

This paper reports the results of an experimental study of the prototype rotary-piston air motor RPD-4,4/1,75 in the form of speed characteristics.

The maxima of the air motor's performance effective indicators have been determined, as well as the rotation change ranges that correspond to them.

It has been established that for the intake receiver's air pressure change range within 0.4...0.8 MPa the maximum value of effective power is 1.7...2.5 kW. In this case, the maximum value of the torque and mean effective pressure for a given pressure range in the intake receiver is 17.0...18.2 N·m and 0.13...0.18 MPa, respectively.

The dependence has been derived of the hourly air consumption on the rotations and pressure in the intake receiver. Depending on the test mode, the hourly air consumption is within 25...226 kg/hour.

It has been established that the minimum values of the specific effective air consumption correspond to 800...1,000 rpm. Thus, for a maximum value of air pressure in the intake receiver of 0.8 MPa, the specific effective consumption is 60.8...93.2 kg/(kW·h), for the minimum value of 0.4 MPa – 49.7...81.3 kg/(kW·h).

The potential of the adiabatic expansion capacity has been determined, brought to the air motor, as well as the effective adiabatic efficiency. The maximum efficiency of the air motor corresponds to 800...1,000 rpm. In this case, the maximum efficiency value was achieved at a pressure in the intake receiver of 0.4 MPa; it is 0.41.

The dependences have been derived of the change in the pressure of spent air in the exhaust receiver, the maximum value of which does not exceed 0.075 MPa

Keywords: rotary-piston air motor, energy performance indicators, operating parameters, hourly consumption, expansion

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1. Introduction

Air motors of the different principles of action and design are widely used in different industries, transport, underwater technical means, for the drive of manual tools [1–5]. The widespread application of air motors is predetermined by the series of their technical advantages over other types of engines. Thus, one of the important advantages of air motors can be attributed to their fire safety. This factor is one of the most important ones for the petrochemical, chemical, and various mining enterprises. It is also worth noting the rather low weight-size indicators of air motors, their capacity to provide the reverse, a reliable and simple structure, resistance to vibration and mechanical impact. The relatively simple design makes them easy to maintain, operate, and repair. Recently, the use of air motors in transport power plants (PP) has been developing quite intensively [3, 4, 6–9]. Interest in the application of pneumatic motors in transport PP is primarily associated with zero emissions of harmful substances into the environment. This is especially relevant for the central districts of densely populated cities where air pollution rates are several times higher than acceptable sanitary standards. The formation of

pollution zones is associated with an ever-growing number of vehicles, their increased average service life, their decreased technical condition, while the limited roadway leads to a decrease in the speed of traffic and the formation of traffic jams. Under such operating conditions, internal combustion engines (ICE) that are used in vehicles' PP have low efficiency and high indicators of emission toxicity with flue gases.

In cars' PP, air motors have been used as an alternative to electric motors. Moreover, an air motor can be applied both as part of a hybrid PP and independently, ensuring zero emissions to the environment. The interest in the use of air motors, first of all, is associated with the almost limitless resource of the operation of consumable cylinders as opposed to the limited resource and high cost of rechargeable batteries. However, along with the advantages, transport PPs with air motors have drawbacks. The most significant drawback is considered to be a relatively small mileage of the vehicle until the next charging of the consumable cylinders. This issue can be solved by increasing the reserve of compressed air (which can only be achieved to certain limits) and improving the efficiency of energy conversion in the air motor. In this case, there are two ways to improve power efficiency: via technical improvements to existing air motors or through the construction of new ones.

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DETERMINING THE EFFECTIVE INDICATORS OF A ROTARY-PISTON MOTOR OPERATION

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2. Literature review and problem statement

The use of air motors in vehicles' PP, as well as electric motors, is primarily related to the need to reduce pollution and the use of alternative energy sources.

Theoretical and experimental studies on the use of pneumatic motors in transport PPs can be conditionally divided into two interconnected areas. The first area is related to the design and construction of the air motor and its systems, the second one – to the study of the workflow.

Paper [10] reports the results of a theoretical study on the parameters of the piston air motor operation for different modes and operating conditions. The use of valve air distribution with automatic regulation was considered. However, the issues related to the technical implementation of a given air distribution system, as well as the achievement of such a small value of the relative dead volume, remained undisclosed.

A fairly large number of works address the conversion of ICE into air motors and the subsequent study of their operation patterns. At the same time, it is worth noting the fact that the ICE and air motors have different working cycles, which, accordingly, affect their design. For example, paper [11] reports the results of experimental studies of the petrol engine converted into an air motor. In this case, after the conversion, the ratio of the piston stroke to the diameter of the cylinder is 1.036; as demonstrated by the experience of designing air motors, this ratio should be much less than unity. That is, in essence, air motors are short-stroke, which provides for a reduction in pressure loss when compressed air is entered into the working cylinder and the reduced counter pressure at the inlet. Work [12] proposed, when converting the ICE into an air motor, to change the shape of the piston and the head of the cylinder, which is certainly correct. However, as is the case in [11], the ratio of the piston stroke to the diameter of the cylinder, which is 1, is not taken into consideration.

In addition, when converting ICE into an air motor, there is a need to change the gas exchange system to take into consideration the features of air motor operation. Thus, in order to simplify the conversion, papers [13, 14] apply the valve mechanism of air distribution driven by the upgraded distribution shaft. At the same time, this structure leads to increased values relative to the dead volume and does not make it possible to adjust the degree of filling the working cylinder. A structure of the air spool valve for a pneumatic motor is proposed in works [15, 16]. This method of air distribution reduces the relative dead volume but does not make it possible to regulate the degree of filling.

A large body of both theoretical and experimental research addresses the working cycle of air motors. In particular, work [17] analyzed the indicators of a four-cylinder air motor with a spool air distribution. At the same time, there is no analysis of changes in such indicator parameters as the specific indicator consumption of compressed air, as well as indicator efficiency. These parameters characterize the degree of perfection of the workflow implementation and are quite important parameters when studying the working cycle of the air motor.

Paper [18] reports experimental data on changes in the effective indicators of the piston air motor. However, there are no data on changes in such effective parameters as the specific fuel consumption and efficiency. These parameters make it possible to assess the internal and external losses in an air motor (the degree of efficiency of energy conversion), as well as significantly affect the vehicle's mileage reserve.

Study [19] described a principal diagram of PP with an air motor, developed by scientists at Beihai University (Beijing, China). In addition, the study reported the speed characteristics of the air motor operation at different pressures of compressed air at the inlet. At the same time, the proposed pneumatic motor has quite low values of effective efficiency (25 % at a pressure at the inlet of 2 MPa s and minimum rotations). It is also worth noting the fact of a sharp drop in efficiency when the rotations of the pneumatic engine increase, which is a negative factor when using it in the PP of vehicles. Low air motor efficiency values (24.42 %) are also given in work [16]. The reasons for such low efficiency may be related to the structural features of these air motors, as well as the significant gas-dynamic losses.

Based on the studies reviewed, it can be argued that it is appropriate and promising to create a new air motor rather than converting the ICE or refining existing air motors. At the same time, at the stage of designing and constructing a new air motor, it is necessary to take into consideration the world practice, as well as the specific operating conditions within a PP. Given these features, a new type of air motors was designed at the Motor-Plus engineering plant (Nikolayev, Ukraine), where several prototypes with different dimensions were fabricated. However, the path from the design stage to the industrial production implies a series of experimental studies to confirm the stated effective performance indicators, as well as the reliability of the air motor.

3. The aim and objectives of the study

The aim of this study is to determine the effective performance indicators of the prototype rotary-piston air motor in terms of a speed characteristic, which could make it possible to assess the most effective modes of motor operation.

To accomplish the aim, the following tasks have been set:

- to determine the impact of operational parameters on the energy indicators of the rotary-piston air motor, as well as to establish their ranges at which the maximum values of energy indicators are reached;
- to assess the efficiency of energy conversion efficiency in the rotary-piston air motor, as well as establish the ranges of operational parameters that ensure maximum energy efficiency;
- to assess the impact of the air motor's operational parameters on the amount of resistance to release.

4. Materials and methods to study the effective indicators of a rotary-piston engine performance

We have experimentally studied the specificity of the workflow organization, changes in the basic operational parameters, as well as effective indicators, for different operational modes of the rotary-piston air motor RPD-4,4/1,75 (using a method of physical modeling). Experimental studies make it possible to bring the testing conditions as close as possible to the actual operating conditions of the air motor, as well as to gain experience, and formulate recommendations for the operation, maintenance, and repair of the motor of the new design. The results of experimental studies of the rotary-piston pneumatic motor RPD-4,4/1,75 make it possible to build, and supplement with empirical data, a mathematical model of the working cycle, which significant-

ly increases the level of accuracy, and expands the scope of its application.

The object of our study is the processes of the conversion of compressed air as a result of expansion in the rotary-piston air motor RPD-4,4/1,75. The subject of this study is the experimental speed characteristics of the air motor.

Experimental data for the construction of the speed characteristics of the rotary-piston air motor were acquired at the test bench whose principle of operation is detailed in work [21]. The tests involved the rotary-piston air motor RPD-4,4/1,75, whose principle structure is described in the Patent for invention [20]. The air motor has 12 cylinders with a diameter of 44 mm, and the piston's stroke is 17.5 mm (the ratio of the piston's stroke to the diameter of the cylinder is 0.4).

The bench and a measurement system were designed at the Motor-Plus engineering company in cooperation with a group of scientists from the Center for Advanced Energy Technologies at the National University of Shipbuilding named after Admiral Makarov (Ukraine). Before the pilot studies, we estimated the error of each measuring device and the error of the bench measurements in general. In this case, the maximum tool error did not exceed 5%, which is acceptable for experimental research of the working process of engines. During experimental studies, the rotary-piston air motor was driven to a stationary mode of operation at each operating regime. This was done to prevent the impact of non-stationarity on the measurements of the relevant parameters and to ensure that the results of the experiment are reproduced. We measured the air motor parameters under each mode several times; the data that apparently went beyond the limits of the rational parameters were discarded.

The following operational parameters have a significant impact on the change in the effective performance of the air motor based on a speed characteristic:

- air pressure in the intake receiver P_s ;
- the motor rotor's rotations n .

Determining the optimal ratio of these parameters for each mode of operation would make it possible to obtain the minimum air consumption values, that is, to derive the maximum efficiency of energy conversion.

5. Results of the experimental study of the effective performance indicators of the prototype rotary-piston air motor

5.1. Studying the impact of the rotary-piston air motor performance on energy indicators

Fig. 1–3 show experimental data of changes in the effective power N_e , the mean effective pressure P_e , and the torque M_k of the rotary-piston air motor RPD-4,4/1,75 based on a speed characteristic.

The experimental dependences of changes in these parameters on P_s and n provide an opportunity to assess the energy potential of a rotary-piston air motor, as well as the prospects for its use as part of transport PPs.

The maximum values of M_k and N_e correspond to the different values of engine rotations. Thus, the highest values of the power of the rotary-piston air motor are reached at maximum speeds, which, in our experiment, are 1,200...1,400 rpm.

For the air pressure change range in the intake receiver 0.4...0.8 MPa, the maximum power value is 1.7...2.5 kW, the torque is 17.0...8.2 Nm, and the mean effective pressure is 0.13...0.18 MPa.

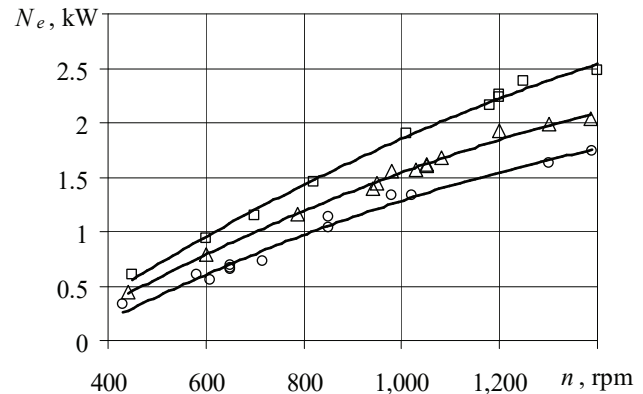


Fig. 1. Change in the effective power of the rotary-piston air motor RPD-4,4/1,75 depending on the rotor's rotations and pressure in the intake receiver: □ - $P_s=0.8$ MPa; △ - $P_s=0.6$ MPa; ○ - $P_s=0.4$ MPa

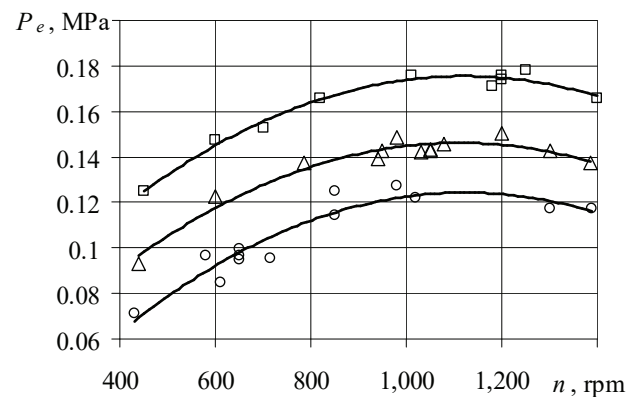


Fig. 2. Change in the mean effective pressure of the rotary-piston air motor RPD-4,4/1,75 depending on the rotor's rotations and pressure in the intake receiver: □ - $P_s=0.8$ MPa; △ - $P_s=0.6$ MPa; ○ - $P_s=0.4$ MPa

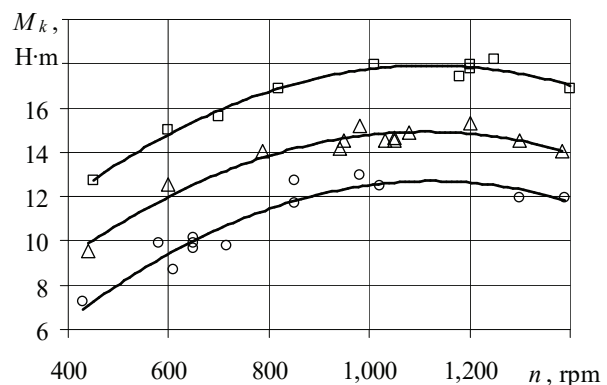


Fig. 3. Change in the torque of the rotary-piston air motor RPD-4,4/1,75 depending on the rotor's rotations and pressure in the intake receiver: □ - $P_s=0.8$ MPa; △ - $P_s=0.6$ MPa; ○ - $P_s=0.4$ MPa

5.2. Studying the impact of the rotary-piston air motor performance indicators on the energy conversion efficiency

The economic indicators that characterize the perfection of the organization of the working process of an air motor are the specific effective consumption of compressed air g_e , kg/kWh, and the effective adiabatic efficiency. Economic indicators are directly dependent on the hourly consumption of compressed air G_{air} , kg/h (Fig. 4).

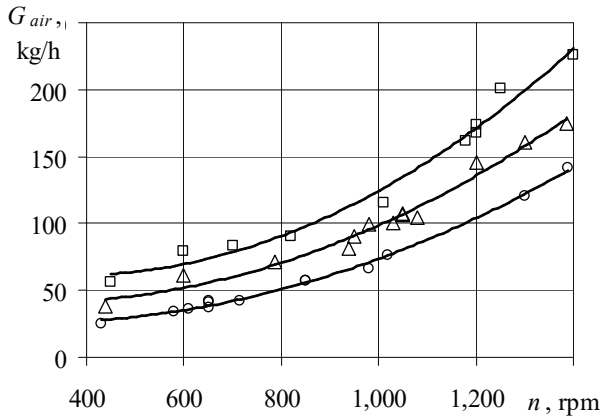


Fig. 4. The hourly consumption of compressed air by the rotary-piston air motor RPD-4,4/1,75 under different test modes: $\square - P_s=0.8$ MPa; $\Delta - P_s=0.6$ MPa; $\circ - P_s=0.4$ MPa

The hourly consumption can be divided into two components: the first is used to execute the work cycle, and the second is the loss due to leaks through the gaps between parts and seals. The magnitude of the first component is significantly influenced by the perfection of the workflow organization, as well as the design of the air motor (for example, the possibility to adjust the phases of gas exchange, the amount of dead volume, etc.). The magnitude of the second component depends on the accuracy and quality of the manufacture of air motor parts, and the sealing techniques. According to Fig. 4, the full hourly consumption of compressed air depending on the pressure in the intake receiver and the rotations of the air motor is in the range of 25...226 kg/h.

The specific effective consumption of compressed air of the prototype rotary-piston air motor RPD-4,4/1,75 is determined by taking into consideration both components of the hourly consumption of compressed air. Fig. 5 shows a change in g_e depending on the rotations of the air motor and air pressure in the intake receiver. The experimental data illustrated in Fig. 5 were obtained without pre-heating the compressed air at the inlet to the air motor, as well as without adjusting the degree of filling. According to the results obtained, the minimum values of the specific effective consumption of compressed air is in the engine rotation range of 800...1,000 rpm, which corresponds to the mean piston speed of the 0.93...1.17. For the test mode $P_s=0.8$ MPa – $g_e=60.8...93.2$ kg/(kW·h); for $P_s=0.6$ MPa – $g_e=57.9...88.1$ kg/(kW·h); $P_s=0.4$ MPa – $g_e=49.7...81.3$ kg/(kW·h).

To determine the effective adiabatic efficiency, it is necessary to know the actual effective air motor power and the potential possible power that can be obtained as a result of the adiabatic expansion of the supplied compressed air. The actual effective power was obtained experimentally in the process of measuring the torque and rotations of the air motor. To calculate the power potential of the adiabatic air expansion N_{ad} , entering the air motor, the actual full hourly air consumption G_{air} (Fig. 4) is used, similar to determining g_e . Thus, Fig. 6 shows a change in the magnitude of N_{ad} for different modes of testing the rotary-piston air motor RPD-4,4/1,75 based on a speed characteristic.

Based on the acquired experimental data (Fig. 1, 6), we determined the value of the effective adiabatic efficiency for different modes of operation of the rotary-piston air motor RPD-4,4/1,75 (Fig. 7).

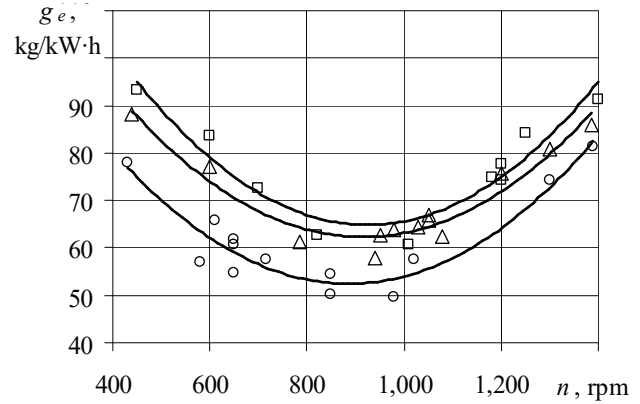


Fig. 5. Change in the specific effective consumption of compressed air by the rotary-piston air motor RPD-4,4/1,75 under different test modes: $\square - P_s=0.8$ MPa; $\Delta - P_s=0.6$ MPa; $\circ - P_s=0.4$ MPa

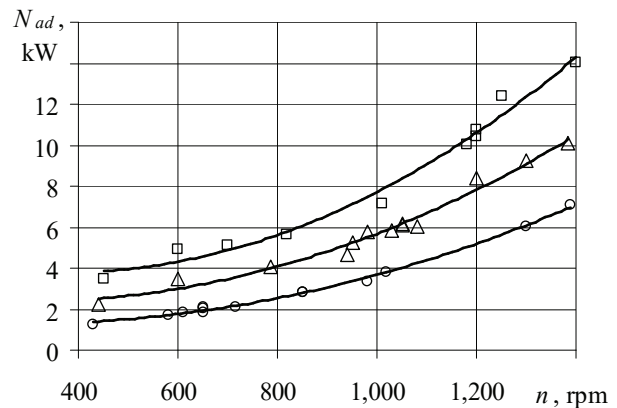


Fig. 6. Change in the power potential of the adiabatic expansion of compressed air, supplied to the rotary-piston pneumatic engine RPD-4,4/1,75, under different test modes: $\square - P_s=0.8$ MPa; $\Delta - P_s=0.6$ MPa; $\circ - P_s=0.4$ MPa

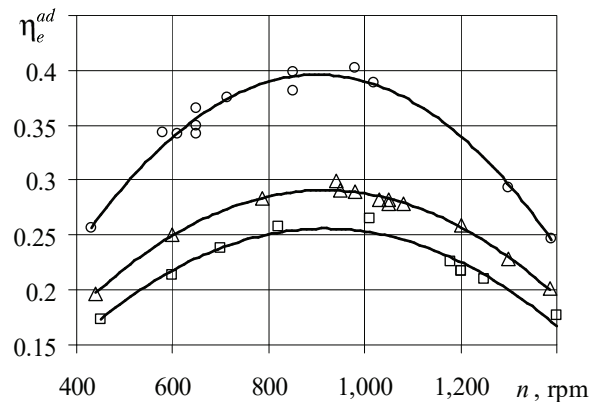


Fig. 7. Change in the effective adiabatic efficiency of the rotary-piston pneumatic engine RPD-4,4/1,75 depending on the rotor's rotations and pressure in the intake receiver: $\square - P_s=0.8$ MPa; $\Delta - P_s=0.6$ MPa; $\circ - P_s=0.4$ MPa

The decrease in efficiency with the increase in the rotations of the air motor rotor is primarily due to the increase in the gas-dynamic losses. The maximum efficiency values for all compressed air pressure values in the intake receiver are within the air motor rotations of 800...1,000 rpm. In this case, the largest value of the air motor efficiency $\eta_e^{ad} = 0.41$

is observed under the mode of the value $P_s=0.4$ MPa. Increasing P_s from 0.4 to 0.8 MPa leads to a 34 % decrease in efficiency but the effective power of the pneumatic engine increases by 46 % (from 1.3 to 1.9 kW).

5.3. Assessing the impact of the rotary-piston air motor operating parameters on the release resistance magnitude

The mean piston speed C_m of any air motor has a significant impact on air pressure loss at the intake and opposition at the release. According to known recommendations, C_m should not exceed 1.5...1.7 m/s [22, 23]. In a rotary-piston air motor, over a single rotation of the central rotor, the piston executes four strokes (moving between extreme positions), so the mean piston speed is $C_m = Sn/15$ m/s. According to the design sizes of the RPD-4,4/1,75 air motor and the range of change in the rotor rotations, the value of C_m is within 0.5...1.65 m/s and does not exceed the recommended values. Thus, Fig. 8 shows the effect of the mean piston speed and pressure in the intake receiver of the air motor RPD-4,4/1,75 on the value of the spent air pressure in the exhaust receiver.

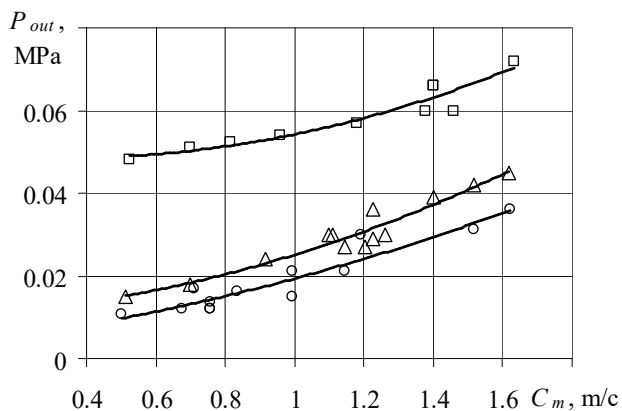


Fig. 8. Change in the pressure of spent air in the exhaust receiver of the rotary-piston air motor RPD-4,4/1,75 depending on the pressure in the intake receiver and the mean piston speed: \square – $P_s=0.8$ MPa; \triangle – $P_s=0.6$ MPa; \circ – $P_s=0.4$ MPa

According to acting recommendations, the resistance of an air motor's exhaust system with an installed silencer should not exceed 0.12 MPa [22, 23]. Thus, according to the experimental data (Fig. 8), the pressure of the spent air at release does not exceed 0.075 MPa, which is much lower than the recommended.

6. Discussion of results of studying the effective performance indicators of the prototype rotary-piston air motor

The results of the pilot trials of the prototype rotary-piston air motor RPD-4,4/1,75, reported in this work, represent only one phase of our study. The study established the characteristics of changes in the basic energy (Fig. 1–3) and economic (Fig. 5, 7) performance indicators of the air motor depending on the main operational parameters. The resulting ranges of operational parameters, at which the maximum efficiency is achieved, make it possible to devise and implement the methodology of further tests in order to study the features of the work cycle in greater depth.

Based on the experimental data obtained, increasing the pneumatic engine rotations and the compressed air pressure in the intake receiver leads to an increase in effective power (Fig. 1). However, the specific effective air consumption and the effective adiabatic efficiency are reduced (Fig. 5, 7) while the air resistance at release is increased (Fig. 8). The results obtained are primarily explained by the lack of regulation of the degree of filling the working cylinder of the air motor during experimental tests. The structure of the rotary-piston air motor implies the possibility of regulating the degree of filling by rotating the adjustable cam [20]. At this stage, experimental studies were conducted without regulation, that is, at the mean position of the regulatory cam. However, it is worth noting that even in the absence of regulation, the prototype rotary-piston air motor showed higher efficiency indicators than the converted engines examined in chapter 2. At the same time, the design of the proposed air motor is quite simple and more compact. Adjusting the level of filling the working cylinder could make it possible to ensure a decrease in g_e and an increase in η_e^{ad} under the modes of high values of P_s and n . Therefore, studying the effect of the degree of filling (a change in the regulatory cam position) on the effective indicators of the air motor under different modes of operation requires further experimental research.

The P_s value during the experiment was limited to a range of 0.4...0.8 MPa, so it is of practical interest to study the rotary-piston air motor operation at the P_s values above the specified range. Increasing P_s would certainly improve the energy indicators of the air motor but only experimental studies could reveal how this would affect the fuel efficiency of the air motor.

Separately, it is worth paying attention to the effect of heating the compressed air before the air motor inlet receiver on the efficiency of energy conversion. In addition, heating the air before the expansion in the working cylinder would resolve the issue of the low temperatures of spent air at the outlet from the pneumatic engine, which is also not tackled in the current study.

7. Conclusions

1. It has been established that for the P_s range of 0.4...0.8 MPa the maximum values of the torque, mean effective pressure, and effective power are 17.0...18.2 Nm, 0.13...0.18 MPa, and 1.7...2.5 kW, respectively. At the same time, the maximum values of the torque and mean effective pressure are in the range of air motor rotations 1,000...1,200 rpm, the effective power – 1,200...1,400 rpm.

2. It has been determined that the minimum values of the specific effective consumption of compressed air are in the range of the rotor rotations of the air motor 800...1,000 rpm. Thus, depending on the pressure in the inlet receiver, g_e varies in the range of 49.7...60.8 kg/kW·h. At the same time, decreasing the pressure P_s decreases g_e . The maximum values of the adiabatic efficiency of the rotary-piston air motor RPD-4,4/1,75 are in the range of rotor rotations of 800...1,000 rpm. Depending on the pressure in the intake receiver, η_e^{ad} is within 0.27...0.41, with the maximum efficiency of 0.41 corresponding to $P_s=0.4$ MPa. Increasing P_s leads to a gradual decrease in the efficiency of the air motor while increasing the effective power.

3. We have derived the experimental dependences of the influence of C_m and P_s on the value of the spent air pressure in the exhaust receiver of the rotary-piston air motor RPD-

4,4/1,75 when it operates with a noise silencer. Thus, according to the experimental data obtained, the maximum value of the pressure of spent air at release is 0.075 MPa, which does not exceed the permissible values.

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