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RESEARCH OF ROTARY PISTON ENGINE USE IN TRANSPORT POWER PLANTS

Summary. A schematic diagram of a transport hybrid power plant using a new design RPE-4.4/1.75 rotary piston air engine is proposed. Its external speed characteristic is determined, according to which the maximum engine power is 8.75 kW at 850 rpm and the maximum torque is 127.54 N·m at 400 rpm. For various gears and speeds, all the components of the power balance were determined and the dynamic characteristic of the hybrid car was obtained when operated on an air engine. According to the dependences of the power balance, the total traction force from the rotary piston air engine on the driving wheels is 5 kN. The performance of acceleration of a hybrid car while working on an air engine is estimated, namely, the dependences of acceleration, time, and acceleration path are obtained. In urban traffic, the required time to accelerate the car to a speed of 60 km/h is 15.2 s and the path is 173 m. The possible drive range of the hybrid car on compressed air without additional recharging is analyzed. On one cylinder with compressed air with a volume of 100 liters, an initial pressure of 35 MPa, and a final pressure of 2 MPa, the hybrid car can travel about 26 km.

1. INTRODUCTION

Urbanization of cities leads to a continuous and rapid increase in the number of public and private transport vehicles. This, in turn, leads to the problem of environmental pollution, especially in the central parts of cities.

The environmental degradation is largely affected by the steady increase in the average age of vehicles, the poor technical condition, and the use of old cars. In addition, the limited carriageway with a high traffic flow leads to a decrease in the speed of vehicles or even large traffic jams. In such conditions, a conventional internal combustion engine (ICE) is quite inefficient and displays increased emissions of toxic elements with exhaust gases. Thus, environmental pollution from vehicle emissions and the consequent deterioration in the health of the population have become one of the most acute problems of a modern city.

2. RECENT RESEARCH AND PUBLICATION ANALYSIS

The problem of air pollution in large cities can be partially solved by increasing the percentage of public electric transport in urban transportation, prohibiting the use of vehicles with internal combustion engines in city centers, and increasing environmental taxes and fees. However, all these measures are not able to fully solve the environmental problem of air pollution and ensure the necessary traffic flow.

One of the possible solutions to the problem may be the use of environmentally friendly vehicles, for example, electric cars [1-4] or hybrid cars [5-9].

The use of electric vehicles has a significant number of advantages and disadvantages. Thus, most of the disadvantages of electric cars are associated with batteries, namely, their significant cost, relatively low power reserve (especially at low ambient temperatures), a fairly long charging time, a small service life, and the cost of disposal. All these disadvantages are still compounded by an extremely undeveloped infrastructure of charging stations. Partially, these can be solved by using hybrid cars: for example, the problem of distance range or operation in winter.

An alternative to electric and hybrid cars can be vehicles running on compressed air [10-13], or hybrid vehicles using an air engine instead of an electric one. Air engines, like electric engines, are environmentally friendly; in addition, the air engine power supply system has significant advantages compared to batteries, although it is somewhat more complicated. The advantages include the long service life of consumable cylinders, their quick refueling, and the fact that expensive and toxic disposal is not required. Thus, the frequency of inspection of cylinders for storing compressed air installed on mobile vehicles is 10 years (external and internal inspection and hydraulic tests with test pressure). The service life of supply cylinders with compressed air is set by the manufacturer. Usually, it is not limited, although in some countries, for example, in Russia, according to industrial safety requirements, it is limited to 20 years. Also, the advantages of using an air engine can be attributed to the fact that in summer, expanded and cooled air can be used in the car air conditioning system.

The main element of a transport power plant is an air engine, where the technical and operational performance of the entire plant directly depends on its technical excellence. Therefore, a significant number of researchers focused on converting a conventional four-stroke engine into a two-stroke air engine, for example, in [14-16]. This has several disadvantages, primarily due to the fact that the design of the internal combustion engine provides for the combustion process, and not just the expansion process, as in an air engine. Typically, convertible engines have more weight (materials and thicknesses are designed for high pressure and temperature of the working fluid), large values of dead volume (due to the combustion chamber), and higher values of the ratio of the stroke of the piston to the diameter of the cylinder (with a decrease in this ratio, the loss in the air engine decreases air pressure at the inlet and backpressure at the outlet). In addition, when converting an internal combustion engine into a pneumatic one, a gas exchange system also requires re-equipment [17-20]. Basically, the converted gas exchange systems do not have the ability to regulate the air engine operating modes by changing the degree of filling, which negatively affects the specific effective consumption of compressed air.

However, the use of convertible engines for experimental research is a quite acceptable and fairly inexpensive way to determine the main characteristics of the air engine [21-23].

3. GOALS AND OBJECTIVES OF THE RESEARCH

A significant number of publications on the use of compressed air energy in transport plants report on the demand and relevance of this area of research. Converting ordinary internal combustion engines into air engines, during vehicles mass production, is economically unprofitable for a number of reasons. The use of air engines, mass-produced for industry, also has its drawbacks, primarily associated with the specifics of their purpose, conditions, and modes of operation.

The development and creation of a new reliable and efficient air engine that meets the specifics and satisfies all operating conditions on the vehicle is more appropriate. First of all, an air engine for a transport power plant must fulfil the following requirements:

- to have minimum weight and dimensions relative to its power;
- to provide minimum compressed air consumption;
- to be reversible and at the same time have the same efficiency;
- to efficiently operate at a wide range of engine inlet pressures and various rotations;
- to ensure normal operation at various ambient temperatures (from minus to plus);
- to have a minimum dead volume and the ability to control operating modes by changing the degree of filling; and
- to be reliable, resistant to overloads, easy to operate, and cheap to manufacture and repair.

The developed RPE-4.4/1.75 rotary piston engine of a fundamentally new design (Fig. 1) fulfills all the specified requirements and can be used as part of a transport power plant, and studying its characteristics and operating modes as part of a power plant is a very important and urgent task [24, 25].

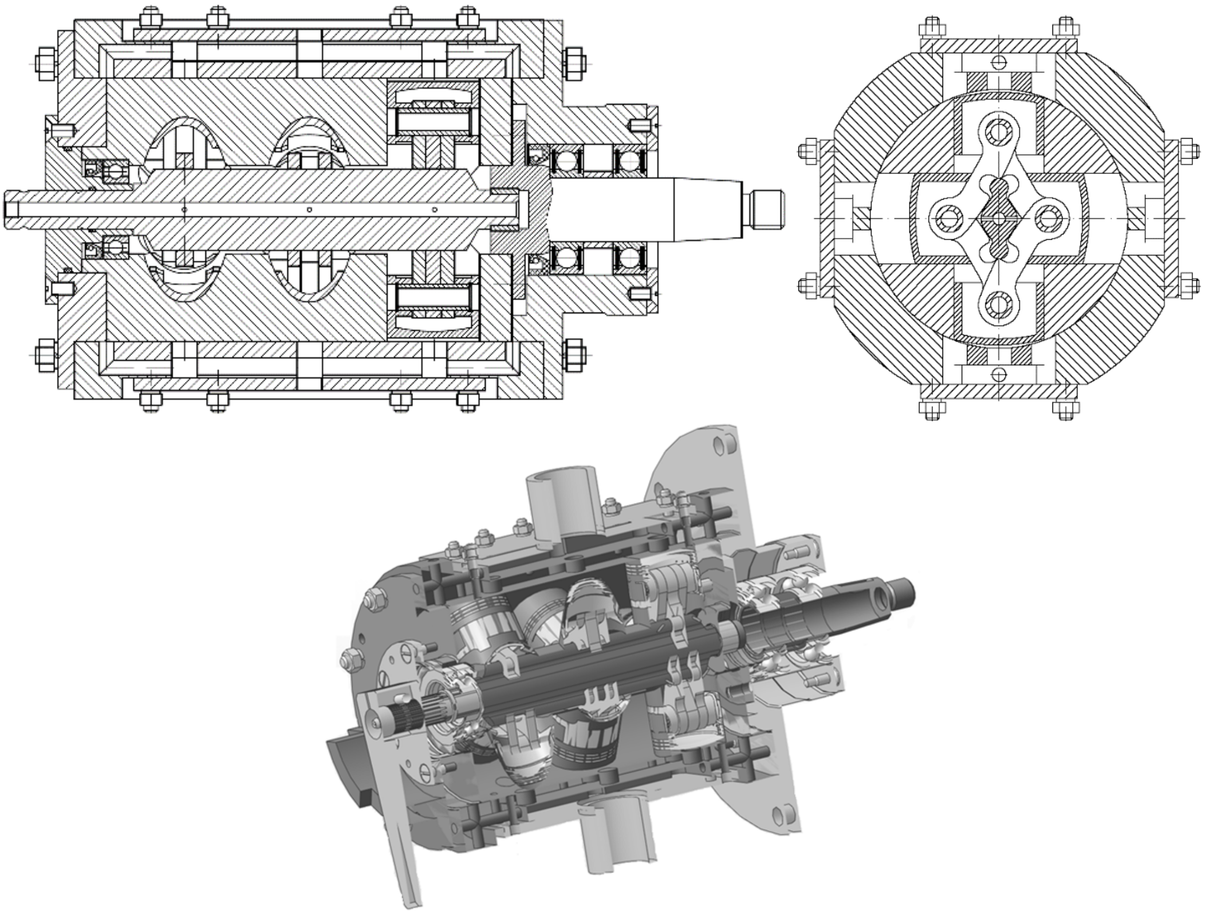

Fig. 1. General view and design of a rotary piston engine

The engine housing contains a central rotor with radial pair-opposed cylinders. In the cylinders, pistons move back and forth, which are interconnected by floating pins and rigid links, wherein, the interconnected links form a hinged quadrangle, in the center of which a regulating cam is installed. Turning the regulating cam allows you to change the degree of filling of the working cylinder, which ensures the regulation of the engine operating modes. Gas exchange in the engine is provided by inlet and outlet openings made in the housing, which are closed and opened when the rotor turns.

The main advantages of a rotary piston engine are its simple, compact, and reliable spool design for regulating the phases of gas exchange, which makes it possible to regulate operating modes by changing the degree of filling. Due to the uniform placement of the cylinders, the engine has high balance, no vibration, and also starts in any position. Due to the combination of the design of the rotary and piston engines, the rotary piston engine, in comparison with rotary ones, has better sealing of the working space, and compared to the piston ones, there is no relative dead volume. Better sealing of the working cylinder minimizes compressed air losses, and the absence of relative dead volume improves efficiency. The ratio of piston stroke to cylinder bore is 0.4, which provides low piston speeds, compactness, and minimum relative weight. Therefore, by reducing the piston speed, the pressure loss at the inlet and the back pressure at the outlet are reduced. In addition, according to experimental studies, the rotary piston engine shows reliable operation at low temperatures of the exhaust air [26].

The aim of this research is to develop a hybrid transport power plant based on a rotary piston air engine and determine its operational characteristics.

The main tasks of the research include the following:
– development of a schematic diagram of a transport hybrid power plant using a new design rotary piston air engine;
– determination of the external speed characteristics of a rotary piston air engine as part of a power plant;
– determination of power balance and dynamic characteristics of a hybrid car using an air engine; and
– evaluation of acceleration performance of a hybrid car using an air engine.

To implement the task of developing a schematic diagram of a transport hybrid power plant using a new design rotary piston air engine, system analysis and generalization are performed. A systematic analysis of the various schemes of hybrid transport systems allows us to evaluate their advantages and disadvantages, as well as highlight a more suitable scheme of a power plant in which it is possible to use an air engine with high efficiency.

Determination of the characteristics of a hybrid power plant with an air engine as well as evaluation of the effectiveness of using a new design rotary piston engine are carried out by mathematical modeling based on preliminary experimental research of a prototype [25, 26].

The object of the research is a hybrid transport power plant with a new design of a rotary piston air engine. The subject of the research is the operational characteristics of a hybrid car when operating on an air engine.

4. RESEARCH RESULTS

In existing hybrid transport power plants, three main schemes are used, namely, serial, parallel, and mixed (serial–parallel).

When using a serial scheme, the internal combustion engine (ICE) is combined with an electric current generator, which, in turn, powers the traction engines or additionally charges the batteries. During the period of insufficient power supply from the ICE and generator, the traction engine is additionally powered by storage batteries. In the event of excess energy, the batteries are charged. The advantages of this scheme are that the ICE operates in a constant mode of minimum fuel consumption. In addition, the serial scheme provides ease of control, there are no transmission units, and there is a possibility of different layout of the power plant. The main disadvantage of the serial scheme is that, due to the repeated conversion of energy (from mechanical to electrical, and then from electrical to mechanical), such power plants have low efficiency values.

When using a parallel scheme, the torque from ICE through the transmission is transmitted to the drive wheels of the vehicle. In the modes of excess power of ICE, energy is directed through a special power take-off system to charge the batteries. In the modes of insufficient power, the accumulated energy is used to power the elements of the electric transmission. The advantages of such a scheme are a higher level of efficiency and the possibility of using one electric machine. Accordingly, the disadvantages of the parallel scheme are the complication of the transmission, the operation of ICE at various modes of fuel consumption, and the complications of the control of the power plant.

When using a mixed ICE scheme, the electric current generator and the traction engine are interconnected by means of a planetary gear. In this case, ICE operates in a constant mode of minimum fuel consumption, and the speed of the transmission outlet shaft is controlled by a traction engine. Accordingly, the advantage of this scheme is high efficiency values. And the disadvantage is a significant complication of transmission design and power plant control system.

Based on the advantages and disadvantages of various schemes, the parallel scheme of a hybrid transport power plant is a kind of optimal compromise between the efficiency of energy conversion and the complexity of the design, and is also the most suitable for using an air engine.

Fig. 2 shows the project of a parallel diagram of a hybrid transport power plant using compressed air energy. In this scheme, ICE and the air engine are interconnected using a drive axle transmission. This interconnection of the two engines makes it possible to increase the efficiency of energy transfer from the internal combustion engine to the wheels of the car (compared to the serial scheme of transport hybrid plants); however, it somewhat complicates the transmission and control of the power plant as a whole. Also, the use of a parallel scheme makes it possible to use the heat of the exhaust gases of ICE for heating compressed air before expansion, as well as the excess energy of the internal combustion engine to power the high-pressure compressor for pumping the cylinders.

In the internal combustion engine operating modes (for example, when the car is moving outside the city), the torque from engine 1 is transmitted through drive axle transmission 2, viscous coupling 3, and rear wheel gear 4 to rear drive axle wheels 5; this is, in fact, a classic scheme of a rear-wheel drive car.

When the car is moving in a traffic flow, a rotary piston air engine 12 is used to reduce environmental pollution. Compressed air, used in a rotary piston engine, is stored in cylinders 9. The transport power plant has two cylinders made of carbon fiber with a Kevlar sheath, which can significantly reduce their weight. The capacity of each cylinder is 100 liters, and the storage pressure is 35 MPa. Refueling from an external source of compressed air is carried out through valve 7. To increase the effective performance of the rotary piston engine, it is possible to preheat the compressed air from the exhaust gases of the internal combustion engine in a special heat exchanger 10. The necessary air pressure in the receiver of the rotary piston engine is provided with gear 13 with electromagnetic control. The gearbox maintains a constant working value of air pressure and, if necessary, can increase it to provide an increase in engine torque.

After throttling and expansion in the working cylinder of a rotary piston engine, the air is cooled. In summer, the air exhausted in the engine is partially or completely directed to the heat exchanger 16 of the car air conditioning system. Regulation of the operation of the air conditioning system of the car is carried out using bypass electromagnetic valves 14 and 15.

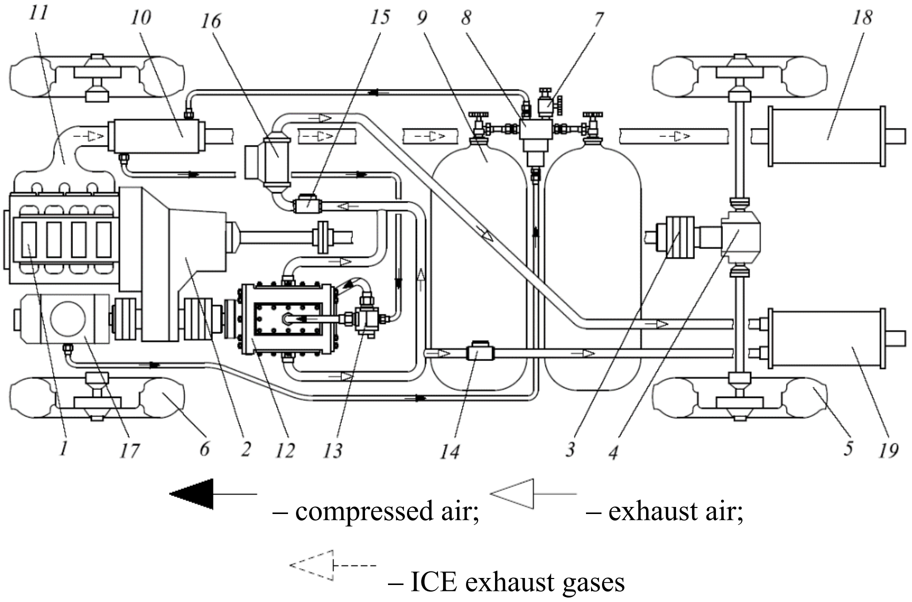

Fig. 2. Schematic diagram of a hybrid transport power plant: 1 – internal combustion engine; 2 – drive axle transmission; 3 – viscous coupling; 4 – rear wheel gear; 5 – rear drive axle wheels; 6 – front non-drive axle wheels; 7 – valve of cylinder refill from an external source; 8 – compressed air distributor; 9 – compressed air storage cylinders; 10 – compressed air heater of ICE exhaust gases; 11 – engine exhaust manifold; 12 – rotary piston engine; 13 – electronically controlled air gear; 14, 15 – exhaust air bypass valves; 16 – car air conditioning heat exchanger; 17 – high-pressure compressor of cylinders pumping; 18 – ICE exhaust gases discharge silencer; and 19 – air discharge silencer

Also, the proposed scheme of the power plant provides for the possibility of recharging the supply cylinders of compressed air using high-pressure compressor 17, which operates from ICE in excess power modes. At above average vehicle speeds, ICE transfers part of the energy to the wheels and another part to the high-pressure compressor. In addition, in braking modes, the inertial mass of the vehicle is used to power the compressor. The compressor operating modes are consistent with the overall control system of the power plant. The parameters of the rotary piston engine of the transport power plant should provide the necessary dynamics and speed of the car in urban traffic. When determining the effective indicators and speed characteristics of a rotary piston engine, it is necessary to establish the value of the maximum vehicle speed that the engine must provide. According to the traffic laws in inhabited localities, the movement of vehicles is limited to a speed of 50 km/h. Therefore, taking into account a certain margin of speed, we take the maximum vehicle speed when the rotary piston engine is 60 km/h. The main technical characteristics of the hybrid car are shown in Table 1. Therefore, as the project of a possible hybrid vehicle is proposed, the main parameters for the calculation were selected based on similar vehicles and their characteristics [27–32]. It is also worth clarifying that in Table 1, the car curb weight is the total mass of the vehicle with all equipment (including the pneumatic system and the air motor), all the necessary operating consumables, and a full tank of fuel, excluding passengers and cargo. The value of the gear ratio of the gearbox corresponds to the VAZ 1111 car, and the gear ratio of the main gear was selected taking into account the torque of the rotary piston engine, provided that starting off was ensured using only an air engine.

Table 1

Technical characteristics of a hybrid car with a rotary piston air engine

No.	Parameter	Designation/dimension	Value
General parameters of a hybrid car			
1	Curb vehicle weight	m_0, kg	720
2	Static radius of a car wheel	R, m	0,289
3	Overall dimensions of the car: - length - width - height	 L, m B, m H, m	 3,40 1,62 1,40
4	Gear Ratio: - first - second - third - fourth - fifth	 u_{k1} u_{k2} u_{k3} u_{k4} u_{k5}	 3,70 2,06 1,27 0,90 0,78
5	Final drive gear ratio	u_{k0}	3,1
6	Number of passengers	–	4
7	Volume of compressed air cylinder	V, m^3	0,1
8	Number of cylinders	$i_б$	2
9	Cylinder weight	$m_б$, kg	35
10	Maximum air pressure in the cylinder	$p_б$, MPa	35
11	Maximum speed of a car on an air engine	$V_{p.max}$, km/h	60
Internal combustion engine parameters			
12	Effective power	N_e, kW	30
13	Maximum torque	$M_к$, N·m	100
14	Maximum rotational speed of the crankshaft	n, rpm	4200
Parameters of a rotary piston air engine			
15	Effective power	N_e, kW	8,75
16	Maximum torque	$M_к$, N·m	127,54
17	Engine weight	kg	22

In Fig. 3, the external speed characteristic of a rotary piston air engine in urban traffic with a maximum permissible speed of 60 km/h is shown.

To build the dynamic characteristics of a hybrid car for all gears and speeds, it is necessary to determine the components of the power balance equation, which are determined by the known dependencies [33, 34] as follows:

$$P_k - P_f - P_w - P_j = 0, \quad (1)$$

where P_k is the tractive effort on driving wheels of the car; P_f is the total road resistance (which takes into account the coefficient of rolling resistance and the total car weight); P_w is the air resistance force (which takes into account the coefficient of air resistance and the frontal area of the car); and P_j is the acceleration resistance.

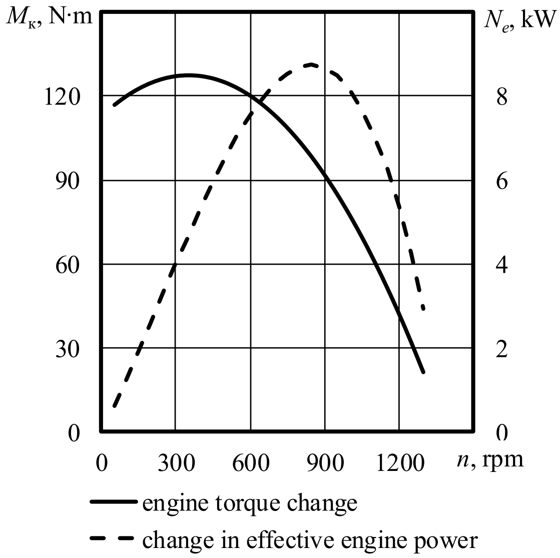

Fig. 3. External speed characteristic of a rotary piston air engine

The tractive effort on driving wheels of the car is determined by the formula

$$P_k = \frac{M_k u_{ki} u_0 \eta_{tr}}{R}, \tag{2}$$

where M_k is the current torque value and η_{tr} is the transmission efficiency of the corresponding gear.

In the calculations, it is assumed that the vehicle is moving on a horizontal surface, that is, there is no scope for the resistance to increase when determining the force of the total road resistance. Then, the force of the total road resistance is determined by the formula:

$$P_\psi = m_a g f_0 \left(1 + \frac{v^2}{1500}\right), \tag{3}$$

where m_a is the vehicle gross weight; g is the acceleration of gravity; f_0 is the rolling resistance coefficient; and v is the vehicle speed.

The total weight of a passenger car in accordance with [33] is determined as follows:

$$m_a = m_0 + 80 n_1,$$

where n1 is the number of passengers.

The value of the rolling resistance coefficient was chosen as 0.01, which corresponds to the conditions of the asphalt pavement in good condition [34].

The force of air resistance is determined by the formula:

$$P_w = \frac{C_x \rho}{2} F_a v^2, \tag{4}$$

where C_x is the drag coefficient (for a passenger car, it is 0.26...0.38); ρ is the air density, kg/m^3 (ρ = 1.225 kg/m^3); and F_a is the frontal area of a car, m^2.

The value of the frontal area of a car is determined from the drawing. In the absence of a drawing, for an approximate calculation of the frontal area of the car, the following dependence is used:

$$F_a = (0{,}78...0{,}8) \cdot B \cdot H. \tag{5}$$

The value of the acceleration resistance is defined as the difference between the tractive effort and the sum of the resistance to movement. It is advisable to plot the power balance and dynamic characteristics of a hybrid car as a function of speed, which is directly related to the speed of the rotary piston engine, the gear ratio of the corresponding gearbox and final drive, and also the static radius of the car's wheel [33, 34]:

$$v = \frac{R \cdot \omega}{u_{ki} u_0} \text{ m/s} \quad (6)$$

where ω is the angular speed of rotation of the air engine rotor, s^{-1}.

If we express angular velocity ω in terms of revolutions of rotary piston engine n and change dimensions from m/s to km/h, the speed equation will take the following form:

$$V = 0{,}377 \cdot \frac{R_n}{u_{ki} \cdot u_0}, \text{ km/h} \quad . \quad (7)$$

Fig. 4 shows the graphs of the power balance and the dynamic characteristics of the car when operating on a rotary piston air engine.

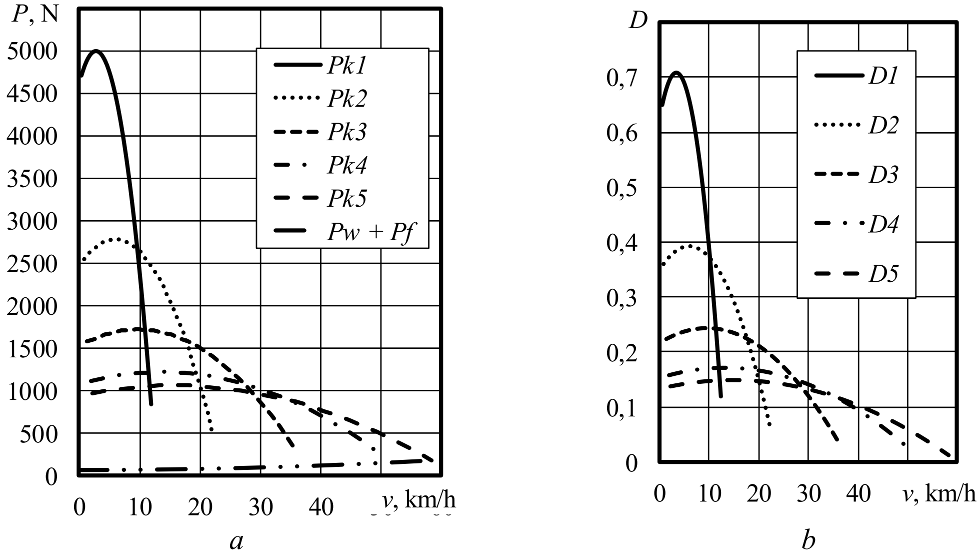

Fig. 4. Characteristics of a hybrid car when operating on a rotary piston air engine in urban traffic: *a* is the power balance and *b* is the dynamic characteristic

The dynamic characteristic is the dependence of dynamic factors in different gears on vehicle speed. Therefore, the dynamic factor is determined by the formula:

$$D = \frac{P_k - P_w}{m_a g} \quad . \quad (8)$$

The results of calculation of the traction-speed characteristics of a hybrid vehicle are presented in Table 2, and the dynamic factor results are presented in Table 3.

The dynamics of acceleration of a hybrid car with an air engine is dependent on the change in acceleration, time, and acceleration distance from the car speed.

Therefore, the vehicle acceleration is determined by the known dependencies for all gears and speeds, using the corresponding values of the dynamic characteristics. The acceleration of a hybrid vehicle in various gears when driving on a horizontal section of the road is determined by the formula [34]

$$j = \frac{(D - f)g}{\delta} \quad , \quad (9)$$

where δ is the coefficient taking into account the rotating mass of a vehicle for different gears.

The moment of inertia of rotating parts of a vehicle is not known; hence, the value of the coefficient can be estimated using the equation:

$$\delta = 1{,}04 + 0{,}04 u_{ki} \quad . \quad (10)$$

Fig. 5 shows the dependences of changes in accelerations and reverse accelerations when moving on a rotary piston air engine.

The results of calculation of the acceleration of a hybrid vehicle are presented in Table 4.

Table 2

Results of calculation of the traction-speed characteristics of a hybrid vehicle when operating on a rotary piston air engine in urban traffic conditions

ω, s^{-1}	M_k, N·m	Gear 1					Gear 2				
		v, km/h	P_k, N	$P_ψ$, N	P_w, N	$P_ψ + P_w$, N	v, km/h	P_k, N	$P_ψ$, N	P_w, N	$P_ψ + P_w$, N
10.47	120	0.95	4705	70.64	0.02	70.66	1.71	2620	70.64	0.08	70.72
20.93	125	1.90	4889	70.65	0.10	70.74	3.42	2722	70.67	0.32	70.99
31.40	127	2.85	4981	70.66	0.22	70.88	5.13	2773	70.73	0.72	71.45
41.87	128	3.81	4981	70.68	0.40	71.08	6.84	2773	70.80	1.28	72.08
52.33	125	4.76	4889	70.71	0.62	71.33	8.55	2722	70.90	1.99	72.89
62.80	120	5.71	4705	70.75	0.89	71.64	10.25	2620	71.01	2.87	73.88
73.27	113	6.66	4429	70.79	1.21	72.00	11.96	2466	71.15	3.91	75.06
83.73	104	7.61	4061	70.84	1.58	72.42	13.67	2261	71.31	5.10	76.41
94.20	92	8.56	3602	70.90	2.00	72.90	15.38	2005	71.49	6.46	77.95
104.67	78	9.52	3050	70.96	2.47	73.43	17.09	1698	71.69	7.97	79.67
115.13	61	10.47	2406	71.03	2.99	74.02	18.80	1340	71.92	9.65	81.56
125.60	43	11.42	1671	71.11	3.56	74.67	20.51	930	72.16	11.48	83.64
136.07	22	12.37	843	71.19	4.18	75.37	22.22	470	72.43	13.48	85.90

Gear 3					Gear 4					Gear 5				
v, km/h	P_k, H	$P_ψ$, H	P_w, H	$P_ψ+$ P_w, H	v, km/h	P_k, H	$P_ψ$, H	P_w, H	$P_ψ+$ P_w, H	v, km/h	P_k, H	$P_ψ$, H	P_w, H	$P_ψ+$ P_w, H
2.77	1615	70.66	0.21	70.87	3.91	1144	70.69	0.42	71.11	4.49	997	70.71	0.55	71.26
5.54	1678	70.74	0.84	71.58	7.82	1189	70.85	1.67	72.53	8.98	1036	70.93	2.20	73.13
8.32	1710	70.88	1.89	72.77	11.74	1212	71.13	3.76	74.89	13.47	1055	71.29	4.95	76.25
11.09	1710	71.08	3.36	74.44	15.65	1212	71.52	6.68	78.21	17.96	1055	71.80	8.81	80.61
13.86	1678	71.33	5.25	76.58	19.56	1189	72.02	10.44	82.47	22.45	1036	72.46	13.76	86.23
16.63	1615	71.64	7.55	79.19	23.47	1144	72.63	15.04	87.67	26.94	997	73.27	19.82	93.09
19.41	1520	72.00	10.28	82.28	27.38	1077	73.36	20.47	93.83	31.43	939	74.22	26.98	101.20
22.18	1394	72.42	13.43	85.85	31.30	988	74.19	26.74	100.93	35.93	861	75.32	35.23	110.56
24.95	1236	72.89	16.99	89.89	35.21	876	75.14	33.84	108.97	40.42	763	76.57	44.59	121.16
27.72	1047	73.42	20.98	94.40	39.12	742	76.19	41.78	117.97	44.91	646	77.96	55.05	133.01
30.49	826	74.01	25.39	99.40	43.03	585	77.36	50.55	127.91	49.40	510	79.50	66.62	146.11
33.27	574	74.65	30.21	104.86	46.94	406	78.64	60.16	138.80	53.89	354	81.18	79.28	160.46
36.04	289	75.35	35.46	110.81	50.85	205	80.03	70.60	150.63	58.38	179	83.01	93.04	176.06

To determine the necessary time and acceleration path of a hybrid car when driving on a rotary piston air engine, it is necessary to calculate certain integrals accordingly [33; 34]:

$$t = \int_{v_1}^{v_2} \frac{1}{j} dv; \quad S = \int_{t_1}^{t_2} v dt \quad . \tag{11}$$

In addition, the acceleration time can be obtained graphically by determining the area limited by the inverse acceleration curves $1/j_i = f(V)$ (see Fig. 5, *b*), and the acceleration path by calculating the area of the dependence of the acceleration time $t = f(V)$. The area under the curves is divided into a random number of sections. In the corresponding scale, the areas of sections F_{ti} on the reverse acceleration graph are the acceleration time:

$$t_i = \mu_{\frac{1}{j}} \cdot \mu_v F_{ti}, \tag{12}$$

where $\mu_{\frac{1}{j}}$ is the scale-back acceleration factor; μ_v is the scale speed factor; and F_{ti} is the corresponding section area. In the corresponding scale, the areas of sections F_{si} on the acceleration time graph are the acceleration path:

$$S_i = \mu_v \cdot \mu_t F_{si} \tag{13}$$

where μ_t is the scale acceleration time factor and F_{si} is the area of the corresponding acceleration time section. Graphs of time and acceleration path of a hybrid car depending on the speed of movement are shown in Fig. 6, and the calculation results are shown in Tables 5 and 6.

Table 3

Results of calculation of the dynamic factor of a hybrid vehicle when operating on a rotary piston air engine in urban traffic conditions

Gear 1				Gear 2				Gear 3			
v, km/h	P_k-P_w, N	*D*	*f*	*v*, km/h	P_k-P_w, N	*D*	*f*	*v*, km/h	P_k-P_w, N	*D*	*f*
0.95	4705.09	0.67	0.010000	1.71	2619.52	0.37	0.010002	2.77	1614.79	0.23	0.010004
1.90	4888.91	0.69	0.010002	3.42	2721.67	0.39	0.010006	5.54	1677.28	0.24	0.010016
2.85	4980.73	0.71	0.010004	5.13	2772.46	0.39	0.010014	8.32	1707.79	0.24	0.010036
3.81	4980.56	0.71	0.010007	6.84	2771.90	0.39	0.010024	11.09	1706.32	0.24	0.010063
4.76	4888.39	0.69	0.010012	8.55	2719.99	0.39	0.010038	13.86	1672.87	0.24	0.010099
5.71	4704.22	0.67	0.010017	10.25	2616.73	0.37	0.010054	16.63	1607.44	0.23	0.010142
6.66	4428.06	0.63	0.010023	11.96	2462.12	0.35	0.010074	19.41	1510.04	0.21	0.010194
7.61	4059.90	0.57	0.010030	13.67	2256.15	0.32	0.010096	22.18	1380.65	0.20	0.010253
8.56	3599.74	0.51	0.010038	15.38	1998.84	0.28	0.010122	24.95	1219.28	0.17	0.01032
9.52	3047.59	0.43	0.010047	17.09	1690.17	0.24	0.010150	27.72	1025.93	0.15	0.010395
10.47	2403.44	0.34	0.010056	18.80	1330.15	0.19	0.010182	30.49	800.60	0.11	0.010478
11.42	1667.29	0.24	0.010067	20.51	918.77	0.13	0.010216	33.27	543.30	0.08	0.010569
12.37	839.14	0.12	0.010079	22.22	456.05	0.06	0.010254	36.04	254.01	0.04	0.010668

Gear 4				Gear 5			
v, km/h	P_k-P_w, N	*D*	*f*	*v*, km/h	P_k-P_w, N	*D*	*f*
3.91	1144.07	0.16	0.010008	4.49	996.42	0.14	0.01001
7.82	1187.55	0.17	0.010031	8.98	1033.74	0.15	0.010041
11.74	1207.82	0.17	0.010071	13.47	1050.47	0.15	0.010093
15.65	1204.90	0.17	0.010126	17.96	1046.61	0.15	0.010166
19.56	1178.77	0.17	0.010197	22.45	1022.18	0.14	0.010259
23.47	1129.45	0.16	0.010283	26.94	977.16	0.14	0.010373
27.38	1056.92	0.15	0.010386	31.43	911.55	0.13	0.010508
31.30	961.19	0.14	0.010504	35.93	825.36	0.12	0.010664
35.21	842.26	0.12	0.010638	40.42	718.59	0.10	0.01084
39.12	700.13	0.10	0.010787	44.91	591.23	0.08	0.011037
43.03	534.80	0.08	0.010952	49.40	443.29	0.06	0.011255
46.94	346.26	0.05	0.011134	53.89	274.76	0.04	0.011494
50.85	134.53	0.02	0.011330	58.38	85.65	0.01	0.011753

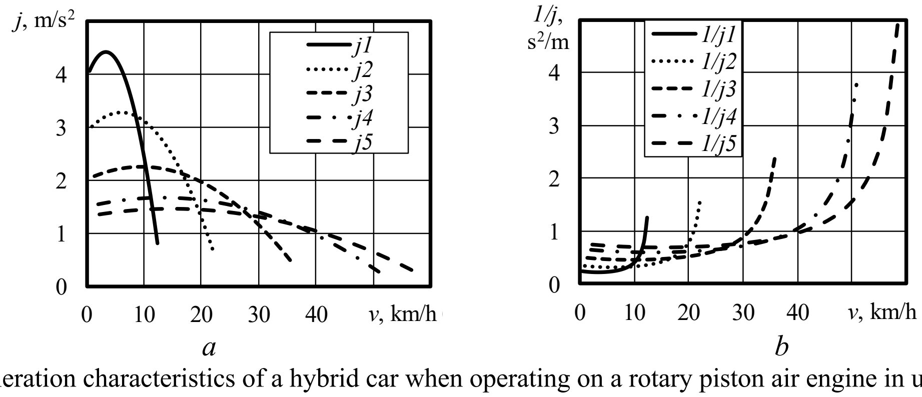

Fig. 5. Acceleration characteristics of a hybrid car when operating on a rotary piston air engine in urban traffic: *a* is the acceleration and *b* is the reverse acceleration

Thus, according to the obtained dependences, a rotary piston air engine provides a hybrid car with a speed of up to 60 km/h in urban traffic. At the same time, the rotary piston air engine and transmission provide maximum traction in the first gear of 5 kN, an acceleration time to a maximum speed of 15.2 s, and an acceleration path of 173 m.

Table 4

Results of calculation of the acceleration of a hybrid vehicle when operating on a rotary piston air engine in urban traffic conditions

Gear 1					Gear 2					Gear 3				
v, km/h	*D*	*f*	*j*, m/s^2	*1/j*, s^2/m	*v*, km/h	*D*	*f*	*j*, m/s^2	*1/j*, s^2/m	*v*, km/h	*D*	*f*	*j*, m/s^2	*1/j*, s^2/m
0.95	0.67	0.010000	4.18	0.24	1.71	0.37	0.010002	3.09	0.32	2.77	0.23	0.010004	2.12	0.47
1.90	0.69	0.010002	4.34	0.23	3.42	0.39	0.010006	3.21	0.31	5.54	0.24	0.010016	2.20	0.45
2.85	0.71	0.010004	4.42	0.23	5.13	0.39	0.010014	3.26	0.31	8.32	0.24	0.010036	2.24	0.45
3.81	0.71	0.010007	4.42	0.23	6.84	0.39	0.010024	3.26	0.31	11.09	0.24	0.010063	2.23	0.45
4.76	0.69	0.010012	4.34	0.23	8.55	0.39	0.010038	3.20	0.31	13.86	0.24	0.010099	2.19	0.46
5.71	0.67	0.010017	4.18	0.24	10.25	0.37	0.010054	3.09	0.32	16.63	0.23	0.010142	2.11	0.47
6.66	0.63	0.010023	3.94	0.25	11.96	0.35	0.010074	2.91	0.34	19.41	0.21	0.010194	1.99	0.50
7.61	0.57	0.010030	3.61	0.28	13.67	0.32	0.010096	2.67	0.37	22.18	0.20	0.010253	1.82	0.55
8.56	0.51	0.010038	3.21	0.31	15.38	0.28	0.010122	2.38	0.42	24.95	0.17	0.010320	1.62	0.62
9.52	0.43	0.010047	2.73	0.37	17.09	0.24	0.010150	2.02	0.49	27.72	0.15	0.010395	1.38	0.73
10.47	0.34	0.010056	2.16	0.46	18.80	0.19	0.010182	1.61	0.62	30.49	0.11	0.010478	1.10	0.91
11.42	0.24	0.010067	1.52	0.66	20.51	0.13	0.010216	1.14	0.88	33.27	0.08	0.010569	0.77	1.30
12.37	0.12	0.010079	0.80	1.26	22.22	0.06	0.010254	0.60	1.65	36.04	0.04	0.010668	0.41	2.45

Gear 4					Gear 5				
v, km/h	*D*	*f*	*j*, m/s^2	*1/j*, s^2/m	*v*, km/h	*D*	*f*	*j*, m/s^2	*1/j*, s^2/m
3.91	0.16	0.010008	1.57	0.64	4.49	0.14	0.010010	1.39	0.72
7.82	0.17	0.010031	1.63	0.61	8.98	0.15	0.010041	1.44	0.69
11.74	0.17	0.010071	1.66	0.60	13.47	0.15	0.010093	1.46	0.68
15.65	0.17	0.010126	1.65	0.61	17.96	0.15	0.010166	1.46	0.69
19.56	0.17	0.010197	1.62	0.62	22.45	0.14	0.010259	1.43	0.70
23.47	0.16	0.010283	1.55	0.64	26.94	0.14	0.010373	1.37	0.73
27.38	0.15	0.010386	1.46	0.68	31.43	0.13	0.010508	1.28	0.78
31.30	0.14	0.010504	1.34	0.75	35.93	0.12	0.010664	1.17	0.86
35.21	0.12	0.010638	1.18	0.85	40.42	0.10	0.010840	1.03	0.97
39.12	0.10	0.010787	1.00	1.00	44.91	0.08	0.011037	0.86	1.16
43.03	0.08	0.010952	0.78	1.28	49.40	0.06	0.011255	0.67	1.49
46.94	0.05	0.011134	0.54	1.85	53.89	0.04	0.011494	0.45	2.22
50.85	0.02	0.011330	0.27	3.76	58.38	0.01	0.011753	0.20	4.90

The approximate driving duration of the hybrid car using only the rotary piston air engine at a speed of 60 km/h without parallel recharging on a single cylinder with 100 l compressed air, with a storage temperature of 20°C, and an initial pressure of 35 MPa and a final pressure of 2 MPa is about 26 km. The calculation results for the duration of the movement are rather approximate and conditional. The vehicle's power reserve was calculated based on the conditions of the vehicle's movement along a straight section of the road at a constant speed. In this case, the specific consumption of the working fluid of air engine and the possibility of discharging the cylinders to the minimum possible pressure from the point of view of ensuring the operation of the air engine (according to the data in Table 1) were taken into account. In addition, in the calculations, the acceleration period and the flow rate of the working fluid were not taken into account.

Heavy traffic, especially in central parts of large cities, leads to a decrease in the average vehicle speed. Thus, the average speed of passenger cars in conditions of average traffic intensity is about 40 km/h, and in peak traffic conditions, it can decrease to 12.5...15.0 km/h [35; 36]. Accordingly, in such conditions, conventional ICEs operate ineffectively and have high levels of harmful emissions. In such conditions of vehicle movement, it is efficient to use environmentally friendly rotary piston engines that provide the necessary dynamic characteristics of the vehicle, which is confirmed by the results of the calculations.

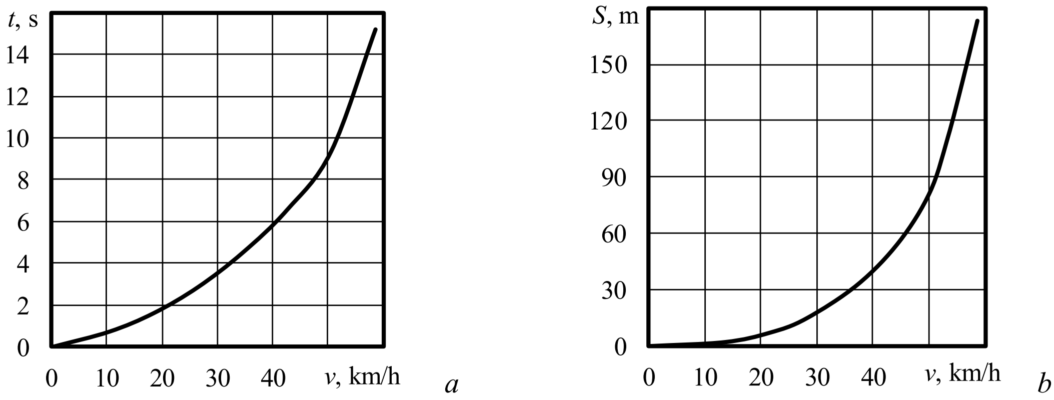

Fig. 6. Dependences of the time and acceleration path of a hybrid car when operating on a rotary piston air engine: *a* is the acceleration time and *b* is the acceleration path

Table 5
Results of calculation of the acceleration time of a hybrid vehicle when operating on a rotary piston air engine in urban traffic conditions

Parameter	Values							
v, km/h	0	10.51	18.51	26.51	34.51	42.51	50.51	58.51
$1/j$, s^2/m	0	0.33	0.49	0.67	0.82	1.04	1.61	4.89
F_{ti}, mm^2	0	36.55	45.47	64.03	83.89	104.76	144.43	299.54
ΣF_t, mm^2	0	36.55	82.03	146.06	229.95	334.71	479.14	778.68
t, s	0	0.71	1.60	2.85	4.49	6.54	9.36	15.21

Table 6
Results of calculation of the acceleration path of a hybrid vehicle when operating on a rotary piston air engine in urban traffic conditions

Parameter	Values									
v, km/h	0	13.57	21.56	28.06	37.28	44.67	50.15	53.29	55.95	58.55
F_{si}, mm^2	0	2.09	4.85	7.34	17.74	22.21	25.78	28.03	29.54	30.96
ΣF_s, mm^2	0	2.09	6.93	14.28	32.02	54.23	80.01	108.04	137.58	168.54
S, m	0	2.14	7.12	14.67	32.89	55.71	82.20	111.00	141.35	173.16

5. CONCLUSIONS

A parallel scheme of a transport hybrid power plant based on the RPE - 4.4/1.75 rotary piston air engine with a power of 8.75 kW has been developed. The air engine provides a maximum car speed of up to 60 km/h, which is more necessary in urban traffic conditions. At the same time, the car's driving range on one cylinder with 100 l compressed air (initial pressure 35 MPa, final 2 MPa) is about 26 km. An external speed characteristic of a rotary piston air engine was obtained, according to which the maximum engine torque is 127.54 Nm at 400 rpm and the maximum power is 8.75 kW at 850 rpm. The components of the power balance and the dynamic factor of the hybrid car are determined when operating on a rotary piston air engine for various gears and speeds. In this case, the highest traction on the driving wheels is 5 kN. The dependences of acceleration, time, and acceleration path of a hybrid car when operating on an air engine to a speed of 60 km/h are obtained. Therefore, the required acceleration time of the car is 15.2 s and the path is 173 m, which is a sufficient indicator in urban traffic conditions.

In developed countries, the demand for and distribution of environmentally friendly vehicles of various designs are increasing steadily. Due to their advantages, hybrid compressed-air transport power plants have great economic potential and further development prospects. In contrast to convertible air engines, the new design rotary piston engine has a much simpler and more compact design, as well as a rather low specific consumption rate of compressed air, which makes it effective for use in transport power plants. However, it is worth noting that it is impossible to take into account all the possible features of using a new design rotary piston air engine as part of a transport power plant in a real-life vehicle operation. Therefore, further comprehensive full-scale road tests are required.

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