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Problems and prospects of creating modern agricultural gas diesel engines: A literature review

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Abstract. In conditions of constant growth in the cost of traditional oil products and their shortage, the issue of using alternative fuels becomes urgent. The purpose of the article is to identify ways of using alternative types of fuel for the operation of diesel engines. Research methods – analysis and verification of data obtained from scientific publications, which are part of the world-famous scient metric databases, for the relevance of the subject of research. The research results reveal the advantages and disadvantages of dual-fuel engines operating on gaseous fuel with diesel fuel additive, the impact of this type of engine on emissions and toxicity of exhaust gases, in particular nitrogen oxides NO_x. The application of the so-called gas nozzle and the cross-section of the holes of its nozzles are substantiated. It was analysed and established that the most economically expedient is the use of liquefied petroleum gas for the operation of diesel engines by implementing the gas-liquid cycle; it was found that the most promising for this is gas cylinder equipment of the so-called 4th generation. A retrospective analysis of studies of internal combustion engines with gas cylinder equipment showed an increase in motor resource when using gaseous fuels, as well as the negative side of using gaseous fuels, which consists in reduced power when converting carburettor engines, however, the use of these fuels for the operation of diesel engines completely eliminates this disadvantage. Based on the research analysis, the influence of the ignition dose, when the engine is operating on the gas-diesel cycle, on the performance at different loads was also established, and a recommendation was found to switch to the diesel cycle from the gas-diesel cycle at loads less than 30% of the nominal one. The optimal scheme for the implementation of the gas-diesel cycle, which is relevant and promising for more widespread energy and transport vehicles, has been substantiated and selected. Based on the analysed schemes, it was established that the scheme that can be taken as a basis for further research in this direction is the scheme of the DG-Flex BOSCH gas-diesel system. The practical value of the work lies in the justification of complex conversion with partial replacement of diesel fuel with liquefied petroleum gas as the most rational way of converting serial diesel engines into dual-fuel engines

Keywords: transport; liquefied petroleum gas; gas cylinder equipment; power supply system

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INTRODUCTION

In the conditions of an increase in the share of fuel costs, many commercial transport operators are thinking about the possibility of compensating for the increase in prices by switching to gas. However, such radical methods as converting diesel engines to gas engines have their drawbacks. In the search for an optimal solution, an alternative option is often considered – the use of a gas-diesel engine, which combines the advantages of a traditional diesel and gas cylinder equipment (HBO) (Kabeyi & Olanrewaju, 2023; Liu *et al.*, 2023). Gas-diesel engines at the beginning of the 21st century (Shyamkishore *et al.*, 2023) are considered as a separate type of engines that are widely used in many sectors of the economy, in particular in agriculture, and which also have environmental advantages over traditional fuels (Emaish *et al.*, 2021). A dual-fuel gas-diesel engine is a power plant, which is additionally equipped with equipment for work involving gas (Sain *et al.*, 2018). The principle of operation of such an installation consists in the simultaneous supply of two types of fuel to the combustion chamber. The main fuel is gas of various origins, and the additional fuel is diesel oil. In this case, diesel fuel is supplied in a much smaller volume than usual. In the gas-diesel design (Zhu & Fan, 2022), diesel fuel acts as a kind of ignition for the air-gas mixture. The supply of diesel fuel is due to the fact that the ignition temperature of gas is higher than that of diesel fuel, and that is why at the moment of compression, in the combustion chamber, the gas itself cannot ignite. For its ignition during the compression stroke, a small amount of diesel fuel is fed into the combustion chamber. Based on the above, it can be concluded that the gas-diesel dual-fuel engine retains the ability to work only on diesel fuel, but is not capable of working on one gas. The use of gas-diesel engines in agriculture is a rather promising direction for the development of agricultural engineering, which preserves all the advantages of a diesel engine in terms of energy capabilities and improving environmental and economic parameters when using gas fuel (Mathur *et al.*, 2022; Saleem, 2022). The existing data of scientific research by scientists for the year 2022 (Bagagiolo *et al.*, 2022; Kutkovetska *et al.*, 2022) allow us to state the prospects for the development of the use of gas-diesel engines, but today there is no systematic approach to the use of this type of fuel equipment in agriculture.

The purpose of the work was to assess the prospects of using the gas-diesel engine system in agriculture. For this purpose, an analysis of modern scientific data on the use of auto-tractor diesel engines with the involvement of liquefied petroleum gas (LPG) was carried out. A search for scientific sources was conducted in the Google Scholar, Scopus, Web of Science databases of publications for the period 2000-2023 according to the set goal. Publications that lacked statistical justification, duplicated results, or contained data that could not be further verified were excluded from further analysis.

GAS-DIESEL ENGINES: PROBLEMS OF THEIR MODIFICATION AND OPERATION

Attention is drawn to the use of the term in the world scientific literature for an engine that uses both conventional diesel fuel and liquefied gas – "liquefied gas and diesel dual-fuel engine" (Ashok *et al.*, 2015). In publications from 2010-2020, dual-fuel LPG engines are modified diesel engines that use LPG as the primary fuel and diesel as the secondary fuel (Pielecha & Sidorowicz, 2021; Pham *et al.*, 2022). Dual-fuel LPG engines have good thermal efficiency at high power, but performance is lower at part-load conditions due to poor utilization of the energy potential of the combined fuel. This problem can be overcome by using a variety of factors such as fuel injection rate, injection timing, gaseous fuel composition and intake charge conditions to improve the performance, combustion and emissions of dual-fuel engines. However, the question of the most effective way to transfer a diesel engine to dual-fuel mode remains open (Bennour, 2021).

Several publications (Murthy *et al.*, 2021; Al-Dawody *et al.*, 2022) review the results of studies conducted to improve the performance, combustion parameters, and emissions of LPG and diesel engines. The data of the work showed that the use of liquefied gas in a diesel engine is one of the effective methods of reducing toxic emissions, but at the same time, under conditions of partial load, there is a drop in the efficiency and effective power of the diesel engine. Specifically, a diesel fuel blend with 10% LPG (Liquefied Petroleum Gas) is shown to produce a 5.35% reduction in NO_x, while diesel with 20 and 30% LPG emits 9.05 and 16.5% less NO_x, respectively. Increasing the percentage of LPG in diesel results in lower soot concentrations because LPG has a lower carbon to hydrogen ratio. The lowest ability to emit smoky combustion is found for fuel with 30% LPG, where a reduction of 7.4% is achieved. It was concluded that the optimal mixing ratio is 30% LPG.

One of the main problems of combining diesel fuel with LPG is the gas density, which is very low under ambient conditions (Anisimov *et al.*, 2016). This affects the fuel supply system, and to inject the required mass of fuel, a much larger cross-sectional area of the fuel injector is required than that of a diesel injector.

In modern units, the operation of gas cylinder equipment (HBO) on a diesel engine is performed according to the principle of the 4th generation of HBO gasoline engines with a slight difference in the fuel supply system (Semenov *et al.*, 2015). If in the gasoline analogue, the engine starts working on gasoline, and then uses only gas, then HBO on a diesel engine uses both types of fuel at the same time, feeding it to the cylinders in turn at different strokes (Kalinichenko *et al.*, 2019). The principle of operation of gas in a diesel engine is based on the fact that both types of fuel alternate in supply. The launch is carried out only on diesel fuel. In the first stroke, a portion of gas fuel mixed with air enters the cylinders, which is then compressed, and at the end of the compression stroke, an igniting dose of diesel fuel is supplied, which self-ignites from compression and ignites the gas-air mixture. The lower the octane number of gas fuel, the faster the gas burns with less heat release, and accordingly, the more it can replace diesel fuel (Poliakov *et al.*, 2015).

In 2010, the use of natural gas in a compressed form became the most widespread in cars with engines with external mixture formation and forced (spark) ignition (Melnyk *et al.*, 2018; Singh *et al.*, 2021). Usually, cylinders for storing natural gas under high pressure, gas reducers, electromagnetic valves and other gas equipment are additionally installed on a car with a carburetor engine, which ensures the possibility of engine operation on gas. The versatility of the power supply of such a vehicle (gasoline or natural gas) is also its disadvantage, since the full potential of the high detonation resistance of natural gas is not used (Lopatin, 2020). At the beginning of the 2020s, carburetor engines in agriculture recede into the background, due to their obsolescence and inefficiency, as well as unsatisfactory environmental parameters (Hua, 2021). However, there are publications about the experience of gas cars manufactured in the USSR (Union of Soviet Socialist Republics) running on compressed natural gas (CNG), which revealed a number of positive aspects (Poliakov & Mariyanko, 2014). The researchers established an increase in the motor resource of the converted engine by 35-40, an extension of the term of use of candles by 30-40%, as well as a reduction in engine oil consumption by postponing the replacement by 2-3 times. However, the same researchers noted a number of disadvantages of using the dual-fuel mode, in particular – a decrease in power by 18-20%, which leads to a decrease in maximum speed by 5-6%, respectively, and an extension of the acceleration time by 24-30%, a decrease in the maximum angles overcome by the climb and mileage limits at one gas station. At the same time, the carrying capacity decreases significantly (9-14%) due to the increase in the weight of the car due to the gas cylinder equipment.

The difficulty of using gas fuel in diesel engines is related to their poor flammability, low cetane number, and high ignition temperature (Zaharchuk & Zaharchuk, 2020). Therefore, to organize the operation of a diesel on natural gas, the gas-diesel process is used, which consists in feeding a dose of flammable diesel fuel into the cylinders, which ensures the ignition of the gas-air mixture (Kryshtopa *et al.*, 2018). Gas-diesel engine start-up and idling work only on diesel fuel. In other modes, an increase in engine power is achieved by increasing the gas fuel supply. The amount of incendiary dose delivery is 15-20% of the total fuel consumption.

LPG AS A PROMISING GAS-DIESEL ENGINE COMPONENT

In addition to liquid fuel – diesel, gaseous fuels such as hydrogen, compressed natural gas (CNG), diesel methyl ether (DME), biogas, and LPG are used in combination (Caban *et al.*, 2013; Kumar *et al.*, 2018). Liquefied petroleum gas (LPG) and CNG turned out to be the most popular among gas fuels in 2010-2020 due to the availability and simplicity of units for their use (Wei & Geng, 2016; Singh *et al.*, 2020). LPG fuel can be used as gas or liquid phase in diesel engines. In the gas phase, air from the intake is fumigated and an LPG-air mixture is formed in the intake manifold (Mueller & Guenthner, 2023). When LPG is a liquid, it is mixed with diesel fuel at a pressure above 0.5 MPa. LPG is mixed with diesel fuel under pressure by a high-pressure pump. A high-pressure pump supplies a mixture of diesel fuel and gas to the injector. The liquid phase of LPG is injected either as a mixture of LPG with diesel fuel at the same time by an injector or separately by a second injector (Vo *et al.*, 2022).

In gas-phase LPG diesel engines, vaporized LPG is fed into the cylinder with intake air and the LPG-air mixture is compressed as in a conventional diesel engine. The LPG-air mixture is not self-igniting due to the high auto-ignition temperature. A small amount of diesel fuel, called pilot, is injected to ignite the LPG-air mixture. Pilot diesel fuel injected by conventional diesel injection equipment only reduces a small fraction of engine power output (Canelada & Tischer, 2007). The use of LPG in the gas phase is quite well studied in many scientific works (Saleh, 2008; Ciniviz, 2010; Mohsen *et al.*, 2023). It was concluded that this combination leads to better engine efficiency, reduction of emissions of solid particles and smoke.

M. Ciniviz (2010) carried out a study of the effectiveness of the use of dual fuel (diesel / LPG) in a diesel engine on power and emissions. A gas control valve

system was designed to supply liquefied gas at a rate of 30% to the intake manifold. The experimental results showed that the engine power, engine torque and specific fuel consumption were improved due to the dual fuel supply. As a result of the use of dual-fuel engines, compared to single-fuel engines, torque and engine power increased by 5.8%, and NO_x emissions and excess air ratio decreased by 5.9 and 1/9%, respectively. Furthermore, CO_2 emissions were shown to be lower than in single-fuel mode, as *CO* emissions cannot be converted to CO_2 in dual-fuel mode.

Also P. Stålhammar *et al*. (2011) studied the performance and emissions of a 100% LPG direct injection diesel engine. They added di-tert-butyl peroxide (DTBP) and aliphatic hydrocarbon (AHC) to LPG fuel to increase the cetane number. The stable operation of the diesel in a wide range was demonstrated. The engine load range has been extended with the improvement of LPG cetane number. Several different LPG mixtures were obtained by varying the concentration of DTBP and AHC. LPG and only AHC fuel blends increased NO_x emissions compared to diesel operation. The results of the experiment showed that the thermal efficiency of a diesel engine running on liquefied gas was similar in basic parameters to running on pure diesel fuel. From the point of view of emissions of exhaust gases, their reduction was ascertained when using different mixtures of LPG, DTBP and AHC.

Attempts to convert YaMZ-240 GD and YaMZ-240 H1-GD diesels to gas diesel were carried out by a group of researchers from Ukraine (Kovbasenko *et al.*, 2016). The obtained data indicate the prospects of this type of conversion using the regulation of the starting ignition volume of a diesel engine with an electromagnet. Regulation of fuel supply to both diesel and gas in this case is carried out by separate screws. It is planned to switch to purely diesel mode when the load in the combined cycle is reduced below 20-30% of the maximum, which establishes the use of gas-diesel mode as the basic one. Also, the same scientists noted the improvement of environmental characteristics in the dual-fuel mode of engine operation in the form of a certain decrease in the content of carbohydrates and carbon monoxide, as well as the smokiness of exhaust gases. With the proposed mechanism of conversion to gas-diesel, slight differences in the emission of carbon oxides were noted in the two modes of engine operation. As for nitrogen oxide, the researchers even found an increase in the content of this compound when operating in gas-diesel mode. There are also significant disadvantages of this system in the form of an increase in the engine design due to the hydraulic amplifier of the gas dispenser drive and the impossibility of correcting the volume of flammable diesel fuel, which limits the amount of replacement of diesel with gas. When using a gas-diesel installation on a YAMZ-236 GD engine with mechanical multi-mode rotation control, the ignition dose of diesel fuel was 30%. The above results of scientists from Ukraine coincide with the conclusions of researchers from other countries and indicate the prospects for further development of gas-diesel engines, however, the very scheme of conversion to gas-diesel requires further improvement.

Also, work on the creation of engines with a gas-diesel type of power supply is carried out both in scientific institutions and by commercial companies in many countries of the world. In particular, as a good example of this is the development of the Bosch company Diesel-Gas System – Bosch (DG-Flex) (D'Agosto *et al.*, 2014). However, data on its installation on agricultural machinery has not been found. As standard, DG-Flex consists of sensors: detonation, air temperature, coolant temperature, phase, crankshaft, gas temperature and pressure, as well as a lambda probe and an electronic gas supply control unit. The use of the Diesel-Gas System – Bosch (Fontaras *et al.*, 2012; Gopalakrishnan & Tischer, 2014) leads to a significant improvement in environmental characteristics in the form of a six-fold reduction in solid emissions and nitrogen oxide volume compared to the diesel cycle. Also, a positive effect is saving money and reducing the volume of fuel consumption. However, some scientists (Owczuk *et al.*, 2019) point to the imperfection of this design in the form of the complexity of the system itself, a mixed method of power regulation with a throttle and a complicated control algorithm of this system.

PROBLEMS AND PROSPECTS OF USING A GAS-DIESEL ENGINE IN AGRICULTURE

The main problem in the practical application of a gas-diesel engine in agriculture is the choice of the principle of rebuilding the power system for the conversion of serial tractor engines (Mattarelli *et al.*, 2019; Giorgi *et al.*, 2020). Fundamental in this case is the difference in the two concepts of converting diesel engines to a gas-diesel power model. The most radical method is the complete replacement of fuel, which is accompanied by spark ignition of the gas-air mixture (Mattarelli *et al.*, 2021). This method involves complete disassembly of the diesel fuel equipment followed by reprogramming of the compression ratio, reducing it to 11-14 units, and at the end, the system is equipped with gas equipment (ignition system, cylinder, gas pipeline). The technical parameters of this conversion method correspond to the parameters of the engine

before the rebuild, and the environmental indicators are significantly improved, since in general this engine runs on gas fuel (Kabeyi & Olanrewaju, 2022). After the conversion, the engine can no longer run on diesel fuel, the reverse operation is economically impractical. Experiments were conducted by researchers M. Kabeyi & O. Olanrewaju (2022) to study the efficiency of a diesel engine with natural gas and diesel fuel in dual fuel mode with different proportions of diesel fuel 10-100% at 10% intervals. The results show that the overall efficiency of using CNG was lower than that of 100% diesel. At lower loads the efficiency was significantly lower and at higher outputs the performance was much better but still lower than when the diesel was running at 100%. The specific fuel consumption of the engine at 1.1 kW when operating on a mixture with 90% CNG was 68% higher than when the engine was operating in purely diesel mode. However, at 2.8 kW, the specific fuel consumption of the engine when running on 90% CNG was only 7% higher. Exhaust gas emissions show that in gas-liquid mode CO_2 and smoke emissions were lower due to the lower carbon to hydrogen ratio in CNG. *CO* emissions were higher due to the lower air-to-fuel ratio, as the injection of LNG into the intake air replaced some of the air in the intake tract.

The next option is the dual-fuel mode of rebuilding the diesel engine. In general, it is a variant of the standard gas-diesel engine with the predominant use of gas as the base fuel and diesel for the ignition of the gas mixture (Dasappa & Sridhar, 2011). However, the use of a specific ratio of diesel and gas in this scheme is a rather variable indicator that primarily depends on the type of gas fuel, individual design features of both the diesel engine and the gas plant. An important factor in this version of the gas-diesel engine is the possibility of using a full-fledged purely diesel mode, which is carried out by the operator himself.

In view of the energy crisis, many alternative fuels have been tested worldwide for use in internal combustion engines (Wang *et al.*, 2022; Das *et al.*, 2022). The conducted review indicates the perspective of conducting research on the use of natural gas as an alternative fuel, corresponds to the trend of finding new types of fuel with improved environmental performance and preservation of the technical characteristics of the diesel engine. Taking into account the above data, one of the promising types in terms of economy is the use of a diesel engine with an LPG system in agriculture. An increase in the number of publications on the study of optimal conversion schemes of diesel engines using biogas and LPG is attracting attention (Wei & Geng, 2016; Singh *et al.*, 2020). Analysis of the publications of scientists from Ukraine on this issue indicates that most of the research is devoted to the conversion of outdated engines or the use of biogas, which is quite debatable regarding the availability of this type of fuel in Ukraine (Zhuk, 2022).

Gas-diesel engines in agriculture can be rebuilt by completely replacing diesel fuel with gas, which leads to environmental improvement, but the loss of the ability to use diesel fuel. On the other hand, a dual-fuel mode can be applied, where gas is used as the base fuel, but diesel remains for ignition, giving greater flexibility of use.

CONCLUSIONS

The conducted review indicates the relevance of developing new schemes for conversion of serial diesel engines to dual-fuel mode using alternative fuel mixtures. Alternative types of gaseous fuels available on the market, such as hydrogen, CNG, diesel methyl ether, biogas and LPG have significant differences in the implementation of engine conversion and technical characteristics after modification. There are several options for converting a diesel engine to work in dual-fuel mode, but there are no generally accepted schemes for modifying diesel engines in agriculture. The diesel engine conversion schemes proposed for 2010-2020 are technically quite complex and require significant intervention in the engine layout, which increases the cost of this manipulation. It was established that the use of dual-fuel engines has a significant thermal efficiency at high power, but at the same time they are characterized by lower performance under partial load conditions due to insufficient use of the energy potential of the combined fuel. They are trying to overcome this problem by optimizing the power and combustion parameters. The optimal way to modify a diesel engine into a dual-fuel mode remains a debatable issue, which prevents serial conversion. Taking into account the available opportunities in Ukraine regarding the availability of various types of gaseous fuel, the most economically feasible type of gaseous fuel when converting a diesel engine is the use of liquefied petroleum gas. Taking into account the available schemes, the scheme of the DG-Flex BOSCH fuel supply system, which provides for the supply of liquefied petroleum gas to the intake manifold and its mixing with air on the intake stroke, and the supply of an ignition dose of diesel fuel, using modern diesel fuel equipment, is promising for the operation of a dual-fuel engine according to the gas-diesel cycle Common Rail. However, the existing schemes need to be improved, taking into account the existing shortcomings in the form of software and maintenance complexity, as well as a multi-level throttle control system. As a result of this

review, the existence of the problem of developing energy-efficient and environmentally safe gas-diesel systems, in particular, for use in the agriculture of Ukraine, was established, which requires further research with the aim of implementation in practical activities.

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CONFLICT OF INTEREST

None.

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Проблеми та перспективи створення сучасних сільськогосподарських газодизелів: літературний огляд

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Анотація. В умовах постійного зростання вартості традиційних нафтопродуктів та їх дефіциту, актуальним постає питання використання альтернативних палив. Метою статті є виявлення шляхів використання альтернативних видів палива для роботи дизельних двигунів. Методи досліджень – аналіз та верифікація даних отриманих з наукових публікацій, що входять до всесвітньо відомих наукометричних баз, на актуальність предмету досліджень. Результатами досліджень є виявленні переваги й недоліки двопаливних двигунів, що працюють на газоподібному паливі з присадкою дизельного палива, вплив цього типу двигунів на викиди та токсичність відпрацьованих газів, зокрема окисів азоту NO_x. Обґрунтовано застосування так званої газової форсунки та поперечного перерізу отворів її розпилювачів. Проаналізовано та встановлено, що найбільш економічно доцільним є використання для роботи дизельних двигунів зрідженого нафтового газу шляхом реалізації газорідинного циклу; виявлено, що найбільш перспективним для цього є газобалонне обладнання так званого 4-го покоління. Ретроспективний аналіз досліджень двигунів внутрішнього згорання з газобалонним обладнанням, показав збільшення моторесурсу при використанні газоподібних палив, а також негативну сторону використання газоподібних палив, яка полягає у знижені потужності при переобладнанні карбюраторних двигунів, однак використання цих палив для роботи дизелів повністю нівелює цей недолік. На основі аналізу досліджень, встановлено також вплив запальної дози, при роботі двигуна по газодизельному циклі, на показники роботи при різних навантаженнях та знайдено рекомендацію переходити на дизельний цикл з газодизельного при навантаженнях менших за 30 % від номінального. Обґрунтовано та вибрано оптимальну схему реалізації газодизельного циклу, що є актуальною і перспективною для більш розповсюджених енергетичних та транспортних засобів. Виходячи з проаналізованих схем, встановлено, що схемою, яку можна взяти за основу при подальших дослідженнях цього напрямку – це схема газодизельної системи DG-Flex BOSCH. Практична цінність роботи полягає в обґрунтуванні комплексного переобладнання з частковим заміщенням дизельного пального зрідженим нафтовим газом як найбільш раціонального способу переведення серійних дизельних двигунів в двопаливні

Ключові слова: транспорт; зріджений нафтовий газ; газобалонне обладнання; система живлення

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