STUDYING THE PROCESS OF THE INTERNAL COMBUSTION ENGINE EXHAUST GAS PURIFICATION BY AN ELECTRIC PULSE

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Resume

The article deals with method of purifying the exhaust gases in an automobile muffler or other transport equipment using electrical pulses. Electrical pulses are formed between the two ring electrodes (anode and cathode) installed in series along the gas flow. The physical picture of the process is described. A mathematical model has been developed and studied. A deterministic relationship has been established between the engine volume, the number of the crankshaft revolutions, the electric field strength and the charge strength and dynamic viscosity of the gas. Experimental studies have been carried out. The goal of the experiment was to confirm the hypothesis of impact ionization of exhaust gases. The effectiveness of electrical pulse purification has been proven.

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1 Introduction

Motor vehicles are the main source of air pollution in cities. Pollution is caused by the emission of exhaust gases into the atmosphere. The toxic component of exhaust gases is nitric oxide, soot that contains a carcinogenic substance, benzopyrene, as well as other substances. These substances cause asthma, vascular-cardiac stroke, neurology and other cardiovascular diseases in the population [1-2]. Mufflers equipped with a purification system can reduce polluting emissions [3].

The requirements to neutralization of exhaust gases from internal combustion engines are growing from year to year. The analysis of the state of work for neutralization of exhaust gases of internal combustion engines suggests that the following methods can be further classified among the promising ways of its development: flame neutralization, liquid neutralization, thermal catalytic neutralization and a number of others, the development of which was dealt with in a number of studies [3].

Liquid neutralization of exhaust gases has become widespread in vehicles and self-propelled equipment operating in confined spaces. The disadvantages of liquid neutralizers include the difficulty of operating vehicles at negative ambient temperatures, since the solution can freeze when the engine is not running. Liquid neutralization is difficult to operate: it requires daily removal and disposal of the used liquid and sludge, flushing the system and filling it with a fresh liquid [4].

Thermal catalytic neutralization of exhaust gases has been developed quite well, has proven itself to be a high degree of purification, especially from nitrogen oxides. On the other hand, thermal catalytic converters are bulky, heavy, they cannot be placed instead of mufflers, the fuel consumption of the engine with thermal catalytic converters increases by 15%. Mounting, the thermal catalytic converters on vehicles requires a reliable automation system to ensure the coordination of the exhaust gas heating system with the engine operating modes [5].

Flame neutralization of exhaust gases is uncompetitive for vehicles because it requires additional fuel consumption, energy costs to maintain the flame, air supply. In addition, the flame neutralization has a low efficiency of exhaust gas purification from NO_2, C_xH_4, CO and soot and a high fire hazard. Meanwhile, this method effectively purifies exhaust gases. Its efficiency can be improved by increasing the proportion of oxygen in exhaust gas [6].

Neutralization of exhaust gases by ultrasound in mufflers is not yet used but relevant studies have been carried out by Kazakh scientists, [7].

A whole area is dealing with the gas purification including exhaust electrostatic precipitators using an electric field and electrical breakdown of gas: a corona discharge [8].

The hypothesis of this study consists in increasing the impact ionization of exhaust gas particles due to its counter movement from the muffler and the electrical discharge directed in the opposite direction. This reduces the opacity (turbidity) of exhaust gases due to the electrons attaching and sticking.

A number of constructive solutions for purifying gases with an electric pulse were proposed [9]. The development of the research hypothesis was preceded by the analysis of a number of patent decisions. For the most part, those solutions are not intended for vehicle mufflers [10].

In some patents designed specifically for purification of the exhaust gases of internal combustion engines, there are the following design features:

- in the design of patent SU1404664A, the liquid injection into a special chamber is proposed [11];
- patent CRU 2398328C2 also proposes to arrange a separate chamber for needle electrodes [12];
- patent SU 1470985 proposes an annular chamber device [13];
- patent RU 2132471C1 implies annealing of exhaust gases with their subsequent processing by an electric field.

The disadvantage of these patents is the need to introduce an additional chamber in front of the muffler into the design of a vehicle. This complicates the design of the muffler and purification system and makes it impossible to upgrade the existing fleet of vehicles.

As a result of analyzing the patented solutions, the authors propose placing the electrodes directly in the muffler, moreover, not flat but annular ones that are mounted not on the inner surfaces of the muffler but along its central axis. This arrangement provides an oncoming movement of gas particles when the discharge is directed from the electrode towards the engine collector. The counter motion increases the impact ionization of gas molecules, the attachment and detachment of electrons.

The purpose of this study is to establish dependences that describe the process of ionization and purification of exhaust gases by providing a corona discharge in the muffler.

To achieve the goal, the objectives of the study include:

- developing and studying a mathematical model for the movement of gas particles in the muffler;
- obtaining deterministic dependences that relate the volume of the engine combustion chambers, the number of revolutions of the crankshaft, the electric field strength and the dynamic viscosity of the gas;
- developing experimental benches, carrying out experiments to determine the opacity and composition of exhaust gases under the action of an electric discharge;
- processing the results of the experiment.

Scientific novelty is determined by obtaining theoretical and experimental relationships between the magnitude of the electrical pulse, gas pressure, particle velocity and dynamic viscosity of the gas, which determine the degree of exhaust gases purification.

The practical usefulness consists in obtaining the data for developing an engineering method of calculating the operating mode of an electric pulse in a muffler.

The obtained data and dependences are of scientific and practical importance.

2 Materials and methods

The physics of the corona discharge process has been sufficiently studied [14]. The charge development begins with application of the high voltage to the charging electrode and producing electrons through the impact ionization. Subsequently, avalanche or chain ionization occurs, the essence of which lies in the fact that a free electron that has a greater energy of communication, when colliding with an atom, knocks out one electron from it and forms one positively charged ion. After the collision, the electron will gain energy and in the next collision, four electrons will appear, then eight, then sixteen and so on. The electrons will move towards the anode and positive ions towards the cathode.

In this case, the number of electrons n obeys the exponential law [15]:

$$n = n_0 \cdot \exp(\alpha x), \tag{1}$$

where x is the particle movement; n_0 is the number of free electrons with the run $x = 0$; α is the coefficient of ionization probability.

The counter movement increases the impact ionization of the gas molecules, attaching and sticking the electrons. The coefficient α increases rapidly with increasing the temperature and the field strength. Free electrons ionize gas atoms or stick to particles and this process is the most active near the corona electrode.

A number of studies determine the relationship between the electric charge density, ion mobility, ionization current, electric field strength E [16].

To prove the hypothesis put forward, it is necessary to study the patterns of particle motion in the muffler design proposed (Figure 1). The electromotive force F_e and the friction force F_c on other particles act on the gas particle located between the two electrodes [17].

The unusualness of the proposed design solution consists in placing the ring electrodes along the central axis of the muffler that allows increasing the friction force of particles determined by the Stokes law:

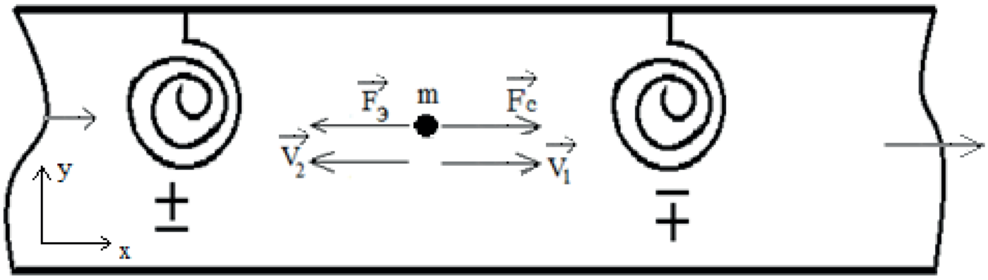
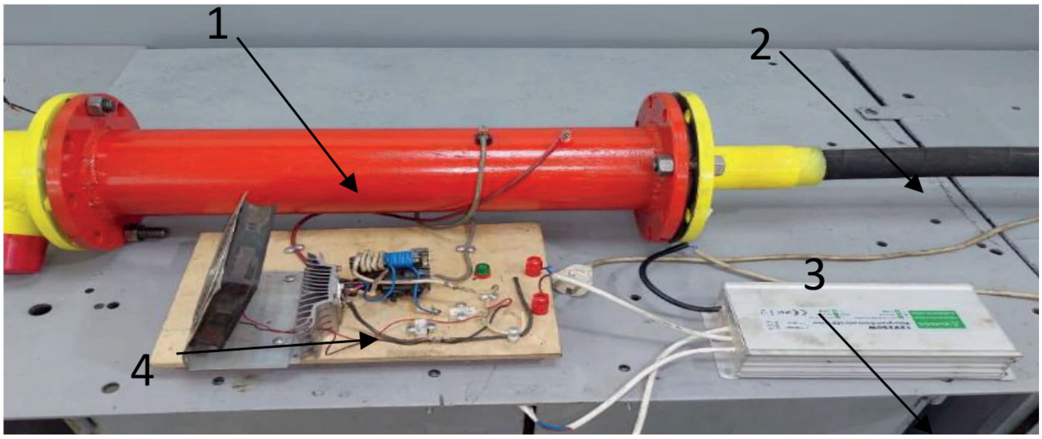


Figure 1 *Forces acting on the gas particle in the muffler*



1 - bench body, 2 - pipeline to the vehicle muffler, 3 - electric current source, 4 - instrument cooling radiator

Figure 2 *Experimental bench*

$$F_c = 6\pi r \mu V, \tag{2}$$

where μ is the dynamic viscosity of the gas particles; r is the particle radius; V is the total velocity after the particles collision [18].

When determining the friction force, it is necessary to take into account the velocity of the particles collision, that is, when the EMF is directed opposite to the movement of the gas

$$V = V_1 + V_2, \tag{3}$$

where V is the total velocity after the collision; V_1 is the particle motion velocity determined by the EMF; V_2 is the velocity of the particle motion provided by the engine operation. The "+" sign in the equation means that the particles move to each other, the "-" sign means that they move in the same direction [19].

It is natural that, when adding velocities, the Stokes friction force increases (Figure 1). The ring shape of the electrodes allows providing an annular corona discharge that increases the efficiency of ionization [20].

The magnitude of the electromotive force is determined by the expression:

$$F_э = Eq, \tag{4}$$

where E is the intensity; q is the charge value.

To analyze the relationship of ionization parameters with the engine crankshaft speed and the capacity of the internal combustion engine chambers, there is the following dependence:

$$V = \frac{\omega \cdot Q}{\pi R^2}, \tag{5}$$

where ω is the number of the crankshaft revolutions; Q is the total capacity of the combustion chamber; R is the average radius of the muffler [21].

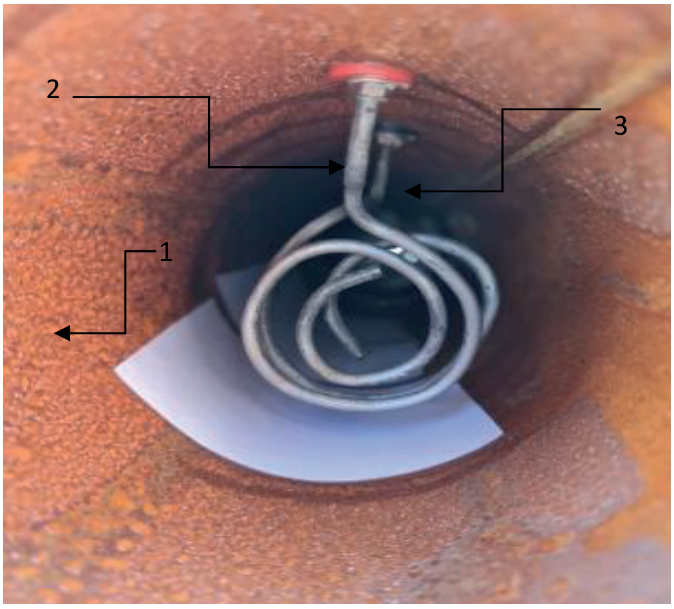
An important issue is accounting for the probability in the equation of particle motion. Taking into account Equations (1) to (5), the following system of equations is obtained:

$$\begin{cases} m\ddot{x} = Eq \pm 6\pi r \mu V, \\ V = \dfrac{\omega \cdot Q}{\pi r^2}, \\ n = n_0\, e^{-\alpha x}, \end{cases} \tag{6}$$

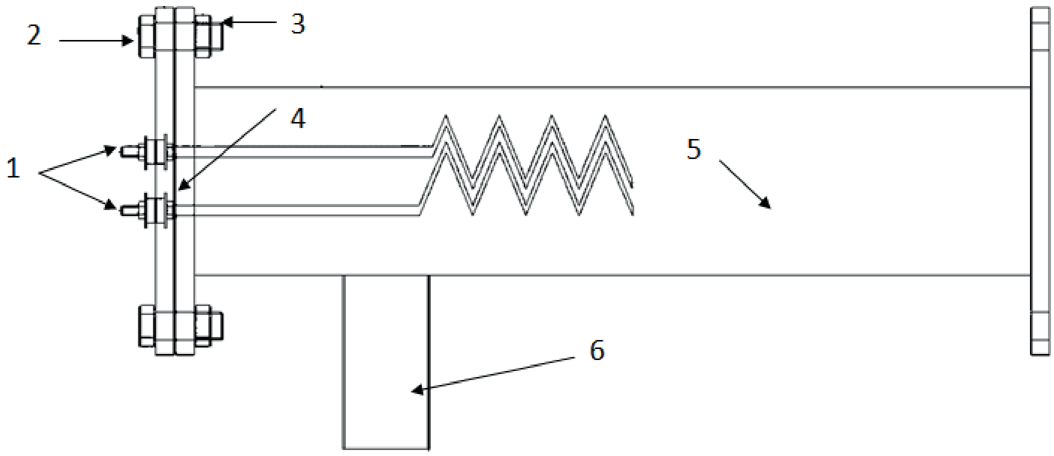
where the first equation of the system of Equations (6) presents a differential equation of the gas particle motion under the action of forces F_c and $F_э$ in the muffler (Figure 1); x is the particle motion; t is the particle life time [22].

The preliminary analysis of the system of equations in (6) leads to the following conclusions:

- analytically, it is necessary to determine the value of X: the law of particle motion;
- experimentally, there is determined the value and pattern of changing the probability α.



1 - inner surface of the steel pipe wall, 2 - anode, 3 - cathode
Figure 3 *Location of the spiral electrodes inside the experimental bench*



1 - electric pulse electrodes, 2 - bolt, 3 - nut, 4 - flange, 5 - steel pipe, 6 - inlet pipe
Figure 4 *Diagram of the bench for reducing the exhaust gases of the diesel engine toxicity*

Therefore, to achieve these objectives and goals of the study, the analytical and experimental research methods were used [23].

An experimental bench has been made for the experiments. The bench (Figure 2) is a steel pipe of the diameter of 110 mm, the length of 500 mm and the wall thickness of 1.5 mm. Flat flanges with the outer diameter of 205 mm, the inner diameter of 110 mm and the thickness of 15 mm are attached to the pipe by means of a bolted connection [24].

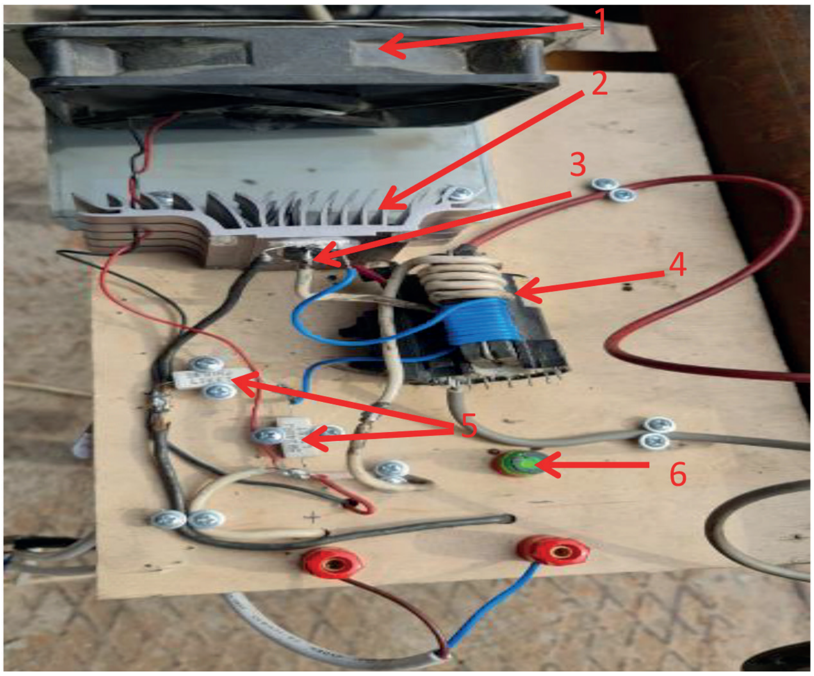
The electrodes, as mentioned, are placed inside the tube of the bench (Figure 3).

The diagram of the experimental bench for reducing the toxicity of the exhaust gases of a diesel vehicle is shown in Figure 4.

The electrical circuit of the bench consists of such elements as a source of high voltage electric current (20 kV) (Figure 5) and two metal plates twisted into a spiral arranged parallel to each other that are separated from each other by air (Figure 3). This device is an air condenser, thus the electric current will not flow in such a circuit, because the layer of air between the plates, as well as other gases, is not capable of conducting electricity. However, by communicating the necessary potential difference to the metal plates, the galvanometer connected to this circuit begins to record the electric current passing due to ionization of the air layer between these plates. In the presented set, the exhaust gases have been cleaned due to impact ionization of the exhaust gas [25].

The goal of the experiment was to confirm the hypothesis of impact ionization of exhaust gases. To achieve the goal, the following tasks have been performed:

- developing and manufacturing an experimental bench;
- developing and assembling an electrical circuit for operation of the electrodes;



1 - cooler; 2 - radiator; 3 - transistor; 4 - multiplier; 5 - resistance (ceramic resistors); 6 - device operation indicator

***Figure 5** High voltage electric current source*

***Figure 6** BOSCH FSA 740 diagnostic center*

- preparing the electrodes;
- selecting the equipment for measuring the composition of exhaust gases;
- selecting the equipment for measuring the exhaust smoke.

The experiment has been carried out in two stages as follows:

- at the first stage, the smoke of exhaust gases has been measured before the impact of the ionizer and 60 seconds after the impact of the ionizer depending on the range of rotation of the engine crankshaft (810, 1080 and 1486 rpm);
- at the second stage, there have been measured the contents of oxygen, carbon dioxide and carbon monoxide gases, hydrocarbons with the use of the gas analyzer before and after exposure to the ionizer [26].

The measurements have been made by the diagnostic center "BOSCH FSA 740" (Figure 6).

The experimental bench has been connected to the vehicle with a rubber hose to the inlet pipe 1 for supplying the exhaust gases to the set (Figure 7). With the ionizer turned on, the exhaust gas has been exposed to a high voltage electric field.

To perform the high-precision toxicity measurements during the experiment, the BOSCH FSA 740 diagnostic complex has been used. The diagnostic complex "BOSCH" includes a diagnostic scanner "KTS 560", a gas analyzer

Figure 7 *The process of connecting the vehicle to the diagnostic complex*

"BEA 050", an optical smoke meter "BEA 070". With the help of the KTS 560 scanner, the speed of the vehicle engine has been monitored to fix the data at a certain moment of the engine crankshaft speed. On the BEA 050 gas analyzer, the composition of the exhaust gases has been determined, namely the content of oxygen in the exhaust gases, carbon dioxide, hydrocarbon and carbon monoxide. The data from the "BEA 070" optical opacity meter has been used to determine the percentage of smoke in the exhaust gases of a diesel engine.

3 Results

As a result of integration of the first differential equation of system of equations in (6), the function of particle displacement between the electrodes has been obtained:

$$X(t) = \left(v_0 - \frac{Eq}{6\pi r\mu}\right) \cdot \left(1 - e^{-\frac{6\pi r\mu}{m}t}\right) + \frac{Eq}{6\pi r\mu}t. \tag{7}$$

Taking into account that the $\left(1 - e^{-\frac{6\pi r\mu}{m}t}\right)$ tends to zero at t → 0, the trend of the X variation law has the form:

$$X = \frac{Eq}{6\pi r\mu}t, \tag{8}$$

where t is the electron life time.

Based on the dependence, it follows that the path of a particle between the electrons can be the greater, the greater the charge strength and intensity, but it decreases with increasing the Stokes force.

The ionization rate has been determined by the derivative of Equation (8); it is equal to:

$$V = \frac{Eq}{6\pi r\mu}. \tag{9}$$

From the third equation of system of equations in (6), by taking a logarithm, the dependence of the probability α on the X displacement and the quantities characterizing the process is determined:

$$\alpha = \frac{X}{\ln\frac{n_0}{n}}. \tag{10}$$

The main result of mathematical modeling is obtaining a dependence that determines the relationship between all the process parameters.

The speed of the particle, from the condition of ionization and dynamic friction in Equation (9), should be equal to the speed of movement developed by the engine Equation (5):

$$\frac{Eq}{6\pi r\mu} = \frac{\omega \cdot Q}{\pi R^2} \tag{11}$$

or

$$\frac{Eq}{\pi r\mu} = \frac{\omega \cdot Q}{R^2}. \tag{12}$$

Equation (12) relates EMF (*Eq*), dynamic viscosity (μ), the crankshaft speed (ω), the engine combustion chamber capacity (Q), the muffler size (R) .

Thus, knowing such characteristics of the engine as the cylinder capacity Q, the crankshaft speed ω, the muffler radius and the reference values of dynamic viscosity μ, one can determine the magnitude of the pulse *Eq*.

At the first stage of the experiment, the opacity of the exhaust gases of a diesel vehicle has been measured.

There have been made 3 measurements of the exhaust gas smoke before exposure to a high-voltage electric field and 3 measurements after exposure to different engine operating ranges of 750, 1000, 1550 rpm. The recorded readings of the exhaust smoke are shown in Table 1. According to the smoke readings, a diagram has been created (Figure 8) that shows the degree of changing the smoke of the exhaust gas of a diesel engine depending on the speed of the crankshaft.

The impact of the high voltage electric field on the

Table 1 *BEA 070 smoke meter readings for diesel engines*

Impact type	Crankshaft rotation speed, rpm	Period of operation, s	Opacity, %
Before the exposure to a high voltage electric field	750		21.5
After the exposure to a high voltage electric field	750		15.7
Before the exposure to a high voltage electric field	1000		30.2
After the exposure to a high voltage electric field	1000		28
Before the exposure to a high voltage electric field	1550		32.4
After the exposure to a high voltage electric field	1550	60	30.6

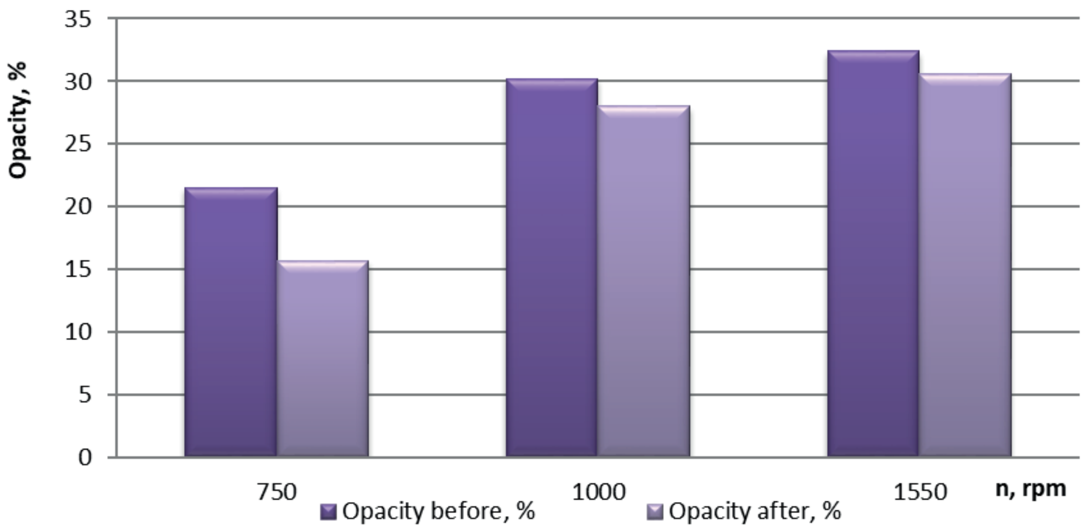


Figure 8 *Diagram of changing the degree of opacity (turbidity) of diesel exhaust gas*

Table 2 *BEA 050 gas analyzer readings before the exposure to a high voltage electric field*

No	Rotation speed, 1/min	O_2 %vol	CO_2 %vol	HC ppm vol	CO %vol	Measurement time, s
1	750	17.18	2.38	22	0.026	
2	1000	17.41	2.28	24	0.051	
3	1550	17.63	2	29	0.065	60

Table 3 *BEA 050 gas analyzer readings after the exposure to a high voltage electric field*

No	Rotation speed, 1/min	O_2 %vol	CO_2 %vol	HC ppm vol	CO %vol	Measurement time, s
1	750	17.27	2.35	22	0.019	
2	1000	17.46	2.27	25	0.049	
3	1550	17.61	2.1	30	0.062	60

exhaust smoke of a diesel engine has been proven in accordance with the diagram shown in Figure 8. After the impact of a high voltage electric field on the exhaust gas of a vehicle, decreasing the smoke concentration has been detected. In particular, with the engine crankshaft speed of 750 rpm, decrease the smoke concentration by 27% has been revealed. With the engine operating range at 1000 rpm, decrease of the smoke concentration by 7.3% has been noted. With the engine speed of 1600 rpm, the smoke concentration decreased by 5.56%.

As a result of the field experiment, decreasing the degree of turbidity of the exhaust gas has been more than 5%. The physical process is explained by the impact ionization of the gaseous medium, which is proven by experiment.

At the second stage of the experiment, 6 measurements have been made to determine the composition of the exhaust gases of the vehicle. Measurements have been made before the impact of the ionizer on the engine operating ranges of 750, 1000, 1550 rpm. The data are shown in Table 2. Then, the experiment has been carried out after the exposure to the ionizer. Measurements of the exhaust gases composition have been recorded and presented in Table 3.

At the second stage of the experiment, according to the data from the diagrams of Figures 9-12, it has been revealed that the high voltage electric field affects the composition of the exhaust gases. With the engine speed of 750 rpm, the effect of impact ionization on the composition of the vehicle exhaust gas has been proven, namely, increasing the percentage of oxygen in the exhaust gases by 0.52% and decreasing carbon dioxide content of 1.26%, decreasing carbon monoxide content of 27% have also been recorded. When the engine has been running at 1000 rpm, increasing the concentration of oxygen by 0.29% and hydrocarbons by 1 unit of carbon concentration in ppm by volume of gas, decreasing carbon dioxide 1.26% and decreasing carbon monoxide by 3.92% have been recorded. During the operation of the engine at 1550 rpm, it has been found that the content of oxygen and carbon monoxide decreased by 0.11% and 4.62% respectively. The carbon dioxide content in the exhaust gases increased by 4.76% and hydrocarbons increased by 1 unit of carbon concentration in ppm by volume of gas.

The hypothesis about the possibility of reducing the toxicity of exhaust gases of a diesel engine under the influence of a high voltage electric field was confirmed.

Figure 13 shows that the humidity of the exhaust

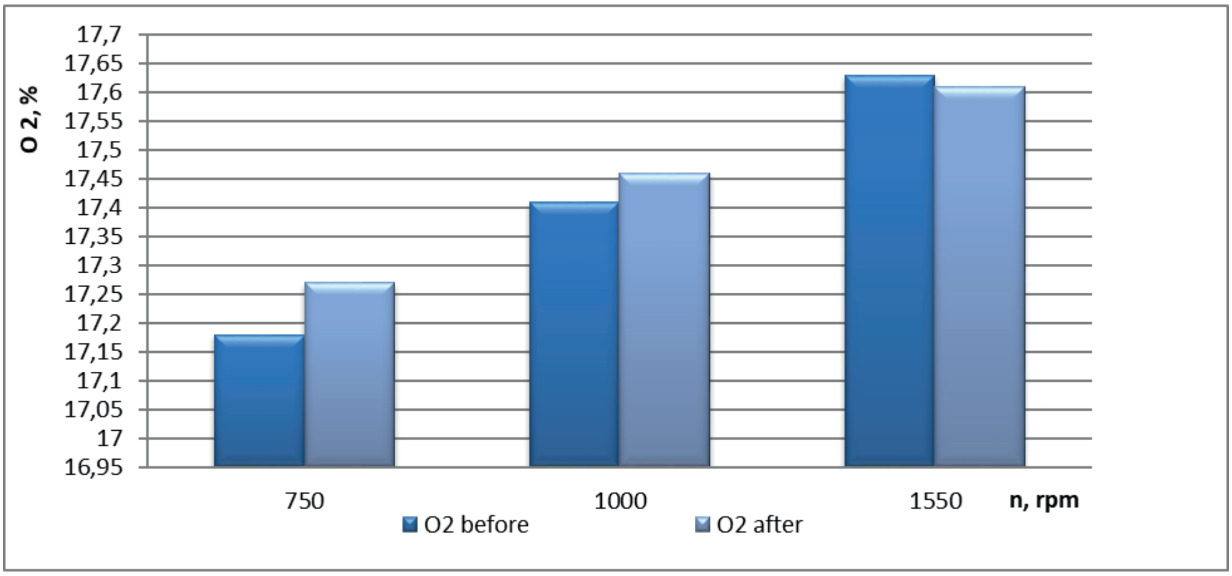


Figure 9 *Diagram of the oxygen content in the exhaust gases before and after the exposure to a high voltage electric field*

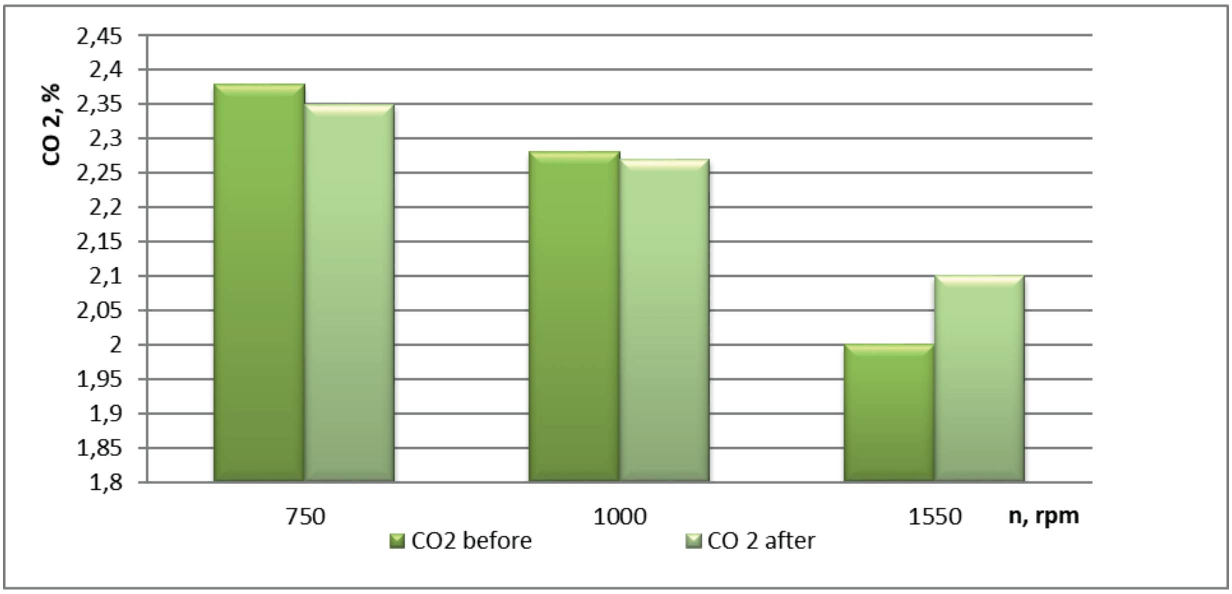


Figure 10 *Diagram of the carbon dioxide content before and after the exposure to a high voltage electric field*

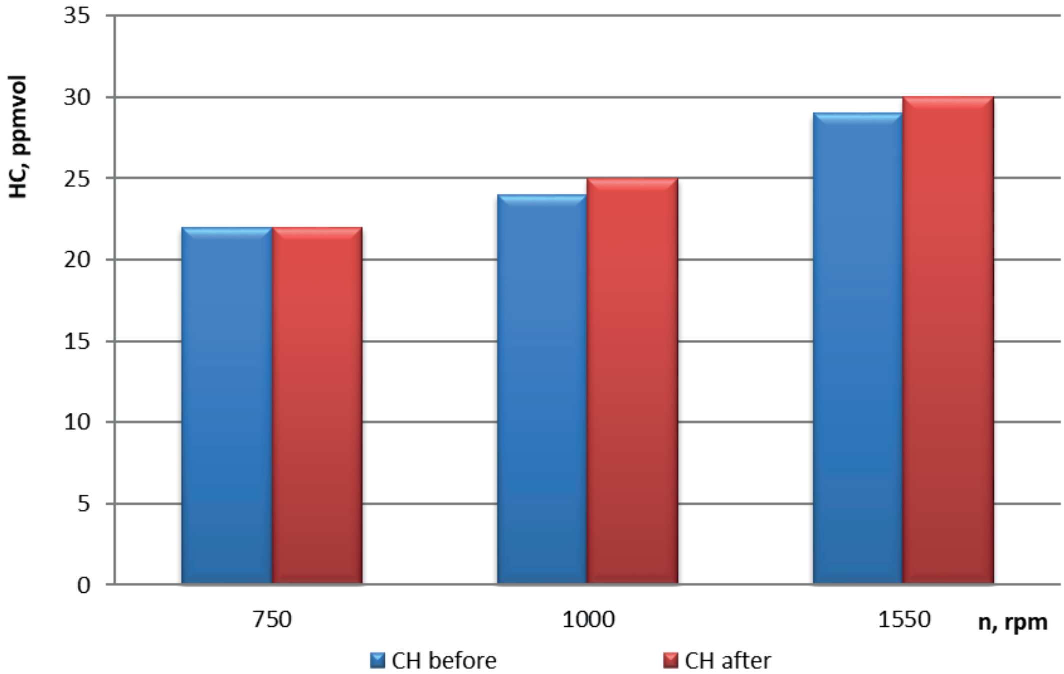


Figure 11 *Diagram of the hydrocarbon content before and after the exposure to a high voltage electric field*

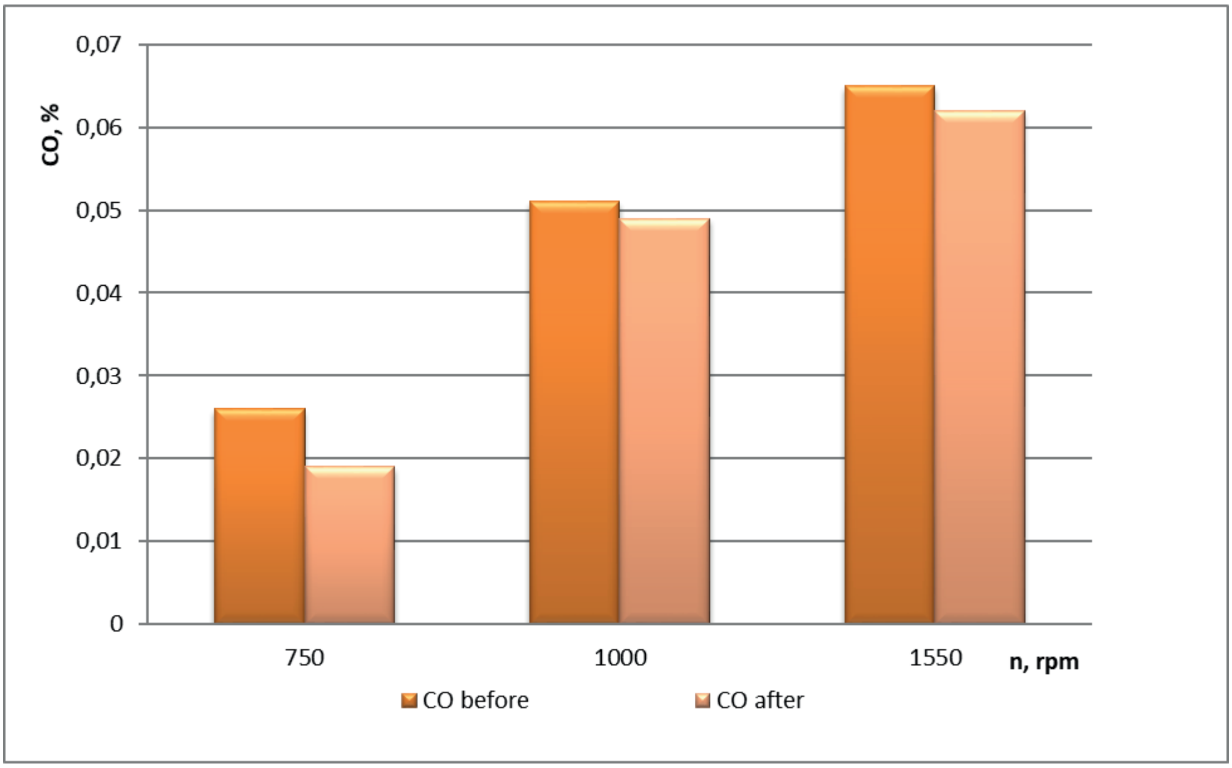


Figure 12 *Diagram of the carbon monoxide content before and after the exposure to a high voltage electric field*

gases increases sharply after the influence of a high voltage electric field.

Figures 14-17 show graphs of the dependence of changes in humidity and gas concentration on the number of revolutions.

As the speed increases, the oxygen content increases and the humidity decreases. This is due to the fact that the electrical pulse purifies the gas.

The amount of hydrocarbon increases due to the increase in oxygen, favorable conditions arise for the chemical reaction of the combination of oxygen with hydrogen.

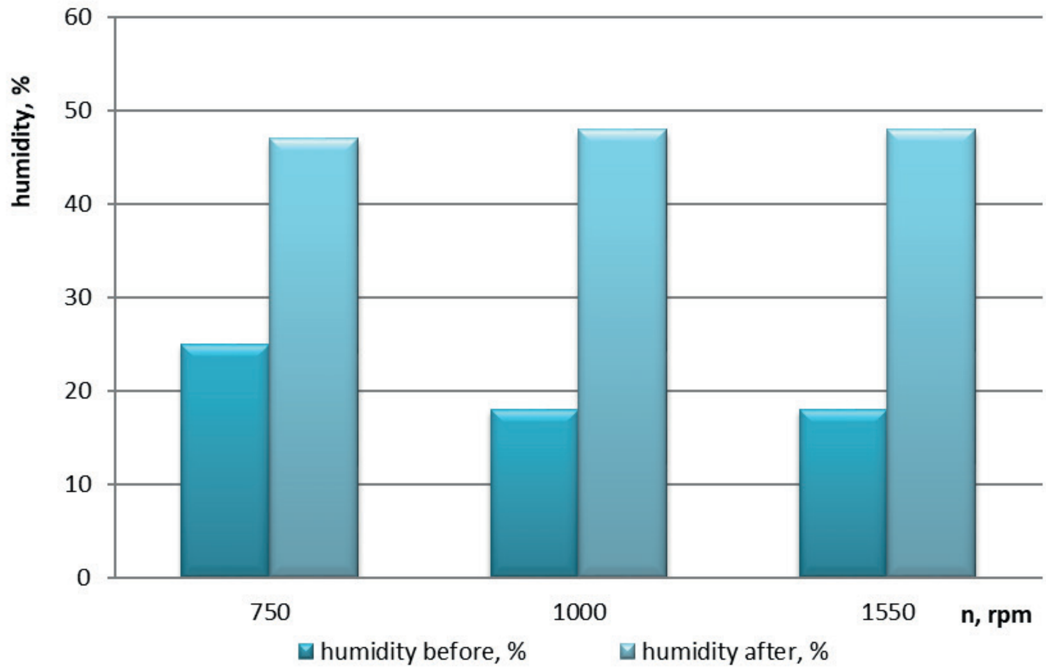


Figure 13 *Diagram of the humidity variation*

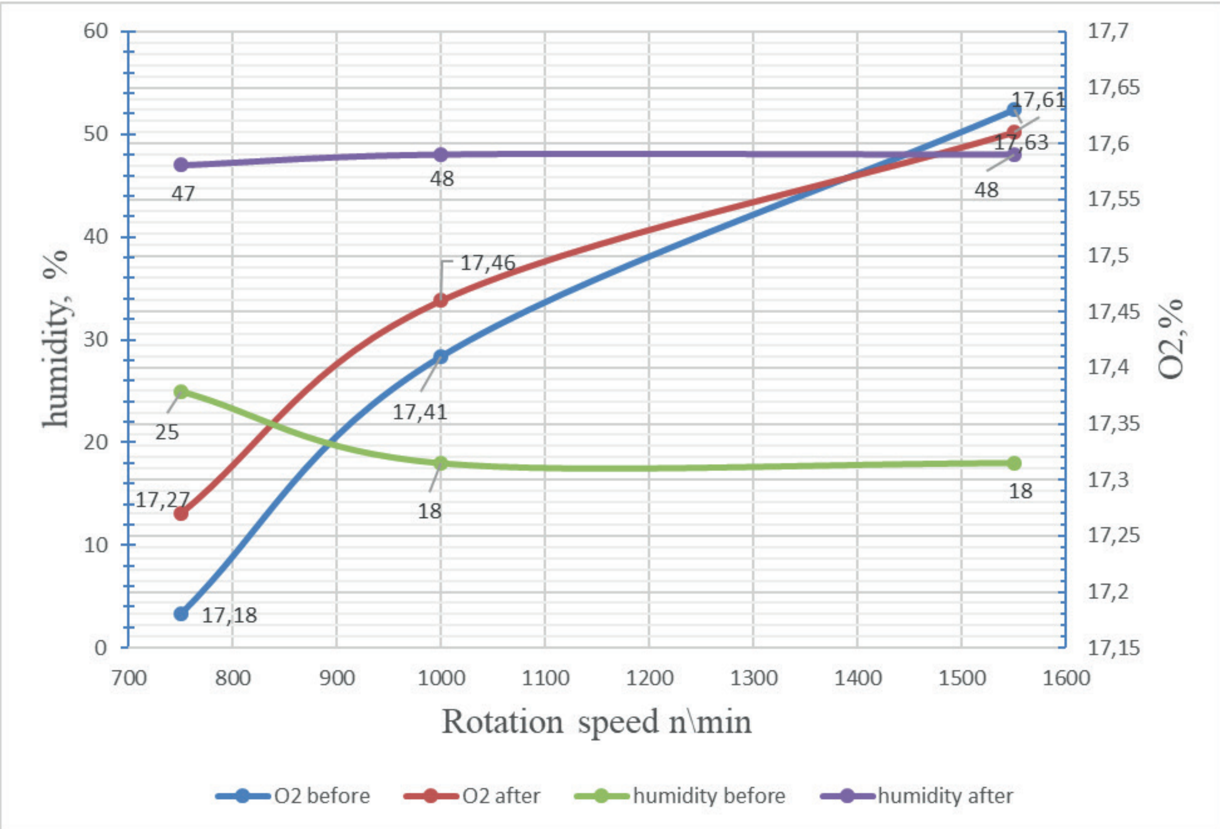


Figure 14 *Changing the oxygen content and humidity before and after the exposure to a high voltage electric field*

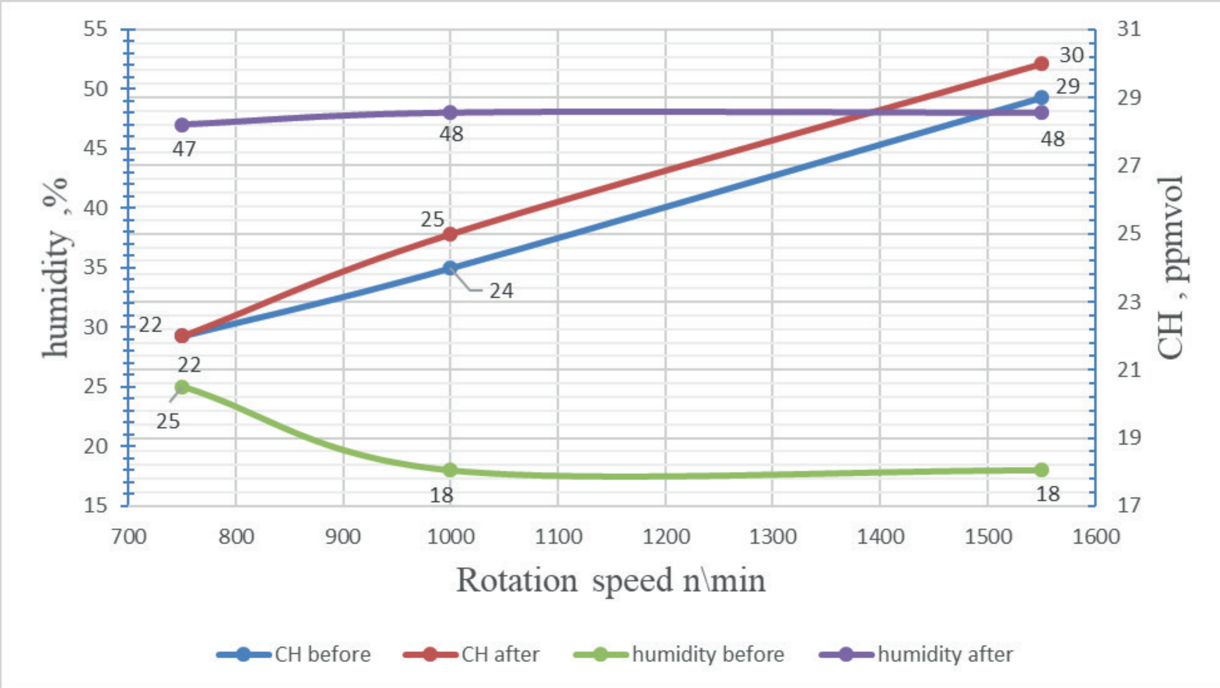


Figure 15 *Changing the hydrocarbon content and humidity before and after the exposure to a high voltage electric field*

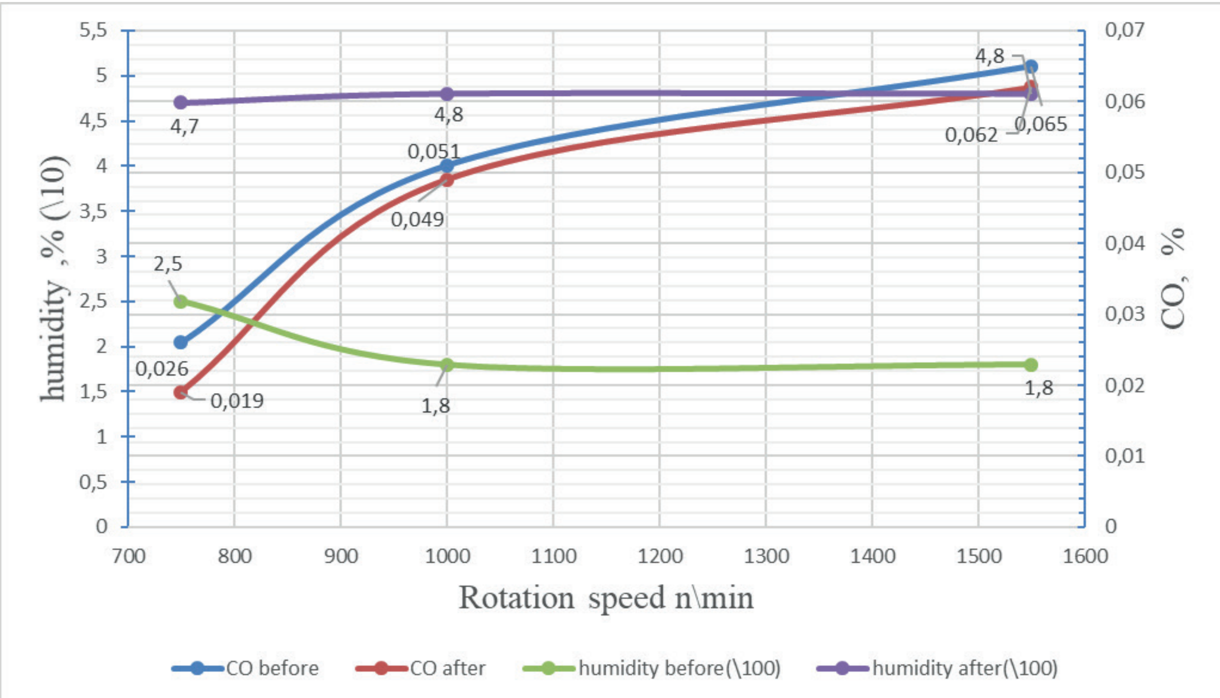


Figure 16 *Changing the carbon monoxide content and humidity before and after the exposure to a high voltage electric field*

The content of carbon monoxide and carbon dioxide decreased after exposure to an electric field. From the analysis of the graphs (Figures 14-17) it follows:

- after the pulse impact, the content of carbon monoxide and carbon dioxide decreases;
- the oxygen content increases, as the air is ozonized;
- increasing the oxygen content in the gas, together with the presence of water molecules and ionization, forms conditions for decomposing heavy organic gas molecules, which leads to increasing the hydrocarbon content.

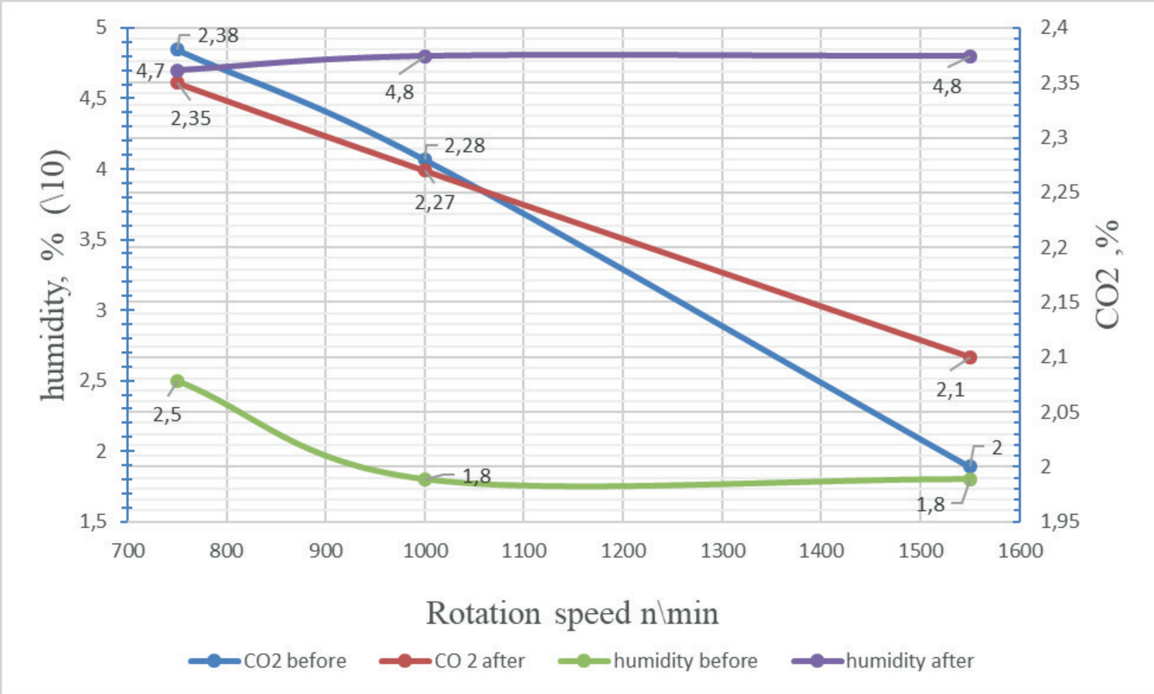


Figure 17 *Changing the carbon dioxide content and humidity before and after the exposure to a high voltage electric field*

4 Conclusions

Based on the results of the studies, the hypothesis of the possibility of purifying the exhaust gases of internal combustion engines by exposing it to a corona discharge in an electric field has been confirmed.

A mathematical model for the movement of gas particles in a muffler has been developed and studied.

A deterministic relationship between the capacity of the combustion chambers, the discharge parameters and the engine speed has been obtained.

An experimental bench has been developed and manufactured. The constructive decision on the location of two ring electrodes along the axis of gas movement and when it moves in the opposite direction from the collector and the discharge has been justified.

With increasing the engine speed and with a constant discharge, the oxygen content increases and that of carbon monoxide and carbon dioxide decreases. The hydrocarbon formation reaction takes place.

In general, the results obtained have practical and scientific significance. The obtained materials form the basis for the calculation method for the design of automobile mufflers with an electric impulse effect on exhaust gases.

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