



**Oleksandr
S. Mytrofanov**
Митрофанов
Александр
Сергеевич

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ANALYSIS OF THE DEVELOPMENT AND CURRENT STATE OF THE USE OF POWER PLANTS BASED ON PNEUMATIC ENGINES

АНАЛИЗ РАЗВИТИЯ И СОВРЕМЕННОГО СОСТОЯНИЯ ПРИМЕНЕНИЯ ЭНЕРГЕТИЧЕСКИХ УСТАНОВОК НА БАЗЕ ПНЕВМОДВИГАТЕЛЕЙ

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Oleksandr S. Mytrofanov

A. С. Митрофанов, канд. техн. наук, доц.
mitrofanov.al.ser@gmail.com

ORCID: 0000-0003-3460-5369

*Admiral Makarov National University of Shipbuilding, Mykolaiv**Национальный университет кораблестроения имени адмирала Макарова, г. Николаев*

Abstract. The article presents the main stages of development and use of compressed air energy in transport plants for various purposes. The domestic and foreign literature on the development of the current state and prospects of the use of compressed air energy and pneumatic engines in the power plant of vehicles have been analyzed. The list of problems arising in the application of pneumatic engines is determined, as well as rational ways of further increasing the efficiency of power plants are established. The main advantages and disadvantages of pneumatic engine using in the composition of transport power plants are highlighted. So, the main advantages include high environmental friendliness, depreciation of vehicle production, lower mass and dimensions parameters. Disadvantages include low efficiency coefficient due to multiple energy conversion, limited power consumption of filling cylinders and engine cooling due to the expansion of air. The most common pneumatic engine designs (piston and rotary) and their performance properties are considered. It has been established that rotary pneumatic engines, in terms of energy, mass and dimensions, and performance parameters, exceed other engines. Some of their inherent operational disadvantages, which may limit their use in some spheres, can be eliminated or reduced to acceptable standards at the right design solution. The variants of the basic schemes of power transport plants with pneumatic engines, namely the use of a pneumatic engine as an auxiliary power unit (hybrid units) or, as the main one in aeromobiles, are considered.

Keywords: energy resources; harmful emissions; power plant; rotary pneumatic engine; piston pneumatic engine; compressed air.

Анотація. Подано основні етапи розвитку та використання енергії стиснутого повітря в транспортних установках різного призначення. Наведено аналіз вітчизняної та зарубіжної літератури щодо розвитку сучасного стану й перспектив використання енергії стиснутого повітря і пневмодвигунів у складі енергетичної установки транспортних засобів. Визначено перелік проблем, що виникають при застосуванні пневмодвигунів, а також установлені раціональні шляхи подальшого підвищення ефективності енергетичних установок. Виділені основні переваги та недоліки використання пневмодвигунів у складі транспортних енергетичних установок. Так, до основних переваг можна віднести високу екологічність, зниження вартості виробництва транспортних засобів, менші масогабаритні показники, до недоліків – низький ККД за рахунок багатократного перетворення енергії, обмеженість енергоємності заправних балонів та охолодження двигуна внаслідок розширення повітря. Розглянуто найбільш поширені конструкції пневмодвигунів (поршневі й ротаційні) та їх експлуатаційні властивості. Установлено, що ротаційні пневмодвигуни за енергетичними, масогабаритними та експлуатаційними показниками перевищують інші двигуни, а деякі притаманні їм експлуатаційні недоліки, що можуть обмежувати їх застосування в деяких сферах, при правильному конструктивному рішенні можуть бути усунуті або знижені до припустимих норм. Розглянуті варіанти основних схем енергетичних транспортних установок з пневмодвигунами, а саме використання пневмодвигуна як допоміжного силового агрегату (гібридні установки) або як головного в аеромобілях.

Ключові слова: енергоресурси; шкідливі викиди; енергетична установка; роторний пневмодвигун; поршневий пневмодвигун; стиснуте повітря.

Аннотация. Представлены основные этапы развития и использования энергии сжатого воздуха в транспортных установках различного назначения. Приведен анализ отечественной и зарубежной литературы по развитию современного состояния и перспектив использования энергии сжатого воздуха и пневмодвигателей

в составе энергетической установки транспортных средств. Определен перечень проблем, возникающих при применении пневмодвигателей, а также установлены рациональные пути дальнейшего повышения эффективности энергетических установок. Выделены основные преимущества и недостатки использования пневмодвигателей в составе транспортных энергетических установок. Так, к основным преимуществам можно отнести высокую экологичность, снижение стоимости производства транспортных средств, меньшие массогабаритные показатели, к недостаткам – низкий КПД за счет многократного преобразования энергии, ограниченность энергоемкости заправочных баллонов и охлаждение двигателя вследствие расширения воздуха. Рассмотрены наиболее распространенные конструкции пневмодвигателей (поршневые и ротационные) и их эксплуатационные свойства. Установлено, что ротационные пневмодвигатели по энергетическим, массогабаритным и эксплуатационным показателям превышают другие двигатели, а некоторые присущие им эксплуатационные недостатки, которые могут ограничивать их применение в некоторых сферах, при правильном конструктивном решении могут быть устранены или снижены до допустимых норм. Рассмотрены варианты основных схем энергетических транспортных установок с пневмодвигателями, а именно использование пневмодвигателя в качестве вспомогательного силового агрегата (гибридные установки) или как главного в автомобилях.

Ключевые слова: энергоресурсы; вредные выбросы; энергетическая установка; роторный пневмодвигатель; поршневой пневмодвигатель; сжатый воздух.

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Problem statement. Ukraine has rather insignificant reserves of oil and gas, so the state fuel and energy balance is formed at the expense of imports from different countries. The reduction of reserves of fossil fuels leads to a constant increase in its price, so most developed countries in the world stimulate the production for the use of various types of alternative energy.

A significant amount of consumed oil fuels goes to the needs of vehicles for various purposes. In addition, transport gives 40% of the total harmful emissions into the atmosphere. The problem of environmental pollution is especially acute for large cities. Most European countries are beginning to refuse the use of vehicles with internal combustion engines (ICE) in large cities. An alternative to vehicles with internal combustion engine is the use of electric vehicles, hybrid cars or engines running on compressed air. Vehicles for various purposes on compressed air for many parameters can be compared with vehicles working on accumulator batteries. Also, pneumatic engines have been widely used in underwater vehicles, mining enterprises, namely for cargo vehicles, drive drilling carriages or telfers.

The use of power-plant vehicles based on pneumatic engines has several advantages, as well as disadvantages. Their analysis, selection and systematization will help in the further study of scientific and technical basis for the creation of power plants for various purposes on the basis of pneumatic engines.

Latest research and publications analysis. The problem of environmental pollution is one of the most significant problems of modern mankind. Every day industry and especially transport emit a huge amount of harmful and poisonous substances, as well as greenhouse gases [1–3].

The problem of energy resources is even more acute, because the reserves of oil, gas and coal are not unlimited, so the demand and prices for energy resources are increasing every year, and there are no reasons for their reduction [4]. In this regard, power plants with the ICE are constantly being improved to meet both pollution standards (UNECE Regulations N 83) and specific fuel consumption ones (UNECE Regulations N 101). Every year, these standards become more stringent [5, 6], therefore, manufacturers of power plants with ICE have to look for new design solutions [7–13] or apply alternative fuels (energy sources) [14–18] to improve these performance.

However, despite all efforts, according to the International Council for Clean Transport, by 2018, the number of registered electric and hybrid cars in Europe is 1,4 % [19]. This is primarily due to the rather significant cost of hybrid and electric vehicles (primarily due to the high cost of electric batteries) compared to gasoline and diesel cars.

Solving the problem of environmental pollution by vehicles and reducing their prices can be realized through the use of pneumatic engines and the energy of compressed air [20–34].

Separation of previously unsolved parts of the general problem. The choice of a pneumatic engine type for a power plant of a vehicle must be based on the compulsory consideration of the basic requirements, such as the possibility of manufacturing an engine with an adjustable airflow degree, the presence of the largest starting torque and the most favorable traction characteristics, the possibility to withstand overload, have the minimum possible costs of the compressed air and a sufficiently high level of reliability and durability. Also today, it is an open question of choosing the optimal scheme for using the pneumatic engines as part of power plant of a vehicle, namely the use of the pneumatic engine as an auxiliary power unit or the main one.

THE ARTICLE AIM — is to analyze ways to improve road transport in order to increase its environmental performance and economical efficiency based on the use of compressed air energy, as well as types of pneumatic engines and schemes for their application, based on literary sources.

Methods, object and subject of research. When performing the research, general logical methods were used, namely the method of analysis and generalization. The task of the analysis was to get a general sense of the current state of development and future trends in the application of pneumatic engines in the composition of power plants of vehicles. When performing the analysis, a systematic approach was used, that is, a search was carried out for integrated solutions that would ensure the achievement of the highest efficiency of the power plant and fulfillment of numerous requirements for its quality. On the basis of the analysis, a generalization of advantages and disadvantages, as well as possible ways to improve the use of accumulated energy of compressed air in transport was made.

The object of the research is the transport power plants and the efficiency of energy conversion in them. **The subject of the research** is pneumatic engines and their characteristics in the composition of transport power plants.

Basic material. The use of compressed air energy as a drive of various systems was quite widespread at the beginning of the XIX [35]. Pneumatic engines of various designs have found their application in various industries, as well as in transport (the use of a pneumatic locomotive on the Gotthard Railway in 1872).

At the Alexander Plant in St. Petersburg in 1861, the engineer and inventor in the field of shipbuilding and transport S. I. Baranowskyi built a pneumatic drive locomotive, called the Baranowskyi chimney [36] and was used on the Mykolaiv Railway. Also in Paris, compressed air was used to drive trams, which were powered

by a central city-wide pneumatic distribution network (developed by Frenchman Louis Mekarski). The compressed air energy has also been used in the military field, namely the submarine, torpedo drive.

Back in 1903, Liquid Air Company began to manufacture compressed air cars. The main problems of the cars were the low torque of the pneumatic engine and the high cost of compressed air.

In the late 80s of the twentieth century in the Soviet Union, a pneumatic engine was developed by the chief designer of the Zavolzhskiy Motor Plant N. Pustynskiy on the basis of a conventional ICE. A negative feature of this engine was the preservation of up to 95 % of standard parts. Widespread use of this engine was not obtained, however, at some industrial enterprises, electric cars were replaced by cheap and practical pneumatic cars, equipped with engines Pustynskiy.

On the basis of the Ukrainian Research Institute of Shipbuilding Technology, a rotary-piston pneumatic engine was developed by Yu. V. Shabalin, V. K. Frolov, O. I. Voloshchuk and V. S. Tietieriev (Fig. 1) [37].

The pneumatic engine contains a body, a rotor in it with radial, pairwise-opposed cylinders and pistons arranged in them, which are interconnected by means of fingers and rigid links with the formation of a pivoting quadrilateral. The cam placed in it with two diametrically opposite vertices, has contact with the links. Such design allows for a smooth change in the rotation speed of the rotor and changes in its rotation direction. The pneumatic engine has all the advantages of rotary engines, and there are no disadvantages inherent to piston engines due to its unusual design. The main advantages of the rotary-piston pneumatic engine are its small mass and dimensions, rather high efficiency coefficient (due to high degree of compaction of the working chamber), as well as resistance to overload.

In 2009, at the Geneva Motor Show, the French-Italian company Motor Development International (official site <https://www.mdi.lu>), co-founded by one of the leading designers of Formula 1 engines Guy Negre [38], the compact cars MDI AIRpod (Fig. 2) with pneumatic engines were presented (Fig. 3).

There are three modifications of the MDI company aeromobiles:

- AIRPod Standart (three seats for adult passengers and one for the child);
- AIRPod Cargo (with a body for transportation of small loads);
- AIRPod Baby (two-seater streetcar).

Due to the use of composite materials, aluminum and plastic in the construction, the mass of the car is about 280 kg. Wheel formula is 4×2. At the same time, the car

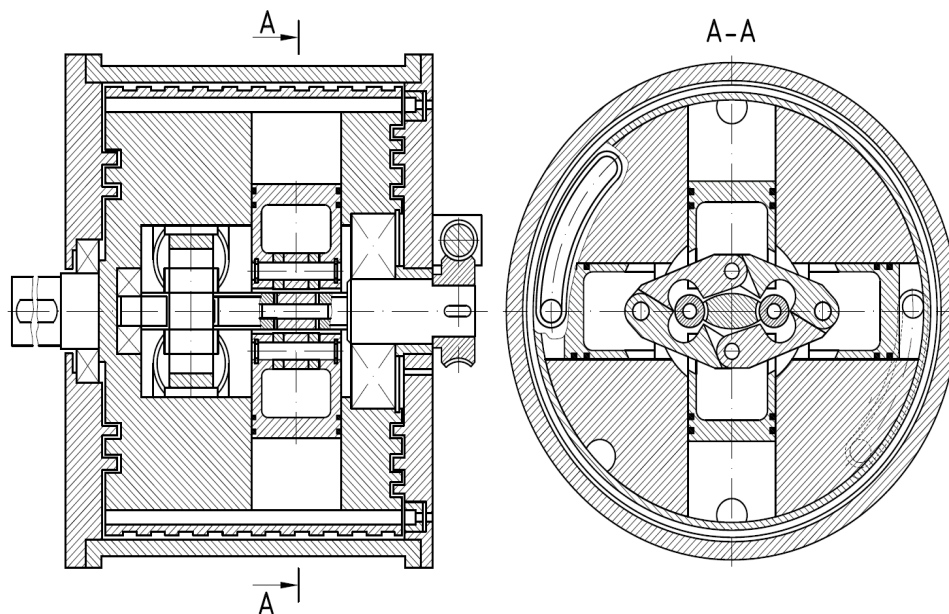


Fig. 1. Rotary-piston pneumatic engine



Fig. 2. MDI AIRpod car

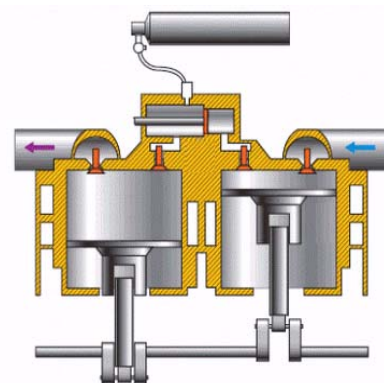


Fig. 3. The operation principle of the pneumatic engine of MDI company

accelerates to 80 km/h, the fuel distance with one filling with compressed air is 130 km in urban mode and 150 km outside the city (without maneuvering). The car is controlled by a joystick, the gearbox is automatic three-speed (plus a back stroke).

The principle of operation of an MDI engine is that air is blown into a small cylinder, where it is compressed by a piston to a pressure of 18...20 bar and warmed up. Then the heated air goes into a spherical chamber where it is mixed with cold air from the cylinders, which instantly, expanding and heating, increases the pressure on the piston of the large cylinder, which transmits the effort to the crankshaft of the engine.

Along with the development of AIRpod, the well-known Indian company Tata launched the MiniCAT car project. The mass of the car is slightly more than 350 kg, the maximum speed is 100 km/h, the fuel distance is

120 km (the specifications of the MiniCAT car are presented in Table 1) [39]. The power plant has four cylinders, which, to reduce weight, are made of carbon fiber with a kevlar cover, length 2 m and diameter of 0.25 m each, contain 400 liters of compressed air under a pressure of 300 bar are placed under the bottom. In this case, the exhausted air in the pneumatic engine has a low temperature and can be used to cool the interior of the car in the summer season instead of the air conditioner. The company planned to put the MiniCAT on the conveyor in mid-2012 and produce about 6,000 units per year, but the running-in of the car is still ongoing, and mass production has been postponed.

In 2011, Australian Dean Bensted demonstrated the world the O2 Pursuit cross motorcycle with a powertrain developed by Engineair (rotary air engine developed by Angelo di Pietro – Fig. 4). The power unit in its design is

Table 1. Specifications of the MiniCAT car

Parameter	Dimension	Mono-energy	Dual-energy 2	Dual-energy 4
Length	m	2,65	2,65	2,65
Width	m	1,62	1,62	1,62
Height	m	1,66	1,66	1,66
Number of seats	–	3	3	3
Luggage compartment volume	dm ³	500/700	500/700	500/700
Weight	kg	550	520	540
Engine	–	41P03	41P01	41P01/4
Power	kW	25	25	50
Maximum speed	km/h	110	125	140
Urban run range (zero pollution)	km	140/150	50	50
CO ₂ emissions in the city	g/km	0	0	0
Run outside the city	km	80	1650	1500
Gasoline consumption outside the city	L	–	1,8	2
CO ₂ emissions outside the city	g/km	0	35	40

a Wankel engine without combustion, the rotor is driven by compressed air supplied to the combustion chamber. The motorcycle is able to drive 100 km at one filling and develop up to 140 km/h.

Also, the pneumatic engine has found its application in hybrid power plants. Thus, the French company Peugeot Citroen plans to produce cars Peugeot 208 Hybrid Air 2L and Citroen C3 in a hybrid version, one of the elements of which will be the installation of Hybrid Air (Fig. 5). The hybrid unit was developed in collaboration with Bosch. Its essence lies in the fact that the ICE energy will be accumulated not in the form of electricity (as in conventional hybrids), but in cylinders with compressed air. The system includes a gasoline engine, a special transmission with a planetary gear, a hydraulic motor and two compressed air cylinders. One cylinder is located in the central part of the chassis, and the second one — under the trunk floor in the area of the rear axle. Only through a compressed air car with such a hybrid power unit can drive a few kilometers at a speed of no more than 70 km/h. Replenishment of air in cylinders is due to the braking energy recovery system. It uses a hydraulic pump that compresses the air and fills the cylinders. The system leads to an increase in the mass of the car by about 100 kg, while reducing the average fuel consumption by 45% compared to conventional powertrains.

A significant contribution to the development of combined power plants for pneumatic engine vehicles was made by domestic scientists: A. M. Turenko, V. O. Bohomolov, F. I. Abramchuk, O. I. Voronkov, S. S. Zhylin, I. M. Nikitchenko, A. I. Kharchenko, V. M. Manoilo, O. Yu. Linkov et al. [9, 21–26]. A series of pneumatic engines was developed at the Department of ICE of the Kharkiv National Automobile and Highway University (KNAHU) on the basis of gasoline engines of MeMZ, ZMZ. Such



Fig. 4. Rotary air engine developed by Angelo di Pietro

a series of engines can work as a separate powertrain, and in one block with the ICE in moderate high-speed modes $n = 600...1500 \text{ min}^{-1}$ and power up to 10...15 kW, which is quite enough for a modern city car that moves at a speed up to 30 km/h [40, 41]. The experimental sample of automobile four-cylinder V-shaped non-reversible piston pneumatic engine with a spool air distributor and combined lubrication system developed by KNAHU is shown in Fig. 6 [42]. This is a converted gasoline engine of the MeMZ-968 with air cooling system.

Also, the staff of the department of ICE KNAHU made a significant contribution to the development of the theory of working processes of pneumatic engines and combined power plants of vehicles. Namely, theoretical methods for organizing working processes and experimental research, methods for influencing design and adjustment parameters on the performance of a pneumatic engine have been developed. The following methods have been developed: the calculation of the air supply process for determining the necessary actual parameters of the inlet and out channels; determination of the necessary power of the pneumatic engine to achieve the maximum vehicle speed (taking into account the specification of routes and time, which made

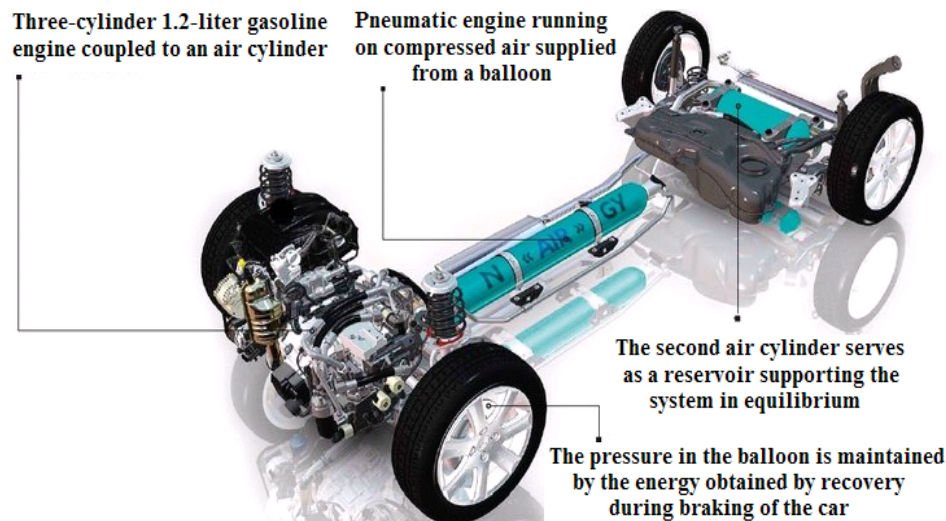


Fig. 5. Peugeot Hybrid Air hybrid unit

it possible to calculate the speed and acceleration of the vehicle); determination of the amount of heat in the process of heating the compressed air to obtain the minimum required an inlet temperature to the pneumatic engine and the effect of the compressed air temperature on the performance of the pneumatic engine work process with spool and valve air distribution [21–26, 40–42]. Patents for combined power plant of vehicles with pneumatic engines are obtained (Fig. 7) [43, 44].

In the scheme proposed by the authors of patents, the ICE and pneumatic engine are combined into a combined power plant and located on a vehicle in a sequential, parallel, or combined schemes with the heating of compressed air. The external speed performance of the pneumatic engine for the ZAZ-968M car, taken off in road conditions is represented in Fig. 8 [42].

Scientists from Beihan University, Beijing, China, proposed a power plant scheme (Fig. 9) with a piston pneumatic engine shown in Fig. 10 (cylinder diameter 85 mm, piston stroke 88 mm, inlet and outlet diameter 12 mm, compression ratio 10) [29].

The power plant consists of a pneumatic engine 9, a cylinder with compressed air 2, a buffer cylinder 4 (provides the corresponding air pressure to the pneumatic engine), two pressure sensors 1, 8, two regulators 3, 7, a pressure relief valve (TESCOM) 5, an electronic control valve (FAIRCHILD) 6, silencer 10 and controller 11.

The output torque (Fig. 11) decreases with increasing rotation speed and increases with increasing supply pressure [29]. The maximum torque can be obtained at the lowest rotation speed and the highest supply pressure. When the supply pressure is 2 MPa, the output torque is 56,55 N·m. By increasing the engine speed, the mass of the charge decreases sharply, which reduces the torque of the engine.

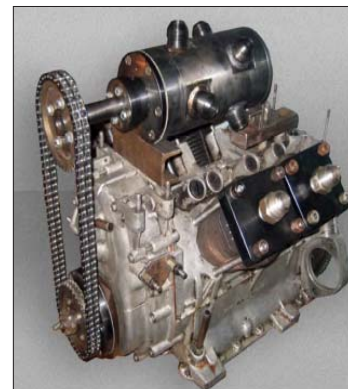


Fig. 6. Pneumatic engine assembled with spool air distributor (without tubes connecting cylinders with spool)

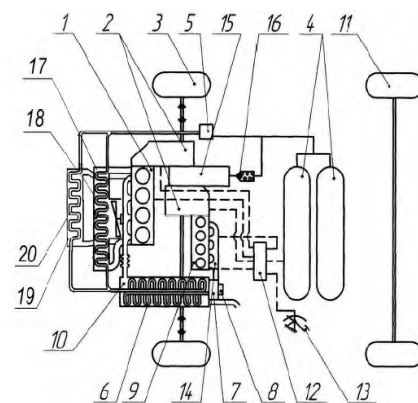


Fig. 7. Scheme of a combined power plant of vehicle:

1 — internal combustion engine; 2 — planetary drive axle transmission mechanism; 3 — drive axle wheels; 4 — pneumatic cylinders; 5 — high pressure regulator; 6 — heat exchanger; 7 — electronic pressure regulator; 8 — electropneumatic valve regulator; 9 — pneumatic engine; 10 — silencer front pipe of ICE; 11 — non-driving axle wheels; 12 — electronic control unit; 13 — cyclic fuel delivery pedal in ICE; 14 — air receiver; 15 — stand-alone three-stage compressor; 16 — high pressure solenoid check valve; 17 — liquid cooling connection system of ICE; 18 — additional heat exchanger; 19 — liquid lubrication connection system; 20 — additional heat exchanger

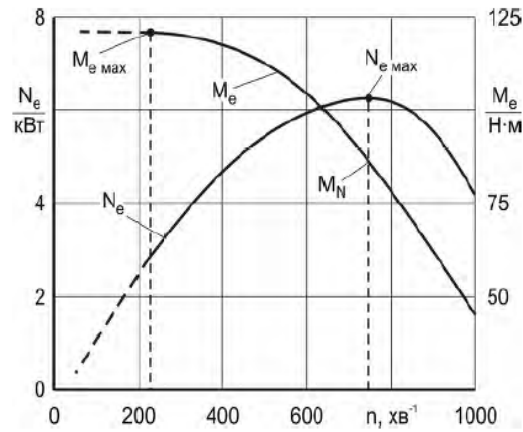


Fig. 8. Full-load curve of the pneumatic engine for the ZAZ-968M car

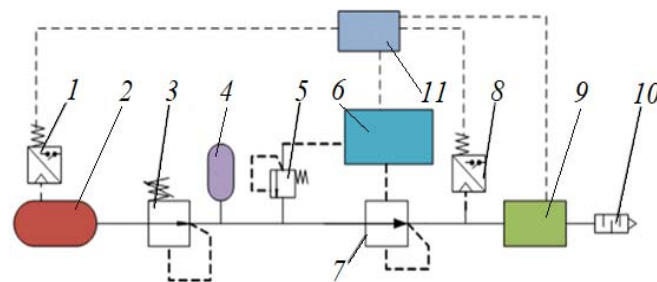


Fig. 9. Schematic diagram of automotive power plant with pneumatic engine

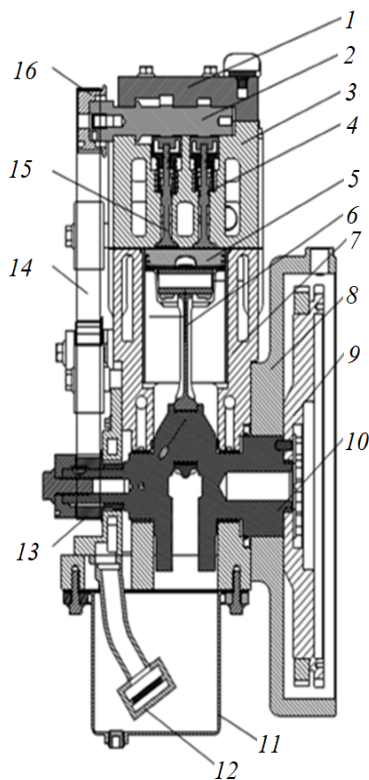


Fig. 10. Pneumatic engine:

1 — cylinder cover; 2 — camshaft; 3 — cylinder head; 4 — outlet valve; 5 — piston; 6 — connecting rod; 7 — cylinder; 8 — flywheel housing; 9 — flywheel; 10 — crankshaft; 11 — oil pan; 12 — oil filter; 13 — low pulley; 14 — driving belt; 15 — inlet valve; 16 — top pulley

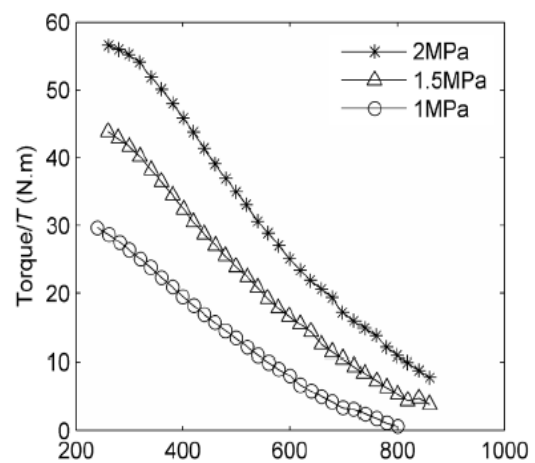


Fig. 11. Changing the torque of the pneumatic engine depending on the frequency of crankshaft rotation

Dependence of the change in the power of the pneumatic engine is represented in Fig. 12 [29]. So, at the beginning, the power sharply increases with increasing rotation speed and reaches the maximum value, then sharply falls. At an air supply pressure of 2, 1,5 and 1 MPa, the maximum output power is 1,92 kW (420 rpm), 1,37 kW (380 rpm) and 0,85 kW (340 rpm), respectively.

The engine efficiency decreases with increasing crankshaft rotation speed and supply pressure (Fig. 13) [29]. When supplying air at a pressure of 2 MPa, the maximum efficiency coefficient is 25%. This is due in particular to the fact that when the pneumatic engine is operating at low speed, the energy of compressed air is more effectively converted into mechanical one. Also, the decrease in the efficiency coefficient with increasing engine speed is associated with an increase in air loss through the throttle, heat loss and exhaust system.

At the University of Kütahya Dumlupınar (Turkey) at the Department of Motor Vehicles and Transport Technology, the four-stroke single-cylinder gasoline engine was converted into a pneumatic engine with a rotary valve operating as a two-stroke [20]. The parameters of the convertible engine are shown in the Table. 2.

Fig. 14 shows the P - V -diagram of the pneumatic engine operation at different values of the crankshaft rotation frequency, Fig. 15 — changing of torque, air loss and pneumatic engine power at a working pressure of 25 bar, depending on the frequency of crankshaft rotation.

The torque of the pneumatic engine is of the highest value when the crankshaft is rotated at 800 rpm. With increasing engine speed, there is a decrease in torque due to significant air losses. The maximum power of the pneumatic engine was 1,72 kW at 1000 rpm. The highest value of air loss was 12,4 m³/h at 600 rpm. The highest effective efficiency coefficient reached 24,42%, while the crankshaft speed was 800 rpm, torque — 17,28 N·m, and power — 1,48 kW [20].

Discussion. The use of vehicles with power plants in compressed air has several advantages as well as disadvantages. The advantages include high environmental friendliness, depreciation of production of vehicles (due

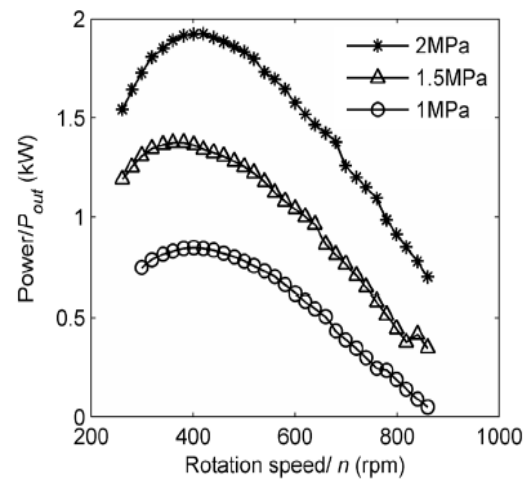


Fig. 12. Changing the power of the pneumatic engine depending on the frequency of crankshaft rotation

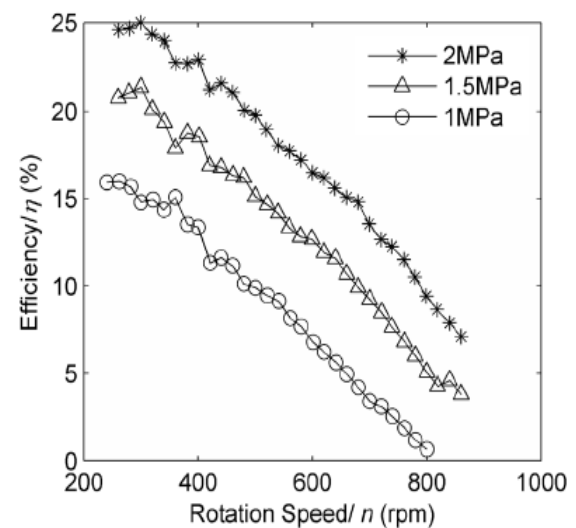


Fig. 13. Changing the effective efficiency coefficient of the pneumatic engine depending on the frequency of crankshaft rotation

to the lack of systems inherent in ICEs), fire safety (an important factor for enterprises of engineering, chemical, petrochemical and mining industries), lower mass and dimensions parameters. In addition, it should be noted the possibility of using cheaper and less durable materials (aluminum, plastic, which have good frictional properties) due to the low fluid temperature, high service life

Table 2. Specifications of the convertible engine

№ n.o.	Parameter	Dimension	Value
1	Type of engine	—	Four-stroke, overhead camshaft
2	Diameter of cylinder	mm	88
3	Piston stroke	mm	64
4	Volume of cylinder	sm ³	389
5	Rated power at 3600 rpm	kW	8,3
6	Maximum torque at 3000 rpm	N·m	26,5
7	Compression ratio	—	8
8	Type of cooling	—	Air

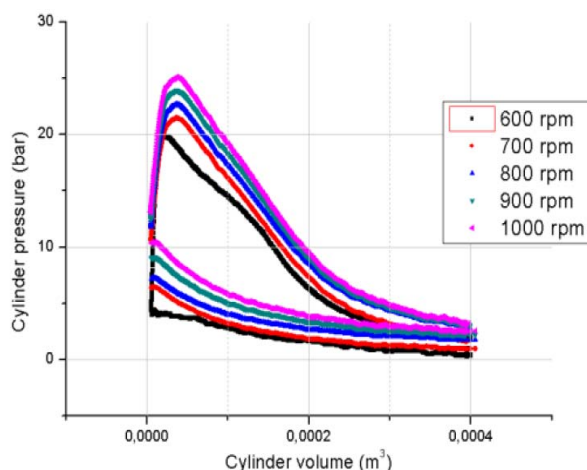


Fig. 14. P - V -diagram of the pneumatic engine operation at different values of the frequency of crankshaft rotation

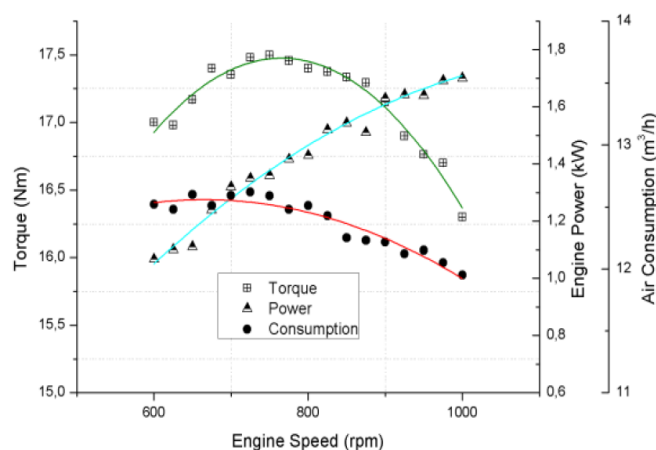


Fig. 15. Characteristics of changes in torque, air loss and engine power, depending on the frequency of crankshaft rotation

of filling cylinders (compared to accumulator batteries). In the presence of specialized filling stations, charging the cylinders does not take much time. Lower vehicle weight contributes to reducing road wear. However, power plants with pneumatic engines also have a number of disadvantages. This is a lower efficiency coefficient at the expense of multiple energy conversion (first you need to spend energy for compressing air, and then from compressed air to get mechanical work), engine cooling due to the expansion of air in the engine. The limited energy consumption of the filling cylinders reduces the duration of the vehicle's movement.

The solution of these and many other problems, in particular, related to the scientific and technical fundamentals of the creation of power plants for various purposes based on pneumatic engines, requires further deeper experimental and theoretical research.

CONCLUSIONS. The analysis of domestic and foreign literature allowed establishing the possibility of using the energy of compressed air in the power plants of vehicles. This made it possible to determine the list of problems arising in its application, as well as establish rational ways of further increasing the efficiency of power plants with pneumatic engines. The main advantages and disadvantages of pneumatic engine using in the composition of transport power plants are highlighted. The variants of the scheme of the use of pneumatic engines in the power unit of the vehicle, namely the use of a pneumatic engine as an auxiliary power unit (hybrid units) or, as the main one, are considered. It's also worth noting that rotary engines, in terms of energy, mass and dimensions, and performance parameters, exceed other engines. Some of their inherent operational disadvantages, which may limit their use, can be eliminated or reduced to acceptable standards at the right design solution.

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Статтю рекомендує до друку
д-р техн. наук, проф. *С. І. Сербін*