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SPECIAL ISSUE PAPERS

Comparative Analysis of Engine Ignition Systems

Albina A. Tropina, Lonnie Lenarduzzi, Sergey V. Marasov, and Anatoliy P. Kuzmenko

***Abstract*—The experimental data of a comparative analysis of a spark-ignition system and a nanosecond-discharge-based ignition system in engines are presented. The effectiveness of the ignition systems used was evaluated on fuel consumption and exhaust-gas composition during the road and laboratory tests. It has been discovered that using a plasma-ignition system rather than a spark-ignition system considerably improves engine performance and reduces tailpipe emissions at the same time. The obtained results are analyzed based on the equilibrium calculations of combustion products and on the analytical evaluation of the flame-extinguishing-layer width near the cylinder walls of the combustion chamber.**

***Index Terms*—Internal combustion engine, nanosecond discharge, nonequilibrium plasma, plasma-ignition system.**

I. INTRODUCTION

IT is known that the organization of a highly effective ignition process combining energy efficiency and engine-emission reduction in spark-ignition engines is a very complicated problem. It is connected not only with operation at high pressures but also with the wide operating loads realized during engine operation and, consequently, with different demands on the ignition system. At low loads in the vicinity of an engine-cylinder top dead center (TDC), lean fuel mixtures require a more effective ignition system to achieve combustion. At high loads in the vicinity of the TDC, a stoichiometric or rich mixture is observed, and a more powerful ignition system is not usually needed. Another problem of highly effective ignition-process organization is cycle-by-cycle and cylinder-to-cylinder irregularity and local mixture characteristics changing from cylinder to cylinder. Last, different combustion chambers have different turbulent intensities, and as a consequence, a more powerful ignition is not needed if turbulent intensity is rather low.

An additional problem with highly effective combustion in engines is the very real problem of ecological and environmental protection from the toxicity of engine exhaust gases. Solving this problem involves the ability to create an initial flame kernel with a very lean mixture. One way to achieve a highly effective ignition-process organization is nanosecond-discharge ignition. Using this technology [1] makes possible to reach high reduced electric fields, resulting in the efficient generation of highly energetic electrons and large amounts of active radical species needed for combustion-process initiation. It has been recently demonstrated that nonequilibrium plasma formed by such discharges can stabilize lean premixed flames, increase the flame blow-off velocity, as well as expand the flammability limits [2].

The question of how different discharges influence the combustion process using different ignition sources has been investigated for a long time. All existing ignition systems can be divided into two groups, namely, thermal- and nonthermal-ignition systems. Such a division is connected with the different mechanisms of combustion-process initiation or by thermal equilibrium-plasma arc, pulsed-arc discharge of the spark-ignition systems, or by nonequilibrium plasma. The latter can be divided into three possible ways that are needed to create a nonequilibrium-plasma arc. These three ways are by using radio-frequency [3], laser-discharge [4], or so-called transient plasma-ignition systems [5], depending on the electrode configuration, such as pulsed-corona discharge or nanosecond discharge in a uniform or streamer form.

The detailed analysis of the most recent experimental data on the effects of nonequilibrium plasma on combustion and ignition processes is presented in [6]. It should be noted that the main properties of nonequilibrium discharges at higher than atmospheric pressures are not yet well studied. One reason for that is the fact that the plasma structures formed become very small at such pressures and that, therefore, their experimental investigations become very complicated.

The review of papers devoted to the use of short-pulsed discharges as the ignition sources in the internal combustion engines presented in [7] does not allow one to make the final decision about their perspectives because the data presented are very controversial. However, the fact is that the flame-front velocity is enhanced in lean fuel mixtures by using nanosecond-discharge ignition. This is demonstrated in [8] and [9]. The potential for improving lean combustion operation by nanosecond plasma ignition is also demonstrated by the results of cylinder-pressure measurements in a single-cylinder gasoline internal combustion engine presented in [10].

II. PROBLEM FORMULATION AND EXPERIMENTAL SETUP

The goal of the investigation is to conduct the comparative analysis of a standard-(spark)-ignition and a nonthermal-ignition system based on a nanosecond discharge. The effectiveness of the ignition systems was evaluated on engine-exhaust-gas composition and fuel consumption during the road tests and the experiments conducted on the laboratory experimental setup.

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A. A. Tropina and S. V. Marasov are with the Department of Mechanics and Hydraulics, Kharkov National Automobile and Highway University, 61002 Kharkiv, Ukraine (e-mail: albina.tropina@gmail.com; sergey.marasov@gmail.com).

L. Lenarduzzi is with Plasmatronics, LLC, Center Moriches, NY 11934 USA (e-mail: lonnie@plasmatronicsllc.com).

A. P. Kuzmenko is with the Department of Internal Combustion Engines, Kharkov National Automobile and Highway University, 61002 Kharkiv, Ukraine (e-mail: an.kuzmenko@gmail.com).

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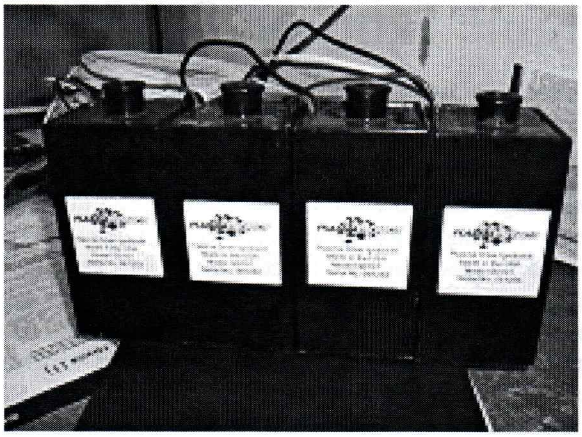

Fig. 1. PDI system.

The nonthermal plasma-ignition system used for the experiments described here is the plasma-drive-ignition (PDI) system [11]. This ignition system is configured in separate blocks for every cylinder of the engine (Fig. 1).

The PDIs used for these experiments are of model GD101 and are configured as follows:

1) Input voltage: 12 V (negative-ground automotive system). The current requirements are 16 A for 1.6 ms/ignition cycle. The standby current draw is 50 mA.
2) Output waveform: The duration is 22 ns. The rise time from 0 to 30 kV is 2 ns.
3) Output energy: 120 mJ.
4) Programming: Slave mode, no timing control, and one plasma discharge per trigger signal. Trigger-signal antibounce, noise rejection, feedback, and diagnostics are enabled, while the CAN interface is disabled.
5) Triggering: Current sourcing at system voltage with 150-Ω pull-up resistor. The plasma event occurs on the rising edge of the trigger-signal square wave.

The experimental setup used for the laboratory tests is shown in Fig. 2. Its main parts are as follows:

1) the engine MeMZ-307 (for DAEWOO Sens);
2) the transmission box;
3) the load control for the rocking-lever mechanism;
4) the rocking-lever-mechanism model MPB 24/28;
5) the weight device for load measurements;
6) the gas fuel container;
7) the scales for liquid-fuel-consumption measurements;
8) the data-acquisition computer system;
9) the device for air-consumption measurements;
10) the gas-reducing gear;
11) the engine radiator;
12) the water heat exchanger;
13) the resonator;
14) the control panel;
15) the air manifold inlet;
16) the exhaust manifold outlet;
17) the manometer.

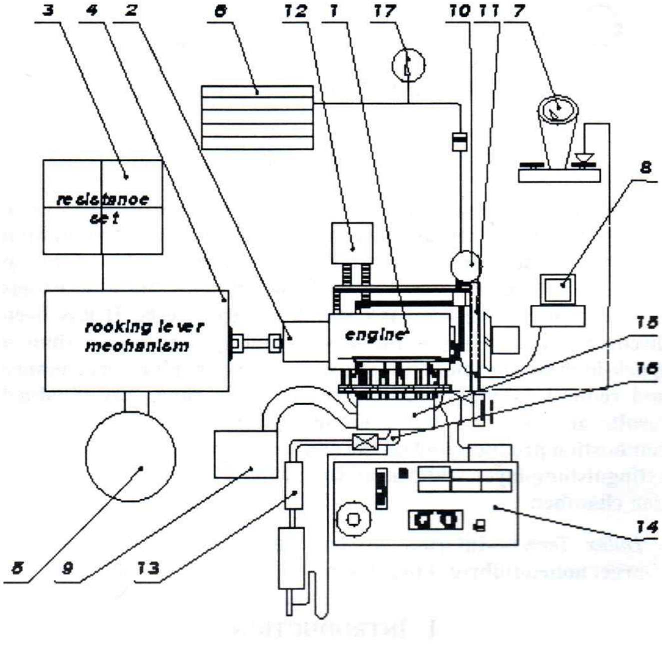

Fig. 2. Experimental setup.

TABLE I
THE ENGINE-LOAD CONDITIONS

Mode number	Engine speed	Percent load (%)	Mode length (min)
1	idle		4
2	3000	100	2
3		75	2
4		50	2
5		25	2
6	3500	100	2
7		75	2
8		50	2
9		25	2

The engine-load conditions are presented in Table I, where 100% load corresponds to $M = 96$ N · m at $n = 3000$ r/min and $M = 101$ N · m at $n = 3500$ r/min. Shaft torque was controlled within ±1% of full scale of shaft torque at maximum load. Engine speed was controlled within ±15–20 r/min, regardless of the dynamometer load.

The experimental setup also includes the sensor devices for oil and exhaust-gas temperature measurements and the sensor devices for oil-pressure measurements and for the determination of the engine-crankshaft speed.

The main characteristics of the four-cylinder engine MeMZ-307 are as follows: 1) The compression ratio is 9.5; 2) the cylinder diameter and the piston stroke are 75 and 73.5 mm, respectively; and 3) the working volume is 1.299 L.

The engine was not equipped with an exhaust after-treatment device. The S/T control mode was used to control the engine speed and torque.

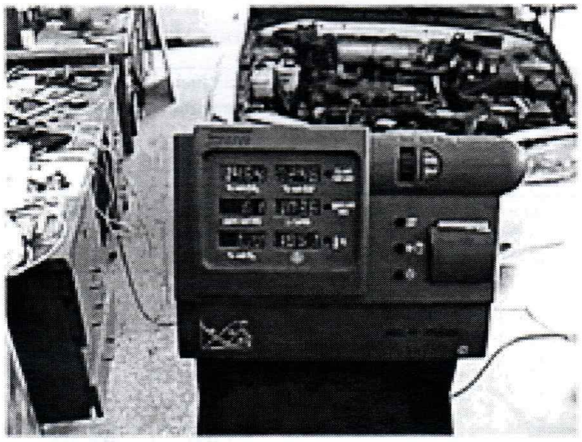

Fig. 3. Gas analyzer SUN MGA 1500S.

The laboratory tests were conducted for engine operations on liquid fuel (95-octane gasoline), as well as on natural gas. Additionally, the effectiveness of the plasma-ignition system operating with different constructions of spark plugs was evaluated. The following four configurations of the ignition system were used:

1) the standard-(spark)-ignition system (one-electrode spark plugs);
2) the plasma-ignition system (one-electrode spark plugs);
3) the plasma-ignition system (multielectrode spark plugs);
4) the plasma-ignition system (spark plugs with additional chamber).

In one cylinder of the engine, a special piezoelectric sensor was installed to detect the pressure changing inside the cylinder, but the indicator-diagram measured results are not presented here. The gap size of all spark plugs used was 0.8 mm, and the pressure of operation at the ignition point in accordance with the indicator-diagram data was $P \sim 15$ atm.

III. ROAD-TEST RESULTS

The comparative analysis of the PDI system and the standard-spark-ignition system consisted of the following experimental stages:

1) exhaust-gas-toxicity measurements during idle engine operation, when the vehicle toxicity is maximal;
2) exhaust-gas-toxicity measurements during the road tests;
3) fuel-consumptiondefinition during the road tests by the weight method.

For analyzing the engine-exhaust-gas composition, the gas analyzer SUN MGA 1500S was used (Fig. 3). For the road test, the four-cylinder engine DONC was used with the following characteristics: 1) The compression ratio is ten; 2) the cylinder diameter and the piston stroke are 75.5 and 83.5 mm, respectively; and 3) the working volume is 1.495 L. The vehicle used was the 2000 Hyundai Accent. The comparative analysis of ignition systems was performed for the engine (Fig. 4) operating on 95-octane gasoline. The standard spark plugs were changed to multielectrode spark plugs made by the company BRISK.

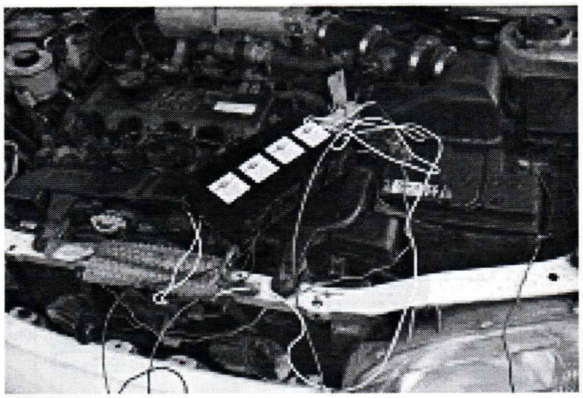

Fig. 4. General view of the engine used for the road tests.

At each condition, all vehicle tests were repeated three times. At the idle emission test, the pollutant concentrations were measured in the tailpipe exhaust of a stationary vehicle with no transient vehicle operation and no engine load. An enhancement of the basic idle test involved putting the vehicle in neutral and revving the engine to 2220–2500 r/min in an attempt to simulate the vehicle emissions under the loaded condition. Such an idle-test procedure was first proposed in the U.S. Clean Air Act Amendments of 1970 as a quick and inexpensive means to identify high emissions.

To measure fuel consumption very accurately, the following procedure was used. The fuel tank was completely drained by activating the vehicle fuel pump, and 1.5 L of the test fuel was added to the vehicle fuel tank. After that, the vehicle was started and driven until it stopped. The procedure was repeated three times with corresponding intervals to cool the engine oil to an initial temperature.

The road tests consisted of three driving cycles, including the dispersal time of 10% to a vehicle speed of 60 km/h; the stationary mode of operation with a vehicle speed of 60 km/h, which lasted to 85%; and the brake time of 5%. The vehicle trajectory was controlled by GPS. At the same climatic conditions, the total distance covered by the vehicle for three cycles was 16.5 km.

The road tests were carried out on a specialized road proving ground with very high quality road surfacing and special road marks with no vehicles, except for the tested one. The vehicle was driven by the same person each time. It allowed us to conduct the road test at the same conditions. The error bars on fuel-consumption measurements and emissions were 2%–3% and −3%–4%, respectively.

The experiments indicated that, for lean mixtures, the PDI system has shown much better ecological characteristics than the standard-ignition system, particularly for idle engine operation (Fig. 5), where $\mathrm{CO}_{\max} = 5\%$.

The use of the PDI system reduces the carbon monoxide content in the exhaust gases, while the engine is idling by 50% compared with the standard-spark-ignition system. At the same time, the carbon monoxide content measured during the road tests does not practically change, with the ignition system changing.

It was also discovered that, at the same air-excess coefficient for conventional spark and plasma ignitions, the combustion

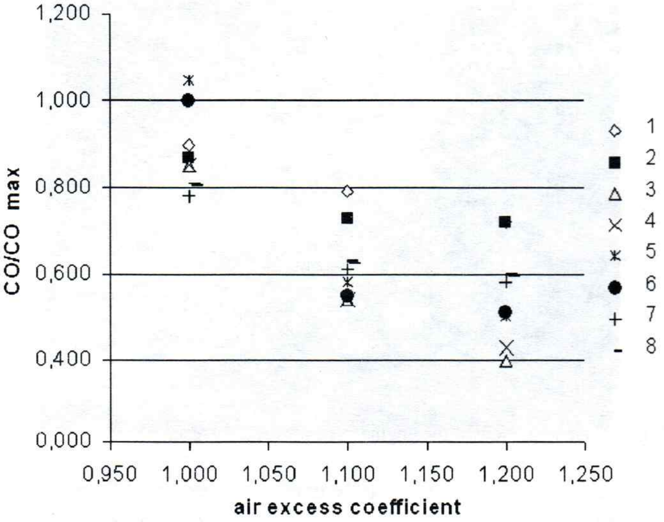

Fig. 5. CO content in the exhaust-gas composition. 1, 2, 3, and 4—2200 r/min. 5, 6, 7, and 8—800 r/min. 3, 4, 5, and 6—PDI system. 1, 2, 7, and 8—Spark-ignition system.

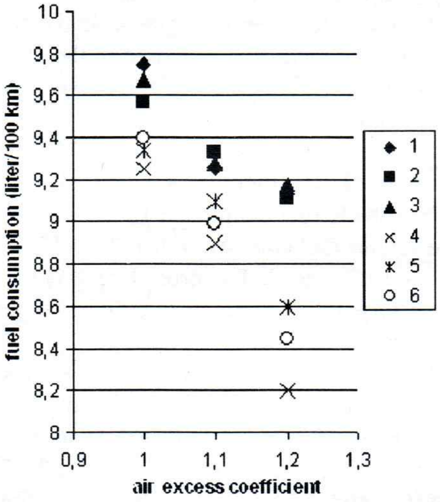

Fig. 6. Fuel-consumption measurements. 1, 2, and 3—Spark-ignition system. 4, 5, and 6—PDI system.

completeness with a PDI system increased with engine speed. This fact was confirmed by the decrease of HC concentration in the exhaust-gas composition when the nonthermal ignition was used. It was also confirmed by the results of fuel-consumption measurements that showed that fuel consumption was reduced by as much as 7% compared with the standard spark ignition (Fig. 6). It has also been learned that ignition-timing variation did not considerably improve the test results.

The next stage of the experiments was carried out in laboratory conditions using the experimental setup shown in Fig. 2.

IV. LABORATORY EXPERIMENTAL RESULTS

The experiments were conducted for two engine-crankshaft speeds: 3000 and 3500 r/min. All the measurements with different ignition systems and different spark plugs were repeated three times for 100% load to evaluate the accuracy of measurements, and the average values of all variables are presented in the following. The error bars on fuel-consumption measurements and emissions were 2%–3% and −2%–4%, respectively. The results of fuel-consumption measurements for four configurations of the ignition system and for 100% load are presented in Table II, where variants a), b), and c) for $n = 3500$ r/min correspond to the data of three repeatable measurements.

TABLE II
THE RESULTS OF FUEL-CONSUMPTION MEASUREMENTS

Number of Complements	Engine crank shaft speed (RPM)	Liquid fuel consumption (kg/hour)	Gas fuel consumption (m^3/hour)
1) the standard ignition system, one-electrode spark plugs	3500	a) 1.178 b) 1.22 c) 1.2	a) 0.085 b) 0.084 c) 0.082
	3000	0.947	0.0735
2) the plasma ignition system, one-electrode spark plugs;	3500	a) 1.11 b) 1.1 c) 1.105	a) 0.083 b) 0.085 c) 0.084
	3000	1.0	0.0735
3) the plasma ignition system, multi-electrode spark plugs	3500	a) 1.057 b) 1.06 c) 1.057	a) 0.085 b) 0.083 c) 0.086
	3000	0.947	0.074
4) the plasma ignition system, spark plugs with additional chamber	3500	a) 1.106 b) 1.099 c) 1.11	a) 0.084 b) 0.084 c) 0.083
	3000	0.947	0.072

It is seen that the engine operation on liquid fuel using the PDI system allows a reduction of fuel consumption by 6%–11%, depending on the spark plugs chosen. It was rather surprising that fuel consumption did not change much for the engine operation on natural gas.

The physical explanation of this fact can be connected with the properties of nanosecond-discharge ignition. Taking into account that the corresponding cross sections of direct ionization by electron impact for methane–air mixtures are lower than that of liquid fuel and that the content percentage of gas in the stoichiometric methane–air mixture is rather low, the main advantages of nonthermal ignition are expected to be maximized with lean gaseous-fuel combustion mixtures.

The basic parameters of the environment in which the PDI system was tested, such as fuel–air-mixture compositions and ignition timing, were not changed during the gaseous-fuel experiments. It would have been very helpful to have the ability to change these parameters in order to obtain more information on exactly how much improvement in combustion efficiency that the PDI system can attain when operating on gaseous fuels. Despite this fact, the results of exhaust-gas-toxicity measurements are rather promising.

As the toxic emissions measured were maximal at 100% load and to make the result presentation more clear, the diagram form was used (Figs. 7 and 8). The details of emission measurements for different modes of engine operation are presented in Table III for the engine operation on liquid fuel for two configurations of an ignition system.

Fig. 7 shows the results of carbon monoxide and HC content measurements in exhaust-gas composition for the engine

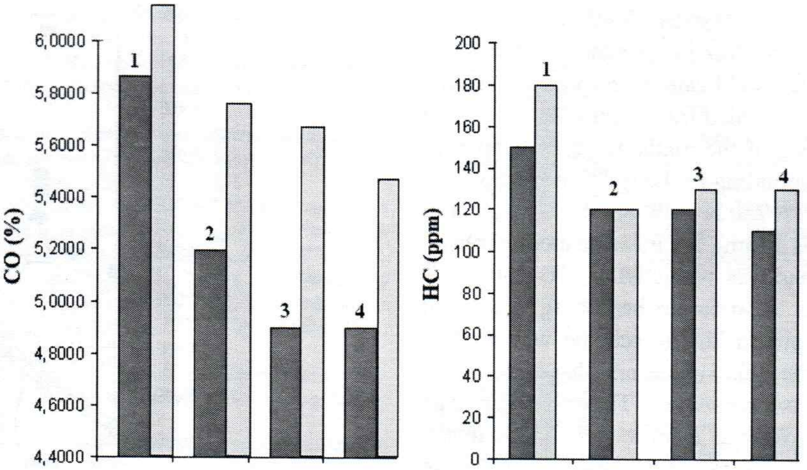

Fig. 7. CO and HC contents in the exhaust-gas composition for the engine operation on 95-octane gasoline for 100% load. ■—$n = 3500$ r/min . □—$n = 3000$ r/min .

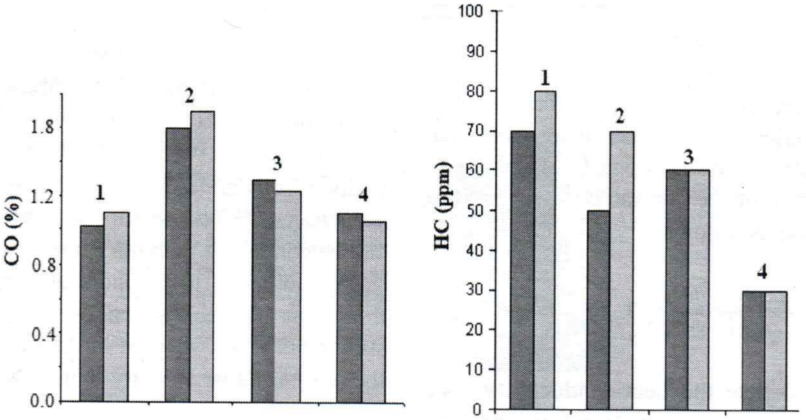

Fig. 8. CO and HC contents in the exhaust-gas composition for the engine operation on natural gas.

TABLE III
THE RESULTS OF EMISSION MESUREMENTS FOR THE ENGINE OPERATION ON LIQUID FUEL

Number of complements	Mode number	CO %	HC ppm	Air excess coefficient
1) the standard ignition system, one-electrode spark plugs	2	6.2	180	0.988
	3	0.84	126	0.99
	4	0.73	140	1.012
	5	0.57	113	1.011
	6	5.87	150	0.99
	7	1.02	99	0.995
	8	0.94	110	1.002
	9	0.76	102	1.010
2) the plasma ignition system, one-electrode spark plugs;	2	5.75	120	0.991
	3	0.71	104	1.010
	4	0.52	125	0.998
	5	0.45	90	1.002
	6	5.2	120	1.012
	7	0.8	75	1.015
	8	0.75	80	0.992
	9	0.60	89	1.015

operation on liquid fuel for four configurations of an ignition system. The numbers in the figure correspond to the numbers of the ignition-system configurations discussed in the previous section. Fig. 8 shows the CO and HC contents in exhaust-gas composition for the engine operation on natural gas (the symbols in Figs. 7 and 8 coincide, and the results correspond to 100% load).

V. DISCUSSION

As the road tests and the laboratory experiments have shown, the main advantages of the PDI system described here include low fuel consumption and much better ecological characteristics compared with the conventional spark-ignition system. It is known that spark-ignition systems are characterized by very low energy-transfer efficiency. It is connected with the fact that the heat generated by spark ignition is dissipated during the diffusive and arc phase of discharge. Therefore, as usual, in combustion-process investigations, the spark discharge is considered as the heat energy source. At the same time, for other kinds of discharges, gas-ionization levels and the ignition process are differentiated very much, depending on the energy-input ways and ignition system used. For nonthermal-ignition systems, the electric-field energy is distributed in gas-molecule internal degrees of freedom by different ways, depending on the signal formed by the pulse generator.

The effectiveness of using a nanosecond discharge as an ignition source can be evaluated on reduced electric-field values E/N, as the rate constants of ionization reactions, electron and vibration excitation, dissociation by electron impact, and attachment reactions have very strong exponential dependence on E/N. The reduced electric-field value is responsible for the generation of active particles needed for the ignition process to initiate. In [12], on the basis of the mathematical model proposed for conditions corresponding to the ignition-process initiation in engines ($T_{\mathrm{mixture}} = 700$ K$-$800 K, $P = 10-15$ atm, and the interelectrode gap is 1 mm), the mean reduced electric-field value in a streamer head was evaluated as 250–280 Td. It should be noted that, since no streamer branching was taken into account, a rather simplified kinetic scheme was used to calculate the reduced electric-field values, and these values can be considered as the approximate ones. The important data point is that such a high reduced electric field leads to the excitation of electron levels of molecules that, in turn, can reduce ignition delay time.

Another possible way that short-pulse discharge influences the combustion and ignition process is connected with the normal-flame-velocity increase caused by additional active-particle production in the discharge zone with a corresponding increase of the chemical reaction rate.

Last, short-pulse discharge can create the additional impulse transfer stimulating the mixing and generation of short-scale turbulence in the combustion zone. The last effect can be evaluated by the Karlovitz number for methane–air-mixture combustion in the gas engine as follows:

$$Ka = \frac{a_0\sqrt{\varepsilon/15\nu_0}}{S_L^2} \leq 1$$

where a_0, ε, ν_0, and S_L denote the heat-conductivity coefficient, the turbulent-kinetic-energy dissipation rate, the kinematic viscosity, and the normal flame velocity, respectively.

It is known that, on the condition that $K \leq 1$, the combustion process is realized in the regime of long-scale turbulence at a negligible influence of short-scale turbulence and, consequently, of a negligible influence of additional short-scale turbulence generated by the discharge. The evaluation performed concerns to the case of nonequilibrium-plasma-assisted combustion; in the case of plasma-assisted ignition considered, the last effect is negligible due to the ultrashort time of discharge action.

The theoretical calculations of combustion-product composition were performed based on the equilibrium conditions and using the detailed GRI-Mech 3.0 mechanism [13] of high-temperature methane oxidation. The influence of discharge was modeled by injection of radicals O and OH. The results of the equilibrium calculations of CO concentration based on the stoichiometric-mixture composition of Stavropol natural gas (CH_4—97.7%, C_3H_8—0.3%, C_2H_4—0.2%, CO_2—0.5%, and N_2—1.3%) are shown in Fig. 9. The observed deviation between the calculated and measured results can be attributed to the unburned gases in the engine cylinder; this fact is easily confirmed by the equilibrium calculations with additional content of HC in the initial mixture composition.

According to the equilibrium calculations, the concentration of HC in the exhaust gases is negligible. The main reason for deviation from equilibrium HC concentration in the experiments is connected with the nonuniformity of temperature and mixture composition in the combustion chamber. Furthermore, the main source of HC formation is situated in the so-called zone of flame extinguishing near the engine-cylinder walls. The width of this zone can be evaluated as $\delta \cong S_L^{-1/2}$; therefore, reduction of HC content in the exhaust gases at plasma ignition can be connected with the decrease of the flame-extinguishing-layer width due to the normal-flame-velocity increase under the action of a nanosecond discharge. The experimental measurements of HC content in the exhaust gases have shown that the normal flame velocity increases at plasma ignition by 1.2–2.25 times.

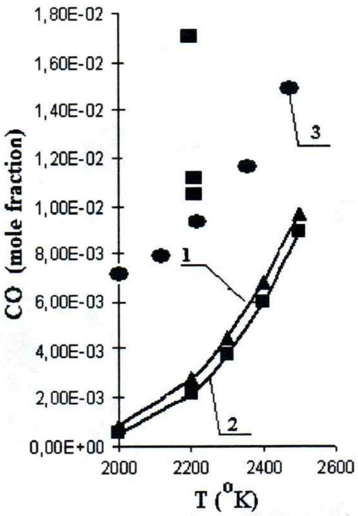

Fig. 9. CO content in the exhaust-gas composition. 1—Without discharge. 2—With discharge. 3—With addition of HC. ■—Experimental data.

VI. Conclusion

The experimental-investigation results have confirmed the effectiveness of a nanosecond discharge as the ignition source in internal combustion engines. Further experimental investigations based on indicator-diagram measurements are needed to gain further insight into the details of the combustion process initiated by a nanosecond-discharge-based ignition system.

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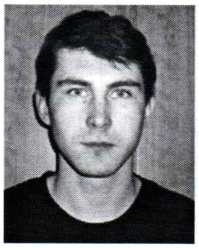
Albina A. Tropina received the Ph.D. degree in mechanics of liquids, gas, and plasma from the School of Mathematics and Mechanical Engineering, V. N. Karazin Kharkiv National University, Kharkiv, Ukraine, in 1999.

From 1990 to 1999, she was a Researcher and an Assistant Professor with V. N. Karazin Kharkiv National University. Since 2000, she has been with Kharkov National Automobile and Highway University, Kharkiv, as a Senior Lecturer and Associate Professor with the Department of Mechanics and Hydraulics. Her research interests are focused on the theoretical investigation of plasma-assisted combustion and combustion processes in engines and combustion in the presence of an electric field.

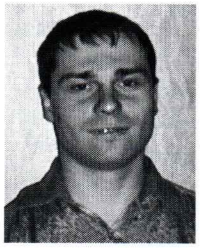
Lonnie Lenarduzzi received the Aeronautical Engineering degree, the Airframe and Power Plant License, and the Aircraft Pilot License from the Pittsburgh Institute of Aeronautics, Pittsburgh, PA, in 1977.

He went on to work for the U.S. Department of Energy while attending California State University, Long Beach. In 1989, he started his own business, providing high-voltage equipment to government and private laboratories worldwide. He is currently with Plasmatronics, LLC, Center Moriches, NY.



Sergey V. Marasov received the Master's degree in computer systems from the Mechatronics Faculty, Kharkov National Automobile and Highway University, Kharkiv, Ukraine, in 2008.

Since 2008, he has been an Engineer with the Department of Mechanics and Hydraulics, Kharkov National Automobile and Highway University. His research interests are focused on automobile computer systems and sensors, as well as computer processing of experimental data.



Anatoliy P. Kuzmenko received the Master's degree in internal combustion engines from National Technical University (KhPI), Kharkiv, Ukraine, in 2007. He has been working toward the Ph.D. degree in the Department of Internal Combustion Engines, Kharkov National Automobile and Highway University, Kharkiv, since 2007.

His research interests are focused on the investigations of working processes in spark-ignition engines.

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