ANALYTICAL-EXPERIMENTAL STUDIES OF DELIVERY RATE AND VOLUMETRIC EFFICIENCY OF ROTOR-TYPE VACUUM PUMPS FOR MILKING MACHINE
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АНАЛІТИЧНО-ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ КОЕФІЦІЄНТІВ ПОДАЧІ І ЗАПОВНЕННЯ РОТОРНИХ ВАКУУМНИХ НАСОСІВ ДЛЯ ДОЇЛЬНИХ УСТАНОВОК

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ABSTRACT
The results of simulation of the pressure at the outlet of the pump and the coefficient of cells filling are given depending on the number of rotor vanes, the structural dimensions of the pump and eccentricity. Experimental investigations were carried out to determine the volumetric efficiency (or filling factor) and a comparison is made by the specific filling factor per unit of power of the pump drive. The power consumption per unit of volumetric efficiency of cells with air for rotary vane pump with rotating stator is 30% lower than for a fixed stator pump. A pump with a rotating stator, for identical structural and kinematic parameters with rotary pump with a fixed stator, at a productivity of 60 m^3/h and a vacuum of 50 kPa consumes 1250 watts less power.

РЕЗЮМЕ
Наведені результати моделювання тиску на виході з насоса і коефіцієнта заповнення комірок в залежності від кількості пластин ротора, конструкційних розмірів насоса, ексцентриситету. Проведено експериментальні дослідження для визначення коефіцієнту заповнення та наведено порівняння за питомим коефіцієнтом заповнення на одиницю потужності приводу насоса. Витрати потужності на одиницю коефіцієнта заповнення комірок повітрям для роторного лопатевого насоса з обертовим статором на 30 % нижчі ніж для насоса з нерухомим статором. Насос з обертовим статором, за однакових конструкційних і кінематичних параметрів що і роторний насос з нерухомим статором, споживає за продуктивності 60 м^3/год і вакууму 50 кПа на 1250 Вт менше потужності.

INTRODUCTION
The issue of upgrading the design of rotary pumps is relevant in the world. According to JARN (*2017*), the annual production for positive displacement rotary compressors alone exceeds 154.3 million pieces and growing at 11.2% annually. The researchers improve the design of rotary pumps without changing the physics of the process of its operation.

The basic structural parameters and technological characteristics for a rotary pump without vanes (or blades) were calculated (*Jafet Ferdhy Monasry, et al., 2018*). They simulated the parameters and analyzed the power consumption of the drive, but did not propose the use of a general coefficient for calculating the useful power and the final productivity of the pump. In the results of modelling of gas flows in a rotary compressor the temperature change, the velocity of gas flow and the mass velocity of floating through the end gaps of the rotor were determined, using the Mach number (*Yeu De Lim, et al., 2018*). The proposed model was not tested by experiment and the complex coefficient of general refinement that can be used for practical calculations is absent.

The rotary roller compressor pump with forced rotation was studied (*Soedel W., 2010*), the rotary vane pump and the influence of the design of the suction and exhaust windows on pump productivity were researched (*Tramschek, A. B. and Ooi, K. T., 1992*). The disadvantage of rotary pumps is that the

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mechanical friction of the rotor-stator and the stator-vanes takes up to 30% of the total power (*Ma G. Y. and Li H. Q., 2001; Dmytriv V. T., 2006*), and the friction power of the tip of the vane and stator is 81.2% of the mechanical force of friction (*Ma G. Y. and Li H. Q., 2001*). Thus, the loss of friction power to the vane-rotor and the reliability of this pair is the bottleneck in research, which holds back the widespread use of rotor blade pumps. A lot of studies have been conducted regarding the loss of friction power and the reliability of friction pairs (*Ma G. Y. and Li H. Q., 2001; Wu J H. et al., 2004; Kong X. Z. et al., 2005; Sarip A. R. and Musa M. N., 2012; Raito Kawamura et al., 2016; Hu Yusheng et al., 2018*). Pressure and temperature of the rotary blade pump were modelled with using the compression coefficient (*Costanzo Ida et al., 2018*). The compression coefficient was determined as the ratio of measured input and output pressures or gas flow. The delivery rate (or feed factor), taking into account the geometrical dimensions of the rotary blade vacuum pump is proposed by (*Dmytriv V.T., 2016*), but the analytical dependence of this feed factor does not take into account the dynamic parameters of the pump operation, in particular the frequency of rotation, the pressure change during the pump operation or the supplied power.

The operating modes of the vacuum pump affect the stability of the technological parameters of the system and in particular the vacuum pressure in the milking equipment. Researchers showed that the pressure variation in the milking machine may exceed the permissible limits and then the pump does not compensate for the loss of pressure (*Dmytriv V. et al., 2018*). The source of pressure fluctuations is the work of pressure regulators, which should stabilize the pressure in the process of work of the system. The frequency characteristics of the regulator may depend on the structural and dynamic parameters of the rotary vane pump (*Dmytriv V. et al., 2017*).

Therefore, the volumetric efficiency value is important at the development stage of rotary vane vacuum pumps. To use practically the analytical equations for modeling the characteristics of rotary vane vacuum pumps we proposed theoretical determinations of delivery rates and experimentally study the volumetric efficiency.

MATERIALS AND METHODS

Analytical model development. Let us consider an analytical treatment the operation process of rotary vane vacuum pump. The vacuum pump is designed to create a vacuum in the milking machine. There is mechanical friction between the vanes and the stator of the pump. The volume of the cell filled with air at atmospheric pressure we determine by dependence (1) taking into account that the cell volume is the product of the cross-section of the cell on the length of the rotor ($V_{np} = S_T^{\min} \cdot L_R$):

$$p_a \cdot (V_{np}) = p \cdot (S_T^{\max} \cdot L_R), \tag{1}$$

where p_a – the pressure at the pump discharge, Pa;

p – the vacuum pressure, Pa;

S_T^{max} – the maximum area of the section of vacuum pump cell;

S_T^{min} – the minimum area of the section of vacuum pump cell;

L_R – the length of the vacuum pump rotor.

From equation (1), the (2) reduced volume is determined:

$$V_{np} = \frac{p}{p_a} \cdot S_T^{\max} \cdot L_R \cdot \tag{2}$$

As the rotor rotates, the compression process takes place in accordance with the polytropic law, the air pressure in the cell with the smallest cross-sectional area will be calculated by equation (3):

$$p_a \cdot \left(S_T^{\min} \cdot L_R\right)^n = p \cdot \left(S_T^{\max} \cdot L_R\right)^n, \quad \text{or} \quad p_a = p \cdot \left(S_T^{\max} / S_T^{\min}\right)^n, \tag{3}$$

where n – polytropic coefficient, n = 1.41.

Equation (2), taking into account the dependence (3), will take the form (4):

$$V_{np} = S_T^{\max} \cdot L_R \cdot \left(S_T^{\min} / S_T^{\max}\right)^n. \tag{4}$$

It is known that the manometric coefficient K_M is determined from the ratio $K_M = p/p_a$ and taking into account the dependence (3), the dependence (5) is obtained for the calculation of the vacuum gauge pressure:

$$K_M = \left(S_T^{min} / S_T^{max}\right)^n. \tag{5}$$

Volumetric efficiency K_{in} is calculated by the amount of air that has filled the cell of the maximum cross-sectional area in vacuum to the amount of air in the cell of the minimum cross-sectional area at atmospheric pressure. The quantity of air in the cell of the maximum cross-sectional area under vacuum and in the cell of the minimum cross-sectional area at atmospheric pressure is calculated from the equation of the state of the ideal gas according to the dependences (6) and (7), accordingly:

- in vacuum: $$G_B = \frac{p \cdot S_T^{\max} \cdot L_R}{R_n \cdot \Theta}; \qquad (6)$$

- in atmospheric pressure: $$G_A = \frac{p_a \cdot S_T^{\min} \cdot L_R}{R_n \cdot \Theta}. \qquad (7)$$

Taking into account the equations (3), (6), (7), for the dependence K_{in} will take the form of (8):

$$K_{in} = \frac{G_B}{G_A} = \frac{S_T^{\max} \cdot \left(S_T^{\min}\right)^n}{S_T^{\min} \cdot \left(S_T^{\max}\right)^n} = \left(S_T^{\max}\right)^{1-n} \cdot \left(S_T^{\min}\right)^{n-1}. \qquad (8)$$

By analogy, the working process of a rotary vane pump with a rotating stator will be considered. Mechanical friction of blades on the stator is absent. For the rotation of the rotor and stator the compression process of the air passes through the isothermal process and the heating of air does not occur, the air pressure in the cell with the smallest area of the cross section is calculated by the equation (9):

$$p_a \cdot \left(S_T^{\min} \cdot L_R\right) = p \cdot \left(S_T^{\max} \cdot L_R\right), \text{ or } \quad p_a = p \cdot S_T^{max} / S_T^{min}. \qquad (9)$$

Taking into account the dependence (9), the reduced volume of (2) will look like of (10):

$$V_{np} = S_T^{\min} \cdot L_R. \qquad (10)$$

Accordingly, the manometric coefficient K_M taking into account the dependence (9) is calculated by dependence (11):

$$K_M = \left(S_T^{min} / S_T^{max}\right). \qquad (11)$$

Similarly, for a rotary stator vacuum pump, the dependence (8) taking into account the dependence (9) takes the form (12):

$$K_{in} = \frac{G_B}{G_A} = \frac{S_T^{\max} \cdot S_T^{\min}}{S_T^{\min} \cdot S_T^{\max}} = 1. \qquad (12)$$

Results and discussions of the experimental research

- **SIMULATION RESULTS**

For rotary vane vacuum pumps the simulation of pressure and delivery rate was carried out: first – with mechanical friction of vanes to the stator, the stator is fixed; second – with a rotary stator. The diameter of the stator is 0.14 m, the diameter of the rotor is within 0.10...0.12 m, the rotor length is 0.20 m, the eccentricity e = 0.01 ... 0.02 m. The results of the simulation are shown in fig. 1.

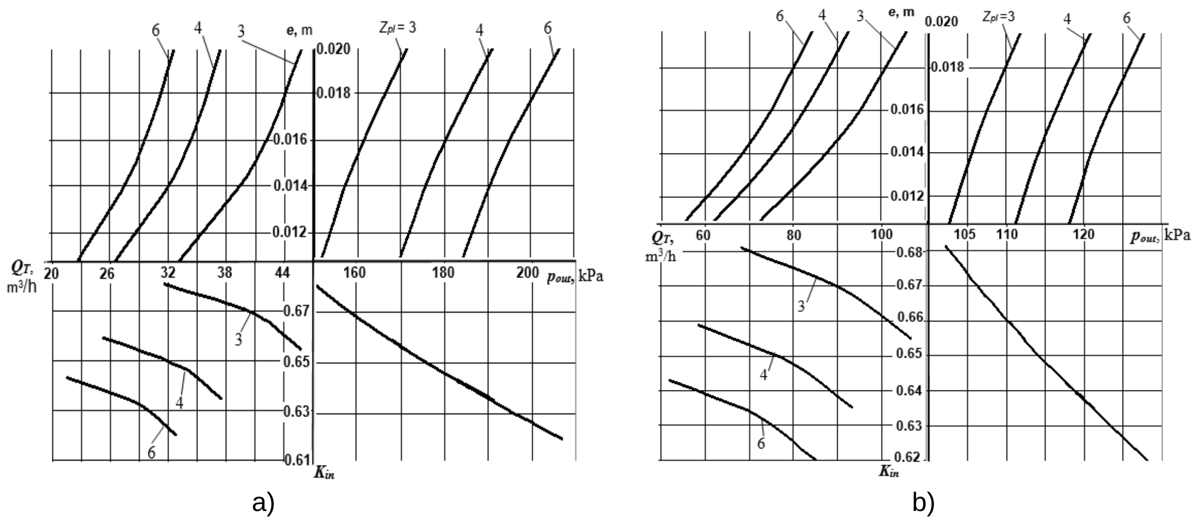

Fig. 1 - The dependence of the p_{out} pressure on the output of the vacuum pump and the K_{in} coefficient of cells filling from parameters:

a – with the fixed stator; b – with a rotary stator; Z_{pl} – number of rotor blades; e – eccentricity; Q_T – productivity

Data analysis of (Fig. 1, a) showed that with increasing the number of vanes, the volumetric efficiency decreased, with three blades and 0.01 m eccentricity, the volumetric efficiency of the cells is 0.68 for a rotary vacuum pump with a fixed stator. With an eccentricity increase up to 0.02 m, the output air pressure increases to 171 kPa, the volumetric efficiency is 0.655 and the theoretical productivity increases up to 46 m^3/h. To a rotary vacuum pump with a rotating stator (Fig. 1, b) with six vanes and an eccentricity of 0.01 m, the productivity is 52 m^3/h and a vacuum of 60 kPa. Increasing the eccentricity up to 0.02 m ensures the 84 m^3/h productivity and a vacuum of 65 kPa. The coefficient of cells filling of the vacuum pump with a rotating stator is less than that of a fixed stator vacuum pump, and is 0.643 at the eccentricity of 0.01 m, and 0.62 at the eccentricity of 0.02 m.

RESULTS

Two rotary vane vacuum pumps were studied – with a fixed stator and a rotating stator. The data of air flow and pressure at the inlet and outlet of the pump were measured experimentally. With the measured values of pressure the air density was recalculated. The volumetric efficiency of the vacuum pump was calculated from the experimental data according to the dependence (13):

$$K_{in}^{\exp} = \frac{W_{out} \cdot \rho_{out}}{W_p \cdot \rho_p}, \tag{13}$$

where W_p – the air flow at the inlet of the vacuum pump in accordance with the air meter displays, м^3/s;

ρ_p – the air density at the given vaccum, kg/m^3;

W_{out} – air flow at the outlet of the vacuum pump, kg/m^3;

ρ_{out} – the air density at the outlet of the vacuum pump, kg/m^3.

According to experimental data, the regression equation is derived in natural values for a rotary vane vacuum pump with a fixed stator (14) and for a rotary vane vacuum pump with a rotating stator (15):

$$K_{in}^{\exp} = 0.7182 + 0.0003 \cdot p_V - 6.7143 \cdot 10^{-6} \cdot p_V^2, \tag{14}$$

$$K_{in}^{\exp} = 0.9054 + 0.0004 \cdot p_V - 8.4286 \cdot 10^{-6} \cdot p_V^2. \tag{15}$$

The results of the verification of the adequacy and reproducibility of the obtained regression equations for experimental studies are presented in the table.

Table

Calculated coefficients for checking the adequacy and reproducibility of regression equations of experimental research on rotary vane pumps

(volumetric efficiency of the pump)

Type of rotary vane vacuum pump	With fixed stator	With rotating stator
Regression model	$K_{in}^{exp} = f(p_V)$	$K_{in}^{exp} = f(p_V)$
Regression equation	(14)	(15)
Calculated value of the Cochran criterion G_p	0.234	0.240
Table value of the Cochran criterion G_T	0.684	0.684
Reproducibility of experiment on condition of $G_p \le G_T$	yes	yes
Average dispersion $S^2 = \sum S_n^2 / N$, where N – number of experiments	0.000946	0.000679
Dispersion of the estimation of the regression equation coefficients $S_A^2 = S^2/(N \cdot m)$, where m – repeatability of the experiment	$3.5037 \cdot 10^{-5}$	$2.51481 \cdot 10^{-5}$
Table value of Student's t-criterion	2.28	2.28
$S_A \cdot t$	$7.8063 \cdot 10^{-5}$	$5.603 \cdot 10^{-5}$
The significance of the regression equation coefficients	significant	significant
Calculated value of F-criterion (Fischer) $F_{cal} = S_{ad}^2 / S^2$	0.003136	0.002240
Dispersion of adequacy $S_{ad}^2 = \sum(\widehat{y_{ci}} - \overline{y_{pi}})^2/(N-d)$, where $\widehat{y_{ci}}$ – average experimental value of the variable; $\overline{y_{pi}}$ – average calculated variable value; d – the number of significant coefficients in the regression equation	$1.4827 \cdot 10^{-5}$	$7.6129 \cdot 10^{-6}$
Table value of F-criterion	4.103	4.103
Condition of $F_p \le F_T$ for assessing the adequacy of the model	adequate	adequate

The graphical representation of the regression equations is shown in fig. 2.

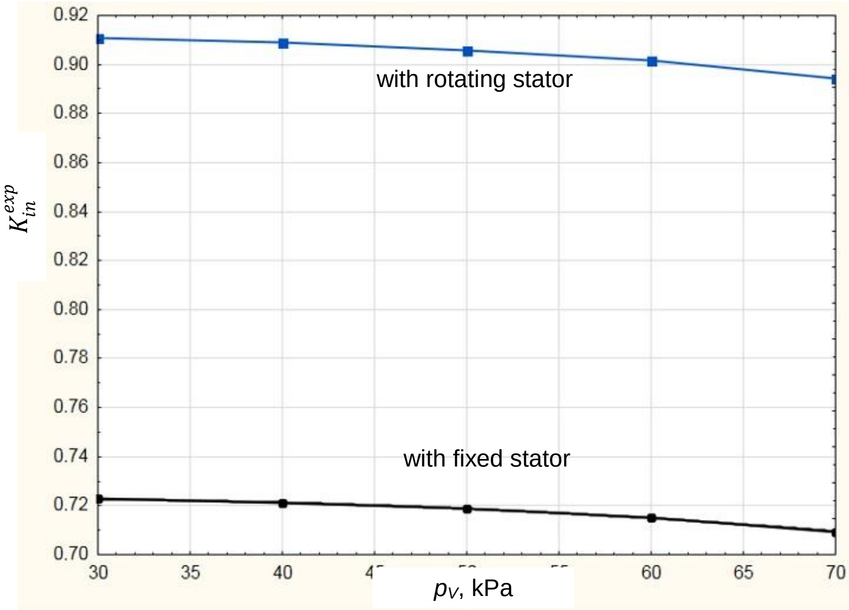

Fig. 2 - Dependence of the K_{in}^{exp} filling factor of cells with the air from the p_V created vacuum for the rotary vane vacuum pump

The specific factor of vacuum pump filling was determined as the ratio of the $K_{in}^{\exp}$ experimental coefficient of pump filling to the N_p power of the vacuum pump drive; for two types of pumps, the results are shown in fig. 3.

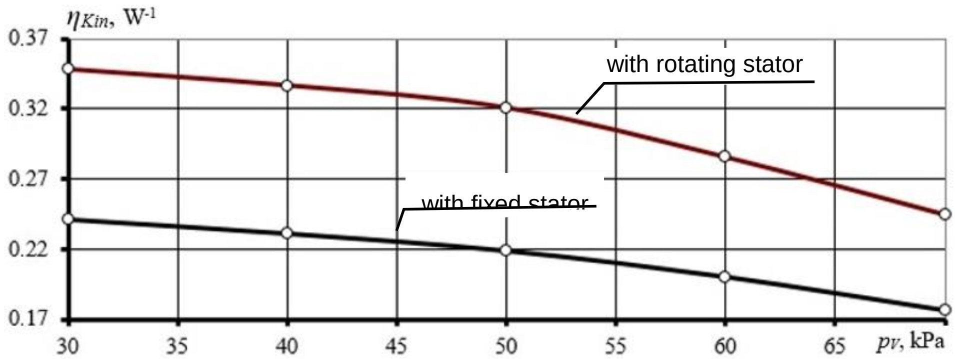

Fig. 3 - Dependence of the η_{Kin} specific coefficient of pump filling from the p_V vacuum created with the vacuum pump

An analysis of experimental data shows that the vacuum pump with a rotating stator consumes 1250 watts less power for identical structural and kinematic parameters with rotary vacuum pump with a fixed stator at the 60 m^3/h productivity and a vacuum of 50 kPa.

The power consumption per unit of factor of pump cells filling with the air of the rotary vane vacuum pump with rotating stator is 30% lower than for the vacuum pump with fixed stator.

CONCLUSIONS

An analysis of the dependencies of feed coefficients (delivery rate) has shown that the operation of the rotary vane vacuum pump with a rotating stator is more efficient than a rotary vane vacuum pump with a stationary or fixed stator. The absence of mechanical friction of the vane to the stator is due to its rotation with a frequency equal to the rotor speed. This reduces the wear of the rotor vanes and increases the stability of the technological characteristics of the vacuum pump and the duration of operation.

The efficiency of the rotary vane vacuum pump with a rotating stator is ensured by the absence of mechanical friction between the plate of the rotor and the stator and accordingly lowering of air heating in the compression stroke. This ensures an increase in the productivity of this vacuum pump compared to a rotary vane vacuum pump with a fixed stator and accordingly the effectiveness of milking machine is increased.

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