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ANALYTICAL STUDY OF THE EFFICIENT OPERATION MODES OF OIL-GAS JET PUMPS USED IN OIL WELLS

Abstract: A perspective way of oil wells operation is to use sucker rod pumps, in combination with oil-gas jet pumps. Placing a jet pump above the dynamic level in the well and operating it simultaneously with the sucker rod pumps allows to stabilize the work of the rod pump, avoid fluctuations of the dynamic level and facilitate the rise of the production liquid to the surface due to the reduction of the density of the mixed flow after the jet pump. In order to implement such oil-gas jet pump in oil wells that are operated by sucker rod pumps, it is necessary to determine their operating modes and choose the most effective among them. A methodology for calculating the operation mode of such well was created that allows determining the efficient location of jet pumps in oil wells and their geometry. When developing this methodology two conditions were taken as a main aim: the whole amount of free gas, which enters the casing annulus of the well, must pass through the oil-gas jet pump and to reach the maximum possible decreasing of the string load. For the 753-D oil well in Dolyna Oil Field calculated efficient operation mode shows the possibility to decrease string load by 26%, reduce electricity consumption and, respectively, investments in oil extraction.

Keywords: oil well, sucker rod pump, jet pump, thermobaric parameters, mixed flow, tandem installation, string load

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1. INTRODUCTION

Jet pumps are widely distributed in various areas of modern technology. In recent decades they are used directly in oil production. In Russia, during the wells operation with the help of electrical centrifugal pumps (ECP), additional usage of jet pumps, which are installed directly above the ECP, ensures the stabilization of ECP work. At the same time, the energy of the free gas in the injected flow is effectively used and to a certain extent this provides an increase in the production of wells [1]. Such tandems have shown their high efficiency in abnormal operating conditions (high wellhead pressure and low reservoir pressure).

There is also a case, when the jet pump was installed above the dynamic level of the well in order to extract gas from its casing annulus, which provided the stabilization of the dynamic level and increased the reliability of the ECP system [2]. In this case, the free gas from the annulus was an injected stream for the jet pump.

Recently, several works appeared where in the same manner the jet pump was used for operation with the sucker rod pump [3, 4]. Herewith, the use of jet pump, installed in oil well above its dynamic level, can provide a number of positive results if the location of the pump is chosen correctly and its geometrical parameters are substantiated. Such advantages include:

- stabilization of the dynamic level by off taking the whole amount of free gas that comes to the casing annulus, using the jet pump;
- the effective usage of the potential energy of the free oil gas, which facilitates the rise of the production liquid to the surface due to the reduction of the density of the mixed flow after the jet pump;
- decreased electricity consumption and, respectively, investments in oil extraction.

Although, there is a disadvantage. The well's equipment for its operation in this case will be a bit more complicated. It means that the well will be operated by a tandem installation, which includes the sucker rod pump (SRP) and the oil-gas jet pump. The scheme of such tandem installation is shown in Figure 1.

The suggested scheme works in the next way. The production liquid, which is pumped by the SRP 5 into the tubing 3, enters the oil-gas jet pump 8, which is removed beyond the tubing. There, due to the high velocity of the liquid, the free gas from the annulus enters the jet pump through the backpressure valve 7. Then, this gas-liquid mixture again returns to the tubing and moves toward the wellhead. Phase separator 2 must be installed in the tubing at the jet pump's level to ensure the separation between the inlet and outlet of the pump [5].

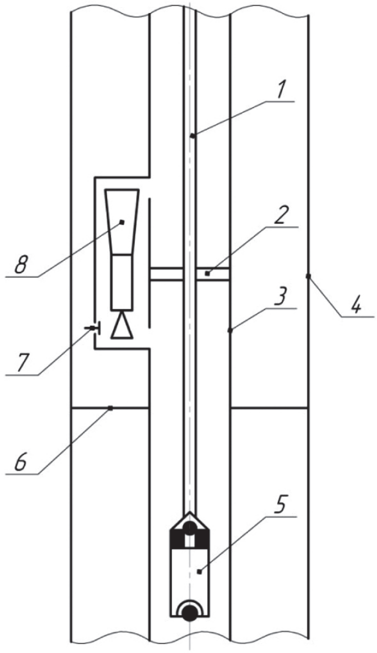

Fig. 1. The scheme of suggested tandem installation:
1 – rods, 2 – phase separator, 3 – tubing, 4 – casing, 5 – SRP,
6 – dynamic level, 7 – backpressure valve, 8 – oil-gas jet pump

In order to create reliable and efficient jet pumps for oil production, it is necessary to develop a methodology of calculation the operation modes for such wells and to determine the working and geometrical parameters of jet pumps. That is why the objective of this article is to find these parameters and to justify the best placement of the jet pump in the well, which will provide the most efficient operation mode.

2. DETERMINATION OF THE THERMOBARIC PARAMETERS DISTRIBUTION ALONG THE WELLBORE

In the case of jet pump installation in oil well and studying its operation modes, it is necessary to know the parameters at its inlet. Such parameters include: pressure p in the cross-section where the jet pump is installed, velocity of the gas-water-oil mixture w_c, its density ρ_c, the density of the free gas ρ_g and consumption gas content β. These parameters will be the characteristic of the working stream of the jet pump.

The calculation of the pressure and temperature distribution along the whole wellbore was done separately for the section between the bottomhole and point of SRP installation and between the wellhead and SRP. Respectively, these two calculations are based on such formulas [5]:

$$\frac{dp}{dz} = \rho_m \cdot g \cdot 10^{-6} + \frac{f \cdot Q_{lst}^2 \cdot (1-\beta_w)^2 \cdot M_c^2}{2.3024 \cdot 10^{15} \cdot \rho_m \cdot D^5} \tag{1}$$

$$\frac{dp}{dz} = \rho_m \cdot g \cdot 10^{-6} + \frac{f \cdot Q_{lst}^2 \cdot (1-\beta_w)^2 \cdot M_c^2}{2.3024 \cdot 10^{15} \cdot \rho_m \cdot \left(d^2 - d_r^2\right)^2 \cdot (d - d_r)} \tag{2}$$

where:

g – gravity acceleration [m/s^2],
f – correlation coefficient,
Q_{lst} – liquid flow rate under standard conditions [m^3/day],
β_w – consumption gas content under working conditions of a well,
D – internal diameter of a casing [m],
M_c – specific mass of mixture (oil, gas and water) per unit volume of degassed oil,
d, d_r – diameters of tubing and rods respectively [m].

To be able to implement the suggested tandem installation in field, the real oil well 753-D in Dolyna Oil Field was chosen for analytical study and necessary calculations. Technological parameters of this well are presented in Table 1.

Table 1

Technological parameters of oil well 753-D Dolyna Oil Field

Parameter	Value
Depth of the well, H [m]	2355
Internal diameter of casing, D [mm]	122
Formation pressure, p_f [MPa]	21.5
Bottom hole pressure, p_b [MPa]	8.2
Saturation pressure at the formation temperature, p_{st} [MPa]	26
Wellhead pressure, p_h [MPa]	0.5
Formation temperature, T_f [K]	341
Temperature at the wellhead, T_h [K]	291.5
Internal diameter of tubing, d [mm]	62
Depth of SRP lowering, L_p [m]	1650
Liquid flow rate under standard conditions, Q [m^3/day]	15
Density of degassed oil under standard conditions, ρ_{ost} [kg/m^3]	847.4

Table 1 cont.

Density of oil gas related to air, ρ_{ga} [kg/m^3]	0.7
Solution gas-oil ratio, S_0 [m^3/t]	220
Producing gas-oil ratio, G_0 [m^3/t]	276
Mass water content under standard conditions, n_w	0.5

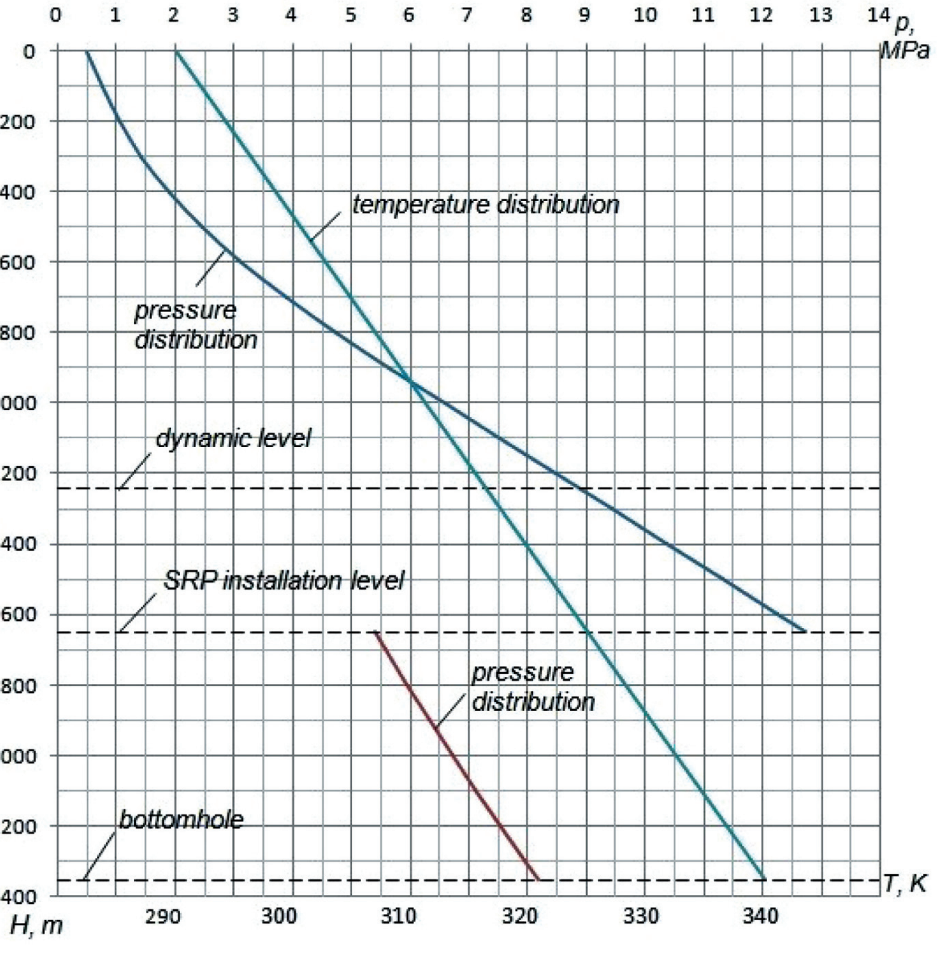

Fig. 2. Pressure and temperature distribution in the well 753-D

Using a standard methodology of calculations [5] a thermobaric parameters distribution was obtained, which is graphically presented in Figure 2. Besides that, an average velocity of the gas-liquid mixture was found, depending on the depth of the cross-section. As it is seen from the graph, the pressure created by SRP is 7.32 MPa, temperature at the inlet of a pump 325.9 K. According to the results of calculations, the annulus pressure equals 1.83 MPa, saturation pressure 6.31 MPa.

3. CALCULATION OF THE OUTLET PARAMETERS FOR THE JET PUMP

Mathematical model that interconnects working and geometrical parameters of the oil-gas jet pumps was obtained based on Bernoulli equation and mass conservation law. It can be used for jet pumps, where the working and mixed flows are compressible two-phase liquids.

To obtain the mentioned equations of oil-gas jet pumps several assumptions were accepted: pressure distribution in the control cross-sections is hydrostatic, liquid and gas phases are evenly distributed in the volume and their velocities in control cross-sections are the same, there is no mass transfer between phases inside the jet pump, the movement of the injected gas within the suction chamber occurs without loss of thermal energy (the process is adiabatic). 3D model that shows the construction of oil-gas jet pump is given in Figure 3.

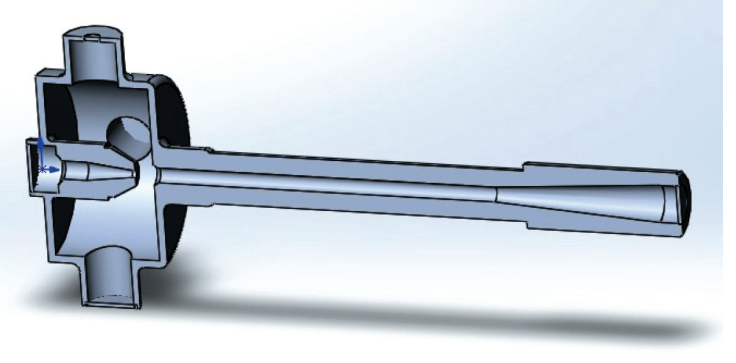

Fig. 3. 3D model of a jet pump

So the final equation that describes the dependence of the pressure drop in the jet pump and its main geometrical parameters is:

$$\frac{2f_1^2\rho_1^2}{(1+\xi_n)\rho_w f_3}\left(p_w - p_1\frac{\rho_w}{\rho_1}+\frac{\rho_w w_w^2}{2}\right)\cdot\left[\frac{1}{f_2\rho_2}+\frac{\rho_{in2}}{\rho_2^2 f_{in2}}u_2^2 - \right.$$
$$\left. -\frac{1}{2}\left(1+\frac{\rho_{in2}}{\rho_2}u_2\right)^2\left(\frac{\xi_d+\xi_{mc}+1}{f_3\rho_3}+\frac{f_3\rho_3}{f_m^2\rho_m^2}\right)\right]-p_m\frac{\rho_3}{\rho_m}+p_2=0 \qquad (3)$$

where:

f_1 – cross-section area in the outlet of a nozzle,
ρ_1 – density of the working liquid at the outlet of a nozzle,
ρ_w – density of the working liquid before entering the nozzle,
f_3 – cross-section area at the outlet of a mixing chamber,
p_w – pressure of the working liquid before entering the nozzle,
p_1 – pressure of the working liquid at the outlet of a nozzle,
w_w – velocity of the working liquid before entering the nozzle,
f_2 – cross-section area before entering the mixing chamber,
ρ_2 – density of the mixed flow before entering the mixing chamber,
ρ_{in2} – density of the injected gas before entering the mixing chamber,
f_{in2} – cross-section area of the injected gas before entering the mixing chamber,
u_2 – injection ratio before entering the mixing chamber,
ρ_3 – density of the mixed flow at the outlet of the mixing chamber,
ξ_n, ξ_{mc}, ξ_d – resistance coefficients for the nozzle, mixing chamber and diffuser,
f_m – cross-section area at the outlet of the diffuser,
ρ_m – density of the mixed flow at the outlet of the diffuser,
p_m – pressure of the mixed flow at the outlet of the diffuser.

Inserting previously found thermobaric parameters of the well into this equation (that would be the inlet parameters of the working and injected flow of the jet pump) it is possible to calculate pressure and velocity in the outlet of it. On this stage it is necessary to estimate the range of possible jet pump installation. For example, installing jet pump near the wellhead will not give appreciable positive effect. That is why, the considered depths of jet pump installation is from 700 m to 870 m while the depth of dynamic level is 1243.3 m.

The basic geometrical parameter, which influences on most remaining working and geometrical parameters, is unknown cross-section area in the outlet of a nozzle:

$$f_1 = w_w f_w \left[(1-\beta_w) p_1 + \beta_w p_w \right] \sqrt{\frac{(1+\xi_n)\rho_w}{\left[2p_w (1-\beta_w) + \rho_w w_w^2 \right] p_1^2 - 2(1-\beta_w) p_1^3}} \quad (4)$$

After several calculations it became possible to make a conclusion that the depths of jet pump installation slightly influences on the possible changing in pressure before it. Increasing the installation depths will lead to insignificant decreasing of the pressure along the borehole. The inlet pressure will decrease significantly if to take jet pumps with a smaller ratio f_3/f_1.

4. JUSTIFYING THE INSTALLATION PLACE OF THE JET PUMP IN THE WELL AND ITS OPERATION MODE CALCULATION

The smallest ratio $f_3/f_1 = 3$, which was assumed to be possible to reach. Such jet pump was considered to be installed at different depth: 700 m, 800 m, 850 m, 870 m. As soon as we have previously calculated the distribution of working parameters along the wellbore, pressure and average velocity at these points will be the inlet parameters of the working flow for the jet pump. Then, with the help of a certain methodology, based on the formula (3), a pressure drop inside the jet pump was found. After obtaining values of outlet parameters of the mixed flow after the jet pump, the pressure distribution between the wellhead and jet pump was the calculated. It turned out that, due to the great decreasing of mixture density, pressure losses after the jet pump reduced in comparison with the previous case. That is why, pressure at the wellhead, instead of necessary 0.5 MPa, can reach the value of 1.8 MPa. In turn, it means that we can decrease the pressure along the whole wellbore starting from the outlet of SRP, finding such minimal outlet pressure, which will supply the technologically necessary pressure at the wellhead equal to 0.5 MPa.

Calculation results for different installation depth are shown in Table 2.

Table 2

Technological parameters of oil well 753-D after installing the jet pump in it

Parameters and their dimensions	Depth of jet pump installation [m]			
	700	800	850	870
Known parameters				
Pressure at the inlet of jet pump p_w [MPa]	3.91	4.75	5.20	5.38
Density of working liquid ρ_w [kg/m^3]	806.4	876.7	904.0	913.6
Consumption gas content β_w	0.125	0.052	0.024	0.014
Density of free gas ρ_g [kg/m^3]	32.5	40.1	44.2	45.8
Velocity of the working liquid before entering the nozzle w_w [m/s]	2.9	2.7	2.6	2.6
Calculated parameters				
Density of the mixed flow at the outlet of the jet pump ρ_m [kg/m^3]	418.7	485.9	523.6	541.9
Pressure of the mixed flow at the outlet of the jet pump p_m [MPa]	2.99	3.64	4.09	4.34
Injection ratio before entering the mixing chamber u_2	1.36	1.57	1.69	1.74
Velocity of the working liquid before outflowing from the nozzle w_w [m/s]	64.9	76.6	82.1	84.2

Graphical representation of pressure distribution inside the oil well 753-D for both cases with simply installing the jet pump in the well at depth 870 m and decreasing a pressure at the outlet of SRP is given in Figure 4.

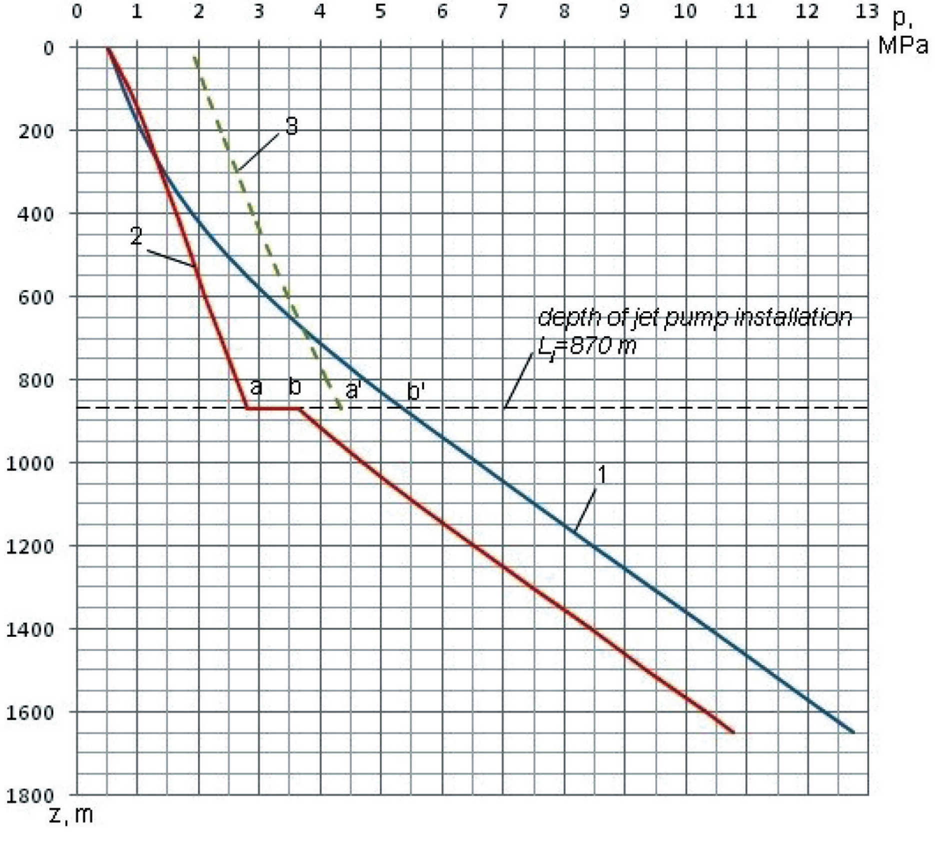

Fig. 4. Pressure distribution in the well between SRP and wellhead:
1 – without the jet pump; 2 – with the jet pump (f_3/f_1=3);
3 – with the jet pump after the decreasing of pressure at the outlet of SRP

As it is seen from the Figure 4, if the pressure at the inlet of the jet pump is just equal to the pressure, which was in the well at this cross-section (point *b'* in Fig. 4), pressure at the wellhead is greater than necessary. Consecutively decreasing inlet pressure for the jet pump, such value of it was found, which provides the wellhead pressure of 0.5 MPa. Table 3 shows basic geometrical and working parameters of four jet pumps, installed at different depth, which ensures desired wellhead pressure. Knowing the inlet pressure and temperature for jet pump at their installation point, calculations were made to determine the pressure distribution from the jet pump to SRP.

Table 3

Basic parameters of jet pump with ratio $f_3/f_1 = 3$, which provide a complete free gas off taking from annulus and the necessary wellhead pressure 0.5 MPa

Depth of jet pump installation [m]	Basic parameters of jet pump				
	Outlet diameter of the nozzle d_n [mm]	Internal diameter of the mixing chamber d_{mc} [mm]	Outlet diameter of the diffuser d_d [mm]	Pressure at the inlet of jet pump p_w [MPa]	Pressure at the outlet of jet pump p_m [MPa]
700	4.7	8.2	21.8	2.88	2.36
800	4.2	7.2	19.3	3.33	2.62
850	4.0	6.9	18.4	3.55	2.75
870	3.9	6.7	18.0	3.63	2.81

Using jet pump inside of the oil well, operated with the SRP allows decreasing the outlet pressure for SRP, which was proved on the example of 753-D oil well. For this case such pressure decreasing can be up to 1.96 MPa. Accordingly, such decrease will lead to loads reduction on the tubing. For the well 753-D, when using jet pump with ratio $f_3/f_1 = 3$, installed at depth 870 m, tubing load can be reduced by 26%. That means the suggested mode can be considered as the most efficient operation mode for the tandem installation.

5. CONCLUSIONS

The following conclusions based on the conducted analytical research and calculation results can be done:

1. Using tandem installations with oil-gas jet pump instead of operating wells just with sucker-rod pumps allows to increase the efficiency of them and to provide a number of economic benefits, such as decreasing investments in oil extraction due to smaller electricity consumption.
2. Minimizing tubing load depends on two factors: the smallest possible cross-sections areas ratio f_3/f_1 and greater installation depth. Herewith decreasing f_3/f_1 for the jet pump can significantly reduce tubing loads, while increasing installation depth gives a much smaller effect.
3. The best proven operation mode for the 753-D oil well is to use the tandem installation, which consists of the sucker-rod pump and the jet pump with the ration $f_3/f_1 = 3$ and placed at depth 870 m.

4. The suggested jet pump is able to offtake whole amount of free gas from annulus and to provide the SRP outlet pressure decreasing $\Delta p = 1.96$ MPa. Geometrical parameters for such jet pump are: diameter of the nozzle $d_n = 3.88$ mm, diameter of the mixing chamber $d_{mc} = 6.72$ mm, outlet diameter of the diffuser $d_d = 3.88$ mm.

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