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Experimental investigation of the near-bit jet pump

*Ye. I. Kryzhanivskyi, D. O. Panevnyk**

Ivano-Frankivsk National Technical University of Oil and Gas;
15, Karpatska Str., Ivano-Frankivsk, 76019, Ukraine

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Abstract

The nature of the flow distribution in the hydraulic system of the near-bit jet pump has been analyzed. The peculiarities of searching the pumping station operating point have been shown and the equation for determining hydraulic losses in the elements of the ejection system has been given. Based on experimental studies, an error in the theoretical determination of the relative pressure of a jet pump has been established when using a known and advanced model of its working process. In contrast to the known method, the proposed model provides for the determination of the hydraulic resistance of the chisel flushing system, which is located in the area of mixed flow at the cost of working, not mixed flow. Improving the mathematical model of the ejection system allows to reduce the error of theoretical determination of the relative pressure of the jet pump.

Keywords: *chisel flushing system, ejection coefficient, hydraulic resistance, near-bit jet pump.*

A priority area for the formation of an independent energy market is to increase its own hydrocarbon production. According to the current concept of development of oil and gas industry of Ukraine [1], natural gas in 2035 will occupy the first stage (28 %) in the structure of the energy market of the country. The share of oil in the overall consumption structure also projected to increase. Despite the rapid development of renewable energy, hydrocarbons remain an alternative raw material for many industries. Today, due to economic reasons and existing geological and industrial conditions, significant problems have arisen with the growth of oil and gas production. The share of hydrocarbon reserves is increasing, the extraction of which is complicated by geological causes and well watering. The fund for inactive wells is growing, and requirements for the protection of the subsoil, the environment and the safety of work at the fields are increasing. Under these conditions, increasing the efficiency of hydrocarbon field development has been achieved through wider use in the drilling and operation of wells of unconventional technologies and, in particular, the use of downhole jet pumps.

The simple design and absence of moving parts make it possible to use jet pumps in difficult geological conditions. A significant advantage of the use of borehole ejection systems is the preservation of high permeability of the producing horizon during its primary developing [2], reduction of the period of elimination of accidents during drilling [3], resumption of low-profit wells operation [4], increasing the efficiency of production of formation fluid with a significant content of paraffin [5]. The working process of a downhole jet pump is based on a complex mechanism of interaction of coaxial potential flows with a boundary layer placed between them with an uneven velocity profile and a variable structure. The assumptions made in modeling the process of mixing flows require experimental verification of the developed algorithms and the establishment of acceptable limits of their use.

In the 30s of the last century I. Goslin and M. Brown (University of California) [6] conducted numerous experimental studies of jet pumps and supplemented the theory of G. Zeiner and M. Rankin with empirical relations. In 1957, the applied scientific basis for the use of jet pumps was supplemented by experimental studies of G. G. Cunningham (University of Pennsylvania) [7], who considered the possibility of jet pump cavitation conditions and, thus, set the limiting modes of operation ejecting system in the well. Conducted experimental studies allowed to determine the area of permissible characteristics of downhole ejection systems and became the basis for technologies for the use of jet pumps in the construction and operation of oil and gas wells development. A wide range of ejection technologies applications has led to numerous laboratories, display and industrial studies to determine the pressure [8], energy [9] and cavitation [10] characteristics of the jet pump. The French petroleum Institute determined the characteristics of bit jet pumps for the first time [11]. Bit jet pumps that implement a local reverse flushing of bottom-hole zone were studied by the Sunstone Corporation [12]. Bit ejection systems of pressure-suction type were studied by China University of Petroleum [13], Southwest Petroleum University (China) [14] and Ukhta University [15].

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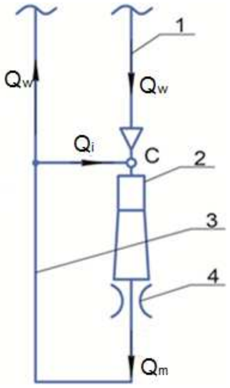
* Corresponding author:
den.panevnik@gmail.com

Despite extensive experience, extra longitudinal ejection systems designed for local direct flushing of the bottomhole area, have not been sufficiently studied. Ultralight jet pumps of this type are often used without taking into account the specific conditions of their operation in the well. Hence, approximate values of design and operational parameters are accepted. Because insufficient level of exploration of overhead jet pumps they are not always effective.

The studies presented here are devoted to the experimental determination of the hydrodynamic parameters of a suprathole ejection system intended for direct flushing intensification of the face and reduction of the differential pressure in the well during drilling.

The flow of flushing fluid generated by the drilling pump, through the hydraulic channel of the drill string 1 enters the working nozzle of the jet pump 2 at a flow rate Q_w (draft 1).

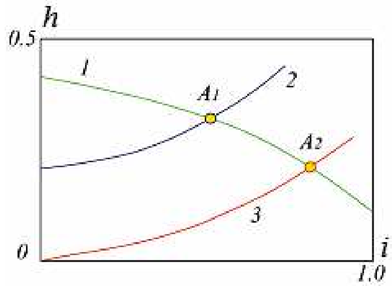


1 – the hydraulic channel of the drill string;
2 – jet pump; 3 – hydraulic channel of annulus;
4 – chisel flushing system;
Q_w – drilling pump consumption; Q_m – mixed flow consumption; Q_i – injected flow consumption

Figure 1 – Hydraulic diagram of ejection system intended for direct injection flushing of well

The high rate of the wash solution leakage from the working nozzle of the jet pump causes the low pressure area. The latter creates the conditions for injected stream suctioning. In the mixing chamber, the velocity equalization occurs, and in the diffuser, the mixing pressure is restored. After leaving the diffuser jet pump 2 mixed flow with consumption Q_m through the flushing system of the chisel 4 enters the suprathoracic space where its separation occurs. Part of the flow of the flushing fluid consumption Q_w along the hydraulic channel of the annulus 3 moves in an upward direction to the wellhead, and the part with the consumption Q_i generates an injected stream that enters the receiving chamber (point C in figure 1) of the jet pump. The use of a supercharged injection pump allows to increase the flow of the washing solution on the bottom of the well while maintaining the constant performance of the drilling pump.

The well ejection system operation mode is determined by the united solution of the equation of the pump characteristics and its hydraulic system (Fig. 2).



1 – the jet pump characteristics; 2 – the hydraulic system characteristics according to the basic methodology; 3 – the hydraulic system characteristics according to the new methodology

Figure 2 – Dependence of the relative pressure of the jet pump on the injection ratio

The intersection of these characteristics (points A_1, A_2) determines the operating point of the pump installation. The equation of the jet pump hydraulic system performance is determined by the magnitude of the hydraulic losses in the elements of the ejection system (Fig. 1)

$$h = \frac{1}{1 + \dfrac{\Delta P_w}{\Delta P_b}}, \tag{1}$$

where ΔP_w, ΔP_b are hydraulic losses, respectively, in the jet pump nozzle and chisel flushing system caused by injection flow.

For the known (basic) [16] equation characteristics of the hydraulic pressure loss system in the chisel flushing system ΔP_b are determined by the amount of flow (Fig. 1) of the mixed Q_m stream

$$\Delta P_b = K_b Q_m^2 = K_b Q_w^2 (1+i)^2, \tag{2}$$

where K_b is generalized hydraulic resistance of the chisel washing system.

The magnitude of the injection ratio i, which is included to the equation (2) is determined by the cost ratio of the injected Q_i and the work Q_w flows. The equation (2) determines the position of curve 2 in Fig. 2.

According to modern ideas about the operation of the pump within the closed circuit, all the pressure created is spent on overcoming the hydraulic resistance within the system. The geometric difference between the receiving and pressure levels location is $h_l = 0$.

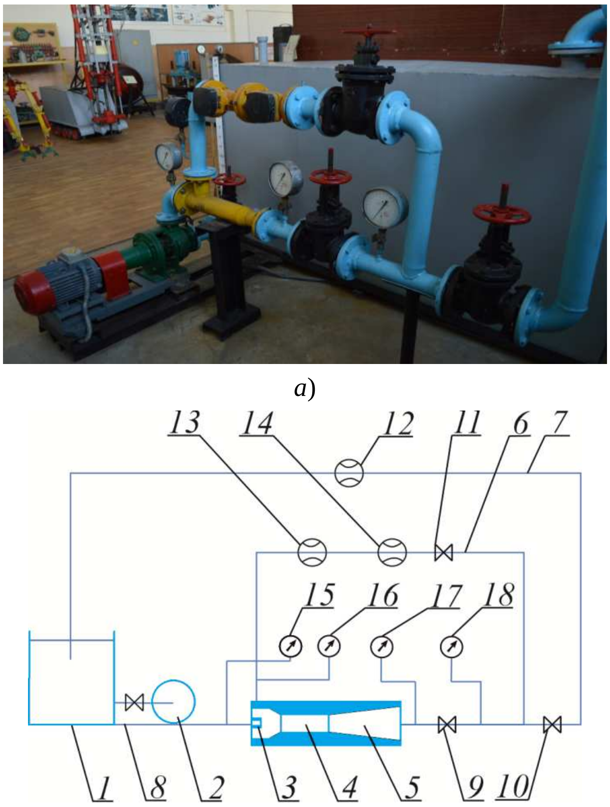
Thus, in the case of zero values of the injection coefficient, the pressure of the pump unit must be zero, that is, the characteristic of the hydraulic system must pass through the origin. Known equation of the hydraulic system characteristics [16], obviously, does not meet the generally accepted concept of the peculiarities of the jet pump operation in the closed loop contour of the well circulation.

The authors of this study suggested that the jet pump generates the pressure difference required to overcome the hydraulic resistance of the chisel flushing system, which is caused solely by the flow of the injected stream, whereas the drill pump creates the pressure necessary to overcome the hydraulic impedance of the flushing system of the chisel. In this case, the equation of the hydraulic system of the jet pump will contain a component that determines the pressure loss in the flushing system of the bit caused by the motion of the injection flow

$$\Delta P_b = K_b Q_i^2 = K_b Q_w^2 i^2. \tag{3}$$

According to the equation given, the characteristic of the hydraulic system of a jet pump will pass through the origin of the system coordinates (curve 3 in Fig. 2). Thus, the improved structure of the equation of characteristic of the hydraulic system will be consistent with the theoretical positions of the pump in the closed-loop circuit. In the course of the experimental studies, it is necessary to establish which of the considered equations: basic (2) or advanced (3) provides greater accuracy of analytical determination of the regime parameters of the ejection system.

The experimental setup (Fig. 3) consists of a receiving vessel 1, a centrifugal pump 2, a jet pump in the form of a working nozzle 3, a mixing chamber 4 and a diffuser 5, a suction line 6 in the form of an additional closed circuit of the circulation and a pressure line 7. and the jet pump by means of latches 8–11. Flowmeters 12–14 and pressure gauges 15–18 are used to control the operation of the jet pump.



a)

b)

Figure 3 – Physical form (*a*) and hydraulic diagram (*b*) of the laboratory machine

The power drive 2 supplies the power fluid from the receiving vessel 1 to the working nozzle 3 of the jet pump. Due to the increase in the motion speed of the fluid at the outlet of the working nozzle in the outlet section of the mixing chamber 4, the pressure is reduced, which promotes the flow of fluid through the intake line 6. In the mixing chamber 4 the working flow (supplied through the working nozzle 3) and the injected flow (which comes through the intake line 6) are mixed. The mixed fluid flows from the mixing chamber 4 and enters the diffuser 5, where there is a gradual pressure recovery. After leaving the diffuser the mixed flow is separated: part of the flow with the flowrate Q_i moves along the intake line 6, forming an additional circulation circuit, and the part with the flowrate Q_w enters the downstream line 7 and the receiving vessel 1.

Valves 9, 11 allow to change the amount of the injected flow, and the latch 10 changes the working flow. Valve 9 also allows to change the mode of operation of the jet pump from the straight (fluid in the additional circulation circuit moves clockwise) to the reverse (the fluid in the additional circulation circuit moves counterclockwise).

The flowmeter 12 allows to determine the flowrate of the working flow Q_w, and flowmeters 13, 14 determines the flowrate of injected flow Q_i, respectively, for the direct and reverse modes of operation of the jet pump. Pressure gauges 15, 16, 17 (accuracy class 0.4) allow to control the pressures of working P_w, injected P_i and mixed P_m flows, respectively. The difference in the performance of the pressure gauges 17 and 18 allows to determine the hydraulic losses in the element (valve 9) located on the site of mixed flow of hydraulic system. The jet pump operating parameters (experimental values of relative pressure h_e and injection ratio i_e) were determined by the experimental values of the working pressure P_{we}, injected P_{ie} and mixed P_{me} flows and the experimental values of the injected Q_{ie} and working Q_{we} flowrates

$$h = \frac{P_{me} - P_{ie}}{P_{we} - P_{ie}}, \quad i_e = \frac{Q_{ie}}{Q_{we}}. \tag{4}$$

In the process of experimental verification of equation (1) it is necessary to compare the accuracy of determining the characteristics of the hydraulic system of the jet pump when using the basic (equation (2)) and proposed by the authors of this study (equation (3)) methods for determining hydraulic costs in the washing system of the bit.

The experimental values of the relative head and injection ratio are determined in the following sequence.

1. Determine the magnitude of the pressures of the working P_w, mixed P_m and injected flows P_i according to pressure gauges 15, 17 and 16 and represent them in the form of a relative pressure of the jet pump $h = (P_m - P_i)/(P_w - P_i)$.

2. Determine the consumption of working Q_w and injected flows Q_i according to flowmeters 12, 13 and calculate the value of the injection coefficient $i = Q_i/Q_w$.

3. The value of the relative head h injection ratio is determined by the constant value of the operating flow generated by the power pump 2 (Fig. 3 b) and the variable opening rate of the latch 11.

According to the proposed hypothesis, the pressure created by the power pump 2, which is analogous to the drilling pump for the scheme of the ejection system shown in Fig. 1, is spent to overcome the hydraulic losses in the latch 9 (analog of the washing system of the bit) caused by the movement of the work flow. Then the pressure created by the jet pump is spent to overcome the hydraulic losses in the latch 9 caused by the flow of injected flow. In conducting experimental studies [17], the dependence of hydraulic losses in the element placed on the mixed flow section of the ejection system was determined from the flow rate of the work flow and the self-similarity with respect to the flow rate of the injected flow. Changing the flow rate of the injected flow through the latch 9 did not affect the amount of hydraulic loss in this element. In view of the results obtained in [17], the following scheme of studies of the hydraulic system of a jet pump is adopted.

1. Determination of coordinates of working points of ejection system experimentally.

2. Establishing a view of the dependence of hydraulic losses in the latch 9 from the value of the working flow with zero flow of injected flow $\Delta P = f(Q)$.

3. Establishing the coordinates of the working points of the ejection system in the theoretical determination of the relative head $\Delta P = f(Q)$ using empirical dependence $\Delta P = f(Q)$. For comparative analysis dependency is used for two cases:

cost Q is the value of the workflow cost $Q = Q_w$;

flow Q takes the value of the mixed flow rate $Q = Q_m = Q_w(1+i)$.

The theoretical value of relative pressure which correspond to a sensitive operating points of ejection system we compare with the experimental values and establish which method of determining the hydraulic losses in the element located in the mixed flow section of the jet pump provides greater accuracy of the analytical determination of its characteristics.

This (indirect) method of checking equations (2) and (3) is adopted in connection with the inability to allocate experimentally that part of hydraulic losses in the element placed on the site of the mixed flow, which is caused exclusively by the movement of the inject flow. During the research, the experimental values of the relative pressure are compared with its theoretical values obtained in accordance with the basic and improved methodology. Taking into account that these models differ only in the way of determining the hydraulic losses in the local resistance placed on the mixed flow line, the value of pressure losses in other elements of the ejection system is determined by a single methodology by using experimental data. This approach will improve the correctness of the comparison of the basic and improved mathematical model and the reliability of the research.

In the process of experimental verification of the equation of the hydraulic system characteristics, the theoretical values of the relative pressure are compared directly with its experimental values obtained for the same values of the injection coefficient. Thus it is unnecessary to define an empirical function and pre-test of the hypothesis of the distribution of random substances.

When planning experimental studies, we consider the features of determining the pressure in the characteristic sections of the experimental stand. The working, mixed and injected flow pressures are determined by the amount of hydraulic losses in the separate elements of the hydraulic system

$$P_w = \Delta P_w + \Delta P_m + \Delta P_9 + \Delta P_{10}; \tag{5}$$

$$P_m = \Delta P_9 + \Delta P_{10}; \tag{6}$$

$$P_i = \Delta P_{10} - \Delta P_{11}, \tag{7}$$

were ΔP_w, ΔP_m, ΔP_9, ΔP_{10}, ΔP_{11} are hydraulic losses in the working nozzle, in the mixing chamber and in the latches respectively.

While determinating of equations (5) – (7) linear losses are neglected due to a small length of hydraulic channels.

Taking into account equation (5) – (7), we write an expression to determine the relative pressure of the jet pump

$$h = \frac{P_m - P_i}{P_w - P_i} = \frac{\Delta P_9 - \Delta P_{11}}{\Delta P_p + \Delta P_m + \Delta P_9 + \Delta P_{11}} = \frac{1}{1 + \dfrac{\Delta P_w + \Delta P_m}{\Delta P_9 + \Delta P_{11}}}. \tag{8}$$

Based on the hydraulic diagram of the experimental bench, we write down

$$\Delta P_w + \Delta P_m = P_w - P_m \ , \tag{9}$$

$$\Delta P_{11} = P_{ent} - P_i \, , \tag{10}$$

where P_{ent} is the pressure value at the outlet of the jet pump pressure line. Taking into account expressions (9), (10) equation (8) we rewrite in formula

$$h = \frac{1}{1 + \dfrac{P_w - P_m}{\Delta P_9 + \left(P_{ent} - P_i\right)}}. \tag{11}$$

Let us first consider the method of hydraulic losses determination in a mixed flow element. Their experimental value is defined as the pressure difference according to the experimental bench scheme.

$$\Delta P_9 = P_m - P_{ent} \, . \tag{12}$$

The possibility of conducting these experimental studies is complicated by the movement through the local resistance of the mixed flow. While conducting studies, it is necessary to separate the workflow passing through the local resistance from the injected flow, which is impossible. The solution of this problem is to investigate the operation of the jet pump, which operates in zero-cost conditions of the injected flow. In this case, hydraulic losses in concentrated hydraulic resistance located in the pressure line of the jet pump will be caused solely by the movement of the working flow. The characteristics of the hydraulic losses formation in the local resistance that are caused by the action of the jet pump are preserved. Such jet pump operates as part of a closed-loop circulation circuit.

Table 1 – Determination hydraulic losses due to workflow

Experiment	$Q\cdot10^3$, m³/s	ΔP, MPa	Experiment	$Q\cdot10^3$, m³/s	ΔP, MPa	Experiment	$Q\cdot10^3$, m³/s	ΔP, MPa
1	8.76	0.006	8	10.75	0.007	15	15.08	0.008
2	8.60	0.004	9	11.10	0.014	16	15.31	0.009
3	8.60	0.004	10	10.60	0.007	17	15.13	0.008
4	8.60	0.005	11	10.41	0.006	18	15.08	0.009
5	8.46	0.003	12	10.86	0.007	19	16.42	0.009
6	8.53	0.003	13	15.30	0.008	20	17.33	0.009
7	9.10	0.006	14	15.64	0.009	21	17.61	0.008

Table 2 – Experimental verification of the equation of performance of the hydraulic jet pump system

Experiment	i	h_e	h_b	h_n	δ_b,%	δ_n,%
1	1.081	0.099	0.113	0.102	14.1	3.8
2	0.973	0.101	0.116	0.105	14.6	3.6
3	0.941	0.104	0.119	0.108	14.4	3.6
4	0.902	0.115	0.130	0.119	12.9	3.1
5	0.862	0.131	0.143	0.132	9.2	0.7
6	0.719	0.144	0.156	0.145	8.1	0.6
7	0.710	0.149	0.161	0.151	7.7	0.6
8	0.616	0.169	0.179	0.169	6.3	0.5
9	0.468	0.192	0.199	0.191	3.5	0.7
10	0.294	0.212	0.216	0.211	2.0	0.6
11	0	0.248	0.243	0.243	2.1	2.1

A certain position of the gate lock element is equal to zero value of injected flow losses. This element is located in the secondary circuit and circulation of the pilot plant. In this case, the flow of the jet pump at the outlet is only moving through the concentrated resistance. Modifying the design of the jet pump and the characteristics of the jet system, we adjust the flow rate corresponding to the zero-flow rate of the injected flow.

The dependence of hydraulic losses in the element located at the outlet of the jet pump on the workflow losses is obtained on the basis of 21 experimental points (Table 1).

The experimental dependence that was obtained $\Delta P = f(Q)$ can be approximated as a square three term

$$\Delta P = a + bQ + cQ^2, \tag{13}$$

with constant coefficients

$$a = -0.13945;\, b = 0.029552;\; c = -9.6284\cdot10^{-4}.$$

Given the results of theoretical studies, the magnitude of hydraulic losses in the element of mixed flow is determined solely by the value of operating cost Q_w

$$\Delta P_9 = a + bQ_w + cQ_w^2. \tag{14}$$

According to the basic methodology, this value is determined by the equation

$$\Delta P_9 = a + bQ_w(1+i) + cQ_w^2(1+i)^2. \tag{15}$$

Given Eqs. (11), (14), (15), we write expressions for determining the jet pump relative pressure according to the base h_b and new h_n methods

$$h_b = \frac{1}{1+\dfrac{P_w - P_m}{a + bQ_w(1+i) + cQ_w^2(1+i)^2 + P_{ent} - P_i}}; \tag{16}$$

$$h_n = \frac{1}{1+\dfrac{P_w - P_m}{a + bQ_w + cQ_w^2 + P_{ent} - P_i}}. \tag{17}$$

Equation (16) is obtained using the base method , and the equation (17) – according to the new method.

Errors determination of relative header by base δ_b and new δ_n method is determined by comparing theoretical values h_b, h_n with experimental h_e.

The reduction of the error of determination of the relative pressure by the new method testifies to its advantages in comparison with the existing method of determining the characteristics of the hydraulic system.

For the experimental studies, a jet pump with a diameter of 16 mm working nozzle and a distance between the nozzle and the mixing chamber 26.5 mm was used. Comparative analysis used 11 experimental values of the jet pump head for a fixed value of operating flow $Q_q = 8.6\cdot10^{-3}$ m³/s (Table 2).

The results obtained allow us to determine the benefits of using the proposed mathematical model of hydraulic pump system, which is operated in the maximum efficiency mode. This mode of operation of the jet pump corresponds to the value of injection coefficient close to one $i \to 1$.

The conducted studies allowed us to formulate the following conclusions.

1. Hydraulic losses in the element located on the site of the mixed flow ejection system affect its characteristics. Thus, the equation of characteristic of the hydraulic system must contain a component that takes into account the energy loss in the local resistance of the mixed flow.

2. The hydraulic resistance of the element placed on the mixed flow section is determined by the flow rate of the working rather than the mixed flow. When constructing mathematical models of a suprathole ejection system, it is necessary to take into account the amount of hydraulic losses in the washing system of the bit caused by the movement of the work flow.

3. Improvement of the mathematical model of operation of the ejection system allows to reduce the error of theoretical determination of the relative head of the jet pump by 10.9 %.

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Експериментальне дослідження наддолотного струминного насоса

Є. І. Крижанівський, Д. О. Паневник

Івано-Франківський національний технічний університет нафти і газу;
вул. Карпатська, 15, Івано-Франківськ, 76019, Україна

Проаналізовано характер розподілу потоків в гідравлічній системі наддолотного струминного насоса. Показано особливості пошуку робочої точки насосної установки та наведено рівняння для визначення гідравлічних втрат в елементах ежекційної системи. На основі експериментальних досліджень встановлено похибку теоретичного визначення відносного напору струминного насоса при використанні відомої та удосконаленої моделі його робочого процесу. На відміну від відомої методики запропонована модель передбачає визначення гідравлічного опору промивальної системи долота, розміщеної на ділянці змішаної течії за величиною витрати робочого, а не змішаного потоку. Удосконалення математичної моделі роботи ежекційної системи дозволяє зменшити похибку теоретичного визначення відносного напору струминного насоса.

Ключові слова: *гідравлічний опір, коефіцієнт ежекції, наддолотний струминний насос, промивальна система долота.*