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DETERMINING THE POWER OF MECHANICAL LOSSES IN A ROTARY-PISTON ENGINE

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This paper reports an experimental study into the magnitude of the power of mechanical losses of the prototype of a rotary-piston engine with an articulated cam mechanism for transforming movement, which was aimed at resolving the issue related to improving the efficiency of energy conversion.

It has been experimentally established that the greatest component of the power of mechanical losses in a rotary-piston engine with an articulated cam motion transformation mechanism is friction losses. Depending on the rotational speed, they are about 68.4...74.4 % of total losses.

The influence of the rotor rotation frequency on the total change in the power of mechanical losses and its components has been determined (an increase in the rotations by 3.75 times leads to an increase in the power of mechanical losses by 3.3 times). It is established that the rotation frequency of the rotor does not have the same effect on the power components of mechanical losses. Thus, an increase in the rotations by 3.75 times leads to an increase in friction losses by 3.0 times, and the component of losses on pumping strokes by 4.1 times.

It was found that an increase in the pressure of working body by 2.0 times contributes to an increase in the mechanical efficiency of the rotary piston engine by 1.1 times. At the same time, it was determined that the rational speed range, which corresponds to the maximum values of the mechanical coefficient of efficiency, regardless of the pressure of working medium, is 800...1200 min^{-1}.

The resulting experimental data on studying the magnitude of the power of mechanical losses in the form of an analytical model of the influence of the main operational parameters of the rotary-piston engine with an articulated-cam mechanism for converting movement into a mechanical coefficient of efficiency have been generalized.

The results reported here could make it possible to preliminary assess losses at energy conversion at the design stage and to construct a rotary piston engine for different purposes

Keywords: rotary piston engine, compressed working fluid, degree of filling, power of mechanical losses

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1. Introduction

One of the promising types of pneumatic motors is a rotary-piston engine with uniformly spaced radial cylinders [1]. Its design combines the advantages, as well as the features of the piston and rotary pneumatic motors. The pneumatic motor is short-stroke and is equipped with boxer working cylinders located in the central rotor. Given its unique design and operational features, the rotary-piston pneumatic motor can be used at critical infrastructure facilities [2]. It can also be successfully employed in places where the operability of the equipment should not depend on the availability of external sources of electricity, for example, in sea docks to control pumps [3].

The efficiency of a rotary piston engine is highly dependent on mechanical energy losses. An increase in energy losses will lead to an increase in consumption and a decrease in the reliability of the engine and the installation in general. Mechanical losses depend on the design and operational parameters of the engine.

Part of the indicator power generated in the engine slave cylinder from the available energy is irretrievably consumed in the engine itself to overcome mechanical losses. The decrease in the effective power of the engine compared to the indicator power is associated with overcoming the frictional forces, losses for the execution of pump strokes of the piston, as well as for the drive of the auxiliary equipment mounted on the engine. The magnitude of mechanical losses, according to various estimates, can be 20 % of the energy supplied to the engine, that is, in fact, it is irretrievably lost.

A significant proportion of all losses in the engine are friction losses that occur in the coupled pairs of engine parts. The greatest sources of friction in the engine are the parts of the motion conversion mechanism (especially the piston with piston rings, piston pin, crankshaft necks), working cylinder, bearings, as well as parts of the gas exchange bodies. Friction power losses primarily directly depend on the design of the engine, the quality of its manufacture, the pressure of working fluid in the cylinder, the rotational speed, the lubrication and oil system used, as well as the general technical condition.

In addition to the loss of energy supplied to the engine, friction leads to wear of engine parts and, accordingly, its failure.

The effective power of the engine is also significantly reduced by losses associated with the performance of pumping strokes. This type of loss is most dependent on the accepted design of the gas exchange bodies, the resistance of the intake and exhaust manifold, as well as the engine operating mode.

The need to assess and control the magnitude of the power of mechanical losses is due to several factors, the main of which is the assessment of the technical condition during operation, as well as the impact of losses on the efficiency of energy conversion. Devising and implementing a set of measures to reduce the power of mechanical losses could not only increase the motor resource of the engine but also ensure a reduction in the specific effective consumption of energy. Given this, ensuring the minimum value of the power of mechanical losses is an urgent task of scientific research, especially at the stage of design and refinement of a new engine.

2. Literature review and problem statement

To determine the magnitude of the power of mechanical losses of engines, the following methods are most often used:

– running the engine from an external energy source (electric motor);

– sequential shutdown of working cylinders in a multicylinder engine;

– indication of working process (the power of mechanical losses in this case is defined as the difference in indicator and effective power);

– run-out method (determining the intensity of deceleration of the engine output shaft when the fuel supply is turned off);

– extrapolation of the load characteristic of the engine.

Each method has advantages and disadvantages in terms of technical implementation, as well as the accuracy of the results obtained.

Paper [4] reports the results of an experimental study of the mechanical losses of a four-stroke minicar engine HONDAGX25 by twisting a DC electric motor. The method is characterized by the simplicity of organizing and conducting measurements during the experiment. However, according to the authors of the cited paper, the method of comparing the indicator and effective capacities is more reliable, albeit more complex.

Work [5] reports the results of experimental studies of changes in the effective energy indicators, power of mechanical losses and mechanical efficiency of the pneumatic motor by speed characteristics. However, the cited work does not fully disclose the method by which the magnitude of the power of the mechanical losses of the engine was determined.

Numerical study of mechanical losses is a cost-effective alternative that makes it possible to predict losses by empirical ratios based on the performance of the engine. These include crankshaft speed, average piston speed, intake manifold pressure, maximum cylinder pressure. The numerical studies in work [6] include mathematical modeling based on engine dynamics, kinematics, and tribological characteristics. However, it is possible to use the generalized dependences proposed in the cited work only based on experimental studies of a particular engine.

In [7], the total mechanical losses, pump losses, the sum of friction forces, the mechanical efficiency of a single-cylinder engine with spark ignition Robin EY15 at different rotational speeds and loads are determined and analyzed by the method of indicating working process. In addition, the experimental results were compared with the results calculated using some of the dependences available in the literature. Several empirical dependences for determining the mechanical efficiency of the tested engine have been proposed.

Paper [8] reports the results of measuring the mechanical losses of the MPI EA211 piston engine in two new ways and explains the necessary engine tuning for these measurements. At the same time, the results of measuring mechanical losses by traditional methods and new methods are compared. The first way is not to change the charge of fresh air in the cylinder but to adjust the pressure in the cylinder by supplying compressed air through automatic valves. The second technique is a closed working circuit involving the connection of the exhaust to the intake, in which the boost pressure in the cylinder is set and maintained by an adjusTable supply of compressed air to the intake manifold. The first method turned out to be more suiTable for studying mechanical losses in ICE and determining the dependence of these losses on the pressure in the engine cylinder. However, the use of this technique for the examined rotary piston engine is not possible due to the design features of its intake system.

Paper [9] considers a method for experimentally determining the power of mechanical losses of a car and units (engine, transmission, and wheels of a car) on a bench with running drums, as well as an algorithm for processing the results obtained. The results of the car's run-out on the bench are given: the change in instantaneous speed on time. The initial evaluation of the regression model was performed and the values of the coefficients were derived by the least-square method regarding the deviations of the car speed. A mathematical model of subsequent processing of experimental data has been built to separate mechanical losses by power units separately for the engine, transmission, and wheels of the car. The difficulty of using a given technique is the need to take into consideration the magnitude of energy losses in the bench with running drums.

In work [10], a procedure for calculating mechanical losses is proposed, which makes it possible to determine with an accuracy of about 10 % the effect of the number of disconnected cylinders on the effective engine power, the power of mechanical losses, and mechanical efficiency. A correlation between mechanical efficiency and effective engine power has been established: with an increase in the number of disabled cylinders (factor feature) in the engine, the power of mechanical losses increases (an effective feature) while the mechanical efficiency decreases. However, this procedure is applicable to high-power engines.

Because the rotary-piston engine has a number of significant design differences from engines of similar purpose, it is necessary to conduct experimental studies into the power of mechanical losses. The study results could become the basis for devising practical recommendations regarding the structure of new engines of this type.

3. The aim and objectives of the study

The purpose of our experimental study is to determine the magnitude of the power of mechanical losses in a rotary-piston engine with an articulated cam movement mechanism, which will make it possible to assess the efficiency of energy conversion of the compressed working medium.

To achieve the set aim, the following tasks have been solved:

– to determine the effect of the rotor speed in the rotary piston engine on the change in the magnitude of the power of mechanical losses;

– to determine the effect of working fluid pressure and rotor speed on the change in the mechanical efficiency of the rotary piston engine;

– to summarize experimental data in the form of an analytical model of the change in the mechanical efficiency of the rotary-piston engine depending on the main operational parameters.

4. The study materials and methods

We have determined the power of mechanical losses in a rotary-piston engine with an articulated cam movement mechanism by bench tests of the prototype 12 RPD 4.4/1.75 (Fig. 1) whose basic parameters are given in Table 1.

Table 1

Basic parameters of the engine 12 RPD 4.4/1.75

No. of entry	Parameter	Measurement unit	Value
1	Cylinder diameter	mm	44
2	Piston stroke	mm	17.5
3	Ratio of cylinder bore to stroke	–	0.4
4	Number of cylinders	–	12
5	Working volume	cm^3	320.6
6	Relative dead volume	–	0.015
7	Engine weight	kg	32.86
8	Engine dimensions: – length – width – height	mm	 380 255 255

The rotary piston engine includes housing 1 in which rotor 2 is housed with radially pairwise boxer 12 cylinders 3 and 12 pistons 4 arranged therein. The pistons are connected to each other by means of fingers 5 and movable links 6 and, at the same time, form an articulated quadrangle, in the middle of which a cam 7 is placed coaxially to rotor 2. Cam 7 has two diametrically opposed vertices and contacts links 6 that form the sides of the quadrilateral.

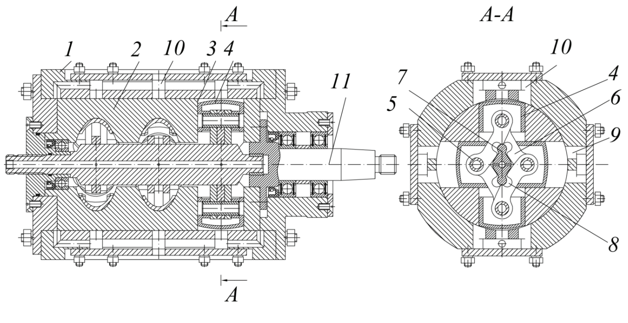

Fig. 1. General structure of the rotary-piston pneumatic motor: 1 — body of the pneumatic motor; 2 — rotor; 3 — working cylinder; 4 — piston; 5 — piston pin; 6 — mobile link; 7 — adjusting cam; 8 — groove; 9 — intake receiver; 10 — exhaust receiver; 11 — power take-off shaft

Bench tests of the prototype make it possible to obtain data on the change in the power components of mechanical losses (friction losses and pump strokes) under different operating modes. In addition, the results could become the basis for devising practical recommendations and a set of measures to reduce these losses in the process of energy conversion. The object of our study is mechanical losses in a rotary-piston engine with an articulated cam mechanism of movement; the study's subject is experimental characteristics of their changes in the process of energy conversion.

The experimental studies of changes in the power of mechanical losses during the operation of a rotary piston engine were carried out at a test bench, which ensures the stability of load parameters under all modes. The schematic diagram of the experimental bench for studying the power of mechanical losses in the rotary-piston engine is shown in Fig. 2.

The prototype of a rotary-piston engine with an articulated cam movement mechanism, the bench, and measurement systems were produced at the Machine-Building Enterprise «Motor-Plus» together with the Center for Advanced Energy Technologies of the Admiral Makarov National University of Shipbuilding (Ukraine).

The rotary piston motor is driven by a 3.15 kW 2PB-132MG DC electric motor. The rotational speed of the electric motor and, accordingly, the operating mode of the rotary piston engine is set using the AOSN-20-220-75 UKHL4 autotransformer; it was controlled by the digital tachometer GM 8905-EN-00. The power of mechanical losses in a rotary piston engine was determined by the amount of electrical energy consumed, taking into consideration the efficiency of the electric motor (82 %). The values of current and voltage were determined by an ammeter and a voltmeter, respectively. During the tests, the rotary piston engine was brought to normal thermal conditions to ensure the necessary viscosity of the oil and normal lubrication of the parts of the articulated cam movement mechanism.

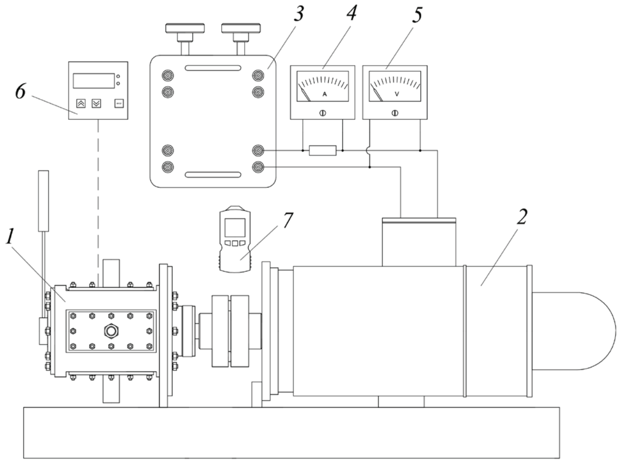

Fig. 2. Schematic diagram of the experimental bench for determining the power of mechanical losses based on the prototype of a rotary-piston engine with a hinged-cam movement mechanism: 1 — rotary piston engine 12 RPD 4.4/1.75; 2 — DC motor 2PB-132MG; 3 — autotransformer AOSN-20-220-75 UKHL4; 4 — ammeter; 5 — voltmeter; 6 — multifunctional eight-channel meter-regulator «OVEN» UKT38-SCH4.TP; 7 — tachometer

Based on the generally accepted procedure of testing natural combustion engines, as well as taking into consideration the absence of combustion in the working cylinder, the power of mechanical losses of the rotary piston engine will depend only on the speed of rotation of the central rotor. Given this, our experimental studies of changes in the power of mechanical losses were carried out taking into consideration this parameter.

5. Results of experimental studies of changes in the power of mechanical losses of the rotary piston engine

5. 1. Investigating the influence of rotational speed on a change in the magnitude of the power of mechanical losses

Fig. 3 shows the results of experimental studies of the magnitude of the power of mechanical losses depending on the revolutions of the rotary piston engine. The data presented were obtained without adjusting the degree of filling of working cylinder ε_1, that is, the regulating cam was in the middle position. With an increase in the speed n of the engine, the inertial forces increase while the resistances of the intake and exhaust manifolds also increase. Thus, with an increase in speed from 400 to 1500 min^{-1}, the value of the power of mechanical losses N_m increases from 262 to 865 W.

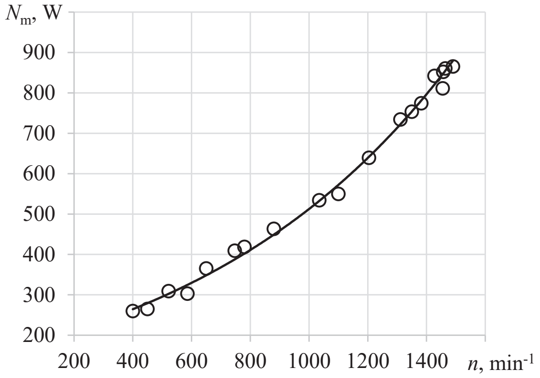

Fig. 3. Dependence of the power of mechanical losses in a rotary-piston engine with an articulated cam movement mechanism on the revolutions of the rotor

The power of mechanical losses in a rotary-piston engine with an articulated cam movement mechanism, due to the lack of mounted equipment, consists of losses for friction and the execution of pumping strokes. The structure of the engine makes it possible to estimate the amount of friction losses of the movement mechanism separately from the losses on pump strokes, thereby separating the power components of mechanical losses. The separation of the two components could make it possible to devise practical recommendations for their reduction.

We determined the proportion of mechanical friction losses by turning the control cam without rotating the engine rotor. Thus, the movement of the parts of the articulated-cam mechanism occurs without performing gas exchange. Fig. 4 shows the results of experimental studies into the magnitude of the share of power of mechanical losses for overcoming the frictional forces.

Thus, the value of power losses for friction N_f, depending on revolutions, is 195...592 W (68.4...74.4 % of the total losses in the rotary piston engine); the losses associated with the execution of pump strokes – 67...273 W.

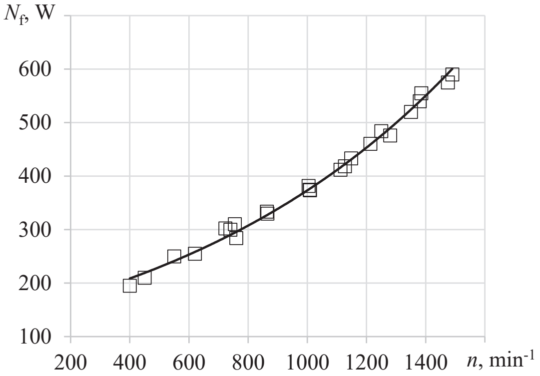

Fig. 4. Dependence of changes in power losses on overcoming the friction forces in a rotary-piston engine with an articulated cam movement mechanism on revolutions

It is possible to ensure a reduction in friction power losses in a rotary-piston engine by improving the quality of surface machining of mating parts, using high-quality oils and additives corresponding to the operating conditions. It is possible to reduce power losses for pumping strokes by reducing the resistance of the gas exchange bodies (selection of the optimal area of the passage sections of the intake and exhaust holes, depending on the operational parameters of the engine). This can also be achieved by selecting the optimal area of the passage sections and the lengths of the channels of the intake and exhaust manifolds.

5. 2. Investigating the influence of the operational parameters of the rotary piston engine on mechanical efficiency

The power of mechanical losses and its change depending on operational parameters such as rotational speed and pressure of working fluid in the intake receiver is determined for the engine of a specific design and size. Using it as a parameter for comparing and estimating losses of different engine sizes is difficult. A more convenient from a practical point of view and universal parameter is the mechanical efficiency η_m, defined as the ratio of effective to indicator power:

$$\eta_m = \frac{N_e}{N_i} = \frac{N_e}{N_e + N_m} = 1 - \frac{N_m}{N_i},$$

where N_e is the effective power, kW; N_i is the indicator power, kW; N_m is the power of mechanical losses, kW.

Mechanical efficiency makes it possible to evaluate the structural perfection of the engine, as well as compare it with other engines. Fig. 5 shows the change in the effective power and the power of mechanical losses without adjusting the degree of filling at different values of the pressure of working medium in the intake receiver of the rotary piston engine. The pressure of working fluid in the intake receiver varied in the range of 0.4...0.8 MPa.

Fig. 6 shows the change in the mechanical efficiency of a rotary piston engine depending on the speed and power generated. Thus, at P_s=0.4 MPa, depending on the engine speed, the mechanical efficiency is η_m=0.54...0.71, at P_s=0.6 MPa – η_m=0.58...0.76, and at P_s=0.8 MPa – η_m=0.63...0.78.

Based on our data, the rational range of engine speed from the point of view of ensuring the maximum value of mechanical efficiency is n=800...1200 min^{-1}. At the same time, an increase in the pressure of working fluid in the intake receiver by 2 times contributes to an increase in mechanical efficiency by 1.1 times.

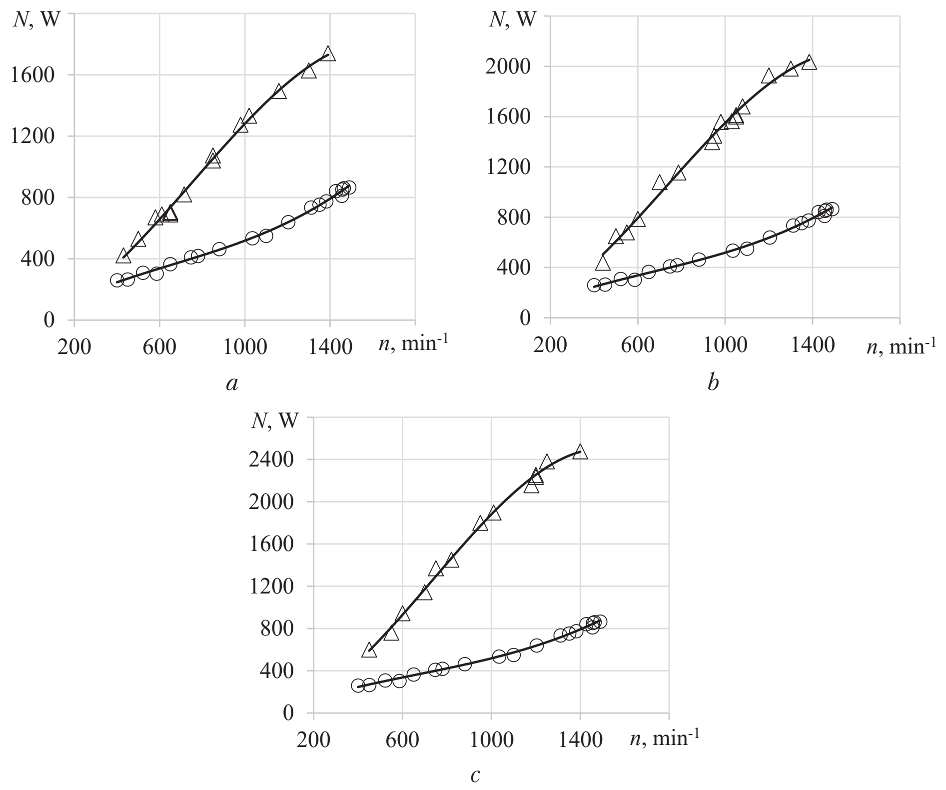

Fig. 5. Dependence of changes in the effective power and the power of mechanical losses depending on engine speed: *a* – P_s=0.4 MPa; *b* – P_s=0.6 MPa; *c* – P_s=0.8 MPa: Δ – effective power N_e; ○ – power of mechanical losses N_m

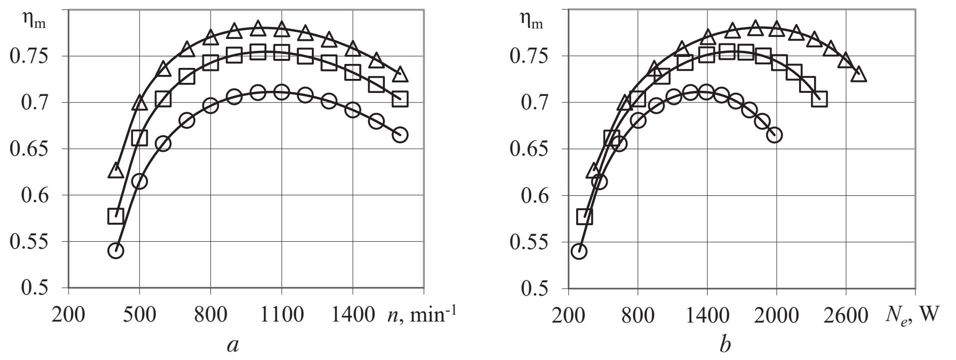

Fig. 6. Change in the mechanical efficiency of the rotary piston engine depending on working pressure in the intake receiver: *a* – the dependence of mechanical efficiency on revolutions; *b* – the dependence of mechanical efficiency on the generated power: ○ – P_s=0.4 MPa; □ – P_s=0.6 MPa; Δ – P_s=0.8 MPa

5. 3. Analytical model of changes in the power of mechanical losses in a rotary piston engine with an articulated cam movement mechanism

Based on our experimental studies, as well as data processing, an analytical model of changes in the mechanical efficiency of a rotary piston engine was built, depending on the basic operational parameters $\eta_m = f(P_s; n)$.

The experimental points were fitted using a polynomial of the sixth degree, which made it possible to construct the curves of changes in mechanical losses with acceptable accuracy. Accordingly, the analytical model of changes in mechanical efficiency is a polynomial of the sixth degree that takes the form:

$$\eta_m(P_s;n) = a \cdot n - b \cdot n^5 + c \cdot n^4 - d \cdot n^3 + e \cdot n^2 + f \cdot n,$$

where the respective coefficients are:

$$a = -75.250 \cdot 10^{-19} P_s^2 +$$
$$+88.145 \cdot 10^{-19} P_s - 17.067 \cdot 10^{-19};$$

$$b = -4{,}282.279 \cdot 10^{-17} P_s^2 +$$
$$+4{,}992.813 \cdot 10^{-17} P_s - 9{,}846.416 \cdot 10^{-18};$$

$$c = -9{,}516.028^{-14} P_s^2 +$$
$$+1{,}101.501 \cdot 10^{-13} P_s - 2{,}238.260 \cdot 10^{-14};$$

$$d = -1{,}028.641^{-10} P_s^2 +$$
$$+1{,}176.316 \cdot 10^{-10} P_s - 2{,}528.803 \cdot 10^{-11};$$

$$e = -5{,}362.988^{-8} P_s^2 +$$
$$+5{,}989.928 \cdot 10^{-8} P_s - 1{,}478.969 \cdot 10^{-8};$$

$$f = 1{,}041.801^{-5} P_s^2 -$$
$$-1{,}087.755 \cdot 10^{-5} P + 4{,}316.651 \cdot 10^{-6}.$$

Fig. 7 shows a graphical representation of the change in the mechanical efficiency of the rotary piston engine as a function of working fluid pressure in the intake receiver and engine speed $\eta_m=f(P_s; n)$.

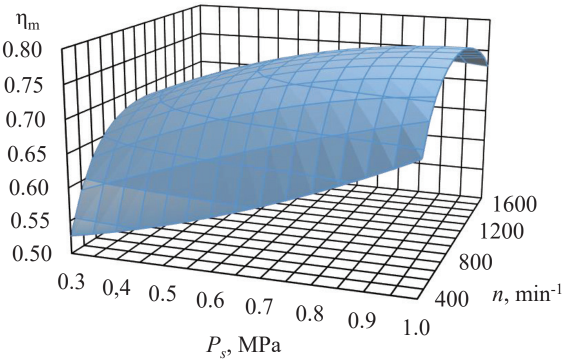

Fig. 7. Change in the mechanical efficiency of a rotary piston engine with an articulated cam movement mechanism depending on working pressure in the intake receiver and the revolutions of the central rotor

The change in the mechanical efficiency of the rotary piston engine corresponds to the neutral position of the control camshaft (without taking into consideration the degree of filling of working cylinder).

6. Discussion of results of the experimental study of changes in the power of mechanical losses

In accordance with the experimental data obtained, shown in Fig. 3, 4, with an increase in the speed of the rotary-piston engine, the magnitude of the power of mechanical losses increases in all components. The reported results are explained by the fact that with an increase in speed, the relative speeds of the rubbing parts of the engine, the forces of inertia, as well as gas-dynamic losses increase. At the same time, with an increase in the pressure of working fluid in the intake receiver, as well as the effective power generated by the engine, the mechanical efficiency does not decrease but, on the contrary, increases (Fig. 6, 7). This is explained by the fact that the indicator and effective power of the engine increases much faster than the power of mechanical losses while the mechanical efficiency is the ratio of power. The obtained experimental data and an analytical model of changes in mechanical efficiency make it possible to perform a preliminary assessment of the effective performance of a rotary-piston engine with an articulated cam movement mechanism at the design stage.

The results of our experimental studies into the power of mechanical losses are limited to several factors, both operational and structural. Operational limitations include the range of changes in the pressure of working medium, 0.4...0.8 MPa, revolutions, 400...1500 min^{-1}, as well as the lack of regulation of the degree of filling of working cylinder. The structural ones are the geometric characteristics of the bodies of gas exchange, and the mechanism of movement of a particular sample of the rotary-piston engine.

A distinctive feature of the tested rotary-piston engine is the ability to adjust the degree of filling of working cylinder in a fairly wide range; our preliminary experimental studies have shown a significant effect of this parameter on the change in mechanical efficiency. Thus, under the engine operating mode at $P_s=0.7$ MPa, $n=1500$ min^{-1}, $\varepsilon_1=0.45$, the generated effective power is $N_e=4.86$ kW while the mechanical efficiency is $\eta_m=0.87$. Accordingly, additional experimental studies into other ranges of changes in operational parameters, as well as the effect of adjusting the degree of filling of working cylinder on mechanical efficiency, are of practical interest. In addition, it is expedient to conduct studies into the influence of the geometric dimensions of the gas exchange bodies on the gas-dynamic component of the power of mechanical losses, as well as the structural relationships of the movement mechanism on the component of friction losses.

7. Conclusions

1. It has been experimentally established that an increase in the speed of a rotary-piston engine with an articulated cam movement mechanism by 3.75 times leads to an increase in the power of mechanical losses by 3.3 times. At the same time, the component of the losses associated with friction increases by 3.0 times; that with the execution of pumping strokes – by 4.1 times.

2. The influence of the pressure of working medium and the rotor rotation frequency of the rotor-piston engine on the change in the magnitude of the mechanical efficiency was established. Based on our experimental data, an increase in the pressure of working medium by 2.0 times contributes to an increase in mechanical efficiency by 1.1 times, while the rational engine speed range is 800...1200 min^{-1}.

3. As a result of generalization of the obtained experimental data on changes in the power of mechanical losses, an analytical model of the influence of the main operational parameters of a rotary-piston engine with an articulated cam movement mechanism on mechanical efficiency has been built.

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