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EXPERIMENTAL RESEARCH OF THE PROTOTYPE OF THE ROTARY-PISTON ENGINE OF THE TRANSPORT HYBRID POWER PLANT

ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ДОСЛІДНОГО ЗРАЗКА РОТОРНО-ПОРШНЕВОГО ДВИГУНА ТРАНСПОРТНОЇ ГІБРИДНОЇ ЕНЕРГЕТИЧНОЇ УСТАНОВКИ

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Abstract. Aim. The purpose of the research is to experimentally determine the operational characteristics of a prototype rotary-piston air engine. **Methodology.** To determine the operational characteristics of the prototype rotary piston air engine, the method of physical modeling was used. The choice of the research method is primarily due to the design and working process of the air engine. The results obtained make it possible to supplement the mathematical model with empirical dependencies and coefficients to increase its accuracy, as well as to obtain practical recommendations for the operation and maintenance of an air engine of a new design. **Results.** The results of experimental researches of the prototype of the RPD-4.4/1.75 rotary-piston air engine are presented. Experimental studies were carried out without preheating the air at the inlet to the inlet receiver of the air engine, as well as without adjusting the engine operating modes due to the degree of cylinder filling, that is, the control cam was in the middle (neutral) position. The air pressure in the receiver of the air engine, depending on the established test mode, was 0.4, 0.6, and 0.8 MPa. The rotational speed of the central rotor of the air engine varied within 400...1400 rpm. Experimental dependences of changes in effective indicators (average effective pressure, effective power) and torque of a rotary-piston air engine on rotations for various values of air pressure in the intake receiver are given. The maximum effective power of the air engine at the nominal operating mode at an air pressure in the intake receiver of 0.8 MPa and a speed of 1400 rpm was 2.5 kW, and a torque of 17 N·m. In this case, the maximum torque and average effective pressure are in the speed range n = 950...1200 rpm. The maximum torque value is 18.2 N·m and the average effective pressure is 0.18 MPa. The dependences of the change in the temporary air consumption depending on the speed and load of the air engine are obtained.

So, for the minimum value of air pressure in the inlet receiver of 0.4 MPa and depending on the load, the value of the temporary air flow is in the range of 25...141 kg/h, while for 0.8 MPa – 55...226 kg/h hour. It was found that when regulating the operating modes of the air engine by changing P_s, its optimal value until a power of 1.4 kW is reached is 0.4 MPa. A further increase in the air engine load requires a gradual increase in P_s. **Scientific novelty.** On the basis of experimental researches, an assessment of the effective and operational qualities of a prototype of the rotary-piston air engine of a new design was carried out. **Practical significance.** The operational characteristics of the prototype of the RPD-4.4/1.75 rotary-piston air engine were obtained, and the optimal ranges of variation of the main operational parameters of work were determined, at which the highest efficiency of the air engine was achieved.

Key words: compressed air, rotary piston air engine, effective indicators, degree of filling of the working cylinder, movement mechanism, transport hybrid power plant.

Анотація. Мета. Метою дослідження є експериментальне визначення експлуатаційних характеристик дослідного зразка роторно-поршневого пневмодвигуна. **Методика.** Для визначення експлуатаційних характеристик дослідного зразка роторно-поршневого пневмодвигуна використовувався метод фізичного моделювання. Вибір метода дослідження зумовлений, перш за все, особливостями конструкції та робочого процесу пневмодвигуна. Отримані результати дають змогу доповнити математичну модель емпіричними залежностями та коефіцієнтами для підвищення її точності, а також отримати практичні рекомендації щодо експлуатації та обслуговування пневмодвигунів нової конструкції. **Результати.** Наведено результати експериментальних досліджень дослідного зразка роторно-поршневого пневмодвигуна РПД-4,4/1,75. Експериментальні дослідження проводилися без попереднього підігріву повітря на вході у впускний ресивер пневмодвигуна, а також без регулювання режимів роботи двигуна за рахунок ступеня наповнення циліндра, тобто регулюючий кулачок знаходився в середньому (нейтральному) положенні. Тиск повітря в ресивері пневмодвигуна залежно від установленого режиму випробування становив 0,4, 0,6, та 0,8 МПа. Частота обертання центрального ротора пневмодвигуна змінювалася у межах 400–1400 об/хв. Подано експериментальні залежності змінення ефективних показників (середнього ефективного тиску, ефективної потужності) та крутного моменту роторно-поршневого пневмодвигуна залежно від його обертів для різних значень тиску повітря у впускному ресивері. Максимальна ефективна потужність пневмодвигуна на номінальному режимі роботи при тиску повітря у впускному ресивері 0,8 МПа та частоті обертів 1400 об/хв становила 2,5 кВт, а крутний момент – 17 Н·м. При цьому максимум крутного моменту та середнього ефективного тиску знаходиться в діапазоні обертів $n = 950–1200$ об/хв. Максимальне значення крутного моменту становить 18,2 Н·м, а середній ефективний тиск – 0,18 МПа. Отримано залежності змінення часової витрати повітря залежно від обертів та навантаження пневмодвигуна. Так, для мінімального значення тиску повітря у впускному ресивері 0,4 МПа та залежно від навантаження значення часової витрати повітря знаходиться у межах 25–141 кг/год, тоді як для 0,8 МПа – 55–226 кг/год. Встановлено, що при регулюванні режимів роботи пневмодвигуна шляхом зміни P_s, оптимальним його значенням до досягнення потужності в 1,4 кВт є 0,4 МПа. Подальше збільшення навантаження пневмодвигуна потребує плавного підвищення P_s. **Наукова новизна.** На базі експериментальних досліджень виконана оцінка ефективних та експлуатаційних якостей дослідного зразка роторно-поршневого пневмодвигуна нової конструкції. **Практична значимість.** Отримані експлуатаційні характеристики дослідного зразка роторно-поршневого пневмодвигуна РПД-4,4/1,75, а також визначені оптимальні діапазони зміни основних експлуатаційних параметрів роботи, при яких досягається найбільша ефективність роботи пневмодвигуна.

Ключові слова: стиснуте повітря, роторно-поршневий пневмодвигун, ефективні показники, ступінь наповнення робочого циліндра, механізм руху, транспортна гібридна енергетична установка.

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Problem statement. Quite a long time and a number of tests and studies pass from the stage of development of new engine samples to their serial production. So, one of the important stages in the creation of a new engine is research and development tests. These tests are very diverse both in content and in nature. The main goal of research tests is, first of all, a deep study of the processes of energy conversion in the engine, its units and systems, the study of the features of the engine operation under various operating conditions, the determination of the effect of various loads on units and parts, the analysis of the service life and much more.

The RPD-4.4/1.75 rotary-piston air engine is one of the prototypes designed and manufactured at the machine-building enterprise Engine-Plus LLC. This engine has a number of structural differences from many known air engines and has its own characteristics in the organization of the work process. In accordance with this, for the introduction of this type of air engine into wide mass production, it is necessary to carry out a number of research and development tests for various operating conditions.

Latest research and publication analysis. A significant number of scientists in the study of new models of engines follow the path of physical modeling, since it is precisely this that can give a complete picture of the processes occurring in the engine, and also allows the conditions of the experiment to be as close as possible to real operating conditions. A significant contribution to the experimental and theoretical study of the air engine was made by such domestic scientists as F.I. Abramchuk, O.I. Voronkov, V.O. Bogomolov, A. M. Turenko, A. I. Kharchenko, I.M. Nikitchenko, S.S. Zhilin and others.

In the development of transport power plants, two types of air engines are usually used. Thus, the majority of researchers use piston air engines, which in fact are converted internal combustion engines [1–3], but some also use rotary engines [4]. The use of this or that type of air engine has its own advantages and disadvantages, both economic and operational.

Despite the rather simple design and principle of operation, the working process of the air engine has a number of its own characteristics [5] and requires experimental research, which is confirmed by a significant number of both domestic and foreign works in this direction [6–8]. In the context of the study of the operating cycle, special attention should be paid to the effect of air heating at the inlet to the air engine on the change in effective indicators. As noted in [9–10], it is the heating of the working fluid that can significantly increase the efficiency of the air engine, as well as ensure the utilization of secondary energy resources of the internal combustion engine of a hybrid energy transport plant. An example of such a hybrid power plant is a prototype vehicle based on the MeMZ-968 converted air-cooled gasoline engine [10; 11], developed by a group of scientists on the basis of the Kharkiv National Automobile and Highway University. The development, creation and implementation of such vehicles will contribute to solving the environmental problem of air pollution in large cities.

Separation of previously unsettled parts of the general problem. The operation of engines in power plants of vehicles has a certain specificity, and their characteristics are the dependences of changes in the main performance indicators (average effective pressure, torque, effective power, time consumption of the working fluid) on the rotations.

Due to the fact that the RPD-4,4/17,5 rotary piston air engine is a prototype, there are no characteristics of its operation for it. Therefore, in order to assess the technical and operational parameters of an air engine of a new design as part of a hybrid transport power plant, it is necessary to obtain reliable experimental characteristics that clearly reflect the relations between the main performance indicators in various operating conditions.

The article aim is to determine the operational characteristics of the rotary-piston air engine of a transport hybrid power plant. In addition, the obtained experimental data will provide further improvement of prototypes of air engines and a mathematical model for calculating the operating cycle of a new type of engines.

Methods, object and subject of research. It is possible to obtain the characteristics of the operation of the air engine necessary for the consumer by means of mathematical or physical modeling. The prototype of a rotary-piston air engine differs from serial air engines in its design. First of all, the difference in design is associated with the mechanism of movement and gas exchange, which, in turn, leads to the peculiarity of features of the working process. That is why the determination of the characteristics of the operation of a rotary-piston air engine by only mathematical modeling will lead to errors and can be used only as a first approximation. Only experiments will make it possible to fully investigate the change in the main indicators of the engine, supplement the mathematical model with empirical dependences and coefficients, significantly increase its accuracy and allow it to be used in the further design of engines of this type. In addition, experimental research will make it possible to obtain and formulate practical recommendations for the operation and maintenance of air engines of a new type.

The object of the research is a prototype of a rotary-piston engine and the processes of energy conversion of the working fluid in it. ***The subject of the research*** is the dependences of changes in the main indicators of the operation of an air engine of a new design.

The basic material (results). Experimental studies of the prototype of the RPD-4.4/1.75 rotary-piston air engine (Fig. 1) were carried out on a special experimental stand jointly developed and created by the machine-building enterprise Engine-Plus LLC and the Center for Advanced Energy Technologies of the Admiral Makarov National University of Shipbuilding (Fig. 2).

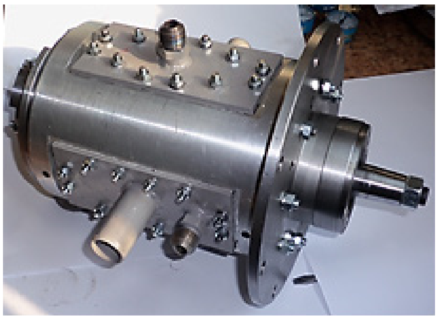


Fig. 1. Prototype of the RPD-4.4/17.5 rotary-piston air engine of a hybrid transport power plant

Structurally, due to a special movement mechanism, the RPD-4,4/17,5 air engine combines the design of a rotary and piston engine [12]. The rotary-piston engine has 12 evenly spaced pistons with a diameter of D = 44 mm and a stroke of S = 17.5 mm (S/D = 0.4). The working volume of the air engine is 320.6 cm^3, while the relative dead volume, which is due only to the technological gaps during manufacture, is only 0.015. The experimental stand and the design of the prototype of the RPD-4,4/1,75 rotary-piston air engine are described in more detail in [12; 13].

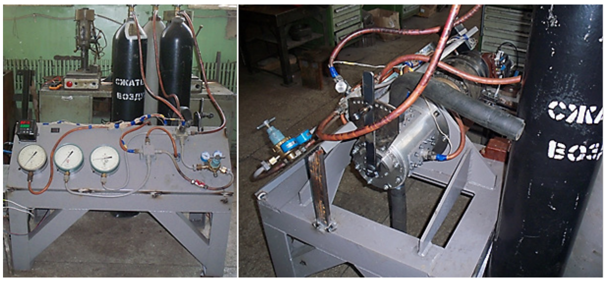
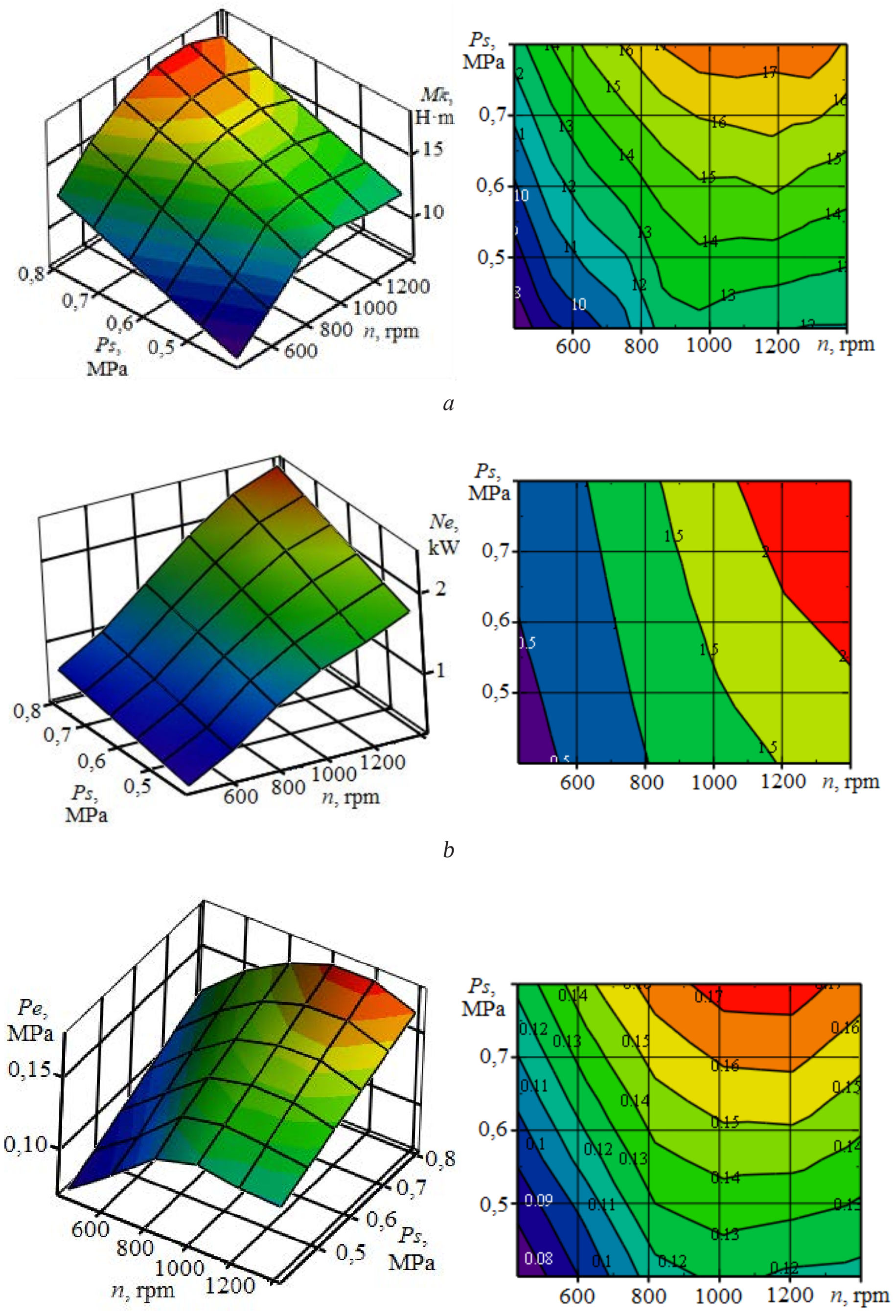


Fig. 2. General view of the experimental stand and the dashboard based on the RPD-4.4/1.75 rotary-piston engine

So, at the first stage, experimental studies were carried out without preheating the air at the inlet. In this case, the value of the temperature of the working fluid, depending on the ambient temperature, was in the range of 18–28°C, and the air pressure in the engine receiver, depending on the set test mode, varied in the range of 0.4–0.8 MPa. The initial air pressure in 40-liter supply cylinders was 15 MPa. To ensure sanitary noise standards (up to 80 dB) in the laboratory room, the air engine was equipped with an exhaust silencer. Installing a silencer not only ensures acceptable noise levels, but also brings engine operation closer to real operating conditions. At this stage, experimental studies of the rotary-piston air engine were carried out without adjusting the engine operating modes due to the degree of cylinder filling, that is, the control cam was in the middle (neutral) position.

Figure 3 shows the experimental dependences of the change in the torque and the effective indicators of a rotary-piston engine on the speed for various values of the air pressure P_s in the intake receiver. The tests were carried out for three pressure values of 0.4, 0.6, and 0.8 MPa, while the rotational speed of the central rotor of the air engine varied within 400–1400 rpm. During the tests, the values of the parameters of torque and power were determined with a sufficiently high accuracy due to the installation of an electric current generator according to the “engine-scales” scheme (the generator is mounted on supports that allow it to rotate freely around its axis, while rotation around the axis is limited by a thrust lever, which, in turn, transfers the force to the scales). According to the obtained experimental data (see Fig. 3), there is a direct dependence of the effective parameters of the air engine on the pressure value P_s. Thus, the maximum effective power of the air engine in the nominal operating mode at P_s = 0.4 MPa was N_e = 1.7 kW, and at P_s = 0.8 MPa – N_e = 2.5 kW, while the torque value varies from 12 to 17 N·m. The maximum values of the torque and average effective pressure are achieved by the air engine in the speed range n = 950...1200 rpm and, accordingly, are $M_к$ = 18.2 N·m, p_e = 0.18 MPa.

The power reserve of a vehicle with a hybrid power plant depends on the design features of the compressed air storage and supply system, the perfection of the air engine itself (effective efficiency), as well as on the operating conditions. So, to estimate in a first approximation the range of a vehicle with a hybrid power plant, it is necessary to know



a

b

c

Fig. 3. Change in torque and effective indicators of the RPD-4.4/17.5 rotary-piston air engine depending on the speed and pressure in the inlet receiver: *a* – torque; *b* – effective power; *c* – average effective pressure

the volume of the supply cylinders, the air storage pressure in them (the preserved air mass), the working pressure in the receiver (P_s limits the minimum pressure to which the supply cylinders can be discharged), as well as the time consumption of compressed air G_{air} (Fig. 4) by a rotary-piston air engine.

According to the conditions of the experiments (no regulation of the degree of filling and heating of the air at the inlet to the air engine), the value of G_{air} varied in the range of 25–141 kg/h for P_s = 0.4 MPa and 55–226 kg/h for P_s = 0.8 MPa. The value of G_{air} is greatly influenced by the mode of operation of the air engine, the regulation of which can be ensured by the degree of filling (by turning the control cam) and by changing the pressure of compressed air in the receiver of the air engine.

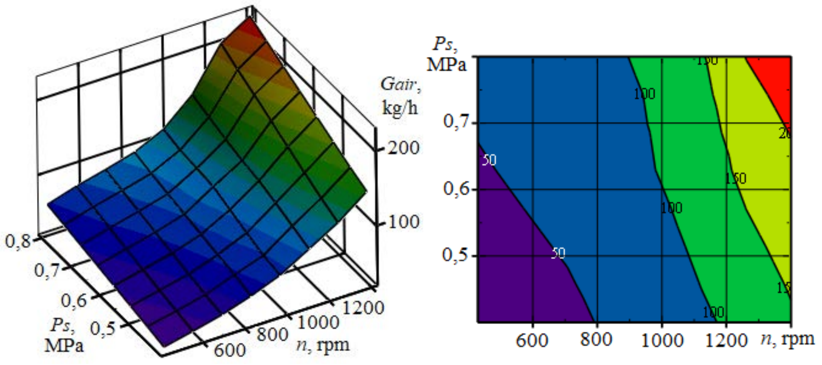


Fig. 4. Time consumption of the working fluid by the RPD-4.4/17.5 rotary-piston air engine without preheating the air at the inlet and regulating the degree of filling depending on the pressure in the inlet receiver and rotations

So, Figure 5 shows the dependences of the change in the time consumption of compressed air on the engine load for various values of the air pressure in the intake receiver.

According to the experimental data shown in Fig. 5 it is possible to ensure the minimum values of the temporary consumption of compressed air over the entire range of variation of the air engine load by regulating the pressure of compressed air in the intake receiver of the engine. Technically, it is possible to realize this by reducing the compressed air using a gas reducer. So, the optimal value of P_s at load modes up to 1.4 kW is 0.4 MPa. A further increase in the air engine load at a constant value of P_s = 0.4 MPa leads to a significant increase in the temporary air flow, therefore, with an increase in the load and the lack of regulation of the degree of filling, P_s needs to be adjusted.

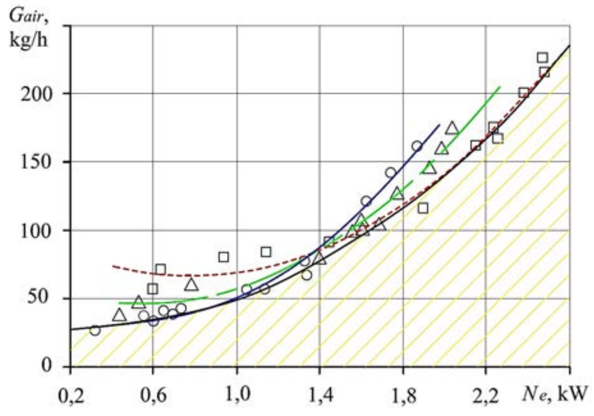


Fig. 5. Dependence of the time consumption of the working fluid by the RPD-4.4/17.5 rotary-piston air engine without preheating the air at the inlet and regulating the degree of filling: □ – P_s = 0.8 MPa; Δ – P_s = 0.6 MPa; ○ – P_s = 0.4 MPa

Discussion of the results. Experimental studies of the prototype of the RPD-4,4/17,5 rotary-piston air engine of the transport hybrid power plant made it possible to obtain the first significant data on the change in the main operational characteristics of the work. Analysis of the results allows you to adjust and plan further stages of experimental research.

First of all, it is necessary to conduct a series of studies on the effect of regulating the operating modes of the air engine, by changing the degree of cylinder filling, on the effective indicators. This control method is the most effective way to reduce the temporary consumption of compressed air, a rather important indicator for a hybrid vehicle. Further experimental tests are required to study the effect of compressed air pressure in the inlet receiver of a rotary-piston air engine.

At this stage, experimental studies were carried out for the range of pressure changes P_s = 0.4–0.8 MPa, therefore, the next stage may be to expand this range towards increasing P_s.

In addition, further experimental research requires the influence of an increase in speed on the effective performance of the air engine and a change in the minimum cycle temperature (due to an increase in the exhaust air flow rate). In a separate series of experimental tests, it is necessary to highlight the consideration of the influence of preheating of compressed air. This series of studies will require some improvement of the experimental stand, namely the addition of a heating subsystem and measurements of the corresponding parameters.

Conclusions. The main operational characteristics of the prototype of the RPD-4.4/17.5 rotary-piston air engine without preliminary heating of air at the inlet to the inlet receiver of the air engine and control of the degree of filling were obtained and analyzed.

The range of changes in the effective indicators and torque of the air engine, depending on the speed for various values of air pressure in the intake receiver, has been established. For example, a twofold increase in pressure P_s (from 0.4 to 0.8 MPa) at a speed of 1400 rpm increases the effective power of the air engine by almost one and a half times (from 1.7 to 2.5 kW).

It has been determined that the range of changes in the speed of the air engine 950–1200 rpm corresponds to the maximum values of the torque (M_t = 18.2 N·m) and the average effective pressure (p_e = 0.18 MPa).

To achieve the minimum values of the temporary air consumption in all operating modes of the air engine, it is necessary to regulate the degree of filling of the working cylinder. So, in the absence of regulation, the value of G_{air} depending on the engine load (N_e = 0.4–2.5 kW) is in the range of 25–226 kg/h.

It was determined that in the absence of regulation of the operating modes of a rotary-piston air engine due to a change in the degree of filling, an effective way to reduce the temporary consumption of compressed air is to change the pressure in the intake receiver. Thus, it has been experimentally established that the optimal value of P_s of the RPD-4.4/17.5 rotary-piston air engine before reaching a power of 1.4 kW is 0.4 MPa.

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