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Operational Process and Characteristics of Liquid-Gas Jet Pumps with the Ejected Vapor-Gas Medium

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Abstract

In many industrial processes, the use of a liquid-gas jet pump refers to the ejection of the vapor-gas medium, i.e. a medium containing non-condensable and condensable gases in the liquid jet. Conventional calculation methods are used for jet devices that eject non-condensable gases. However, the presence of steam in the medium ejected makes a significant contribution to the operational process and, consequently, its mathematical description and device specifications. The article deals with the development of physical and mathematical models and determination of properties of liquid-gas jet pumps (LGJP) with an ejected vapor-gas medium. While calculating the performance there were used: Bernoulli equation – for spin-up of the active flow in the nozzle device; water balance equation, heat balance, conservation of momentum – for vapor condensation in the suction chamber; momentum equation and isothermal state equation of liquid-gas mixture – for mixture of media in the mixing chamber; liquid-gas mixture flow equation– for transformation of excess kinetic energy into the potential energy in the diffuser. Extremal characteristics that reflected the potential of the LGJP work were calculated on the basis of the equations. Analysis of specifications was carried out in a non-dimensional coordinates – in terms of the ejection coefficient by dry gas and compression ratio. The calculation of set of extremal characteristics with different ratios of the steam flow to the liquid showed that the presence of steam in the pumped medium degrades performance, i.e. the ejection coefficient is reduced at a constant compression ratio.

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Keywords: non-condensable gas; vapor-gas medium; physical-and-mathematical model; extremal characteristic; potential of jet pump; compression ratio; ejection coefficient by dry gas

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Nomenclature

m_l, m_g, m_v	mass rate of liquid in the *i*-th section, of gas and of vapor
T_{mix}, T_l, T_v	the absolute temperature of the gas-liquid mixture, of liquid and vapor
C_l, C_v	isobaric heat capacity of liquid and vapor
L_k	specific heat of evaporation
p_i	absolute static pressure of the medium in the *i*-th section
ρ_{gi}	density of gas in the *i*-th section
ρ_{mix}	density of the mixture
R_g	the gas constant
T_g	the absolute temperature of the gas
Q_{vg3}	volume flow rate of the saturated gas-vapor mixture in the 3rd section
$\overline{p_i}$	the absolute total pressure in the section 1-1
U_{li}	fluid velocity at *i*-th section
d_{i}	the diameter of the *i*-th section
ζ_{10}, ζ_{34}	coefficient of resistance of the nozzle passage and the mixing chamber
φ	the nozzle velocity ratio
$U_{\text{mix}4}$, U_{g3}	velocity of gas-liquid and gas mixture in sections 4-4, 3-3
τ_{34}	length-averaged wall shear stress
λ_{34}	coefficient of hydraulic friction in the mixing chamber
A_{34}	surface area of the mixing chamber
d_3	diameter of the mixing chamber
k_{vi}	correction factor for the pressure of the saturated liquid vapor in *i*-th section
p_{sv}	pressure of the saturated liquid vapor
ζ_{dif}	coefficient of resistance of the diffuser
α_{2g}	volume coefficient of ejection to dry gas
Q_{2g}	volume flow rate of the gas in the 2nd section
μ_v	mass coefficient of ejection to vapor
ε_{42}, ε_{52}	gas compression ratio
Γ	jet dynamic parameter
c	parameter of resistance
k_t	correction factor for difference of liquid and vapor
B	coefficient, which considers physical properties of flows

1. Introduction

Liquid-gas jet pumps (LGJP) due to their simple design, availability of a variety of assembly options, absence of moving parts, are widely used in engineering [1-3]. In many industrial processes application of LGJPs is associated with ejection of the vapor-gas medium, i.e. a medium containing non-condensable and condensable gases in the liquid jet. For example, in the oil industry it is necessary to pump a mixture of saturated steam and multicomponent gas from the well after the steam-stimulation [4, 5], while in engineering it is required to create a vacuum in steam turbines condensers [6, 7]. Review of the literature on LGJPs [8-12] has shown that the well-known methods of calculation are designed for inkjet devices which eject non-condensable gases. However, the presence of steam in the medium ejected makes a significant contribution to the operational process and, consequently, its mathematical description and device specifications. In this regard the development of physical and mathematical model and determination of properties of liquid-gas jet pumps (LGJP) with vapor-gas medium ejected becomes increasingly relevant.

The aim of the article is to develop liquid-gas jet pump-related theory and determine its properties, including extremum ones, when vapor-gas mixture is ejected.

2. Schematic diagram and operational process of a liquid-gas jet device. Physical and mathematical model

Schematic diagram of a liquid-gas jet pump (LGJP) with vapor-gas medium ejected is shown in Fig. 1; the stages of operational process are shown in Fig. 2.

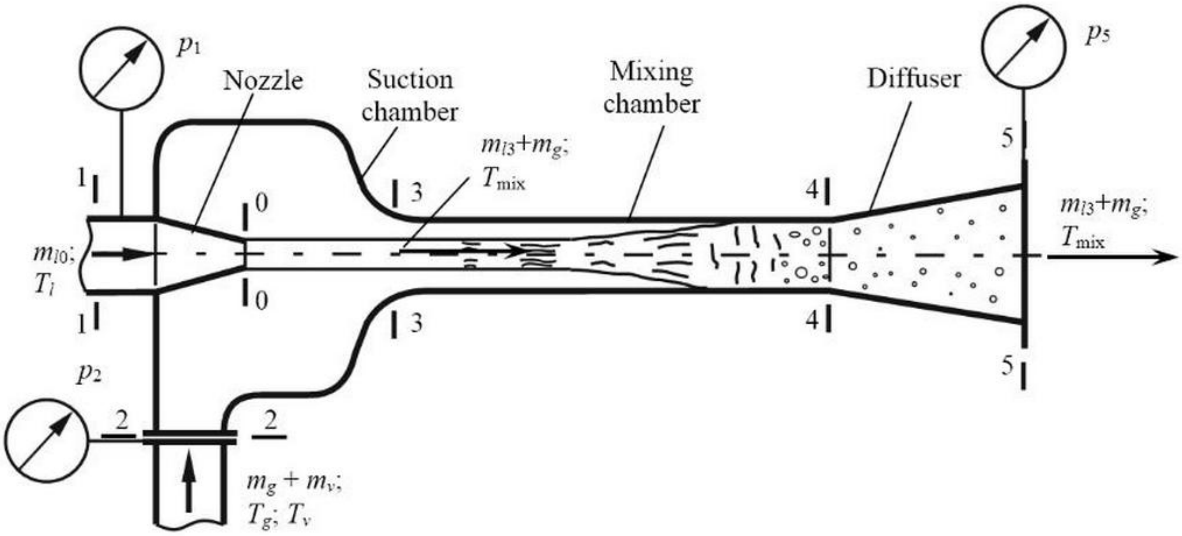

Fig. 1. Schematic diagram of a liquid-gas jet pump with vapor-gas medium

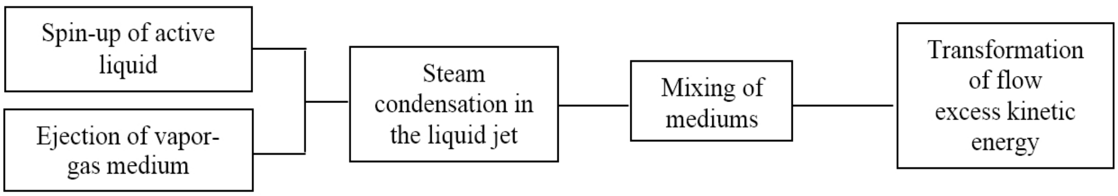

Fig. 2. Block scheme of the stages of operational process

LGJP (see. Fig. 1) includes a nozzle, an inlet and a mixing chamber, and a diffuser. [13]. Spin-up of liquid flow occurs in the nozzle unit (see. Fig. 2). A high-speed jet of liquid, which was formed before, ejects gas-vapor medium in the suction chamber.

The suction chamber also generates steam condensation in the liquid jet. Further, the kinetic momentum exchange between media in the process of their mixing takes place in the mixing chamber, followed by increase of the static pressure of the mixture flow. At the end of the operational process of LGJP, excess kinetic energy is transformed of the mixture flow is transformed into potential energy in the diffuser.

Construction of physical-and-mathematical model of the LGJP operational process with vapor-gas medium ejected is based on the following assumptions: 1) the uneven distribution of liquid and gas velocities in control sections is negligible; 2) flow of media in suction chamber is isobaric; 3) condensation of vapor ejected in the liquid jet is full size.

The initial equations that reflect the stages of the operational process are as follows:

- Bernoulli equation – for spin-up of the active flow in the nozzle device (see Fig. 1) for the area between sections 1-1 and 0-0 [14] (see Fig. 1).

$$\overline{p}_1 - p_2 = \frac{\rho_l \cdot \left(U_{l0}\right)^2}{2} \cdot \left(1 + \zeta_{10}\right) = \frac{\rho_l \cdot \left(U_{l0}\right)^2}{2 \cdot \varphi^2}\,; \qquad (1)$$

- water balance equation – for the stage of steam condensation of medium ejected in the suction chamber

$$m_{l0} + m_v + m_g = m_{l3} + m_g\,, \qquad (2)$$

heat balance equation

$$T_{mix} \cdot C_l \cdot \left(m_{l3} + m_g\right) = L_k \cdot m_v + m_{l0} \cdot T_{l0} \cdot C_l + m_v \cdot C_v \cdot \left(T_v - T_{l0}\right), \qquad (3)$$

conservation of momentum

$$m_{l0} \cdot U_{l0} = \left(m_{l0} + m_v\right) \cdot U_{l3}\,; \qquad (4)$$

- momentum equation for the area between sections 3-3 and 4-4 (see Fig. 1) – for the stage of mixing of media in the mixing chamber

$$(m_{l3} + m_g) \cdot U_{\text{mix}4} - m_{l3} \cdot U_{l3} - m_g \cdot U_{g3} = \frac{(p_3 - p_4) \cdot \pi \cdot \left(d_3\right)^2}{4} - \tau_{34} \cdot A_{34} \qquad (5)$$

and isothermal state equation of liquid-gas mixture [15]

$$\frac{\rho_{\text{mix}}}{\rho_l} = \left(1 + \frac{m_g}{m_{l3}}\right) \cdot \left(1 + \frac{m_g}{m_{l3}} \cdot \rho_l \cdot \frac{R_g \cdot T_{\text{mix}}}{p_{g2}}\right)^{-1}; \qquad (6)$$

- flow equation of liquid-gas mixture in the diffuser – to describe the operational process for the stage of transformation of excess kinetic energy into potential energy

$$p_4 + \frac{m_g \cdot R_g \cdot T_{\text{mix}} \cdot \ln(p_4) \cdot \rho_l}{m_{l3}} + \frac{\rho_l \cdot \left(U_{\text{mix}4}\right)^2}{2} = p_5 + \frac{m_g \cdot R_g \cdot T_l \cdot \ln(p_5) \cdot \rho_l}{m_{l3}} + \frac{\rho_l \cdot \left(U_{\text{mix}5}\right)^2}{2} + \\ + \frac{m_g \cdot R_g \cdot T_{\text{mix}} \cdot \ln \frac{k_{v5}}{k_{v4}} \cdot \rho_l}{m_{l3}} + \zeta_{\text{dif}} \cdot \frac{\rho_l \cdot \left(U_{\text{mix}4}\right)^2}{2}. \qquad (7)$$

Here, density of the mixture is determined from the expression [16]

$$\rho_{\text{mix}} = \frac{m_{l3} \cdot \left(1 + \dfrac{m_g}{m_{l3}}\right)}{Q_l \cdot \left(1 + \dfrac{Q_{vg3}}{Q_l}\right)}; \qquad (8)$$

volume flow rate of the saturated gas-vapor mixture in the 3rd section [16]

$$Q_{vg3} = \frac{m_g \cdot R_g \cdot T_l}{p_3 - p_{sv}}; \tag{9}$$

the absolute total pressure in the section 1-1 [14]

$$\overline{p}_1 = p_1 + \frac{\rho_l \cdot \left(U_{l1}\right)^2}{2}; \tag{10}$$

length-averaged wall shear stress [17]

$$\tau_{34} = \lambda_{34} \cdot \rho_{\text{mix}4} \cdot \left(U_{\text{mix}4}\right)^2 / 8; \tag{11}$$

correction factor for the pressure of the saturated liquid vapor p_{sv} in i-th section

$$k_{vi} = 1 - \frac{p_{sv}}{p_i}. \tag{12}$$

Physical and mathematical model is closed and allows us to calculate the most important characteristics of the liquid-gas jet pump with vapor-gas medium ejected.

3. Characteristics of a jet device with vapor-gas mixture ejected

It is feasible to undertake the analysis of the LGJP operation in non-dimensional coordinates, the most important of which are [18]:

- volume coefficient of ejection to dry gas

$$\alpha_{2g} = \frac{Q_{2g}}{Q_l}; \tag{13}$$

- mass coefficient of ejection to vapor

$$\mu_v = \frac{m_v}{m_l}; \tag{14}$$

- gas compression ratio

$$\varepsilon_{42} = \frac{p_4}{p_2} \text{ (for LGJP without a diffuser),} \tag{15}$$

$$\varepsilon_{52} = \frac{p_5}{p_2} \text{ (for LGJP with a diffuser);} \tag{16}$$

- jet dynamic parameter.

$$\Gamma = \frac{\rho_l \cdot (U_{l0})^2}{p_2}. \tag{17}$$

Potential for efficient operation of LGJP with pumped gas-vapor mixture is evaluated by its extremum properties that express the dependence of the maximum achievable rate of ejection α_{2g} on compression ratio ε_{42} (or ε_{52}). These characteristics are obtained by the study of the extremum of basic system of equations (1)-(7). For LGJP without a diffuser the analytic form of extremum characteristic is as follows

$$\frac{\alpha_{2g}}{k_{v4} \cdot k_t \cdot \varepsilon_{42}} = \left(\frac{\Gamma}{4 \cdot c \cdot (\varepsilon_{42} - 1) \cdot (1+\mu_v)^2} - 1 \right) \cdot \frac{(1+\mu_v)^2}{B \cdot \mu_v + 1}, \tag{18}$$

where

$$c = 1 + 0,5 \cdot \zeta_{34}; \tag{19}$$

$$k_t = T_g / T_l; \tag{20}$$

$$B = \frac{L_k}{T_l \cdot C_l} + \left(\frac{T_v}{T_l} - 1 \right) \cdot \frac{C_v}{C_l}. \tag{21}$$

If we take the mass coefficient of ejection to vapor as $\mu_v = 0$, then we will obtain the expression characteristic or LGJP with dry gas ejected [19].

The expression (17) shows that the coefficient of ejection to dry gas α_{2g} depends on the gas compression ratio ε_{42}, jet dynamic parameter Γ and mass coefficient of ejection to vapor $\mu_{п.}$ Thus, we find four variables. However, if we pass on to complex parameters $(\varepsilon_{42} - 1)/\Gamma$ and $\alpha_{2g}/(k_{v4}{\cdot}k_t{\cdot}\varepsilon_{42})$; the variable parameter of the set of extremum properties will remain μ_v ratio.

One can envision in the coordinate plane $[(\varepsilon_{42} - 1)/\Gamma;\ \alpha_{2g}/(k_{v4}{\cdot}k_g{\cdot}\varepsilon_{42})]$ the set of extremum properties of LGJP without a diffuser, with gas-vapor mixture ejected, under mass coefficients of ejection to vapor equal to $\mu_v = 0$; 0.2; 0.4; 0.6; 0.8; 1.0 (Fig. 3). Also we take as a liquid the water with the temperature $T_l = 283$ K; as a non-condensable gas – air with the temperature $T_g = 313$ K; as a condensable gas-vapor with temperature $T_v = 343$ K [20]. The coefficient of resistance of the mixing chamber is equal to $\zeta_{34} = 0,4$ [21], and the correction factor for the saturated vapor pressure of the liquid is equal to $k_{v4} = 1$.

Extremum properties indicate the maximum achievable operating conditions of LGJP. In addition, each point belonging to a curve describes the most efficient operating conditions for the device with certain geometric dimensions.

In the graph (see Fig. 3) curves divide the coordinate plane into two regions: the lower region, which is an area with achievable device operating parameters; and the top region, which is an area with non-achievable device operating parameters.

For example, the operating conditions, which correspond to the point with coordinates $(\varepsilon_{42} - 1)/\Gamma = 0,03$ и $\alpha_{2g}/(k_{v4}{\cdot}k_t{\cdot}\varepsilon_{42}) = 6$ (see Fig. 1), are really achievable for LGJP with entrained dry air ($\mu_v = 0$) and non-achievable for LGJP with entrained vapor-gas medium ($\mu_v > 0$). Operating conditions in point 1 correspond to the ejector with a relative area of the nozzle $\Omega_{03} = 2{\cdot}(\varepsilon_{42} - 1)/\Gamma = 0,06$ [18]. Let us suppose that for LGJP with entrained gas-vapor medium of $\mu_v = 0,2$, complex parameter remains equal to $(\varepsilon_{42} - 1)/\Gamma = 0,03$. Then the graph shows that the complex parameter $\alpha_{2g}/(k_{v4}{\cdot}k_t{\cdot}\varepsilon_{42})$ is reduced to 4 (point 2 in Fig. 3). If we take the dynamic parameter of the stream equal to $\Gamma = 100$, gas compression ratio equal to both LGJPs is $\varepsilon_{42} = 4$. However, coefficient of ejection to dry gas α_{2g} for LGJP with entrained dry gas will be equal to $\alpha_{2g} \approx 26,5$, and for LGJP with entrained vapor-gas medium is $\alpha_{2g} \approx 17,7$.

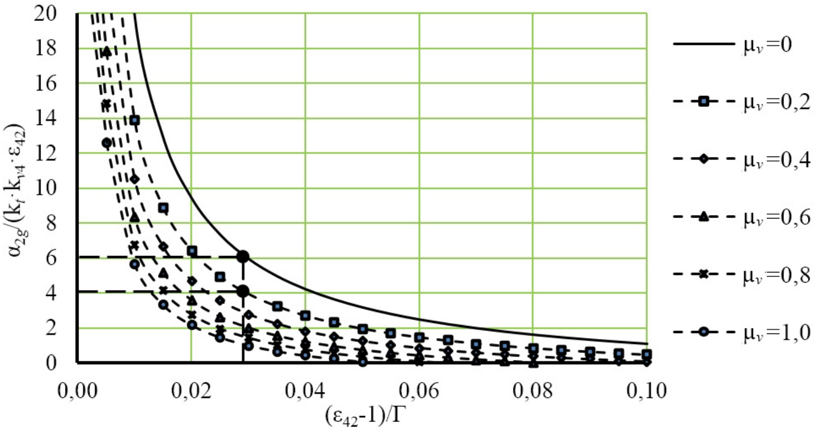

Fig. 3. Extremum properties of liquid-gas jet pumps with vapor-gas medium ejected

With increasing amounts of entrained vapor μ_v, the extremum property decreases and is placed below the full curve that narrows the really achievable parameters and causes certain reduction of the maximum achievable parameters of the device operation.

Thus, the developed physical and mathematical model for liquid-gas jet pumps with vapor-gas medium ejected allows us to calculate the most important characteristics of the device and to evaluate its potential.

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