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Pneumatic Hybrid Power Plants Efficiency

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Abstract: ***Tightening environmental requirements and rising fuel prices are forcing developers to look for ways to improve the efficiency of vehicle engines. The use of a combined power plant with more than one energy source is the most efficient. Therefore, there is a need to improve the efficiency of pneumatic hybrid power plants by utilizing thermal energy emitted into the atmosphere with exhaust gases and energy removed from the cooling system of an internal combustion engine.***

One of the possible systems for using the heat of an internal combustion engine exhaust gases is the combined power pneumatic with separate gas flows which is a piston pneumatic motor with internal heat supply. The pneumatic motor with internal heat supply is based on the PD-10U (ПД-10У) two-stroke starting engine, from which the standard fuel and ignition systems were dismantled. A crankshaft driven pneumatic valve is mounted on the cylinder head.

During the research work the polynomial equation was obtained. It allows to assess qualitatively and quantitatively the influence on the effective power, generated by the pneumatic engine, of the compressed air supply system adjusting parameters, cylinder walls temperatures, as well as the temperatures of exhaust gases, entering the cylinder from internal combustion engine.

Index Terms: ***compressed air, compressor, exhaust gases, heat storage unit, heat, hybrid power plant, internal combustion engine, pneumatic motor.***

I. INTRODUCTION

Nowadays the civilization can't do without vehicles. The mankind got used to move on long distances. These mass movements lead to increase in number of vehicles and, as a result, growth of toxic substances emissions in environment. Concentration of people in the cities leads to increase in number of vehicles in limited territories. At the same time mass media allow citizens to become more informed on influence of environmental pollution and climate. The society toughens standards of vehicles exhaust gases (EG) emissions provoking climate change [1]-[4]. Ecological requirements and increase of fuel prices make developers search the alternative vehicles with smaller impact on environment [5]. Today there are some decisions for decrease in quantity and toxicity of the exhaust gases and increase of fuel economy. One are well-known, and others still are in development. Examples of such decisions are VVA (Variable Valve Actuation - a control system of gas distribution phases), EGR (Exhaust Gas Recirculation), direct injection, hybridization of vehicles and others [6], [7]. The most effective is the use of the combined power plant having more than one power source, i.e., the so-called hybrid power plant.

II. LITERATURE REVIEW

Transport hybridization can be executed in various ways. The most known example of the vehicles hybrid power plant is the electric hybrid (Fig. 1) [8].

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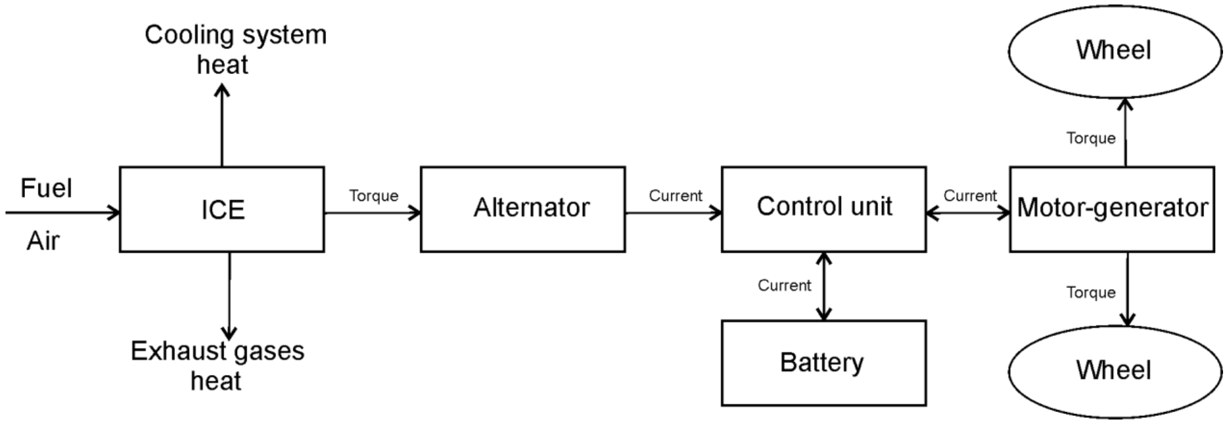

Fig. 1. Electric hybrid power plant

However other hybrids, such as hydraulic ones [9], fuel elements, flywheels and pneumatic hybrids are developed now. The main idea of electric hybridization consists in reduction of fuel consumption due to recirculation of the lost brake energy. Hybrid work also allows the internal combustion engine (ICE) to function in the most optimum working point in respect of load and speed. Today almost each car producer works on an electric hybrid prototype and some already have a product in the market [10]. Electric hybrids provide impressive decrease in fuel consumption (60% less in comparison with the ordinary cars working at gasoline). The main electric hybrids' disadvantage is that they demand an additional electric energy source and big heavy batteries with limited lifetime. It leads to additional production expenses which are compensated by the final products higher price, comparable with the price of hi-tech cars. However it is necessary to remember that the price will fall in process of increase in hybrid cars sales volume.

One of the ways of smaller additional cost preservation and, therefore, of appeal to buyers increase is the pneumatic hybrid power plants use (Fig. 2).

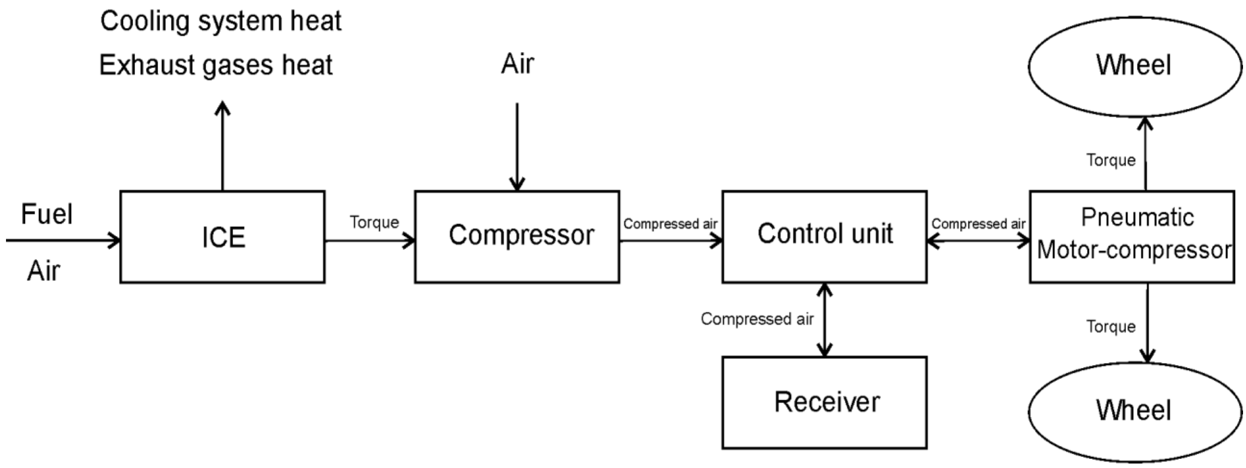

Fig. 2. Pneumatic hybrid power plant

It works similarly to the electric hybrid [11]-[13]. During the slowing down of the car the pneumatic motor is used as the compressor which transforms the moving vehicle kinetic energy to energy in the form of the compressed air stored under pressure in the receiver. For the movement the compressed air passing under pressure from the receiver to the pneumatic motor is used. Its quantity is controlled by the control unit.

One of the major factors, allowing to judge efficiency of some type of power plant, is its performance factor.

Modern gasoline engines working in steady-state mode have performance factor $\boldsymbol{\eta_g = 0,30\ldots0,35}$, and diesel ones –$\boldsymbol{\eta_d = 0,35\ldots0,45}$. One of the reasons of piston engines low efficiency are the considerable losses of heat, generated in engine cylinders by fuel oxidation thermochemical reactions, with the exhaust gases $\boldsymbol{Q_{eg}}$. Other reason consists in the heat transfer by the cooling system for increase of the engine parts resources $\boldsymbol{Q_{cs}}$. The percentage of these losses ($\boldsymbol{Q_{hl} = Q_{eg} + Q_{cs}}$) reaches 50% of all heat, received from combustion of fuel [6].

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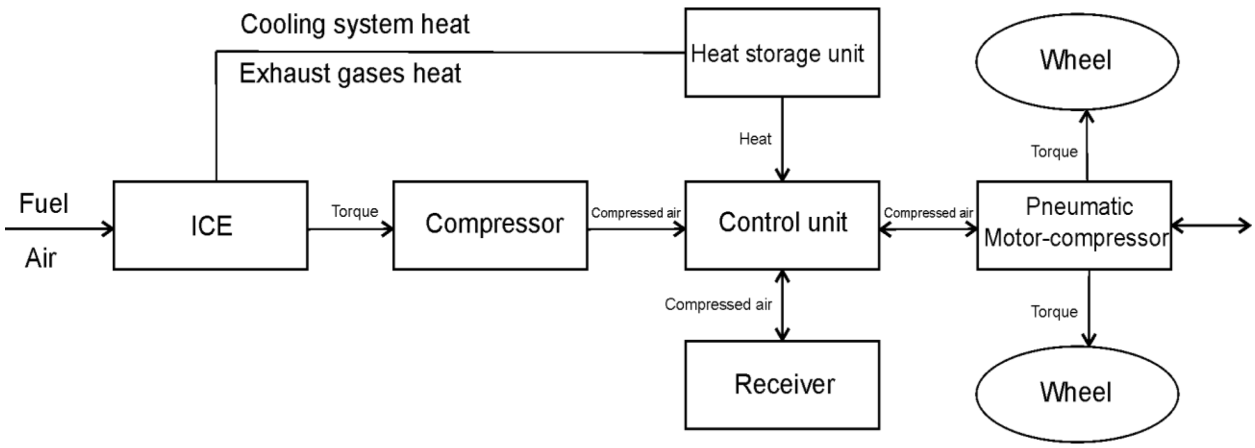

Fig. 3. Pneumatic hybrid power unit with heat storage unit

The use of an internal combustion engine thermal energy which, because of its difficult transformation in the electric one, on electric hybrids is released into the atmosphere by the cooling system and exhaust gases allows raising the pneumatic hybrid power plant economic and environmental performance. Because of an unstable heat flow of exhaust gases and the cooling system from the moment of engine start to its stop it is stabilized it in the heat storage unit (Fig. 3) [14], [15].

III. PROPOSED METHODOLOGY

A. General description

In order to improve the efficiency of pneumatic hybrid power plants efficiency by using heat of internal combustion engine cooling system and exhaust gases, the authors of the article carried out theoretical studies, developed a combined power plant with separated gas flows, conducted a series of experiments and processed experimental data (Table I).

B. Algorithm

After theoretical research, the combined power plant with separate gas flows which is a piston pneumatic motor with internal heat supply was developed.

The preliminary stage of experimental research was to determine the proposed device's workability.

The tests were carried out in the following sequence:

- Start and operation of the pneumatic motor at operating pressure;

- Determination of the pneumatic motor external speed characteristics.

Then an experiment was conducted to determine the influence of various factors on the device effective power.

When planning this experiment, the task was to define a mathematical model in the form of a second-order equation that adequately describes the change in the device effective power as a function of five factors. To determine the control coefficients, the Hartley's experimental hypercube plan was implemented.

According to the experiment plan, 27 experiments were conducted. To eliminate random errors, each experiment was performed three times. To reduce systematic errors, experiments were performed in a random order using a random numbers table.

During the processing of experimental data, after testing the dispersion homogeneity hypothesis (Cochran's C test was used for this, taking the significance level $\boldsymbol{q = 5\%}$, the degrees of freedom number $\boldsymbol{V_1 = m - 1 = 2}$ and $\boldsymbol{V_2 = N = 27}$), the reproducibility dispersion and mean square experimental error were determined by the known formulas.

The regression equations coefficients were calculated using the formulas for second-order plans. After calculating the coefficients, they were checked for statistical significance using Student's t-test. In order to exclude the statistically insignificant coefficients, a sequential regression analysis was performed.

The adequacy of the model was tested using the Fisher's ratio test. To test the model adequacy hypothesis, the significance level was set to $q = 5\%$, the degrees of freedom number $V_1 = N - 1$ and $V_2 = N(m - 1)$.

C. Flow chart

Table I. Research algorithm

№	Name of the research phase
1	Theoretical research
2	Development of a combined power plant
3	Experimental studies
3.1	Preliminary stage. Determination of device workability
3.2	Determination of the influence of various factors on the device effective power
3.3	Experimental data processing

IV. RESULT ANALYSIS

A. Theoretical research

Analysis of the pneumatic engines parameters dependence on the compressed air temperature shows that the specific energy (e) represents the change in the total specific air (gas) energy at the air inlet and outlet of the pneumatic motor [16]. To estimate the specific energy of air in the isothermal and adiabatic processes of air expansion in a pneumatic motor, the Bernoulli equation can be used [17]:

$$e_{is} = \left(\frac{\alpha_1 v_1^2}{2} + 2{,}3\frac{P_1}{\rho_1} lg\, \rho_1 + g z_1\right) - \left(\frac{\alpha_2 v_2^2}{2} + 2{,}3\frac{P_2}{\rho_2} lg\, \rho_2 + g z_2\right); \quad (1)$$

$$e_{ad} = \left(\frac{\alpha_1 v_1^2}{2} + \frac{kP_1}{(k-1)\rho_1} + gz_1\right) - \left(\frac{\alpha_2 v_2^2}{2} + \frac{kP_2}{(k-1)\rho_2} + gz_2\right) \quad , \quad (2)$$

where $\alpha_1 and \alpha_2$ - non uniformity coefficients of gas flow rates; v_1, v_2- flow rates; P_1, P_2 - gas pressures; ρ_1, ρ_2- gas densities; z_1, z_2- geometric head in the input and output sections, respectively; k - ratio of specific heats (adiabatic index).

The specific energy of air (gas) with an isothermal process is greater than with adiabatic one. This is explained by the fact that in order to maintain the constancy of the air temperature during an isothermal expansion process, thermal energy must be supplied from the outside. Since at normal speeds of moving elements there is a slight heat transfer between the air and the walls of the pneumatic motors, their working process can be considered adiabatic with a sufficient degree of accuracy [18]. Therefore, the degree of perfection of pneumatic motors is estimated by the adiabatic efficiency η_{ad}, which is determined by the ratio of the pneumatic motor output power to its power consumption calculated by the adiabatic process.

In the process of air expansion, its temperature in the pneumatic motor decreases. According to the Clapeyron – Mendeleev equation, the following conditions are valid for the initial state of air and its final state:

$$\frac{P_1}{\rho_1} = RT_1; \frac{P_2}{\rho_2} = RT_2, \quad (3)$$

where R – gas constant; T_1 and T_2– initial and final absolute air temperatures.

Solving together these equations for the adiabatic expansion process, we find the final temperature:

$$T_2 = T_1 \frac{P_2 \rho_1}{P_1 \rho_2} = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}. \quad (4)$$

The final air temperature in pneumatic motors should not be below 0 °C (T_{2min}= 273 K), since frosting can occur. Therefore, it is necessary to increase the initial temperature at the pneumatic motor inlet.

The internal combustion engine exhaust gases and the cooling system heat is the source of heat supplied to the air and the pneumatic motor (pneumatic engine). For the accumulation and storage of thermal energy, it is necessary to use a heat storage unit (heat accumulator), the accumulated heat of which can be determined by the equation:

$$Q = mc(T_2 - T_1), \quad (5)$$

where Q – accumulated heat; m – mass of the heat carrier; c - specific heat capacity of the heat carrier.

The total energy efficiency of heat accumulators η_{HA} is equal to the ratio of the energy rejected during the discharge Q_r to the energy Q_s supplied during the charge:

$$\eta_{HA} = Q_r / Q_s. \quad (6)$$

Analysis of modern heat accumulators revealed that their efficiency is within $\eta_{HA} = 0,6 \ldots 0,8$ [15].

When recycling and subsequent accumulation of the internal combustion engine thermal energy in a heat accumulator, having on average $\eta_{TA} = 0{,}7$, thermal energy, the potential of which is up to 50% of the engine thermal capacity, is supplied to the air and to the pneumatic motor. Thus, the heat, accumulated in the heat storage unit and supplied to the compressed air and the pneumatic engine, will be up to 35% of the engine thermal capacity($Q_{HA} = 50 \cdot 0{,}7 = 35\%$.

B. Structure and operation of the device

One of the possible systems for using the heat of an internal combustion engine exhaust gases is the combined power plant with separate gas flows which is a piston pneumatic motor with internal heat supply, developed by the authors of this paper (Fig. 4).

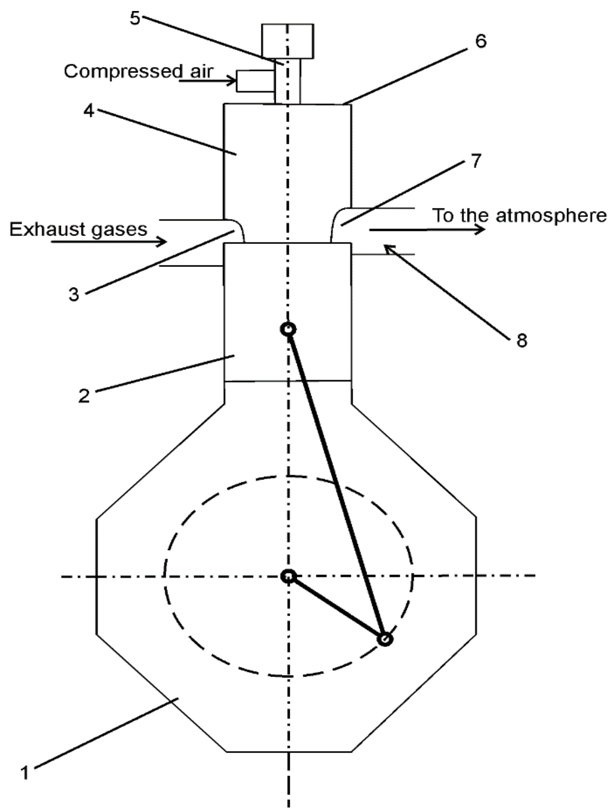

Fig.4. Schematic diagram of a piston pneumatic motor with an internal heat supply:

1 - crankcase; 2 - piston; 3 - inlet window; 4 - cylinder; 5 - pneumatic valve; 6 - head; 7 - outlet window; 8 - exhaust pipe

The pneumatic motor with internal heat supply is based on the PD-10U (ПД-10У) two-stroke starting engine, from which the standard fuel and ignition systems were dismantled [11]-[13]. A crankshaft driven pneumatic valve is mounted on the cylinder head. The base of the engine is crankcase 1. There are two windows 3 and 7 in the cylinder from the flywheel side, one of which (inlet) is connected to the exhaust pipe of the internal combustion engine (UMZ-417), and the other (exhaust) – to the exhaust pipe 8, through which the outgoing cylinder gases are released into the atmosphere.

The unit works as follows. In the cylinder of the engine, the internal combustion engine exhaust gases are compressed, and compressed air is supplied to them through the pneumatic valve. Experiments show that the temperature at the end of compression can reach 1500 ^{0}C [19], [20]. To the compressed air, the heat from the exhaust gas is supplied, the working medium is expended, producing useful work. After expansion, the working medium is rejected from the cylinder, and the cycle repeats – a pneumatic piston engine with an internal heat supply operates in a two-stroke cycle.

C. Experimental studies

For a qualitative and quantitative assessment of the influence of the pneumatic motor cylinder compressed air supply system adjusting parameters, the temperature of the inside cylinder walls and the exhaust gas temperature to the pneumatic motor effective power, a statistical method was used to plan the experiment.

In the present work, the dependence of the effective power from five following factors was established:

1. Pressure of compressed air supplied to the cylinder ($\boldsymbol{P_{ca}}$);
2. Temperature of the cylinder's inside walls ($\boldsymbol{T_W}$);
3. The exhaust gas temperature ($\boldsymbol{T_{EG}}$) at the entrance to the cylinder;
4. Temperature of compressed air supplied through a pneumatic valve ($\boldsymbol{T_{ca}}$);
5. The moment of the compressed air supply into the cylinder beginning in degrees of crankshaft rotation relative to the top dead center ($\boldsymbol{\theta}$).

As a mathematical model, a second-order equation of the following form was used:

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i \neq j}^{k} b_{ij} x_i x_j + \sum_{i=1}^{k} b_{11} x_1^2, \qquad (7)$$

where $\boldsymbol{b_0}, \boldsymbol{b_i}, \boldsymbol{b_{ij}}$ –coefficients of the mathematical model k – number of the mathematical model elements; $\boldsymbol{x_i}$and $\boldsymbol{x_j}$– factor values.

During the preliminary experiments, dependencies were established between:

- the mode of operation of the internal combustion engine and the temperature of its exhaust gases;
- the position of the rheostat handle and the temperature of the cylinder walls, which is heated using an electric heating coil.

Because the other factors (P_{ca} , T_{ca} , $\boldsymbol{\theta}$) are adjusting parameters of pneumatic engine, the regulators' positions, corresponding to each factor accepted variation levels, were found and noted. The accepted variation levels and intervals of all factors are presented in Table II.

Table II. Factors' variation levels and intervals

Factors				Variation levels			
Name	Units of measure	Symbol: In kind	Symbol: Code mark	Code mark -1 (In kind)	Code mark 0 (In kind)	Code mark 1 (In kind)	Variation intervals
Pressure of compressed air	MPa	P_{ca}	X_1	5	10	15	10
Temperature of the cylinder's inside walls	°C	T_W	X_2	80	115	150	70
Temperature of supplied compressed air	°C	T_{ca}	X_3	0	25	50	50
Temperature of exhaust gases	°C	T_{EG}	X_4	450	650	850	400
moment of the compressed air supply beginning	degrees of crankshaft rotation	θ	X_5	10 to TDC	5 to TDC	0 (TDC)	10

As a result of processing the experimental data to determine the pneumatic engine effective power, the following polynomial dependence was found:

$$N_e = 266,63 + 286X_1 + 14,3X_2 + 149,7X_3 + 181,4X_4 + 11,2X_5 + 75,6X_1^2 - \\ -58,07X_4^2 + 28,9X_1X_3 + 75,4X_1X_4 + 16,1X_2X_3 - 14,4X_3X_4 - 18,6X_3X_5 + \\ +14,5X_4X_5. \qquad (8)$$

The resulting equation allows us to estimate the effect of each of the factors listed above and their interaction on the pneumatic engine effective power.

In qualitative terms, this influence is determined by the sign before the corresponding coefficient, and the coefficient's absolute value reflects the strength of the factor influence. The contribution of one or another factor was estimated during the transition from the lower to the upper level (the factor effect).

The impact on the pneumatic engine effective power of the pressure of compressed air supplied to the cylinder is 100.0%; temperature of cylinder walls –5.0%; exhaust gas temperature at the entrance to the cylinder – 63.3%; temperature of compressed air supplied through a pneumatic valve – 52.2%; moment of the compressed air supply beginning – 3.9%.

V. CONCLUSION

As can be seen from equation (8), the pneumatic engine effective power depends most of all on the compressed air pressure, its temperature and the internal combustion engine exhaust gases temperature. As a result of the exhaust gases' thermal energy use increases the pneumatic engine specific effective power.

A positive, albeit weak, effect on the growth of this indicator has an increase in the temperature of the intra-cylinder space walls and the advance angle of the compressed air supply to the pneumatic engine cylinder.

Thus, the obtained polynomial equation (8) allows us to assess qualitatively and quantitatively the influence on the effective power, generated by the pneumatic engine, of the compressed air supply system adjusting parameters, cylinder walls temperatures, as well as the temperatures of exhaust gases, entering the cylinder from ICE.

The use of "waste" heat of an internal combustion engine exhaust gases and cooling system to increase the compressed air energy allows improving the economic and environmental performance of a pneumatic hybrid power plant, and the total performance factor of a pneumatic hybrid system can increase to $\eta = 0{,}50\ldots0{,}65$.

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