STUDY OF WORK OF BLADES OF ROTARY COMPRESSORS AND VACUUM PUMPS IN THE CONTACT ZONE WITH THE BODY SURFACE

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Abstract. In the article the matter of alignment speeding-up of movable conjugations of rotary vacuum pumps in major and current repairs is examined. At present the blade edge of the vacuum pump is trimmed at angle of 45°, therefore the vacuum pump alignment needs some time and causes the spotty wear of the body. The mechanisms of wear of the upper blade edge during the alignment in major and current repairs are given and substantiated by recommendations for the alignment reduction. The article materials are useful for operatives.

Introduction

The development of new manufacturing processes of current and major repairs and the enhancement of the existing ones increase the reliability of vacuum pumps, that are ones of main and less reliable component parts of milking machines. Each new or repaired vacuum pump is subject to running-in in order to check the quality of assembly and alignment of movable conjugations [1]. It is shown, that the quality of pump assembly should be checked after achieving the operating temperature 368 K (95 °C), that corresponds to the temperature of the working condition during operation, within the maximal pump warm-up – 20 minutes [2]. If assembly clearances in movable conjugations are less or more than accepted values, then at operating temperatures the parts jamming occurs or the pump parameters decrease past the nameplate values. For example, when fixing the axial clearance between the rotor and covers and clearances between the blades and covers above the acceptable ones, the pump capacity will be lower than the nominal one. The check of the limiting residual pressure (maximal vacuum) allows to determine the accuracy of fixing the radial clearance between the rotor and the body in the point of their maximum approach. When increasing above the accepted limits of clearances between the blades and rotor slots noise and vibration increase. The pump heating takes place at the expense of heat from the compressed air work and friction of blades on the body and in rotor slots. Therefore the heating of pump parts is speeded up by the decrease of residual pressure to 11–13 kPa [2].

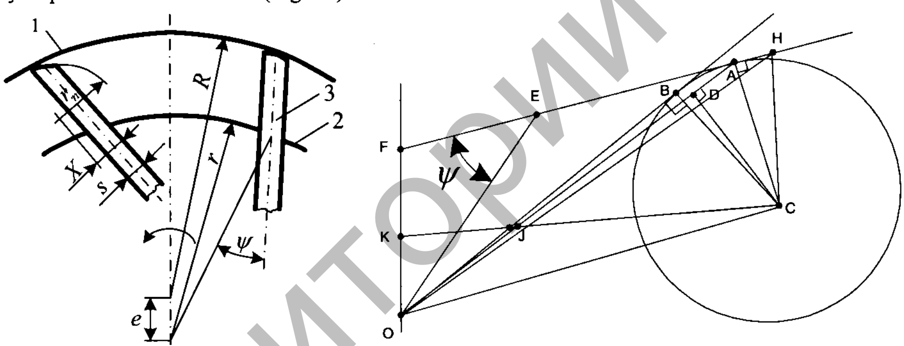
The length and quality of alignment of vacuum pumps determine the load, speed and heat conditions, type and consumption of the used lubricating fluid. The length of vacuum pumps running-in is more than 56 hours, the consumption of lubricating fluid (5% aqueous solution of emulsol ET-2) is 150 grams per hour [2]. Under real conditions all operating factors change simultaneously. Therefore the received result is the sum of action of different factors. Finishing of the alignment is determined by comparing main parameters of the pump in the established thermal conditions with nameplate values. It is evident, that the criterion of finishing of the alignment is not revealed. Therefore, in spite of practical mastering of technologies of current and major repairs of vacuum pumps, the quality of their repair remains low. The average overhaul resource of pumps doesn't exceed 60% pre-repair resource. Therefore the criterion of finishing the alignment is the form of the aligned edge of the pump blade. After all from movable conjugations of rotary pumps only two parts are broken in – the blade and body. During the alignment of friction conjugations the intensive change of roughness and geometry of part surfaces occurs as a result of physical and chemical interaction and mechanical engagement of microirregularities. Therefore it is important to define more exactly the operating power factors and reveal the regularities of wear of inclined plates of vacuum rotary pumps and maximal decrease of the alignment length of the guided-vane vacuum pump. Complex studies for estimating the alignment of parts of movable conjugations of rotary vacuum pumps are the object of the work. In particular, the task was by using the methods of planning the experiment to define more exactly optimal conditions and the alignment length of vacuum pumps in current and major repairs by taking into account the design factor, having built linear functions and estimated the significance of operation conditions.

Main Part

At the experimental plant the research of the wearing capacity of blades, made of construction textolite PT-8, grade I GOST 5-78, and the body, made of grey iron SCh-21 GOST 1412-79 was carried out. It is established, that the body wear in zones, adjacent to the air intake and discharge port, is corrugation, determined organoleptically. The corrugation represents periodically repeated rises and recesses with relatively large steps. The wave length is 3,5–9 mm. Moreover, the corrugation wear of the cylinder surface is peculiar to pumps with the debugged supply of lubricating oil. As the blade thickness decreases, eccentricity and vacuum value increase, scalloping wear of the body increases. It depends on the frequency of the rotor rotation, lubrication type, blade material, position of clearances in the rotor and rotation direction. The pump with the damaged internal body surface is characterized by the increased noise and decreased characteristics. The studies show that the blades wear takes place on the arc of a definite radius. The arc radius of the upper blade edge decreases as it wears in thickness in the rotor slots. The test values of rounding radii, received by means of the enhanced shoot of working blade end surfaces showed the interval of their values, equal to 12–20 mm. The period of the final alignment is 150–200 hours.

The search of the rational alignment process is to find after a small number of tests such combination of running-in conditions that would optimize the indices of alignment quality of vacuum pumps. On the basis of the existing information and the number of factors, which influence the alignment of vacuum pumps, five most significant factors are singled out – frequency of rotor rotation n (c^{-1}), residual pressure value in the suction cavity p (kPa), oil consumption q (г/ч), testing length t (min) and curvature of the upper blade edge r_n (mm^{-1}).

The curvature of blade edge was determined automatically by taking into account the parameters – radius of (internal) body R, plate thickness S, eccentricity e, rotor radius r and angle between the middle plate plane and rotor radius ψ (Fig. 1a). For this purpose the plate that touches the body in point C was examined (Fig. 1b).



a) b)

Fig. 1. **Diagrams of calculation of arc radius of the blade edge**: a) kinematic; b) geometrical

The perpendicular from point C to the straight line, passing through the rotor centre O and the middle of the radial plate is equal to BC. The plate turn by some angle round the point of contact with the body C allows to determine the radius of plate rounding in one point of contact for different angles of its inclination. In the new position point B comes to point A. Consequently, $BC = AC$. Taking into account, that $OE = r$, we obtain $r \cdot \sin\psi \approx \rho \cdot \sin\angle EAO$. Wherefrom $\sin\angle EAO = (r/\rho)\sin\psi$. From the triangle DAC: $\angle DAC = \pi/2 - \angle EAO$. Then $DC = AC \cdot \cos\angle EAO = BC \cdot \sqrt{1-(r\sin\psi)^2/\rho^2}$.

Thus after the plate inclination the perpendicular from the point of contact to the straight line (through the plate centre) decreases by $\sqrt{1-(r\sin\psi)^2/\rho^2}$ times. $KC = R$, $OK = e$. From the triangle OKJ: $(R-r_n)/\sin\varphi = e/\sin\angle KJO$. We also have $\angle KJO = \angle DJC$, $\sin\angle DJO = CD/r_n$.

Knowing, that $BC = (S/2)\cdot\sin\varphi$, and $(r/\rho) = \varepsilon_1$, we obtain $r_n = R \cdot S/\left[\left(2e/\sqrt{1-\varepsilon_1^2\sin^2\psi}\right)+S\right]$ and $X = (r_n r/R)\sin\psi + S/2$. The extreme point, that is on the straight line, passing through the middle of the plate, is when it turns not at point A, but at point H. Therefore the radius of the plate rounding $r_n = R \cdot S/\left[\left(2e/\sqrt{1-\varepsilon^2\sin^2\psi}\right)+S\right]$, where $(r/R) = \varepsilon$.

For a guided-vane vacuum pump with the body radius $R = 73$ mm, rotor radius $r = 61{,}5$ mm and blade thickness $s = 6$ mm the dependence of r_n and X on angle ψ is plotted (Fig. 2).

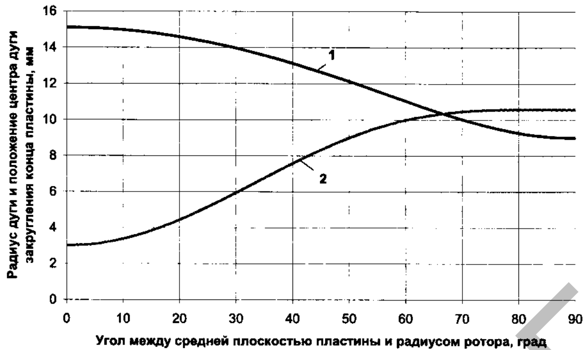


Fig.. 2. **Parameters of rounding of the upper blade edge for different inclination angles**: 1 – radius; 2 – distance from the rounding centre to the back blade plane вертикально: arc radius and position of arc centre of the rounded plate end, mm горизонтально: angle between the middle plate plane and rotor radius, degrees

From the diagram in Fig. 2 its follows, that with increase of angle ψ the decrease of r_n occurs. The contact area of the plate with the pump body is moved along the surface of its edge (Fig. 3). The latter is the evidence of the fact, that the blade is in contact with the body on some strip, whose width determines the bearing stress in the contact place.

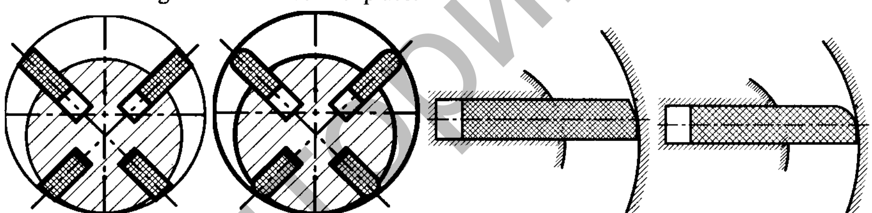


Fig. 3. **Movement of the plate contact area**: a) radial – before alignment; b) radial – after alignment; c) inclined – before alignment; d) inclined – after alignment

In order to solve the task put the experiment plan was made (Table 1), in which intervals and levels of factor variation were designated. As the optimization parameters (response functions) two indices, characterizing the pump status after alignment were taken: time of the rotor stopway (y_1), that is, time from the moment of the pump disconnection until the full stop of the rotor, and the wear of blades (y_2) (Table 1). The value of vacuum-gauge pressure was regulated by the productivity indicator KI-4840, and the action speed of the vacuum pump was measured by a gas-meter. The rate of wear of the blades was determined by weighing, and the body corrugation by a hole-gauge.

When working as a part of the milking machine the residual pressure in the working plane of the vacuum pump changes from 48 kPa to atmospheric one. During the running-in of pumps when manufacturing or repairing the rate of compression in their working plane can be increased by creating on the line of suction the limiting (minimal) residual pressure, which in accordance with GOST 13783-81 shall be 11–13 kPa. The check of the limiting residual pressure (maximal vacuum) allows to determine the accuracy of setting the radial clearance between the rotor and the body in the place of their maximal approach. With the increase above the accepted limits of clearances between blades and rotor slots noise and vibration increase.

The pump heating occurs at the expense of heat from the air compression work and blades friction on the body and in the rotor slots. Consequently, the heating of pump parts can be speeded-up at the expense of the increase of friction work and compression work, that is, by decreasing the residual pressure. Assuming that the heat output at the heat exchange of the pump with the environment and the heat, evolved from the blades friction on the body and rotor, are equal between themselves, the final temperature of air with the adiabatic process of compression is determined from the adiabatic equation at the working $p_1 = 48$ kPa and limiting residual pressure $p_1 = 11$ kPa:

$$T_{2c} = T_1\left(\frac{p_1}{p_2}\right)^{\frac{1}{k}-1} = 293\left(\frac{48}{101{,}3}\right)^{\frac{1}{1{,}4}-1} = 368\ K = 95^\circ C;$$

$$T_{2n} = T_1\left(\frac{p_1}{p_2}\right)^{\frac{1}{k}-1} = 293\left(\frac{11}{101{,}3}\right)^{\frac{1}{1{,}4}-1} = 558\ K = 285^\circ C,$$

where $T_1 = 263$ K – the initial air temperature;
$p_1 = 48$ kPa or $p_1 = 11$ kPa – the pressure in the suction pump nozzle;
$p_2 = 101{,}3$ kPa – air pressure in the discharge nozzle of the pump;
$k = 1{,}4$ – the adiabatic index.

The running-in length till achieving this temperature of the vacuum pump with rotor radius $r = 0{,}061$ m is determined by taking into account Fourier coefficients (F_0) and temperature conductivity a [4]:

$$\tau = \frac{F_0 r^2}{a}.$$

The temperature conductivity coefficient a is determined by values of heat conductivity $\lambda = 39{,}8$ W/m·K [6], grey iron density $\rho = 7{,}22\cdot10^3$ kg/m^3 and rotor thermal capacity $c = 525$ J/kg·K [5]:

$$a = \frac{\lambda}{\rho\cdot c} = \frac{39{,}8}{7{,}22\cdot10^3\cdot525} = 10{,}5\cdot10^{-6},\ \text{m/s}^2.$$

Fourier coefficient is determined by taking into account Bio coefficient (Bi) and dimensionless temperature on the rotor axis ($\theta_{r=0}$) [5]:

$$Bi = \frac{\alpha\cdot r}{\lambda} = \frac{30{,}3\cdot0{,}061}{39{,}8} = 0{,}0465,$$

where $\alpha = 0{,}105\cdot\left(\frac{T}{100}\right)^3 + 12 = 0{,}105\left(\frac{558}{100}\right)^3 + 12 = 30{,}3$ W/m^2·K – heat-transfer coefficient;

$$\theta_{r=0} = \frac{T_{r=0} - T_в}{T_0 - T_в} = \frac{368-558}{293-558} = 0{,}717,$$

where $T_{r=0} = T_{2c} = 368\ K\ (95^\circ C)$ – temperature on the warmed-up rotor axis;
$T_0 = T_1 = 293\ K\ (20^\circ C)$ – initial temperature of the rotor;
$T_в = T_{211} = 558\ K\ (285^\circ C)$ – compressed air temperature.

For values $Bi = 0{,}0465$ and $\theta_{r=0} = 0{,}717$ we determine according to the diagram the value of Fourier criterion $F_0 = 3{,}4$ [5]. Then

$$\tau = \frac{F_0 r^2}{a} = \frac{3{,}4\cdot0{,}061^2}{10{,}5\cdot10^{-6}} = 1200\ c = 20\ \min.$$

Fourier criterion values for the body (plates with the ratio of thickness and radius of internal surface $\frac{\delta}{r} = 0{,}137$) at Bio coefficient values $Bi = \frac{\alpha\cdot\delta}{\lambda} = \frac{30{,}3\cdot0{,}01}{39{,}8} = 0{,}0076$ (where $\delta = 0{,}01\ m$ is thickness of the plate (body) and the value of dimensionless excess temperature $\theta_{r=0} = \frac{T - T_в}{T_1 - T_в} = \frac{368-558}{293-558} = 0{,}717$, is $F_0 = 42{,}5$.

Therefore the warming-up time of the pump body to temperature $95^{\circ}C$ is by three times less than the time of rotor warming-up.

$$\tau = \frac{F_0 \delta^2}{a} = \frac{42{,}5 \cdot 0{,}01^2}{10{,}5 \cdot 10^{-6}} = 400 \ c = 6{,}5 \ \text{min}.$$

The pump covers and blades are warmed up fully much quicker than the rotor and the motor, because they have smaller volume and weight in comparison with them. Thus, the time of warming-up of the vacuum pump to temperature 368 K ($95^{\circ}C$), corresponding to the operating mode temperature during the operation, running-in at the limiting residual pressure, is determined according to the maximal time of rotor warming-up and is 6 minutes. Just this determines the minimal design length of running-in.

Table 1. **Interval and levels of variation of operating factors of the fractional factorial experiment**

Variation interval and level of factors	Factors				
	n, c^{-1}	***p*, kPa**	**r_n, mm^{-1}**	***q*, g/h**	***t*, min**
Factor designation	x_1	x_2	x_3	x_4	x_5
Variation interval Δx_i	6	20	0,01	10	40
Lower level $x_i = -1$	12	30	0,05	10	20
Upper level $x_i = +1$	24	70	0,07	30	100

By the results of experiments it is established, that the curvature of the blade edge influences most significantly the time of the rotor stopway or quality of alignment of friction conjugations of the vacuum pump, in the less degree – the residual pressure and oil consumption. The length of tests, as well as the vacuum gage pressure and oil consumption influence most significantly the wear of textolite blades during the alignment. The alignment finishes when the profile of the upper plate edge takes a definite form, run-in in accordance with ratios of radii of the rotor and cylinder, inclination angle and plate thickness. The deviation of sizes of the upper blade edge from the optimal form is the reason of the scalloping wear and long alignment. The presence of corrugation decreases the service life of mated elements. It is connected mainly with the fact, that the presence of wave decreases the reference area by 5–10 times in comparison with the same rough surface. The increase of the corrugation height changes the frequency of blades vibration. Hence, the physical essence of the received results is in the following: length reduction and increase of quality of alignment of vacuum pumps at minimal initial wears can be achieved at the expense of provision of the required curvature of blade edge and by the decrease of the residual pressure (Table 2).

Table 2. **Results of industrial tests of vacuum pumps UVB 02.000, aligned according to developed and existing modes**

Name of indices	**Alignment conditions**	
Curvature of the upper blade edge	Cut at angle 45°	Arc of radius 15 mm
Power consumption at pressure 48 kPa, KW	4,3	3,8
Pump capacity, m^3/min.	1,10	1,14
Limiting residual pressure, kPa	13	10
Limiting temperature of body heating, K	384	358
Sound level, dBA	79	75
Arithmetic mean deviation of the profile of the body friction surface, mcm	0,50	0,45
Alignment length, hours	200	0,1

Conclusions

New methods of substantiating the alignment conditions of vacuum pumps are developed. It is shown, that the design factors influence more significantly the length and quality of alignment of friction pairs iron-textolite. The friction pair blade-body is subject to friction at rolling with sliding. The alignment length of repaired pumps is minimal when processing upper blade edges on the arc of the design curvature. The analytical formula of curvature of the upper blade edge is defined more exactly. The rounding centre is displaced away from the axial line of the blade and lies on the intersection of the cylinder radius, drawn through the middle of the contact area, and the line, passing through the middle of rounding arc and rotor centre. The wear of blades in thickness also decreases the radius of the edge rounding to 11 mm. The change of lubricating and speed conditions influences insignificantly the alignment of friction surfaces. The advantages of the mentioned alignment method consist in decreasing the alignment length, decrease of consumption of lubricating fluids and electric power expenses, regular wear of the body. The proposed way of preparation of blade edges provides the high quality of alignment of friction surfaces and gives the opportunity to exclude pre-operation running-in of vacuum pumps, being a part of milking machines.

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