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THE IMPACT OF THE SHARE OF CNG ON THE COMBUSTION PROCESS IN A DUAL-FUEL COMPRESSION-IGNITION ENGINE WITH THE COMMON RAIL SYSTEM

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Abstract

The struggle against global warming necessitates the search for new sources of energy, which limit the emission of carbon dioxide into the atmosphere. Among various fuels used to supply energy nowadays, the importance of natural gas is constantly growing. This is caused by the fact that this fuel is characterised by the lowest share of coal among all fossil fuels. Because of its properties, natural gas can be used directly to power spark-ignition engines. The use of this fuel for compression-ignition engines on the other hand is limited due to the high autoignition temperature of methane.

Currently, research is being conducted in numerous centres on the possibility of using fuel gases to power CI engines operating in a dual-fuel system. The present article discusses the impact of the share of CNG in the supply dose on the operation of a CI engine. An engine with the Common Rail injection system programmed for mono-fuel operation was used in the research. Based on the conducted tests it has been proved that supplying this type of engine with fuel gas considerably changes the course of the combustion process, which is caused by the fact that the gas and air mixture present in the combustion chamber starts burning now of the autoignition of the first portion of liquid fuel. The obtained test results confirm the necessity to change the injection parameters of the pilot dose of diesel fuel (the timing angle of injection and the pressure of fuel) in cases when this type of engine operates in a dual-fuel system.

Keywords: *natural gas, dual-fuel compression-ignition engine, Common Rail system, combustion process*

1. Introduction

The increasing share of fuel gases in the overall energy balance is currently one of the main directions of development for internal combustion engines. This is related primarily to the limited global resources of crude oil, as well as the necessity to reduce the emission of greenhouse gases, especially carbon dioxide (CO_2). This necessitates the search for new alternative sources of energy, which could be used as fuel for internal combustion engines [5-8].

One of the possible methods of reducing the emission of carbon dioxide into the atmosphere is a more extensive use of natural gas as fuel for internal combustion engines. This is related to the fact that methane, the main component of natural gas, as the simplest hydrocarbon features the most advantageous hydrogen/carbon ratio. This, therefore, results in a lower emission of CO_2 into the atmosphere compared to other fuels containing more complex hydrocarbons [1, 2, 7, 10].

Powering internal combustion engines with natural gas is becoming increasingly popular, which may be evidenced by the continuous increase in the number of filling stations capable of loading this fuel. Natural gas may be stored in two forms: compressed (CNG) and liquefied

(LNG). An important limitation in the use of methane as fuel for internal combustion engines is the necessity to keep the temperature low in order to store it in its liquid form (-162°C), which is why the propulsion systems most frequently used in practice nowadays use this fuel in its compressed form. Such a solution is unfortunately associated with the necessity to use relatively large fuel tanks of special construction, considerably increasing the mass and limiting the range of a vehicle [7, 10].

In many European cities, public transport buses are powered only by CNG. The use of CNG as fuel for engines allows the considerable reduction of the concentration of toxic compounds and the smoke opacity of exhaust fumes. Not only does the popularity of natural gas result from the existence of vast resources of this fuel, but it is also necessitated by ecological and economic aspects. CNG is currently the cheapest fuel in wide commercial use [3, 4].

Due to its relatively high autoignition temperature (approx. 540°C), methane is used primarily as fuel for spark-ignition engines. Nonetheless, numerous science centres conduct research on the use of natural gas for powering compression-ignition engines [1, 6, 7, 9].

The high autoignition temperature of methane makes its spontaneous combustion in a compression-ignition engine impossible, which is why in order to ignite it in this type of engine, a small amount of liquid fuel is injected, its purpose being to initiate the ignition of fuel gas.

This type of powering is currently used primarily in the case of engines with large diameters of cylinders. Attempts are also underway to use this type of engine to propel farm tractors. For example, the VALTRA Company has patented an engine with Common Rail fuel injection, in which about 80% of all energy is acquired from fuel gas [11, 12].

2. The object, purpose and methodology of the research

In order to determine the impact of the share of CNG in a supply dose on the combustion process, a series of tests has been performed involving a compression-ignition engine powered by the Common Rail system. The tests were conducted on an ADCR-type engine, manufactured by the Andoria-Mot company. The basic technical specifications of this engine are presented in Tab. 1.

Tab. 1. Technical details of an ADCR engine

Engine	ADCR
Type	diesel, 4-stroke, turbocharged with intercooler
Fuel injection	Common Rail fuel accumulator system
Engine layout	4 cylinder inline, vertical
Cylinder diameter / piston travel	94 / 95 mm
Piston displacement volume	2636 cm^3
Compression ratio	17.5: 1
Rated power* / rotational speed	85 kW / 3700 rpm
Max. torque* / rotational speed	250 Nm / 1800-2200 rpm
Min. idle rotational speed	750 rpm
Fuel consumption at torque peak*	210 g/kWh
Injection system (Bosch)	accumulator injection system (Common Rail) CR2.0
Turbocharger	radial, with exhaust extraction valve
EGR system	pneumatic EGR valve with exhaust cooler

The tested engine was attached to an AVL engine test stand (Fig. 1). In order to enable dual-fuel powering of the engine, a gas mixer was mounted in the intake system before the turbine, to which the required dose of fuel gas was delivered. Fuel gas was supplied from cylinders in which

compressed natural gas was stored, collected from a natural gas installation. The gas used for the tests was characterised by the following chemical composition:
- methane (CH_4) – approximately 97.8%,
- ethane, propane, butane – approximately 1%,
- nitrogen (N_2) – approximately 1%,
- carbon dioxide (CO_2) and other components – 0.2%.

The calorific value of the gas according to the supplier's information amounted to 36.374 MJ/m^3.

In order to enable recording of the pressure in the combustion chamber, an adapter with a sensor allowing the measurement of dynamic pressures was mounted in one of the cylinders, replacing a glow plug. An optical encoder was attached to the free end of the crankshaft of the engine, making it possible to record the angular location of the crankshaft. The tested engine had a factory-fitted Common Rail 2.0 power system from the Bosch Company, controlled by means of a type EDC16C39 Bosch controller, programmed for mono-fuel operation.

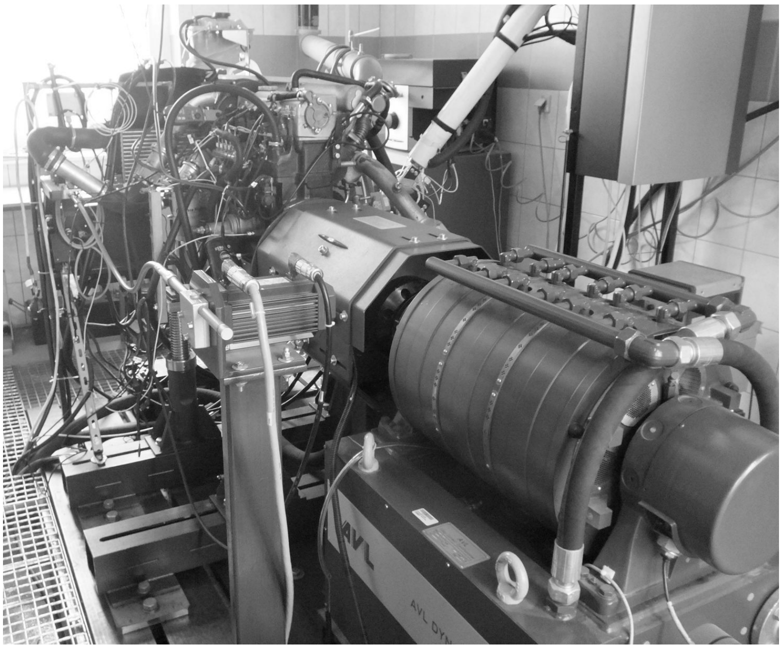

Fig. 1. A view of the test stand

During tests, the engine was supplied with a predetermined dose of fuel gas, while the dose of liquid fuel was adjusted by the controller in order to maintain the adopted engine load level.

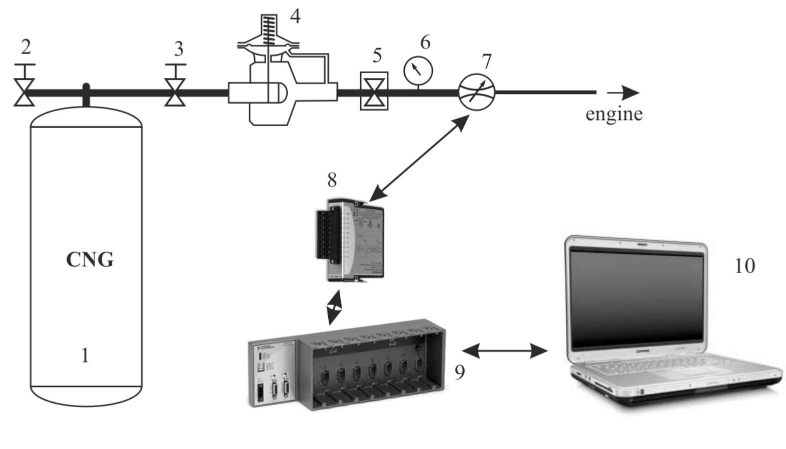

Fig. 2. Block diagram of the fuel gas supply installation: 1 – CNG cylinder, 2 – fill valve, 3 – stop valve, 4 – two-stage regulator, 5 – solenoid valve, 6 – pressure gauge, 7 – MasStream mass flow regulators, 8 – input-output cards controlling the flow regulators, 9 –programmable CompactRio controller, 10 – PC

The energy share of fuel gas (U_g) in the dose powering the engine has been determined based on the following equation:

$$U_g = \frac{\dot{m}_{CNG} \cdot W_{CNG}}{\dot{m}_{on} \cdot W_{on}} \cdot 100\%, \qquad (1)$$

where:

$\dot{m}_{on}$ – the mass flux of diesel fuel during mono-fuel operation,

$\dot{m}_{CNG}$ – the mass flux of fuel gas supplied to the engine,

W_{on} – the calorific value of diesel fuel,

W_{CNG} – the calorific value of CNG.

Therefore, the U_g determined the percentage equivalent of energy supplied along with fuel gas, in relation to the energy, which the engine was supplied with along with liquid fuel during mono-fuel operation.

For each measurement, 50 subsequent pressure cycles in the combustion chamber were recorded. The recorded cycles were then averaged and subjected to smoothening using the procedure of the "Savitzky-Golay filter method". The smoothening of an averaged pressure cycle was meant to obtain the proper smoothness of the course of a derivative, in order to be able to conduct numerical calculations.

The heat release process was traced based on a smoothened pressure cycle. The calculations were made based on the equation and the rules of thermodynamics, as well as the equation of state for a closed part of the cycle from α_1 = 220 °CA, corresponding to the angle of closing the inlet valves up to α_2 = 490, corresponding to the opening of the outlet valve. This assumes that the change in the system's energy caused by the impact of fuel injection is negligibly low, and that the agent in the cylinder may be modelled as ideal gas. The total heat given off during the combustion process was determined by the integration of the heat release process $dQ/d\alpha$, after a full calculation interval from the moment of closing the suction valve until opening the exhaust valve.

3. Test results

The tests were conducted for two rotational speeds of the engine's crankshaft: 1500 and 3000 rpm. The selection of these rotational speeds was necessitated by various control strategies implemented by the controller. At a rotational speed of 1500 rpm, the controller implements split fuel injection, at first injecting a pilot dose followed by the main dose. On the other hand, at a speed of 3000 rpm the split injection is implemented at low loads, with a single fuel injection being implemented at higher loads. It should also be pointed out that, when changing the volume of the injected dose of fuel, the controller also changed the value of the timing angle of diesel fuel injection.

Figure 3 presents sample pressure change cycles in the combustion chamber, recorded at a rotational speed of 1500 rpm and with various engine loads, as well as at various shares of fuel gas in the dose powering the engine.

Figure 4, on the other hand, presents the heat release processes and the total heat calculated based on the recorded pressure cycles.

The pressure cycles and heat release processes presented above clearly indicate that with such an injection strategy (the split injection of liquid fuel) the combustion of fuel gas is initiated by the pilot dose of diesel fuel. The intensity of the combustion of the gas and air mixture increases along with the increasing share of fuel gas in the supply dose.

Figure 5 presents a sample impact of the share of CNG in the supply dose on the general performance of the engine. The presented relation indicates that the increasing share of fuel gas in the supply dose considerably impairs the general performance of the engine. This is caused primarily by the premature injection of the pilot dose of diesel fuel, which initiates the premature combustion of fuel gas.

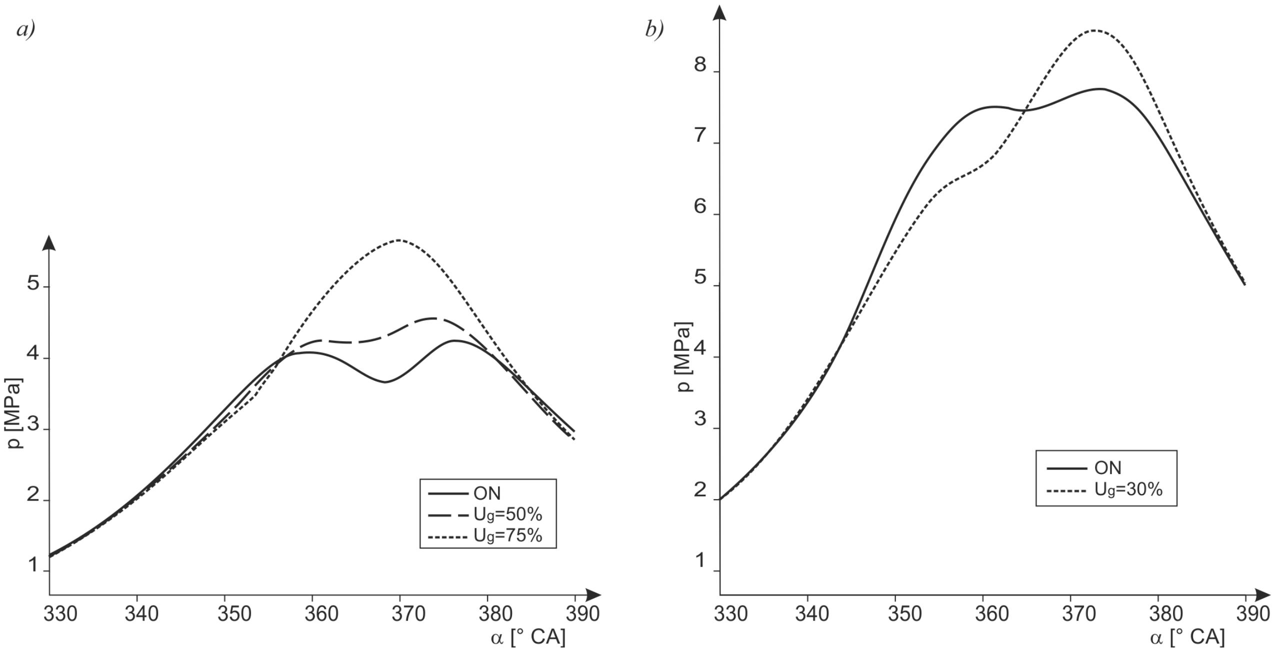

Fig. 3. The impact of the share of fuel gas in a supply dose on pressure change cycles in the combustion chamber at n = 1500 and with engine loads of: a) T = 100 Nm, b) T = 200 Nm

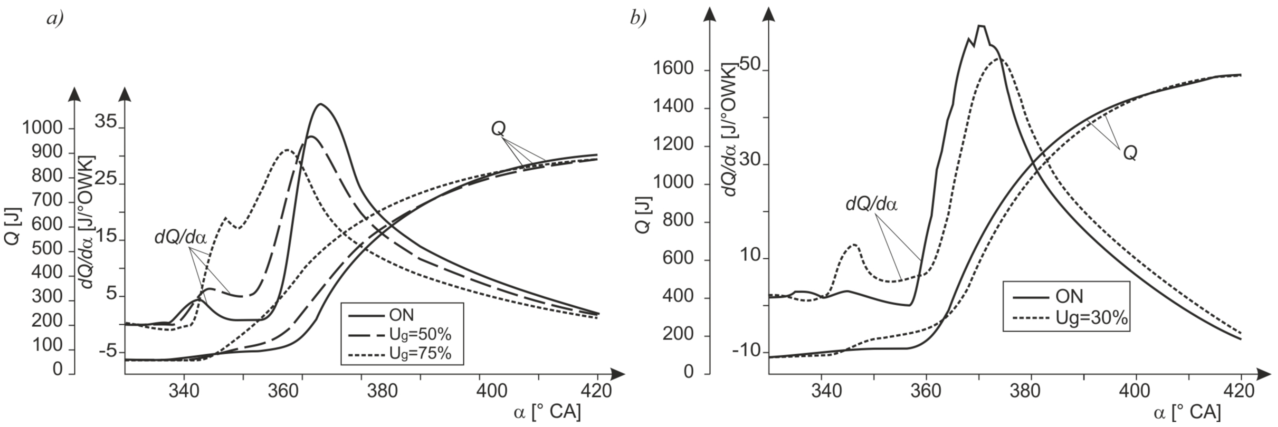

Fig. 4. The impact of the share of fuel gas in a supply dose on heat release processes and on the total heat at n = 1500 and with engine loads of: a) T = 100 Nm, b) T = 200 Nm

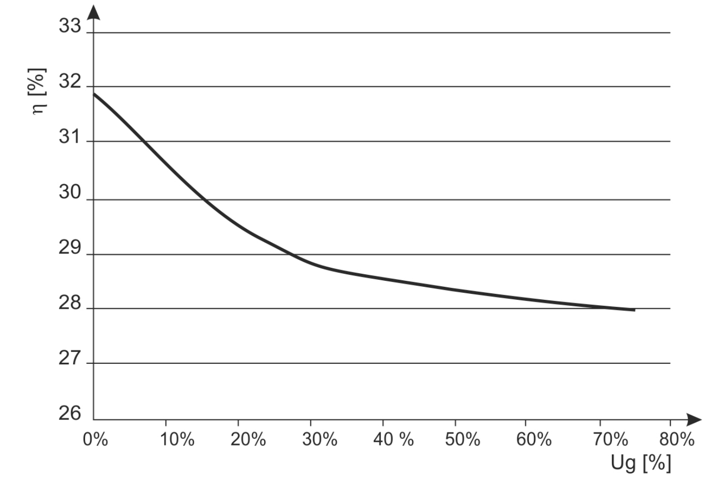

Fig. 5. The impact of the share of fuel gas in a supply dose on the general performance of the engine at n = 1500 and T = 100 Nm

The following tests were conducted at a rotational speed of 3000 rpm. Fig. 6 presents sample recorded pressure cycles in the combustion chamber. Fig. 7, on the other hand, presents the heat release processes at this rotational speed. Based on an analysis of these processes, it can be clearly seen that the increasing share of fuel gas in the supply dose considerably affects the load compression process. The recorded pressure cycles clearly indicate that the presence of fuel gas in the dose reduces the pressure in the combustion chamber, which results in lowering the temperature near the end of compression, which in turn considerably affects the delay in the autoignition of liquid fuel.

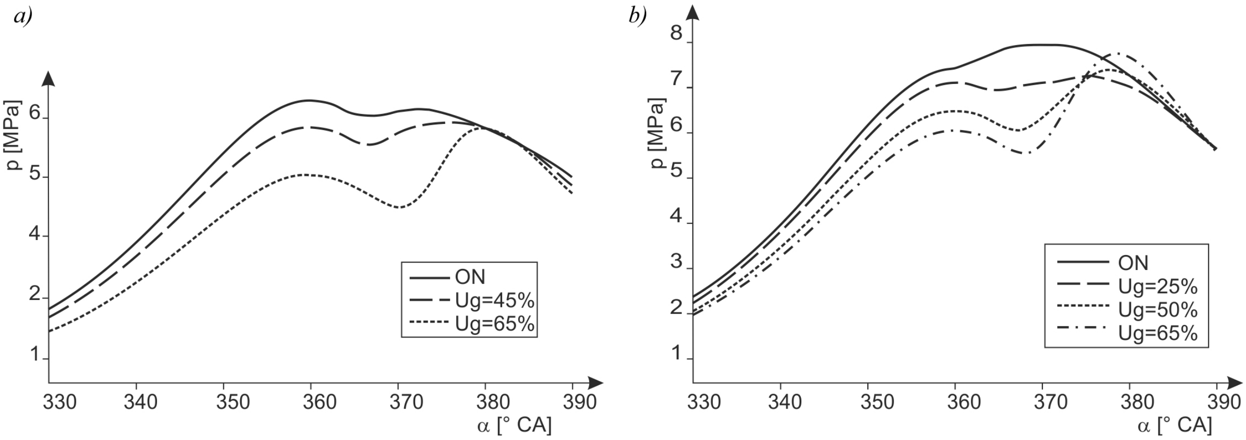

Fig. 6. The impact of the share of fuel gas in the supply dose on pressure change cycles in the combustion chamber at n = 3000 and with engine loads of: a) T = 100 Nm, b) T = 200 Nm

It can also be noted that with a load of T = 100 Nm and a 65% share of fuel gas in the dose powering the engine, the controller has changed its fuel dose injection strategy, dividing it into two parts.

At this rotational speed, it is clearly visible that the increasing share of fuel gas in the supply dose considerably delays the beginning of heat emission (an increase in the delay of autoignition). The emission of heat is, on the other hand, much faster than in the case of mono-fuel operation (shorter combustion time).

Figure 8 presents a sample impact of the share of CNG in the supply dose on the general performance of the engine at n = 3000 rpm. Similar to a lower rotational speed, the presented relation indicates that the increasing share of fuel gas in the supply dose results in impairing the general performance of the engine.

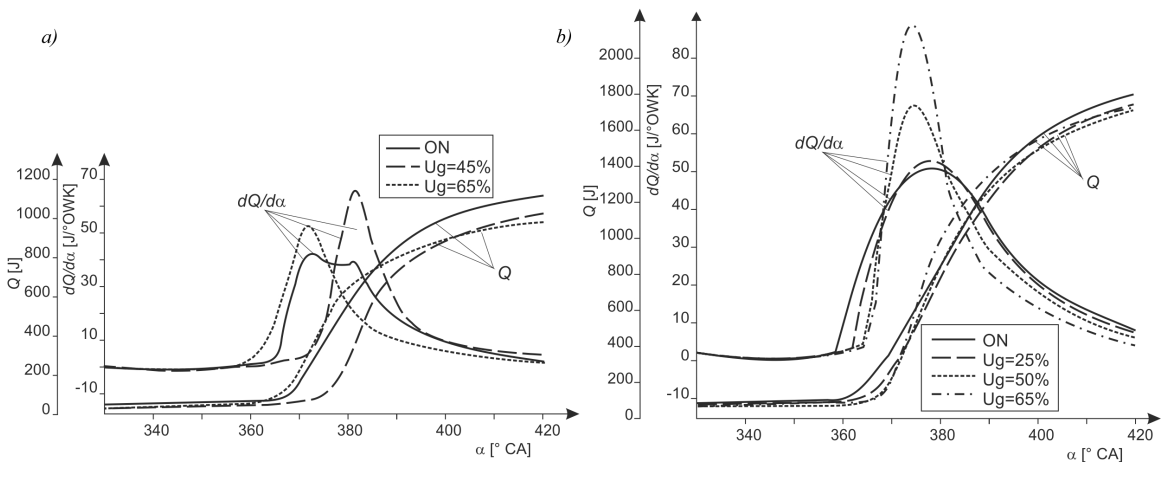

Fig. 7. The impact of the share of fuel gas in the supply dose on heat release processes and on the total heat at n = 3000 and with engine loads of: a) T = 100 Nm, b) T = 200 Nm

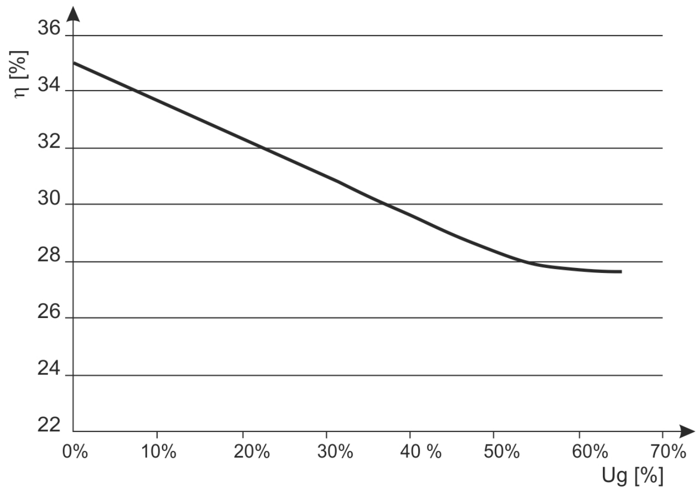

Fig. 8. The impact of the share of fuel gas in the supply dose on the general performance of the engine at n = 3000 and T = 200 Nm

It should be pointed out that with the doses of natural gas higher than those listed the operation of the engine became irregular, which made it impossible to conduct further tests. This fact is caused by the injection of diesel fuel being improper for dual-fuel operation, which prematurely initiates the combustion of the gas and air mixture.

4. Summary

The sample results of the tests on the use of natural gas for supplying power presented above clearly indicate that contemporary compression-ignition engines with Common Rail systems are not adjusted to operating in a dual-fuel system.

The primary disadvantage of this type of solution is the premature injection of the pilot dose of liquid fuel, which initiates the ignition of the gas and air mixture. The share of natural gas in the supply dose changes the parameters of load compression in the combustion chamber, which consequently leads to lower pressures and temperatures near the end of compression, which results in a higher delay of the autoignition of liquid fuel.

In order to ensure the correct operation of this type of engine in a dual-fuel system, it is necessary to change the strategy of injecting the dose of diesel fuel, which initiates the autoignition. The selection of the timing angle for the dose of liquid fuel, on which depends the moment of the ignition of fuel gas, seems to be particularly important.

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