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DESIGN OF CONTROL SYSTEM FOR THE GAS ENGINE WITH AN ELECTRONIC CONTROL UNIT AND SEQUENTIAL FUEL INJECTION

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This paper reports the results of studying the electronic control system designed for a gas internal combustion engine with spark ignition operated on liquefied petroleum gas. A new feature in the control system is the possibility to provide the most effective sequential type of gas fuel injection, in which fuel is injected in a sequence corresponding to the order of operation of the cylinders. The special feature of the designed control system is that a movable voltage distributor (ignition distributor) of the ignition system was modified to ensure sequential injection. The ignition distributor modification involves installing an additional setting disc with one integrated permanent magnet on its drive shaft and an additional Hall sensor on the body of the ignition distributor. This makes it possible to ensure that the electronic control unit receives a signal about the angular position of the camshaft, thereby enabling consistent fuel injection. The principle of operation of the gas engine control system provided by the electronic control unit has been described. The structure of the modified ignition distributor is shown. Tests of the gas engine with a new control system involving the designed electronic control unit Avenir Gaz 37 "B" and the software module "B2" were carried out. The tests confirmed the feasibility of the designed electronic control system, which implies consistent injection of gas fuel. In addition, idling tests have shown that the carbon monoxide and hydrocarbon content in exhaust engine gases is significantly lower than the maximum allowable for motors without catalysts. The control system designed could be used for converting the diesel vehicles in operation into gas engines. The use of this control system ensures their safe operation

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1. Introduction

Designing new multifunctional electronic control systems for internal combustion engines (ICEs), especially those operated on alternative environmentally friendly motor fuels, is a way to build environmentally-friendly and energy-efficient vehicles. The use of such fuels, which include gas motor fuels and, above all, liquefied petroleum gas (LPG), could help reduce critical environmental pollution. At the same time, according to the World LPG Association (WLPGA) [1], it is the LPG that ranks third in terms of fuel consumption in the world (after conventional gasoline and diesel fuel).

The most expedient way to increase the share of the use of gas fuels is the production of new engine models or the conversion of the diesel engines in operation into gas ICEs with spark ignition [2, 3]. In such gas ICEs, 100 % of the diesel fuel is replaced by cheaper and more environmentally-friendly gas fuel, which can significantly reduce the operating costs of vehicles [4]. Such conversion makes it possible to achieve a particularly high economic effect for those vehicles that have high operating costs related to diesel fuel.

New models of gas ICEs are designed under industrial conditions based on diesel engines. Such technology significantly reduces the cost of their production since it does not require the construction of a new complete manufacturing system but makes it possible to only introduce changes in the structure of individual engine parts or its systems. As a result, new gas ICEs based on diesel engines are reliable and

durable; their components are designed to work under heavy loads characteristic of engines with a high compression ratio. In addition, new gas ICEs are equipped in advance with control systems designed and manufactured by specialized firms. In turn, gas ICE control systems are also produced to be installed on new engines. Therefore, when preparing to produce gas ICEs, manufacturers make the necessary changes in the design of exactly those parts and systems on which elements or components of the control system kit should be installed.

However, given the specific structure of modern control systems designed for certain new gas ICEs, they cannot be used in most cases for conversion, especially in those diesel engines that have been in operation for a long time. First of all, this applies to the engines whose standard structure lacks a camshaft angular position sensor (CAPS) and a master disk mounted onto this shaft.

Thus, designing control systems that are intended for the conversion of diesel engines in operation is a relevant scientific and practical issue addressing which could improve the environmental parameters of the engines and reduce their operating costs.

2. Literature review and problem statement

The operation of gas ICEs can be effectively managed only by an electronic control system. Such a control system

should include in its structure at least a subsystem of power supply and gas fuel injection, an electronic subsystem for ignition and filling the cylinders with a charge of working mixture. The joint operation of these systems can be ensured only with the help of an electronic control unit (ECU).

In [5], it is proved that the use of LPG has a positive effect on the effective properties of combustion, as well as contributes to lower harmful emissions and provides higher resistance to detonation. The characteristics of emissions and combustion of LPG were investigated and defined. The sequential injection of LPG is carried out by gas electromagnetic nozzles whose operation is enabled by a microcontroller.

Paper [6] proves that the operation of those subsystems should be managed by an electronic control unit (ECU) based on acquiring and analyzing signals from certain sensors and subsequent calculations of control signals for the relevant actuating elements.

Study [7] shows that the use of compressed natural gas (CNG) to power the gas engine makes it possible to improve not only economic indicators but also to comply with higher emissions standards. In addition, the cited study reports a new electronic engine control system and the structure of ECU hardware.

Work [8] investigates the effect of the duration of direct sequential injection of compressed natural gas (CNG) into the combustion chamber of a gas ICE on its power and level of harmful emissions. The duration of injection was set by ECU. It is shown that with increasing engine speed, emissions of oxides and carbon dioxide decreased.

Study [9] proposes a hierarchical structure of tasks for ECU intended to control a car engine. It is shown that the implementation of the proposed architecture corresponds to the unit approach set by the international standard IEC 1499. In addition, it is demonstrated that the ECU receives a signal from the inductive speed sensor generated by a master disk of type 60-2.

In [10], a new electronic control system for a gas engine powered by CNG is presented. The authors described an engine control system, the ECU hardware structure, as well as an electronic engine control strategy. Test results show that the engine works reliably with the new designed power supply system and sequential injection of CNG.

All the above papers proved that the most effective type of gas fuel injection is sequential injection. The cited works showed that to ensure this type of injection, the ECU receives signals about the angular position of the crankshaft, as well as the angular position of the camshaft [11]. The reviewed literature considered serial gas engines with camshafts on which master disks have already been mounted, with camshaft angular position sensors (CAPS) also installed on the cylinder block heads. In addition, the above studies have shown that sequential injection ensures the effective combustion of gas fuel and is one of the effective ways to reduce the level of pollutants in exhaust gases from ICEs.

However, the application of such a technical solution during the conversion of diesel engines in operation is quite complex and economically impractical. This solution requires the design, manufacture, and installation of a new special cylinder block head on the converted engine.

That necessitated devising a new universal technical solution that would ensure the sequential injection of gas fuel without installing a master disk on the camshaft.

Therefore, one of the promising areas is to design control systems for gas ICE with the consistent injection of LPG and

to investigate the systems that could be used to convert such diesel engines.

3. The aim and objectives of the study

The aim of this study is to design a gas engine control system with an electronic control unit and a software module that enables the sequential injection of liquefied petroleum gas without mounting a master disk on the camshaft and a camshaft angular position sensor (Hall sensor). This would make it possible to convert the diesel engines of operating vehicles into gas engines with the consistent injection of liquefied petroleum gas. Applying the designed control system could improve the environmental parameters of the engine and increase the share of use of alternative environmentally friendly motor fuels.

To accomplish the aim, the following tasks have been set:

- to build a schematic diagram of the electronic control system for a gas engine with an electronic control unit, which enables the sequential injection of liquefied petroleum gas in the absence of the diesel engine's camshaft angular position sensor (Hall sensor) and a master disk;
- to modify the movable voltage distributor (ignition distributor) of the contactless electronic ignition system and install the ignition distributor on the gas engine;
- to design and manufacture the electronic control unit Avenir Gaz 37 level "B", as well as develop a software module that enables the sequential injection of liquefied petroleum gas, and install the unit on the gas engine;
- to test the gas ICE D-240-LPG-"B2" in order to determine the feasibility of the control system with ECU Avenir Gaz 37 level "B", as well as environmental indicators of the engine.

4. The study materials and methods

The object of our research is the processes in the electronic control system of the gas engine, in particular when managing the sequential injection of gas fuel.

To solve the tasks set for studying the electronic control system, both theoretical and experimental methods have been used.

To build an electronic control system for a gas ICE, an analytical approach was applied using the methods from the theory of automated control systems for the ICE rotation frequency.

In the experimental studies, bench (motor) tests of the electronic gas ICE control system with ECU Avenir Gaz 37 "B" with a downloaded software module (SM) of level "B2" were used as part of the gas engine of model D-240-LPG-"B2".

The proposed technical solutions regarding the feasibility of the control system were validated by comparing the signals from input sensors and controlling elements from the oscillograms acquired during experimental studies with a list of functions assigned to the system.

5. Results of studying the operation of an electronic control system of the gas engine

5.1. Schematic diagram of the electronic gas engine control system with an electronic control unit and sequential injection of gas fuel

Fig. 1 shows a schematic diagram of the electronic control system of gas ICE with ECU and sequential injection of LPG [12].

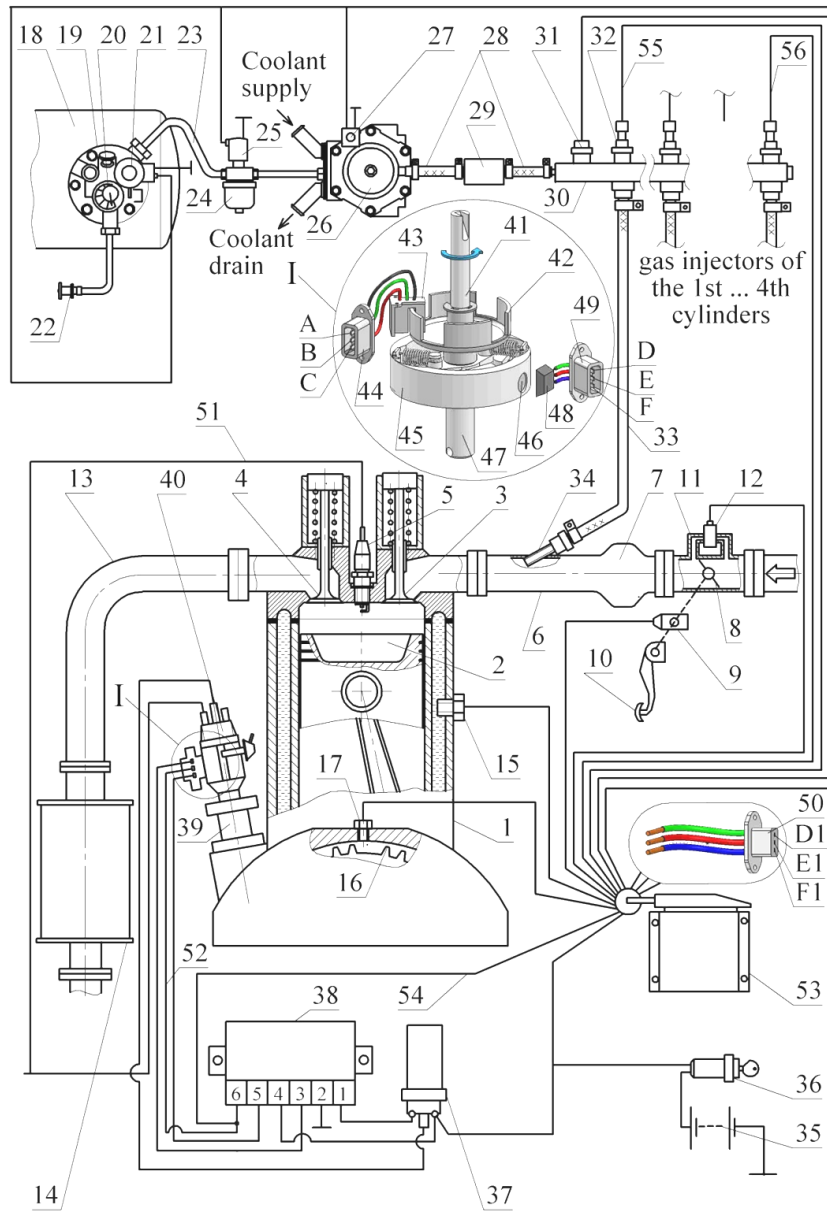


Fig. 1. Schematic diagram of the electronic gas engine control system with an electronic control unit and sequential injection of gas fuel

Fig. 1 shows: 1 – gas ICE; 2 – combustion chamber; 3 – intake valve; 4 – exhaust valve; 5 – spark plug (installed in the modified hole of the dismantled diesel nozzle); 6 – intake manifold pipe; 7 – the combined part of the intake manifold; 8 – throttle device with mechanical drive and throttle; 9 – throttle position sensor; 10 – control pedal of the speed mode of ICE operation (gas pedal); 11 – idle regulator; 12 – valve; 13 – exhaust pipeline; 14 – silencer; 15 – coolant temperature sensor; 16 – toothed master disk, type 60-2 or 60-2-2; 17 – CAPS; 18 – automobile gas cylinder for LPG; 19 – multivalve of gas cylinder; 20 – indicator of the LPG level in the gas cylinder; 21 – shut-off multi-valve solenoid valve; 22 – fuel unit; 23 – high-pressure gas line for LPG; 24 – gas filter; 25 – shut-off solenoid valve integrated into the gas filter; 26 – single-stage gas reducer-evaporator for LPG; 28 – low-pressure gas line; 29 – gas filter of the steam phase of LPG; 30 – common gas rail; 31 – combined pressure and temperature sensor for gas fuel; 32 – gas electromagnet-

ic nozzles; 33 – pipes; 34 – gas nozzles; 35 – battery pack ; 36 – ignition lock; 37 – ignition coil; 38 – electronic switch with integrated terminals from number 1 to number 6; 39 – ignition distributor special drive; 40 – ignition distributor; 41 – ignition distributor drive shaft; 42 – a regular master disk (in the form of screens that alternate with slots, and the number of screens or slots corresponds to the number of ICE cylinders); 43 – Hall sensor; 44 – connecting pad with integrated contacts “A”, “B”, “C”; 45 – an additional master disk (with one integrated permanent magnet 46), kinematically connected to the support plate of the centrifugal regulator, which is rigidly connected to the lower part of drive shaft 47 of ignition distributor 41; 48 – additional Hall sensor; 49 – connecting pad with integrated contacts “D”, “E”, “F”; 50 – reverse pad with integrated contacts “D1”, “E1”, “F1”; 51 – high-voltage wire(s); 52 – electrical connection of contact “B” of the connecting pad 44 with terminal number 6 of switch 38; 53 – ECU; 54 – electrical

connection of ECU 53 with terminal number 6 of switch 38; 55 – electrical connection of ECU 53 with gas electromagnetic nozzle 32 of the first cylinder; 56 – electrical connection of ECU 53 with the gas electromagnetic nozzle of the fourth cylinder. Contacts “D1”, “E1”, “F1” of the reverse pad 50 are electrically connected to the electronic control unit 53. The principle of operation of the control system is described on the example of the operation of a four-cylinder gas ICE. The master disk 42, which has four screens and four slots, also corresponds to the structure of the master disk for a four-cylinder engine.

The control system works as follows. When starting the operation of engine 1, the driver turns the key in the ignition lock 36, and the voltage from battery pack 35 is fed to the ignition system (ignition coil 37, switch 38, and ignition distributor 40) and ECU 53. In addition, the voltage is supplied to the starter (not shown in Fig. 1). At the same time, engine 1 starts to rotate; the signal generated by CAPS 17 from the interaction with the master disk 16 is fed to ECU 53. The signal generated by a Hall sensor 43, from the interaction with the master disk 42, from the contact “B” of pad 44, via electrical connection 52, is fed to terminal 6 of switch 38. Next, the signal via electrical connection 54 is duplicated to ECU 53. The pulse rate of this signal is proportional to the current speed of the crankshaft of engine 1.

ECU 53 processes the received signals, compares them and, if they are matched, supplies a voltage of +12 V to normally closed shut-off solenoid valves 21, 25, and 27. As a result, shut-off valves 21, 25, and 27 open, passing the LPG from the gas cylinder 18 through multivalve 19, the high-pressure gas line 23, and the gas filter 24 to the evaporator reducer 26. In the evaporator reducer 26, LPG, due to the supply of coolant (from the engine cooling system), evaporates to a gas state. Next, the gas through the low-pressure line 28, the gas filter 29 enters the common gas rail 30 and to the gas electromagnetic nozzles 32 closed at that time.

At the same time, a Hall sensor 48 (when passed by magnet 46) generates a signal corresponding to the position of the piston of the first cylinder, which approaches the upper dead point (UDP) at the compression stroke. The signal generated by the Hall sensor 48, through the contacts “E” and “E1” of the connecting pads 49 and 50, is supplied to ECU 53. Next, ECU 53 processes the received signal and, based on it, determines the moment, duration, and order of injection of LPG with gas nozzles 32, which corresponds to the order of operation of the cylinders of the gas ICE.

The throttle 8 is in a closed position at the time. And the flap (gate) 12 of the idle regulator 11, according to the signal calculated by ECU 53, is set to a position that corresponds to the starting speed of the crankshaft of engine 1. At the same time, the air under the action of rarefaction, by passing throttle 8 due to the closed flap (gate) 12 of the idle regulator 11, enters the intake pipeline 7.

At the same time, switch 38 of the contactless electronic ignition system sends a signal to the ignition coil 37. The coil generates a high voltage, which, along a high-voltage wire, enters the ignition distributor 40, and, from there, to the spark plug 5, which forms a spark of ignition in the combustion chamber 2.

At the same time, gas electromagnetic nozzles 32, through pipes 33 and gas nozzles 34, inject the LPG into the zone close to the closed intake valve. As a result, in each intake pipe 6 of the intake pipeline 7, a gas-air mixture is formed. When opening intake valve 3, the gas-air mixture

enters combustion chamber 2, where it is ignited from the spark plug 5. As a result, engine 1 is launched. At the same time, the value of the starting supply of LPG depends on the temperature of the coolant.

After starting engine 1, ECU 53 sets the flap (gate) 12 of the idle regulator 11 to a position that corresponds to the minimum speed of the crankshaft of engine 1. In turn, ECU 53 calculates the value of LPG supply depending on the temperature of the coolant and thereby adjusts the minimum speed of the engine idle.

With an increase in the load on engine 1 in order to increase the speed of the crankshaft, the driver presses pedal 10 of speed control. Throttle 8 opens and the amount of air that enters the intake pipeline 7 and the intake pipe 6 increases. At the same time, ECU 53, based on the signal calculated on the basis of acquiring and processing the signals from sensors 9 and 17, computes the beginning of moments and the duration of the pulses of LPG supply (injection) by the gas electromagnetic nozzles 32. As a result, the speed of gas engine 1 increases.

Thus, the designed system to control the operation of a gas ICE with ECU enables the sequential injection of LPG without installing a special master disk on the camshaft and a CAPS. Consequently, such a system, which does not require a significant complication of the structure (in particular, the installation of a new cylinder block head), should be used when converting the diesel engines in operation.

5.2. Features of modification of the moving voltage distributor (ignition distributor) of the ignition system

The gas ICE is equipped with a well-known contactless electronic ignition subsystem for four-cylinder ICEs, whose principle of operation is an intermediate variant between the electromechanical system and fully electronic ignition [13]. The main elements of the ignition subsystem are a movable voltage distributor (ignition distributor) of the model 40.3706 (Russia) with an integrated standard Hall sensor and a master disk (Fig. 2), an ignition coil, an electronic switch, a TESLA TS kit (Czech Republic) with 5 high-voltage wires and 4 Bosch spark plugs (Germany).

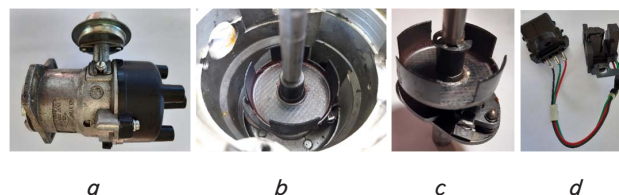


Fig. 2. Standard movable voltage distributor (ignition distributor): *a* – assembled ignition distributor; *b* – master disk installed in the body of the ignition distributor; *c* – standard ignition distributor drive shaft with a master disk and centrifugal regulator; *d* – standard Hall sensor

To enable the consistent injection of LPG, we modified the movable voltage distributor (ignition distributor). The ignition distributor modification was carried out by installing an additional master disk with one integrated permanent magnet and an additional Hall sensor, which are shown in Fig. 3, 4.

To manufacture an additional master disk, as well as to arrange it with an ignition distributor drive shaft, we constructed 3D models that are shown in Fig. 3.

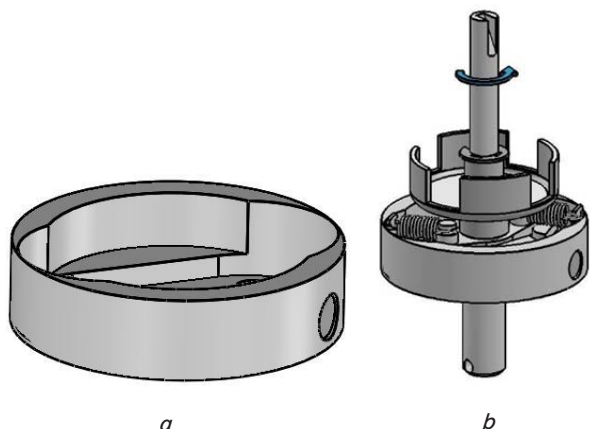


Fig. 3. 3D models of an additional master disk and an ignition distributor drive shaft with an additional master disk installed: *a* – 3D model of an additional master disk; *b* – 3D model of the ignition distributor drive shaft with an installed additional master disk

Based on the 3D model of an additional master disk, a plastic master disk was printed on a 3D printer (Fig. 4, *a*). Next, one permanent magnet was integrated into the plastic disk, and the disk was installed and fixed on the drive shaft of the ignition distributor (Fig. 4, *b*). In addition, Fig. 4, *c* shows an additional Hall sensor of model SS461A (manufactured by Honeywell Inc.) [14], as well as a modified ignition distributor. Fig. 4, *d* demonstrates that an additional Hall sensor is installed inside a specially made plastic case, which is fixed to the body of the ignition distributor. The Hall sensor is connected with an additional cable to the Avenir Gaz 37 level “B” ECU.

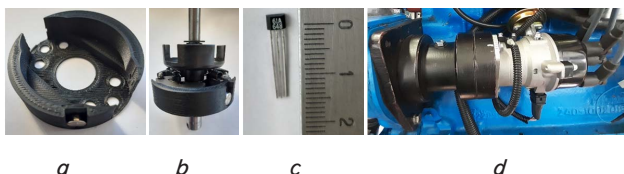


Fig. 4. Modified ignition distributor: *a* – a plastic additional master disk printed on a 3D printer with an integrated permanent magnet; *b* – the drive shaft of the ignition distributor with an additional master disk installed; *c* – an additional Hall sensor; *d* – assembled modified ignition distributor installed in a gas engine

An additional master disk is fixed to the ignition distributor drive shaft in the position in which a permanent magnet passes by the additional Hall sensor when the first cylinder-piston approaches the UDP during a compression stroke.

The modified movable voltage distributor (ignition distributor) is installed in the engine at the site of the dismantled standard UTN-5 CAPS (Fig. 4, *d*). To this end, a special mechanical drive was designed and manufactured, which is enabled by the engine gear unit.

5. 3. The microprocessor electronic control unit Avenir Gaz 37 “B”

To manage the operation of a gas ICE, the multifunctional microprocessor ECU Avenir Gaz 37 level “B” (Ukraine) was designed and manufactured; it is shown in Fig. 5.

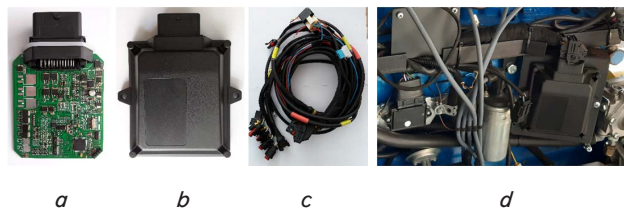


Fig. 5. Multifunctional microprocessor ECU Avenir Gaz 37 “B”: *a* – assembled board Avenir Gaz 37 “B”; *b* – the appearance of the ECU; *c* – harnesses of the control unit connection wires with sensors and devices; *d* – electronic control unit Avenir Gaz 37 “B”, installed in the gas ICE D-240-LPG-“B2”

The Avenir Gaz 37 level “B” ECU was built on the platform of high-performance 16-bit microcontroller PIC24F (Microchip Technology Inc., USA) [15] using the nanoWatt XLP technology, which enables ultra-low power consumption. The maximum clock speed is 32 MHz. The computing power (productivity) of the microcontroller at operating frequency reaches 16 DMIPS.

For commissioning, the electronic control unit is connected to a personal computer using the USB-UART interface converter, based on the PIC16F1825 microcontroller (Microchip Technology Inc., USA) and the FT232 interface converter (Future Technology Devices International Ltd., UK).

We have developed algorithms and software that make it possible to control the operation of the gas ICE D-240-LPG-“B”, in particular, its subsystem of multipoint sequential injection of LPG with gas electromagnetic nozzles into the intake pipeline, as well as a subsystem for filling cylinders with the charge of a working mixture (Fig. 6, *b*).

ECU Avenir Gaz 37 “B” with a downloaded software module (SM) of level “B2” enables the sequential injection of LPG into the intake pipeline into the zone close to the intake valve.

5. 4. Experimental studies of the electronic gas engine control system with an electronic control unit and sequential fuel injection

The gas ICE of model D-240-LPG-“B2” was converted on the basis of the transport diesel engine D-240 (Belarus). First, the diesel power supply and injection system was dismantled from the diesel engine, and the head of the diesel cylinder block was finalized to install spark plugs. Second, to reduce the compression ratio, new modified pistons with a modified shape (volume) of the combustion chamber were installed. As a result, the geometric compression ratio of diesel equal to $\epsilon=16.0$ was reduced to $\epsilon=9.5$ [12, 16]. Next, the gas ICE D-240-LPG-“B2” was equipped with an accumulative subsystem of power supply and injection of LPG, the type of Common Rail, produced by BRC Gas Equipment (Italy). The subsystem includes the reducer-evaporator BRC Genius MB1500 mbar; a Certools gas filter; BRC gas rail with 4 BRC IN03 MY09 LPG/CNG gas nozzles and PTS SENSATA sensor; a gas nozzle. All elements of the accumulative subsystem of power supply and sequential injection of LPG installed on the gas ICE of model D-240-LPG-“B2” (Fig. 6, *a*) meet the requirements set out in [17].

At the same time, a contactless electronic ignition subsystem with a modified ignition distributor was installed in the gas ICE (Fig. 4, *d*). The structure and features of the installation of the ignition subsystem are described in detail in [13].

In addition, the engine was equipped with a cylinder filling subsystem with a charge of working mixture with the mechanism of bypass control of airflow and ECU Avenir Gaz 37 level “B” (Fig. 6, *b*). The filling subsystem consists of a throttle device of model 4062.1148100 with an integrated sensor of the angular position of the throttle of model 406-113000-01 and a mechanism for bypass control of airflow – the idle controller, PXX 40.1147051 model.

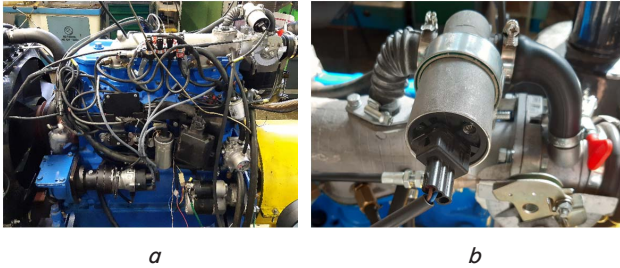


Fig. 6. General view of the gas engine of model D-240-LPG-“B2”: *a* – general view of the gas engine of model D-240-LPG-“B2”, installed on the Zöllner bench; *b* – general view of the cylinder filling subsystem with a charge of the working mixture with the mechanism of bypass control of airflow

To determine the angular position and speed of the engine crankshaft, the designed and manufactured ferromagnetic master disk, the periphery of which hosts 60-2 teeth of a square profile, is installed on its pulley. In front of the teeth of the master disk, a standard contactless inductive CAPS of model 2112-3847010 is installed. The master disk is rigidly fixed on the pulley of the crankshaft in such a way that the UDP of the first cylinder corresponds to the fifth tooth of the master disk after two missing teeth.

We determined the feasibility of the designed electronic control system with ECU Avenir Gaz 37 “B” with loaded SM of level “B2” and sequential injection of LPG at the gas ICE D-240-LPG-“B2”. The feasibility of the designed electronic control system was determined by testing the engine at the Zöllner (Germany) type B-350AS electric load bench.

We determined the feasibility of the designed gas ICE control system during the operation of the engine at idle modes and partial loads.

The tests showed that under all speed and load modes of operation, the gas ICE D-240-LPG-“B2” with the developed control system involving ECU Avenir Gaz 37 “B” worked steadily and without detonation.

In addition, to check the feasibility of the designed Avenir Gaz 37 “B” ECU and the compliance with the implementation of the algorithm of SM “B2”, some signals from the input sensors and actuating elements of the control system were acquired for oscilloscope. In particular, signals from the CAPS and the additional ignition distributor’s Hall sensor were oscilloscoped (Fig. 4, *c, d*). In addition, we oscilloscoped signals from actuating elements, in particular the signals of control over the operation of four gas electromagnetic nozzles. The results of signal oscilloscopy were recorded by the digital oscilloscope ISDS205A. The oscilloscope communicates with a computer via a high-speed USB cable.

Fig. 7 shows the oscillograms of signals from CAPS (blue) and an additional ignition distributor’s Hall sensor (yellow). Oscillograms were acquired during the operation of the gas engine at a constant mode of operation at a speed of 1,080 min⁻¹. Blue displays a signal from the CAPS; yellow – from the ignition distributor’s additional Hall sensor. The two vertical yellow lines “Cur1” and “Cur2” indicate the two positions of the piston of the first cylinder in UDP at the end of the compression stroke. That is, during this period, the crankshaft turned at 720°.

The oscillograms demonstrate that a signal from the CAPS generated by the marker (in the form of two missing teeth) of the master disk of the crankshaft, is displayed with gaps that alternate every 360° rotation of the crankshaft. The oscillogram shows that a signal from only one CAPS cannot unequivocally determine on which cycle stroke (compression or release) the piston of the first cylinder of the gas engine approaching the UDP is. In this case, the Avenir Gaz 37 “B” is not able to uniquely determine the sequence of injection of LPG among the ICE cylinders and, as a result, to ensure the sequential injection of LPG.

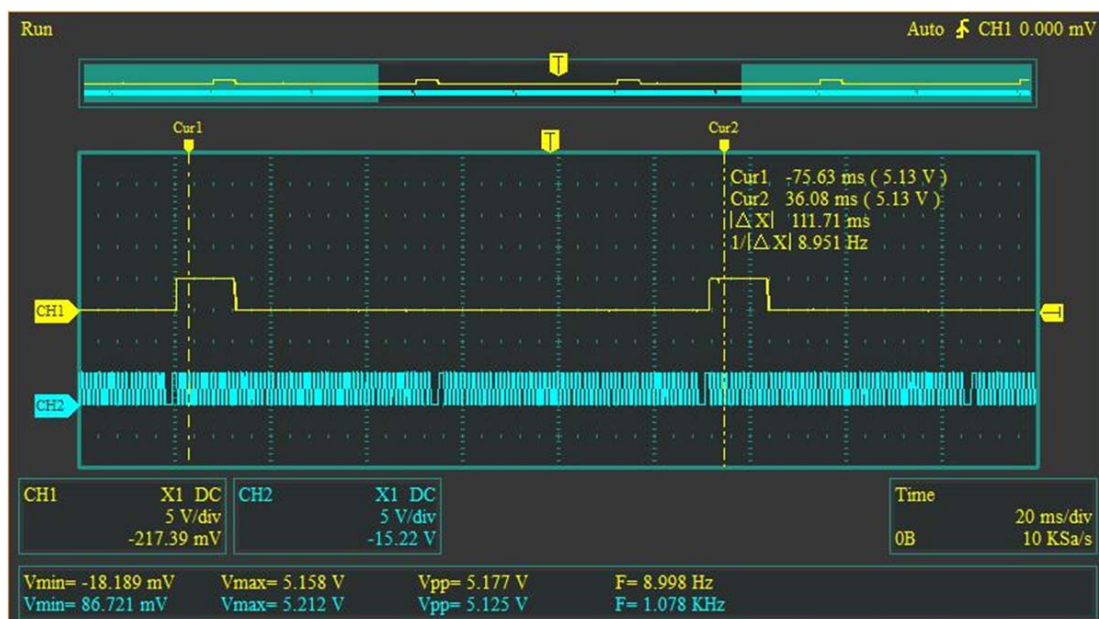


Fig. 7. Oscillograms of signals from the angular position sensor and crankshaft speed

In turn, a signal from the ignition distributor's additional Hall sensor generated by a permanent magnet is displayed on the oscillogram by rectangular pulses that alternate every 360° rotation of the camshaft corresponding to 720° of the crankshaft. This signal defines the moment when the piston of the first cylinder approaches the UDP at the compression stroke. Thus, based on the signal from CAPS and the ignition distributor's additional Hall sensor, the Avenir Gaz 37 "B" ECU uniquely determines the sequence of injection of LPG among the ICE cylinders and, as a result, enables the sequential injection of LPG.

Fig. 8 shows the oscillograms of the signal from the ignition distributor's additional Hall sensor (yellow), and signals from ECU Avenir Gaz 37 "B" that controls the operation of gas electromagnetic nozzles (blue color) with the sequential injection of LPG. The oscillograms were acquired during the operation of the engine at a constant mode of operation at a speed of 1,110 min⁻¹.

The oscillograms demonstrate that the signal from the operation of each of the four gas electromagnetic nozzles alternates every 360° turn of the camshaft, or 720° rotation of the crankshaft.

The injection of LPG by four gas nozzles (denoted in Fig. 8 ing1–ing4) occurs in sequence with the alternating working strokes of a four-cylinder gas ICE, that is, 1 – 3 – 4 – 2. The moment of the onset of LPG injection with gas nozzles relative to the nozzle of the first cylinder is equal to the 180° turn of the crankshaft.

Thus, the oscillograms that are shown in Fig. 8 confirm that the ECU Avenir Gaz 37 "B" with SM of level "B2" enables the sequential injection of LPG.

Fig. 9 demonstrates the oscillograms of the signal from the ignition distributor's additional Hall sensor, as well as the signal from ECU Avenir Gaz 37 "B" to control the operation of the gas electromagnetic nozzle of the first cylinder during the launch of the gas ICE.



Fig. 8. Oscillograms of signals from the ignition distributor's additional Hall sensor and the electronic control unit Avenir Gaz 37 "B" that control the operation of gas electromagnetic nozzles

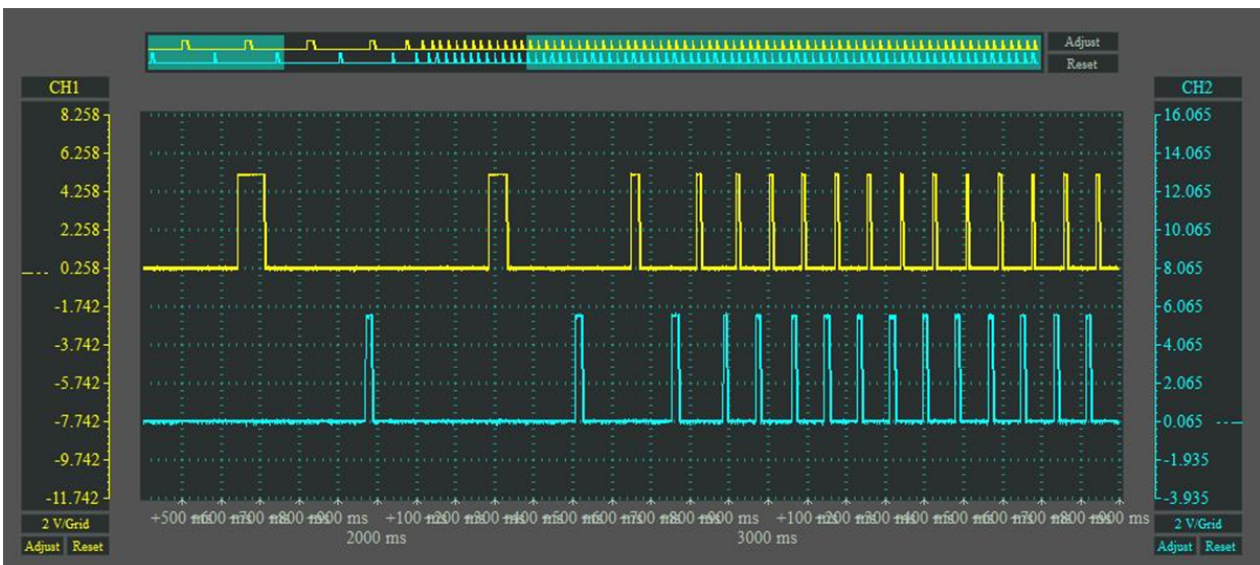


Fig. 9. Oscillograms of signals from the ignition distributor's additional Hall sensor and the electronic control unit Avenir Gaz 37 "B" that controls the operation of the gas nozzle of the first cylinder

The oscillograms show that after the first signal generated by the additional Hall sensor, the Avenir Gaz 37 “B” ECU determined the moment, duration, and order of LPG injection with gas nozzles. And as a result, it enabled the first injection of LPG with the nozzle of the first cylinder. Then, after eight revolutions of the crankshaft, the engine begins to gain rotational speed. This is evidenced by a decrease in the time between the signals from both the additional Hall sensor and the Avenir Gaz 37 “B” ECU signals to control the operation of the nozzle of the first cylinder. The oscillograms that are shown in Fig. 7–9 confirm the sequence and order of operation of the electronic control system of gas ICE D-240-LPG-“B2” with ECU Avenir Gaz 37 of level “B” and the sequential injection of LPG.

We have tested the gas ICE D-240-LPG-“B2” in accordance with the requirements set out in [18]. The test results show that the D-240-LPG-“B2” engine with the sequential injection of LPG demonstrates a lower content of carbon monoxide and hydrocarbons in exhaust gases than that in the gas ICE D-240-LPG-“A” with the supply of LPG through a gas-air mixer [13].

6. Discussion of results of studying the electronic gas engine control system with spark ignition

The results of our study of the electronic control system of the gas engine with spark ignition have demonstrated the possibility of enabling the sequential injection of LPG during the conversion of such diesel engines, whose standard configuration lacks CAPS and a special master disk installed on the camshaft – Fig. 1.

Enabling the sequential injection of LPG is achieved by modifying the ignition system distributor, which involved installing an additional master disk with an integrated permanent magnet and an additional Hall sensor – Fig. 3, 4. The use of a signal from the additional Hall sensor generated by a master disk makes it possible to determine the moment when the piston of the first cylinder approaches the UDP on the compression stroke – Fig. 7, 9. As a result of analyzing signals from the CAPS and the additional Hall sensor, ECU is able to uniquely determine the sequence of injection of LPG among the ICE cylinders and enable the sequential injection of LPG – Fig. 8.

The tests showed that the electronic control system with ECU Avenir Gaz 37 “B” with SM of level “B2” executes all the functions assigned to them and ensures the stable and detonation-free operation of the gas engine D-240-LPG-“B2”.

Thus, the use of an electronic control system for a gas engine with spark ignition is an effective way to increase the share of alternative energy sources in the overall structure of energy supply to transport.

In addition, the use of the designed electronic control system for a gas engine with spark ignition does not require special expensive equipment and can be used to convert diesel engines in operation.

At the same time, it is obvious that the applied configuration of the electronic gas engine control system lacks the following:

- a contactless electronic ignition subsystem with dual-spark or individual ignition coils;
- a subsystem of lambda-adjustment of the composition of the gas-air mixture;
- a detonation control subsystem.

The presence of such subsystems in the gas engine could subsequently significantly reduce the level of emissions of pollutants.

Therefore, further research is associated with the design of a multifunctional electronic control system for a gas ICE with the new Avenir Gaz 37 of level “C”. The new Avenir Gaz 37 of level “C” is built on the platform of the microcontroller of model STM32F4, based on the high-performance 32-bit ARM Cortex-M4 core [19]. The new system could enable control over the above additional subsystems, which would improve the environmental level of the converted gas ICE.

7. Conclusions

1. We have designed a new schematic diagram of the electronic control system for a gas ICE with ECU, which enables the sequential injection of LPG in the absence in the diesel engine structure of the CAPS and the master disk installed on the camshaft.

2. The movable voltage distributor (ignition distributor) has been modified by installing a plastic master disk with one integrated permanent magnet and an additional Hall sensor on the body of the ignition distributor on its drive shaft.

3. We have designed and fabricated a special multifunctional ECU, Avenir Gaz of “B2” level, as well as SM of level “B2”, which enables the sequential injection of LPG. The designed electronic control system with ECU Avenir Gaz 37 of level “B” and the modified movable voltage distributor (ignition distributor) were installed on the gas ICE D-240-LPG-“B2”.

4. Bench tests of the gas ICE D-240-LPG-“B2” were carried out at an electric loading bench. The results of the tests proved that the electronic control system with ECU Avenir Gaz 37 “B” with SM of level “B2” executes all the predefined functions and ensures stable and detonation-free operation of the gas ICE D-240-LPG-“B2”. In addition, the designed control system enables the sequential injection of LPG. The results of the tests showed that the conversion of diesel engines into gas ICEs is an effective way to increase the share of the use of alternative environmentally-friendly gas motor fuels.

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