Istraživanja i projektovanja za privredu
ISSN 1451-4117
DOI:10.5937/jaes0-45196
www.engineeringscience.rs

publishing

Journal of Applied Engineering Science
Vol. 22, No. 1, 2024
Original Scientific Paper
Paper number: 22(2024)1, 1170, 89-99

ESTABLISHING THE PARAMETERS OF THE OPERATION MODE OF THE ELECTRIC PULSE AUTOMOBILE MUFFLER

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The purpose of the research in the article is to obtain analytical and experimental results on the purification of internal combustion engine exhaust gases by an electric pulse, allowing us to determine the main parameters of the muffler operation. The set goal was achieved by performing the following methodology. A mathematical model of the motion of a gas particle in a muffler has been developed and investigated, the relationship between the capacity of the engine combustion chamber, the number of revolutions of the crankshaft, the pulse intensity, and the dynamic viscosity of the medium has been established. The condition of the muffler operation is determined through the parameter – the distance between the electrodes. The optimality criterion is justified – the smokiness of the gas before and after purification. A nonlinear experimental plan has been compiled using the methods of similarity theory and dimension analysis. An experimental stand has been developed and results linking the process parameters have been obtained. The results obtained are the basis for the methodology for calculating the design of electric pulse mufflers with optimal smoke ratios.

Keywords: automobile, internal combustion engine, muffler, exhaust gas, electric pulse

1 INTRODUCTION

Exhaust gases from automobile and other transport vehicles significantly worsen the environmental situation, especially in large settlements [1,2]. This leads to an increase in diseases of the population [2,3].

The reduction of this harm is carried out in the following areas: the operation of electric vehicles and cars with hybrid engines, as well as with the help of catalysts of various actions built into the muffler of the car.

Despite the relevance of the above solutions, they have a number of disadvantages: in the coming decades, replacing all cars with electric vehicles is impossible, due to the inability of electric vehicles to overcome a long distance on a single charge (100-120 km) and their long charging at stations (from 7 to 10 hours) [4], at the same time, catalysts are very expensive and have a short (no more 100 thousand/km) service life [5]. In practice, the following methods of exhaust gas purification are used: dry, wet, electric, catalytic and ultrasonic methods [6]. Until now, no electric gas purification method has been used in car mufflers [7]. There are a number of patents that propose the creation of a special chamber for electric air purification placed between the engine collector and the muffler [8,9]. This in turn leads to significant changes in the design of the car in the space between the engine and the muffler.

In our opinion, it is much more efficient to place an electric gas purification system in a car muffler. This makes it possible to modernize cars and, very importantly, replace very expensive catalytic converters. However, we have not found any data on the operation and research of such mufflers. In this regard, we believe that research aimed at developing the design and determining the operating modes of mufflers with electric gas purification is relevant. In our preliminary studies, the proposed method has shown its effectiveness, but it is necessary to establish the criterion of optimality and the optimal mode of operation of the electric muffler (EG).

The hypothesis of the study is the assumption that, depending on the frequency and power of the charge, its type (corona or spark), the engine crankshaft speed and the capacity of the combustion chambers, the distance between the electrodes, there is an optimal exhaust gas purification mode that ensures its maximum transparency. In this regard, the purpose of the study was to establish dependencies describing the operating mode of the EG, that is, the ratio of the main parameters of its operation.

The methodological sequence of the study was determined by the following tasks:

1. Mathematical modeling of the motion of a gas particle to determine the main relationships of the regime parameters;
2. Justification of the optimality criterion;
3. The establishment of similarity theory and dimensionality criteria for the development of an experimental plan;
4. Development of an experimental stand;
5. Conducting an experiment and analyzing the results obtained.

The scientific novelty of the research lies in the establishment of relationships between the parameters of the process: the capacity of the combustion chambers, the number of revolutions, the intensity of the electric field, the dynamic viscosity of the gas, provided that the optimality criterion is minimized. The practical significance is determined in obtaining criteria dependencies for the method of engineering calculation of the muffler.

2 MATERIALS AND METHODS

In the proposed engineering solution, the electrodes are placed in a muffler and the gas is cleaned by corona or spark discharge. The physics of the corona discharge process has been sufficiently studied. Charge development begins with the application of high voltage to the charging electrode and the formation of electrons through shock ionization. In the future, avalanche or chain ionization occurs. The essence of which lies in the fact that a free electron with energy of a higher binding energy, when colliding with an atom, knocks out one electron from it and a single-charged positive ion is formed. After the collisions, the electrons will gain energy, and four electrons will appear in the next collisions. Then eight, then sixteen, etc. Electrons will move to the anode, and positive ions to the cathode [10].

In this case, the number of electrons n is determined by the exponential law. In the case of the movement of the electron wind against the movement of the gas from the muffler, the probability of shock ionization of the gas increases. Corona and spark discharges can pass into each other.The appearance of a spark discharge is explained by the occurrence of shock ionization. The fact is that under normal conditions, there are always a certain number of ions and electrons in the air that can carry an electric charge, but there are not so many of them and the gas is considered a dielectric. But with an increase in the electric field strength, these free particles begin to move faster and there comes a moment when kinetic energy becomes sufficient and when colliding with other neutral molecules, the latter lose a negative electron and a positively charged anion remains, which begins to move towards the cathode. In the process of movement, the anion collides with other particles. As a result, shock ionization increases and the number of charge carriers in the gas increases sharply and an ion avalanche occurs. The formation of such avalanches is the process of gas breakdown by a spark. Thus, we see that the ionization of the gas is explained by the destruction of molecules and atoms due to their collision with cations and anions [11].

In the proposed automobile muffler, depending on the engine speed, the pressure, gas density, speed of its movement and dynamic viscosity change. At low engine speeds, the fuel burns worse than at high, the density and composition of the exhaust gas are different. At the same time, the dynamic viscosity is higher, since there are more heavy oil particles in the gas. At the same time, it is difficult to constantly maintain the efficiency of the cleaning process, since the corona discharge may fade or a spark discharge may occur. The process is described as follows. When voltage is applied to the electrode, a corona discharge occurs (Figure 1).

Fig. 1. Corona discharge

With an increase in tension, a breakdown occurs and the charge will turn into a spark (Figure 2).

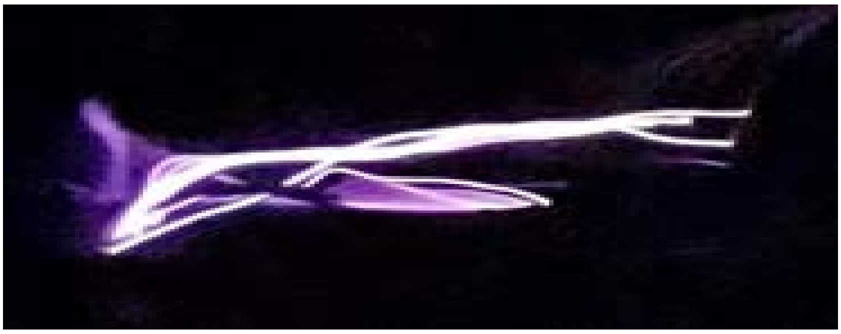

Fig. 2. Spark discharge

If the distance between the electrodes is increased at constant voltage, the charge will again turn into a corona. Thus, the adjustment of the cleaning mode is possible in two ways: by changing the voltage and the distance between the cathodes .

As practice shows, a corona discharge is more effective at cleaning gases with electric filters than a spark discharge. This is explained by the fact that electrofilters operating on a corona discharge have a significant cathode length. (Figure 3).

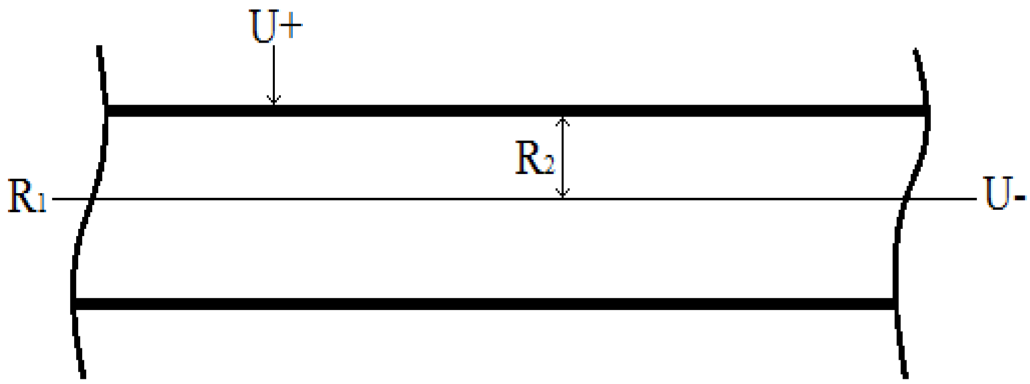

Fig. 3. Schematic diagram of the electrofilter-section

Corona discharge compared to spark discharge is more resistant to voltage spikes, since part of the energy generated in the ionization process is smoothly dissipated during the movement of electrons from the cathode, therefore, the voltage values do not drop dramatically. Moreover, due to the effect of the corona discharge, the surrounding gas becomes more conductive, which leads to an increase in the virtual diameter of the electrode and increases the efficiency of the ionization process [13]. In addition, the spark discharge can cause destruction of the anode under certain conditions, namely when the length of the discharge gap is small, there is a specific destruction of the anode metal, which is called erosion [14].

But in the muffler, because of its size and bends of the gas line, it is impossible to apply electrodes, which are used for electric filters.

In this regard, we propose the following muffler design (Figure 4).

Fig. 4. Location of the muffler electrodes

The advantage of this scheme: small size, significant roundness of the electrodes in two planes. One of the electrodes is movable along the axis of the muffler.

To prove the hypothesis put forward, a diagram of the forces acting on a gas particle in a muffler is presented (Figure 5).

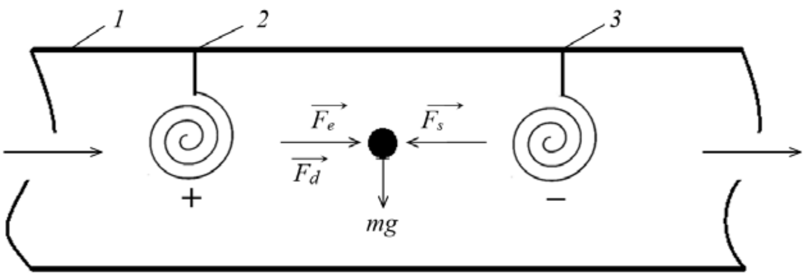

Fig. 5. Diagram of the forces acting on a gas particle in the muffler

1 – the muffler shell; 2 and 3 – positive and negative electrodes

Particles of mass m are resisted by the dynamic friction force of Stokes F_s under the influence of pressure from the engine F_d and the electromotive force F_e.

The placement of the electrodes along the axis of the muffler makes it possible for the oncoming movement of the electron wind acting on the particles to meet the gas velocity ϑ. In the calculations, the velocity of the electron wind can be ignored, since it is an order of magnitude less than the velocity of the gas ϑ. The pressure force from the engine when considering the process is taken into account by the velocity ϑ, which determines the Stokes force, so the pressure on the particle is proportional to the fourth order of smallness based on its size.

The system of equations describing the motion of a gas particle in relation to the parameters of the regime The system of equations describing the motion of a gas particle in relation to the parameters of the regime, which is given as:

$$\begin{cases} m\ddot{x} = 6\pi r\mu\vartheta - Eq \\ \vartheta = Q\omega/\pi R^2 \\ E = U/\Delta \end{cases} \quad (1)$$

The first equation of the system describes the motion of the particle; the second is the relationship of the particle velocity with the capacity of the combustion chambers and the angular speed of rotation of the crankshaft; the third is the relationship of tension with the interelectrode distance.

The equation of the electromotive force in this case is determined by the field strength E and the charge strength q. With this arrangement of charges, the magnitude of the tension depends on the voltage *U* and the distance between the electrodes Δ.

The task of analyzing the system of equations was to establish relationships between the parameters of the engine and the electric pulse cleaning system.

When shock ionization occurs, the intensity value *E* must be greater than the critical value E_c, It is given as:

$$E > E_c \quad (2)$$

Therefore, taking into account the equation of the three systems, the following can be obtained:

$$\frac{U}{\Delta} > \mathrm{E_c} \text{ and } \Delta < \frac{U}{E_c} \quad (3)$$

The value of the smoke ratio before (D_1) and after (D_2) purification could be obtained as the criterion of optimality. It is given as:

$$K_o = \frac{D_1}{D_2} \to min \quad (4)$$

The amount of smoke is standard in determining the quality of gas purification. Smokiness is the most comprehensive indicator characterizing the toxicity of exhaust gases [15]. And the ratio of smokiness before exposure to the gas by electric pulse to the smokiness after exposure to the gas by electric pulse makes it possible to determine the extent to which the exhaust gas was cleaned from harmful impurities. Thus, the ratio of smoke values is the best criterion for assessing the smokiness and toxicity of exhaust gases in the electro-pulse silencer.

A significant number of parameters affect the amount of smoke are shown in Table 1.

Table 1. The main parameters affecting the value of the gas smoke index

No.	Nomination of parameters	Designation	Unit of measurement	Dimension formula
1	Angular speed of rotation of the crankshaft	ω	1/s	T^{-1}
2	Electric pulse frequency	*f*	1/s	T^{-1}
3	Distance between electrodes	Δ	m	*L*
4	Electric field voltage	*U*	V	$LMT^{-3}I^{-1}$
5	The smokiness of the gas before exposure to an electric pulse	D_1	lk	$J \cdot L^{-2}$
6	The smokiness of the gas after exposure to an electric pulse	D_2	lk	$J \cdot L^{-2}$
7	Electric current strength	*I*	A	*I*
8	The diameter of the body of the electric pulse muffler	*d*	m	*L*
9	Gas density	ρ	kg/m^3	*ML-3*
10	Dynamic viscosity of the gas	μ	Pa s	*ML-1 T-1*
11	Gas particle velocity	ϑ	m/s	*ML-1*
12	The power of light	J_v	cd	*J*

Conducting an experiment taking into account all the parameters of the classical plan is very time-consuming. In this regard, we use the method of similarity theory to build an optimal experimental plan. On the basis of the considered parameters, an equation depending on the parameter of the smokiness of a gas previously exposed to an electric pulse was compiled using the method of similarity theory. The functional ratio of the parameters from the smokiness parameter of the gas exposed to an electric pulse is presented in the following form:

$$D_2 = f(\omega, f, \Delta, U, D_1, I, d, \rho, \mu, \vartheta, J_v) \quad (5)$$

Hence follows the following equation:

$$\left(\omega, f, \Delta, U, I, d, \rho, \mu, \vartheta, J_v, \frac{D_1}{D_2}\right) = 0 \quad (6)$$

To conduct experimental studies, a full-size stand was developed, which is shown in Figure 6 [10].

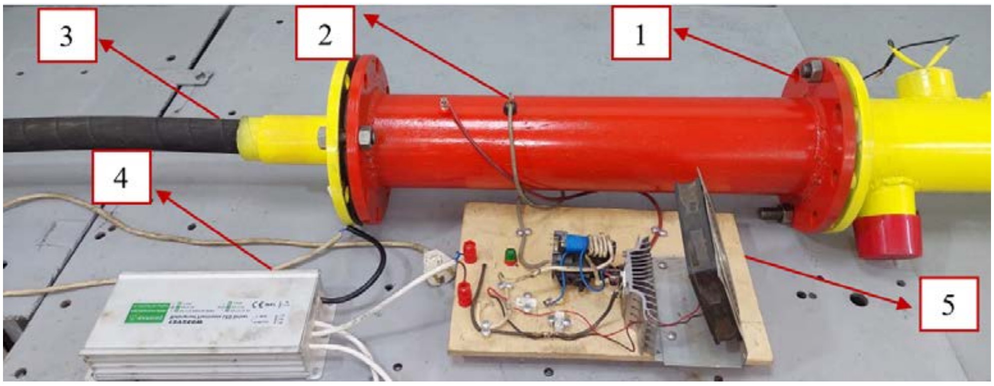

Fig. 6. Experimental installation for a gasoline-powered internal combustion engine

1 – the body of the stand, 2 – two electrodes mounted inside the stand, 3 – hose to the muffler inlet, 4 – the source of electric current 5 - high voltage

The electric pulse stand consists of a cylindrical housing 1, an inlet pipe for passing exhaust gases 2, an electric current source 3 and a radiator for cooling devices 4. Two electrodes were installed inside the housing, on which a current is supplied from a high-voltage electric current source through high-voltage wires. The electrical circuit of the stand consists of elements such as a high voltage electric current source (20 kV) and two metal plates twisted into a spiral in parallel to each other. The electric pulse stand is connected to the car through the inlet pipe using a rubber hose that supplies exhaust gases to the installation. In an electric pulse stand, gas is passed through an inhomogeneous electric field formed by two electrodes located inside the body of the stand, to which a constant high-voltage electric current is supplied. At a sufficiently high voltage applied to the interelectrode gap, intense shock ionization of the gas occurs at the surface of the corona electrode, accompanied by the appearance of a corona discharge. Due to the corona discharge, gas ions of different polarities, for example, positive ions move to the corona electrode and are neutralized on it, and negative ions and free electrons move to the precipitation electrode. Coming into contact with oncoming dispersed particles in the gas, they inform the latter of their charge and carry them to the precipitation electrode. As a result, the gas is purified and its particles settle on this electrode.

During the experiment, measurements are taken on the indicators of the smoke content of the gas before and after exposure to an electric pulse after 1 minute, depending on the rotation range of the engine crankshaft (750,1000 and 1550 rpm).

3 RESULTS

Integration of the first equation of the system (1) gave the following solution:

$$X = \left(\vartheta_0 - \frac{Eq}{6\pi r\mu}\right)\left(1 - e^{\frac{6\pi r\mu t}{m}}\right)t + \frac{Eq}{6\pi r\mu}t \quad (7)$$

The second factor of the first term of the equation tends to 0, since the degree at e tends to infinitesimal due to the fourth order of smallness of r and t in the numerator.

Then they are depicted as:

$$x = \frac{Eq}{6\pi r\mu}t; \quad (8)$$

$$\vartheta = \frac{Eq}{6\pi r\mu} \quad (9)$$

Equate (9) sequentially to the second and third equations of the system (1), the following equation can be obtained:

$$\frac{Eq}{6\pi r\mu} = \frac{Q\omega}{\pi R^2} \quad (10)$$

$$\frac{Uq}{6\Delta r\mu} = \frac{Q\omega}{R^2} \quad (11)$$

When regulating the ionization process in order to achieve a spark discharge by changing the value of Δ, taking into account the third equation of the system and inequality (3) the following equation can be obtained:

$$\Delta < \frac{UqR^2}{\omega \cdot Q \cdot 6r \cdot \mu} \quad (12)$$

The dependence determines the necessary and obligatory relationship between the parameters of the operating mode of the system: the engine is an electric pulse muffler. This equation made it possible to calculate the planned parameters Δ for the experiment

It follows from expression 9 that the value Δ is more effective the stronger the voltage and the larger the average size of the muffler and decreases with increasing viscosity, engine volume and angular velocity of the engine.

According to expression 9, calculations were carried out to determine the distance between the electrodes in the case of an increase in the voltage value U in the range from 10 to 60 kV, in increments of 10 kV. The calculation results are presented in Table 2.

Table 2. Change in the distance between the electrodes d from the voltage U

U [V]	10000	20000	30000	40000	50000	60000
Δ [m]	0,0008	0,001	0,0025	0,0033	0,0041	0,005

Calculations were also carried out to determine the distance between the electrodes in the case of an increase in the angular velocity value ω in the range of the number of revolutions n from 1000 to 6000 rpm, in increments of 500 rpm. (105-628 rad\s). The calculation results are presented in Table 3.

Table 3. Change in the distance between the electrodes d from the engine speed n

N [rpm]	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000
ω [rad/s]	105	157	209	262	314	366	419	471	523	575	628
Δ [m]	0,0062	0,0041	0,0031	0,0025	0,0020	0,0017	0,0015	0,0013	0,0012	0,0011	0,0010

Based on the obtained values, a general graph of the dependence of the voltage U and the angular velocity ω on the distance between the electrodes Δ was constructed (Figure 7).

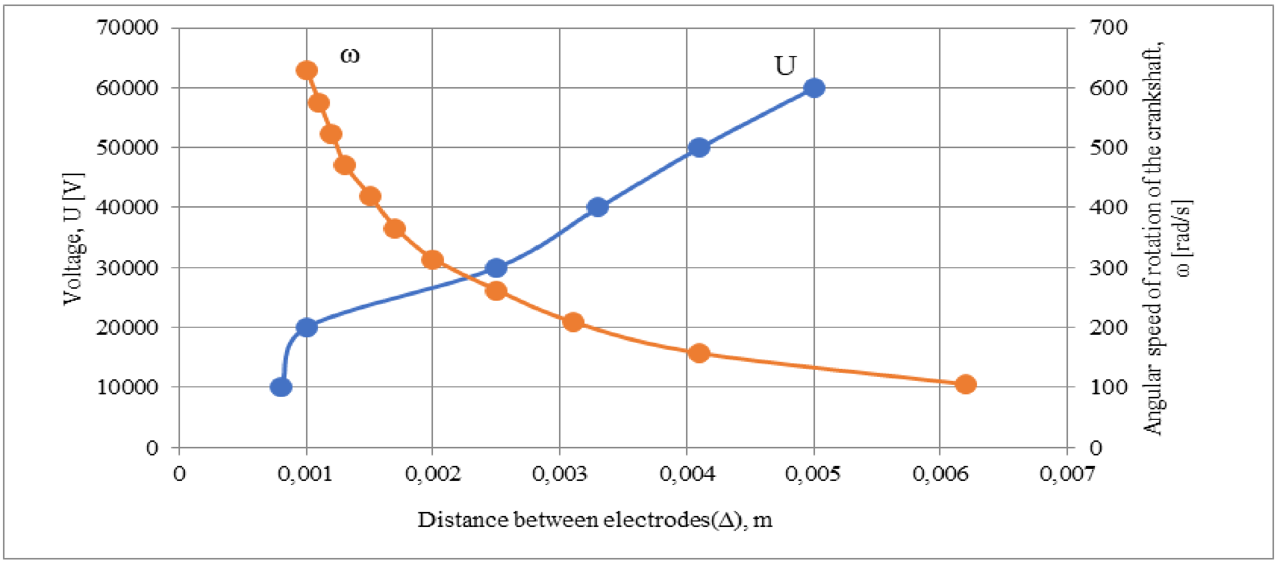

Fig. 7. Dependences of parameters on the distance between the electrodes

As follows from the graph, there are opposite trends in the magnitude of Δ: with an increase in *U*, its value should increase, with an increase in *ω*, it decreases. In this regard, the problem arises of choosing the optimal mode of operation of an electric pulse muffler.

According to the methods of similarity theory and dimensionality, appropriate calculations were carried out to determine the similarity criteria that allow to establish the optimal mode of operation of an electric pulse muffler.

According to the obtained equation (6), according to the similarity theory, the number of parameters is *n=11*, and the number of basic units of measurement is *k=5*, in accordance with the *π*-theorem, the number of basic dimensionless parameters that make up the similarity criteria will be equal to: *m=n-k=11-5=6*. Consequently, the following equation, allowing us to determine 6 dimensionless parameters can be obtained as:

$$\pi = \varphi(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6) \quad (13)$$

Hence the following equation is given as:

$$\varphi(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6) = 0 \quad (14)$$

From among the *n* parameters, we will choose five with independent dimensions, including five basic units (length *L*, mass *M*, time *T*, electric current strength *I* and light intensity J_v), let it be the diameter of the muffler housing (*d*), the velocity of the gas particle (ϑ), the gas density (*p*), the electric current strength current (*I)* and light intensity (J_v).

The selected five variables (d, ϑ, p, I, J_v) will be included in each of the *π*-terms, the remaining variables, namely: *n, f* ,Δ ,*U* ,*μ*,$\frac{D_1}{D_2}$ one by one they will be part of the previously formed π -members with five main variables. Exponents of the degree of the five main variables defining dimensionless parameters are unknown, therefore we denote them by *x, y, z, α, β*. The exponents of the other variables are assumed to be equal to -1. As a result, the relations for the *π*-terms are shown in the following form:

$$\pi_1 = d^{x_1}\vartheta^{y_1}\rho^{z_1}I^{\alpha_1}J_v^{\beta_1}\omega^{-1} \tag{15}$$

$$\pi_2 = d^{x_2}\vartheta^{y_2}\rho^{z_2}I^{\alpha_2}J_v^{\beta_2}f^{-1} \tag{16}$$

$$\pi_3 = d^{x_3}\vartheta^{y_3}\rho^{z_3}I^{\alpha_3}J_v^{\beta_3}\Delta^{-1} \tag{17}$$

$$\pi_4 = d^{x_4}\vartheta^{y_4}\rho^{z_4}I^{\alpha_4}J_v^{\beta_4}U^{-1} \tag{18}$$

$$\pi_5 = d^{x_5}\vartheta^{y_5}\rho^{z_5}I^{\alpha_5}J_v^{\beta_5}\mu^{-1} \tag{19}$$

$$\pi_6 = d^{x_6}\vartheta^{y_6}\rho^{z_6}I^{\alpha_6}J_v^{\beta_6}(\frac{D_1}{D_2})^{-1} \tag{20}$$

The variables included in the *π*-terms can be expressed in terms of the basic dimensions. Since these terms are dimensionless, the exponents of each of the main dimensions should be equal to zero. As a result, three independent equations (one for each dimension) can be compiled for each of the *π*-terms, which relate the exponents of the variables included in them. The solution of the resulting system of equations makes it possible to find numerical values of unknown exponents of *x, y* and *z*. As a result, each of the π-terms is defined in the form of a formula composed of specific quantities to the appropriate degree.

Then the equation of dimension for the first term π_1 can be obtained:

$$\pi_1 = L^{x_1}\left(\frac{L}{T}\right)^{y_1}\left(\frac{M}{L^3}\right)^{z_1}(I)^{\alpha_1}(J)^{\beta_1}\left(\frac{1}{T}\right)^{-1} \tag{21}$$

Exponents with the same bases add up. They are given as:

$$\pi_1 = L^{x_1+y_1-3z_1}T^{-y_1+1}M^{z_1}I^{\alpha_1}J^{\beta_1} \tag{22}$$

In order for the dimension π_1 to be equal to one, it is necessary to equate all exponents to zero. They are given as:

$$\begin{cases} x_1 + y_1 - 3z_1 = 0 \\ -y_1 + 1 = 0 \\ z_1 = 0;\ I_1 = 0;\ J_1 = 0 \end{cases} \tag{23}$$

The system of algebraic equations contains five unknown quantities x_1, y_1, z_1, I_1, J_1. Solving this system of equations, we find that $x_1 = -1, y_1 = 1, z_1 = 0, I_1 = 0, J_1 = 0$.

Substituting these exponent values into the first term π_1, we obtain the first dimensionless parameter, which is given as:

$$\pi_1 = \frac{\vartheta}{d\omega} \tag{24}$$

We perform a similar calculation for the remaining π–terms and, accordingly, obtain the second, third, fourth, fifth and sixth dimensionless parameter, which are depicted as:

$$\pi_2 = \frac{\vartheta}{df} \tag{25}$$

$$\pi_3 = \frac{d}{\Delta} \tag{26}$$

$$\pi_4 = \frac{d^2\vartheta^3\rho}{IU} \tag{27}$$

$$\pi_5 = \frac{d\vartheta\rho}{\mu} \tag{28}$$

$$\pi_6 = \frac{D_1}{D_2} \tag{29}$$

Substituting the obtained π-terms into equation (14), we obtain six dimensionless parameters, which are given as:

$$\varphi\left(\frac{\vartheta}{d\omega},\frac{\vartheta}{df},\frac{d}{\Delta},\frac{d^2\vartheta^3\rho}{IU},\frac{d\vartheta\rho}{\mu},\frac{D_1}{D_2}\right)=0 \quad (30)$$

We solve the equation with respect to π_6, where we output $\frac{D_1}{D_2}$ to the left side of the equation, Taking into account the proportionality between the parameters d,ϑ, p and μ, we express the fifth term of π_5 by the Reynolds criterion *Re*. Then we reduce the dimensionless parameters of the first and second π-terms between each other and obtain a single criterion. So we can write the previous equation (30) in the following form:

$$\frac{D_1}{D_2}=\varphi\left(\frac{f}{\omega},\frac{d}{\Delta},\frac{d^2\vartheta^3\rho}{IU},Re\right) \quad (31)$$

Thus, the fundamental variables we selected were reduced to dimensionless parameters and transformed into five similarity criteria. They are given as:

$$k_1=\frac{d^2\vartheta^3\rho}{IU} \quad (32)$$

$$k_2=\frac{f}{\omega} \quad (33)$$

$$k_3=Re \quad (34)$$

$$k_4=\frac{d}{\Delta} \quad (35)$$

$$k_5=\frac{D_1}{D_2} \quad (36)$$

The obtained similarity criteria theoretically describe the process of operation of an electric pulse muffler. The criterion in the form of k_1 characterizes the productivity of the electric pulse muffler by the ratio of power, namely, the power of the electric pulse muffler to the power of the resistance to its operation. The second criterion k_2 allows you to determine at what ratios of the frequency of the electric pulse to the engine speed, the operation of the electric pulse muffler will be considered optimal. The third criterion k_3 describes the mode of gas passage inside the muffler, namely its transition from laminar to turbulent mode. The fourth criterion k_4 takes into account the geometric parameters of the electric pulse muffler, necessary for drawing up the methodology of engineering calculation of the muffler design. The fifth criterion k_5 allows you to determine the efficiency of the electric pulse muffler, namely the quality of exhaust gas purification. On the basis of the criteria obtained, an experimental plan was drawn up to determine the criterion for the optimality of the operation of an electric pulse muffler (corresponding to the criterion k_5), namely, the change in the smoke indicators (D_1) and (D_2) from the engine speed parameters (n) before and after exposure to gases by an electric pulse. In this regard, the matrix of the experiment plan has the following form (Table 4):

Table 4**.** Experiment matrix

Stand working hours (*t*) / Engine rpm speed number (*n*)	t_1	t_2	k_5
n_1	D_{11}	D_{12}	k_5^1
n_2	D_{21}	D_{22}	k_5^2
n_3	D_{31}	D_{32}	k_5^3

According to the conducted experimental studies, quantitative indicators of smokiness were obtained depending on the change in engine speed by 750, 1000 and 1550 rpm (Table 5).

Table 5. Results of the experiment

Stand working hours (*t*) / Engine rpm speed number (*n*)	t_1=60 (without the impact of an electric impulse)	t_2=60 (with the impact of an electric impulse)	k_5
	Smokiness indicators (D_1)	Smokiness indicators (D_2)	
750	21,5	15,7	1,36
1000	30,2	28	1,07
1550	32,4	36	0,9

The graph of the gas smokiness indicators $\frac{D_1}{D_2}$ from the change in the engine speed *n* with and without the influence of the electric pulse is shown in Figure 8.

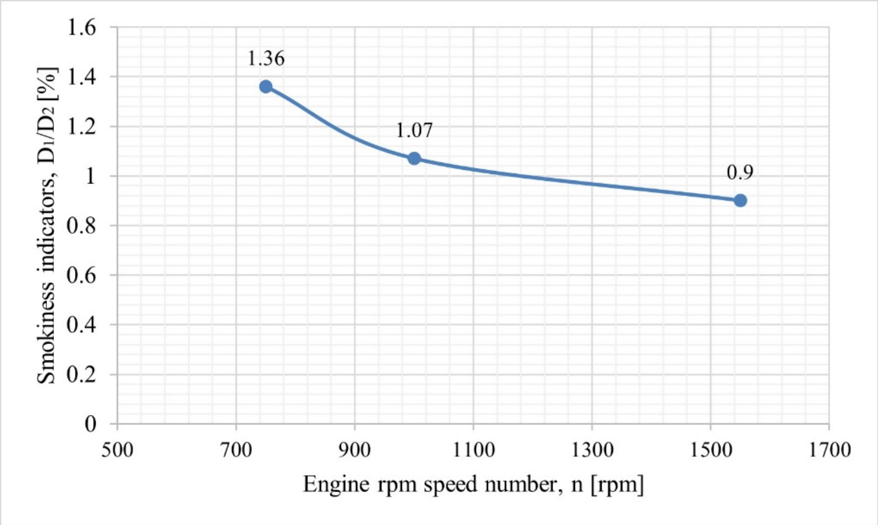

Fig. 8. Graph of the dependences of the optimality criterion on the change in engine speed *n*

According to the obtained graph, it follows that the electric pulse has a positive effect on the gas, which leads to a significant decrease in its smokiness. A decrease in the smoke content of the gas, in turn, satisfies the condition of the optimality criterion, the value of which should tend to a minimum, which indicates an increase in the quality of gas purification and an increase in the efficiency of the electric pulse muffler.

In addition to the quantitative indicators of smokiness obtained during the experiment, numerical values of the criteria k_1 and k_3 were also obtained, at the corresponding engine speed numbers. Numerical values of criteria k_1 and k_3 are presented in Table 6.

Table 6. Numerical values of criteria *k1* and k_3

Parameters	Descriptions	Unit	Indictors		
Engine speed	n	rpm	750	1000	1550
Angular speed of rotation of the crankshaft	ω	rad/s	78.5	104.66	162.23
Engine capacity	Q	m^3	0.0016	0.0016	0.0016
Muffler radius	R	m	0.055	0.055	0.055
Gas particle velocity		m/s	13.22	17.63	27.32
Muffler diameter	d	m	0.11	0.11	0.11
Installation capacity	P	W	250	250	250
Dynamic viscosity of the gas	μ	Pa·s	$3.92{\cdot}10^{-5}$	$3.92{\cdot}10^{-5}$	$3.92{\cdot}10^{-5}$
Gas density	ρ	kg/m^3	0.43	0.43	0.43
Criterion k_1, (power ratio)	k_1		0.048	0.11	0.42
Criterion k_3, (Reynolds number)	k_3		15971.77	21295.69	33008.33

On the basis of the previously analytically obtained dependence (9), the optimal distances between the electrodes for the corresponding engine revolutions with a combustion chamber volume of 1600 cm^3 were established. The necessary parameters for calculations are presented in Table 7.

Table 7. Parameters for calculating the optimal distance between the electrodes

Parameters	Descriptions	Unit	Indictors		
Voltage	U	B	20000	20000	20000
Engine speed	n	rpm	750	1000	1550
Engine capacity	Q	m3	0.0016	0.0016	0.0016
Angular speed of rotation of the crankshaft	ω	rad/s	78.5	104.66	162.23
The amount of charge	q	Kl	$1.6{\cdot}10^{-19}$	$1.6{\cdot}10^{-19}$	$1.6{\cdot}10^{-19}$
Muffler radius	R	m	0.055	0.055	0.055

Parameters	Descriptions	Unit	Indictors		
Average radius of a gas particle	r	m	$56 \cdot 10^{-12}$	$56 \cdot 10^{-12}$	$56 \cdot 10^{-12}$
Dynamic viscosity of the gas (accepted for nitrogen)	μ	Pa·s	$3.92 \cdot 10^{-5}$	$3.92 \cdot 10^{-5}$	$3.92 \cdot 10^{-5}$

The calculations gave the following values:

$$\Delta_1^{700} = \frac{20 \cdot 10^3 \cdot 1{,}6 \cdot 10^{-19} \cdot 0{,}055^2}{78{,}5 \cdot 0{,}0016\text{м}^3 \cdot 6 \cdot 56 \cdot 10^{-12} \cdot 3{,}92 \cdot 10^{-5}} = 0{,}0058$$

$$\Delta_2^{1400} = \frac{20 \cdot 10^3 \cdot 1{,}6 \cdot 10^{-19} \cdot 0{,}055^2}{104{,}66 \cdot 0{,}0016\text{м}^3 \cdot 6 \cdot 56 \cdot 10^{-12} \cdot 3{,}92 \cdot 10^{-5}} = 0{,}0043$$

$$\Delta_3^{1900} = \frac{20 \cdot 10^3 \cdot 1{,}6 \cdot 10^{-19} \cdot 0{,}055^2}{162{,}23 \cdot 0{,}0016\text{м}^3 \cdot 6 \cdot 56 \cdot 10^{-12} \cdot 3{,}92 \cdot 10^{-5}} = 0{,}0028$$

According to the obtained calculation results, a graph of the dependences of the criteria k_1, k_3 and k_5 on the change in engine speed (n) and the distances between the electrodes (Δ) was constructed (Figure 9).

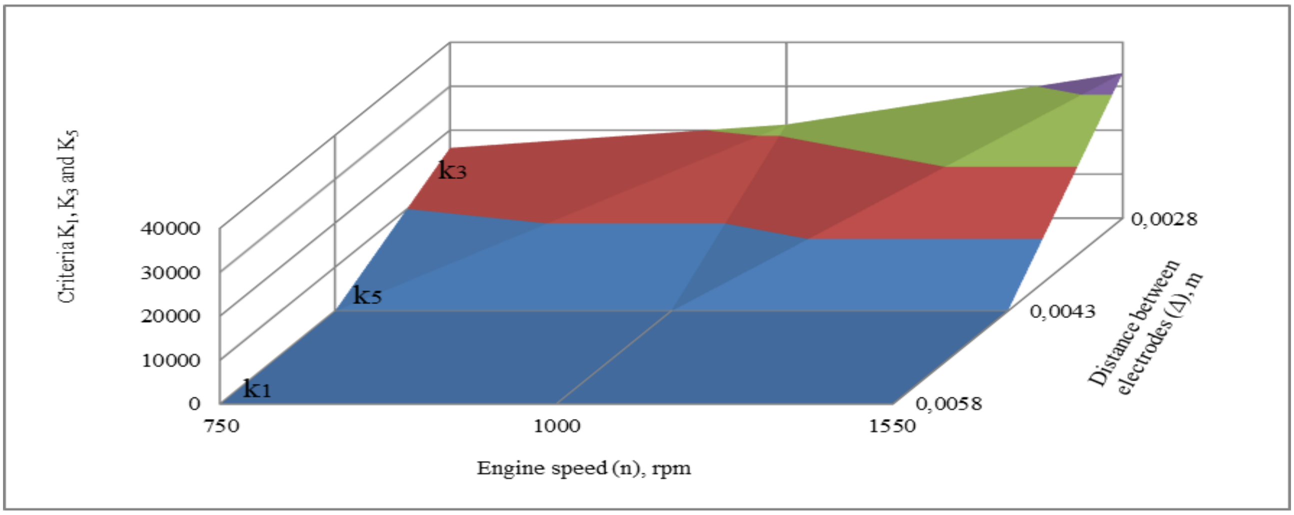

Fig. 9. Graph of dependencies of criteria k_1 and k_3 on changes in engine speed (n) and distances between electrodes (Δ)

At the considered engine speed values, the electric pulse muffler shows its optimal operation. Firstly, with an increase in engine speed, the smoke index decreases, characterized by the k_5 criterion, which proves the effectiveness of gas purification with an electric pulse muffler. Secondly, the indicators of the k_1 criterion, taking into account the ratio of the operating power and the resistance of the electric pulse muffler, are in the range in which the operation of the muffler is considered stable. Thirdly, according to the numerical values of the k_3 criterion, it can be concluded that the gas flow has not passed into a turbulent mode, since its value at the maximum number of revolutions considered by us is Re = 33000. It should be noted that for the laminar gas flow mode Re ≤ 2300, and for the critical laminar gas flow mode Re = 2000-4000. Therefore, with the engine speed we have considered and the calculated values of the distances between the electrodes, the operation mode of the electric pulse muffler is considered optimal.

4 CONCLUSIONS

According to the results of the conducted studies, the hypothesis of the possibility of determining the optimal mode of exhaust gas purification of an electric pulse muffler, depending on the distance between the electrodes, the rotational speed of the crankshaft engine and the capacity of the combustion chamber has been confirmed.

Analytically, a system of equations was obtained, which theoretically allows us to establish the relationship between the parameters determining the optimal mode of operation of an electric pulse muffler. As a criterion for the optimality of the operation of an electric pulse muffler, it is proposed to consider the ratio of exhaust gas smoke before (D_1) and after (D_2) its purification, which allows evaluating the effectiveness of gas purification after exposure to an electric pulse. Also, based on the method of similarity theory and dimensions, criteria were obtained that characterize the productivity of an electric pulse muffler.

An experimental stand was designed and manufactured, the purpose of which was to obtain the dependences of the smoke content of the gas and determine the optimal distance between the electrodes from the engine speed.

According to the conducted experimental studies, it was found that when the gas flow is affected by an electric pulse, its smokiness index decreases at about 36%, thereby confirming the effectiveness of exhaust gas purification by an electric pulse muffler. Also, based on the criteria obtained, an evaluation of the operation of the electric pulse muffler was carried out, which proved its high performance. The criterion k_1, which takes into account the ratio between the operating power and resistance of the electric pulse silencer, confirms the stability of operation in the considered range. The values of criterion k_3 indicate the absence of transition of gas flow into turbulent mode, since at maximum revolutions its value is Re = 33000. Thus, at the considered engine revolutions and calculated values of distances between electrodes it is possible to conclude that the operating mode of the electric pulse muffler is optimal.

The results obtained make it possible to have scientific and practical significance for the development of methods for calculating the design of electric pulse mufflers designed to increase the efficiency of the exhaust system of internal combustion engines of cars.

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Paper submitted: 26.06.2023.

Paper accepted: 13.03.2024.