Analysis of the effect of diesel oil injection timing on combustion parameters that affect durability of a dual-fuel combustion engine operating on natural gas

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Abstract. The paper presents results of investigation on a dual-fuel CI engine operating on natural gas, considering possibility to ensure durability of such operating engine comparable to that of a conventionally operating engine. During the investigation, comparable values of maximum combustion pressures and maximum rates of pressure rise were assured for both engine versions. To achieve the assumed objective, injection parameters of the pilot diesel fuel dose were adjusted. In result, the overall efficiency and main exhaust emissions of the engine operating in a dual-fuel mode were changed as well. Comparison of the described changes is presented in this paper.

1. Introduction
The main advantage of a dual-fuel combustion engine operation on diesel oil and a primary fuel having low cetane rating (methane, propane, ethanol, gasoline) is the possibility to apply a high share of the primary fuel [9, 10]. Solutions in which the energy share of the primary fuel reaches 99% mainly relate to low-speed engines applied in marine transport vessels. A specific character of LNG over-sea transportation in cargo tanks forced the necessity to handle and utilize the boil-off-gas, i.e. a part of the LNG in the tank that continuously evaporates as a result of imperfect insulation. One of the methods to solve this problem is using the gas as a fuel in marine propulsion units. This may be possible mainly by application of a direct gas injection at the end of the compression stroke to avoid spontaneous self-ignition and knocking combustion [5, 7]. A part of energy necessary to initiate combustion has to be delivered with a fuel having a high cetane rating. However, this solution is not very popular in the case of smaller propulsion units applied in road transportation. On the other hand, there exist solutions that enable modern CI engines to operate, at the same time, on two fuels, i.e. the traditional one and the primary fuel delivered usually in a gaseous form into the intake manifold [2, 3, 8]. The desire to reduce operating costs of big engines used as power sources in heavy trucks, agricultural and construction machinery and power-generating units was a major objective to develop solutions that enable alternative fuel combustion in a dual- fuel system. The additional benefit resulting from the application of such system for CI engines is reduction of the harmful exhaust emissions, mainly – the particulate matter emission [4, 6, 11]. The technical solutions currently applied in road vehicles provide only 30% energy share of the alternative fuel – mostly LPG or CNG. From the economic point of view, such solution is not very satisfying and far from that what is achieved in marine transportation. Therefore, it raises the question about the reason for which the share of energy gained from burning the alternative fuel is not too much and if limitations responsible for such state may be eliminated without an expensive
modification of the drive unit. The is a great interest in dual-fuel operation of CI engines what may be confirmed by many studies published in Poland and abroad. Investigations on such operation, carried out for many years, enabled to analyse many phenomena which take place during the combustion [1, 4, 7, 11, 12]. Authors’ proper experience, resulting from the carried out investigation, shows that the energy share of a gaseous fuel may reach ca. 70% at full engine load. However, there is a need to control the basic combustion parameters that determine engine durability, among them the maximum pressure $p_{\text{max}}$ and the maximum rate of pressure rise $\frac{dp}{d\alpha}_{\text{max}}$. The first parameter determines mechanical loads of engine knots (especially, the piston and crankshaft assembly) as well as thermal loads of the combustion chamber and piston bottom. The second parameter determines the character of pressure rise during combustion as well as combustion dynamics, is a key distinguishing factor regarding diesel knock and also determines strongly the durability of engine parts, mainly of the piston and piston rings system.

The paper presents results of investigation on a dual-fuel CI engine operating on natural gas. Natural gas has a high energy density and very high octane number. The combustion of natural gas releases lower levels of harmful exhaust emissions. For such reason, natural gas is considered to be a very good substitute fuel for CI engines. Operation of a dual-fuel diesel engine on natural gas requires taking into consideration the following results:

- the achieved torque,
- the achieved overall efficiency,
- exhaust emissions,
- providing the dual-fuel engine durability comparable to that of the conventionally operating engine.

Within the framework of the carried out and presented investigation the Authors decided to analyse possibility of maintaining comparable durability of the both investigated engine versions. It was assumed that when suitably established injection parameters of the diesel pilot dose would result in a combustion pressure course comparable to that observed in a conventionally operating engine, a durability of such modified dual-fuel engine should also be comparable. The investigated engine is equipped with a common rail system and thus it gives opportunity to affect in a wide range the combustion process by a proper selection of diesel pilot dose injection parameters.

2. The investigation object and the test stand

The investigation object was an AVL 5402 single-cylinder test engine. The engine fuel system was modified by installing an additional system for CNG delivery. Natural gas was delivered into the intake manifold in the gaseous state. In order to prevent the fuel charge escape during the valve overlap, the gas injector was mounted very close to the intake manifold. The fuel system is presented in schematic form in (Fig. 1).

![Figure 1. Scheme of the dual fuelling system of the CI engine modified to combust CNG](image-url)
The test bed used for investigation was equipped with AVL measurement system. A view of the test bed is presented in (Fig. 2).

![Figure 2. AVL test bed: (a) general view of the test bed, (b) view of the control room](image)

The test bed was equipped with:
- a single cylinder AVL 5402 compression ignition research engine
- electrorotational brake,
- indicating software (IndiCom),
- boost system (AVL boost - electric powered compressor),
- system for the exhaust gas analysis (SESAM i 60),
- system for the measurement of particulate matter mass concentration (Micro Soot Sensor),
- system for the measurement of hourly diesel consumption with temperature conditioning,
- system for the measurement of hourly NG consumption (mini CORI-FLOW).

3. Investigation programme

Investigations were carried out under conditions for load characteristic preparation at the constant engine speed \( n = 2200 \text{ rpm} \) for both engine versions (conventional operation on diesel fuel and dual-fuel operation on diesel fuel and CNG). During the investigation, there were registered cylinder pressure values versus crankshaft angle \( p = f(\alpha) \) for each successive load (\( T = 10, 15, 20, 25 \text{ [Nm]} \)) for:
- conventional operation with an adjustment of injection parameters for diesel fuel,
- dual-fuel operation with standard adjustment of injection parameters for diesel fuel,
- dual-fuel operation with such adjustment of diesel fuel injection parameters (selected during investigation) that enabled to obtain combustion pressure courses comparable to those observed in a conventionally operating engine.

The registered cylinder pressure values versus crankshaft angle enabled to calculate values and courses of the remaining important combustion parameters, such as:
- heat release rate \( \frac{dq}{d\alpha} \text{[kJ/m°CA]} \),
- maximum combustion pressure \( p_{\text{max}} \text{[bar]} \),
- maximum rate of pressure rise \( \frac{dp}{d\alpha}_{\text{max}} \text{[bar/°CA]} \).

The registered parameters enabled to calculate:
- overall efficiency \( \eta_{\text{ol}} \),
- thermal efficiency \( \eta_{\text{th}} \),
- mechanical efficiency \( \eta_{\text{m}} \).

Moreover, volume concentrations of such harmful exhaust constituents as: CO, THC, NO\( \text{X} \) and methane were registered at each measuring point. Each measurement was made at a steady value of the pilot dose, equal to \( E \approx 300 \text{ [J/cykl]} \). Load changes were realized through an increase of the gaseous fuel share.
4. Combustion investigation results

As it was described above, the investigations were carried out under conditions for load characteristic preparation at the constant engine speed \( n = 2200 \text{ rpm} \) obtained at each of the established operation modes (conventional operation on diesel fuel, dual-fuel operation with standard adjustment of injection parameters for diesel fuel, dual-fuel operation with proper adjustment of diesel fuel injection parameters). The established strategy of load changes by an increase of the gaseous fuel share with the engine load resulted in changes of the air – natural gas mixture composition. The described changes are presented in (Figs. 3 and 4).

![Figure 3](image)

**Figure 3.** Changes of CNG and diesel fuel energy shares versus the engine load $T \ [\text{Nm}]$

![Figure 4](image)

**Figure 4.** Changes of the air excess ratio $\lambda$ for: diesel fuel, natural gas and both fuels versus the engine load $T \ [\text{Nm}]$ (at constant diesel fuel injection parameters)

In effect of the established way of the engine load alteration, the air – natural gas mixture becomes more rich (the air excess ratio decreases) with the load.

According to the established procedure, a proper selection of injection parameters of the diesel pilot dose enabled to meet the condition to maintain maximum combustion pressure $p_{\text{max}}$, and maximum rate of pressure rise $dp/d\alpha_{\text{max}}$ comparable to those observed in a conventionally operating engine.

Diagrams presented in (Fig. 5) show the registered combustion chamber pressure versus crankshaft angle $p(\text{bar})=f(\alpha) \ [\text{CA}]$ for the applied load values and for three operation modes: conventional operation on diesel fuel, dual-fuel operation with standard adjustment of injection parameters for diesel fuel, dual-fuel operation with standard adjustment of injection parameters for diesel fuel, dual-fuel operation with proper adjustment of diesel fuel injection parameters.
Figure 5. Characteristics of the combustion chamber pressure versus crankshaft angle for conventionally operating engine (DF), dual-fuel operating engine with standard adjustment of injection parameters for diesel fuel (DF + CNG std.) and dual-fuel operation with proper adjustment of diesel fuel injection parameters (DF + CNG reg.)

Preliminary visual analysis of diagrams presented in (Fig. 5) indicates the necessity to adjust injection parameters for diesel fuel in the range of higher engine load. Moreover, it should be mentioned that...
delivery of the gaseous fuel changes the cylinder ignition angle delay. The higher the gaseous fuel share the higher the cylinder ignition angle delay. According to the Authors, an increase of the auto-ignition delay time in a dual-fuel engine results from lower compression pressure and therefore also from lower temperature in this point of the cycle. It happens mainly due to higher heat capacity, of the properly compressed air – CNG mixture. Moreover, lower oxygen concentration in the compressed mixture delays the ignition process. Higher auto-ignition delay times result in higher maximum rate of pressure rise that sharply exceeds the value specific for conventional operation on diesel fuel (Fig. 7). Capabilities of the common rail system, i.e. possibility to divide the diesel pilot dose and to select the main and pilot dose quantities, enable a relatively simple control of the auto-ignition delay as well as heat release parameters and thus to control the maximum combustion pressure and the maximum rate of pressure rise.

5. Results confirming maintaining comparable values of the maximum combustion pressure and the maximum rate of pressure rise in a dual-fuel and conventionally operating engines

Analysis of the obtained combustion pressure runs \( p \ [\text{bar}] = f(\alpha \ CA) \) enabled to prepare diagrams presented in (Fig. 6) that illustrate maximum pressures measured for each successive engine load.

![Figure 6. Comparison of maximum pressures \( p_{\text{max}} \) for three analysed operation modes: DF, DF+CNG std. and DF+CNG reg.](image)

The diagram presented above shows that a proper selection of injection parameters of the pilot diesel fuel dose enabled to lower the maximum combustion pressure in a dual-fuel engine to the value comparable to that typical for conventional engine operation. Proper calculations enabled to prepare diagrams put together in (Fig. 7). The diagrams show maximum rates of pressure rise.
Figure 7. Comparison of maximum rates of pressure rise $\frac{dp}{d\alpha}$ for three analysed operation modes: DF, DF+CNG std. and DF+CNG reg.

The diagram presented above shows that a proper selection of injection parameters of the pilot diesel fuel dose enabled to lower the maximum rate of pressure rise to the value comparable to that typical for conventional engine operation. Only for the lowest load, a value of this parameter exceeds the value obtained in the case of conventional engine operation. However, it should be mentioned that the absolute value of this parameter is acceptable. Thus, it was demonstrated that it is possible to meet two conditions (established in preliminary investigation) necessary to ensure comparable durability of the engine operating in both investigated modes, even at a relatively high share of the gaseous fuel (Fig. 3).

6. Results regarding influence of the selection of injection parameters of the pilot diesel fuel dose on overall, thermal and mechanical efficiencies, taking into consideration durability of the dual-fuel engine

The hourly consumption of both fuels $G_e$ [kg/h] as well as the achieved torque $T$ [Nm] were measured during investigations. The obtained results enabled to calculate the engine overall efficiency $\eta_o$. The registered combustion chamber pressure values were used to calculate thermal $\eta_{th}$ and mechanical $\eta_m$ efficiencies. The obtained results are presented in (Fig. 8).
Figure 8. Comparison of thermal (a), mechanical (b), and overall (c) efficiencies for three analysed operation modes: DF, DF+CNG std. and DF+CNG reg.

Analysis of the obtained results reveals that, after application of the above described regulations of the pilot dose injection parameters, the overall efficiency $\eta_o$ of the dual-fuel engine is comparable to that of the conventionally operating engine over the range of full loads and lower by ca. 2.5% (of the absolute value) over the range of low loads. This is a result of lower thermal efficiency over this range.

7. Results regarding influence of the selection of injection parameters of the pilot diesel fuel dose on exhaust emissions, taking into consideration durability of the dual-fuel engine

During investigations the following emissions were measured: CO, CH$_4$, THC, NO$_X$ and PM. The results are presented in (Fig. 9).
Analysis of the presented diagrams reveals that the carbon monoxide emission from the dual-fuel engine is significantly higher than that from the conventionally operating engine. This negative feature is particularly visible at low loads. According to the Authors, this is result of incomplete combustion of the air – CNG mixture over the range of low loads (flame quenching of a very lean mixture) (Fig. 4) and incomplete combustion of the pilot dose over the range of full loads resulting from reaching the air – CNG mixture and thus limited access to oxygen of injected diesel fuel. It should also be noticed that total hydrocarbon emission from the dual-fuel engine is significantly higher than that from the conventionally operating engine (Fig. 9c). Increased methane (CH$_4$) emission (Fig. 9b) is responsible for this effect. Methane emission increases in result of an escape of the air – CNG mixture during the valve overlap period as well as in result of incomplete combustion, particularly over the range of low loads (very lean mixture) (Fig. 4).

Investigations conducted and published previously demonstrate that this effect may be reduced synchronizing injection parameters with injection timing. Unfortunately, this may create a conflict of priorities between two objectives, i.e. low emissions but at the same time – such combustion process that would secure high durability of the dual-fuel engine.

**Summary**

Proper selection of injection parameters of the pilot diesel fuel dose in a dual-fuel compression ignition engine operating on CNG makes possible obtaining combustion pressures and rates of pressure rise comparable to that typical for conventional engine operation (Figs. 6 and 7). In this way, there may be meet the established conditions to reach comparable durability of the engine operating: conventionally on diesel fuel and in a dual-fuel mode on diesel fuel and natural gas. It should be mentioned that this concerns dual-fuel operation with the energy share of natural gas equal to ca. 70% at full load. Meeting the conditions of comparable durability of a dual-fuel engine by selection of injection parameters of the pilot diesel fuel dose results in a slight lowering of the overall efficiency $\eta_o$ (in comparison with the conventional engine operation) over the range of low loads due to lower thermal efficiency $\eta_{th}$ (Fig. 8). Meeting the conditions of comparable durability of a dual-fuel engine by selection of injection parameters of the pilot diesel fuel dose (in comparison with the conventional engine operation) results in:

- significantly higher THC emission from a dual-fuel engine. Responsible for this effect is a clear increase of methane emission,
- significantly higher CO emission from a dual-fuel engine,
- higher NO$_x$ emission from a dual-fuel engine over the range of high loads,
- significantly lower PM emission from a dual-fuel engine.
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