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WATER-JET PUMP DESIGN (RASCHET VODOSTRUYNOGO EZHEKTORA), (U)
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WATER-JET EJECTOR DESIGN

Water-jet ejectors are commonly used aboard ships as drainage systems. This article proposes a fairly simple and reliable method of calculating highly efficient water-jet ejectors.

The procedure described here makes use of energy balance formulas cited by P. N. Kamenev in [Gidroelevatory i Drugiye Stroynyye Apparaty (Water-jet Pumps and Other Jet-type systems), Mashstroyizdat Publisher, 1950]. The formulas deal with the theory of analysis of similar high-efficiency equipment. The data derived from this theory show good agreement with the results of bench tests conducted on a number of shipboard ejectors.

The calculation of a water-jet ejector consists basically of determining the necessary head of the operating water, both ahead and after the ejector, the water flow rate, the ejection factor, as well as all principal dimensions. The calculations are based on the law of conservation of momentum due to impact, jet continuity equations and velocity/head relationships for liquid discharge from the nozzles.

Shipboard water-jet ejectors are generally designed with inlet (suction) pipes positioned at an angle (α=60°) to the ejector axis, this being the most appropriate arrangement in a drainage system. Sometimes, however, this pipe is set at an angle of α=90°. In the latter case, the entire jet kinetic energy is wasted, which makes this type of ejector rather inefficient.

The basic energy losses in the ejector occur when the operating and ejectable stream are mixed in the mixing chamber. An ejector will show maximum efficiency only when its design will assure the least hydraulic losses and, consequently, maximum pressure. Efficiency increases considerably when pressure increases not only in the diffusor but along the length of the mixing chamber as well.

In order to reduce hydraulic losses during inflow to the mixing chamber, it is desirable that the angle between the ejectable flow and the ejector axis be minimal; furthermore, it is important that the flow rate at the mixing chamber inlet (outlet end of nozzle) be most advantageous, that the diffusor be designed with a minimum aperture at the beginning and that this aperture be gradually expanded toward the diffusor outlet.

The velocity head ahead of the ejector nozzle depends on the position of the operating water feed source (pump, force line) and the vacuum in the mixing chamber. If the ejector is positioned on a level different from that of the source, then the head ahead of the nozzle must be determined by taking into account the geometrical height equal to the length from the ejector axis to that of the operating water source (plus or minus); here one must subtract from the head the local resistances and friction losses on the given section of the force line.

Design Formulas

To simplify the calculation without significantly affecting its final results, the following assumptions were made: the specific weight of the operating and ejectable waters, as well as the mixture of both, are assumed to be same and equal γ=1000kg/cm^2; in some formulas, specific weight was not taken into account due to a decrease in γ or the expression of the head in meters of water column. In computing the operating water velocity at the exit from the nozzle, the effect of its velocity head ahead of the nozzle and the pressure of the ejectable liquid was not taken into account. The friction losses and local resistances in both the intake and delivery lines were not specified; therefore, both terms "suction head" and "delivery head" are understood here to mean their total resistances, i.e., the geometrical height plus total losses that are to be taken into account when calculating or selecting an ejector design.

With the ejector in a steady-state operating mode, the water flow from the nozzle is forced into the mixing chamber, the vacuum in which is determined (in water column) as

$$H_{vac} = H_2 + \frac{v_2^2}{2g},$$

where H_2 is the suction head of the ejectable flow, m wat.col;

V_2 is the velocity of ejectable flow at the mixing chamber inlet (outlet nozzle end), m/sec;

g=9.81 is gravity acceleration.

For an ejector operating in the suction mode, one should consider that the sum of all resistances on the intake line added to the velocity head of the drawn-in flow at the beginning of the mixing chamber must be much below atmospheric pressure: H_{vac}<10m wat.col.

For properly designed ejectors the geometric suction head is as high as H_2=7m wat.col.

The pressure head gradient of the operating water in the nozzle is written as

$$H_1 = H_0 - H_{vac} = \frac{v_1^2}{2g} - \left(H_2 - \frac{v_2^2}{2g}\right), \qquad (1)$$

where H_o is the pressure head of operating water ahead of the nozzle, m wat.col.

The operating water flow rate, on leaving the nozzle (m/sec) is written as

$$v_1 = \varphi\sqrt{2g(H_1 + H_2)}, \qquad (2)$$

where φ is the nozzle efficiency taken to be 0.95 to 0.97 for properly machined nozzles.

For an ejector operating in immersed condition, the magnitude H_2 (ignoring local losses) may be considered that of the water raise height that will appear with a minus sign in the expressions for H_{vac} and H_1.

The most advantageous ejectable flow rate in the beginning of the mixing chamber is achieved when the specific weights of the liquids entering the ejector ($\gamma_1 \approx \gamma_2$) are equal, the cross section of the mixing chamber (of cylindrical shape) is constant and the inlet angles between the operating water and the ejectable flow are equal to zero ($\alpha_1 = \alpha_2 = 0$), i.e., their supply lines arranged along the ejector axis.

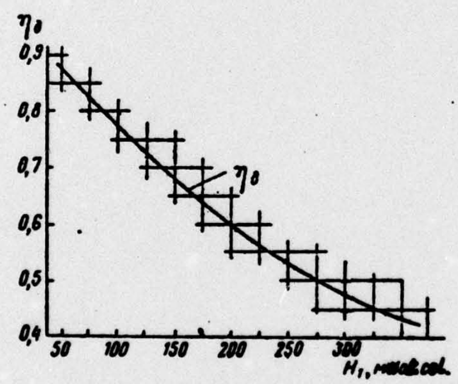

Figure 1. Efficiency of Cast Diffusers

For ejectors performing in the high suction mode (vacuum) generally fitted with conical mixing chambers and ejectable water lines at an angle to the ejector axis, the assumed flow rate will always be lower than the most advantageous one.

In selecting the optimum ejectable flow rate, one must bear in mind that increasing it will lower the impact losses due to mixing the flows and, to a certain extent, justify the energy expended for producing it; yet, the selected high flow rate may not satisfy the equation H_{vac}<10m wat.col., and thus will have to be reduced.

In order to attain the optimum ejectable flow velocity in the beginning of the mixing chamber, ejectors are often designed with flap nozzles. When the first model is bench-tested, the most efficient performance of the of the ejector is used for determining the most advantageous distance from the outlet end of the nozzle to the beginning of the diffusor throat which represents both a specific cross section of the mixing chamber at the outlet end of the nozzle and the optimum velocity.

There are three cases of flows entering the mixing chamber:

$$v_3' = v_3; \quad v_3' > v_3; \quad v_3' < v_3,$$

where v'_3 -- is the averaged velocity of the mixture of both flows in the beginning of the mixing chamber, determined from the momentum equation (2), m/sec; (2)

v_3 -- is the mixture flow rate in the narrow cross section (throat) of the diffuser, m/sec

In the first case, the hydrodynamic pressure along the mixing chamber remains constant, in the second--increases and in the third--decreases.

The momentum before and after mixing the flows with least mixing losses may be expressed in the following form.

$$G_1v_1 + G_2v_2\cos\alpha = G_3v'_3, \tag{3}$$

where G_1, G_2 and G_3 are the amounts of the operating and ejectable waters and then mixture, m^3/s ;

α--is the inlet angle of the ejectable flow into the mixing chamber.

The ejection factor or the ratio of the amount of ejectable water to the consumption of operating water:

$$\beta = \frac{G_2}{G_1} = \frac{v_1 - v'_3}{v'_3 - v_2\cos\alpha}.$$

Introducing β into equation (3) and reducing it by G_1, we obtain

$$v_1 + \beta v_2\cos\alpha = (1+\beta)v'_3 \tag{5}$$

or

$$v_1 = (1 + \beta - n\beta\cos\alpha)v'_3,$$

Where n is the ratio of the ejectable flow velocity to the averaged flow rate of the mixture at the beginning of mixing.

With the ejector performing in a steady-state mode, the energy balance with allowance for losses, may be reprinted by the following equations:

for case 1, when $v'_3 = v_3$

$$G_1H_1 = G_1\left[\frac{v_1^2}{2g}\gamma_1 - \left(H_2 + \frac{v_2^2}{2g}\gamma_2\right)\right] = G_2H_2 + G_3H_3 +$$
$$+\left(G_1\frac{v_1^2}{2g}\gamma_1 + G_2\frac{v_2^2}{2g}\gamma_2 - G_3\frac{(v'_3)^2}{2g}\gamma_3\right) + \zeta_д G_3\frac{(v'_3)^2}{2g}\gamma_3;$$

for case 2, when $v'_3 > v_3$

$$G_1H_1 = G_1\left[\frac{v_1^2}{2g}\gamma_1 - \left(H_2 + \frac{v_2^2}{2g}\right)\right] = G_2H_2 + G_3H_3 +$$
$$G_1\frac{v_1^2}{2g}\gamma_1 + G_2\frac{v_2^2}{2g}\gamma_2 - G_3\frac{(v'_3)^2}{2g}\gamma_3\Big) + \frac{G_3}{\gamma_3}\frac{(v'_3 - v_3)}{2g} + \zeta_д G_3\frac{v_3^2}{2g}\gamma_3;$$

for case 3, when $v'_3 < v_3$ it is the same as in case 1 plus $\zeta_{ind} G_3\frac{v_3^2}{2g}\gamma_3$.

In these expressions H_2 and H_3 are given as $H\gamma$ in kg/m^2 with specific weights introduced in kg/m^3 for a general case of an ejector using various liquids. The addend values enclosed in parentheses are the total losses caused by mixing the flows in the ejector.

Since frictional losses in the mixing chamber cannot be determined prior to identifying the dimensions of both the chamber and the diffusor throat, they are arbitrarily categorized as losses in the diffusor, as a result of which the latter's efficiency is lower than usual.

The total head m wat.col. developed by the ejector for case 1 ($v'_3=v_3$) will be found from the energy balance

$$H_2+H_3=\eta_{\text{д}}\frac{(v'_3)^2}{2g}-\frac{v_2^2}{2g};\tag{6}$$

for case 2 ($v'_3>v_3$):

$$H_2+H_3=\eta_{\text{д}}\frac{v_3^2}{2g}-\frac{v_2^2}{2g}+\frac{v_3}{2g}(v'_3-v_3);\tag{7}$$

for case 3 ($v_3<v_3$):

$$H_2+H_3=\eta_{\text{д}}\frac{(v'_3)^2}{2g}-\frac{v_2^2}{2g}-\zeta_{\text{вх}}\frac{v_3^2}{2g},\tag{8}$$

where H_2--is the suction head (with allowance for losses), m wat.col;

H_3--is the delivery head of the ejector, m wat.col;

$\eta_{\text{д}}$--is the diffusor's coefficient of local resistances;

ζ_{inl}--is the coefficient of local resistances when the flow of the mixture entering the diffusor from the mixing chamber becomes constricted.

It is well known that the ejector's efficiency $\eta_{\text{д}}(\%)$ is determined as the ratio of useful work to that spent, i.e.,

$$\eta_{\text{д}}=\frac{G_2}{G_1}\frac{H_2+H_3}{H_1-H_3}.100=\xi\frac{H_2+H_3}{H_1-H_3}100.\tag{9}$$

The interrelationship between efficiency (η), velocity factor (φ)

and local resistances (ξ) is $\eta=\varphi^2=1-\zeta$.

The diffusor's efficiency as a function of its conicity and the duration and quality of machining may vary within $\eta_{д}$=0.7 to 0.8.

For diffusors with properly machined surfaces that are in contact with the liquids $\eta_{д}$=0.8 to 0.85.

The efficiency for unfinished cast diffusors should be taken according to Fig. 1, as a function of the operating water head ahead of the nozzle.

The coefficients of local resistances for a mixture whose flow is constricted when entering the diffusor from the mixing chamber are determined from curves in Figs. 2 and 3.

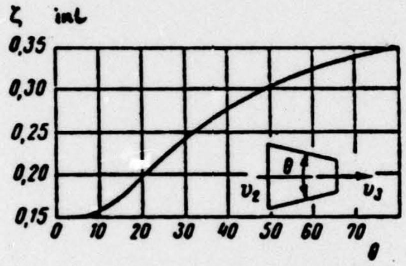

Fig. 2. The local resistance coefficient for a flow which is constricted when entering the diffusor from a conical chamber.

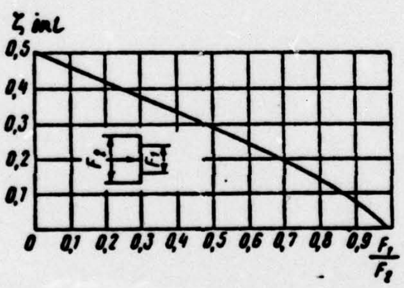

Fig. 3. The local resistance coefficient for a flow which is constricted when entering the diffusor from a rectangular chamber or from that of a different shape (other than conical).

The equality of the balance and the total heads (6) to (8) shows that the least total losses due to mixing the flows in the chamber as well as in the diffusor occur with $v_3' > v_3$, i.e., when the mixing of flows is concurrent with an increase in pressure.

It is, therefore, recommended that water-jet ejectors be designed only on the basis of case 2 of mixing the flows.

Basic Dimensions of Ejectors

The basic ejector dimensions include the diameter and length of the nozzle, the mixing chamber, the throat and diffusor, as well as the diameters of the inlet pipes for the operating and drawn-in water and the mixture's outlet.

The diameters of these elements are determined on the basis of a jet continuity equation which, for a general case, may be expressed by the following relationships:

$$v = \frac{G10}{3{,}6f} = \frac{G10}{2{,}82d^2}; \quad f = 0{,}785d^2; \quad d = 1{,}13\sqrt{f};$$

where v is the flow velocity, m/sec;

G is the flow rate of the liquid, $m^3/ч$;

f is the flow cross sectional area (of the pipe), cm^2
d is the diameter of the flow (pipe), cm.

The diameters of the inlet and outlet pipes are determined on the basis of permissible flow rates assuring normal ejector operation, while those having connecting flanges or half-nuts are accepted on the basis of GOST or other standards.

Flow Rates Recommended for Inlet and Outlet Pipes, m/sec

Operating water inlet v_0	3 - 6
Ejectable water inlet v'_2	1 - 3
Mixture outlet v_4	2 - 4

Higher mixture flow rates in the outlet pipe after the ejector diffusor are permissible only when the pipes are short and the number of areas of local resistances with low values of their coefficients is small.

The nozzle aperture is generally assumed to be within 20-30°, that of the diffusor - 8 - 12°, their length being defined by the formula

$$l=\frac{D-d}{2\,\mathrm{tg}\,\frac{\alpha}{2}},$$

where D, d are the major and minor diameters of the nozzle or diffusor, mm;

α is the diffusor aperture.

The nozzle's outlet edge (the cylindrical portion) must be as short as possible (no more than one half of the diameter of that cross section) in order to reduce friction losses which may be quite considerable at a high flow rate.

The length of the mixing chamber together with the diffusor throat for complete mixing of the flow is assumed as

$$l_{\kappa_3}=(7\div 8)\,d_3$$

where d_3 is the throat diameter of the diffusor, mm.

The length of the mixing chamber from the outlet end of the nozzle to the beginning of the diffusor throat is recommended as follows:

$$l_{\kappa}=(1{,}5\div 2{,}5)\,d_3.$$

It may be well to point out that with greater lengths of mixing chambers and diffusors in them (and higher flow rates in the diffusor throat) there will be rather considerable friction losses while shorter lengths will result in poor mixing and lower productivity.

Using the formulas cited in this procedure and having available a calculated ejector (or its basic dimensions), one could recalculate it to other operating modes for increasing the suction head, productivity or the delivery head by raising either the pressure head or the consumption of the operating water (in the latter case, it will be necessary to increase the diameter of the outlet end of the nozzle.

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