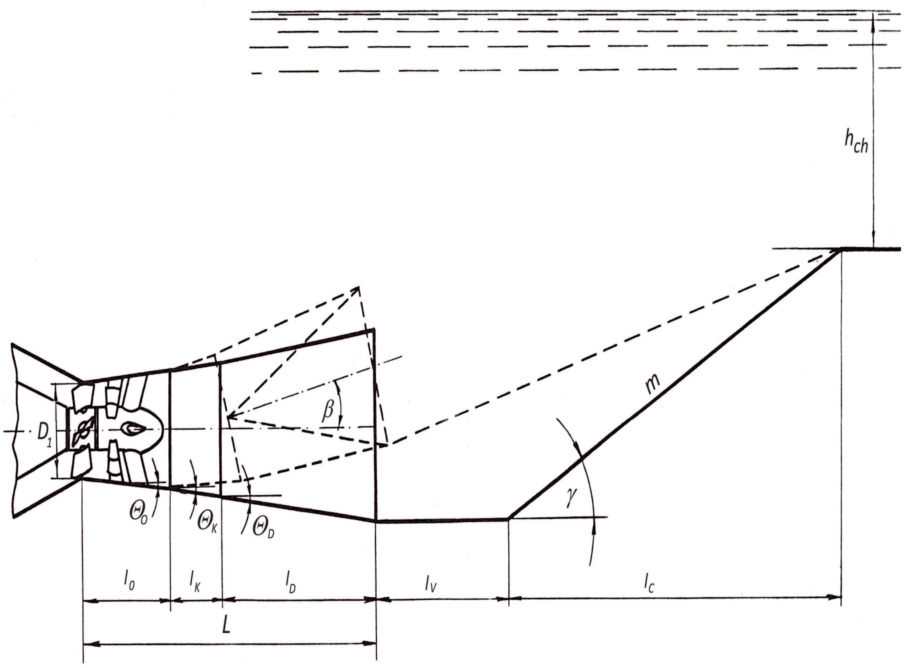


Figure 2: Geometric parameters of the outlet system.

Here l – length of vane section chord; t – blade cascade pitch. The guide vane cascade effect is assessed basing on the computational fluid dynamic analysis. The reversed task of water axial flow in the hydraulic machine was solved [21].

Experimental simulation was carried out in compliance with the conditions: Froude number Fr = idem in the area of self-similarity at Reynolds number $\mathrm{Re} > 5 \times 10^5$. Energy and hydraulic studies of the outlet tube of a pump station block with a bulb unit were conducted in accordance with international guidelines for model tests (IEC 60193:1999, Hydraulic turbines, storage pumps and pump-turbines. Model acceptance tests) [17]. The performance characteristics of the pump unit were developed for fixed setting of impeller blades and the straightening guide vane apparatus.

While studying the influence of conjunction parameters on performance characteristics of the pump unit two outlet systems were investigated: straight one with various conjunction slope and a bent one with various angle of diffuser axis slope. Figure 4 shows the geometrical parameters of outlet systems with circular/square transition of the diffuser cross-section. The transition from circular to square

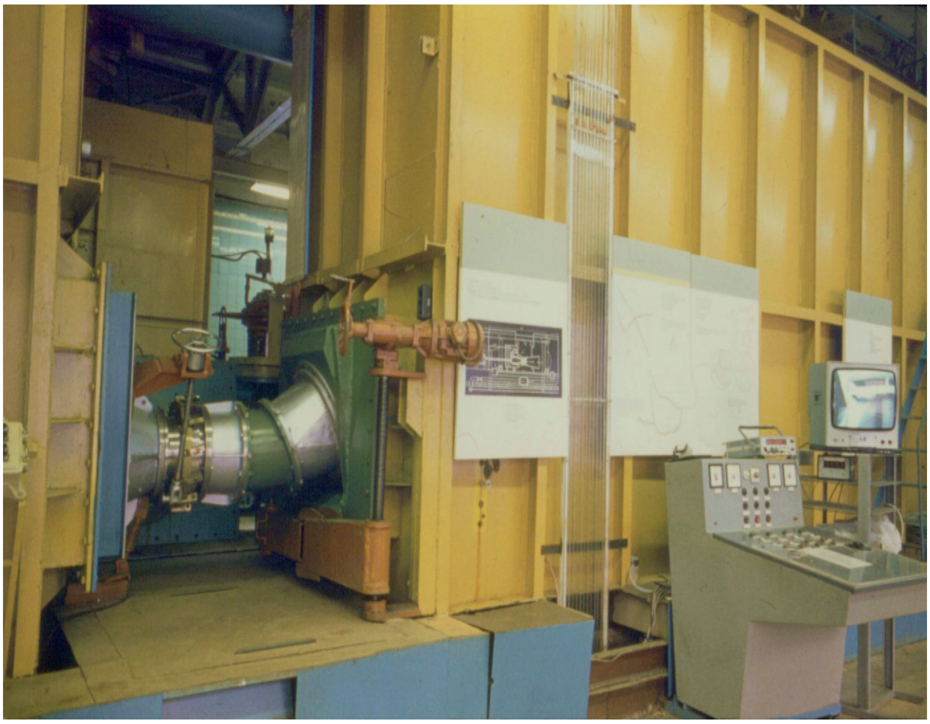


Figure 3: Photo of the experimental stand.

section takes place at 2.5 D_1 distance from the inlet. The length of the outlet system is equal $L = 4.5D_1$.

The following models of outlet tubes were studied: straight divergent cone of circular section with transition to a square section and with transition to a rectangular section. We have also investigated the models of outlet systems with diffuser axis slope angle $\beta = 0°$, $7°$, $15°$, and $25°$. Experimental studies were conducted at the constant shape and size of the remaining flow part.

The hydraulic investigations of outlet unit were carried out with the purpose to estimate the head losses and to determine the velocity fields. Water velocity was measured in section behind the correcting device for diffuser inlet and for output from it (Fig. 5). The measurement of water velocities flow was conducted by means of five-channel spherical probes and velocity meters. Measurement of water flow was carried out by a venture flow meter. The torque at the shaft was measured by means of a motor-balance with a DC motor, the pressure was determined from the readings of the piezometers [16].

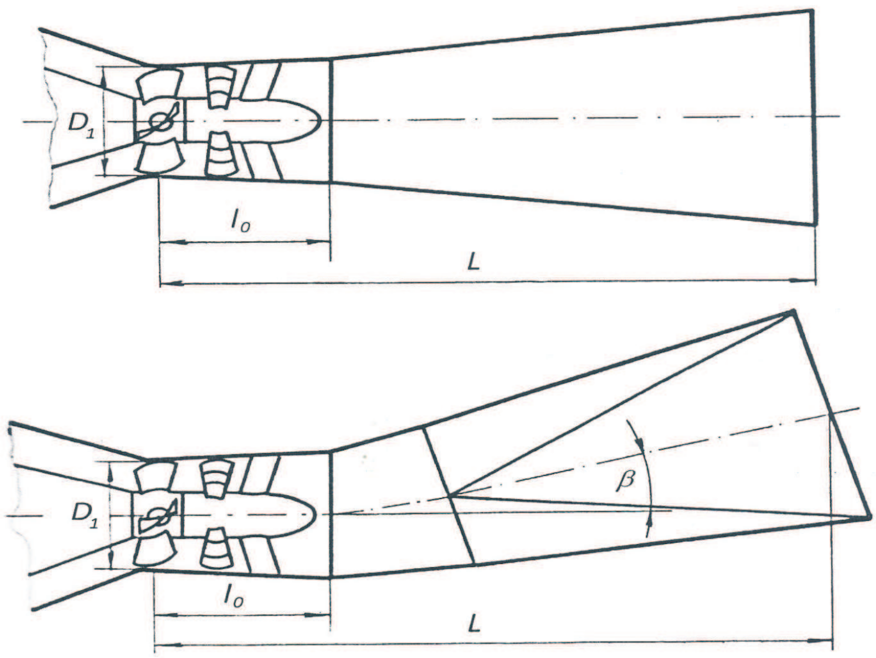
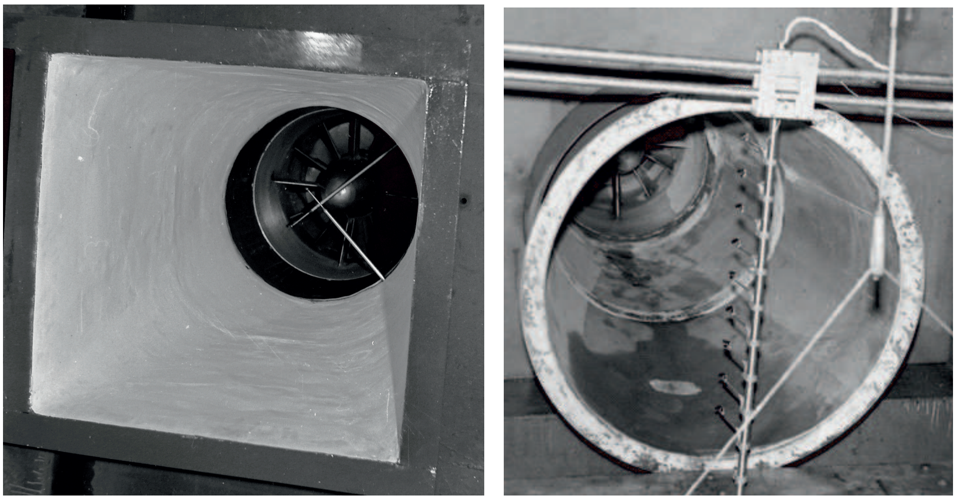


Figure 4: Investigated types of outlet tubes: straight and bent one.

3 Results of performance tests

The water velocity fields at the unit inlet and outlet have been investigated for various layout parameters of the unit. The following notation is used furtheron for velocity components: V_z – axial velocity, V_u – peripheral velocity, and V_r – radial velocity (Fig. 6). For example, in Fig. 7 the flow pattern at the unit inlet and outlet (the last one featured by a circular-cross section) are shown. Inlet section 1-1 is located at the distance of $l_0 = 1.25\,D_1$ from the pump impeller. The distributor with 12 guide vanes, stator with 4 stay vanes and small capsule, closing the discharge bulb contour, are located there.

It has been established experimentally that at the inlet of the discharge diffuser the symmetric velocity structure is formed (Fig. 7). However distribution of water velocity is nonuniform. The central part of the cross-sectional velocity field is occupied by the hydrodynamic wake downstream the flow straightening system bulb. The zone of the negative axial component of the velocity vector takes from



a) b)

Figure 5: Models of outlet system of a horizontal bulb pump unit with outlet tube diffusers: a) straight discharge system with diffuser featured by the circular/square; b) with the diffuser of circular section.

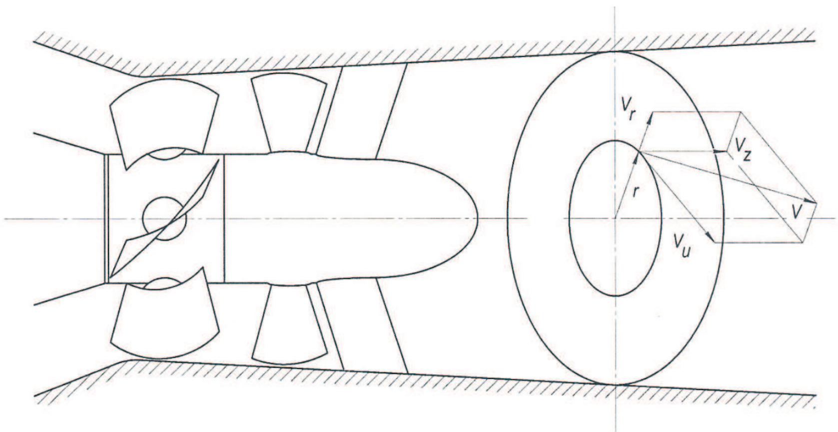
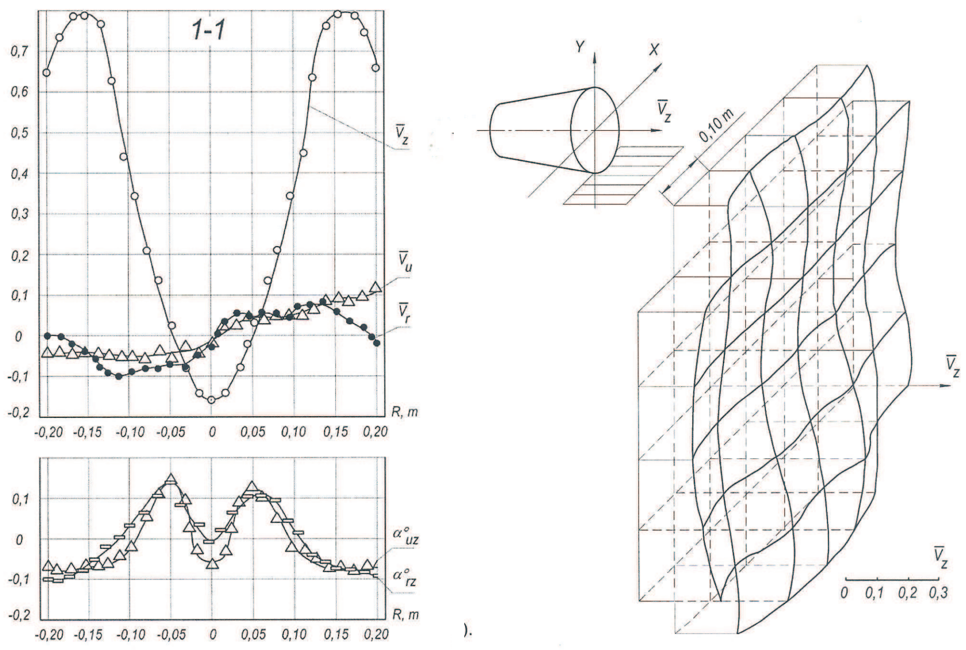


Figure 6: Water velocity components.

5% up to 7% of the cross-sectional area. The maximum values of axial component are displaced at the peripheral part of section (on radius equal to 0.15 m).

The cross-sectional velocity distribution in section 1-1 is shown in Fig. 7.



a) b)

Figure 7: Water average velocities distribution a) at inlet (section 1-1); b) and outlet (section 2-2) of the straight discharge system with conical diffuser and interfacing slope ratio equal to $m = 0$.

The velocity structures show symmetric pattern. The peripheral water velocity component grows monotonously from the central part to the periphery. The distribution of the radial water velocity component is more complex. The radial velocity value V_r at the peripheral part is practically zero, grows closer to the center and then decreases to zero at the diffuser axis. The axial water velocity component in section 1-1 makes 95–99% of the absolute velocity.

The corner peripheral swirl angles of water:

$$\alpha_{uz} = \arctan \frac{V_u}{V_z} , \tag{1}$$

show the maximal value of 20–22° at radius 0.05 m and decrease down to $\alpha_{uz} =$ 3–4° in the peripheral part of section. The radial swirl angle of water in the peripheral part of the section:

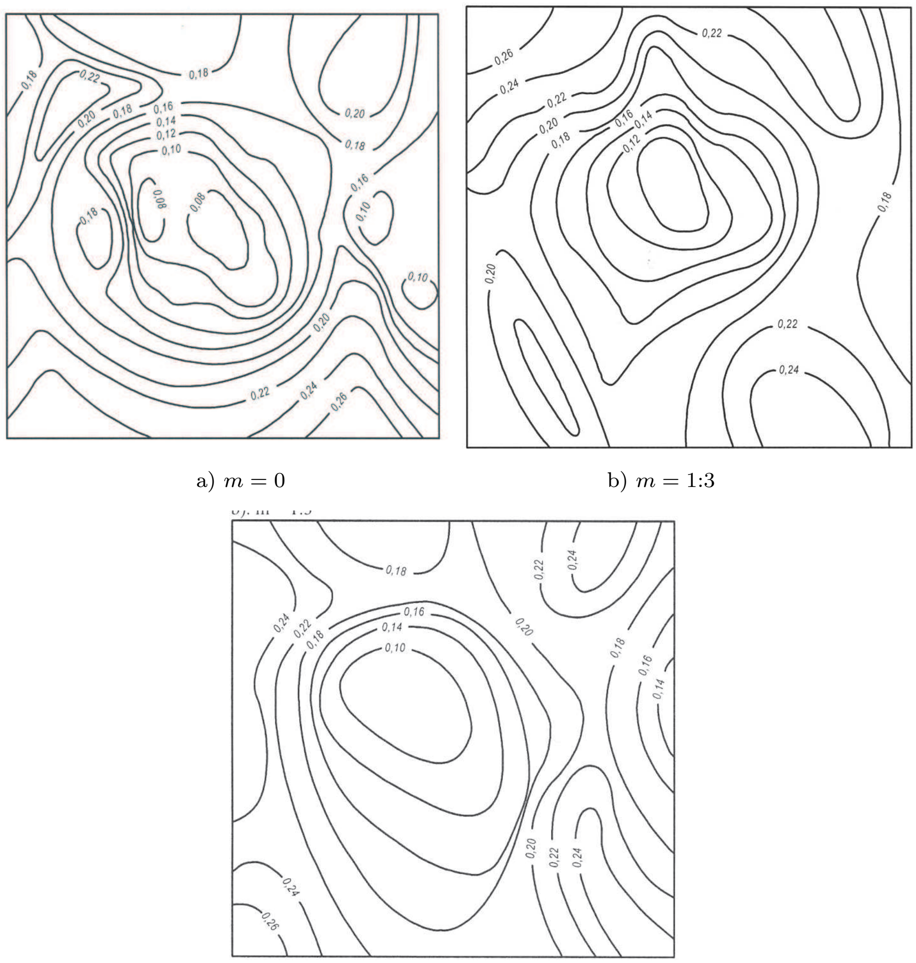
$$\alpha_{rz} = \arctan \frac{V_r}{V_z} , \tag{2}$$

takes the values of $\alpha_{rz} = 1\text{–}2°$, and 20° when closer to the central portion at radius 0.05 m. The average weighted value of the axial and radial swirl angles in section 1-1 at discharge factor $K_Q = 0.44$ are $\alpha_{uz} = 7°6'$ and $\alpha_{rz} = 5°46'$, respectively. The Coriolis factor in section 1-1 is $\alpha_K = 1.62$.

As a result of the water flow analysis in section 1-1 it has been shown, that the inlet structure is defined by the form and geometrical parameters of the upstream flow system portion in which the flow straightening system is established. The analysis of water flow structure in section 1-1 has shown, that the type of discharge system does not influence character of water flow at inlet to this system, which is defined by the mode of pump operation.

For section 1-1 it has been established that the water flow structure is formed by the impeller and the flow straightening system. It depends also on the operation mode. Further research was carried out on operation of the pump power block model with the open inlet pump chamber width $2D_1$ and capsule diameter $D_K = 0.676D_1$. The measurements were carried out in optimum operational modes of pump power block model. In section 2-2 at outlet of the discharge system with diffuser of circular section ($L = 4.5D_1$, $F_{outlet}/F_{inlet} = 4$) at a optimum point of operation the water flow velocity field is nonuniform.

The hydrodynamic wake of the flow straightening system is observed in the target section of the diffuser (area of small velocity is the central part of section). The axial velocities are distributed nonuniformly in section 2–2. In the central part of this section the maximum value of axial water velocity are about a wall, and minimal are closer to an axis of a flow $V_{zmax}/V_{cp} = 1.506$. The value of the axial velocity in section 2-2 makes 87-94% of the absolute water velocity. The peripheral and radial velocities are distributed more regularly than the axial velocity. Figure 8 shows the distribution of axial velocities in section 2-2 of the discharge system with diffuser accomplishing transition from the circular to the square cross-section, at $2D_1$ distance from the impeller. In comparison with diffuser of circular cross-section the nonuniformity of velocity distribution is higher. In section 2-2 of velocity in the central part are small. The maximum value of axial velocity is attained close to the wall. We have established experimentally that the flow field pattern in the target section of the discharge system is influenced by the conditions at interface with the outlet channel. The characteristics of water flow at outlet of the straight discharge system such as at various embankments are shown in a Fig. 8.



a) $m = 0$ b) $m = 1{:}3$

c) $m = 1{:}2$

Figure 8: Cross-sectional velocity distribution at outlet section 2-2 of the straight discharge system with diffuser featured by the circular/square cross-section transition ($L = 4.5D_1$, $F_{outlet}F_{inlet} = 4$) at various conjunction slope ratios, m.

Transformation of the water velocity field at outlet section of the discharge flow system with increasing the embedment conjunction slope up to $m = 1{:}2$ can be noticed. In section 2-2 the nonuniformity of axial velocities is increased, that results in rising energy losses in the discharge system. The decrease of axial water velocities in the bottom part of section is appreciable, and in the top part of section an increase of axial water velocities can be noticed (Fig. 9).

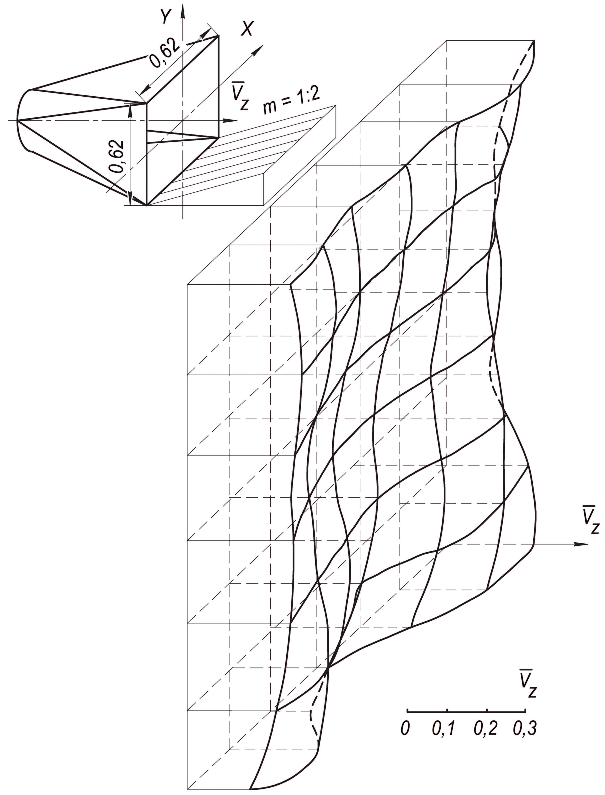


Figure 9: Cross-sectional velocity distribution at outlet section 2-2 of the straight discharge system with diffuser featured by transition from the circular to square cross-section ($L = 4.5D_1$, $F_{outlet}/F_{inlet} = 4$) and the conjunction slope ratio $m = 1{:}2$.

As a result of experimental studies following depedencies for efficiency and head coefficient the outlet system type have been established:

$$\eta = f_\eta(T, \bar{l}, \beta, \theta, m, K_Q) , \tag{3}$$

$$K_H = f_H(T, \bar{l}, \beta, \theta, m, K_Q) , \tag{4}$$

where T is the outlet system type, $\bar{l}$ – mixing length, β – slope angle of the outlet diffuser axis, θ – the outlet system type and m denotes conjuction slope ratio. Models (3) and (4) are based on the optimization of the outlet tubes of pumping stations with horizontal capsular unit. These are the results of experimental

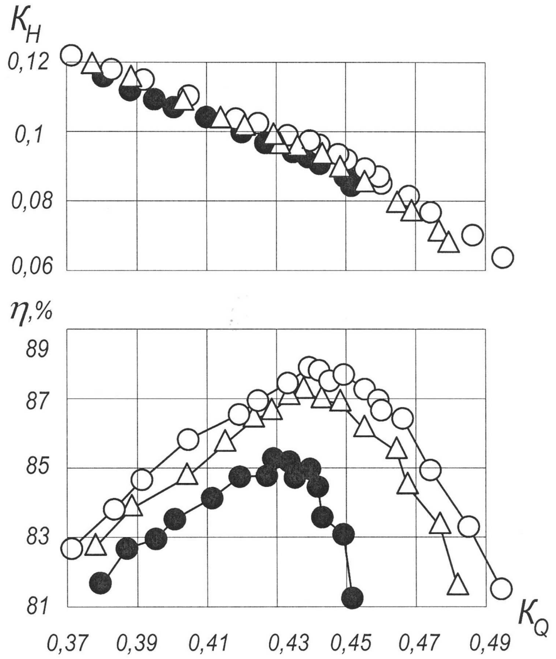


Figure 10: Influence of conjunction slope m on performance characteristics of a pumping station with a bulb unit. ○ – $m = 0$, △ – $m = 1{:}5$, ● – $m = 1{:}2$.

studies of the outlet tubes of straight and crank types which have been plotted using dimensionless coordinates of head K_H and discharge coefficients K_Q:

$$K_H = \frac{H}{n^2 D_1^2}\,, \tag{5}$$

$$K_Q = \frac{Q}{n D_1^3}\,, \tag{6}$$

where H and Q are the head and discharge, respectively, n is the rotation speed and D_1 is the impeller diameter. Some simplified functions (3) and (4) obtained on the basis of performance tests are shown in Fig. 10.

4 Conclusions

1. It is an established fact that the size and shape of the flow part of the outlet tube in the feeding tract of a low-pressure pump have a profound influence

on the performance characteristics of the pumping station. Therefore, the effectiveness of a pumping station with bulb units is intimately associated with determination of the optimum shape and dimensions of the outlet tube.

2. It has been established experimentally that for the outlet tubes of straight type with diffuser of circular section, maxima of efficiency occur when the length of the outlet tube is equal to $5D_1$ and the ratio F_{outlet}/F_{inlet} equals 4. The outlet tubes with diffuser transitions to square and rectangular cross-sections at the $2.5D_1$ length of the tube of the total length $L = 4.5D_1$, reduce the maxima of the efficiency of the pump unit, respectively to 0.7% and 0.9% in comparison with the diffusers of circular section. The use of the outlet tube of a cranked type with an angle of ascent of the diffuser axis of 15°, starting at the distance $2D_1$ of the impeller axis of the pump, reduces the value of efficiency by 0.5% in the zone of the optimum characteristics in comparison with the outlet tube of straight type (for $L = 4.5D_1$, $F_{outlet}/F_{inlet} = 4$).

3. The experimental performance characteristics of the pump power plant block model have been determined for various conjunction slopes downstream the diffuser outlet section. A decrease in the maximum efficiency values occurs at the conjunction channel slope m = 1:2 No influence on the power efficiency was observed for conjunction channel slopes m = 1:5 and m = 1:4. The increase of the slope from $m = 0$ to m = 1:2 results in a decrease of efficiency by 0.6% and the displacement of the efficiency characteristics optimum zone to the left. At the conjunction slope m = 1:1 the decrease of power efficiency by 2.5% takes place.

4. Practically equal decrease of efficiency by 0.5% and 0.6%, respectively, has been established in the zone of maximum values of the bent type outlet system with $\beta = 15°$ and the straight type outlet system with conjunction channel slope m = 1:2, beginning right behind the discharge tube outlet section.

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