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ENGINEERING PHYSICS

The Development of a Physico-Mathematical Model for the Functioning of an Underwater Waterjet Cutting Machine

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Abstract—A single-phase physico-mathematical model of a high-speed waterjet forming process that uses the underwater abrasive waterjet cutting technology while an abrasive-liquid flow under a pressure ranging from 60 to 80 MPa passes through the jet-forming path of a mobile abrasive waterjet machine has been developed. The results of a numerical experiment are presented. It has been shown that the main structural parameters of the internal profile of the jet-forming element (the profile of the focusing cavity, diameter and length of the output-channel) influence the geometric and kinematic parameters of the formed jet and the consumption of the hydro-abrasive suspension.

Keywords: underwater abrasive waterjet cutting, high-speed waterjet, jet-formation process, mathematical modeling.

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INTRODUCTION

The technology of ultrajet treatment and cleaning with a high-speed liquid jet is actively used in mechanical engineering [1–3]. At the same time, these technologies are beginning to be applied in other domains, including underwater technology. As an example, manned and unmanned submersible vehicles are successfully used to execute various underwater technical works and to develop the resources of the World ocean [3–7]. In many cases, it is impossible to fulfill the required tasks without equipping a submersible vehicle with a special tool that is capable of executing underwater cutting of various materials. Cutters of different types, circular and chain saws, and perforators, as well as drill and milling heads are used for this. However, the long-term experience from using the traditional underwater tools has shown that often the existing traditional underwater cutting technologies do not perform the required works. Therefore, the problem of development of new methods for cutting under underwater conditions that are universal with respect to the type of treated materials and the geometry of cutting is of great relevance.

One of the technologies that is capable of solving this set of problems is the abrasive waterjet cutting (AWJ) technology, which fragments different structural elements of various materials, including their dimensional treatment, for example, for welding, deep-hole drilling, etc. Since the surrounding sea water is a limitless expendable material for AWJ, the use of such a technology under underwater conditions is quite logical and promising. However, development of the AWJ technology requires a serious scientific adaptation because of the specificity of its application in the submerged state; its practical implementation imposes specific requirements on the parameters of the jet-forming path, namely, on the hydro-abrasive suspension supply system, the parameters of the nozzle unit, and others.

Studies have been devoted to using the AWJ technology under underwater conditions [8], as well as material treatment by submerged jets [3, 9, 10]. However, the problem of optimization of underwater hydro-abrasive treatment with respect to the suspension consumption and the processing speed remains practically unstudied. Therefore, the aim of this study was to determine the influence of structural parameters of the nozzle unit (including geometrical, strength, and technological parameters) on the process of formation of a hydro-abrasive jet under

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water and to develop practical advice to enhance the efficiency of the considered technological process. To estimate the parameters of the efficiency of the formed jet flow, we used the time functional dependence obtained by calculations that characterizes the change in the depth of the formed cavity in the water and analyzed the interrelation between the structural parameters of the hydrosystem, the character of the process of hydro-abrasive suspension outflow (the diameter and velocity of the formed flow, the degree of its dispersion), and the value of the hydro-abrasive suspension consumption.

1. PROBLEM FORMULATION AND CALCULATION PROCEDURE

The structural schemes of the jet-forming elements used in the investigations on the influence of their parameters on the process of formation of the high-speed hydro-abrasive jet are presented in Fig. 1. The following numerical values of structural parameters were used: $D_s = 7.2$ mm is the outer diameter of the nozzle unit; $d_0 = 4.8$ mm, $d_1 = 0.5d_0$, $d_s = 0.2$–0.8 mm are the input (two first quantities) and output diameters of the nozzle, respectively; $H_3 = 10$–76 mm is the height of the nozzle unit; $H_1 \geq 1.5$ mm, $H_2 = 6.3$–8.5 mm is the height of the cylindrical part of the nozzle unit adjacent to the input hole; $\alpha = 13$–$180°$ is the cone angle of the conic part of the nozzle unit. According to the calculation scheme (Fig. 1), other parameters of the jet-forming path were taken as follows: $H_4 = 20$ mm; $H_5 \approx H_3 - H_1$. As a model of hydro-abrasive suspension, we have taken the model of homogeneous substance under a pressure $p = 60$–80 MPa (Fig. 1, no. 3). The initial suspension density was calculated from the condition 11% ($K_{V_a} = 0.11$) of the volume content of finely dispersed particles of garnet sand in water ($\rho_a = 2.38$ g/cm^3) and its value was found to be $\rho_{\text{j}} = 1.15$ g/cm^3. As a liquid medium located before the back cut of the jet-forming unit (Fig. 1a–1d, no. 2) and before the input to the jet-forming element (Fig. 1b, no. 4), we used light water, whose initial density was determined according to the shock adiabat from the condition of correspondence to the external pressure applied to it. It is obvious that at the zero external pressure ($p_m = 0$), the initial water density is $\rho_0 = 1.0$ g/cm^3. As the material of the jet-forming element, we used the model of absolutely rigid body.

The formulated problem was solved numerically in the two-dimensional axisymmetric statement in the stationary coordinate system with the use of the hydrodynamical model of interacting materials in the environment of the ANSYS/Autodyn programming complex. The process of high-speed hydro-abrasive

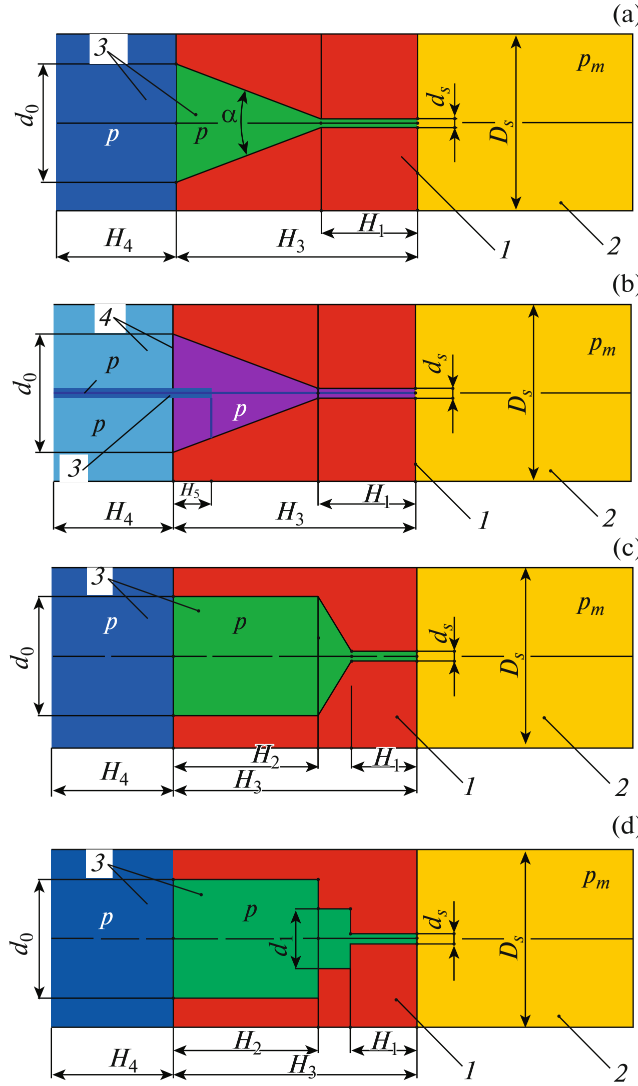


Fig. 1. The scheme of the jet-forming element (a nozzle or a focusing tube): *1*, nozzle unit; *2*, surrounding medium (water under pressure p_m); *3*, water with abrasive under pressure p; *4*, water with no abrasive under pressure p.

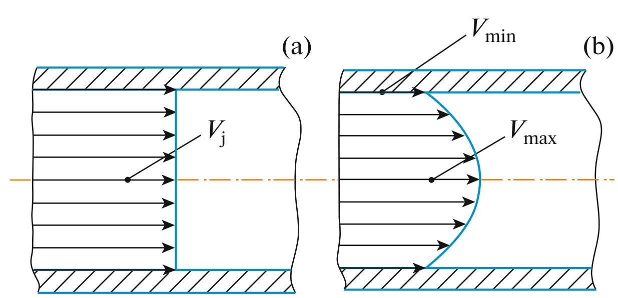


Fig. 2. The velocity vector distribution over the cross section of the jet-forming channel (a), theoretical and (b) real.

Table 1. The influence of the output diameter and length of the focusing tube and the pressure in the hydraulic system on the axial component of the velocity of flowing hydro-abrasive suspension ($K_{V_a} = 0.11$; $\rho_{\text{j}} = 1.15$ g/cm^3, $V_R = 0$)

No.	p/p_m, MPa	d_{out}, mm	Shape of the jet-forming path			$V_{\text{j}}/V_{\text{j2}}$, km/s	W_{th}, l/min ($\eta = 0.89$)	W_{cal}, l/min ($\eta = 0.7$)
			Schemes of Fig.1	H_3, mm	H_1, mm			
1	80/–	0.2	*a*	10	1.5	0.373/0.35	0.63–0.59	0.49–0.46
2	80/–	0.3	*a*	10	1.5	0.373/0.36	1.41–1.36	1.10–1.07
3	50/–	0.4	*a*	10	1.5	0.295/–	1.98	1.55
4	60/–	0.4	*a*	10	1.5	0.323/0.31	2.17–2.08	1.70–1.63
5	80/–	0.4	*a*	10	1.5	0.373/0.365	2.81–2.75	1.96–1.92
6	100/–	0.4	*a*	10	1.5	0.417/–	2.80	2.20
7	150/–	0.4	*a*	10	1.5	0.511/–	3.43	2.69
8	200/–	0.4	*a*	10	1.5	0.590/–	3.96	3.11
9	80/–	0.4	*a*	76	67.5	0.373/0.3	2.50–2.01	1.96–1.58
10	80/–	0.3	*a*	10	4	0.373/0.36	1.41–1.36	1.10–1.07
11	80/–	0.4	*a*	10	4	0.373/0.365	2.50–2.45	1.96–1.92
12	80/–	0.5	*a*	10	4	0.373/0.365	3.91–3.83	3.07–3.00
13	80/–	0.3	*a*	20	11.5	0.373/0.35	1.41–1.32	1.10–1.04
14	80/–	0.4	*d*	10	1.5	0.373/0.3	2.50–2.01	1.96–1.58
15	85/5	0.4	*d*	10	1.5	0.373/0.32	2.50–2.15	1.96–1.68
16	90/10	0.4	*d*	10	1.5	0.373/0.335	2.50–2.25	1.96–1.76
17	100/20	0.4	*d*	10	1.5	0.373/0.34	2.50–2.28	1.96–1.79
18	120/40	0.4	*d*	10	1.5	0.373/0.34	2.50–2.28	1.96–1.79
19	80/–	0.6	*a*	10	1.5	0.373/–	5.63	4.42
20	80/–	0.7	*a*	10	1.5	0.373/–	7.66	6.01
21	80/–	0.8	*a*	10	1.5	0.373/	10.01	7.86

jet formation was described by the following system of differential equations [11, 12]:

$$\frac{d\rho}{dt} + \rho\left(\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} + \frac{V_y}{y}\right) = 0,$$

$$\rho\frac{dV_x}{dt} = -\frac{\partial p}{\partial x}, \quad \rho\frac{dV_y}{dt} = -\frac{\partial p}{\partial y},$$

$$\rho\frac{de}{dt} = \frac{p}{\rho^2}\frac{d\rho}{dt}, \quad p = p(\rho, e), \qquad (1)$$

where ρ is the density; p is pressure; e is the specific internal energy; t is the current time; x, y are the axial and radial coordinates, respectively; V_x, V_y are the axial and radial components of the velocity vector, respectively. In system of equations (1), the differential equations are presented in the following order: the equations of mass, momentum, and energy conservation, and the state equations of the interacting media in the general form. As the state equations for water, the following relationships were used:

$$p = A_1\mu + A_2\mu^2 + A_3\mu^3 + (B_0 + B_1\mu)\rho_0 e,$$

$$\mu = (\rho/\rho_0 - 1) \geq 0$$

$$\text{and} \quad p = T_1\mu + T_2\mu^2 + B_0\rho_0 e, \quad \mu \leq 0, \qquad (2)$$

where ρ_0, ρ and μ are the initial and current values of the water density and compressibility, respectively; $A_1 = 2.2$ GPa, $A_2 = 9.54$ GPa, $A_3 = 14.57$ GPa, $B_0 = B_1 = 0.28$, $T_1 = 2.2$ GPa, $T_2 = 0$ GPa are empirical coefficients [11]. To consider the liquid cavitation in the process of outflow from the nozzle and subsequent motion of the hydro-abrasive jet in the water in the region of negative pressures, we have taken $p = 0$. In this case, the liquid is incapable of responding to the tensile forces and behaves as a bulk substance or, in other words, is destroyed. It was also

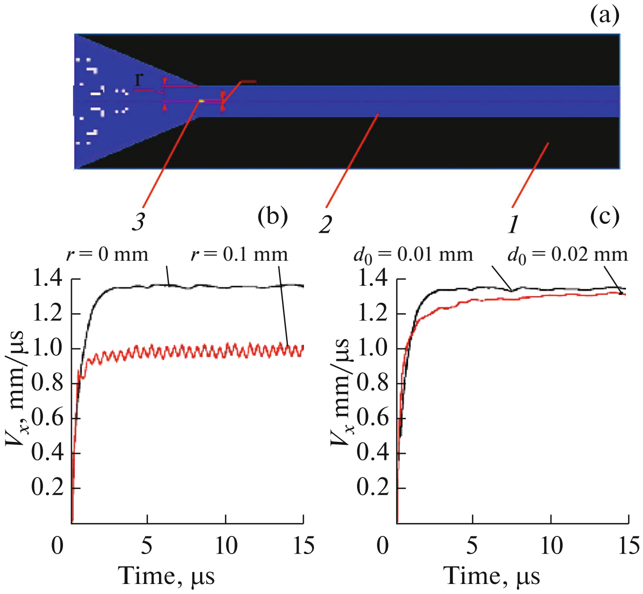


Fig. 3. The calculation model (a) and the character of acceleration of the abrasive particles (*1*) in the channel (*2*) of the focusing tube (*3*) depending on their location (b) and size (c), where d_a is the diameter of an abrasive particle; r is the distance between the particle and the symmetry axis; V_x is the axial component of the velocity of abrasive particles.

assumed that at the initial instant, the considered liquids are immobile, however they experience external pressure. For the above-described interacting liquid components, the initial conditions are as follows:

$$t = 0, \quad V_x = V_y = 0,$$
$$p = 60\text{–}80 \text{ MPa}, \quad p_m = 0\text{–}10 \text{ MPa}, \qquad (3)$$

where p is the pressure in the jet-forming system; p_m is the pressure in the surrounding medium (Fig. 1, no. 2). The densities of hydro-abrasive suspension and water at the initial instant were determined according to relationship (2) with condition (3) taken into account.

2. DISCUSSION OF RESULTS

The calculations revealed some peculiarities of the process. In particular, it was shown that the inner profile and the outlet diameter of the focusing tube do not cause a considerable effect on the axial component of velocity of the flowing jet. From the condition of pressure constancy in the jet-forming system (see Fig. 1, nos. 3 and 4), the numerical values of the velocity of the flowing jet (V_{j}) can be calculated with a high accuracy according to the Bernoulli formula:

$$V_{\text{j}} = \sqrt{2(p - p_m)/\rho_{\text{j}}}, \qquad (4)$$

where ρ_{j} is the density of the hydro-abrasive jet. The results of the calculations are presented in Table 1,

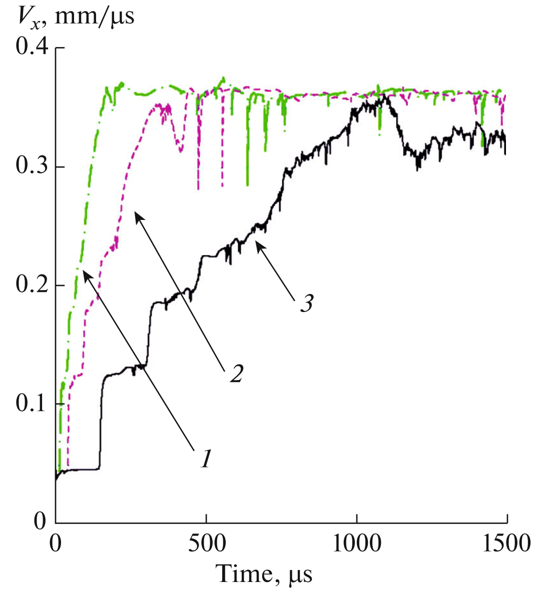


Fig. 4. The axial component of the velocity (V_x) attained by the suspension at the output of the nozzle d_s = 0.4 mm with time (*1*) for the nozzle with a length of 10 mm, (*2*) for the nozzle with a length of 12 mm, (*3*) for the nozzle with a length of 20 mm).

where V_{j2} are the numerical values of the jet velocity obtained by numerical integration of the system of equations (1) provided that the constancy of pressure in the hydraulic system occurs.

Along with the kinematic parameters of the hydro-abrasive flow, Table 1 presents the numerical values

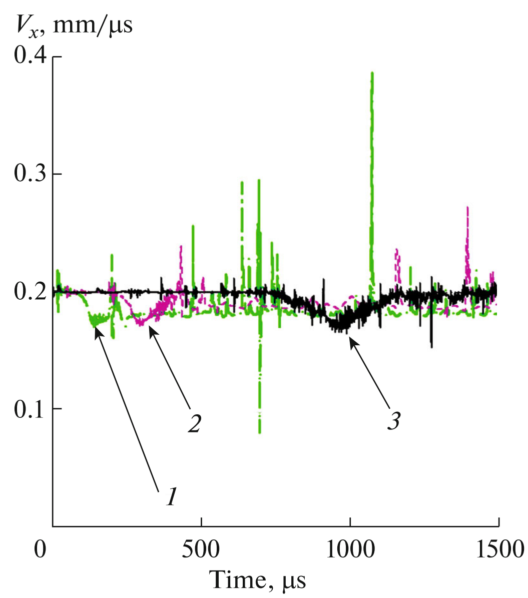


Fig. 5. The radial component of velocity (V_y) attained by suspension at the nozzle output d_s = 0.4 mm with time (*1*) for the nozzle with a length of 10 mm, (*2*) for the nozzle with a length of 12 mm, (*3*) for the nozzle with a length of 20 mm.

Table 2. The influence of the hydrosystem parameters on the axial component of the outflow velocity and the flow rate of the hydro-abrasive suspension ($K_{V_a} = 0.29$; $\rho_j = 1.4$ g/cm^3, $V_R = 0$)

No.	p/p_m, MPa	d_{out}, mm	Shape of jet-forming path			V_j, km/s	W_{th}, l/min ($\eta = 0.71$)	W_{cal}, l/min ($\eta = 0.558$)
			Schemes of Fig. 1	H_3, mm	H_1, mm			
1	80/–	0.2	*a*	10	1.5	0.338	0.452	0.355
2	80/–	0.3	*a*	10	1.5	0.338	1.017	0.799
3	50/–	0.4	*a*	10	1.5	0.267	1.430	1.123
4	60/–	0.4	*a*	10	1.5	0.293	1.566	1.230
5	80/–	0.4	*a*	10	1.5	0.338	1.809	1.420
6	100/–	0.4	*a*	10	1.5	0.378	2.022	1.588
7	150/–	0.4	*a*	10	1.5	0.463	2.477	1.944
8	200/–	0.4	*a*	10	1.5	0.535	2.860	2.245
9	80/–	0.4	*a*	76	67.5	0.338	1.809	1.420
10	80/–	0.3	*a*	10	4	0.338	1.017	0.799
11	80/–	0.4	*a*	10	4	0.338	1.809	1.420
12	80/–	0.5	*a*	10	4	0.338	2.826	2.219
13	80/–	0.3	*a*	20	11.5	0.338	1.017	0.799
14	80/–	0.4	*d*	10	1.5	0.338	1.809	1.420
15	85/5	0.4	*d*	10	1.5	0.338	1.809	1.420
16	90/10	0.4	*d*	10	1.5	0.338	1.809	1.420
17	100/20	0.4	*d*	10	1.5	0.338	1.809	1.420
18	120/40	0.4	*d*	10	1.5	0.338	1.809	1.420
19	80/–	0.6	*a*	10	1.5	0.338	4.070	3.195
20	80/–	0.7	*a*	10	1.5	0.338	5.540	4.349
21	80/–	0.8	*a*	10	1.5	0.338	7.235	5.680

of the flow rate of the used hydro-abrasive suspension (W) depending on the diameter of the outlet hole of the jet-forming tube (d_s), which were calculated 0.25 ms after the moment when the device was turned on. Here, W_{th} is the theoretical value of the suspension flow rate determined on the assumption of an uniform distribution of the velocities over the cross section (Fig. 2a) and W_{cal} is its calculated value. We note that W_{cal} is somewhat less than W_{th}. This fact can be explained by the results of calculations that show that the velocities of the particles located closer to the walls are lower than those of the particles located in the jet center (Fig. 3). The velocity distribution over the cross section of the cylindrical channel is parabolic (Fig. 2b); the maximum value of the axial component of velocity is on the symmetry axis, while its minimum value is near the channel walls.

Based on all the above, we can propose the following dependence to determine the flow rate of hydro-abrasive suspension (l/min):

$$W = W_{cal} = \eta 60\pi (d_s/2)^2 V_j \quad (5)$$

where d_s (mm) is the diameter of the outlet hole;

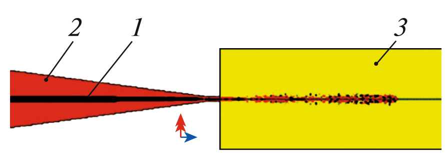
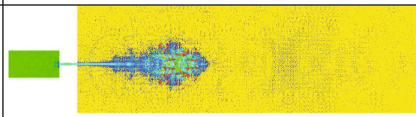
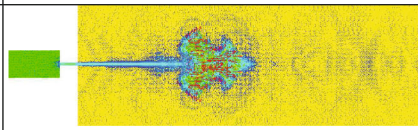
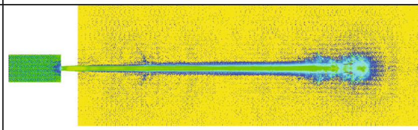
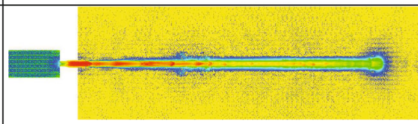


Fig. 6. The specificity of the process of formation and the structure of the hydro-abrasive jet in the case of a central supply of suspension to the focusing tube (*1*, abrasive suspension under pressure; *2*, water with no abrasive under pressure; *3*, surrounding medium).

Table 3. The influence of the nozzle diameter on the character of the jet-forming process at $p = 80$ MPa

No.	d_s, mm	Point in time, ms	Visualization
1	0.2	0.25	
2	0.3	0.25	
3	0.4	0.25	
4	0.5	0.20	

V_j (km/s) is the velocity of hydro-abrasive suspension flowing from the jet-forming tube, respectively; η is the coefficient considering the volume concentration of abrasive in the suspension and inhomogeneity of the distribution of the axial component of velocity over the radius of the jet flow. In the general case, this coefficient can be calculated by using the following formula:

$$\eta = (1 - K_{V_\alpha})\frac{V_R R + \pi R(V_j - V_R)/4}{V_j R} \quad (6)$$

$$= (1 - K_{V_\alpha})\frac{V_R + \pi(V_j - V_R)/4}{V_j}, \quad (7)$$

where K_{V_a} is the abrasive volume concentration; $R = d_j/2 \approx d_s/2$ is the jet radius (d_j is the jet diameter), V_j and V_R are the longitudinal components of velocity of the formed jet flow at the symmetry axis and at the periphery, respectively. At $K_{V_a} = 0$ and $V_R = V_j$, we have $\eta = 1$; at $K_{V_a} = 0.11$ and $V_R = V_j$, $\eta = 0.89$; at $K_{V_a} = 0.11$ and $V_R = V_j/2$, $\eta = 0.7945$; and at $K_{V_a} = 0.11$ and $V_R = 0$, $\eta = 0.7$. It should be noted that the data presented in Table 1 and denoted by W_{th} correspond to $\eta = 0.89$; those denoted by W_{cal}, to $\eta = 0.7$. Using the developed approach (relationships (4)–(6)), we can calculate the parameters of the formed jet flow for a suspension with any volume concentration of abrasive (see, for example, Table 2).

On the one hand, a decrease in the nozzle diameter allows reducing the consumption of the suspension (Tables 1 and 2); on the other hand, there is a lower limit of such a reduction. Therefore, we have estimated the minimum value of the outlet diameter. As the criterion parameters of such an estimate, we have used the kinematic parameters of the jet flowing from the nozzle, the continuity of the jet flow, and the depth of its penetration to the surrounding water medium.

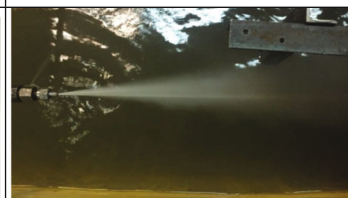
The illustrations in Table 3 show the results of calculations of the change in the character of the jet flow when using jet-forming nozzles with various diameters of the outlet hole. They show that at the pressure $p = 80$ MPa in the jet-forming system and the outlet-hole diameter $d_s \leq 0.2$ mm, an abrupt deceleration of the jet flowing into the surrounding water medium occurs, which leads to a considerable decrease in the efficiency of the impact of the formed jet upon the obstacle already in the immediate vicinity of the nozzle exit section. As the outlet diameter grows up to 0.3 mm at the same values of pressure (p), the depth of jet penetration into the surrounding medium increases insignificantly (see Table 3, no. 2). The further increase in the outlet diameter leads to a gradual stabilization of the jet flowing into the water (Table 3, nos. 3 and 4). However, in this case, the flow rate of working fluid increases by 1.5 times (Table 2, nos. 2 and 5). Therefore, the lower permissible limit of the nozzle outlet diameter d_s should be 0.4 mm.

It should be noted that with growing depth of immersion of the hydro-abrasive device, the pressure in the surrounding water increases. This enhances the stability of the formed jet and increases the depth of its penetration into the surrounding water due to the lowering of the probability of development of the cavitation process in the formed jet flow.

The study of the influence of the nozzle length on the character of the cutting jet has shown that an elongation of the nozzle does not lead to an increase in the axial component of the velocity of the flowing suspension; on the contrary, this results in its reduction (Fig. 4). In addition, elongation of the channel length does not lead to an additional stabilization of the suspension velocity (Fig. 5). Therefore, it is not reasonable to elongate the nozzle, especially for operating at large depths, where the stabilization of the jet in the radial direction is provided by the pressure of the surrounding medium.

The study of the jet-forming path shown in Fig. 1b, as an analogue of the construction scheme proposed in the patent no. 2500518 [13] and applied with the purpose of making the service life of the focusing tube longer, has shown that this scheme may be efficient only in the case where the jet of hydro-abrasive suspension is directly at the top of the outlet nozzle (Fig. 1b, no. 3), i.e., at $H_5 \approx H_3 - H_1$. Otherwise (at $H_5 < H_3 - H_1$), the hydro-abrasive suspension does not fill the entire area of the outlet hole. Moreover, the main part of the jet flowing from the nozzle consists of light water (Fig. 6, number *2*), which fills the main part of its internal volume.

Table 4. Results of experiments

No.	H_3, mm	d_s, mm	In the air	In water
1	10	0.4		
2	20	0.4		
3	20	0.2		
4	76	0.51		

3. EXPERIMENTAL VERIFICATION

The results of the experimental registration of the jet flow in the air and water using focusing tubes of different lengths (H_3) with different outlet diameters (d_s) are contained in Table 4. It was noted that the jets formed by the nozzles with larger diameters are more stable, which corresponds in full measure to the results of the numerical analysis described above. As expected, it has been shown that the surrounding medium has a significant influence on the character of the behavior of the jet flowing from a short nozzle (Table 4, nos. 1 and 2). Thus, a denser medium (in our case, water) grades the radial components of the jet velocity, preventing its dispersion. Comparing the results obtained when using focusing tubes of different lengths and diameters (see Table 4, nos. 1, 2, and 4), we can conclude that the length of the focusing tube does not have a significant effect on the length of the jet formed in water.

CONCLUSIONS

In analyzing the results of this study we come to the following conclusions.

1. A single-phase mathematical model of a hydro-abrasive suspension that considers the abrasive density and volume concentration, as well as the water compressibility and cavitation has been developed. Based on this model, an algorithm for the numerical analysis of formation of a high-speed abrasive waterjet using the technology of underwater hydro-abrasive waterjet hole drilling in the details of various structural materials has been proposed. The developed algorithm is based on numerical solution of a system of differential equations that describe the behavior of a compressible hydrodynamic continuous medium in the two-dimensional formulation in Euler coordinates with consideration of the initial and boundary conditions determined by the structural peculiarities of the jet-forming path of the abrasive waterjet machine.

2. In the framework of the considered structural schemes of the jet-forming path that create the passage of the hydro-abrasive flow under the pressure generated by the pump of the abrasive waterjet machine, it is established that the geometrical parameters of the focusing tube (the shape of the internal profile, length and diameter of the outlet cylindrical channel) influence on the character of motion of the hydro-abrasive suspension inside the cylindrical channel and on the flow rate of the hydro-abrasive suspension in the process of operation of the abrasive waterjet machine. In addition, we have revealed the features of the hydro-abrasive jet formation, its

integrity, and cinematic parameters in the process of its motion in the air and water. The minimum permitted numerical value of the diameter of the outlet cylindrical channel is determined to be 0.4 mm. It is shown that application of AWJ in the water medium allows using a shorter focusing tube compared with the one that is usually used, which is explained by the characteristics of the formation of the hydro-abrasive suspension and the character of its motion in the surrounding medium.

3. The analytical relationships that describe the kinematic parameters of the formed hydro-abrasive jet and the flow rate of the hydro-abrasive suspension depending on the pressure in the abrasive waterjet machine, pressure in the surrounding water medium, volume concentration of abrasive in the suspension, and physical-mechanical properties of the abrasive and liquid components of the hydro-abrasive suspension have been determined.

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