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Performing the optimization of compressed air specific consumption depending on the defining dimensionless structural and operating parameters of the motor-car pneumatic motor

Abstract. *Optimization of compressed air consumption depending on the determination of the dimensionless design and operating parameters of the pneumatic motor for the specific consumption of compressed air* $g_e = f_1(\varepsilon_0, \varepsilon_1, \varepsilon_5, p_s, n)$ *at its maximum power of* $N_e = f_2(\varepsilon_0, \varepsilon_1, \varepsilon_5, p_s, n)$ *is carried out.*

The relevance of the topic.

Over the last two decades, in the global automotive industry the implementation of combined power plants, which consist of a traditional internal combustion engine and an auxiliary one, as a rule, a less powerful electric drive is rising. The auxiliary engine is used under those operational conditions in which the internal combustion engine does not operate efficiently so that it produces high emissions (when driving, parking, etc.). Implementation of such hybrid power installations in practice allows saving up to 30% of fuel and significantly reduces harmful emissions containing exhaust gases. However, when using the electric motor in a vehicle there is a number of disadvantages: the driver is placed near a source of strong electromagnetic field, harmful to human health; disposing of used batteries causes pollution of the environment; electrical equipment adds weight to the whole facility; insufficient operational efficiency due to low temperatures, etc.

The alternative to the electric motor, which does not have these disadvantages, in automotive hybrid power plants, is the environment-friendly, simple, and reliable pneumatic motor. The use of pneumatic motors in transport plants that operate in hangars or premises with easily flammable substances is most relevant.

The object of research is the operational processes and structural indicators of the D/S= 7.6/6.6 pneumatic motor used as an auxiliary power unit of the combined power plant of a city car.

The optimum relationship between the power and compressed air consumption as well as the constructive defining and adjusting parameters, their influence on the operational processes of the pneumatic motor of a combined power plant of the vehicle, which is significantly different from relationships of the known pneumatic actuators used in the mining, gas and oil extracting industries is determined; recommendations for selecting design and controlled parameters of pneumatic engines are given. A detailed description of three key design dimensionless parameters (the relative harmful volume ε_0, the degree of filling ε_1, and the degree of reverse compression ε_5) as well as the controlled parameter – the pressure of compressed air at inlet p_s in the process of conversion of the potential energy of compressed air entering the cylinder into mechanical work and the effect of these parameters on power, air consumption, and the efficiency of the pneumatic piston engine was presented for the first time.

The study was carried out under the following conditions:

– calculation of the working processes was carried out for the modes of maximum effective power $N_e^{\max}$ at pressures of compressed air at the inlet corresponding to experimental speed characteristics (p_s = 0.5; 0.7; 0.9, and 1.1 MPa) and constant inlet temperature of 20 °C;

– back pressure at the outlet was considered unchanged ($p_в$= 0.12 MPa);

– rotational speed of the crankshaft corresponded to modes $N_e^{\max}$;

– mechanical efficiency and specifying factors as well as criteria, which depend on the pressure of compressed air at the inlet of the pneumatic engine and the rotation speed of the shaft, were taken according to the experimental data.

Increasing the relative harmful volume ε_0 always leads to an increase of the usable area of the indicator diagram F_i, i.e. the usable indicator work L_i, and, consequently, to the increase of indicator power N_i as well as the net power N_e of the pneumatic engine. However, this positive effect of increasing the harmful volume is non-significant when compared to the negative one – increasing of compressed air consumption. Increasing the pneumatic power by only 28% while increasing the harmful volume, raises compressed air consumption by almost 2.5 times.

Without changing the key design parameters ε_5 , ε_0 , ε_1 it is possible to obtain the same increase in power N_e (by 28 %) by increasing the inlet pressure from 0.50 to 0.58 MPa. This method of the higher power of the pneumatic engine obtaining is economically advantageous, since the specific air consumption g_e slightly decreases from 49.2 to 48.0 kg/(kW·h), and consumption per hour increases by 25%.

In the presented design and experimental study the air temperature $t_{2'}$ = (– 50 °C) at the end of expansion process, that corresponds to the minimum allowable design temperature at the end of adiabatic expansion of moist air with a relative humidity of $\varphi = 1$. According to experimental data, the polytropic coefficient for air with such humidity is n_p= 1.32.

Such temperature level t_3 at the ambient temperature $t_{н.с} = (+20\ °C)$ is achieved at the degree of filling ε_1 = 0.4. This value of the degree of filling was taken as a reasonable one for the pneumatic engine with spool air distribution, where possible in terms of the design minimum value of the relative harmful volume may not be less than $\varepsilon_0^{\min} = 0.4$.

Pneumatic piston engines with valve air distribution, which usually have a relatively small harmful volume (within ε_0 = 0.04–0.06), may not have reverse compression.

In the case of pneumatic piston engines with spool air distribution, where the relative value of harmful volume in terms of design cannot be reduced to less than

ε_0 = 0.4–0.5, the use of reverse compression improves the efficiency of the working process by 8–10 %, but at the same time the losses of efficient power are 10 – 28 %. Based only on condition of achieving the maximum efficiency of the engine, the level g_e^{min} for all values of pressure of compressed air at the inlet is achieved with one and the same value of back compression $\varepsilon_5 = 0.7$.

The paper includes the performed comparison of the calculation results of the working processes of the pneumatic engine with different systems of air distribution, having real and recommended sizes of the compression chamber (Table 2). The calculation of parameters is shown for the maximum power of experimental engines.

Table 2

Technical and economic indicators of pneumatic engines with different systems of air distribution

Item No.	Names of indicators and parameters	Options	
		Engine with spool air distribution	
1	Type of engine	2-stroke	
2	Diameter of engine, mm	76	
3	Stroke of piston, mm	66	
4	Air supply system	cylinders with compressed air, P_k = 20 MPa	
5	Design parameters: – relative harmful volume ε_0 – degree of filling ε_1 – degree of reverse compression ε_3	 0.935 0.288 0.491	 0.4 0.4 0.7
6	Inlet pressure, MPa	1.1	1.1
7	Inlet air temperature, К	293	293
8	Effective power, kW	6.22	5.79
9	Torque, N·m	76	67
10	Rated speed of crankshaft rotation, min^{-1}	780	780
11	Indicator efficiency, η_i	0.340	0.285
12	Mechanical efficiency, $\eta_м$	0.793	0.776
13	Net efficiency, η_e	0.270	0.221
14	Specific air consumption g_{espec}, kg/(kW·h)	91.5	61.1

According to the design and experimental data of the working processes of the pneumatic piston engine, the rated values of key dimensionless design parameters were determined: the degree of filling for the pneumatic engine with spool air distribution $\varepsilon_1 = 0.4$; the degree of reverse compression $\varepsilon_5 = 0.7$.

The largest influence on the change of specific air consumption g_i and the indicator power N_i, except the design parameters ε_0, ε_1 i ε_5, falls on the pressure of compressed air at the inlet p_s and the speed of crankshaft rotation n of the engine. Two multiple nonlinear regression equations for N_e and g_e according to the least squares method (using only binary interactions between the independent variables) were proposed.

The analysis of variance is used to verify the validity of the proposed models.

The multiple nonlinear regression equation for effective power N_e

$$\begin{gathered}N_e = -1.24 + 2.16\varepsilon_0 + 2.07\varepsilon_1 + 0.001\varepsilon_5 + 1.66p_s - 0.0034n - 4.2\varepsilon_0\varepsilon_1 + \\ + 3.59\varepsilon_0\varepsilon_5 + 1.41\varepsilon_0 p_s + 0.0026\varepsilon_0 n + 0.37\varepsilon_1\varepsilon_5 + 5.83\varepsilon_1 p_s + \\ + 0.0033\varepsilon_1 n - 0.13\varepsilon_5 p_s - 0.0021\varepsilon_5 n + 0.0036p_s n - 4.24\varepsilon_0^2 - \\ - 3.8\varepsilon_1^2 - 1.14\varepsilon_5^2 - 0.42p_s^2 - 2.05\cdot 10^{-6}n^2.\end{gathered} \tag{1}$$

The model is valid; the determination coefficient $R^2 = 0.997$.

The multiple nonlinear regression equation for g_e

$$\begin{gathered}g_e = 130.42 - 131.79\varepsilon_0 - 82.37\varepsilon_1 - 0.001\varepsilon_5 - 109.06p_s - \\ - 0.016n + 47.36\varepsilon_0\varepsilon_1 - 117.56\varepsilon_0\varepsilon_5 + 103.01\varepsilon_0 p_s + \\ + 0.12\varepsilon_0 n - 52.54\varepsilon_1\varepsilon_5 + 36.97\varepsilon_1 p_s + 0.087\varepsilon_1 n - \\ - 65.05\varepsilon_5 p_s - 0.107\varepsilon_3 n + 0.032p_s n + 89.23\varepsilon_0^2 + \\ + 59.202\varepsilon_1^2 + 128.309\varepsilon_5^2 + 51.554p_s^2 - 8.28\cdot 10^{-6}n^2.\end{gathered} \tag{2}$$

The model g_e is valid; the determination coefficient $R^2 = 0.66$.

To find the solutions, the objective function was selected to determine the parameters ε_0, ε_1, ε_5, p_s, and n, to achieve the maximum power of the pneumatic engine N_e with minimum specific consumption of compressed air:

$$y = \frac{N_e^{\gamma 1}}{g_e^{\gamma 2}} \to \max, \tag{3}$$

where: γ_1, γ_2 are the parameters, which make it possible to vary the degrees of importance of values N_e and g_e, respectively, where $\gamma_1 + \gamma_2 = 1$.

Optimization of the parameters ε_0, ε_1, ε_5, p_s, and n was carried out using the program of working with Excel spreadsheets by the method of generalized reduced gradient under such limitations.

According to the calculations, at $\gamma_1 = 0.5$ and $\gamma_2 = 0.5$ the following optimal parameters were obtained: $\varepsilon_0 = 0.4$, $\varepsilon_1 = 0.4$, $\varepsilon_3 = 0.75$, p_s = 1.1 and $n = 780$ min^{-1}. At this, $N_e = 5.79$ kW and $g_e = 61.1$ kg/(kW · h).

Conclusion

Optimization of the compressed air consumption depending on the determination of the dimensionless design and operating parameters of the pneumatic motor $g_e = f_1(\varepsilon_0, \varepsilon_1, \varepsilon_5, p_s, n)$ at its maximum power of $N_e = f_2(\varepsilon_0, \varepsilon_1, \varepsilon_5, p_s, n)$ is carried out.

Physical and mathematical modeling of the workflows was performed, justified and the defining dimensionless design parameters of the pneumatic motor with spool-type air distributor were recommended:

– relative harmful volume of ε_0=0.4;

– the degree of filling ε_1=0.4;

– the degree of reverse pressure ε_5 = 0.7.

The method of experimental testing of pneumatic motors with different air distributing systems was developed:

– piston automotive pneumatic motors with spool-type air distributors reached the nominal power N_e = 6.22 kW, respectively, with operating consumption of the compressed air g_e = 91.5 kg/(kW·h);

Recommendation by the optimization:

– piston automotive pneumatic motors with spool type air distributors reached the nominal power N_e = 5.79kW, with operating consumption of compressed air g_e = 61.1 kg/(kW·h);

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