IMPACT OF ENGINE CONTROL ON THE ENERGETIC INTER CHANGE ABILITY OF DIESEL OIL BY GAS IN DUAL FUEL CI ENGINE

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Abstract

A compression ignition engine fuelled simultaneously with two fuels: a fuel with low cetane number used as the main fuel, and Diesel oil used to initiation of ignition, is assumed to be called as a dual fuel engine. This system is perfectly suited to adaptation to supply of CNG gas in majority of compression ignition engines. Such adaptations can concern both an older engine equipped with classic injection system, and modern engine with common rail system. In traction engines, interchangeability of liquid fuel by the gas belongs to important issues, what is a condition of profitability of the adaptation and operation of dual fuel engines. In the paper are presented test results of the 1CA90 engine with piston pump to injection of liquid fuel, and a system with mixer to supply of the gas; and the SB3.1 engine equipped with common rail system and injection of the gas in area of the inlet valve. On the base of performed tests one has shown variability of energetic fraction of the CNG gas in total energy supplied to the engine. The tests were performed in complete field of variability of engine parameters, i.e. rotational speed and engine load. Obtained results have shown that in spite of decreasing fraction of the gas at partial loads of medium size traction engines, substantial reduction of operational consumption of the Diesel oil is possible. Due to significant differences in price of the CNG gas and the Diesel oil, it gives considerable savings in operational costs of the engines. It should encourage users of the engines to adaptation of the fuelling to the CNG gas. In the paper is presented a proposal of control system to dual fuel traction engine, from maintaining its performance parameters point of view.

Keywords: *dual fuel, engine control, natural gas, pilot dose, gas share, thermal efficiency*

1. Introduction

For the nearest decades is anticipated gradual introduction of alternative fuels to supply of combustion engine. It will concern a liquid bio-fuels and gases. Due to big resources and common use, the CNG gas will play a crucial importance among gaseous fuels. One anticipates, than in the EU countries up to the year 2020, the CNG gas will have about 8% share in total market of engine fuels [11, 12].

Gaseous fuels can be combusted both in spark ignition engines, is such case the gas is the only autonomous fuel [2], and in dual fuel compression ignition engines, where energetic fraction of gaseous fuel can change depending on load and assumed criterion of engine control [1, 3, 4, 6].

A compression ignition engine powered simultaneously by two fuels: a fuel with low cetane number being the main fuel, and the Diesel oil to initiate ignition, are assumed to be called as dual fuel engine. Characteristic feature of the dual fuel engine is initiation of combustion of homogenous combustible mixture by small dose of the Diesel oil, injected in final stage of compression. Owing to large energy released from combustion of the initial dose and spatial range of liquid fuel's stream, one obtains robust ignition of the mixture in broad range of the air excess number [3–5, 11]. Due to spatial character of the stream, such type of the ignition is assumed to be called as a stream ignition.

Dual fuel compression ignition engine can be powered according to different supply systems of the gas: with mixer, with low-pressure injection to suction manifold, with direct injection to the cylinder (high injection pressure). The most often, these two first systems are used, which are shown in Fig. 1.

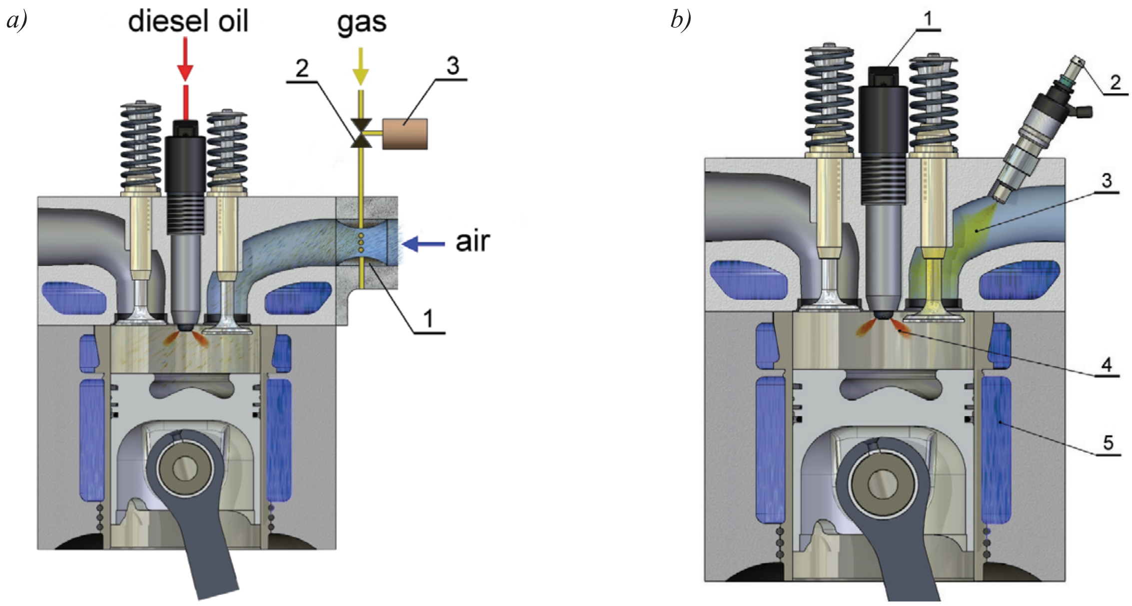

Fig. 1. Supply systems of dual fuel engine: a) with mixer: 1 – mixer, 2 – gas valve, 3 – stepper motor, b) injection of the gas to suction manifold: 1 – diesel oil injector, 2 – gas injector, 3 – gas stream, 4 – diesel oil stream

System with the mixer is most often used in stationary engines powered directly from gas network, with a pressure slightly higher than the atmospheric one. To the fuelling are used such gases like: natural gas from the network, sewage and waste gases, mine gases and generator gases. Advantage of such system is fact that compression of the gas in not needed.

The most often in the traction engines is used multipoint injection of the gas in area near the inlet valve, accomplished by gaseous injectors controlled electronically. To fuel supply is commonly used compressed CNG gas or liquid LNG gas. There are used injection pressures in range of 0.4––1.0 MPa. Disadvantage of such system is need of compression of the gas, and reduction of storage volume of the gas through not complete emptying of gas cylinders from the CNG gas.

2. Fraction of energy of the gaseous fuel

In adaptations of compression ignition engines to dual fuel supply, as a rule, one strives after minimization of consumption of liquid fuel. It results from big difference between price of liquid fuel and gaseous fuel (frequently are used waste gases with low unit price). The most often to ignition of the gas is used a normal Diesel oil, a furnace oil, or a vegetable oils. Amount of the liquid fuel consumption decides about operational costs and profitability of its usage. Such factor frequently also prejudges selection of the gaseous fuel's type – single fuel with spark ignition or dual fuel system. Due to it, energetic fraction of the gas, when fuelling in dual fuel system, frequently called as stage of interchangeability of liquid fuel, is of very important meaning.

In the dual fuel supply, stream of energy supplied to the engine is determined by the equation:

$$\dot{Q} = \frac{N_e}{\eta_o} = \dot{m}_{on} \cdot H_{on} + \dot{m}_g \cdot H_g \,, \tag{1}$$

where:
$\dot{Q}$ – stream of energy supplied to the engine [kJ/s],
N_e – effective power output of the engine [kW],
η_o – overall efficiency of the engine,

$\dot{m}_{on}$, $\dot{m}_g$ – stream of mass of Diesel oil and gas [kg/s],
H_{on}, H_g – caloric values of Diesel oil and gas [kJ/kg].

Energetic fraction of the gas is determined by the following equation:

$$U_g = \frac{\dot{m}_g \cdot H_g}{\dot{m}_{on} \cdot H_{on} + \dot{m}_g \cdot H_g}, \tag{2}$$

In majority of dual fuel applications one uses a constant initial dose, does not master the engine load and rotational speed are. Its size, dependent on a potential of implemented injection apparatus and fuel supply system, is more often expressed in the following units:

- volume of the fuel to a single operational cycle [mm^3/cycle],
- mass of liquid fuel to a single cycle, referenced to swept volume of the cylinder, expressed in dm^3 [kg/dm^3],
- percentage energetic fraction of liquid fuel referenced to nominal conditions [%].

Stream of energy supplied to the engine in nominal conditions can be determined by the equation:

$$\dot{Q}_{zn} = \frac{N_{ezn}}{\eta_{ozn}}, \tag{3}$$

where N_{ezn}, η_{ozn} is effective power output and overall efficiency of the engine in nominal conditions, while the initial dose:

$$\dot{q} = U_{on} \cdot \dot{Q}_{zn} = U_{on} \cdot \frac{N_{ezn}}{\eta_{ozn}}, \tag{4}$$

where N_{ezn}, η_{ozn} is effective power output and overall efficiency of the engine in nominal conditions, and U_{on} is the energetic fraction of the Diesel oil.

Stream of chemical energy of the gas in any point of engine operation can be determined by the following dependency:

$$\dot{m}_g H_g = \dot{Q} - \dot{q} = \frac{N_e}{\eta_o} - U_{on} \cdot \frac{N_{ezn}}{\eta_{ozn}} = \frac{N_e \cdot \eta_{ozn} - U_{on} \cdot N_{ezn} \cdot \eta_o}{\eta_o \eta_{ozn}} = \frac{N_e\left(\eta_{ozn} - U_{zn} \cdot \frac{N_{ezn}}{N_e} \cdot \eta_o\right)}{\eta_o \eta_{ozn}}. \tag{5}$$

According to definition, energetic fraction of the gas is determined by the dependency:

$$U_g = \frac{\dfrac{N_e\left(\eta_{ozn} - U_{zn} \cdot \frac{N_{ezn}}{N_e} \cdot \eta_o\right)}{\eta_o \eta_{ozn}}}{\dfrac{N_e}{\eta_o}}, \tag{6}$$

and after ordering:

$$U_g = 1 - U_{on} \cdot \frac{N_{ezn}}{N_e} \cdot \frac{\eta_o}{\eta_{ozn}}. \tag{7}$$

From the equation (7) is seen, that energetic fraction of the gas depends on energetic fraction of the initial dose, relative change of power output and overall efficiency, referenced to nominal conditions (or reference conditions).

In stationary engines operating at constant rotational speed $n = \text{const}$ it can be assumed, that $n_{zn} = n$ and $p_{ezn} = p_{\max}$, than the equation (7) takes form of:

$$U_g = 1 - U_{on} \cdot \frac{p_{\max}}{p_e} \cdot \frac{\eta_o}{\eta_{ozn}}. \tag{8}$$

Changes of fraction of the gas U_g in case of stationary engine operating at constant speed, for different initial doses, are presented in Fig. 2. They point out that in case of stationary engines; use of the initial dose with energetic size of about 5% enables more than 90% interchangeability of the liquid fuel in complete range of change of engine loads. It requires, however, usage of separate injectors for the initial dose and for the dose for traditional fuel supply.

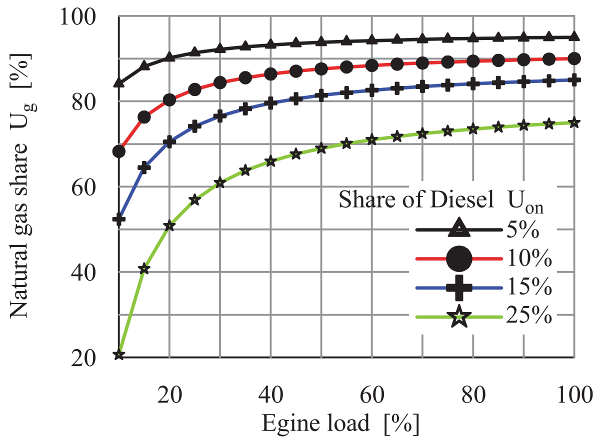

Fig. 2. Effect of load of dual fuel engine on energetic fraction of the gas for various initial doses: constant rotational speed, with assumed linear change of overall efficiency of the engine from 0.362 for $p_{e\,max}$ to 0.125 for $p_e = 0.1p_{e\,max}$

In case of the doses with energetic fractions of about 10%, which are possible in common rail systems with carefully selected injector, it is possible to achieve replacement of the gaseous fuel above 80% for engine loads higher than 20% of nominal load.

It is also worth to pay attention, that in case of adaptation of older engines with classic injection apparatus, when doses with energetic value of about 25% are used, it is possible to achieve substitution of the liquid fuel bigger than 60%, for engine loads higher than 30% of nominal load. It should give a signal, that even in case of older traction engines it should bring about economical benefits.

3. The share of energy in real engines

The investigations were performed on two engines differing from each other with injection apparatus of the initial dose:

– the 1CA90 engine – classic piston pump, mixer-type fuelling with the gas,
– the SB3.1 engine – injection of the Diesel oil in *common rail* system and injection of the gas to the manifold.

The SB3.1 engine, i.e. single cylinder research engine was constructed on the base of 6 cylinders engine of the SW 680 type, produced by a former Wytwórnia Sprzętu Komunikacyjnego in Mielec on license of Leyland Company. Technical data of the engines are presented in Tab. 1.

In commercial engines, energetic fraction of the gas also depends on engine's rotational speed (Fig. 3). It results both from changing dosing by the piston pump as rotational speed changes, and from change of maximal power output developed by the engine.

In the 1CA90 engine at rotational speed of 2000 rpm, fraction of energy of the gas changed in range of 20-70%, depending of change of engine load (Fig. 3a). In the same position of the toothed bar, growth of rotational speed to 2750 rpm resulted in growth of energetic fraction of the gas to 40-75%.

Tab. 1. Technical data of engines 1CA90 and SB3.1

Type	1CA90	SB3.1
Number of cylinders	1	1
Bore/Stroke	90/90 mm	127/146 mm
Displacement	573 cm^3	1848 cm^3
Compression ratio	16.8	15.8
Rated power/Engine speed	6.1 kW/3000 rpm	22.5 kW/2200 rpm
Maximal torque/Engine speed	27 Nm/1600 rpm	Nm/1400 rpm
Type of combustion chamber	toroidal in the piston, direct injection	
Injection pump	traditional – pistons	common rail

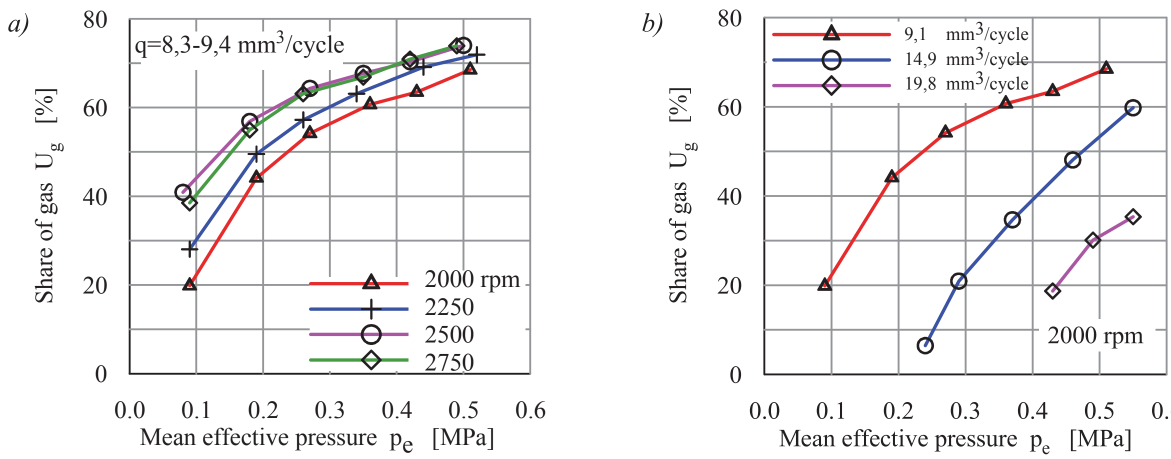

Fig. 3. Fraction of energy supplied with the gas in function of load of the 1CA90 engine run in dual fuel system: a) various rotational speeds, b) various initial doses

In each dual fuel engine, increase of the initial dose results in reduction of fraction of the gas in total portion of the energy supplied to the engine (Fig. 3b). Moreover, it results in increase of engine load, being a limit value allowing engine operation on Diesel oil only.

Similar effect of the rotational speed on change of the energetic fraction can be observed in case of modern injection systems with *common rail* (Fig. 4). With constant initial dose, is seen a tendency to increase fraction of the gas U_g together with growth of the rotational speed. However, such tendency is clearly seen only in area of partial loads. At maximal engine load of the engine, energetic fraction of the gas is nearly independent from the rotational speed. Results obtained for other initial doses also point out that at maximal engine loads, the U_g practically doesn't depend on the rotational speed (Fig. 5). It results from implementation of electronic systems to injection of the gas and the initial dose, where doses of the both fuels depend on opening times of the injectors only. As seen from Fig. 5, effect of operational parameters of the engine, inclusive of temperature of *common rail* injector, on quantity of injected fuel is small.

These results are different from the ones obtained in case of the engines with traditional injection apparatus and mixer-type supply with the gas. In traditional engines, change of quantity of supplied fuels distinctly depends on the rotational speed, what effects in diverse run of speed characteristics of the maximal load (so called „external characteristics").

In the SB3.1 research engine, when the initial dose amounted to about 20 mm^3/cycle, energetic fraction of the gas was changing in range of 45-82% in complete field of engine operation, i.e. at engine loads changing in range of 0.1-0.7 MPa and rotational speed 1200-2000 rpm.

In course of the investigations shown in Fig. 4, one intentionally used a bigger initial dose of about 20 mm^3/cycle, than possible to be obtained, i.e. about 15 mm^3/cycle. It resulted from safety of injectors operation and identification of true interchangeability of the fuels within operational conditions. It is worth to pay attention on the fact, that as early as in range of medium loads, the U_g does not exceed 60%, what allow supposing that even in traction engines operated in urban traffic conditions it is possible to obtain high interchangeability of the Diesel oil.

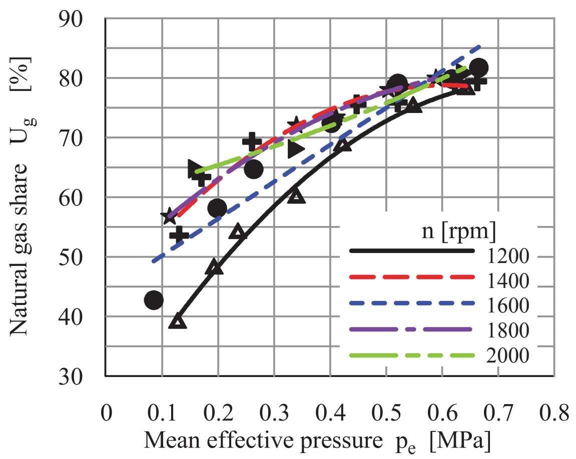

Fig. 4. Effect of the load on energetic fraction of the gas in total dose of energy supplied to the SB3.1 engine run in dual fuel system: various rotational speeds, dose q = 19.8 mm³/cycle, injection advance angle 22°CR before the TDC

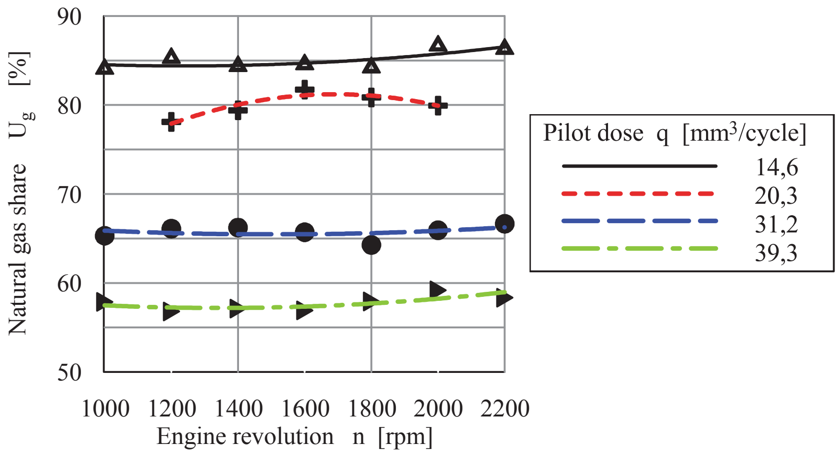

Fig. 5. Comparison of energetic fraction of the gas in the SB3.1 engine run in dual fuel system for various initial doses: engine load close to the maximal one; constant injection advance angle 22°CR

4. Controlling of dual fuel engines

Contemporary dual fuel engines with electronically controlled fuel supply systems of liquid and gaseous fuels assure controlling of the combustion process, leading to optimization of external, ecological, and durability parameters of the engines. Control and maintenance of beneficial parameters of the engine is possible owing to high energy of ignition dose, many times exceeding energy of the spark in gaseous spark ignition engines. Moreover, in some conditions it is possible to increase energy of the ignition through increase of fraction of liquid fuel in total energy supplied to the cylinder. It enables combustion of gaseous mixtures in broad range of change of the λ_o number, not possible in case of spark ignition. Optimization of parameters of engine operation is most often performed in complete field of engine operation, determined by change of torque and rotational speed. To the most common criteria of the optimization can be included:

– maximal thermal efficiency of the engine,
– minimal emission of exhaust gases, the NO_x mainly,
– minimal fraction of liquid fuel,
– limited maximal temperature of exhaust gases,

– high durability of engine components,
– correct engine operation in case of considerable changes of composition of the gas.

Optimization of operational parameters of the engine is obtained through change of adjustment parameters of fuel supply system, leading to controlled process of combustion.

Controlling of combustion process in dual fuel engines is possible through:
– size of initial dose,
– injection advance angle of the initial dose,
– division of the dose at a bigger fractions of liquid fuel,
– composition of gaseous mixture within assumed values of the air excess number λ_o,
– in the engines with direct injection of the gas, through a suitable correlation of injection time of liquid fuel and gas.

Controlling of the engine depends on its size and destination, is easier in a stationary engines operating within small range of change of engine load, and at constant rotational speed, and are much more difficult in low power output traction engines, due to wide range of change of engine loads and rotational speed.

In a big traction engines, combustion processes are controlled individually in each cylinder, where for each cylinder are selected: dose of total energy, fractions of the both fuels and parameters of injection. It enables obtainment of high thermal efficiency of the engine and extremely low emission of the NO_x. Stable and fully controlled combustion leads to reduction of thermal and mechanical loads, what assures long operational life of the engine.

Correct operation of dual fuel engine is possible in case of composition of gaseous mixtures between knocking combustion limit and misfiring limit. The limits depend on the air excess number λ_o of the gaseous mixture and engine load (Fig. 6). The biggest tendency to knocking combustion show the mixtures with composition $\lambda_o = 1.0\text{-}1.2$, what restricts maximal engine load to about $p_e \approx 1.0\text{-}1.1$ MPa. Together with leaning of the gaseous mixture, the tendency to knocking combustion decreases, what enables more high engine loads.

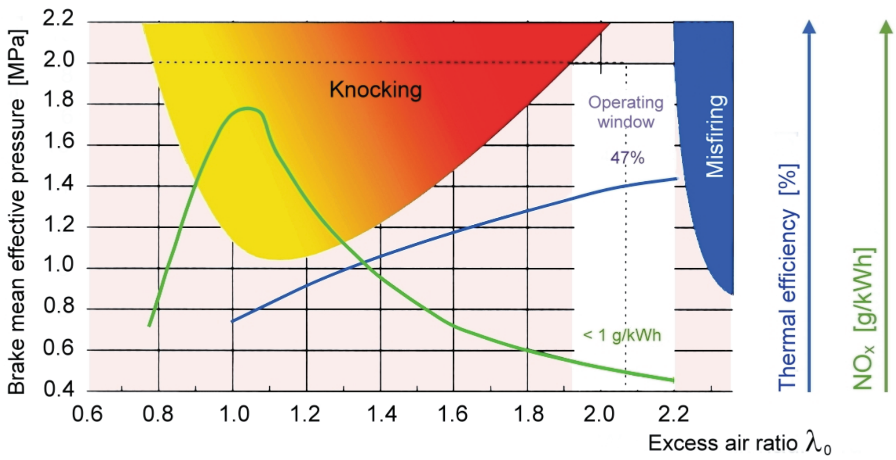

Fig. 6. Ranges of operation of dual fuel Wärtsila 50 DF engine [110]

In a stationary dual fuel engines, the most often are used a mixtures with composition $\lambda_o =$ $= 1.9\text{-}2.1$, what in engines having big cylinder bore, enables obtainment of effective pressures of about 2.0 MPa.

Limits of the knocking combustion and misfiring depend in a considerable measure from cylinder bore; tendency to knocking combustion at constant air excess number λ_o decreases together with decrease of cylinder bore. Due to it, in engines with smaller cylinder bore is possible to develop higher effective pressures. For instance, in case of the engine of the 32GD type produced by Wärtsila, having cylinder bore of 320 mm, there was obtained mean effective pressure of 2.3 MPa.

From Fig. 6 is seen, that in gaseous engines with spark ignition, operated at lean mixtures of

$\lambda \approx 1.6$, is possible to generate $p_e \approx 1.5$ MPa, what means reduction of the power output with 25% comparing to dual fuel engine of the 50DF type. Even bigger reduction of the power output is present in gaseous spark ignition engines, combusting stoichiometric mixtures.

Together with leaning of the gaseous mixture decrease maximal temperature of the combustion and its duration, what promotes generation of smaller quantities of the NO and results in lower emission of the NO_x. Usage of gaseous mixture with $\lambda \approx 2.0$ in the 50DF engine enabled obtainment of unit emission on the level of $NO_x < 1$ g/kWh (Fig. 7), what should be considered as very low value.

Traction engines are characterized by high variability of the rotational speed and load (range of change of the torque $M_o = 0\text{-}M_{o\,\max}$ for each rotational speed). Moreover, change of the operational parameters can occur very fast, what is enforced by conditions of traffic. Another important difficulty is also long lasting operation of the engines at partial loads, even at idling, especially in conditions of urban traffic. Partial loads generate especially difficult conditions of dual fuel engine operation, due to excessive leaning of the gaseous mixture and worsening of its economical and ecological parameters. Maintaining correct quality of the charge in conditions of transient operation of the traction engine can be also considered as important drawback. For this reason, in case of classic injection apparatus and mixer-type fuelling, range of engine operation in dual fuel system is limited, as a rule, to a higher engine loads. In such case one uses much bigger initial doses than required, only due to need of more reliable ignition of gaseous mixture. Such activities reduce interchangeability of the liquid fuel by gaseous fuel and increase operational costs of dual fuel engine. With substantially lower prices of the gas, it encourages to use gaseous engines with spark ignition, in spite of fact that such engines are characterized by much smaller overall efficiency.

Contemporary traction engines operated in dual fuel system can be powered by the CNG gas or the LNG gas, and locally by compressed biogases (fermentation type mainly). Due to gas cylinder pressure within limits 20-25 MPa, it seems irrational to use direct injection of the gas, because it further restricts already low mileage between successive fillings of the engines powered by the CNG gas. Traction engines should be, therefore, powered by the gas through a mixer or multipoint indirect injection to area near the inlet valve.

The tests performed by the author on various traction engines point at a certain principles, which should be followed to restrict adverse phenomena occurring during combustion of lean mixtures, and at partial load of dual fuel engine. To such principles belong:

- Assurance of full interchangeability of fuel supply – traditional with Diesel oil only, and in dual fuel system.
- Changeable initial dose, decreasing as the engine load decreases. The investigations have shown that it is possible, in a limited range, both in the systems with piston pumps and systems with *common rail*. Bigger injection dose should be used at maximal engine loads, what protects the injectors against overheating, and additionally allows to restrict loss of engine power, resulted from gaseous feeding of the engine.
- Partial throttling of the air at minimal engine loads. Extent of the throttling should change in scope of 5–30%, depending on rotational speed and engine load.
- Changeable injection advance angle Θ_{ww} [°CR] specified on the base of the table-map with values of optimal angle, determined according to selected optimization criterion: maximal overall efficiency, permissible concentration of the NO_x in exhaust gases, permissible concentration of the THC in exhaust gases, maximal combustion pressure, global optimum of many variables.
- Start-up and operation at loads 0–20% N_{ezn} should occur when the engine is powered by the Diesel oil only. It should promote reduction of the CO and THC emissions and rational consumption of energy by the engine.
- To assure high durability of the engine, in case of dual fuel supply, the maximal engine power output should be limited to about 90-95% of the power output when the engine is fuelled traditionally.
- Engines, for which is necessary to maintain rated power output, at engine load of 90-100% N_{ezn}, should be also powered by the Diesel oil (it should concern a part of duel fuel engines

only). In modern traction engines are used high compression ratios and high supercharging ratios. In case of some engines, it promotes knocking combustion when the engine is powered by the gas with minimal initial dose. Moreover, to maintain the power output on a stable level it is necessary to reduce average air excess number λ, what could lead to thermal overloading of the engine.

– In a new dual supply engines are preferred *common rail* systems and multipoint injection of the gas to the suction manifold. The both systems, controlled electronically, facilitate maintaining proper composition of the charge in any point of engine operation, and enable automatic switching of engine operation mode (traditional or dual fuel) without intend of a driver.
– Proposed ranges of traction engine operation are presented in Fig. 7. Due to small share of engine operation at maximal loads, operation with traditional fuel supply should not have any considerable effect on reduction of interchangeability of the liquid fuel with the gas. In the engines, for which reduction of maximal power output is acceptable by the customers, dual fuel supply can be accomplished in range of engine load's change of 20-100%.

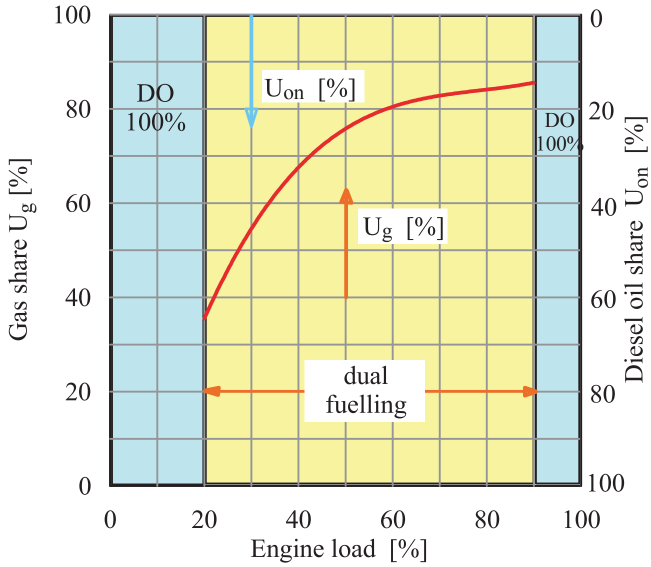

Fig. 7. Range of dual fuel engine operation

5. Summary

– Control of the dual fuel engine depends on whether is maintained full interchangeability of the fuel supply – traditional with the Diesel oil only, or in dual fuel system. If this condition is preserved, serial injection apparatus should be left in the engine, what restricts value of minimal initial dose and reduces interchangeability of the Diesel oil with the gas.
– In bigger stationary engines it is worth to use a special apparatus to injection of the initial dose, what allows obtainment of the interchangeability, in nominal conditions of the liquid fuel, above 95%.
– In a medium size traction engines, in time of introduction of gaseous fuelling and shortage of filling stations with CNG gas, it is essential to maintain full interchangeability of the fuel supply. Minimal doses, which should be used, are dependent on injection system of the liquid fuel. Due to correct operation of the engine and durability of the injectors, the doses shouldn't be smaller than:
  – 20% of nominal dose of piston pumps,
  – 15% of nominal dose of common rail systems.
– Usage of the doses mentioned above enables, in conditions of engine load higher than 20% of the nominal load, interchangeability of the liquid fuel in rage of 40-80%, for the piston pumps, and 55-85% for the common rail systems. Due to considerable differences in price of the fuels,

adaptations of the engines are profitable both in case of an older, already operated engine, and in case of modern engine with electronically controlled injection systems of liquid fuel.

– In all types of traction engines, in area of the load lower than 20% of the nominal load, the engine should be fuelled with the Diesel oil only. It would allow reduction of the CO and emissions THC, and improve overall efficiency of the engine.
– In an engines, where it is important to maintain the maximal power output at engine loads higher than 90%, the engine should be operated on the Diesel oil only. In other dual fuel engines, maximal power output should be reduced to 90-95%. Interchangeability of the liquid fuel by the gas will depend on a method of engine operation. However, due to small contribution of minimal and maximal loads in total time of engine operation, interchangeability of the liquid fuel should not undergo a significant reduction.

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