# Determining limiting conditions for the operation of hydrocarbon recovery system jet apparatus

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*The cavitations sensitivity design procedure for oil and gas emissions system jet apparatus in the free space of oil reservoir was provided. Based on the Bernoulli equation, written for specific sections of the hydraulic system, was defined a relationship between the level of oil in the tank and the minimum pressure in the flow of the jet apparatus. The studies provide an opportunity to determine the minimum diameter of the working nozzle jet apparatus that helps make its operation in pre-cavitations condition.*

In the unpressurized oil collection and treatment systems are extensively used oil tanks in which the loss of light fractions reaches 3% of production from the well [1]. Significant economic losses, increased fire and explosion hazard, and environment pollution led to the formation in regulatory and legislative framework the limits for hydrocarbon emission into the atmosphere. Protecting ecosystem balance and promoting sustainable economic development is one of the main priorities of the EU’s VI Framework Programme (Section "Sustainable Ecosystems"). Continued growth of attention of the international community to the problem of oil gas emissions shows the relevance of research aimed at improving the operation efficiency of the hydrocarbon recovery systems [2].

Given the technical complexity of regulating the amount of free space in the oil tank, the main way to reduce emissions is the extraction of oil evaporation products. One of the main hydrocarbon trapping schemes provides the use of jet apparatus as a part of hydrocarbon recovery system [3, 4]. The deficiency of jet system design is the need for stand-alone actuator of the jet apparatus as a centrifugal pump. In the design of the jet system developed by Ivano-Frankivsk National Technical University of Oil and Gas, the actuation of jet apparatus is performed by the energy of the oil column in the tank (Fig. 1) [5]. The work [6] describes a theoretical justification of the system workflow based on the determination of pressures in specific sections of jet apparatus and the derivation of the performance equation of hydraulic system, followed by calculation of the pumping unit operating point parameters. Boundaries for using the developed mathematical model are limited by preservation of flow continuity in the hydraulic system of the jet unit. High probability of flow discontinuity and cavitation occurrence in the proposed hydraulic system requires clarification of the field of application of the method of designing jet apparatus with a hydrostatic actuator.

The aim of the research, the results of which are given in this article, was to determine the cavitation characteristics of the jet apparatus of hydrocarbon recovery system and the calculation of the limiting design and operational parameters to ensure its effective operation.

Cavitation properties of the jet pump define one of the limiting modes of its operation and have a direct impact on the value of the limiting parameters such as the maximum flow rate and the minimum diameter of the working nozzle. In the jet pump cavitation occurs mainly in the jet near-boundary layer at the interface of dividing working and injected flows, where due to intensive vortex activity in a mixing chamber occur areas of minimum pressure [7]. As a result of intensive emission of gas-vapour bubbles the mixing process is broken and the pump pressure decreases sharply. Gas-vapour bubbles are concentrated in the jet near-boundary layer and only in rare cases fill the entire cross section of the mixing chamber. Therefore, the flow section in the jet pumps is less susceptible to cavitation destruction compared to the blade hydraulic machines, which reduces the likelihood of cavitation conditions in the device operation.

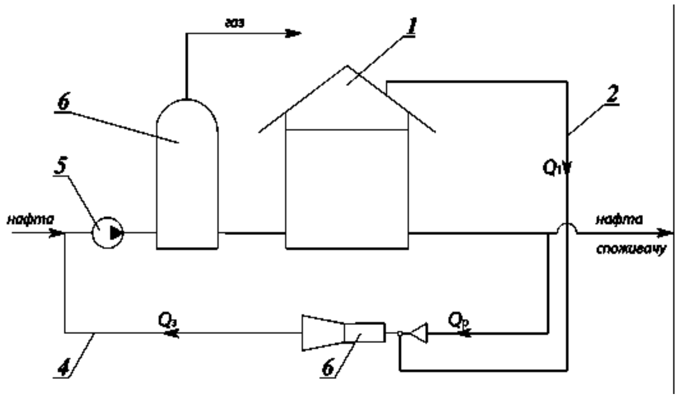

Fig. 1. Hydrocarbon recovery system: 1 - Oil tank, 2 – Jet apparatus suction line, 3 - Jet apparatus, 4 - Jet apparatus discharge line, 5 - Centrifugal pump, 6 - Separator

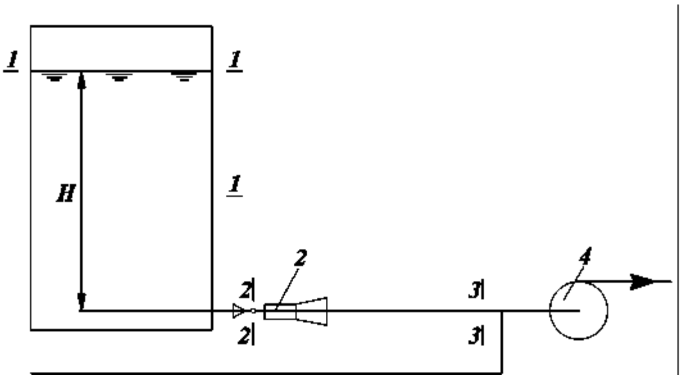

Fig. 2. Design model of the jet apparatus hydraulic system: 1 - Tank 2 - Jet apparatus, 3 – Pipeline, 4 - Centrifugal pump

The study of the fluid flow in the flow section of the jet pump revealed that the occurrence of cavitation is most likely in two areas: at the output of the work flow from the nozzle and in the input section of the injected flow in the mixing chamber. When calculating the operation mode of the jet pump it is necessary to take into account the part of its flow section, where primarily begins cavitation. Given that it is not known in advance in which area of the jet apparatus under these conditions primarily occurs cavitation, in each case it is necessary to define the cavitation parameters both of the nozzle and mixing chamber. Research objective of cavitation characteristics is simplified in the case of using jet apparatus of hydrocarbon recovery system. The working medium is oil and injected medium is gas, so in practice only cavitation mode of the nozzle can be implemented.

In the study of cavitation properties of the jet apparatus we use the law of energy conservation in specific sections of the jet system. The study involves determining the cavitation characteristics of fluid flow in the hydraulic system of the jet apparatus.

Bernoulli equation for the sections 1–1 and 3–3 (Fig. 2):

$$z_1+\frac{p_1}{\rho g}+\alpha_1\frac{V_1^2}{2g}=z_3+\frac{p_3}{\rho g}+\alpha_3\frac{V_3^2}{2g}+h_{1-3}, \qquad (1)$$

where $z_1$, $z_3$ – marks of geometric positions of sections under consideration $p_1$, $p_3$ – the pressure values in sections 1–1 and 3–3 respectively; ρ — oil density; $g$ – free fall acceleration; $V_1$,$V_3$ – flow velocities; $a_1$, $a_3$ – coefficients of velocity distribution unevenness; $h_{1-3}$ – hydraulic losses in the fluid flow between sections 1–1 and 3–3.

Given the peculiarities of the design model, analyse the components of the equation (1).

The inputs to the analysis of equation (1) have the following form:

$$\begin{aligned} &z_1=H;\ p_1=p_г;\ V_1=0;\\ &z_3=0;\ p_3=p_к, \end{aligned} \qquad (2)$$

where $p_г$ – the pressure at the free surface of the oil in the tank; $p_к$ – cavitation margin of the centrifugal pump pressure.

Below is an explanation of the choice of input data (2).

According to the design model the geometric mark of the section 1–1 is determined by the height of the oil in the tank $H$. The pressure value $p_1$ is characterized by the gas pressure at the free surface of the oil in the tank. The velocity of the oil on the surface of the tank is small, since the area of section 1–1 is significantly higher than the area of the pipeline cross-section. Geometric mark $z_3$, considering that the area of comparison is drawn through the axis of the pipeline is set to zero. Pressure value at section 3–3 is taken considering minimum rating necessary for the normal operation of a centrifugal pump. Then equation (1) has the following form:

$$H+\frac{p_Г}{\rho g}=\frac{p_к}{\rho g}+\alpha_3\frac{V_3^2}{2g}+h_{1-3}. \qquad (3)$$

The last component of equation (3) is determined by the total pressure loss in the working nozzle of jet apparatus $h_р$ and in the linear part of the pipeline $h_{тр}$. The pressure loss in the working nozzle is determined by the following formula [8]:

$$h_p=\frac{\Delta p_p}{\rho g}=\frac{Q^2}{2\mu_{рн}^2 f_{рн}^2 g}=\frac{8}{\pi^2}\,\frac{Q^2}{\mu_{рн}^2\, g\, d_{рн}^4}, \qquad (4)$$

where $\Delta p_р$ – pressure loss in the working nozzle; $m_{рн}$ – discharge coefficient of the working nozzle; $f_{рн}$ – sectional area of the working nozzle; $d_{рн}$ – working nozzle diameter.

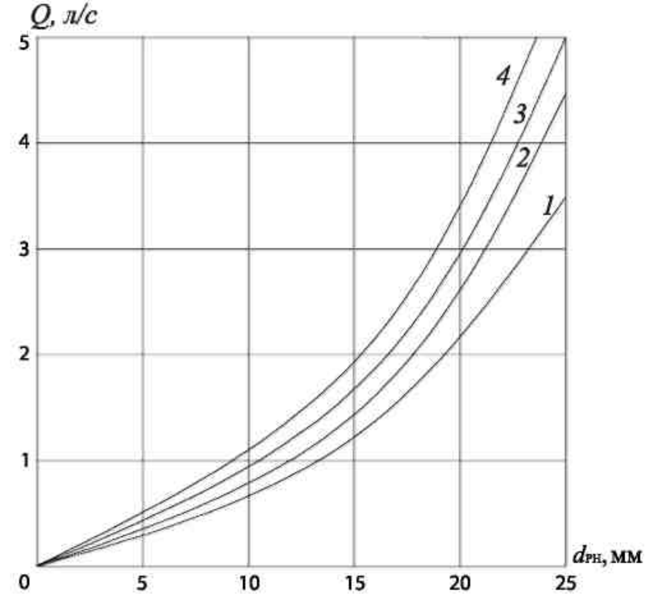

Fig. 3. The dependence of discharge on the diameter of the jet apparatus nozzle for different levels of oil in the tank: 1 – 8 m; *2* – 10 m; *3* – 11 m; *4* – 12 m

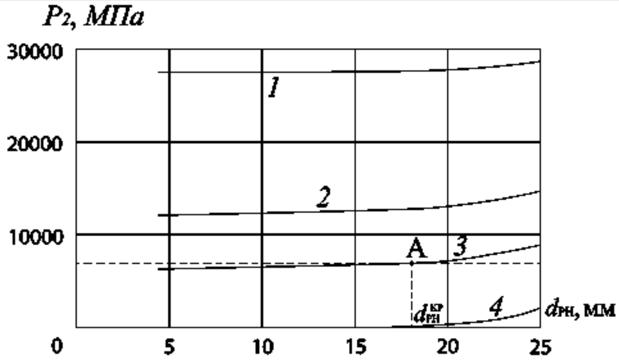

Fig. 4. The dependence of the pressure in the mixing chamber of the jet apparatus on the nozzle diameter for different levels of oil in the tank: *1* – 8 m; *2* – 10 m; *3* – 11 m; *4* – 12 m

Pressure loss in the linear part of the pipeline is determined based on the Darcy–Weisbach equation [9]:

$$h_{\text{тр}}=\lambda\frac{l_{\text{тр}}}{d_{\text{тр}}}\frac{V_{\text{тр}}{}^{2}}{2g}=\frac{8}{{}^{2}}\frac{\lambda l_{\text{тр}}Q^{2}}{g\,d_{\text{тр}}^{5}}, \qquad (5)$$

where λ – coefficient of the linear hydraulic resistance; $l_{\text{тр}}$, $d_{\text{тр}}$ – length and diameter of the pipeline respectively; $V_{\text{тр}}$ – velocity of the oil in the pipeline.

In the process of conversion (5) the relationship between velocity and flow rate was taken into account.

Determining the coefficient λ provides a standard procedure for calculating fluid velocity, Reynolds number, turbulent zone boundaries and determining their type.

Considering equations (4) and (5), the formula for determining the pressure loss in areas between sections 1–1 and 3–3 becomes as follows:

$$h_{13}=\frac{8}{\pi^{2}g}\left(\frac{1}{\mu_{\text{рн}}^{2}\,d_{\text{рн}}^{4}}+\frac{\lambda l_{\text{тр}}}{d_{\text{тр}}^{5}}\right)Q^{2}. \qquad (6)$$

After changing the velocity with flow rate and substituting formula (6) into equation (3) the following can be written:

$$H+\frac{P_{\Gamma}}{\rho g}=\frac{P_{к}}{\rho g}+\alpha_{3}\frac{8Q^{2}}{\pi^{2}gd_{\text{тр}}^{4}}+\frac{8}{\pi^{2}g}\left(\frac{1}{\mu_{\text{рн}}^{2}\,d_{\text{рн}}^{4}}+\frac{\lambda l_{\text{тр}}}{d_{\text{тр}}^{5}}\right)Q^{2}. \qquad (7)$$

Solution of equation (7) allows determining the flow through the flow section of the jet apparatus:

$$Q=\left(\frac{\rho gh+P_{\Gamma}-P_{к}}{\dfrac{8\rho}{\pi^{2}}\left(\dfrac{\alpha_{3}}{d_{\text{тр}}^{4}}+\dfrac{1}{\mu_{\text{рн}}{}^{2}d_{\text{рн}}^{4}}+\dfrac{\lambda l_{\text{тр}}}{d_{\text{тр}}^{5}}\right)}\right)^{0,5}. \qquad (8)$$

Considering the dependence of *λ* on the flow rate *Q*, the solution of equation (8) involves the application of the method of successive approximations.

Fig. 3 shows graphic representation of equation (8). Flow through the flow section of the jet apparatus is proportional to the diameter of the nozzle and the height of the oil level in the tank.

The study of cavitation characteristics necessitates comparing the pressure at the outlet of the jet apparatus nozzle with the saturated oil vapour pressure. The value of the pressure at the outlet of the jet apparatus nozzle can be calculated using the Bernoulli equation written for the sections 1–1, 2–2 (see Fig. 2).

$$z_{1}+\frac{p_{1}}{\rho g}+\alpha_{1}\frac{V_{1}^{2}}{2g}=z_{2}+\frac{p_{2}}{\rho g}+\alpha_{2}\frac{V_{2}^{2}}{2g}+h_{1-2}. \qquad (9)$$

Contrary to equation (1), the last component of the formula (9) defines the pressure loss exclusively in the jet apparatus nozzle.

The last equation can be simplified by using the obvious relations

$$z_1=H;\ p_1=p_{\text{г}};\ V_1=0;\ z_2=0.$$

Then, taking into account the relation for determining the pressure loss in the working nozzle of the jet apparatus (equation (4)), we obtain the formula for determining the minimum pressure of the jet system

$$p_2=\rho gH+p_{\text{г}}-\left(\alpha_2+\frac{1}{\mu_{\text{рв}}^2}\right)\frac{8\rho Q^2}{\pi^2 d_{\text{рн}}^4}. \qquad (10)$$

Equation (10) allows determining the likelihood of cavitation conditions in the jet apparatus by comparing the pressure $p_2$ with the value of saturated oil vapour pressure $p_{\text{НП}}$ for a given temperature. Normal operation of the jet apparatus obviously corresponds to the condition $p_{\text{Г}}>p_{\text{НП}}$.