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COMPRESSORS, PUMPS, AND PIPELINE FITTINGS

DESIGN OF LIQUID-RING VACUUM PUMP WITH ADJUSTABLE DEGREE OF INTERNAL COMPRESSION

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Liquid-ring vacuum pumps are used in oil recovery, in processing of plastics, in distillation processes, and other elsewhere. A major drawback of liquid-ring vacuum pumps is the presence of a constant degree of internal compression in the impeller cells, a factor that produces excessive consumption of the compressive power of the gas phase, an increase in the overall power consumption in the evacuation process and, as a consequence, reduces the overall efficiency of the pump. A design of a liquid-ring vacuum pump with adjustable discharge window that is free of these drawbacks and produces an increase in the overall efficiency of the pump is proposed. In this design dynamic adjustment of the dimensions of the discharge window is achieved with the use of an automatically adjustable flap. The advantages of the newly designed design of a liquid-ring vacuum pump with adjustable discharge window as compared to designs of liquid-ring vacuum pumps with constant degree of compression are confirmed by the results of theoretical and experimental studies; these include a 25% decrease in the expenditure of the power in the evacuation process and a 10% increase in the speed of action. The use of the principle of a variable internal degree of compression in different operating regimes makes it possible to create new types of liquid-ring vacuum pumps with adjustable discharge window that exhibit improved operational indicators.

Keywords: liquid-ring vacuum pump, power expenditures, degree of compression, section of discharge window.

Liquid-ring vacuum pumps are used in oil recovery, in the processing of plastics, in distillation, drying, filtration, degassing, and vacuum distillation processes, in freshwater desalination systems, as well as for pumping of rare and dangerously explosive gases and steam [1–4].

A major drawback of liquid-ring vacuum pumps is the constant degree of internal compression in the impeller cells, a factor that tends to produce over-consumption of the compressive power of the gas phase and increases the overall power consumption in the evacuation process, and, as a consequence, reduces the overall efficiency of the pump.

This is explained by the fact that on the initial stage of operation of a liquid-ring vacuum pump (pneumatic pump regime) complete ejection the gas phase from the working cavity of the vacuum pump requires a discharge pressure greater than the pressure at the exit of the discharge conduit hindering passage of the gas phase. Where the pressure in the impeller compression cells is excessive, gas phase overflows from the discharge region into the suction region accompanied by the formation of a "harmful volume" of gas phase (Fig. 1a). As the gas phase

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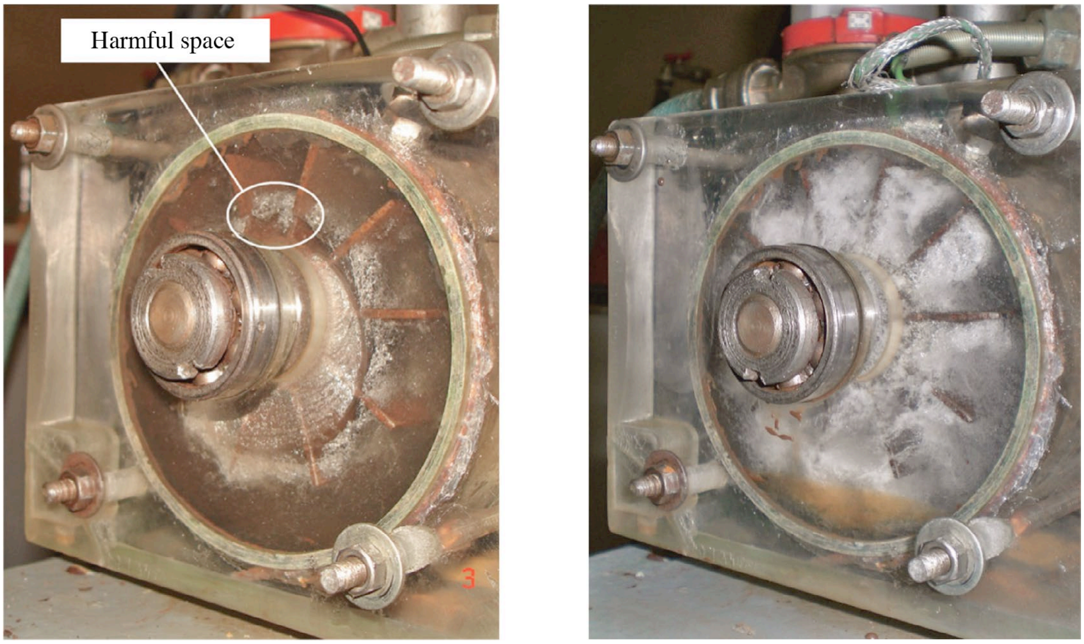


(a) (b)

Fig. 1. Photograph of liquid-ring of fluid vacuum pump in different operating regimes: (a) – pneumatic pump regime; (b) – ultimate vacuum regime.

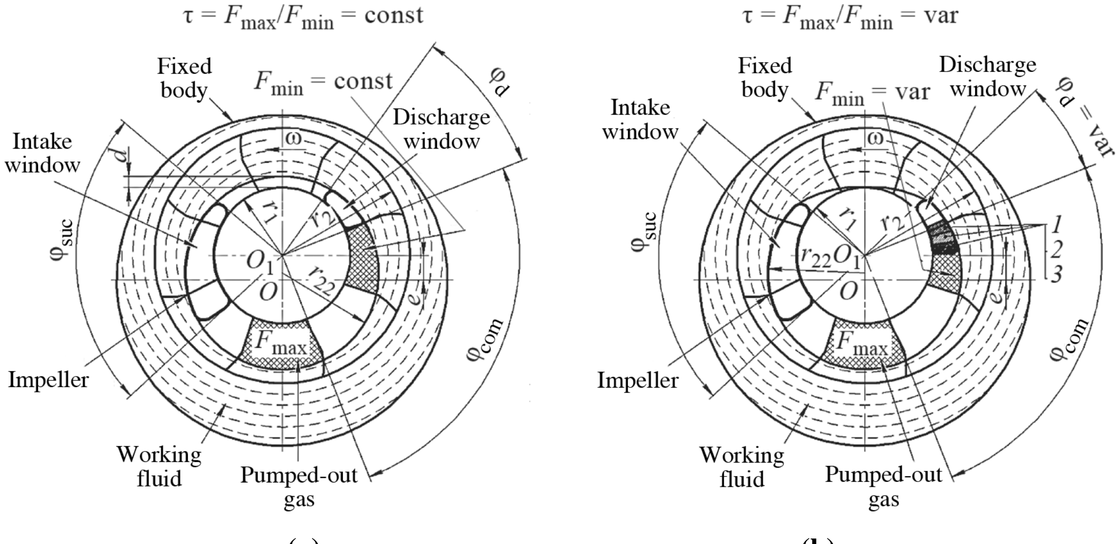
expands the useful space in the working cavity of the vacuum pump fills up, as a result consuming additional power that compresses the gas phase in the cells of turbine wheel which in turn increases the power consumption of the shaft of the vacuum pump.

On the final stage of evacuation the volume of gas phase in the compression cell of the impeller is not sufficient, which results in low values of the degree of compression. The discharge pressure decreases, with the value of the latter not sufficient for contracting the gas phase through the discharge window. As a result an effect of "suppression" of the vacuum pump arises, accompanied by destabilization of the dynamic equilibrium of the liquid ring together with intensive turbulization of the fluid throughout the space of the liquid ring (cf. Fig. 1b). As a consequence, the power consumption grows sharply and the dynamic load on the moveable elements of the vacuum pump (shaft and blades of impeller) increase. Such an operating regime of a vacuum pump is referred to as a stalling regime.

In order for the gas phase to pass through the discharge window on the final stage of evacuation, the dimensions of the flow section of the discharge window must be reduced and the degree of internal compression also varied (increased), with the discharge pressure needed for displacement of gas phase from the working cavity of the pump also increasing.

We also wish to propose a design of a liquid-ring vacuum pump with adjustable discharge window that is free of these drawbacks and produces an increase in the overall efficiency of the pump. In this design dynamic adjustment of the dimensions of the discharge window is achieved with the use of an automatically adjustable flap [5].

Let us consider the features of the compression process in the free cavity of the liquid-ring vacuum pump. Depending on the physical properties of the working bodies (evacuated gas and working fluid), and their thermodynamic properties, the compression process in a liquid-ring vacuum pump may occur in different thermodynamic processes, specifically isothermally, polythermally, or adiabatically.



(a) **(b)**

Fig. 2. Functional diagram of construction of liquid-ring vacuum pumps: (a) – liquid-ring vacuum pump (traditional design); (b) – liquid-ring vacuum pump with adjustable discharge window (proposed design).

A polytropic compression process in a liquid-ring vacuum pump is described by the equation

$$pV^m = p_1V_1^m = \text{const} \tag{1}$$

or

$$\frac{V_1}{V} = \left(\frac{p}{p_1}\right)^{1/m} \Rightarrow V = \left(\frac{p}{p_1}\right)^{1/m} V_1.$$

The work of displacement and compression of gas in the working cavity of a liquid-ring vacuum pump is determined by means of the formula

$$A = \int_{p_1}^{p_2} V\,dp = \int_{p_1}^{p_2} \left(\frac{p}{p_1}\right)^{1/m} V_1\,dp = \frac{m}{m-1} p_1V_1\left[\left(\frac{p_2}{p_1}\right)^{(m-1)/m} - 1\right]. \tag{2}$$

The index of polytropy m is calculated by means of the formula [6]

$$m = \frac{\log(p_d/p)}{\log(p_d/p) - \log(T_{in}/T_{mix})}, \tag{3}$$

where p is the suction pressure, Pa; p_d – discharge pressure, Pa; T_{mix} – temperature of mixture of fluid and gas, K; and T_{in} – temperature of intake air, K.

The power consumed in compression of the steam-gas mixture is determined as

$$N_{com} = pS\frac{m-1}{m}(\tau^{(m-1)/m} - 1)\alpha, \tag{4}$$

where S is the speed of action of the vacuum pump, m^3/hr; $\tau = F_{\max}/F_{\min} = V_{\max}/V_{\min}$ – internal degree of compression (Fig. 2); $V_{\max}$ and $V_{\min}$ – volume of maximal and minimal cells, respectively, m^3; $F_{\max}$ and $F_{\min}$ – cross-sectional area of maximal and minimal cells, respectively, m^2; and α = 1.0–1.5 – a coefficient that expresses the inverse expansion of the gas phase [6].

The volume of the largest cell and volume of the smallest cell depend on the internal configuration of the liquid ring which is bounded by the radius $r_{22\varphi}$

$$r_{22\varphi} = r_2\sqrt{\frac{r_1^2}{r_2^2} - \frac{2k_{\nu\varphi}\delta\xi}{\psi} + \frac{2k_{\nu\varphi}(2e+\Delta)\xi}{r_2\psi}} - e(1+\cos(\varphi)), \tag{5}$$

where r_2 is the radius of the impeller wheel, m; r_1 – radius of impeller vane, m; ψ – a coefficient that expresses the influence of the thickness of the blades; φ – turning angle of impeller, rad; $\delta = \Delta/r_2$ – relative gap; Δ – least gap between impeller and structure, m; $\xi = b/b_0$ – coefficient; b – width of structure of vacuum pump, m; b_0 – width of impeller, m; and e – eccentricity of impeller, m.

The rate factor $k_{\nu\varphi}$ of bladed and blade-free spaces is a function of the turning angle of the impeller φ and takes into account variations of the speed of two-phase flow in the radial cross-section of the working cavity as a function of the operating regimes of a liquid-ring vacuum pump, the physical properties of the working fluid, the thermodynamic parameters of the gas phase, as well as the working characteristics of a liquid-ring vacuum pump (angular spin rate); The values of the factor $k_{\nu\varphi}$ are determined from the results of mathematical modeling or experimentally [7–10].

Thus, the rate of compression N_{com} of the steam and gas mixture in the pump is a function of the angular spin rate of the impeller ω, the average speed of the fluid in the bladed and blade-free spaces $\nu_{\text{av}\varphi}$, and the internal degree of compression τ:

$$N_{\text{com}} = f(\omega, \nu_{\text{av}\varphi}, \tau). \tag{6}$$

Let us consider the distinctive features of the two constructions we are considering, an ordinary liquid-ring vacuum pump and liquid-ring vacuum pump with adjustable discharge window (cf. Fig. 2) with the following geometric parameters: r_1 = 20 mm – radius of impeller vane; r_2 = 45 mm – radius of impeller vane; e = 7 mm – eccentricity; φ_{suc} – suction angle, rad; φ_{com} – compression angle, rad; φ_{d} – discharge angle, rad; and 1, 2, 3 – positions of discharge window as a function of the operating regime of the liquid-ring vacuum pump.

As a consequence of the fact that the dimensions of the discharge window remain constant for traditional constructions of a liquid-ring vacuum pump, the position of the minimal compression cell and its dimensions $F_{\min} = \text{const}$ remain invariant (cf. Fig. 2a) and the magnitude of the internal degree of compression does not vary $(\tau = F_{\max}/F_{\min} = \text{const})$ in any operating regime of a liquid-ring vacuum pump.

In the new design of a liquid-ring vacuum pump with adjustable discharge window, the dimensions of the discharge window varies dynamically in accordance with the patent [5] and the position and dimensions of the compression cell correspondingly vary, $F_{\min} = \text{var}$ (cf. Fig. 2b). As a result, the internal degree of compression in the working cavity of a liquid-ring vacuum pump with adjustable discharge window is adjusted $\tau = F_{\max}/F_{\min} = \text{var}$ and the condition $p(\tau^{(m-1)/m} - 1) \geq p_{\text{d}} = \text{const}$ is satisfied in a number of different operating regimes of the vacuum pump. This makes it possible to eliminate overcompression of the gas phase and leakage of gas phase from the discharge region into the suction region on the initial operating regimes of the vacuum pump; achieve expulsion of the gas phase from the workspace and eliminate the effect of “occlusion” of

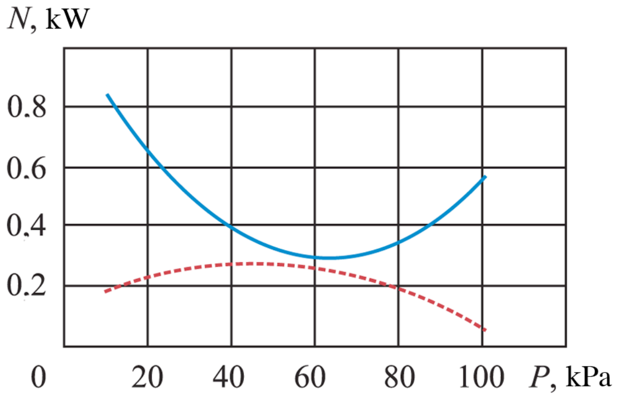


Fig. 3. Theoretical dependence of compression power of pump as a function of the power generated by the pump: — ordinary liquid-ring vacuum pump; - - - liquid-ring vacuum pump with adjustable discharge window.

the vacuum pump on the limiting operating regimes. Ultimately, the most economical operating regime of a liquid-ring vacuum pump with adjustable discharge window (as compared to the operating regime of liquid-ring vacuum pumps with a traditional design) from the point of view of expenditure of power on compression of the gas phase is achieved, as is confirmed by calculations based on formula (4) of the theoretical power of compression of a liquid-ring vacuum pump with constant degree of compression and a liquid-ring vacuum pump with adjustable discharge window (Fig. 3).

Adjustment of the magnitudes of the internal degree of compression $\tau = \text{var}$ also affects the magnitude of the true speed of action of the vacuum pump

$$S_{\text{sp}} = S_{\text{T}}\lambda_{\text{eff}}, \tag{7}$$

where $S_{\text{T}} = \pi(r_{22\varphi}^2 - r_1^2)b\psi n$ is the theoretical speed of action and m – rotational speed of impeller, min^{-1}.

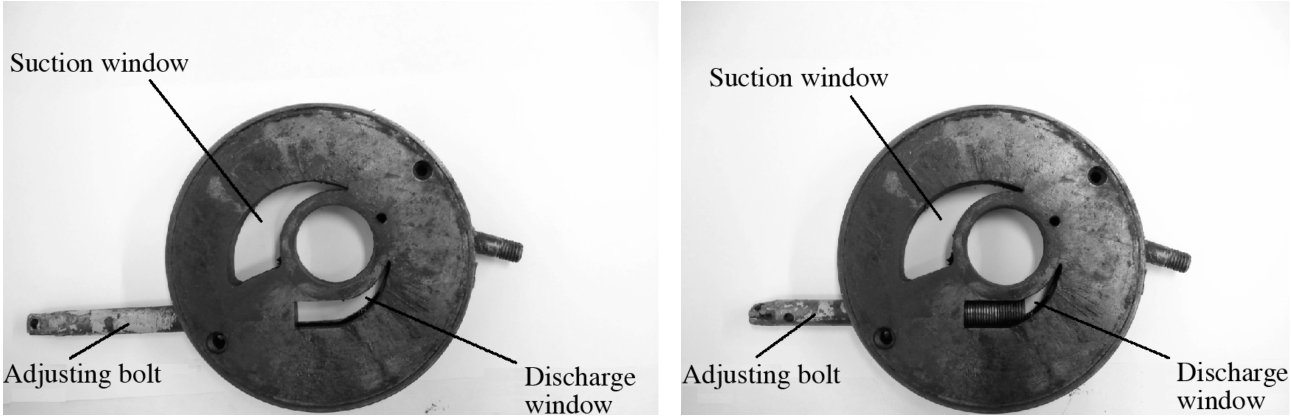
The volume efficiency λ_{eff} is determined from the formula

$$\lambda_{\text{eff}} = 1 - \lambda_1 - \lambda_2 - \lambda_3, \tag{8}$$

where λ_1, λ_2, and λ_3 are the loss factors of the speed of action.

Losses of the true speed of action as a result of the flow of a volume of gas from direction of discharge to the direction of suction (cf. Fig. 1a) are taken into account by means of the coefficient λ_1. In the design of a liquid-ring vacuum pump constancy of the degree of compression $\tau = \text{const}$ on the initial regimes of evacuation leads to significant over-compression of the gas and, consequently, the creation of “dead” space. In the proposed design of a liquid-ring vacuum pump with adjustable discharge window, the pressure in the compression cell and discharge window is smoothly evened out because of the variable value of the degree of compression $\tau = \text{var}$ at the initial moment of evacuation and this leads to elimination of the above harmful effect and, consequently, $\lambda_1 = 0$.

In constructions of a liquid-ring vacuum pump with constant degree of compression some of the volume of the gas phase leaks through the end gaps (between the impeller and the side covers) as the liquid ring rotates, and this tends to decrease the true speed of action of the vacuum pump. These losses are taken into account by the coefficient λ_2. In order to eliminate this effect, we wish to propose that additional fluid should be delivered through channels created in the end covers and in the nave of the impeller [11].



(a) (b)

Fig. 4. End disk of liquid-ring vacuum pump with adjustable discharge window and adjusting bolt in assembled state: (a) – adjusting bolt in initial position (pneumatic pump regime); (b) – adjusting bolt in final position (limiting position).

Heat- and mass-exchange processes arise in the course of operation of a liquid-ring vacuum pump, as a result of which fluid droplets evaporate in the useful part of the volume of working cells, which leads to a decrease in the effective speed of action. These losses in the speed of action are characterized by the factor λ_3. Heating of fluid occurs in connection with friction of the fluid against the wall of the fixed structure and as a result of heat exchange with the evacuated gas. The loss factor λ_3 may be decreased through cooling of the liquid ring by automated feeding (and diversion) of additional working fluid [12].

Achieving an effective speed of action with reduced overall weight and dimensional characteristics in the pump is maximally possible for vacuum pumps of a given type in light of these structural changes in a liquid-ring vacuum pump with adjustable discharge window.

Experimental investigations of the consumed power and effective speed of action of a vacuum pump as a function of the intensity of the created vacuum were carried out to arrive at a comparative assessment of the efficiency of the new design of a liquid-ring vacuum pump with adjustable discharge window and the traditional design of a liquid-ring vacuum pump with constant degree of compression. In the experimental plant of a liquid-ring vacuum pump with adjustable discharge window the problem of adjusting the dimensions of the discharge window was realized in the end disk (in which the suction and discharge windows were situated with the use of an adjusting bolt) (Fig. 4).

From the results of the experiment the consumed power (Fig. 5a) by the shaft of a liquid-ring vacuum pump with adjustable discharge window was 25% less (by comparison with the power consumed by a liquid-ring vacuum pump with constant degree of compression), moreover, the speed of action of a liquid-ring vacuum pump with adjustable discharge window was 10% higher (cf. Fig. 5b).

These results serve to confirm theoretical assumptions pointing to the value gained by varying the degree of internal compression in different operating regimes of a vacuum pump through adjusting the flow section of the discharge window.

CONCLUSION

The advantages of the newly developed design of a liquid-ring vacuum pump with adjustable discharge as compared to a liquid-ring vacuum pump with constant degree of compression were confirmed from the results of

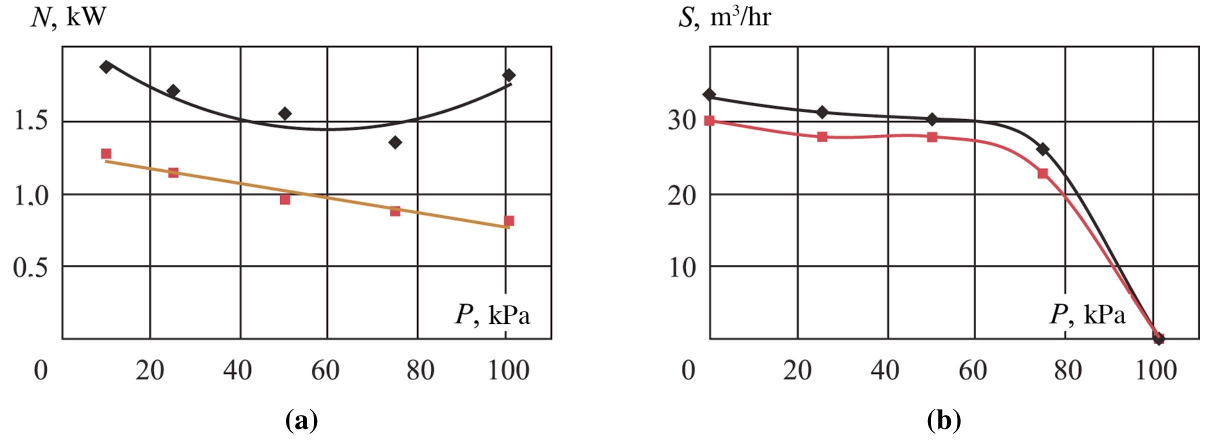


Fig. 5. Experimental dependence of consumption of power N on pump shaft (a) and speed of action S of vacuum pump (b) as a function of the created vacuum P: ◆ ordinary liquid-ring vacuum pump; ■ liquid-ring vacuum pump with adjustable discharge window.

theoretical and experimental investigations. These advantages included a 25% decrease in the expenditures of power on the process of evacuation and a 10% increase in the speed of action.

Application of the principle underlying variations in the internal degree of compression in a number of different operating regimes of the pump, including where it is possible to create new types of liquid-ring vacuum pumps with adjustable discharge window that exhibit improved operational indicators, is demonstrated.

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