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ANALYSIS OF OPERATING PARAMETERS AND INDICATORS OF A COMPRESSION IGNITION ENGINE FUELLED WITH LPG

Summary. This article presents the possibilities for using alternative fuels to power vehicles equipped with compression ignition (CI) engines (diesel). Systems for using such fuels have been discussed. Detailed analysis and research covered the LPG STAG autogas system, which is used to power dual-fuel engine units (LPG+diesel). A description of the operation of the autogas system and installation in a vehicle has been presented. The basic algorithms of the controller, which is an actuating element of the whole system, have been discussed. Protection systems of a serial production engine unit to guarantee its factory-controlled durability standards have been presented. A long-distance test drive and examinations of the engine over 150,000 km in a Toyota Hilux have been performed. Operating parameters and performance indicators of the engine with STAG LPG+diesel fuelling have been verified. Directions and perspectives for

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the further development of such a system in diesel-powered cars have been also indicated.

Keywords: Diesel engines; dual-fuel (LPG+diesel); STAG LPG+diesel

1. INTRODUCTION

In the last decade, a growing interest among the authors of research papers published in industry magazines on the issue of supplying CI engines (diesel) with gas fuels has been observed. This is partly caused by the economic reasons, which directly influence a reduction in the costs of the operation of the vehicle. In the case of high mileage, the operation of such a car is clearly less expensive. Savings can be up to around 35%, which means that the ROI time for the autogas system installation is short. The use of alternative fuels to power diesel engines in cars allows strict exhaust emission standards to be met without the necessity of using complex systems for the neutralization of toxic components in fumes. In the process of diesel combustion combined with LPG combustion, the vehicle generates a reduced amount of the harmful components found in fumes (carbon monoxide, carbon dioxide, nitrogen oxides and PM particles), thus, it is more environmentally friendly. Such a supply can be an alternative to electrical motors, particularly in trucks, where the installation of electrical drives is limited by the drive distances and total weight [1-4].

2. CHARACTERISTICS OF FUELS USED TO SUPPLY DIESEL ENGINES

The conventional fuel used to power CI engines is diesel. This is a mixture of hydrocarbons containing 14÷20 atoms of carbon per molecule, which has a boiling temperature within the range of 150°C÷380°C. Diesel is manufactured from petroleum with a secondary processing of the heavy fractions left from petroleum distillation. Its properties must be modified through special additives, which improve fuel performance, even when small amounts are added. Fuel obtained in this way does not meet all the requirements as diesel includes paraffinic and naphthenic hydrocarbons, as well as aromatic hydrocarbons [5].

The amount of individual hydrocarbon fractions in diesel has an impact on its physical and chemical properties. This influences the parameters and performance indicators of operating engines, particularly on the toxicity of fumes and the engine's operating efficiency. The high content of aromatic hydrocarbons makes the fuel self-ignition delay longer, which causes a generation of build-ups in the combustion chamber and increases emission of solid particles. This, in turn, leads to a reduction of the content of heavy hydrocarbons and sulphur in diesel, which influences the lubricity and density. Additionally, fuels for diesel engines should have the following properties: high capabilities of spraying, mixing with air and evaporating, which influences cold engine starts. The important properties of diesel include the ability to generate self-ignition after the injection of a measured dose of fuel to the cylinder and to achieve full and complete combustion. This is influenced by many factors, such as fractional composition, viscosity, volatility, surface tension, density, solidification and cloud point. Paraffinic hydrocarbons show the best ability to self-ignite. Their disadvantage is the high solidification temperature, which causes the blocking of the engine fuelling system in low ambient temperatures [6, 7].

The leading trend in the development of modern CI engines (diesel) is the search for and application of various alternative fuels. Such fuels may include vegetable oils or their esters, ethers, alcohols, LPG, CNG or LNG, biogas, hydrogen or synthetic fuels [8, 9].

3. POSSIBILITIES OF SUPPLYING DIESEL ENGINES WITH LPG

CI engines have been fuelled only with diesel oil for years. This fuel shows good self-ignition properties (high cetane number). While LPG-type fuels show a high octane number and a high resistance to spontaneous ignition as a consequence. This causes problems with using this fuel to power diesel engines. This is why a combination of both diesel and LPG is needed. Supplying LPG to a diesel engine can be carried out by using various methods [10, 11]:

- mixer,
- injector assembly in the intake manifold,
- injector delivering fuel via the suction valve,
- injector in the combustion chamber.

4. LPG STAG AUTOGAS SYSTEM FOR POWERING DUAL-FUEL ENGINE UNITS (LPG+DIESEL)

With the development of the automotive industry and market demand for gas systems for vehicles equipped with CI engines (diesel), the Centre for Research and Development of AC S.A. started research work into commercial LPG systems dedicated for such systems. The work made use of the extensive experience with LPG systems for spark-ignited engines. High requirements were set for future LPG systems supporting diesel engines. The focus was put on operational properties, such as the life and durability of the engine unit. From a commercial point of view, it is the first and most important criterion specified for such systems. Economic and performance factors were also taken into consideration, as they are equally important.

The dual-fuel system allows us to extract energy from new diesel resources (e.g., burning solid particles in the cylinder). If the autogas installation is properly installed and tuned, it is possible to gain a significant increase in power and torque by 10%÷30%, while reducing the operating costs and improving engine parameters and performance indicators. In diesel engines with a mechanical injection, the gas is injected into the intake manifold, which results in a more efficient burning of diesel, the additional combustion of gas increases the power of the engine and the combustion thermodynamic efficiency is improved. The vehicle shows better dynamic qualities thanks to the power and torque increase. Financial benefits (savings) are present in both dynamic driving and eco-driving [12].

The controller is an important element of such an autogas system. For the needs of CI engines, a new design of a controller specifically dedicated to such engines (STAG diesel controller) has been introduced. It can be used for fuelling 2÷16 cylinder engine units. The whole system has been based on the latest technical and technological solutions, enabling the dosing of the gas fuel with air, which are then mixed with diesel in the cylinder. The controller does not exclude driving on diesel oil alone, as the autogas system does not interfere with the internal parts of the engine. The controller is capable of the intelligent controlling of the fuel dosing process during engine operation. This is possible when the following sensor measurements are read: exhaust temperature or oxygen sensor (lambda probe). An advanced algorithm for sequential gas injection is based on the current demand for fuel. Measurements cover the amount of injected oil as well. The engine protection system has been extended with a temperature control system for the safety of the unit. The system is also able to read the ATF ratio and control it with an independent wideband lambda probe dedicated for CI engines (diesel). Figure 1 presents the STAG diesel controller, while Table 1 describes its functions and its technical and operating capabilities.

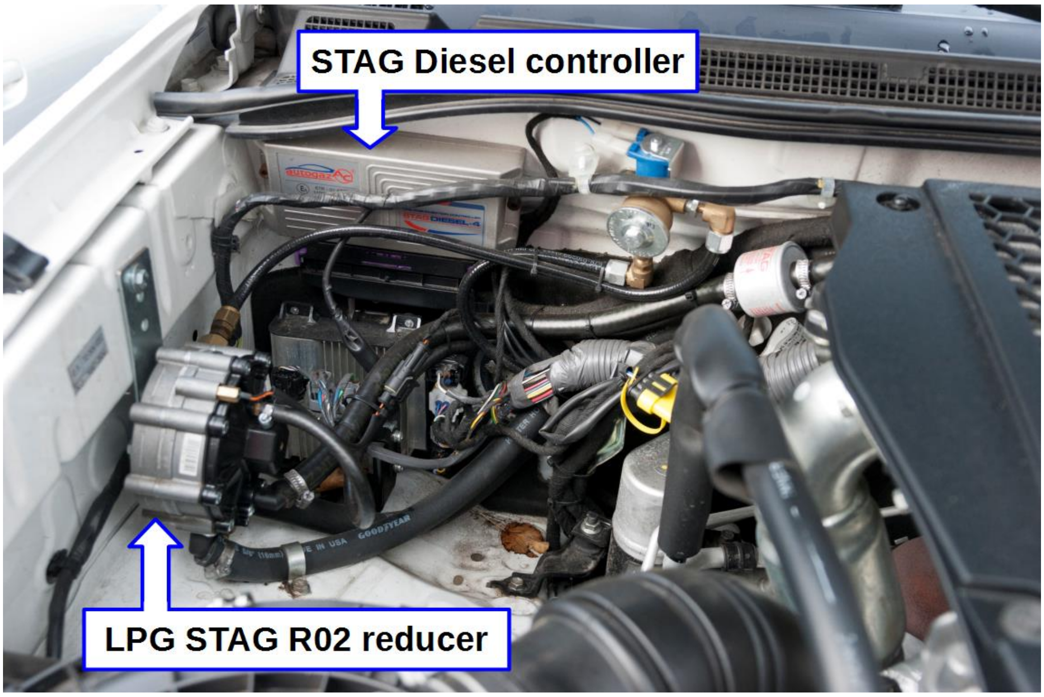

Fig. 1. STAG diesel controller and LPG STAG R02 reducer

Table 1.

Key technical parameters of the STAG diesel controller

Supported engines	Diesel with mechanical injection
	Diesel with common rail electronic injection
	Diesel with unit injectors
Fumigation options	LPG or CNG
Control systems and algorithms	Advanced algorithm of sequential gas injection
	Precise gas dosing based on current engine demand
	Measurements and control of injected diesel in common rail engines
	Advanced algorithm for engine protection
	Controlled exhaust gas temperature for improved safety of the drive unit
	Reading a wideband oxygen sensor, control of air-to-fuel rate with an independent wideband oxygen sensor designed for diesel engines (optional installation for engines without factory-mounted sensors),
	Support for cars provided with cruise control
	Modification of gas injection sequence

For the purpose of gas pressure reduction, the STAG R02 reducer (Fig. 1) was used. The basic features distinguishing the STAG R02 are the compact size and unique design, including two aluminium castings and Actherm-rated cover, which prevents gas cooling, thus, providing excellent thermal insulation. Due to its unique design, the AC R02 heats up very quickly, such that switching to gas is also performed quickly. Therefore, no additional work, such as temperature correction, is required of the controller. Its high thermal efficiency and resistance to LPG contamination make the reducer the best option when selecting autogas system components. Table 2 presents the technical specification of the applied reducer.

Table 2.

Technical specifications of the LPG STAG R02 reducer

Material	Two aluminium castings and a cover made of hard, resistant plastic
Weight	1.56 kg
Dimensions	125x122x89
Maximum inlet pressure	30 bar
Outlet pressure	0.9-1.5 bar
Gas inlet diameter	M10x1
Gas outlet diameter	Hose Ø12
Water outlet diameter	Ø16
Maximum engine power	100 kW (136 hps)
Approval	67 R - 01 6865

The LPG supply system was equipped with the ACW01 injection rail (Fig. 2). This type of injector is designed for sequential gas injection in compression injection and spark injection engines. It ensures the precise dosing of vaporized gas to the intake duct separately for each engine cylinder. As with all other AC injection rails, this rail exhibits high durability, which has been confirmed in long-distance road tests for various makes of car and various road and weather conditions. Additionally, the AC rail is provided with 2Ω coils, which eliminate the risk of overloading the control systems. The coils have been equipped with IP67-rated connections. The main component is the body, which is made of anodized aluminium. The connections are made of brass, while the sealing is based on rubber compounds compatible with other elements. The technical specification of this injection rail is presented in Table 3.

Fig. 2. ACW01 injector rail

Table 3.
Technical specifications for the ACW01 injection rail

Rated operating pressure	0.95÷1.2 bar
Maximum operating pressure	4.5 bar
Injector opening time	~2.1 ms
Injector closing time	~1.5 ms
Performance range	11÷29 kW/cylinder
Maximum flow	90 l/min for p=1 bar

5. TESTING THE OPERATING PARAMETERS OF A COMPRESSION IGNITION ENGINE FUELED WITH LPG

The STAG diesel system was installed in a new Toyota Hilux with a CI engine. Figure 3 presents the vehicle (test unit) with the locations of the LPG system components. Table 4 specifies the technical parameters of the Toyota Hilux. Measurements and test drives of the LPG+diesel system were performed over a distance of 150,000 kilometres.

Test-driving was performed in the city, on express roads, on country drives and under extreme conditions (off-road). This mode of testing offered an exact representation of the operating conditions for this type of vehicle. Figure 4 presents a diagram of the STAG diesel in the LPG+diesel system.

Table 4.
Technical (factory) specifications of the test vehicle, Toyota Hilux

Type	Pickup
Year of manufacture	2012
Emission standard compliance	EURO 5
Engine type	Turbocharged with an intercooler
Capacity	2,494 cm^2
Number of cylinders	4
Fuel supply	Common rail with electronic injection control
Maximum power	106 kW at engine rpm of 3,400
Maximum torque	343 Nm at engine rpm of 2,000
Maximum speed	170 km/h
Transmission	Five-gear, manual

Fig. 3. View of the test unit (vehicle) with the locations of the LPG system components

Technical inspections of the engine were performed every 10,000 km. These checks involved measurements of the compression ratio and valve clearance. Inspections of the cylinder working faces, valve guides and valves (valve face) were also carried out. Visual inspections of these elements were performed with the use of an endoscope. The results of engine unit tests were compared with the manufacturer's requirements.

It was observed that the wear of individual components did not exceed the factory limits. Therefore, it can be concluded that the installation of an LPG+diesel fuelling system does not significantly affect the durability of the engine unit.

Figure 5 presents the speed characteristics of the tested vehicle. The measurements of the torque and power trends vs. rpm were performed for the three fuelling systems:

- only diesel,
- only LPG+diesel.

Analysis of the curves shows an increase in torque and power, respectively. The engine power increase in the LPG+diesel mode was 20 hp and the torque increase was 42 Nm. Analysis of torque curves indicates a shift in the maximum torque towards higher engine speeds. This results in a lower ratio of engine flexibility to its power. As a consequence, the engine is more dynamic, which directly influences acceleration in different gears.

Long-term tests covering 150,000 km in urban, country and off-road conditions allowed us to estimate the economy of the dual-fuel system: the average reduction of the operating costs related to the engine demand for diesel in mixed cycles was 31%.

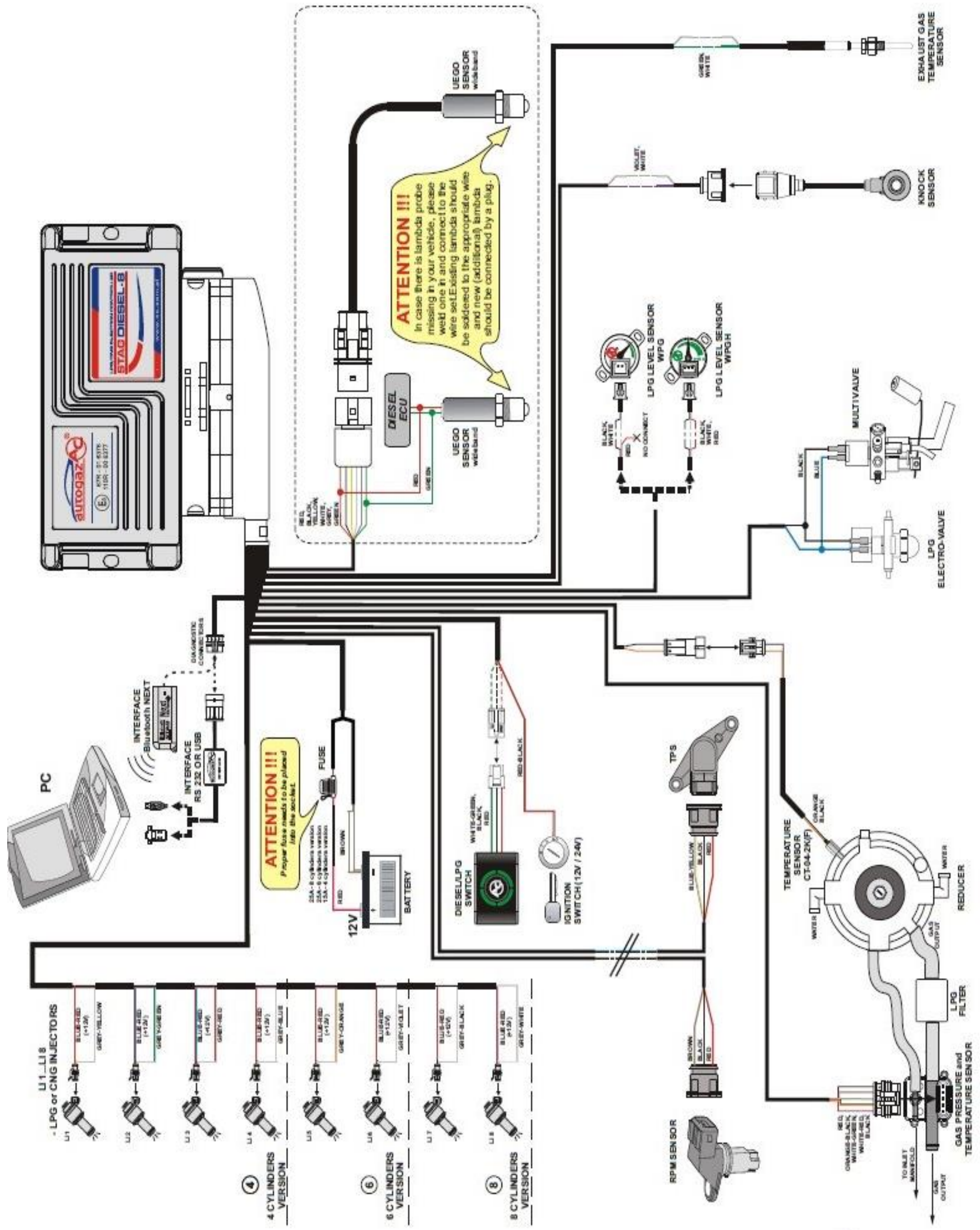

Fig. 4. Diagram of the STAG diesel-based LPG+diesel system

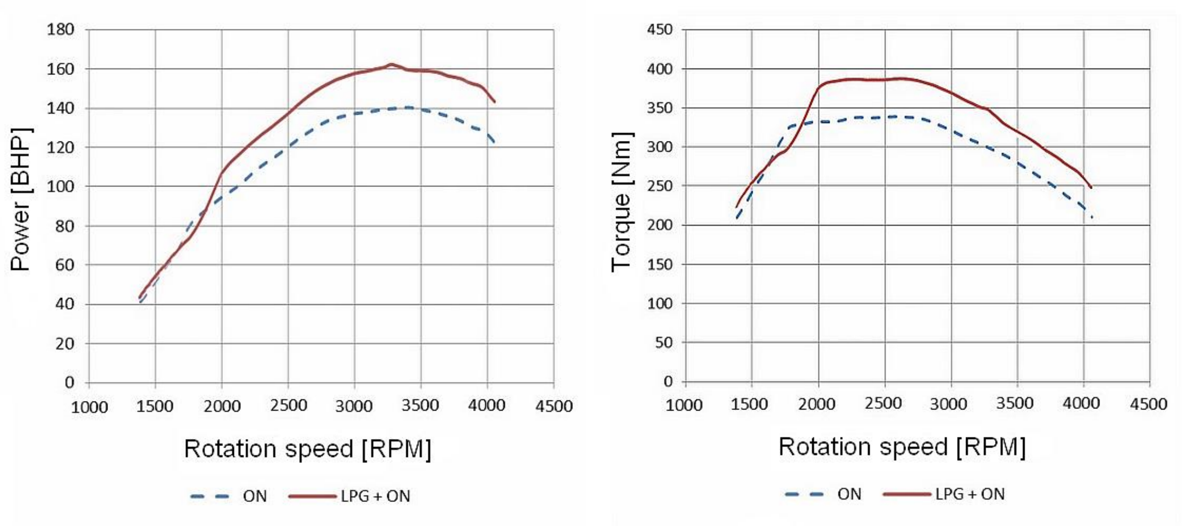

Fig. 5. Power and torque characteristics of the tested vehicle

6. CONCLUSION

Summing up the results of the tests presented in the research paper leads to the conclusion that there are extensive possibilities for the application and development of CI engines with dual-fuel (LPG+diesel) systems. This is supported by the excellent distribution of LPG fuelling stations in Poland. It is a very important element for vehicle operation, as the number of CNG stations in still limited in Poland.

Using the fuelling system presented in the tested vehicle ensures a reduction in the operating costs related to fuel by 31% when compared to diesel. Additionally, the power and torque levels were observed to be 20% higher, which makes the car much more dynamic to drive. A further benefit of the dual-fuel system is the reduction of harmful exhaust gases, resulting from the limited emissions of nitrogen oxides, solid particles and carbon dioxide, which are released into the natural environment. Long-term operating tests over a distance of 150,000 km were performed under urban, country and off-road conditions, confirming the reliability of dual-fuel (LPG+diesel) systems. The results of the inspections of the technical condition of the engine did not show any increased wear on the engine components, which means that the engine parameters remain within the standards and technical specifications of the manufacturer.

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