№ 3 (134) / 2026
ISSN: 2520-6168 Vol. 134, № 3 / 2026
Техніка, енергетика, транспорт АПК
Technology, energy, agriculture transport AIC
UDC 631.436
DOI: 10.37128/2520-6168-2026-3-15

# DEVELOPMENT AND EXPERIMENTAL RESEARCH OF A POWER SUPPLY SYSTEM FOR A AUTOTRACTOR DIESEL ENGINE FOR OPERATION IN GAS-DIESEL MODE ON LIQUEFIED PETROLEUM GAS

**Vadym RYABOSHAPKA**, Candidate of Technical Sciences, Associate Professor
**Roman LYSENKO**, Postgraduate Student
Vinnytsia National Agrarian University

**РЯБОШАПКА Вадим Борисович**, к.т.н., доцент
**ЛИСЕНКО Роман Дмитрович**, аспірант
Вінницький національний аграрний університет

*Modernization and conversion of agricultural machinery to alternative fuels is a key tool for improving its environmental and economic performance. The use of liquefied petroleum gas (LPG) in dual-fuel systems allows for a significant reduction in emissions of harmful substances (CO2, CO, NOx), however, the successful conversion of serial tractor diesel engines with the provision of stable operational characteristics at all load modes remains an unsolved scientific and practical prob-lem. The purpose of the work is to develop methods and techniques for experimental research of a diesel engine in a gasodiesel cycle, which ensures its stable operation at various load-speed modes with different fuel mixture compositions.*

*To implement the tasks set, an original schematic diagram of the gas-diesel engine power supply system with a mechanical device for manual adjustment of the position of the high-pressure fuel pump (HPFP) rail of the UTN-5 type was developed, which made it possible to eliminate the instabil-ity of the standard all-mode regulator. Experimental studies were carried out on a KI-5542 brake running-in stand based on a four-cylinder diesel engine 4F11.0/12.5, additionally equipped with gas cylinder equipment, a panel rotameter LZM-15ZT-4 and an electronic gas flow weight control sys-tem. The tests were performed according to the "loading - unloading" cycle. The least squares meth-od (LSK) was applied to build mathematical models of trends of the main parameters.*

*Graphical and mathematical dependences of hourly fuel consumption (Gg, Gdp) and torque (Mk) on the effective engine power (Ne) were constructed. It was established that the torque demonstrates a clear linear dependence on power. The influence of thermal and fuel inertia in the form of a "load-unload" loop was revealed. It was proved that the maximum intensity of liquid fuel substitution by gas is achieved in the middle power range. During the comparative analysis, at the same power, the maximum degree of diesel fuel substitution by gas was recorded, without the risk of detonation phenomena. For comparison, fuel consumption in a purely diesel mode was studied. The proposed method and the developed experimental setup confirmed their full operability and can be used to remove the characteristics of full load and serial conversion of autotractor engines. The results of research work 0125U000363 are presented in this scientific article.*

***Keywords:*** *fuel consumption, diesel fuel equipment, gas-diesel engine, liquefied petroleum gas (LPG), pilot dose, power system, engine power, torque.*

***Eq. 4. Fig. 3. Table. 2. Ref. 20.***

## 1. Problem formulation

The continuous increase in the cost of conventional petroleum fuels, the depletion of fossil energy resources, and the strengthening of environmental requirements for mobile agricultural machinery necessitate the development of new approaches to improving the energy efficiency of internal combustion engines. Diesel engines remain the main power source for tractors and other agricultural machines because of their high torque, fuel efficiency, reliability, and ability to operate for long periods under variable-load conditions. At the same time, their widespread use is associated with significant consumption of diesel fuel and emissions of nitrogen oxides, particulate matter, carbon monoxide, hydrocarbons, and carbon dioxide. Therefore, reducing the consumption of conventional diesel fuel while maintaining the required power and operational characteristics of tractor engines is an important scientific and practical problem [1–4].

ANALYTICAL SUBSTANTIATION OF THE INFLUENCE OF PULSATION PARAMETERS AND TEAT LINER CHARACTERISTICS ON MILK FLOW INTENSITY © 2026 by Elchyn ALIIEV, Yevhenii NOSENKO is licensed under CC BY 4.0
Article received 18.07.26 Review completed 23.09.26 Article accepted 30.09.26 Article published 12.10.26

One promising approach is the partial replacement of diesel fuel with liquefied petroleum gas (LPG). LPG is commercially available, relatively easy to store and transport, and has a developed refuelling infrastructure. Its main components, propane and butane, are characterized by a lower carbon-to-hydrogen ratio and a high lower heating value. These properties create favourable conditions for reducing the carbon intensity of the fuel mixture and improving the combustion process under properly selected operating parameters. In addition, LPG is generally less expensive than conventional diesel fuel, which can reduce the operating costs of agricultural machinery. However, the environmental and economic benefits of LPG cannot be considered independently of engine load, gas substitution ratio, pilot fuel quantity, air–fuel ratio, and combustion conditions [1, 2, 5, 6].

Due to its low cetane number and high autoignition temperature, LPG cannot be used directly as the only fuel in a conventional compression-ignition engine without substantial modification of the fuel system or combustion process. For this reason, LPG is introduced into the intake system, where it mixes with air and forms a homogeneous gas–air mixture. A small quantity of diesel fuel is then injected directly into the cylinder near the end of the compression stroke. The self-ignition of the diesel pilot dose initiates combustion of the main gas–air mixture. This operating principle makes it possible to preserve the original compression-ignition method and use a significant proportion of gaseous fuel without installing an additional ignition system [3, 6, 10–12].

Despite the apparent simplicity of this approach, converting a conventional tractor diesel engine to LPG–diesel operation involves a number of technical difficulties. The main challenge is to coordinate the supply of gaseous and liquid fuels under continuously changing load and speed conditions. The amount of the diesel pilot dose must be sufficient to ensure reliable ignition of the gas–air mixture, stable combustion, and acceptable rates of cylinder pressure rise. At the same time, an excessively large pilot dose reduces the degree of diesel fuel substitution and, consequently, the economic benefits of dual-fuel operation. Conversely, an excessively small diesel dose may lead to delayed ignition, unstable combustion, cycle-to-cycle variations, power loss, and deterioration of the engine's operational characteristics [7, 9, 11, 19].

The LPG supply rate must also be adjusted according to the amount of intake air and the current engine load. At low loads, the temperature and pressure at the end of compression may be insufficient for complete combustion of a lean gas–air mixture. Under such conditions, increasing the LPG fraction may cause incomplete combustion and higher emissions of carbon monoxide and unburned hydrocarbons. At medium loads, more favourable combustion conditions can be created, making it possible to achieve a higher degree of diesel fuel substitution. At high loads, however, an excessive LPG supply can lead to rapid combustion, an excessive pressure-rise rate, knock-like phenomena, increased thermal loading of engine components, and loss of operational stability. Therefore, the maximum permissible gas fraction cannot be regarded as a constant value for the entire operating range of the engine [8–12, 17, 18].

The problem becomes particularly relevant for serial tractor diesel engines equipped with mechanically controlled high-pressure fuel pumps. Their standard all-speed governors are designed to regulate the diesel fuel supply during conventional single-fuel operation. When the maximum displacement of the fuel pump rack is mechanically restricted to form a pilot dose, the operating conditions of the governor change. This may cause unstable rack movement, insufficient correspondence between fuel delivery and engine load, and difficulties in maintaining the required crankshaft speed. Consequently, the simultaneous regulation of the diesel pilot dose and LPG supply cannot always be achieved using the standard control system without additional technical solutions.

Many previous studies have investigated the performance, combustion, and emission characteristics of LPG–diesel engines [6–15, 17–20]. Various approaches have been proposed, including changes in pilot injection timing, regulation of LPG flow rate and pressure, exhaust gas recirculation, mathematical optimization, and the use of adaptive neuro-fuzzy control models. The obtained results confirm that LPG can replace a considerable proportion of diesel fuel while maintaining acceptable engine performance. However, the reported substitution ratios, fuel consumption values, and emission indicators differ considerably because of differences in engine design, operating conditions, fuel composition, control strategy, and experimental methodology.

A significant proportion of the available investigations has been conducted using single-cylinder laboratory engines, electronically controlled injection systems, or substantially modified combustion and fuel-supply systems. Such solutions are useful for studying the fundamental processes of dual-fuel combustion, but their direct implementation in serial agricultural diesel engines may be technically complicated or economically unjustified. Agricultural enterprises predominantly operate engines with mechanical fuel equipment, for which conversion systems must be simple, reliable, maintainable, and compatible with existing engine controls. Therefore, there is a need to develop a conversion method that does not require major intervention in the basic engine architecture and can be implemented using commercially available gas-cylinder equipment.

Reliable assessment of a converted engine also requires the simultaneous measurement of the main operating parameters. These include crankshaft rotational speed, braking force, torque, effective power, LPG flow rate, diesel fuel consumption, test duration, and the thermal state of the gas pressure regulator–evaporator. On the basis of these measurements, it is necessary to determine the relationships between fuel consumption, torque, and effective engine power. Mathematical approximation of the experimental data can be used to identify general trends, evaluate the stability of the operating process, reduce the influence of random measurement errors, and determine the load range in which the maximum diesel substitution ratio is achieved [9, 20].

A separate methodological problem is the correct comparison of diesel and gas–diesel operating modes. Such a comparison should be performed at nearly identical values of effective power or torque because the direct comparison of fuel consumption at different loads does not adequately characterize the efficiency of fuel substitution. It is also necessary to consider the different densities and lower heating values of LPG and diesel fuel. The percentage of gaseous fuel calculated only by the mass ratio characterizes the composition of the consumed fuel mixture but does not fully reflect the share of energy supplied by each fuel. Therefore, further energy-based evaluation is required to provide a more comprehensive assessment of the dual-fuel process.

Thus, the analysis of previous research shows that the problem of ensuring stable operation of serial tractor diesel engines in LPG–diesel mode has not yet been fully resolved. There is insufficient information on technically simple systems that provide coordinated control of the LPG flow and diesel pilot dose in engines equipped with mechanical high-pressure fuel pumps. The influence of the loading–unloading sequence on the measured operating parameters also requires further experimental investigation. Moreover, the maximum feasible degree of diesel fuel substitution must be established while maintaining engine power, torque, combustion stability, and safe operation.

Accordingly, the scientific and practical problem addressed in this study consists in developing and experimentally validating an LPG–diesel fuel supply system for a serial tractor diesel engine that does not require substantial modification of its basic design. The proposed system should ensure a stable diesel pilot dose, controlled LPG delivery, limitation of the maximum crankshaft speed, and reliable engine operation at different load conditions. Experimental studies should determine the relationships between effective power, torque, hourly LPG consumption, and hourly diesel fuel consumption during successive loading and unloading.

Solving this problem will make it possible to evaluate the technical feasibility of converting existing tractor diesel engines to dual-fuel operation, identify the load range that provides the highest LPG utilization efficiency, and determine the maximum diesel substitution ratio without loss of engine performance or occurrence of abnormal combustion. The obtained results can provide a methodological basis for further investigations of the combustion process, energy efficiency, economic performance, and exhaust emissions of agricultural engines operating on LPG–diesel fuel mixtures.

## 2. Analysis of recent research and publications

The improvement of the environmental and economic performance of diesel internal combustion engines used in agricultural production remains an important area of modern research. Diesel engines are widely used in tractors and other mobile agricultural machinery because of their high torque, relatively low specific fuel consumption, reliability, and ability to operate for long periods under variable-load conditions. At the same time, their operation is associated with considerable consumption of petroleum-based diesel fuel and emissions of nitrogen oxides, particulate matter, carbon monoxide, hydrocarbons, and greenhouse gases. According to the review presented in [2], further improvement of conventional diesel engines alone cannot fully solve the combined problems of energy efficiency and environmental safety. Therefore, the use of alternative and renewable fuels, as well as the development of dual-fuel combustion systems, is considered a promising direction for reducing the dependence of agricultural production on conventional petroleum fuels [1–4].

Among gaseous alternative fuels, liquefied petroleum gas (LPG) attracts considerable attention because of its availability, relatively low cost, high lower heating value, and well-developed storage and transportation infrastructure. LPG consists mainly of propane and butane, although the proportion of these components may vary depending on climatic conditions, season, and fuel quality requirements. Compared with diesel fuel, LPG has a lower carbon-to-hydrogen ratio. Therefore, its use can potentially reduce emissions of carbon dioxide, soot and particulate matter. LPG can be stored in liquid form under moderate pressure, which makes it more convenient for use in mobile machinery than gaseous fuels that require high-pressure cylinders or cryogenic storage systems [1, 4, 6].

The dual-fuel concept involves supplying gaseous fuel together with intake air and injecting a reduced quantity of diesel fuel directly into the cylinder. The diesel fuel acts as a pilot dose whose self-ignition initiates

the combustion of the LPG–air mixture. This approach allows the main design features of a compression-ignition engine to be retained while replacing part of the diesel fuel with a gaseous energy carrier. As noted in [1, 6], the main advantage of the dual-fuel cycle is the possibility of combining the high compression ratio and efficiency of a diesel engine with the environmental and economic advantages of gaseous fuel. However, the actual effects of conversion depend on the engine design, load and speed conditions, pilot injection parameters, LPG substitution ratio, and method of gaseous fuel supply.

The literature indicates that the environmental results of LPG application are not unambiguous and depend significantly on engine operating conditions. Under properly selected parameters, LPG–diesel operation may reduce smoke, particulate matter, and, in certain modes, nitrogen oxide and carbon dioxide emissions [2, 10, 18]. The lower carbon content of LPG contributes to a reduction in carbonaceous products of combustion compared with conventional diesel fuel. At the same time, the introduction of LPG into the intake manifold can lead to incomplete combustion of a lean and relatively homogeneous gas–air mixture, especially at low engine loads. Consequently, carbon monoxide and unburned hydrocarbon emissions may increase. Therefore, the environmental advantages of LPG should be evaluated over the entire operating range rather than on the basis of a single steady-state mode.

The limitations of the use of liquefied petroleum gas (LPG) in a conventional diesel engine are discussed in particular in [11, 19], where its low autoignition ability under typical compression ignition conditions is considered. According to the authors [11, 19], LNG has a significantly higher autoignition temperature and lower cetane characteristics than diesel fuel. For this reason, for stable operation, a pilot injection of diesel fuel is usually required. The amount and timing of the pilot injection determine the ignition delay, the initial combustion rate, the maximum pressure in the cylinder, the rate of pressure increase and the completeness of LNG combustion. An insufficient pilot injection can cause ignition delay, unstable operation, misfires and increased emissions of incomplete combustion products. Therefore, according to the authors of [11, 19], an excessive pilot dose improves ignition stability, but reduces the diesel fuel substitution coefficient and the expected economic benefit from conversion [11, 19].

Several configurations of dual-fuel engines have been proposed, each of which has certain advantages and limitations [6, 7]. In the simplest configuration, LPG is supplied into the intake manifold through a mixer, whereas diesel fuel is injected by the standard high-pressure fuel system. This method is attractive for serial tractor engines because it requires relatively limited modification of the original engine design. More advanced systems use electronically controlled gas injectors, separate control units, pressure sensors, and programmable diesel injection systems. Such configurations provide more accurate regulation of the fuel composition but increase the cost and complexity of conversion and may be difficult to implement on agricultural machinery equipped with mechanical fuel pumps.

More et al. [7], investigated the optimization of the operating parameters of a compression-ignition engine fuelled with LPG and diesel. Response surface methodology was used to establish relationships between the control factors and engine performance and emission indicators. The results demonstrated that the gas fraction, engine load, and diesel injection parameters must be optimized simultaneously because changes in one parameter influence several performance and emission characteristics. Mathematical optimization makes it possible to determine favourable combinations of operating parameters, but the obtained optimum is generally applicable only to the investigated engine configuration and experimental conditions.

Vardhan et al. [8] analysed the performance and emissions of a modified compression-ignition engine operating with gasoline and LPG under variable-load conditions. The results showed that a diesel engine can be adapted to alternative fuels while maintaining operating characteristics comparable with conventional diesel operation. At the same time, the use of a modified experimental engine does not fully address the problem of converting serial tractor engines with mechanical fuel equipment. The operation of such engines is strongly influenced by the characteristics of the standard all-speed governor, the position of the high-pressure fuel pump rack, and the mechanical connections between the fuel control elements.

Tarigonda et al. [9] studied a diesel engine operating in LPG–diesel mode and used an adaptive neuro-fuzzy inference system to optimize its performance and emission characteristics. The reported optimal parameters included an injection pressure of 194.32 bar, an LPG flow rate of 1 l/min, and an LPG pressure of 1.13 bar. The study demonstrated the potential of intelligent mathematical methods for identifying favourable engine settings. However, the implementation of such results on serial mechanically controlled engines remains complicated because these engines do not allow flexible real-time regulation of injection timing, pilot fuel quantity, and LPG supply. In addition, an operating point obtained through multi-criteria optimization does not necessarily ensure stable engine performance during rapid changes in load.

Toledo et al. [10] experimentally assessed the performance and fine particulate matter emissions of a four-cylinder direct-injection turbocharged diesel engine operating in LPG–diesel mode. The study demonstrated the possibility of substantially reducing diesel fuel consumption at high load. However, an increase in carbon monoxide and hydrocarbon emissions was also observed in certain operating conditions, whereas nitrogen oxide emissions and exhaust gas temperatures generally decreased with an increasing LPG fraction, except for some full-load modes. These results confirm that increasing the gaseous fuel share does not automatically improve all environmental indicators. The permissible LPG substitution ratio must be selected considering combustion stability, load, speed, air availability, and exhaust emissions.

The simulation results obtained by Mohsen and Al-Dawody [11] showed that the addition of LPG changes the ignition and combustion characteristics of a compression-ignition engine. The distribution of heat release over the crank angle and the maximum cylinder pressure depend on both the LPG fraction and the diesel pilot dose. Simulation methods are useful for analysing processes that are difficult to measure directly, but their reliability depends on the accuracy of the combustion model and the adequacy of its calibration using experimental data. Therefore, numerical investigations should be supplemented by tests of the actual engine and fuel supply equipment.

Tchato Yotchou et al. [12] experimentally investigated the combined effects of load and the air–gas/fuel ratio on the performance, emissions, and combustion characteristics of a stationary diesel engine operating with LPG. The authors established that the response of a dual-fuel engine differs considerably at low, medium, and high loads. At low load, the temperature conditions are less favourable for complete combustion of the gas–air mixture. At medium load, increasing the LPG proportion may provide a higher diesel substitution ratio and more efficient combustion. Near full load, the LPG supply must be limited to prevent an excessive pressure-rise rate, knock-like combustion, and thermal overloading of engine components.

The results presented in [13, 17, 18] also confirm that LPG significantly affects diesel engine fuel consumption, combustion, and emissions. The use of LPG as a secondary fuel generally reduces the absolute consumption of diesel fuel, although the total mass consumption of the two fuels may increase because of differences in their physical and chemical properties and combustion efficiency. For this reason, the effectiveness of substitution should not be assessed exclusively from the mass fraction of LPG. A more comprehensive comparison should consider the lower heating values of both fuels, their energy shares in the total fuel supply, brake thermal efficiency, brake-specific energy consumption, and the cost of the consumed energy carriers.

The timing and quantity of the diesel pilot injection are among the most important control parameters of a dual-fuel engine. Jacobs and Assanis [19] showed that pilot injection timing affects the development of in-cylinder flow, ignition, combustion intensity, and exhaust emissions. Advancing or retarding injection can change the ignition delay and the proportion of fuel burned during the premixed and diffusion-controlled combustion phases. However, serial tractor diesel engines with mechanically controlled high-pressure pumps have limited possibilities for adjusting injection timing during operation. Therefore, fuel-system conversion methods for these engines should provide acceptable performance without relying on complex electronic regulation.

Poku and Bebeteidoh [14] considered the influence of diesel injection timing on the combustion and emission characteristics of a diesel–propane compression-ignition engine. Their research confirms that the pilot injection parameters should be coordinated with the gaseous fuel fraction. At the same time, the use of propane or LPG at a fixed injection timing may produce different results at different engine loads. This emphasizes the need to experimentally determine the permissible gas substitution range for each specific engine and fuel-supply system.

Emission control technologies can additionally affect the dual-fuel combustion process. Issa et al. [15] investigated the determination of an optimal exhaust gas recirculation rate for an LPG engine. Exhaust gas recirculation can reduce the combustion temperature and nitrogen oxide formation, although an excessive recirculation rate may deteriorate combustion stability and increase incomplete-combustion products. Although the study concerned a spark-ignition LPG engine, its results demonstrate the importance of coordinating mixture composition, residual gas fraction, and thermal conditions. Nevertheless, the installation of an additional exhaust gas recirculation control system increases the complexity of converting a serial tractor diesel engine.

Rajput and Tiwari [20] applied mathematical modelling and multi-objective optimization criteria to dual-fuel converted internal combustion engines. Their approach makes it possible to analyse several conflicting indicators simultaneously, including power, fuel efficiency, and harmful emissions. However, mathematical models require reliable experimental data obtained under controlled test conditions. When such models are developed only for separate steady-state points, they may not adequately describe the engine response during successive loading and unloading or during changes in the ratio between gaseous and liquid fuels.

When a conventional high-pressure fuel pump is used, the formation of a stable diesel pilot dose is especially important. Mechanical limitation of the pump rack displacement can restrict the maximum diesel

supply, but it also changes the operating conditions of the standard all-speed governor. As a result, the governor may attempt to compensate for a reduction in engine speed by increasing the diesel supply, while the mechanical stop prevents the rack from reaching the required position. This interaction can lead to unstable control, irregular fuel delivery, and difficulties in coordinating the LPG and diesel supplies. Consequently, an additional mechanical control device is required to regulate the pump rack position and the gas throttle simultaneously while preserving the function of the maximum-speed limiter.

The available publications confirm the technical feasibility of LPG application in compression-ignition engines and demonstrate the possibility of reducing diesel fuel consumption [6–14, 17–20]. Nevertheless, they do not provide a universal method for converting a serial tractor diesel engine equipped with a mechanical high-pressure fuel pump. There is also insufficient experimental information on the behaviour of such an engine over a complete loading–unloading cycle and on the relationship between effective power, torque, LPG flow rate, and diesel pilot-fuel consumption. The maximum substitution ratio that can be achieved without power loss, unstable combustion, or risk of knock remains dependent on the design and settings of the particular engine.

Thus, the unresolved part of the problem is the development of a technically simple and reliable LPG–diesel fuel supply system that can be installed on a serial tractor engine without major modification of its basic architecture. This system should ensure coordinated control of the LPG supply and diesel pilot dose, stable engine operation under different load and speed conditions, and limitation of the maximum crankshaft speed. It is also necessary to develop an experimental procedure that makes it possible to determine fuel consumption, effective power, and torque during both increasing and decreasing load and to establish the operating range with the greatest technically permissible diesel fuel substitution.

## 3. The purpose of the article

The purpose of the research is to develop methods and technical means for experimentally investigating a serial tractor diesel engine operating in the LPG–diesel cycle and to ensure its stable operation under different load-speed conditions and with different proportions of gaseous and liquid fuels.

Research objectives:

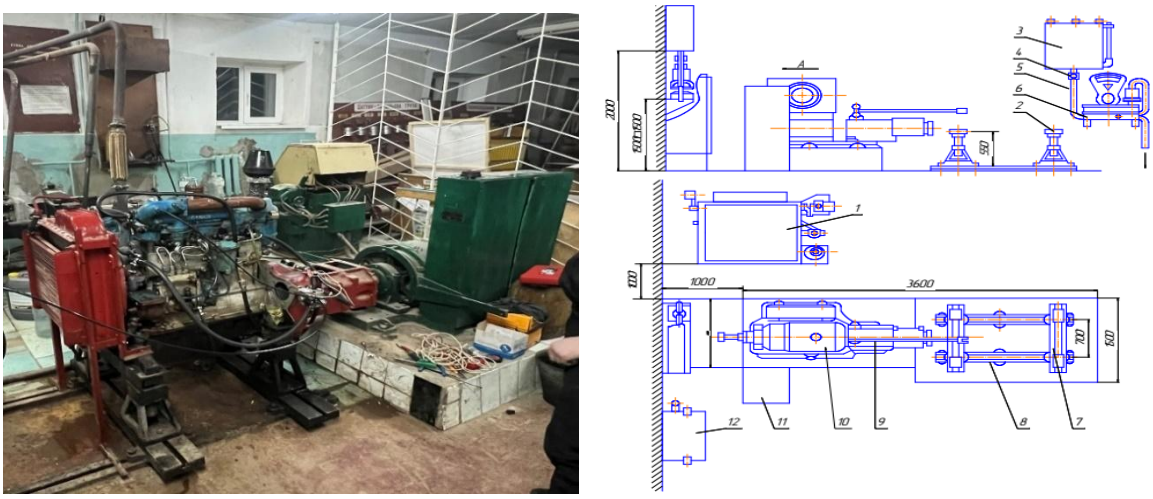
– establish the maximum degree of substitution of liquid fuel with gaseous fuel;

– to establish the optimal method of converting diesel engines using liquefied petroleum gas;

– conduct comparative engine tests in diesel and gas-diesel modes.

## 4. Results and discussion

For the experimental study, a KI-5542 brake running-in stand with a 4F11.0/12.5 engine equipped with gas cylinder equipment was used (Fig. 1). The KI-5542 stand consists of the following main components: an electric dynamometer 10, a rheostat 1, an electrical cabinet 12, a control panel, installation stands, longitudinal and transverse plates 8.7, a fuel tank 3, and a weighing device 6 (Fig. 1(b)).




*a – general view* *b – schematic diagram*

***Fig. 1. Brake and running-in stand KI-5542 with engine 4F11.0/12.5:***
***a – general view b – diagram: 1 – rheostat; 2 – stand; 3 – fuel tank; 4 – three-way valve; 5 – fuel line; 6 – load; 7, 8. – plate; 9 – thrust; 10 – dynamometer; 11 – control panel; 12 – electrical cabinet.***

To conduct the planned experimental studies, the KI-5542 test stand and the investigated 4F11.0/12.5 diesel engine were retrofitted with the LPG equipment shown in Fig. 2. The additional equipment included a toroidal LPG cylinder, a reducer-evaporator, gas pipelines, an electromagnetic shut-off valve, an LZM-15ZT-4 rotameter, a gas supply control valve, and a special device for adjusting the position of the UTN-5 high-pressure fuel pump rack.

A toroidal cylinder was used to store liquefied petroleum gas and ensure a continuous fuel supply to the experimental engine. The reducer-evaporator reduced the LPG pressure and heated the fuel, thereby converting it from the liquid to the gaseous state before delivery to the engine intake system. An LZM-15ZT-4 rotameter was used to measure and regulate the gas supply. The rotameter was calibrated for a propane–butane mixture under standard conditions and enabled the LPG flow rate to be adjusted during each experimental run.

Initial tests showed that the liquefied petroleum gas (LPG) supply system using a fourth-generation evaporator reducer and diesel fuel did not provide stable engine operation over the entire load and speed range studied. When the LNG supply was increased and the diesel fuel regulator control lever remained in a fixed position, the crankshaft speed either remained unchanged or increased only slightly. This behavior was explained by the operation of the standard UTN-5 high-pressure fuel pump speed regulator, which automatically adjusted the diesel fuel supply to maintain a given crankshaft speed.

Based on these observations, the standard all-speed governor was disconnected, unlike the control method used in the conventional KAMAZ LPG–diesel system [16]. A special mechanical device was developed to replace its control function and provide manual adjustment of the UTN-5 pump rack position. This modification made it possible to set and maintain the required diesel pilot dose independently of the LPG supply and thereby improve the stability of the engine during experimental testing. The final configuration of the experimental engine equipped with the LPG system, measuring devices, and the pump-rack control mechanism is presented in Fig. 2.

***Fig. 2 Experimental installation with gas cylinder equipment:***

***1,9 – connection points of the gas reducer to the cooling system, 2 – reducer-evaporator for reducing the supply pressure and heating the gas, 3 – gas supply control board from the reducer to the engine, 4 – pressure gauge-vacuum gauge, 5 – liquefied petroleum gas supply tube from the cylinder to the reducer, 6,8 – gas supply hoses from the reducer to the engine intake manifold, 7 – rotameter with a gas supply control valve, 10 – gas supply shut-off valve, 11 – gas supply fitting to the engine intake manifold, 12 – device for adjusting the position of the HPFP rail, 13 – electromagnetic valve, 14 – temperature sensor.***

The experimental results were obtained using the standard recommendations for testing tractor diesel engines [16], with appropriate adjustments to account for the specific features of LPG–diesel operation. During the experiments, the crankshaft rotational speed was maintained as close as possible to its nominal value, while the engine load was varied using the dynamometer.

For each experimental point, the time required to consume a fixed volume of 100 ml of diesel fuel was recorded. Simultaneously, the LPG flow rate was gradually increased in equal increments of 0.25 l/min using the rotameter. The measurements were initially performed with a successive increase in LPG supply and engine load until the maximum investigated operating condition was reached. The tests were then repeated in reverse order by gradually decreasing the gas supply and engine load. This loading–unloading procedure made it possible to evaluate the stability of the engine operating parameters and identify the influence of thermal and fuel-system inertia on the recorded characteristics.

The measured parameters obtained during the complete experimental cycle are presented in Table 1. These data were subsequently used to calculate the effective engine power, torque, hourly LPG consumption, and hourly diesel fuel consumption. The calculated results presented in Table 2 form the basis for analysing the relationships between engine load, fuel composition, power output, and fuel consumption in LPG–diesel operation.

***Table 1***

***Test results 4F11.0/12.5 at different load conditions***

| Numbering of columns and experiments | n, rpm | T, seconds | m, g | Vdp, ml | Q, l/min | t, ˚C. | Pg, kgf |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 1 | 1880 | 58 | 70 | 100 | 0.5 | 48.9 | 12 |
| 2 | 1920 | 60 | 50 | 100 | 0.75 | 49.5 | 13.5 |
| 3 | 1930 | 60 | 70 | 100 | 1 | 50.3 | 13 |
| 4 | 1890 | 43 | 60 | 100 | 1.25 | 51.7 | 20 |
| 5 | 2150 | 49 | 80 | 100 | 1.5 | 52.2 | 18 |
| 6 | 2220 | 46 | 70 | 100 | 1.75 | 51.7 | 17 |
| 7 | 2240 | 41 | 80 | 100 | 2 | 52.7 | 21.5 |
| 8 | 2200 | 45 | 80 | 100 | 2.25 | 54.2 | 24.5 |
| 9 | 2200 | 41 | 90 | 100 | 2.5 | 55.2 | 27 |
| 10 | 2220 | 42 | 70 | 100 | 2.5 | 52.7 | 28 |
| 11 | 2200 | 38 | 50 | 100 | 2.25 | 56.6 | 29 |
| 12 | 2150 | 36 | 60 | 100 | 2 | 57.4 | 28.25 |
| 13 | 2150 | 40 | 60 | 100 | 1.75 | 58.1 | 28 |
| 14 | 2080 | 37 | 60 | 100 | 1.5 | 59 | 27 |
| 15 | 2000 | 40 | 50 | 100 | 1.25 | 58.9 | 25 |
| 16 | 1920 | 39 | 40 | 100 | 1 | 60.7 | 25.25 |
| 17 | 1900 | 37 | 35 | 100 | 0.75 | 58.4 | 24.75 |
| 18 | 1820 | 38 | 30 | 100 | 0.5 | 57 | 22 |

Based on the indicators given in Table 1, the following parameters were calculated:

Ne – engine power in different load modes and at different percentages of gas-diesel mixture, kW. To determine the power, we use formula 1

$$Ne = 736 \cdot 10^{-6} P_g \cdot \mathrm{n} \quad (1)$$

where: n – speed, rpm; Pg – force measuring mechanism effort, kgf; $G_{LPG}$ – hourly gas consumption, kg/h. To determine it, we use formula 2

$$G_{LPG} = \frac{3{,}6 \cdot \Delta \mathrm{g}}{\mathrm{T}} \quad (2)$$

where: T – measurement duration, sec; Δg – fuel consumption during the experiment, g; $G_{DF}$ – hourly diesel fuel consumption, kg/h. To determine it, we use formula 3:

$$\mathrm{G}_{DF} = \frac{3{,}6 \cdot \Delta V_{DF} \cdot j_n}{\mathrm{T}} \quad (3)$$

where: $\Delta V_{DF}$ – volume of fuel consumed, ml; $j_n$ is the density of diesel fuel, which is equal to 0.840 kg/l.

We will also determine the torque of the test engine using formula 4:

$$M_k = \frac{9550 \cdot Ne}{\mathrm{n}} \quad (4)$$

where: Mk is the torque, N·m.

All calculation results were entered into a Table 2.

*Table 2*

***Dependence of hourly fuel consumption and torque on effective engine power***

| Experiment number. | Ne, kW | Gg, kg/h | $G_{DF}$, kg/h | Mk |
|---|---|---|---|---|
| 1 | 16,604 | 4,345 | 5,214 | 84,346 |
| 2 | 19,077 | 3,000 | 5,040 | 94,889 |
| 3 | 18,466 | 4,200 | 5,040 | 91,374 |
| 4 | 27,821 | 5,023 | 7,033 | 140,576 |
| 5 | 28,483 | 5,878 | 6,171 | 126,518 |
| 6 | 27,777 | 5,478 | 6,574 | 119,490 |
| 7 | 35,446 | 7,024 | 7,376 | 151,119 |
| 8 | 39,670 | 6,400 | 6,720 | 172,206 |
| 9 | 43,718 | 7,902 | 7,376 | 189,778 |
| 10 | 45,750 | 6,000 | 7,200 | 196,806 |
| 11 | 46,957 | 4,737 | 7,958 | 203,835 |
| 12 | 44,703 | 6,000 | 8,400 | 198,564 |
| 13 | 44,307 | 5,400 | 7,560 | 196,806 |
| 14 | 41,334 | 5,838 | 8,173 | 189,778 |
| 15 | 36,800 | 4,500 | 7,560 | 175,720 |
| 16 | 35,681 | 3,692 | 7,754 | 177,477 |
| 17 | 34,610 | 3,405 | 8,173 | 173,963 |
| 18 | 29,469 | 2,842 | 7,958 | 154,634 |

Based on the experimental data presented above, a graphical dependence was constructed to illustrate the complete trajectory of the engine tests, from the initial operating conditions through a gradual increase in load and fuel supply to the maximum investigated operating mode, followed by a successive reduction in load to the final test points (Fig. 3). This representation makes it possible to compare the loading and unloading stages, evaluate changes in LPG and diesel fuel consumption, and identify possible differences in engine behaviour caused by the thermal and fuel-system inertia of the LPG–diesel power supply system.

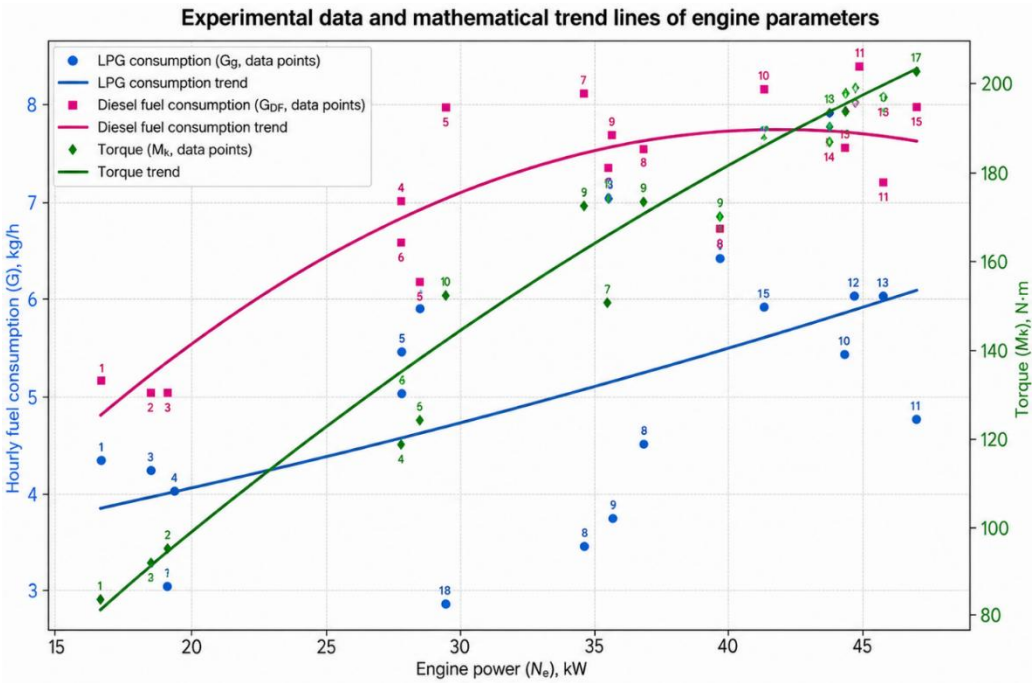



***Fig. 3. Experimental and approximated relationships between fuel consumption, torque, and effective engine power in LPG–diesel operation.***

Figure 3 presents the relationships between the main engine operating parameters and its effective power. The torque (Mk) follows an almost linear upward trend over the entire investigated power range. This relationship is consistent with the approximately constant crankshaft speed maintained during the tests and indicates stable operation of the engine's mechanical system under changing load conditions.

Hourly LPG consumption (Gg) generally increases with effective power. However, the dispersion of the experimental points around the trend line indicates that the gas flow rate was also influenced by the loading–unloading sequence, manual gas regulation, and the thermal inertia of the fuel supply system. Therefore, slightly different LPG consumption values were recorded at comparable power levels during increasing and decreasing engine load.

Diesel fuel consumption ($G_{DF}$) exhibits a nonlinear, arc-shaped dependence on effective power. It increases as the engine load rises, reaches its highest values in the medium-to-high power range, and then tends to stabilize or decrease slightly near the maximum investigated power. This behaviour reflects the redistribution of the fuel components during the experimental cycle and the coordinated use of diesel fuel as the pilot dose and LPG as the supplementary energy carrier.

For a quantitative comparison of the LPG–diesel and conventional diesel operating modes, experiment № 9 was selected because it provided almost identical engine power in both cases and the maximum investigated LPG share in the combined fuel mixture. In LPG–diesel mode, the effective power was (Ne = 43.718 kW), LPG consumption was (Gg = 7.902 kg/h), and diesel fuel consumption was ($G_{DF}$ = 7.376 kg/h). Accordingly, the total mass consumption of the two fuels was: Gsum = 7.902 + 7.376 = 15.278 kg/h.

The mass composition of the consumed fuel mixture consisted of 51.72% LPG and 48.28% diesel fuel. Thus, under the investigated conditions, more than half of the total fuel mass was supplied in the form of LPG.

During conventional diesel operation at a practically identical effective power of (Ne = 43.750 kW), hourly diesel fuel consumption was ($G_{DF}$ = 14.620 kg/h). The difference in effective power between the two operating modes was only approximately 0.07%, which makes their comparison sufficiently representative. The transition to LPG–diesel operation reduced the absolute diesel fuel consumption by 7.244 kg/h, corresponding to approximately 49.55%, while maintaining virtually the same engine power. These results confirm the possibility of replacing a substantial proportion of diesel fuel with LPG under the investigated load conditions.

## 5. Conclusion

The engine operating mode investigated in experiment № 9 (Ne = 43.718) kW) was characterized by the maximum degree of liquid fuel substitution with gaseous fuel. LPG consumption was 7.902 kg/h, while diesel fuel consumption was 7.376 kg/h. Accordingly, LPG accounted for 51.72% of the total mass of the fuel mixture, whereas the share of diesel fuel was 48.28%.

A comparative analysis with the conventional diesel mode at the same load level (Ne = 43.750 kW) demonstrated the high technical and economic feasibility of the LPG–diesel process. When the engine operated on the combined fuel mixture, the absolute consumption of diesel fuel was reduced to a stable pilot-dose level of 7.376 kg/h. Thus, more than half of the total fuel mixture was replaced with liquefied petroleum gas while practically the same effective engine power was maintained.

Maintaining approximately the same effective power of 43.7 kW in both operating modes confirms the effectiveness of the mixed-fuel combustion process under the investigated conditions. Since the lower heating value of LPG (approximately 46 MJ/kg) is higher than that of diesel fuel (approximately 42.5 MJ/kg), the established ratio of the fuel components provides a favourable thermal balance of the operating cycle without signs of abnormal combustion or detonation, which may limit the further increase in the gaseous fuel proportion near the nominal engine operating mode.

The analysis of the experimental dependences also showed that torque changed almost linearly with increasing effective power, indicating stable operation of the mechanical components of the engine throughout the investigated load range. At the same time, the differences between fuel consumption during the loading and unloading stages indicate the influence of the thermal and fuel inertia of the engine. The obtained mathematical dependences make it possible to describe these changes and identify the operating range in which the most intensive substitution of diesel fuel with LPG is achieved.

Therefore, the proposed method for determining LPG and diesel fuel consumption is fully operational and suitable for experimental studies of tractor diesel engines operating in dual-fuel mode. The developed system can be used in further research to construct complete engine load characteristics, determine rational LPG–diesel ratios, and evaluate the operational, energy, economic, and environmental performance of converted diesel engines.

## References

1. Tan, H., Othman, M. H. D., Ng, J. H., Wang, B., Lee, C. T., Tan, K. Y., & Wong, K. Y. (2025). Dual fuel-engine interactions: A review of the impact of fuels on internal combustion engine emissions and performance. *Chemical Engineering Transactions, 122,* 247–252. https://doi.org/10.3303/CET25122042 [in English].
2. Joshi, A. (2022). Review of vehicle engine efficiency and emissions. *SAE International Journal of Advances and Current Practices in Mobility, 4(5),* 1704–1733. https://doi.org/10.4271/2022-01-0540 [in English].
3. Ryaboshapka, V., & Lysenko, R. (2023). Problems and prospects of creating modern agricultural gas diesel engines: A literature review. *Ukrainian Black Sea Region Agrarian Science, 27(4),* 81–89. https://doi.org/10.56407/bs.agrarian/4.2023.81 [in English].
4. Dzieniszewski, G., Kuboń, M., Pristavka, M., & Findura, P. (2021). Operating parameters and environmental indicators of diesel engines fed with crop-based fuels. *Agricultural Engineering, 25(1),* 13–28. https://doi.org/10.2478/agriceng-2021-0002 [in English].
5. Wu, S., Xiao, Y., Pacala, A., Badulescu, A., & Khan, S. (2024). Understanding Chinese farmers' behavioral intentions to use alternative fuel machinery: Insights from the technology acceptance model and theory of planned behavior. *Sustainability, 16(24),* Article 11059. https://doi.org/10.3390/su162411059 [in English].
6. Khan, D., & Goga, G. (2023). A review on performance and emission characteristics of a diesel engine fueled with gaseous and liquid fuels. *Materials Today: Proceedings, 80,* A14–A22. https://doi.org/10.1016/j.matpr.2023.04.197 [in English].
7. Ouchikh, S., Lounici, M. S., Loubar, K., & Tazerout, M. (2025). Optimization of injection strategy for $CH_4$/diesel dual-fuel engine using response surface methodology. *Energies, 18(8),* Article 2115. https://doi.org/10.3390/en18082115 [in English].
8. Vardhan, A., Rajput, R. S., Tiwari, A. C., & Randa, R. (2022). Performance and emission analysis of modified compression ignition engine from diesel engine to variable load using petrol and LPG fuel. *Chemical Engineering and Processing: Process Intensification, 181,* Article 109115. https://doi.org/10.1016/j.cep.2022.109115 [in English].
9. Tarigonda, H., Anjaneyulu, B., Reddy, R. R., & Narasimhamu, K. L. (2023). *Optimization of performance and emission characteristics of a diesel engine in dual-fuel mode with LPG using adaptive-neuro fuzzy inference system model.* Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2023.02.290 [in English].
10. Toledo, E., Guerrero, F., Amador, G., & Toledo, M. (2022). Experimental assessment of the performance and fine particulate matter emissions of an LPG-diesel dual-fuel compression ignition engine. *Energies, 15(23),* Article 9035. https://doi.org/10.3390/en15239035 [in English].
11. Mohsen, M. J., & Al-Dawody, M. F. (2022). The combustion characteristics of compression ignition engine fuelled partially by LPG-diesel blends (simulation study). *Al-Qadisiyah Journal for Engineering Sciences, 15(3),* 157–164. https://doi.org/10.30772/qjes.v15i3.828 [in English].
12. Tchato Yotchou, G. V., Issondj Banta, N. J., Kabini Karanja, S., & Ngayihi Abbe, C. V. (2023). Experimental study on the effect of load and air-gas/fuel ratio on the performances, emissions and combustion characteristics of diesel–LPG fuelled single stationary CI engine. *Engineering Reports, 5(9),* Article e12654. https://doi.org/10.1002/eng2.12654 [in English].
13. Suresh Balaji, R., Daniel Das, A., Marimuthu, S., & Manivannan, S. (2023). *Impact of liquefied petroleum gas on the emission characteristics of diesel in a single cylinder four stroke engine* (SAE Technical Paper №. 2023-01-5136). SAE International. https://doi.org/10.4271/2023-01-5136 [in English].
14. Poku, R., & Bebeteidoh, O. L. (2026). Effects of diesel fuel injection timings on combustion and emissions of a diesel-propane compression ignition engine. *ISA Journal of Engineering and Technology, 3(2),* 95–111. https://doi.org/10.5281/zenodo.19369919 [in English].
15. Issa, N., Kim, J. K., Chun, K. W., Choi, J. H., & Lee, W. J. (2025). Investigation of an optimal exhaust gas recirculation rate on a four-stroke spark-ignited LPG engine. *Journal of the Energy Institute, 120,* Article 102048. https://doi.org/10.1016/j.joei.2025.102048 [in English].
16. Sandomyrskyi, M. H., Boiko, M. F., Lebediev, A. T., Varvarov, L. M., Antypenko, A. M., Makarenko, M. H., Myronenko, H. P., & Denysenko, A. H. (2000). *Traktory ta avtomobili. Chastyna 1. Avtotraktorni dvyhuny [Tractors and automobiles. Part 1. Automobile and tractor engines].* Vyshcha shkola. [in Ukrainian].
17. Mucak, A., Karabektas, M., Hasimoglu, C., & Ergen, G. (2016). Performance and emission characteristics of a diesel engine fuelled with emulsified biodiesel-diesel fuel blends. International *Journal of Automotive Engineering and Technologies, 5(4),* 176–185. https://doi.org/10.18245/ijaet.287183
18. Vardhan, A., Rajput, R. S., Tiwari, A. C., & Randa, R. (2022). Comparative performance analysis on newly design CI to SI single cylinder engine. *International Journal of Engineering Research in*

*Mechanical and Civil Engineering, 9(11).* https://www.technoarete.org/common_abstract/pdf/IJERMCE/v9/i11/Ext_87463.pdf

19. Jacobs, T. J., Assanis, D. N., & Filipi, Z. S. (2003). *The impact of exhaust gas recirculation on performance and emissions of a heavy-duty diesel engine* (SAE Technical Paper №. 2003-01-1068). SAE International. https://doi.org/10.4271/2003-01-1068 [in English].
20. Vardhan, A., Rajput, R. S., Tiwari, A. C., & Randa, R. (2022). Performance and emission analysis of modified compression ignition engine from diesel engine to variable load using petrol and LPG fuel. *Chemical Engineering and Processing: Process Intensification, 181,* 109115. https://doi.org/10.1016/j.cep.2022.109115 [in English].

## РОЗРОБКА ТА ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ СИСТЕМИ ЖИВЛЕННЯ ДИЗЕЛЬНОГО ДВИГУНА АВТОТРАКТОРА ДЛЯ РОБОТИ В ГАЗОДИЗЕЛЬНОМУ РЕЖИМІ НА ЗРІДЖЕНОМУ НАФТОВОМУ ГАЗІ

*Модернізація та переведення сільськогосподарської техніки на альтернативні види палива є ключовим інструментом покращення її екологічних та економічних показників. Використання зрідженого нафтового газу (ЗНГ) у двопаливних системах дозволяє значно зменшити викиди шкідливих речовин ($CO_2$, CO, NOx), проте успішне переведення серійних тракторних дизельних двигунів із забезпеченням стабільних експлуатаційних характеристик на всіх режимах навантаження залишається невирішеною науковою та практичною проблемою. Метою роботи є розробка методів та методик експериментального дослідження дизельного двигуна в газодизельному циклі, що забезпечує його стабільну роботу на різних режимах навантаження-швидкості з різним складом паливної суміші.*

*Для реалізації поставлених завдань розроблено оригінальну принципову схему системи живлення газодизельного двигуна з механічним пристроєм ручного регулювання положення рампи паливного насоса високого тиску (ПНВТ) типу УТН-5, що дозволило усунути нестабільність штатного всережимного регулятора. Експериментальні дослідження проводилися на обкатному стенді гальм КІ-5542 на базі чотирициліндрового дизельного двигуна 4Ч11.0/12.5, додатково оснащеного газобалонним обладнанням, панельним ротаметром LZM-15ZT-4 та електронною системою контролю ваги потоку газу. Випробування проводилися за циклом «навантаження - розвантаження». Для побудови математичних моделей тенденцій основних параметрів застосовувався метод найменших квадратів (LSK).*

*Побудовано графічні та математичні залежності годинної витрати палива (Gg, Gdp) та крутного моменту (Mk) від ефективної потужності двигуна (Ne). Встановлено, що крутний момент демонструє чітку лінійну залежність від потужності. Виявлено вплив теплової та паливної інерції у вигляді петлі «навантаження-розвантаження». Доведено, що максимальна інтенсивність заміщення рідкого палива газом досягається в середньому діапазоні потужностей. Під час порівняльного аналізу, при тій самій потужності, зафіксовано максимальний ступінь заміщення дизельного палива газом без ризику детонаційних явищ. Для порівняння було досліджено витрату палива в чисто дизельному режимі. Запропонований метод та розроблена експериментальна установка підтвердили їх повну працездатність та можуть бути використані для зняття характеристик повного навантаження та серійного переобладнання автотракторних двигунів. Результати дослідницької роботи 0125U000363 представлені в цій науковій статті.*

***Ключові слова:*** *витрата палива, дизельна паливна апаратура, газодизельний двигун, зріджений нафтовий газ (ЗНГ), пілотна доза, система живлення, потужність двигуна, крутний момент.*

***Ф. 4. Рис. 3. Табл. 2. Літ. 20.***

### *INFORMATION ABOUT THE AUTHORS*

**Vadym RYABOSHAPKA** – Candidate of Technical Sciences, Associate Professor of the Department of Agricultural Engineering and Technical Service, Faculty of Engineering and Technology, Vinnytsia National Agrarian University (3 Soniachna St., Vinnytsia, 21008, Ukraine; e-mail: vadym@vsau.vin.ua; https://orcid.org/0000-0003-1812-1030)

**Roman LYSENKO** – Postgraduate Student of the Department of Agricultural Engineering and Technical Service, Faculty of Engineering and Technology, Vinnytsia National Agrarian University (3 Soniachna St., Vinnytsia, 21008, Ukraine; e-mail: romandmytrovich@gmail.com; https://orcid.org/0009-0007-9867-5581)

**РЯБОШАПКА Вадим Борисович** – кандидат технічних наук, доцент кафедри агроінженерії та технічного сервісу інженерно-технологічного факультету Вінницького національного аграрного університету (вул. Сонячна, 3, м. Вінниця, 21008, Україна; e-mail: vadym@vsau.vin.ua; https://orcid.org/0000-0003-1812-1030)

**ЛИСЕНКО Роман Дмитрович** – аспірант кафедри агроінженерії та технічного сервісу інженерно-технологічного факультету Вінницького національного аграрного університету (вул. Сонячна, 3, м. Вінниця, 21008, Україна; e-mail: romandmytrovich@gmail.com; https://orcid.org/0009-0007-9867-5581)