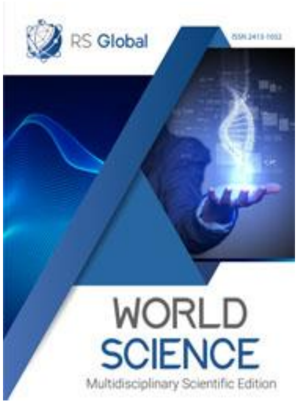

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USE OF PNEUMATIC MOTORS IN PESTICIDE SPRAYERS

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ABSTRACT

Pneumatic motors have existed in many forms over the past two centuries, ranging in size from hand-held motors to engines of up to several hundred horsepower. Some types rely on pistons and cylinders; others on slotted rotors with vanes (vane motors) and others use turbines. Many compressed air engines improve their performance by heating the incoming air or the engine itself. Pneumatic motors have found widespread success in the hand-held tool industry, but are also used stationary in a wide range of industrial applications. Continual attempts are being made to expand their use to the transportation industry. However, pneumatic motors must overcome inefficiencies before being seen as a viable option in the transportation industry.

In the scientific project we discussed the perspective of use of the rotor type pneumo engines in portable splashers (sprinklers). Mathematic modelling of the pneumatic engines is chosen and worked out, gauge sizes, amount of increasing the air, the amount of rotating moment during the rotation of the rotor and the amount of the engine.

KEYWORDS

Engine, Compressed Air, Rotor, Pump, Manometer

CITATION

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1. Introduction

Nowadays, the environmental regulations of the exhaust emission from internal combustion engines are more rigorous every year. Despite the high progress of the new types of combustion processes such homogeneous charge compression ignition (HCCI), controlled auto-ignition (CAI) [1], ATAC [2] and other or applying of different complicated fuel injection systems, the emission of the combustion products of the hydrocarbon fuel is still high, particularly in lower engine loads. Only small energy of fuel (about 25–45%) depending on the engine type is transformed into mechanical power. The application of alternative energy sources and alter- native driving system is need instead of those based on fossil fuels. However, the main environmental problem takes place in big cities with transportation vehicles, where only the fossil fuels are used. Recently, the hybrid systems and fuel cell system are considered for future transportation means. Until now the electricity is produced mostly in many countries by burning fossil fuels. It is connected with production of CO2 and emission of the toxic components of exhaust gases. The electric vehicles have small possibility to drive a long distance. Up to now, the highest distance for such vehicles reaches maximum 150 km at medium speed and load, but real distance is up to 100 km. For that reason, an additional source power for generating an electric energy or driving source is still required. Many works are concerned on range-extender vehicles with a piston engine driving the electrical generator that charges the batteries. The current from batteries is delivered to the electric engine connected with a driving gearbox that transmits power to the wheels. The combus- tion engine works only outside the city.

The alternative proposition of power source is to apply the air energy stored in the tank at high pressure. The idea of air-powered engines is known from many years. Already in the nineteenth century, were given concepts of such an engine. In 1847, Mr Parsey invented the air-compressed locomotive and after many years in 1896, the conception of Porter's pneumatic locomotive appeared [3]. The idea of pneumatic engines for transportation was revived again at the end of twentieth century. Many scientific and research works on pneumatic piston engines were carried out across the world in the past few years [4–6].

A car using energy stored in compressed air produced by a compressor has been suggested as an environmentally friendly vehicle in the future by Creutzig et al. [7, 8]. They analysed the thermodynamic efficiency of a compressed air car powered by a pneumatic engine and con- sider the merits of compressed air versus chemical storage of potential energy. Many proposals of applying the air piston engines were presented by researchers from Asia [9, 10]: for applica- tion in transportation. The researchers presented theoretical studies on engines of a typical small-scale passenger car, which are used for the analyses, and the comparison is based on the shaft work, cooling, efficiency and energy density. They found that optimization of the internal-combustion and recycling of the exhaust energy can increase the vehicle's efficiency from an original 15 to 33%, an overall increase of 18%. A hybrid pneumatic system with recirculation of exhaust gases was proposed by Huang et al. [11]. Huang et al [12] carried out a modification of four-stroke engine for operation in two-stroke engine, which was fed with compressed air. Their study presents an experimental investigation on a piston engine driven by compressed air. The compressed air engine was a modified 100 cm3 internal combustion engine obtained from a motorcycle manufacturer. The experimental and theoretical analysis of a compressed air four-stroke engine was conducted by Chinese researchers, Yu and Cai [13]. The results show that the prototype of such an engine has a good economic performance under low speed and when the supply pressure is 2 MPa. Many works concern to application of the air engine in motorcycles [14], particularly in regions where motorcycle is a main transporta- tion source. A prototype was built with a fuzzy logic speed controller and tested on the real road. Another prototype of motorcycle air engine with a capacity of 100 cm3 was built by Wang et al. [15]. The motorcycle installed with the compressed air engine can operate at a maximum speed of around 38.2 km/h and a distance up to 5 km equipped with two 9 l bottles filled by air under pressure of 25 MPa.

Currently across the world, there are realized several projects of road vehicles with pneumatic drive, including project developed by Motor Development International (MDI) [16], and sold under the name of the Indian company TATA under the name Tata Air Car Mini Cat [17]. This engine operates in a four-stroke cycle and outside air is drawn into the compression chamber and compressed to 20 bar. At top dead centre (TDC), this air reaches 400^0C, and at that point, air from the storage tank is injected into the combustion chamber. The compressed air is stored in carbon fibre tanks at 30 MPa. Recently, the company Peugeot has developed a drive internal combustion engine with a hydraulic system driven by compressed air under the name Peugeot 2008 Hybrid Air [18]. This solution continues to include the concept of the engine powered only with air or the two drive units. The proposed solution is also unique in the world because it includes a combustion engine and air in one drive unit, providing a compact whole drive without having to install a complicated powertrain unit as the current hybrid structures.

Pneumo engines, as many movers of machines, are widely used on explosive places, chemical stores, shipbuilding, in small powered technical means, machine buildings and other public economy.

Engines have a small value of weight, are protected from overloading, easy in construction, cheap for operation, also do not need additional costs on fuel and electrical energy.

These types of engines operate condensed air and do not need additional resources. One of the disadvantages may be considered the fact, that the bottle for storing the condensed air is big, use of pneumatic engines is possible from 3 to 50 kwt power with 75000rpm frequency, either in portable or in stationary equipment.

For small farms it became actual to use pneumo engines with power of 2 to 6 kwt in small mechanical means.

Nowadays pneumo engines are either piston, rotationary, rotational, gear and turbine type. In comparison with other pneumo engines, gear pneumo engines have simple and reliable construction, although they have comparatively large weight and shape.

Piston pneumo engines have alternative rotating sequency, than gear pneumo engines, although such types of engines are selected by large power, which depends on tightness of the piston fingers. Turbine pneumo engines are widely spread in machine building, especially in washing machines, screwdrivers and in those machines, which have large rotating value in case of low rotation. The advantage of rotational pneumo engines is that they have small mars, simple construction and value of the widening factor.

Literature Review

Compressed air energy storage is a promising technology with the advantages of zero pollution, long lifetime, low maintenance, and minimal environmental impact. However, compressed air energy storage has some disadvantages, such as low efficiency and low energy density [1]. A parallel operation mode of pneumatic motor is proposed in this study to improve the power performance, energy conversion efficiency, and economy of compressed air energy storage system. First, the test bench of compressed air energy storage system is established. Then, the influence of key parameters, such as current, rotating speed, and regulated pressure, on the output performance of compressed air energy storage system is investigated in this study. Afterward, the interaction among volume flow rate, rotating speed, torque, output power of pneumatic motor, and the current, voltage, and output power of the generator, as well their influence on one another, are discussed. Finally, the output performances of compressed air energy storage system when the pneumatic motor works alone and in parallel are compared and analyzed. The experimental results show that the power performance, energy conversion efficiency, and economy of compressed air energy storage system can be improved when the pneumatic motor works in parallel operation mode. The minimum compressed air consumption rate is 0.1369 g.

It has been studied that pneumatic motors have many advantages over electric motors, which are commonly used in robotics and automation [2]. However, the control efficiency of air motors is very unsatisfactory, mainly due to air compression. The paper proposes the development of a hybrid pneumatic motor together with an electric motor.

has been studied, the performance of hydraulic and pneumatic motors, and electric AC servo and DC motors has been calculated, surveyed, and evaluated on the basis of specifications listed for them in current catalogs and nonpublic data [3]. Was selected 765 different kinds of electric motors and 404 different kinds of fluid power motors available in the market. Power density, torque–inertia ratio, power rate, and power rate density were selected as the performance indexes for comparison. Rated power and torque were found to be nearly proportional to motor mass and moment of inertia, respectively. The electromagnetic motors have developed high performance with large rated torque and a smaller moment of inertia. The newly developed small-size hydraulic motor was also included in the performance index, and its characteristics were plotted. The compact size of fluid power actuators has great potential for power rating or quick response.

Has been studied a new type of pneumatic motor, a pneumatic step motor (PneuStep). Directional rotary motion of discrete displacement is achieved by sequentially pressurizing the three ports of the motor. Pulsed pressure waves are generated by a remote pneumatic distributor [4]. The motor assembly includes a motor, gearhead, and incremental position encoder in a compact, central bore construction. A special electronic driver is used to control the new motor with electric stepper indexers and standard motion control cards. The motor accepts open-loop step operation as well as closed-loop control with position feedback from the enclosed sensor. A special control feature is implemented to adapt classic control algorithms to the new motor, and is experimentally validated. The speed performance of the motor degrades with the length of the pneumatic hoses between the distributor and motor. Experimental results are presented to reveal this behavior and set the expectation level. Nevertheless, the stepper achieves easily controllable precise motion unlike other pneumatic motors. The motor was designed to be compatible with magnetic resonance medical imaging equipment, for actuating an image-guided intervention robot, for medical applications. For this reason, the motors were entirely made of nonmagnetic and dielectric materials such as plastics, ceramics, and rubbers. Encoding was performed with fiber optics, so that the motors are electricity free, exclusively using pressure and light. PneuStep is readily applicable to other pneumatic or hydraulic precision-motion applications.

Has been discussed into the modeling and control of the low speed of an air motor incorporating a pneumatic equivalent of the electric H-bridge. The pneumatic H-bridge has been devised for speed and direction control of the motor. The system is divided into three main regions of low, medium and high speed. The system is highly nonlinear in the lowspeed region and hence a controller with an ability of intelligence, such as a neuro model and controller, is proposed [5].

has been discussed a design of a control system of a rotary pneumatic motor. Is describedlinearization of control by two different ways. The first method is linearization using inverse approximation of a static characteristic. The second method employs creating a linearization element using neural networks [6].

Has been studied calculations of the parameters of rotary air motors, focuses on the mathematical model of air motor using Matlab Simulink-Simscape and concludes with the comparison of the results of the experiment and a the mathematical model [7].

Has been studied a mathematical model and the results of simulation calculations of piston pneumatic motor. Mathematical model was based on the fundamental principles of mechanics, thermodynamics and rights of airflow. For simulation model parameterization, prototype of such engine was built and installed on dedicated test stand. Performed experimental research allowed achieving values of coefficients and components characteristics used for model estimation[47]. One of the important tasks of this study was to create the control system of the compressed-air supplied engine. For this purpose an appropriate pneumatic and electronic component were selected and also an algorithm was created which would facilitate changing of the engine settings in order to obtain the best performance. Using elaborated simulation model, series of calculation were performed for different parameters of pneumatic motor, like cylinders diameter and stroke, length of the crank, compressed air pressure and valves size. A lot of attention was devoted to determine the influence of control system settings, such as valves opening and closing in reaction to crankshaft position, on motor properties. When discussing the results of calculations considerable attention was paid to the power, torque and efficiency values. To illustrate performance of designed engine, simplified model of light vehicle was used to calculate possible to achieve acceleration, velocity and travel distance [47].

2. Materials and Methods

While calculating the rotational engines, it is necessary to define the operating process in operating chamber while one turning back.

For decision of this item it is enough to consider following:

1. To study the pressing of air on operating wings (vanes) during one operating cycle.
2. To calculate the volume of the operating chamber during one cycle of air.
3. To define the meaning of active rotating moment on the rotor during one period of cycle.
4. Investigate the number of the rotation of the engine and the power during effective operation.

Three methods from above mentioned are defined by the means of differential equation.

$$dA_i = P_i dV \tag{1}$$

where: dA_i - There is a basic workflow,

P_i - by exposure to cut gas, but dV is the volume variation during the cycle.

The process of gas expansion is defined by two processes: isometric and polytropic [7]

The isometric process is defined by the equation:

$$A_i = 2{,}2\, V_1 P_1 lg \frac{V_2}{V_1} \tag{2}$$

and the polytropic process is defined by:

$$A_2 = \frac{V_1 P_1}{n-1}\left[1 - \left(\frac{V_2}{V_1}\right)^{1-n}\right] \tag{3}$$

Where: n - is the indicator of the polytrope, while $V_1 P_1$ - In the initial period of expansion of pressure and volume values. V_2 - Amount of air during the expansion process.

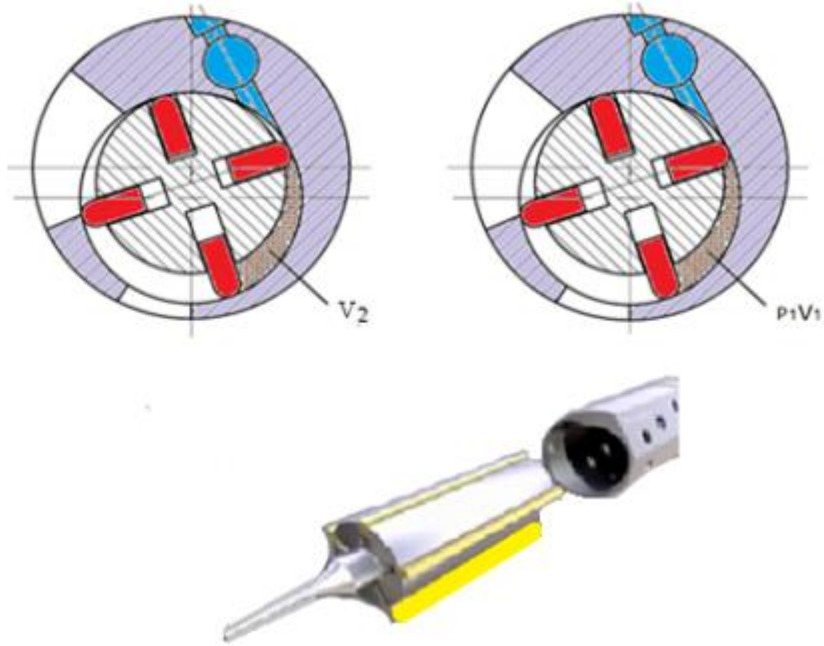

Fig.1. *Pneumatic motor*

We can compare these works by the equation:

$$\frac{A_1}{A_2} = \frac{2{,}2(n-1)log\frac{V_2}{V_1}}{1-\left(\frac{V_2}{V_1}\right)^{1-n}} \tag{4}$$

Let's introduce the mark:

$$\frac{V_2}{V_1} = \lambda \tag{5}$$

Then the formula will take the form:

$$\frac{A_1}{A_2} = \frac{2{,}2(n-1)log\lambda}{1-\lambda^{1-n}} \tag{6}$$

This formula indicates that the working process of the engine depends on the coefficient of expansion λ.
Researches have established that [1] In piston pneumatic engines, it is taken as equal to 1.3 and in rotary engines equal to 1.25. If we consider that the effect of heat generated during the operation of the wings creates resistance in the working chamber, it is possible to assume that λ=1.6

$$\frac{A_1}{A_2} = 1{,}02 \tag{7}$$

It can be said that the difference in air expansion during changes of polytrope up to 1-1.25 do not exceed 3.2 percent.

To determine the working process of the wings, we can get the following assumptions:
1. The meaning of pressure while inlet and outlet is of constant value;
2. Changing of pressure while receiving and opening the exhaust windows;
3. Air temperature in chamber and network temperature are the same in fact;

4. Cap between the rotor is enough for moving the outside evaporated step up, air is condensed in engines condense cycle;
5. Loses of friction may be reached only by motion of the roars toward the rotor, but the lost of friction while motion of roars may be considered equal to zero;
6. The value of the pressure during the inlet and outlet is constant;
7. Variation of pressure during the opening of intake and exhaust windows;
8. The air temperature in the chamber and the temperature in the network are actually the same;
9. The gap between the rotor and the stator is sufficient to allow the exhaust to rise upwards, and the air is compressed by the motor in the compression cycle.
10. Friction losses are achieved only by the movement of the paddle blades relative to the rotor, and during the movement of the paddles, the friction loss can be considered zero.

After assuming it it's possible to calculate main parameters of the pneumoengine while installing the engine on the splasher. [1] It is necessary to calculate the engine power - N kwt, the value of inlet pressure P_1, amount of roars Z, angle values while intel and outlet phases φ_0, φ_1.

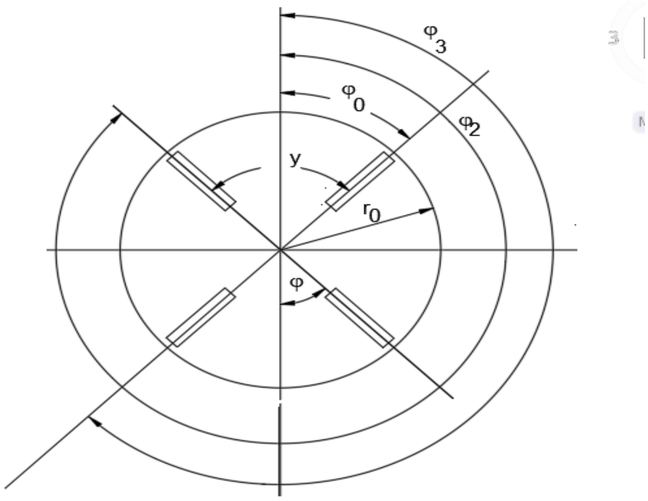

Fig.2. *Pneumatic motor scheme*

The angle between the blades is determined by the equation

$$y = \frac{2\pi}{Z} \tag{8}$$

According to this equation angle while intel time will be:

$$\varphi_0 = \frac{1}{3}y \tag{9}$$

And the angle for the end of the inlet zone will be:

$$360^0 - \varphi_2 \tag{10}$$

where φ_2 is the magnitude of the angle while driving out will be.
At the end of the entry, the angle will be:

$$360^0 - \varphi_2 = 0{,}7y = 65^0 \tag{11}$$

Characteristic of the expansion will be calculated by the equation:

$$\lambda = \frac{C_2}{C_1}, \tag{12}$$

where, C_1 and C_2 are coefficients and according the research [14]

$$C_1 = \frac{1}{a^2}\left[y(a+0{,}5) - 2(a+1)cos\left(\varphi_0 + \frac{\lambda}{2}\right)sin\frac{y}{2} + \frac{1}{2}cos(2\varphi_0 + y)\right] \quad (13)$$

$$C_2 = \frac{1}{a^2}\left[y(a+0{,}5) - 2(a+1)cos\left(\varphi_1 + \frac{\lambda}{2}\right)sin\frac{y}{2} + \frac{1}{2}cos(2\varphi_1 - y)siny\right] \quad (14)$$

$$a = 5 \div 8$$

The radius of the rotor is calculated by the equation:

$$r_0 = \sqrt{\frac{N}{BK_1}} \quad (15)$$

B – coefficient is approximately equal:

$$B = 10^{-6}70{,}4\frac{1}{a_3}k_b q\sigma\eta\left[(a+1)^2 - (a+1)\frac{q}{2}\right] \quad (16)$$

where, roar height – k_b, compactness of a roar – σ, the amount of the coefficient of loss – η.
Length of the rotor is calculated by the equation:

$$l = k_i r_0 \quad (17)$$

And of last the of rotor:

$$r = \frac{a+1}{a}r_0 \quad (18)$$

Sizes of a roar are calculated by the equation:
Height - $h = eq$, and width - $b = k_b r_0$,
Frequency of the motor rotation

$$n = \sqrt{\frac{c_1\left[P - \left(3 - \frac{1-k_y}{1+k_y}\right)\Delta P\right] - c_2 P_0}{3b}} \quad (19)$$

where c_1 and c_2 are appropriate coefficients.
Engine power:

$$N = c_z z\, n \frac{lr_0^2}{60{,}01\cdot 10^4}\,(c_1 P_1 - c_2 P_2 - B r_0^2 n^2)\,\eta \quad (20)$$

rotating moment is calculated by the equation:

$$M = 974 \cdot 10^2 \frac{N}{n} \quad (21)$$

Occupied number of air in the engine is calculated by the equation:

$$Q = 10^{-6}c_1 c_2(1 + k_y) l r_0^2 z n P_1 \quad (22)$$

Air value in the working chamber occupied between the rotor and the stator is calculated by the equation

$$S_0 = xl \quad (23)$$

where x – is the height of the chamber and $x = k_x r_o$, k_x- is the height of the oar, and if we take in account that $\varphi = \varphi_0$, then

$$k_x = \frac{1}{a}\left[\sqrt{(a+1)^2 - sin^2\varphi_0} - cos\varphi_0\right] - 1 \tag{24}$$

or

$$x = k_x r_o\ , S_0 = xl \tag{25}$$

belonging hole for air

$$d = \frac{x}{\frac{k_S}{\sqrt{7+2sin\alpha+7sin^2\alpha}} + \frac{tg\psi}{2sin\alpha}} \tag{26}$$

where: α - is the bending angle of air 60^0,
and $sin\psi = \frac{e}{r} sin\varphi_0,\ \psi = arcsin\frac{l}{r} sin\varphi_o$
coefficient $k_s = 1{,}7$, the occupied air surface will be

$$S = \frac{\pi r^2}{4} \tag{27}$$

number of holes

$$n = \frac{S_0}{S} \tag{28}$$

3. Results and Discussion

Experimental equipment of the portable splasher consists of the following main parts: portable glass (1), pneumobottle (2), pneumomotor (3), pump (4), pressure adjustment (5), reservuar (6), splashing equipment (7).

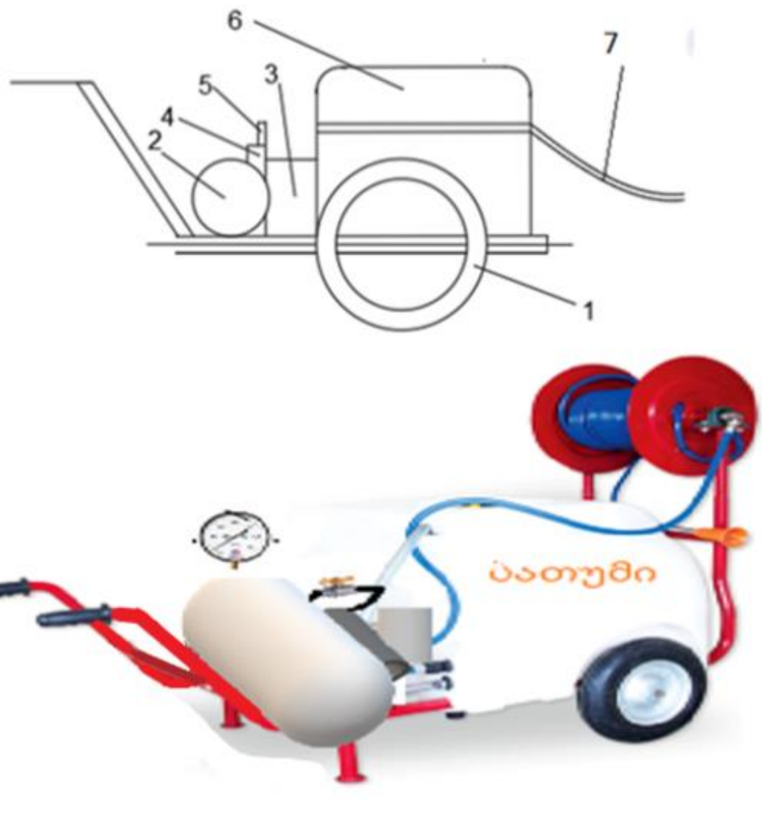

Fig.3. *Portable spayer*
1. Rubber tire, 2. Rubber pneumoballon, 3. Pneumomotor, 4. Pump, 5. Adjustment of pressure 6. Reseryar, 7. fluid tube.

For searching the motor we used the following devices by the following scheme:

1. Rubber pneumoballoon; 2, 5. Manometer. 3. Adjustment of pressure. 4. Pneumomotor. 6. Measurement of noise UT 353.

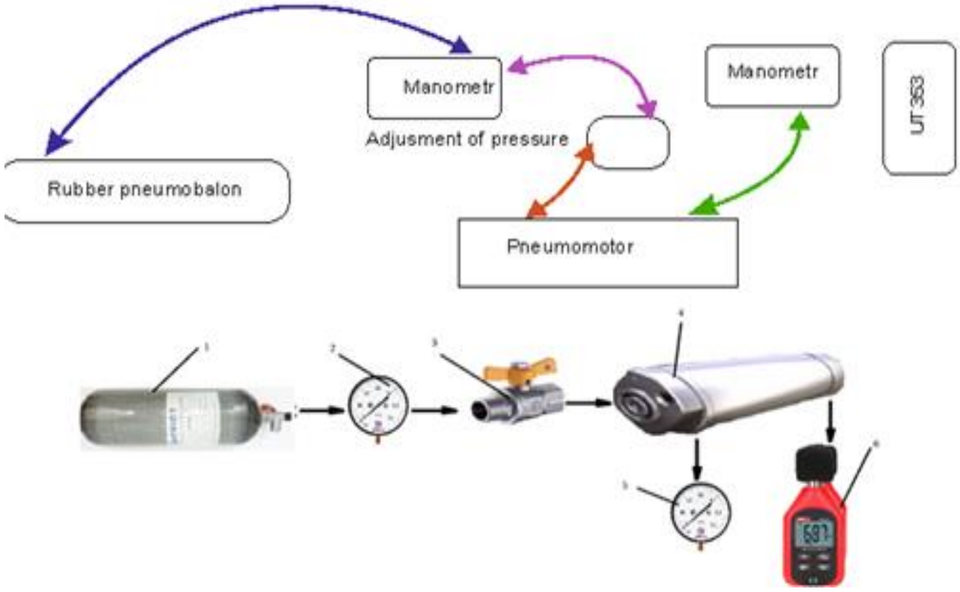

Fig.4. *Toolsand equipment used*

The experiment was held in different case of the motor rotation and we got the following data (readings) in the form of.

Table 1. Engine parametr values at different speeds

Engine rotation meaning n (rot/sec)	Engine power (vt)	Turning point n.m	Air cost l/min	The speed of the air entering the engine m/sec	pressure drop (Pa)	Pressure indicator during spraying (Pa)	system noise (db)
15	560,2	0,725	140	21,5	6820	8,5	85
16,6	689,8	0,623	138	20,3	6720	9,4	84
33,3	1,20	0,423	131	18,2	6020	9,8	80
50	1,42	0,470	143	21,2	7125	9,9	85
66,6	1,470	0,320	156	23,2	8790	10,1	88
83,3	1,220	0,229	170	25,8	10700	10,15	97
91,6	1,200	0,212	180	26,7	11600	10,18	103
100	1,265	0,105	191	28,2	12500	10,19	106
108,3	1,257	0,90	199	29,5	13910	10,20	108

As the result of the experiment we got the dependence of the number of motor rotation to the meaning of the power and noise.

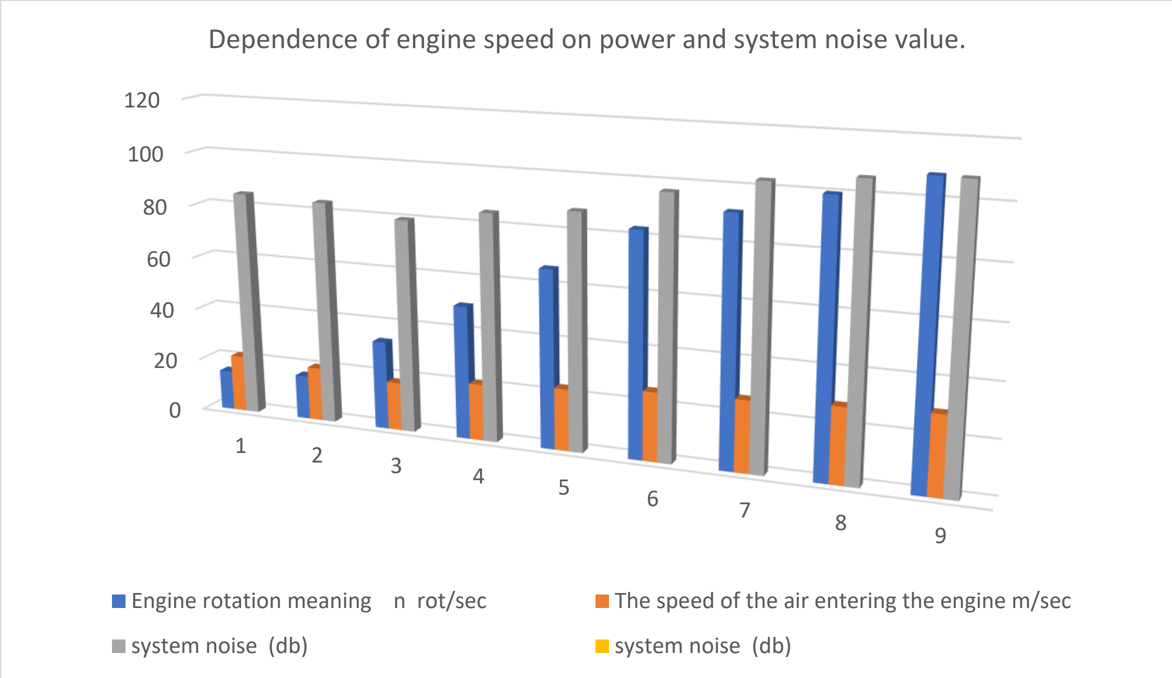

Fig.5. *Dependence of engine speed on power and value of the system noise*

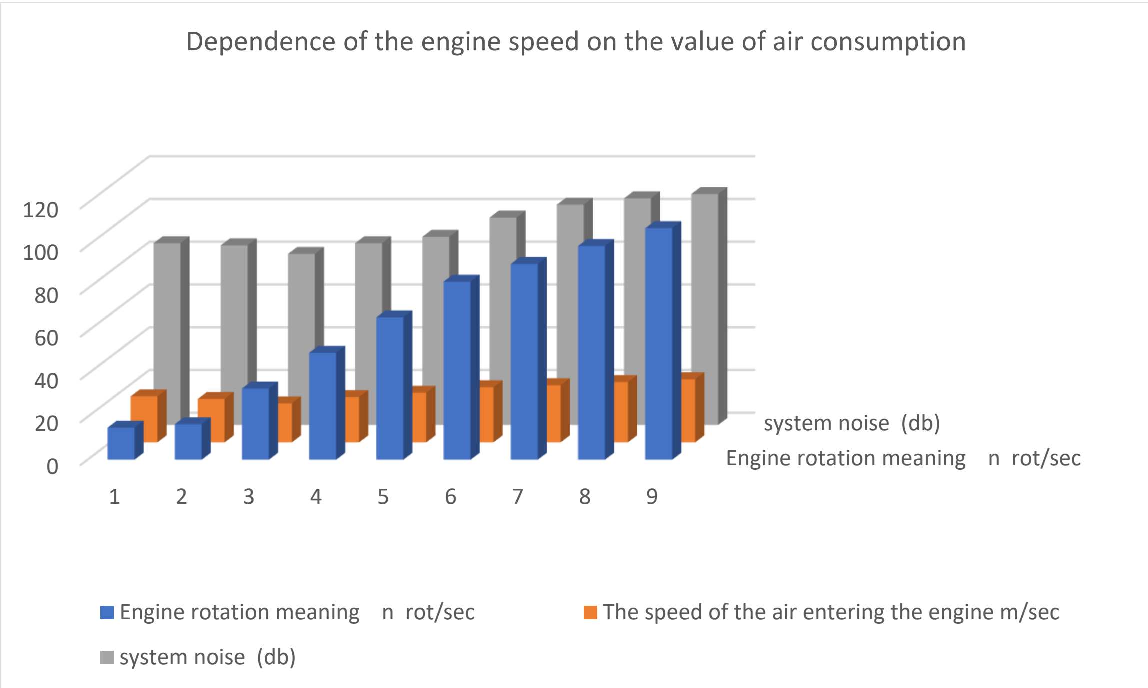

Fig. 6 *Dependence of the engine speed on the value of air consumption*

As the result of the experiment, we took the readings of the motor by the following meanings
- Engine power 1 KWT
- value of pressure in pipe conductors 0,8 MPA
- consumption of air 143 l/minute
- frequency of the motor rotation 41,6 rotation/sec=2500rotation/min

Rubber pneumoballoon data is calculated by the equation:

$$P_1V_1 = P_2V_2 \quad (29)$$

Where P_1 is the pressure of the balloon (500 atmospherec=50 MPA), V_1 is the capacity of the bottle (80 Litre =0.08m^3) P_2 atmospheric pressure, V_2 incase of normal atmospheric pressual the capacity of air from the given aquation.

$$V_2 = \frac{P_1 V_1}{P_2} = \frac{50 \cdot 10^6 \cdot 0{,}08}{101325} = 24{,}6 m^3 \tag{30}$$

time of Rubber pneumoballoon operation will be

$$t = \frac{V_2}{Q} = \frac{24{,}6}{0{,}5} = 29{,}2 \text{ min} \tag{31}$$

4. Conclusions

Pneumo engines, as many movers of machines, are widely used on explosive places, chemical stores, shipbuilding, in small powered technical means, machine buildings and other public economy.

Engines have a small value of weight, are protected from overloading, easy in construction, cheap for operation, also do not need additional costs on fuel and electrical energy.

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In the scientific wort the ability of the use of the pneumatic engines in agriculture is discussed. By the experimental research method we have worked on the ability of the use of the pneumatic engines in portable, or stationary splashers. Mathematic modeling and its main characteristics are calculated:

1 the engine power of 1 kwt;
2 kwt, medium pressure in conducting pipes 0.8 MPA;
3 air consumption 143 l/min;
4 freguency2500 rot/min;
5 of the splasher capacity of airbottles 24,3 m^3;
6 the rotating moment of the engine 0.4 nm.

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REFERENCES

1. Yonghong Xu, Hongguang Zhang, Fubin Yang, Liang Tong, Dong Yan, Yifan Yang, Yan Wang, Yuting Wu- Performance of compressed air energy storage system under parallel operation mode of pneumatic motor, Renewable Energy, Volume 200, November 2022, Pages 185-217
2. F. Takemura; S.R. Pandian; Y. Nagase; H. Mizutani; Y. Hayakawa; S. Kawamura Control of a hybrid pneumatic/electric motor IEEE/RSJ International Conference on Intelligent Robots and Systems, Japan 2002.
3. Yutaka Tanaka, Sayako Sakama, Kazuo Nakano, Hiroshi Kosodo Comparative Study on Dynamic Characteristics of Hydraulic, Pneumatic and Electric Motors ASME/BATH 2013 Symposium on Fluid Power and Motion Control. USA 2013.
4. Dumitru Mazilu; Louis Kavoussi, Alexandru Patriciu; Doru Petrisor-New Type of Motor: Pneumatic Step Motor IEEE/ASME Transactions on Mechatronics (Volume: 12, Issue: 1, February 2007).
5. O.M. Tokhi, R. Marumo- Intelligent modeling and control of a pneumatic motor, Canadian Conference on Electrical and Computer Engineering Niagara Falls, ON, Canada 2004

6. R. Votrubec and M. Vavroušek, "Control system of a rotary pneumatic motor*," Proceedings of the 16th International Conference on Mechatronics - Mechatronika 2014,* Brno, Czech Republic, 2014, pp. 588-593, doi: 10.1109/MECHATRONIKA.2014.7018325.
7. Lukasz Dvorak, Kamil Foytaszek and Vojtech Rzehaczek- Calculations of parameters and mathematical model of rotary air motor, Technical University of Ostrava, Faculty of Mechanical Engineering, Czech Republic 2017.
8. Lavy J, Angelberger C. Towards a better understanding of controlled auto-ignition (CAI) combustion process from 2-stroke engine results analyses; 2001; SAE Paper 2001 01 1859/4276
9. Onishi S, Hong Jo S, Do Jo S, Kato S. Active thermo-atmosphere combustion (A.T.A.C.)— A new combustion process for internal combustion engines; 1979; SAE Paper 790501
10. http://www.douglas-self.com/MUSEUM/LOCOLOCO/airloco/airloco.htm#pars
11. Cai ML, Kawashima K, Kagawa T. Power assessment of flowing compressed air. Journal of Fluids Engineering. 2006;128:402-405
12. Chen Y, Liu H, Tao G. Simulation on the port timing of an air-powered engine. Interna- tional Journal of Vehicle Design. 2005;38:259-273
13. Chen P, Yu X, Liu L. Simulation and experimental study of electro-pneumatic valve used in air-powered engine. Journal of Zhejiang University Science A. 2009;10:377-383. DOI: 10.1631/jzus.A0820373
14. Creutzig F, Papson A, Schipper L, Kammen DM. Economic and environmental evalua- tion of compressed-air cars. Environmental Research Letters. 2009;4:044011 (9pp). DOI: 10.1088/1748-9326/4/4/044011
15. Papson A, Creutzig F, Schipper L. Compressed air vehicles: Drive-cycle analysis of vehicle performance, environmental impacts, and economic costs. Transportation Research Record Journal of the Transportation Research Board. 2010;2191:67-74. DOI: 10.1088/1748-9326/4/4/044011
16. Huang KD, Tzeng SC. Development of a hybrid pneumatic-power vehicle. Applied Energy. 2005;80:47-59. Available from:www.elsevier.com/locate/apenergy
17. Chen H, Ding Y, Li Y, Zhang X, Tan C. Air fuelled zero emission road transportation: A comparative study. Applied Energy. 2011;88:337-342
18. Huang KD, Tzeng SC, Ma WP, Chang WC. Hybrid pneumatic-power system which recycles exhaust gas of an internal-combustion engine. Applied Energy. 2005;82:117-132
19. Huang Ch, Hu Ch, Chih-Jie Yu Ch, Sung Ch. Experimental investigation on the perfor- mance of a compressed-air driven piston engine. Energies. 2013;6:1731-1745; DOI: 10.3390/en6031731
20. Yu Q, Cai M. Experimental analysis of a compressed air engines. Journal of Flow Control Measurement & Visualization. 2015;3:144-153. http://dx.doi.org/10.4236/jfcmv.2015.34014
21. Shen YT, Hwang YR. Design and implementation of an air-powered motorcycles. Applied Energy. 2009;86:1105-1110
22. Wang YW, You JJ, Sung CK, Huang CY. The Applications of piston type compressed air engines on motor vehicles. Procedia Engineering. 2014;79:61-65
23. MDI (Moteur Development International) Available from: http://www.mdi.lu/english/ 2014%20english.php
24. http://www.themotorreport.com.au/5732/tata-air-car-powered-entirely-by-compressed- air-blow-me-down
25. L. Dvorac, K. Fojtasck, V. Rechacek- Calculations of parametrs and mathematical moled of rotory air motor. EPJ web of Conference 143. EPM 2016
26. R. Vortubce, M. Navrouck- Control system of a rotary pneumatic motop. Proceeding of the 16 th International Conference of Mechatronies. Czech Republic -2014
27. L. Dvorac, K. Fojtasck, V. Rechacek- Experimental equipement for measuring of rrotary air motors parametrs EPJ web of Conference 143. EPM 2017
28. T. Pcter- Application Possibilities of Rotary Pneumatic Driver using- American journal of Mechanikal injineering. 2015. Vol.3, N 6, 275-280 p.
29. B. Rouzben, M. Bone, G. Ashby – JEE/ASME Transaction on Mechatronic. Volume 23, ISSUE. 6. 2018. 2774-2781 p.
30. S. Zelensky, E. Rjbkov- Rotary Pneumatic Motors- Russia, Leningrad 1976
31. C. Mixailov- Modeling your and Calculation of Rotational pneumatic Actuators of Technical Machines. Tula-2017
32. Lukáš Dvořák, Kamil Fojtášek - Experimental equipment for measuring of rotary air motors parameters**,** The European Physical Journal Conferences 143:02019, January 2017
33. P.Tuleja. Application Possibilities of Rotary Pneumatic Drives Using. American Journal of Mechanical Engineering, Vol. 3, No. 6, 2015, pp 275-280.
34. Sliding vane Air Motor Market by Offering. Applicationg and End-user industry – Global Opportunity Analysis and Industry Forecast 2018 2025. // Allied Market Research. Aug. 2018. -233 p.
35. Imran M. et al. Volumetric expanders for low grade heat and waste heat recovery applications. // Renewable and Sustainable Energy Reviews. 2016, V.57, p. 1090 – 1109.
36. Montenegro G. et al. Evaluating the Performance of a Rotary Vane Expander for Small Scale Organic Rankine Cycles using CFD tools. // 68- th Conference of the Italian Termal Machines Engineering Association. 2014. Energy Procedia 45, (2014) p. 1136 – 1145.

37. Liermann M. et al. Energy efficiency of pneumatic power take-off for wave energy converter. // Int. Journal of Marine Energy. 2015.
38. Beater P. Modelling and Control of Pneumatic Vane Motors. // Int. Journal of Fluid Power. 2004, vol. 5, №1, pp. 7 – 16.
39. Luo X., Wang J., Spanin L. Development of a Mathematical Model for Vane-type Air Motors with Arbitrary N vanes. // Proc. of the world Congress on Engineering. 2008, V.1, London, pp. 362 – 367.
40. Merkelboch S., Mas I., Murrenhoff H. Mathematical Modeling of pneumatic vane motor in Matlab/Simulink. // The 10-th IFPS Int. Symp. Of Fluid Power. 2017, oct. 24-27, Fukuoka, Japan, pp. 2B20; 1 – 10.
41. Bianchi G., et al. Deforming grid generation for numerical simulations of fluid dynamics in sliding vane rotary machines. // Advaces in Engineering Software. 2017, (112), pp. 180 – 191.
42. Bianchi G., Cipollone R. Friction power modeling and measurements in sliding vane rotary compressors. // Applied Thermal Engineering. 2015, (84), pp. 276 – 285.
43. Fatigati F., Bianchi G., Cipollone R. Development and numerical modelling of superchargine technique for positive displacement expanders. // Applied Thermal Engineering. 2018, (140), pp. 206 – 216.
44. Beskok A., Karniadakis G., Trimmer W. Rarefaction and Compressibility in Gas Microflows // Journal of Fluids Engineering. 1996, v.118, pp. 448 – 456.
45. Beater P. Pneumatic Drives. System design, modelling and control. Springer. Germany. -2007. -323 p. Vladimir I. Ivlev et al. / Procedia Computer Science 190 (2021) 377–387 387 V.I. Ivlev / Procedia Computer Science 00 (2019) 000–000 11
46. Wang J. et al. Identification of Pneumatic Cylinder Friction Parameters Using Genetic Algorithms. // IEEE/ASME Transactions on Mechatronics. 2004, V.9, №1, pp. 100 -107.
47. Flis K. , Pobędza J. Simulation of pneumatic motor used in pneumobile, Journal of KONES Vol. 21, No. 3 Poland 2014