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Analysis of a Dual-Fuel Combustion Engine Fueled with Diesel Fuel and CNG in Transient Operating Conditions

Author, co-author (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)
Affiliation (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)

Abstract

The paper presents the thermodynamic analysis of the engine supplied with small and large diesel fuel doses while increasing natural gas quantity. The paper presents changes in the combustion process thermodynamic indexes and changes in the exhaust gas emissions for dynamically increased share of the gaseous fuel. The cylinder pressure history was subject to thermodynamic analysis, . based on which the mean indicated pressure, the heat release rate, the quantity of heat released as well as the pressure rate increase after self-ignition were determined. These parameters were also referred to the subsequent engine operation cycles by specifying the scope of the change per cycle. The relationship between the engine load and the start, the center and the end of combustion while increasing the gas amount supplied to the cylinder was indicated. The presented analysis of the results indicates significant impact of the changes in the supplied gas amount on the engine operating indexes and exhaust emissions. The conducted tests made it possible to confirm that significant cooling of the cylinder (determined by the constant temperature of exhaust gas) does not allow combustion of a dual-fuel mixture during dynamic change of the engine fueling. It was shown that there is a relation between the thermal history of the cylinder (steady state conditions), the engine fueling rate and the possibility of combustion of a diesel-methane mixture.

Introduction

Limited sources of crude oil, which is the raw material for the production of conventional fuels, is an important aspect contributing to the increase in the use of alternative fuels (gaseous fuels in particular) to power combustion engines. Among the gaseous fuels, the most important is CNG (compressed natural gas) that consists primarily of methane, generating relatively small specific emission of CO_2 during combustion. The gas can also be produced in the process of organic matter decomposition and transported in a liquid or gaseous state. Considering consumption, CNG is the third largest energy source material in the world [1] and is successfully used to power the engines in both mono- and bi-fuel configurations.

Combustion of air and CNG mixture in compression-ignition engines operating in dual-fuel configuration starts after an injection of the initiating diesel fuel dose. The results presented in [2, 3] indicate that for the dual-fuel CI engine (CNG) in comparison to mono-fuel diesel engine, higher thermal efficiency and lower emissions of NO_x and particulate matter were obtained. Louinici et al. [4] showed a reduction in the specific fuel consumption within the range of high engine loads. The injection of natural gas into the intake duct results in lower engine volumetric efficiency due to its expansion [3]. Dual fuel CI engines do not require intake throttle valves, hence, higher volumetric efficiency in comparison to mono-fuel SI engines is expected. Another advantage of dual fuel CI natural gas engines is the fact that igniting the fuel spray creates multiple initiating points increasing the flame propagation, thus combustion. In automotive applications, internal combustion engines operate with variable loads and speeds. The studies conducted by Yang et al. [5] show that the change of the engine work points requires adjustments of the control system for the fuel supply parameters. A literature review indicates a deficiency in the analysis of the combustion process indexes under different dynamic changes of the fueling conditions. This deficiency has been the fundamental incentive for the authors to undertake this study.

Literature review

Dual-fuel supply of a compression ignition engine is based on supplying the engine with a diesel fuel dose as basic fuel and increasing the share of additional fuel, for example CNG. Wei et al. [3] analyzed the application of natural gas in a dual-fuel engine (in combination with diesel oil) and found significant ecological benefits of such a solution. At the same time, the study pointed to the increased stability of engine operation while increasing the load, adding that the cyclic-variable values of engine operation are higher than when fueling the engine exclusively with diesel. The measure used to determine the stability was the coefficient of variation calculated for IMEP (CoV(IMEP)). CoV(IMEP)represents cycle-to-cycle variations in the mean pressure values estimated from the in-cylinder pressure history. The lower the CoV_{IMEP} value the better the combustion stability.

Studies on supplying dual-fuel engines with natural gas relate mostly to mixer-based systems [6, 7] as well as indirect [5, 8, 9] and direct injection systems [1, 10, 11]. However, they do not focus strictly on the widely used gas injected engines. Kalam and Masjuki [10] showed comparable engines (in terms of geometric parameters). Taking into account areas of effective power in the entire range of engine speeds, the power of the CNG-DI (direct injection) engine is approx. 4% lower than the that of the SI-PFI gasoline engine and approx. 20% higher than the CNG-BI (bi-fuel) engine. The fuel consumption of the CNG-DI engine is comparable to the fuel consumption of the SI-PFI (spark ignited-port fuel injection) engine and is approx. 8% lower than a CNG-BI engine.

Zhang et al. [11] indicated that the combustion process with a direct injection of a pilot dose can be divided into four phases (pure compression, mixture preparation, pilot diesel combustion and main fuel combustion). The optical study of the natural gas injection process requires techniques enabling analysis of the natural gas atomization in the gaseous medium [12]. The authors adopted the Schlieren method for the visualization of the medium in a CNG mixer model and estimated the fuel concentrations in certain regions of the analyzed area. A review of studies led by Soid and Zainal [13] indicates that these techniques in the case of alternative fuels are not sufficiently exploited. In this paper, 49 main types of studies were presented, 95% of which were studies on liquid fuels, due to a relative small share of gas engines in service.

The conducted studies, as mentioned above, are designed to determine the effects of several factors on the ignitability of the prepared mixture. The ignitability is determined by a constant engine speed with variable loads resulting from the additional feed of gaseous fuel to the engine. This means that the engine operating conditions are not steady-state and their variability is caused by the increasing load.

Kakaee et al. [14] outlined the impact of natural gas diverse composition on the combustion engine operating conditions. The presented analysis shows that the engine power, which is defined with the appropriate mathematical equation, is proportional to the Wobbe index. It was also reported that the in-cylinder pressure was proportional to the Wobbe index and exhaust emission characteristics were affected by the Wobbe index, fuel composition, spark timing, and burning velocity.

Variable load of a dual-fuel engine fueled with diesel fuel and CNG causes significant changes when forming a combustion mixture. In the study, attention is drawn to:

a) the change in the excess air coefficient [15, 16] and

b) the impact of the diesel injection angle [5, 8, 17].

Zhang and Song [15], have analyzed the changes in the air excess coefficient that describes the composition of the fuel-air mixture. The authors used the equation enabling a determination of the changes of this factor for each fuel. They found that increased gas supply causes a small global change (reduction) of the excess air coefficient estimated for both fuels in comparison to the change (reduction) of this coefficient calculated only for natural gas. They indicated a significant increase in the hydrocarbons concentration in the exhaust gas, which points to incomplete CNG combustion. In these studies, however, the share of NMHC (non-methane hydrocarbons) was not indicated. The ratio of CH_4 to the total emissions of THC (total hydrocarbons) was taken into account and presented by Liu et al. [18] with a conclusion that the share of methane is approx. 90% at low speeds (and smaller lambda value) and approx. 85% at high engine speeds. These values are to a minor extent dependent on the engine load. Li et al. [16] in their studies introduced additional indexes to determine the combustion quality of diesel-natural gas mixture. The research was conducted in terms of variable excess coefficient and the following parameters were analyzed: cycle thermal efficiency, mixture heat capacity, flame development duration, heat release rate etc. Based on the last mentioned parameter, it was found [16] that the quality of the combustion process increases rapidly from the excess air coefficient of 1.8 (towards smaller values).

Tests carried out by Yang et al. [5] indicate a strong influence of the start of injection and injection pressure of the initial diesel fuel dose on the engine operation indexes and exhaust emissions. The injection advance angle of the initial fuel dose increases the thermal efficiency of the engine by approx. 25% and reduces the emission of hydrocarbons by 60% without changing the opacity. The studies conducted by Zhang et al. [8] indicate a more significant impact of the diesel injection advance angle (compared to diesel injection pressure) on the change of the in-cylinder pressure . Tripling the injection advance angle results in a 70% increase in the maximum cylinder pressure, while increasing the injection pressure (from 80 to 140 MPa) results in only a 6% increase in the maximum combustion pressure.

The studies conducted by Wang [17] for large injection advance angles (up to 50 deg before TDC) indicate the possibility of a two-phase combustion. The results of the research indicate obtaining high thermal engine efficiency (35%) and low emissions of hydrocarbons and nitrogen oxides for the injection angle of 42.5 deg before TDC.

The literature review points to two major research directions: variable operating conditions when fueling engines with diesel as basic fuel, and:

a) fuel that is a mixture of fuels (most often diesel and other fuels including biofuels),

b) fuel as a separate energy source, used in dual-fuel engine operation.

The first group of research is very large. This research group includes studies by Rakopoulos et al. [19, 20], where the increased nitrogen oxides emissions were observed for the fueling with a mix of fuels (75% ON + 25% butanol and 70% diesel fuel + 30% biodiesel) along with a smaller value of exhaust gas opacity. Dynamic conditions of the tests involved a change of the engine speed from 1016 rpm (10% load) to 1880 rpm (15% load). In addition, no change in self-ignition delay was indicated when fueling the engine with biodiesel mixtures; however this delay increased when the engine was fuelled with a mixture containing ethanol and n-butanol.

The tests at several fixed values of the engine speed and variable loads were carried out by Tan et al. [21]. In these tests the mono-fuel system was used (biodiesel in different proportion in a mixture with diesel) and only changes in the particle mass and particle number were observed.

The tests on the operating indexes of the mono-fuel engine (CNG or HCNG) in road conditions and the analysis of the exhaust emissions were conducted by Barata and Misul [22]. The conclusions include only the initial and final conditions without the thermodynamic analysis of the transient states.

The specificity of this issue results from the fact that the engine speed does not change, but the engine load increases as a result of the increasing share of natural gas in the charge. Such conditions do not typically occur during operation of a combustion engine; however, they may take place during, as we call it, power generator operation, where there is a change of engine load at a constant (given) value of the engine speed.

Barroso et all. analyzed the operational parameters and exhaust emissions of a dual fuel CI engine operated in transient conditions

[24] and indicated significant limitations in a possible CNG/diesel substitution ratio under transient engine operation. A further literature review shows that the issue presented in this paper is not explored in detail and therefore requires analysis.

3. Methodology

a) engine

The study was carried out on a single-cylinder test 5804 engine by AVL with an autonomous injection system of diesel and natural gas into the channel upstream of the intake valve. Diesel injection was carried out using a high-pressure pump CP 4.2 and a piezoelectric injector. The gas injection was carried out with the use of an electromagnetic injector by Bosch, supplied with the pressure of 0.9 MPa. The engine technical specifications have been shown in Table 1. The asynchronous electrical dynamometer brake AMK ASYN of DW13-170-4-AOW type was used on the test bench.

Table 1. Characteristics of the AVL 5804 test bench.

Parameter	Value
Engine capacity	510.7 cm^3
Piston stroke	90 mm
Cylinder diameter	85 mm
Compression ratio	16.2:1
Number of valves/cycles	4
Angle of opening of the exhaust valves	57.5° before BDC
Angle of closing of the exhaust valves	18° after TDC
Angle of opening of the intake valves	10° before TDC
Angle of closing of the intake valves	46° after TDC
Injector type	piezoinjector, 8-hole, d = 0.117 mm
Fuel injection system	common rail
Cylinder head gasket	2 mm (required to obtain the compression ratio)

b) measurement of the engine parameters

The test stand (Figure 1) was equipped with a control and measurement equipment including:

a) a system for the measurement of fast-varying processes - AVL IndiSmart 621 measuring the in-cylinder pressure (Pcyl) with the use of a pressure sensor - AVL GH14D with the measuring range of 0–250 bar and sensitivity of 18.84 pC/bar,

b) a data acquisition system AVL IndiCom,

c) a system for the fuel injection process enabling the control of the injection time and injection angle with the resolution of $\Delta\alpha = 0.5$ deg and fuel pressure up to 200 MPa by Mechatronika Poland,

d) a system for the measurement of the gaseous exhaust components – Horiba Mexa 7100D used in type approvals, measuring CO, THC (HFID), NO_x, CO_2.

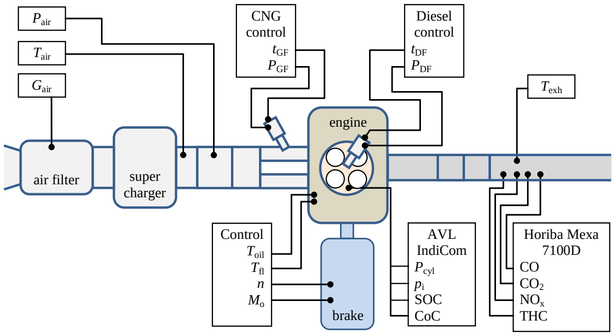


Figure 1. Diagram of the test stand with the testing equipment and characteristic parameters of the process.

The tests were conducted for 800 subsequent measuring cycles for which the following parameters were defined:

a) operating indexes of the combustion engine,

b) thermodynamic indexes of the combustion process,

c) concentration of the exhaust components (CO, THC, NO_x),

d) ignitability defined by readiness for ignition.

The indexes of the combustion engine operation included:

– maximum pressure in the cylinder – P_{max},

– indicated mean effective pressure – designated as IMEP,

– exhaust gas temperature – T_{exh},

The thermodynamic indexes of the engine operation included:

- start of combustion – SOC defined as the beginning of the positive value of heat release during compression,
- temperature of the start of combustion (T_SOC) determined on the basis of the characteristics of the pressure in the cylinder,
- maximum temperature in the cylinder,
- angle of occurrence of the center of combustion which is 50% of the combusted fuel dose – MBF50% (CoC – center of combustion).

4. Experimental procedure

The tests were carried out for a fixed engine speed of 2000 rpm. The analysis was commenced when the engine operated on diesel dosage only (the initial values of the injector opening time was 0.18 ms and 0.26 ms). Then, the dose of natural gas was increased using two rates (slow, rapid). The change rate of the gas dose defined as 'rapid' meant obtaining the injection time of 8 ms in 1 sec, and for the 'slow' rate – in 2 sec. The final conditions of the tests were defined for the gas injection time setting of 8 ms.

The test conditions were limited to the lambda value ranging from 1.8 to 3.5 (for the final energy value of the ratio of the dose of both fuels). The changes in the gas supply were conducted for two values of the coolant temperature. Sixteen different tests were carried out. The procedure of experimental tests has been presented in Table 2.

Table 2. The test plan of the dynamic operating conditions of the dual-fuel engine.

Test No.	tGF [ms]	Initial condition					Final condition	
		t_{DF} [ms]	T_{exh} [deg. C]	T_{oil}, T_f [deg C]	SOI [deg]	dm/dt [s]	t_{GF} [ms]	t_{DF} [ms]
1	0	0.18	60	50	–9 bTDC	slow 2 s	8	0.18
5						rapid 1 s		
2					–5 bTDC	slow 2 s		
6						rapid 1 s		
3		0.26	110		–9 bTDC	slow 2 s		0.26
7						rapid 1 s		
4			115		–5 bTDC	slow 2 s		
8						rapid 1 s		
9		0.18	90	80	–9 bTDC	slow 2 s		0.18
13						rapid 1 s		
10					–5 bTDC	slow 2 s		
14						rapid 1 s		
11		0.26	140 145		–9 bTDC	slow 2 s		0.26
15						rapid 1 s		
12					–5 bTDC	slow 2 s		
16						rapid 1 s		

Test results

a) engine test results

The tests were carried out for variable increase rate of the gaseous fuel dose dm_{GF}/dt, at different values of the engine temperature and injection time of the diesel fuel dose that initiated the process of combustion (the constant value of the diesel injection pressure was set at 70 MPa). Figure 2a shows the changes in the injector opening time and changes in the mass flow rates of the gaseous fuel in the subsequent 100 operation cycles. The characteristics of the changes in the mass airflow rate in relation to the CNG mass flow rates and the total value of the excess air coefficient for 150 consecutive cycles have been shown in Figure 2b.

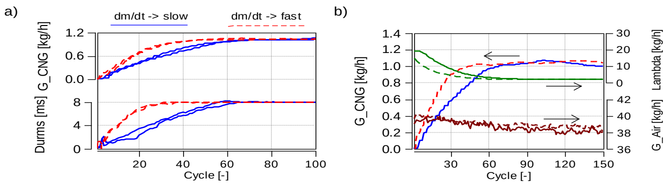


Figure 2. The conditions of CNG feed to the engine (examples of test results): a) the impact of the method of increasing the gaseous fuel injection time on the gas flow rate; b) dynamic change of the fuel feed on the engine conditions.

For high values of dm_{GF}/dt (quick changes in gaseous fuel feed, dashed line) the set injector opening times were obtained within 30 operating cycles, while for the low values of this parameter it took twice as long (solid line). Increasing the dose of the gaseous fuel in both cases resulted in reducing the amount of intake air by the engine, which was the consequence of displacing a portion of fresh charge from the intake channel by the decompressed gaseous fuel.

Also, the impact of the angle of the start of the diesel fuel dose injection initiating the combustion process (Fig. 3 and Fig. 4) and the effect of the engine coolant temperature on the maximum pressure in the combustion chamber were analyzed.

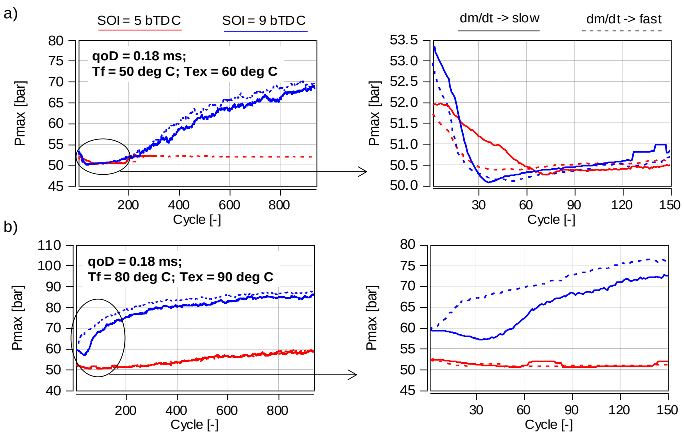


Figure 3. Characteristics of the maximum combustion pressure during the injection of a small diesel fuel dose at different angles of the start of injection and dynamic injection of CNG: a) for low coolant temperature; b) for high coolant temperature.

During the engine operation, at the coolant temperature of 50°C and high rate of changes in the gaseous fuel feed, the decrease in the maximum cylinder pressure was observed during the first 35 operating cycles. At the angle of injection advance of 5 deg bTDC (red color) after reaching the lowest values of P_{max}, a slight increase in the value and its stabilization were observed. Advancing the diesel injection by 4 degrees (blue color) resulted in a further increase in the maximum cylinder pressure and obtaining an approx. 34% higher value after approximately 800 operating cycles.

Higher values of P_{max} (by 15% at SOI = 5 deg bTDC and 25% at SOI = 9 deg bTDC) were obtained during engine operation at the coolant temperature of 80°C. At the same time, the initial value of the pressure increase in subsequent operation cycles was higher.

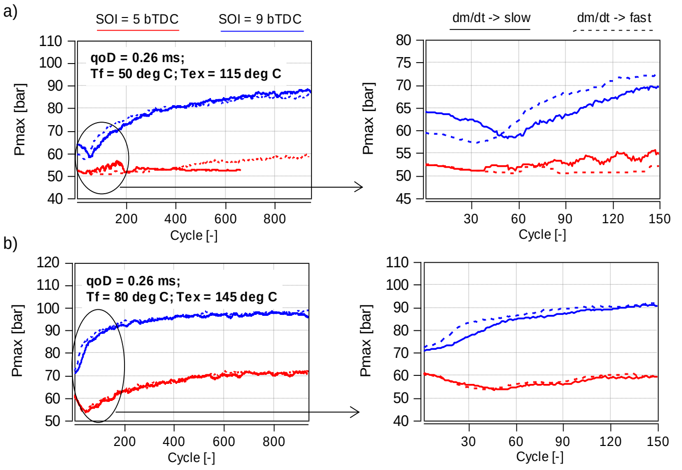


Figure 4. Characteristics of the maximum combustion pressure during injection of a large diesel fuel dose at different angles of the start of injection and dynamic injection of CNG: a) for low coolant temperature; b) for high coolant temperature.

Another variable was the size of the fuel dose (diesel) supplied to the cylinder. An increase in its share causes an increase in the amount of energy derived from the diesel fuel, which means further reduction in P_{max} (for the engine operating at lower values of the coolant temperature). At the same time, greater amplitude of values between the lowest and the highest pressure P_{max} was observed. During the first 200 operation cycles the ΔP_{max} value was much higher for large doses of diesel fuel.

b) the response time of the exhaust emission measurement system

The individual response delay time of individual measurement systems was related to the input signal time of the gaseous fuel flow. The start time of the flow was established based on the CNG fuel injection start (opening of the injector). This time is referred to as a SOI_GF (Fig. 5), which was a reference in determining of the delay: the reaction of the natural gas flow meter (21 cycles, which is equal to 1.25 s) and the response of the exhaust gas temperature sensor (21 cycles, which is 1.25 s). The operation delay of the exhaust gas analyzers was also determined, which was variable, and amounted to: 74 cycles (4.4 s) for the THC analyzer , 97 cycles (3.6 s) for the NO_x analyzer and 118 cycles (7.0 s) for the CO analyzer . On this basis the standardization of the measurement signals was conducted.

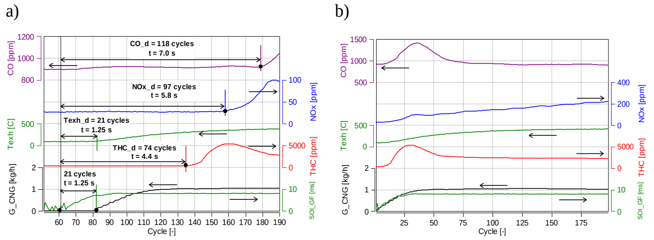


Figure 5. The response time of individual components of the measurement system for dynamic measurement of the exhaust emissions (Horiba Mexa 7100D): a) measurement conditions; b) emission characteristics after the synchronization time.

6. Results and discussion

6.1. Engine indexes

The analysis of the engine indexes was carried out based on the tests of the maximum pressure in the cylinder relative to the first 1000 operating cycles (Fig. 6). For low injection advance angles (SOI = 5 deg bTDC) and low coolant temperatures (50 deg C) no combustion under dynamic conditions for both small and large igniting doses was observed. The increase in the injection advance angle (SOI = 9 deg bTDC) allowed a mixture ignition and obtaining the maximum pressure value of 70 bar for the smaller initializing fuel dose (q_{0D} = 0.18 ms) and 90 bar for the larger fuel dose (q_{0D} = 0.26 ms). The possibility of obtaining ignitability of a mixture of the two fuels was also affected by the initial coolant temperature. When the temperature increased to the value of 40 deg C, the maximum pressure increase of 10% (Fig. 6c, 6d) to 21% (Fig. 6a, 6b) was observed. However, a more important result of increasing of the engine operating temperatures up to 90 deg C was the stabilization rate of the pressure increase during the dm_{GF}/dt change, which enabled a relative stabilization after approx. 300 operation engine cycles.

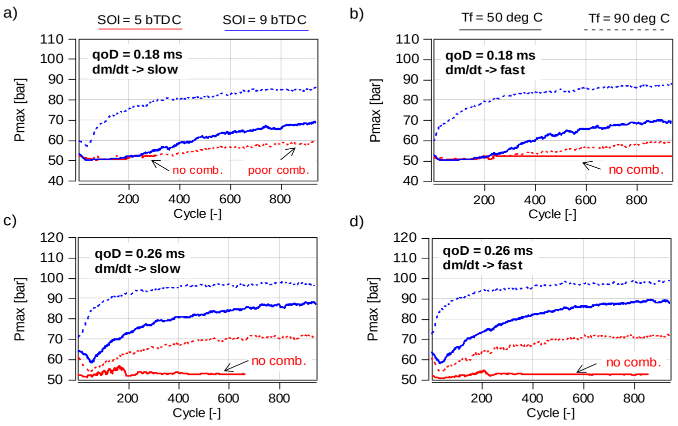


Figure 6. A maximum pressure change in the cylinder under dynamic conditions when fueling the engine with: a) a small diesel fuel dose and a slowly increased CNG fuel dose, b) a small diesel fuel dose and a rapidly increased CNG fuel dose, c) a large diesel fuel dose and a slowly increased CNG fuel dose, d) a large diesel fuel dose and a rapidly increased CNG fuel dose.

The analysis of the changes of the mean indicated pressure against the cycles of engine operation has been shown in Figure 7. For large doses of the initiating fuel (q_{0D} = 0.26 ms) the characteristics are comparable and are defined by a fast stabilization of the values at the level of IMEP = 10 bar. The system responds proportionally to the change in dm_{GF}/dt. During the rapid increase in the share of the gaseous fuel, the number of cycles needed to obtain a fixed value of the maximum process temperature has been reduced by half. A lower dose of the initiating fuel (q_{0D} = 0.18 ms) prolongs the time needed to stabilize the combustion process. A reduction of the initial dosage by 30% results in obtaining the IMEP of 8 bar. The phenomenon of misfiring was observed for all engine fueling strategies, low injection advance angle (SOI = 5 deg bTDC) and low coolant temperature (50 deg C). It is worth noting that the value of the IMEP for a high injection advance angle (SOI = 9 deg bTDC) does not significantly affect the temperature of the test engine. For a high injection advance angle (SOI = 9 deg bTDC) and higher coolant temperature (90 deg C), higher values of P_{max} and IMEP are observed. What it means is that the early injection and the high value of the coolant temperature promote the combustion process in the illustrated system. At the same time, when the injection advance angle is SOI = 5 deg bTDC and the coolant temperature is 50 deg C, it is impossible to obtain a proper combustion process. It means that the late injection and the low value of the coolant temperature prevent rapid self-ignition of the fuel mixture. Therefore, under cold start conditions it will be necessary to use higher initiating doses. Low values of injection advance (SOI = 5 deg bTDC) at a low diesel fuel dose (q_{0D} = 0.18 ms) disturb the ignition of the prepared mixture causing misfiring and unstable operation. The reason for such a course of the process is most likely insufficient initial engine temperature and the lack of the required time to prepare the charge for combustion.

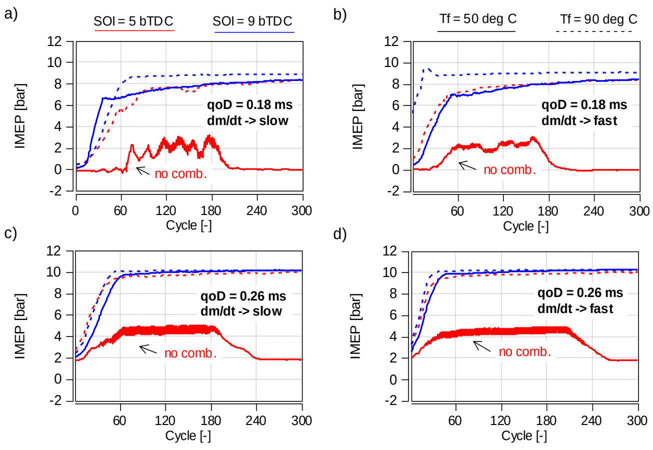


Figure 7. A change of the mean indicated pressure in the cylinder under dynamic conditions when feeding the engine with: a) a small diesel fuel dose and a slowly increased CNG fuel dose, b) a small diesel fuel dose and a rapidly increased CNG fuel dose, c) a large diesel fuel dose and a slowly increased CNG fuel dose, d) a large diesel fuel dose and a rapidly increased CNG fuel dose.

6.2. Thermodynamic indexes

The thermodynamic analysis of the combustion process was conducted on the basis of 300 consecutive engine cycles. This analysis was based on the calculated temperature values at the start of combustion, the maximum temperature in the combustion chamber and the measured values of the exhaust gas temperature. In addition, the analysis includes the angle of 50% of the mass of the combusted fuel, indicated by the angle of the center of combustion.

The analysis of the temperature of the start of combustion was performed in relation to the angle of the start of combustion. For low injection advance angle (SOI = 5 deg bTDC) and low coolant temperature (50 deg C), significant changes of the start of combustion temperature were observed (Fig. 8a). Low temperatures of SOC obtained for large angles of CA after TDC indicate a lack of the combustion process or its incorrect course. It means that the late injection (5 deg bTDC) and the low value of the coolant temperature (50 deg C) prevent rapid self-ignition of the mixture of liquid and gaseous fuels. In addition, the gas content in the charge with a small amount of diesel fuel will not lead to self-ignition.

Increasing the rate of the gas supply does not change this situation (Fig. 8b). Dynamic changes in the supply of fuel at the temperature of the coolant of 90 deg C result in some sort of self-igniting, the values of which fall within the range of 0–2 deg aTDC. Increasing the initial diesel fuel dose at a low coolant temperature causes an intensification of the lack of combustion (Fig. 8c-d). Very high values of self-ignition delay are obtained, at low values of temperature. These are very unfavorable conditions in terms of proper combustion process.

Based on the analysis it can be concluded that increasing the coolant temperature (bright points in Fig. 8) results in higher temperatures at the angle of the start of combustion and, at the same time, in advancing the occurrence of self-ignition by several degrees.

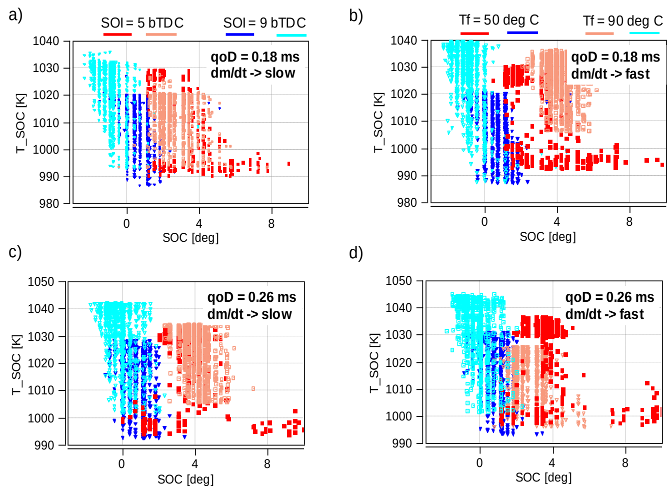


Figure 8. Values of the temperature of the start of combustion (SOC) in the cylinder under dynamic conditions when feeding the engine with: a) a small diesel fuel dose and a slowly increased CNG fuel dose, b) small diesel fuel dose and a rapidly increased CNG fuel dose, c) a large diesel fuel dose and a slowly increased CNG fuel dose, d) a large diesel fuel dose and a rapidly increased CNG fuel dose.

The analysis of the maximum temperature in the cylinder indicates the existence of a close relationship between the process parameters of charge preparation and the CNG dose increasing rate. A low value of injection advance angle at a small diesel fuel dose prevents ignition of the formed mixture. The reason for such a course of the process might be insufficient initial cylinder temperature and lack of sufficient time to prepare the charge for combustion (late injection of a small diesel fuel dose). Similar combustion characteristics were obtained during both slow and rapid injection. Different strategies of gas injection into the intake manifold do not have much effect on the combustion process. In both cases, there was no increase in the temperature above 1300 K in the cylinder. During the slow gas injection, a characteristic misfiring occurred, as noted in Fig. 9a and 9b in the form of sudden changes in the process temperature.

Combustion of a small gas dose is most beneficial during stabilized thermal state of the engine and a relatively large injection advance angle. For such initial condition of the engine, the maximum temperature values during both rapid and slow increase of the gas dose are observed. These values reach the level of approx. 2100 K. The small injection advance angle and the high coolant temperature result in the same values of combustion temperatures as those occurring when running the engine at high injection advance angle and low coolant temperature. It means that the critical initial values of the combustion process are: small injection advance angle and low coolant temperature.

During the combustion of a large fuel dose of natural gas (as a basic fuel), constant low temperatures of the process are observed. These values reach 1600 K and remain unchanged. Constant values of temperature can indicate poor combustion process, which is significantly affected by the late injection of the igniting diesel fuel dose. During combustion of a large dose of gas, the feed rate of the gas is insignificant (Fig. 9c-d). When analyzing combustion of a large gas dose the same values of the maximum process temperature are observed, regardless of the gas feed method. It was also observed, that during the fast increase in the share of the gaseous fuel, the number of cycles needed to obtain a fixed maximum temperature value of the process was reduced by half.

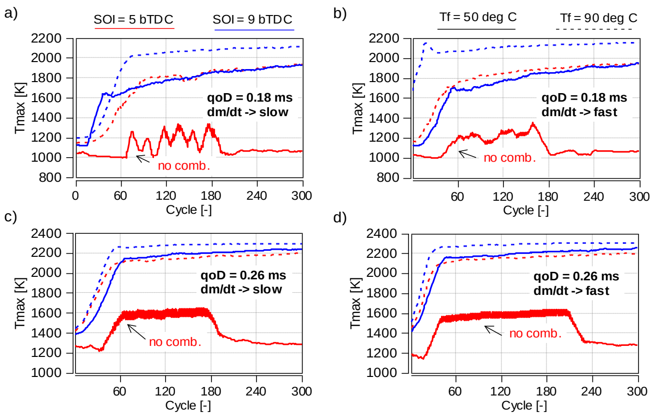


Figure 9. A change of the maximum combustion temperature in the cylinder under dynamic conditions when feeding the engine with: a) a small diesel fuel dose and a slowly increased CNG fuel dose, b) a small diesel fuel dose and a rapidly increased CNG fuel dose, c) a large diesel fuel dose and a slowly increased CNG fuel dose, d) a large diesel fuel dose and a rapidly increased CNG fuel dose.

Another analyzed parameter is the point defining the center of combustion (CoC) (Fig. 10). As is apparent from the above, the characteristics of the changes of the angle of the center of combustion depend not only on the start of the injection angle, but also on the engine coolant temperature. During the tests carried out on the unheated engine, the value of the angle of the center of combustion (CoC) was characterized by high cyclic variation or the combustion process did not occur because of improper initial conditions, particularly insufficient temperatures in the cylinder due to increased absorption of heat by completely cold walls of the combustion chamber. At the same time, no significant positive effect of the change of the value of the fuel dose initiating the combustion process was observed, nor of the dynamics of the change of the size of the gaseous fuel dose.

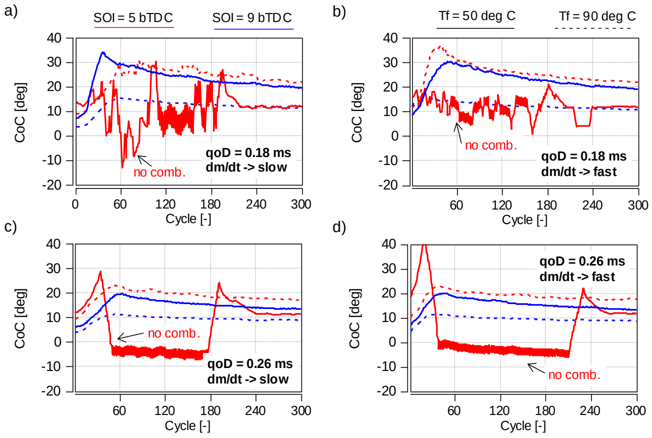


Figure 10. Values of the angle of the center of combustion (50% of released heat) under dynamic conditions when feeding the engine with: a) a small diesel fuel dose and a slowly increased CNG fuel dose, b) a small diesel fuel dose and a rapidly increased CNG fuel dose, c) a large diesel fuel dose and a slowly increased CNG fuel dose, d) a large diesel fuel dose and a rapidly increased CNG fuel dose.

At the angle of injection SOI = 9 deg bTDC and high coolant temperature, high final values (while feeding a high dose of CNG) of the occurrence of the center of combustion (30 deg aTDC) were observed, which then decreased by 5–10 deg CA. The reason for such characteristics of the process was the increase in the CNG dose, which resulted in a prolonged time of combustion. Significant differences were also observed for the characteristics of the exhaust gas temperature (Fig. 11).

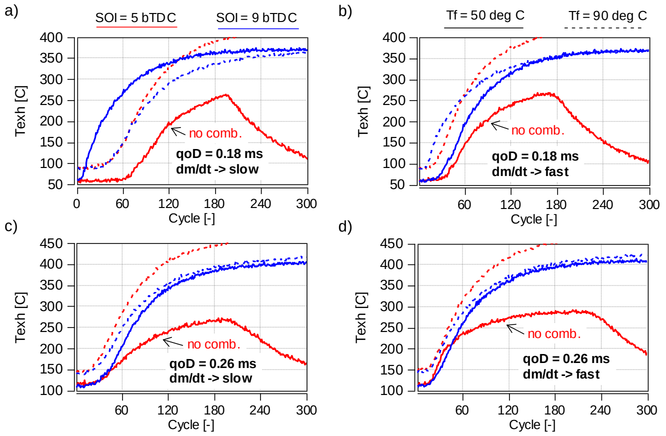


Figure 11. Values of the temperature of the exhaust gas under dynamic conditions when feeding the engine with: a) a small diesel fuel dose and a slowly increased CNG fuel dose, b) a small diesel fuel dose and a rapidly increased CNG fuel dose, c) a large diesel fuel dose and a slowly increased CNG fuel dose, d) a large diesel fuel dose and a rapidly increased CNG fuel dose.

Increasing the diesel fuel dose is associated with a higher increase rate of the exhaust gas temperature. The increase in the change of the dynamics of the CNG dose enabled obtaining a similar exhaust gas temperature approx. 20 cycles earlier than in the case of a slow increase in the CNG dose (Fig. 11a and 11b). At the same time, during the tests carried out on the unheated engine, a positive correlation was observed between the increase rate of the exhaust gas temperature and the dynamics of the increase in the gaseous fuel dose. In all cases of engine fueling with small and large diesel fuel doses and low and high rates of CNG feed, no combustion occurred at a low angle of advance of the diesel fuel injection. The temperature of the exhaust gas did not exceed 250 deg C in this case.

Emission indexes

During the dynamic tests of fueling of a dual fuel engine, an analysis of the emission indexes for each individual exhaust component was also conducted. Figure 12 shows the carbon monoxide concentrations for different fueling methods of the engine. It demonstrates a trend indicating an increase in the CO concentration when the engine is running at a lower coolant temperature. When fueling the engine with small diesel fuel doses and at a low rate of increase of the gaseous fuel, a trend towards lack of combustion can be observed, which is confirmed by low carbon monoxide concentration.

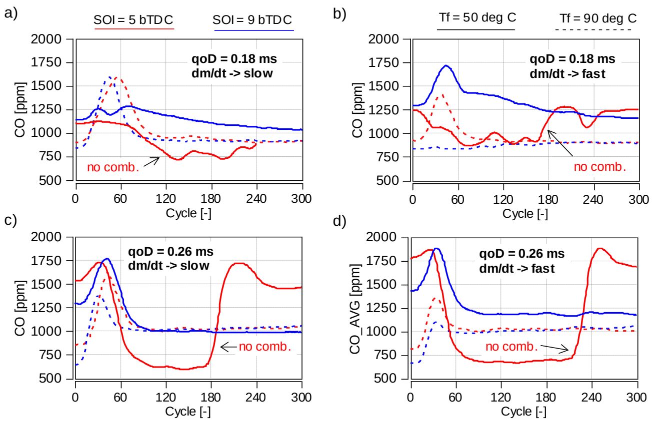


Figure 12. Values of the carbon monoxide concentration under dynamic conditions when feeding the engine with: a) a small diesel fuel dose and a slowly increased CNG fuel dose, b) a small diesel fuel dose and a rapidly increased CNG fuel dose, c) a large diesel fuel dose and a slowly increased CNG fuel dose, d) a large diesel fuel dose and a rapidly increased CNG fuel dose.

Figure 13 presents the concentration of hydrocarbons obtained during the tests. A general trend of growing concentration of this component at low igniting doses is observed, which means that the conditions enabling a proper course of the combustion process are not reached. When feeding the engine with large and small diesel fuel doses at a small injection advance angle, a characteristic high concentration of hydrocarbons in the exhaust gas is observed. This denotes a lack of conditions promoting the occurrence of self-ignition and subsequent charge combustion. The concentration values, in the absence of combustion, obtain values that are approx. 5 times higher than those obtained in a normal process. This means that the analysis of the concentration of hydrocarbons can be a very good diagnostic parameter for the evaluation of the combustion process under dynamic conditions.

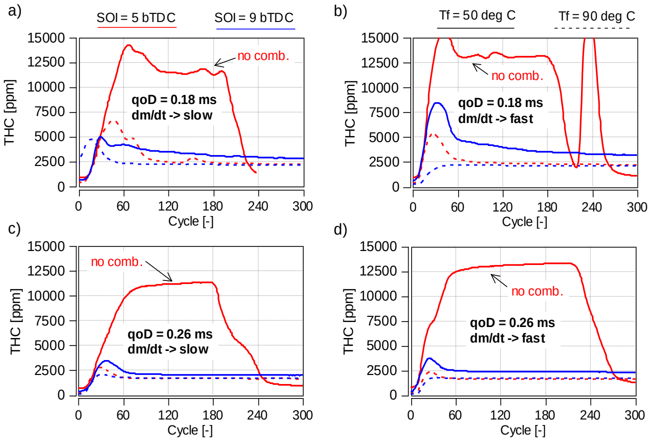


Figure 13. Values of the concentration of hydrocarbons under dynamic conditions when feeding the engine with: a) a small diesel fuel dose and a slowly increased CNG fuel dose, b) a small diesel fuel dose and a rapidly increased CNG fuel dose, c) a large diesel fuel dose and a slowly increased CNG fuel dose, d) a large diesel fuel dose and a rapidly increased CNG fuel dose.

Figure 14 summarizes the concentration of nitrogen oxides obtained during the dynamic tests of the dual-fuel engine. A characteristic feature is the increased value of the concentration of NO_x during engine operation at the coolant temperature of 90 deg C and high diesel injection advance angle. The trend is independent of the size of the dose initiating the combustion. A small dose initiating the combustion (Fig. 14a-b) results in an impaired course of the combustion process, as the NO_x concentration is low and up to the 300th engine cycle it increases continuously. However, the level of achieved concentrations is more than twice smaller than for a large advance angle of the diesel fuel injection. Such a combustion process indicates a deteriorated start of combustion and its inadequate conditions. It is possible that during the charge formation for the combustion process there are too few areas in the combustion chamber in which the self-ignition of the vaporized liquid fuel can occur.

Similar trends were observed when feeding the engine with a large dose initiating the combustion. The best course of the combustion process (large NO_x values) was observed for dual-fuel engines for a high diesel fuel injection advance angle and a high coolant temperature. With a large diesel fuel dose and a low coolant temperature attempts of combustion are observed, however the NO_x values of 200 ppm show a very poor course of this process. It is inhibited by the cold walls of the combustion chamber that indirectly affect the escape of heat during the compression process and result in inadequate charge preparation.

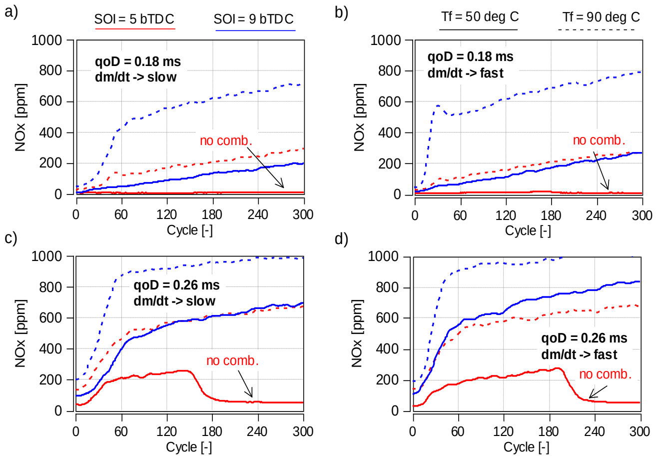


Figure 14. Values of the nitrogen oxides concentration under dynamic conditions when feeding the engine with: a) a small diesel fuel dose and a slowly increased CNG fuel dose, b) a small diesel fuel dose and a rapidly increased CNG fuel dose, c) a large diesel fuel dose and a slowly increased CNG fuel dose, d) a large diesel fuel dose and a rapidly increased CNG fuel dose.

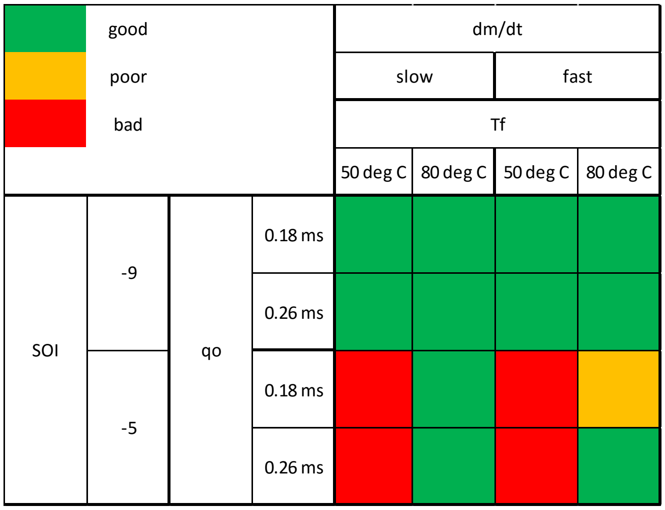
The analysis of the emission tests indicates that there is a close relationship between individual concentrations of the exhaust gas components and the engine thermodynamic conditions. The influence of the coolant temperature and the influence of the injection advance angle are the main parameters that determine the quality of the combustion process under dynamic conditions. The emissions are secondary parameters, the values of which depend on the thermodynamic conditions of the combustion process. However, the concentration of the exhaust gas is the best diagnostic indicator of the combustion process that can be evaluated under all test conditions.

Summary

The analysis of the mixture ignitability was carried out taking into account the impact of the parameters of the dose initiating the combustion process, the coolant temperature and the change rate of the gaseous fuel dose.

The analysis of the combustion process in a dual-fuel engine fueled with natural gas (slowly and rapidly supplied to the engine) and diesel fuel as the initiating dose indicates different course of the combustion process with a possible total lack of combustion. Ignitability conditions depend on the method of fuel supply, as well as on the initial thermodynamic conditions of the engine (coolant temperature and SOI).

The matrix showing the mixture ignitability under the conditions of dynamic changes of the gaseous fuel supply has been shown below.



🟩	good			dm/dt			
🟨	poor			slow		fast	
🟥	bad			Tf			
				50 deg C	80 deg C	50 deg C	80 deg C
SOI	-9	qo	0.18 ms	🟩	🟩	🟩	🟩
			0.26 ms	🟩	🟩	🟩	🟩
	-5		0.18 ms	🟥	🟩	🟥	🟨
			0.26 ms	🟥	🟩	🟥	🟩

Figure 15. Table of mixture ignitability under dynamic changes in the method of fuel feed in dual fuel engines.

At a coolant temperature of T_f = 50 deg C and the initiating diesel fuel dose start of injection of SOI = 5 deg bTDC, the combustion did not occur. During the injection of a small diesel fuel dose at a high rate of the change of the supply of the gaseous fuel, small values of the combustion parameters were obtained. After reducing the amount of the gaseous fuel increase rate, the combustion process was improved.

Based on the research and analysis it was found that the critical initial values of the combustion process during dual-fuel supply (diesel and CNG fuel) and at variable methods of feeding the gas to the cylinder are as follows: small injection advance angle and low value of the coolant temperature. In practical application, the most important parameter for the ignitability is the SOI of the initiating fuel dose that should be advanced during low-temperature engine operation. Indicated low values of the combustion indexes during rapid changes of load at high engine temperatures suggests further SOI advance in engine automotive applications.

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Contact Information

Prof. Ireneusz PIELECHA, M.Eng., Ph.D., D.Sc.
Poznan University of Technology, Institute of Combustion Engines and Transport
3 Piotrowo Street, 60-965 Poznan, Poland
Phone: +48 61 2244502, Fax: +48 61 6652204, e-mail: ireneusz.pielecha@put.poznan.pl)

Prof. Krzysztof WISLOCKI, M.Eng., Ph.D., D.Sc.
Poznan University of Technology, Institute of Combustion Engines and Transport
3 Piotrowo Street, 60-965 Poznan, Poland
Phone: +48 61 6652240, Fax: +48 61 6652204, e-mail: krzysztof.wislocki@put.poznan.pl

Wojciech CIEŚLIK, M.Eng.
Poznan University of Technology, Institute of Combustion Engines and Transport
3 Piotrowo Street, 60-965 Poznan, Poland
Phone: +48 61 2244502, Fax: +48 61 6652204, e-mail: wojciech.cieslik@put.poznan.pl

Przemysław BOROWSKI, M.Eng.
Poznan University of Technology, Institute of Combustion Engines and Transport
3 Piotrowo Street, 60-965 Poznan, Poland
Phone: +48 61 6475966, Fax: +48 61 6652204, e-mail: przemyslaw.t.borowski@doctorate.put.poznan.pl

Wojciech BUESCHKE, M.Eng.
Poznan University of Technology, Institute of Combustion Engines and Transport
3 Piotrowo Street, 60-965 Poznan, Poland
Phone: +48 61 6475966, Fax: +48 61 6652204, e-mail: wojciech.bueschke@put.poznan.pl

Maciej SKOWRON, M.Eng.
Poznan University of Technology, Institute of Combustion Engines and Transport
3 Piotrowo Street, 60-965 Poznan, Poland
Phone: +48 61 6475966, Fax: +48 61 6652204, e-mail: maciej.skowron@put.poznan.pl

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Definitions/Abbreviations

α, A	angle
BI	bi-fuel
CNG	compressed natural gas
CO	carbon monoxide
CoC	center of combustion
dm/dt	gas mass rate
Durms	duration of gas injection
dQ	heat release rate
G	flow
HCNG	hydrogen-CNG
IMEP	indicated mean effective pressure
lambda	excess air coefficient

NMHC	non-methane hydrocarbons
$\mathbf{NO_x}$	nitrogen oxides
PFI	port fuel injection
$\mathbf{P_{max}}$	maximum cylinder pressure
Q	heat release
$\mathbf{q_o}$	fuel quantity
$\mathbf{q_{oD}}$	diesel fuel quantity
SI	spark ignition
SOC	start of combustion
SOI	start of injection
t	time
$\mathbf{T_{exh}}$	exhaust temperature
$\mathbf{T_f}$	coolant temperature
THC	total hydrocarbons
T_SOC	start of combustion temperature
$\mathbf{T_{max}}$	maximum temperature of cylinder
TDC	top dead center (a – after, b – before)

indexes

Air	air
CNG	compressed natural gas
DF	diesel fuel
GF	gas fuel