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Effect of nitrON® cetane-detergent additive to B7 fuel on energy parameters and exhaust gas composition of a 6Dg locomotive with a Caterpillar C27 engine

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In order to avoid the negative effects of increasing the amount of RME in the fuel, the nitrON® package was used, containing 3 different additives: stabilizing, washing and increasing the cetane number of the fuel. The tests were carried out with the use of the Caterpillar C27 engine of the 6Dg locomotive connected to a water resistor. The hourly engine fuel consumption (FC), NO_x concentration and exhaust opacity were measured for 3 points of the F test, in accordance with UIC 624. The concentration of the nitrON® additive in the test fuel was 1500 ppm (v/v). For idling, the reduction in FC value was only 1.5% (in relation to the base fuel), but for a very high engine load and nominal rotational speed, the percentage reduction in FC was as high as 5%. The reduction of NO_x concentration for idling (as a result of using nitrON®) was approx. 10%, while for high engine load, the percentage reduction of NO_x concentration in the exhaust gas exceeded 15%.

Key words: *diesel engine, biofuels, fuel additive, exhaust gas composition*

1. Introduction

In line with the strategy adopted by the European Union regarding the content of biofuels in conventional fuels, in the near future, we should expect an increase in the content of rapeseed oil methyl esters (RME) from the current (April 2021) obligatory concentration of 7% (v/v) to the content of 10%. Unfortunately, the increase in the amount of vegetable oil methyl esters in diesel fuel is related, inter alia, to a reduction in the stability of such fuel during storage, increased fouling of the combustion chamber and fuel atomizer, and an increased concentration of nitrogen oxides (NO_x) in the engine exhaust gas [9]. In this case, the increase in NO_x emissions in the exhaust gas results mainly from the influence of RME on the extension of the autoignition delay (τ_c), which is then associated with an increase in the maximum value of the heat release rate in the kinetic phase of combustion (which in turn leads to an increase in the maximum combustion temperature). Therefore, in order to avoid the aforementioned negative effects of increasing the RME content in the fuel (up to 10%), a special package of additives (under the trade name nitrON®) was used to stabilize, clean and increase the cetane number (LC). Earlier studies conducted at the Poznań University of Technology on the John Deere 6630 tractor engine [1] and at the Cracow University of Technology on the VW 1.9 TDI diesel engine mounted on passenger cars and vans showed the beneficial effect of this additive package (nitrON®) in terms of reducing the NO_x concentration in the exhaust gas, and a slight reduction in hourly fuel consumption compared to fuel without these additives [2, 3]. The purpose of this study was to determine whether the positive effect of the nitrON® additive package on the reduction of nitrogen oxide emissions (NO_x) and the reduction of hourly fuel consumption (FC) will be confirmed in the case of using the nitrON® package for the fuel supplying a larger locomotive diesel engine with a modern design. For this purpose, the Caterpillar C27 engine of the 6Dg locomotive was tested, which is a modernized SM42 locomotive with an engine produced by Cegielski-Poznań. The modernized unit also uses a V-shaped engine, but already a 12-cylinder (not 8-cylinder), with a displacement of only 27.0 dm^3 (not 81.6 dm^3) and a power of 560 kW (instead of 530 kW) with a common rail fuel system (in the previous version, sectional injection pumps were used). The 6Dg locomotive was connected to a water resistor and it was used to measure the hourly fuel consumption of the engine (fueled with B7 fuel and B7 + nitrON® with a concentration of 1500 ppm), NO_x concentration and exhaust smoke for 3 test points F, following UIC 624 (Directive 2004/26/EC) [4, 5].

2. Methodology of applied research

2.1. Characteristics of the fuels used

As mentioned in the Introduction, the base (reference) fuel was diesel oil containing 7% (v/v) RME, the basic physico-chemical parameters of which are presented in Table 1. After the modification (adding 1500 ppm of the nitrON® additive package), some parameters favorably changed so the resulting test fuel. The nitrON® add-on package affects three groups of parameters:

- cetane number.
- detergent/dispersing properties
- oxidative stability

A substance used in petrochemicals to increase the LC value is 2-ethylhexyl nitrate (2-EHN) – NITROCET50®. This compound is formed in the process of esterification of 2-ethylhexanol with nitric acid and is classified as an aliphatic nitroesters. During the combustion process, 2-EHN breaks down to form free radicals. These, in turn, react with the fuel, reducing its thermal stability and thus accelerating the decomposition of the fuel. This, in turn, translates into easier ignition of the fuel in the cylinder and the mentioned reduction of the time between the initiation of injection and the self-ignition of diesel fuel (reduction of the auto-ignition delay τ_c). On the other hand, the formation of free radicals (due to the addition of 2-EHN to the fuel) negatively affects the oxidation stability of the fuel, which accelerates the oxidation reaction of the sediment precursors in the fuel tank (unfavorable phenomenon). The substances that act as detergents in the nitrON® package are derivatives of succinic acid imides. They are characterized by the fact that one of their ends is highly polarized, thanks to which it has an affinity for the metal elements of the fuel system and the formation of a film that prevents the accumulation of impurities. The other end of the chain is non-polar, which makes it possible to mix with the fuel. These properties are very important, especially in modern supply systems, where due to the small diameter of the spray nozzles, they are prone to the accumulation of deposits.

Compounds from the group of phenols or polyphenols, often with steric hindrance, are most often responsible for the antioxidant and stabilizing effect. The mechanism of action of these compounds consists, among other things, in inhibiting unfavorable polymerization reactions, which can lead to the formation of gums and deposits in the fuel, by capturing reactive free radicals which, reacting with oxygen, trigger a cascade of chain reactions.

Table 1. Characteristics of the used fuels

Property	Unit	B7 fuel	B7 + nitrON®
		base fuel	test fuel
Cetane number	–	51.8	59.6
Density at 15°C	kg/m³	840.6	840.6
PAH Content	% (m/m)	2.3	1.1
Sulphur content	mg/kg	7.1	7.2
Manganese content	mg/l	< 0.5	< 0.5
Self-ignition temperature	°C	64.5	64.5
Coking residue (from 10% distillation residue)	% (m/m)	0.01	0.016
Water content	mg/kg	70	105
Solid impurity content	mg/kg	< 12	6
Copper corrosion test (3 h, 50°C)	–	1	1
Oxidation stability	g/m³	3	6
Oxidation stability [110°C] (Rancimat)	h	> 20	23.1
Lubricate, corrected diameter of the wear scar, [60°C]	µm	380	165
Kinematic viscosity [40°C]	mm²/s	2.45	2.64
Fractional composition distils up to 250°C distils to 350°C 95% (V/V) distils to temp.	 % (v/v) % (v/v) °C	 41.0 95.0 349.0	 40.0 96.0 345,0
Content of fatty acid methyl esters (RME)	% (v/v)	7	7
Content after aching	% (m/m)	0.001	< 0.001

Among the aforementioned properties of fuel additives, detergent properties are also important, preventing the phenomenon of coking of fuel atomizers and the accumulation of impurities on the walls of the combustion chamber. The detergency properties of fuel additives become more important the greater the share of biocomponent in it because it is more susceptible to the oxidation process than conventional hydrocarbon fuels. The oxidation of such fuels increases the formation of products that contribute to the accumulation of pollutants in the combustion chamber. The increased presence of 2-EHN in the fuel also contributes to the reduction of oxidative stability in the biofuels (however, not all studies confirm this fact [8]). For this reason, both additives increasing oxidative stability and detergent additives are extremely important when using fuels containing the RME additive. The above-described tasks are carried out through multi-functional additives, which also include the nitrON® package.

The main recipients of the nitrON® additive package are users of off-road machinery, with particular emphasis on mining, agricultural and construction machinery, ships and boats as well as locomotives. For this reason, the research presented in this article concerns the impact of using the nitrON® package for the fuel supplying the locomotive engine of the modern structure.

2.2. Measurement station

The hourly fuel consumption and exhaust gas composition measurements of the Caterpillar C27 engine powered by B7 fuel and B7 fuel with the addition of the nitrON® package (in the 6Dg locomotive) were carried out in Polkowice, on November 21, 2020. The 6Dg locomotive is a modernized version of the SM 42 locomotive with an engine produced by Cegielski-Poznań (Poland). For comparison, the basic technical parameters of both engines are presented in Table 2.

Table 2. Parameters of combustion engines used in the 6Dg locomotive and the SM42 locomotive (before modernization 6Dg)

Engine type	C27	a8C22
Applied in a locomotive	6Dd	SM42
Manufacturer	Caterpillar	H. Cegielski Poznań
Circuit	four-stroke	
Type of fuel ignition	self-ignition	
Fuel supply system	common rail	section pump
Air supply system	Turbocharger	
Intercooler	yes	no
Arrangement/number of cylinders	forked/ 12 cyl.	forked/ 8 cyl.
Displacement volume [dm^3]	27.0	81.6
Rated power [kW]	560	530
Rated speed [rpm/min]	1800	1000
Compression ratio [–]	16.5	13.5
Medium effective pressure p_e [MPa]	1.75	0.86
Volumetric power indicator N_l [kW/dm^3]	20.7	6.49
Massive power indicator N_m [kW/kg]	0.186	0.073
The mass of the combustion engine [kg]	3004	7300
Cylinder diameter D [mm]	137	220
Piston stroke S [mm]	152	270
Ratio S/D	1.11	1.23
Average piston speed $c_{śr}$ [m/s]	9.12	9.00

The measurements of the engine performance parameters of the CAT C27 locomotive 6Dg were carried out consecutively in 3 points of the F test following the UIC 624 regulation. This test is mainly used for approval tests of locomotive engines but is also very well suited for testing various fuels, as it includes both idling (low combustion temperature) and full engine load at nominal speed (high combustion temperature). The engine operating points for test F are shown in Fig. 1.

The engine load resulting from the successive points of test F was carried out with the use of a water resistor, the general view of which is shown in Fig. 2.

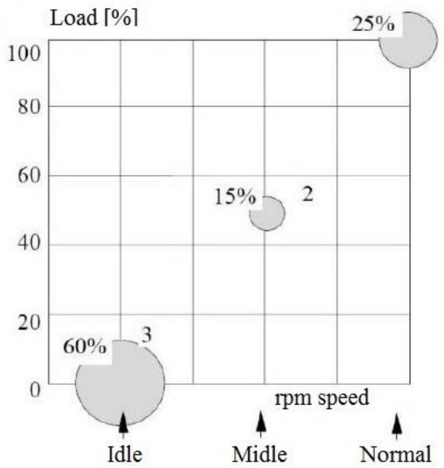

Fig. 1. Schematic of the F test run according to UIC 624 [4]

Fig. 2. General view of the water resistor

The rotational speed of the internal combustion engine was determined employing onboard measurement systems, as shown in Fig. 3.

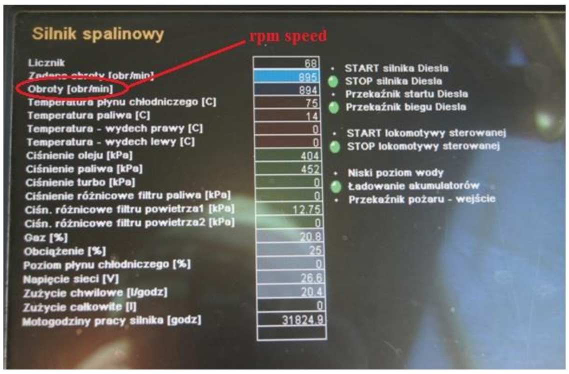

Fig. 3. General view of the onboard measurement system

In this case, the measurement of the exhaust gas composition, following the client's requirements, was limited to determining the concentration of nitrogen oxides (NO_x) with a diagnostic analyzer and smoke opacity with a Bosch opacimeter. A general view of the exhaust gas sampling from the locomotive exhaust system is shown in Fig. 4.

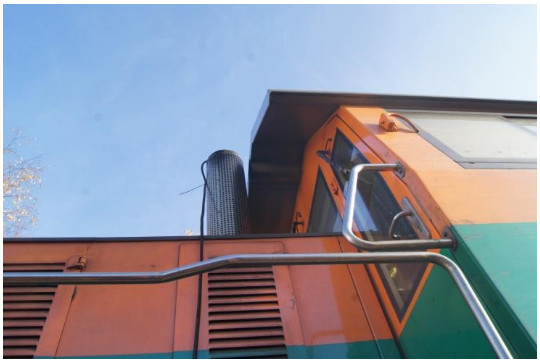

Fig. 4. General view of the exhaust gas sampling from the locomotive

To measure the fuel consumption, a measuring system was applied which is an integral part of the 6Dg locomotive used in the tests (based on 2 hydrostatic probes in the fuel tank, with fuel temperature correction). Data from this measurement system (in the form of measurement screen prints) for 2 tested fuels (base and test) and 3 test points F are presented in Fig. 5–10.

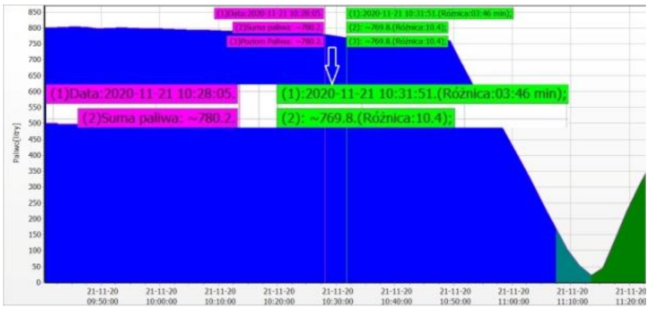

Fig. 5. Measurement of the hourly fuel consumption FC [l/h] of a CAT C27 engine (6Dg locomotives) without additive. Test F, point ❶

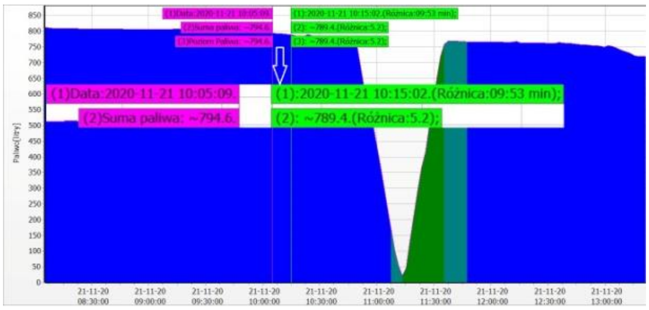

Fig. 6. Measurement of hourly fuel consumption FC [l/h] of a CAT C27 engine (6Dg locomotives) without additive. Test F, point ❷

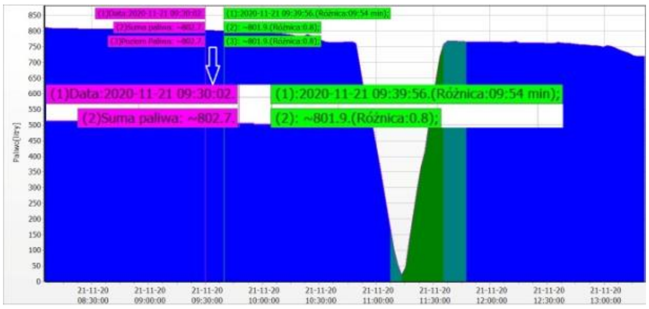

Fig. 7. Measurement of hourly fuel consumption FC [l/h] of a CAT C27 engine (6Dg locomotives) without additive. Test F, point ❸

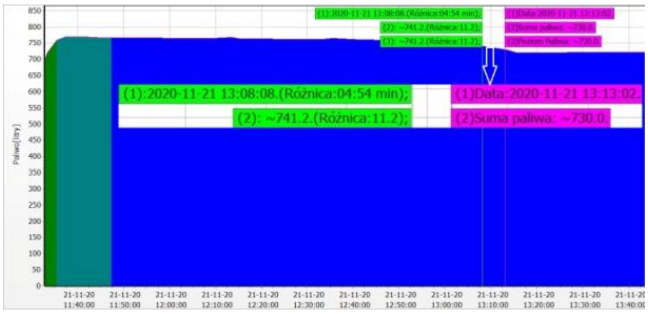

Fig. 8. Measurement of hourly fuel consumption FC [l/h] of a CAT C27 engine (6Dg locomotives) with additive. Test F, point ❶

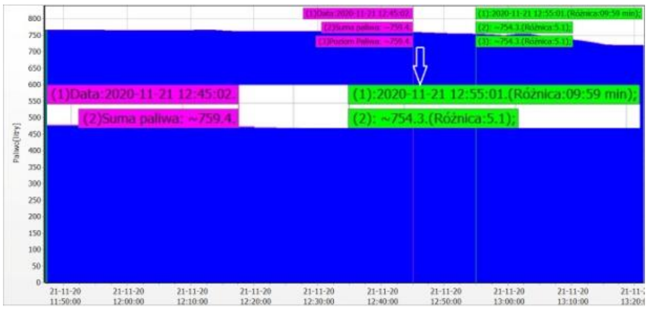

Fig. 9. Measurement of hourly fuel consumption FC [l/h] of a CAT C27 engine (6Dg locomotives) with additive. Test F, point ❷

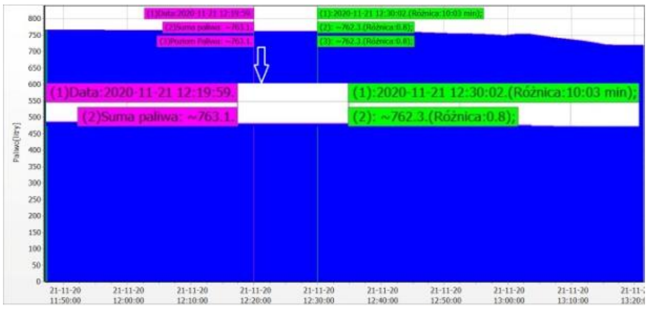

Fig. 10. Measurement of hourly fuel consumption FC [l/h] of a CAT C27 engine (6Dg locomotives) with additive. 1800 rpm. Test F, point ❸

3. Results

3.1. Engine energy parameters

In the tests carried out on the water resistor of the 6Dg locomotive with a Caterpillar C27 engine fueled with B7 fuel with/without the nitrON® additive package, the hourly fuel consumption (FC) was measured at 3 points of the F test as described in point 2.2 of this publication. The data from these measurements are included in Table 3 and the percentages of the base fuel in Table 4. This is shown in graphical form in Figs. 11 and 12.

Table 3. Values of parameters set and measured in test F for the 6Dg locomotive with a C27 engine fueled with the tested fuels

Fuel	point Test F	n	N_{el}	V_{pom}	t_{pom}	**FC**	**NO_x**
		[rpm]	[kW]	[dm^3]	[s]	**[kg/h]**	**[ppm]**
Base	1	1800	500	10.4	230	**162.78**	**240**
	2	1200	95	5.2	593	**31.57**	**190**
	3	650	0	0.8	594	**4.85**	**8**
Test	1	1800	500	11.2	261	**154.48**	**175**
	2	1200	95	5.1	599	**30.65**	**160**
	3	650	0	0.8	603	**4.78**	**7**

Table 4. Percentage reduction of fuel consumption FC and NO_x concentration in the exhaust gas as a result of using nitrON® additive to fuel

point Test F	n	N_{el}	**FC**	**NO_x**
	[rpm]	[kW]	**[%]**	**[%]**
1	1800	500	**5.1**	**15.1**
2	1200	95	**2.9**	**13.2**
3	650	0	**1.5**	**11.0**

From the relative reduction in the hourly consumption of the test fuel (with nitrON® additive package) compared to base fuel B7, illustrated in Fig. 12, it can be seen that the FC efficiency of this additive package increases with increasing engine load.

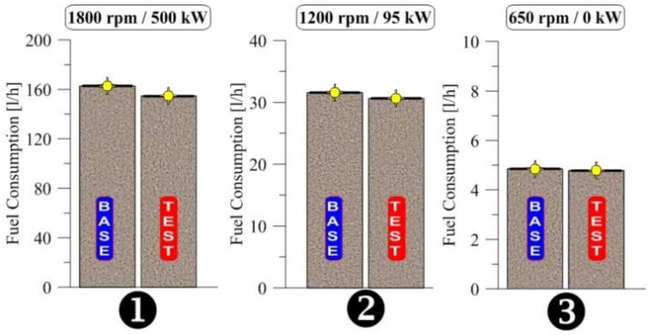

Fig. 11. Hourly fuel consumption FC [l/h] of the CAT C27 engine powered by the base fuel (BASE) and the base fuel with nitrON® (TEST), for 3 test points F (❶❷❸)

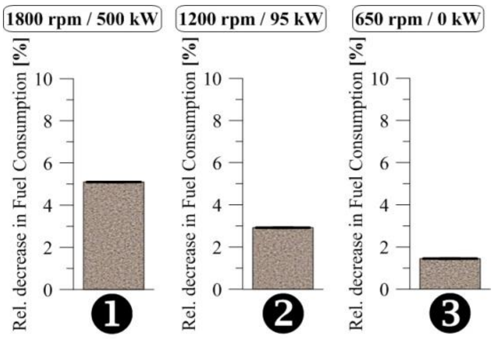

Fig. 12. The relative decrease in hourly fuel consumption [%] of the CAT C27 engine powered by the base fuel (BASE) and the base fuel with nitrON® (TEST), for 3 points of test F (❶❷❸)

As the applied nitrON® additive package does not affect the calorific value of the fuel, the only reason why the FC value for the test fuel is reduced in relation to the base fuel is then to increase the value of the overall efficiency (η_o) of the engine. Such a situation occurs when the applied method influences a different course of the heat release rate ($dQ/d\alpha$) as a function of the crankshaft rotation angle of the engine. An exemplary $dQ/d\alpha$ diagram for a diesel engine is shown in Fig. 13.

In order to increase the efficiency of the combustion process (reduce fuel consumption), it would be necessary (by changing design, regulatory or fuel parameters) to make:

1. the end of combustion (α_{ec}) of fuel in the engine cylinder was earlier,
2. the duration of the combustion process (α_c) of the fuel in the engine cylinder was lower.

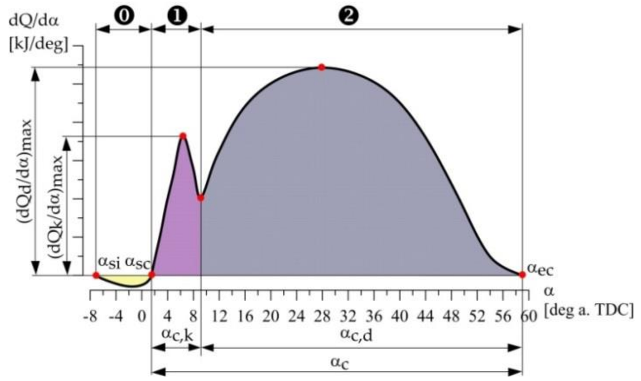

Fig. 13. Heat release rate in the cylinder of the diesel engine [7]: ⓿ – fuel evaporation phase, ❶ – kinetic combustion phase, ❷ – diffusion combustion phase

The earlier end of fuel combustion may be due to higher average combustion rate or earlier onset of fuel auto-ignition (α_{sc}) – with the same fuel injection start (α_{si}), which is the same as shorter auto-ignition delay (τ_c) or earlier fuel injection start. As the tested nitrON® package does not change the fuel viscosity, the start of fuel injection is the same for both fuels (for the same engine operating point). Therefore, in the analyzed situation, a more favorable course of the heat release rate in the cylinder of the engine (from the point of view of thermal efficiency) fueled by the test fuel (compared to the base fuel) may be associated with a shorter auto-ignition delay and, therefore, an earlier start and end of the combustion process. As the main task of the nitrON® package is to shorten the auto-ignition delay and, at the same time, in the tests [2, 3, 6] carried out at the Cracow University Of Technology laboratory using the VW 1.9 TDI diesel engine powered by the same fuels, lower τ_c for the test fuel was confirmed (Fig. 14), it should be assumed that the more favorable dQ/dα mileage is related to the earlier end of the test fuel burn.

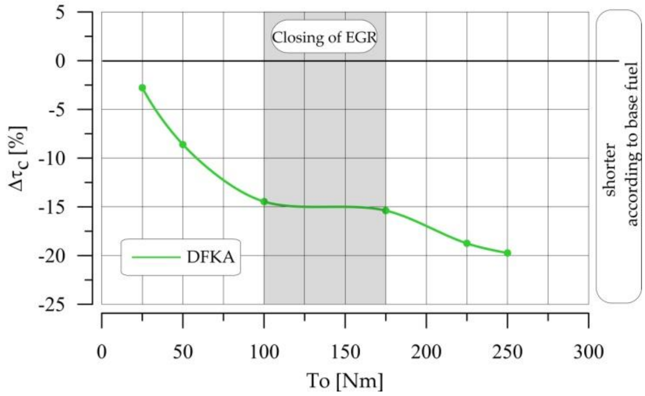

Fig. 14. Percentage difference in auto-ignition delay ($\Delta\tau_c$) of the VW 1.9 TDI engine fueled with test fuel in relation to the base fuel [7]

It can be seen from the data in Fig. 15 that the end of the test fuel (with nitrON® addition) burn is earlier in comparison to the base fuel under high engine loads. The earlier end of combustion reduces the heat loss carried out with the exhaust gas, which translates into an increase in thermal efficiency (η_t) for the test fuel.

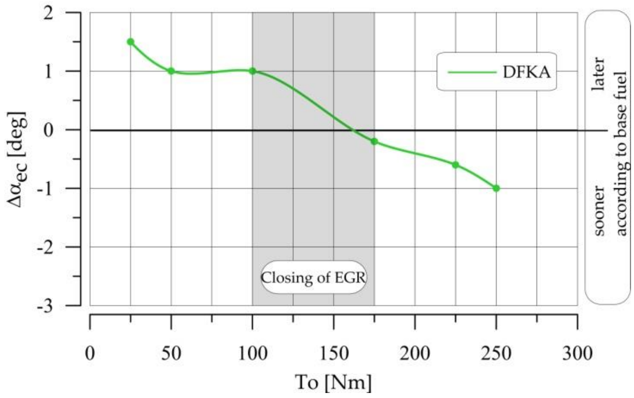

Fig. 15. Angular difference of the end of combustion ($\Delta\alpha_{ec}$) of the VW 1.9 TDI engine powered with the test fuel in relation to the base fuel [7]

In fact, the NITROCET50® additive in the nitrON® package reduces the heat release rate (as a result of shortening the auto-ignition delay), but the action of this additive in relation to dQ/dα is selective and does not reduce the average burning rate, but only reduces the maximum kinetic combustion rate. As can be seen from the diagram (Fig. 13), the kinetic combustion phase is very short compared to the diffusion combustion phase. Therefore, reducing ($dQ_k/d\alpha$) max does not extend the entire combustion process and therefore does not significantly affect the end of combustion.

Also, the analysis of the exhaust gas temperature carried out in the tests [7] (Fig. 16) shows that the engine fueled with the test fuel was characterized by a slightly lower exhaust gas temperature (approx. 2%) compared to the base fuel, which was confirmed by the earlier end of combustion.

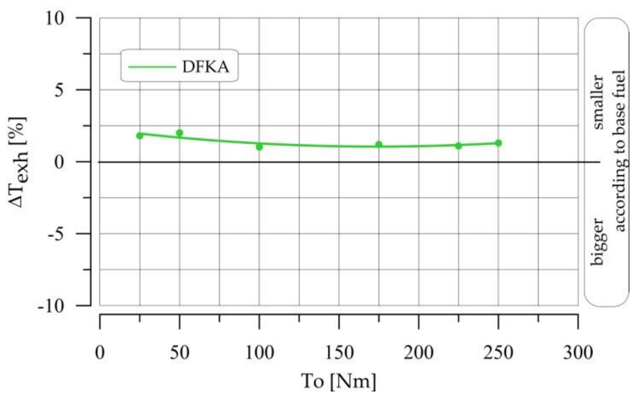

Fig. 16. Percentage difference in exhaust gas temperature of VW 1.9 TDI engine powered with test fuel in relation to base fuel [7]

The percentage differences in the values of the hourly fuel consumption (FC) in the individual points of the F test (at the same engine speed and load of the engine powered by both fuels) are the same as the percentage differences in the values of the overall engine efficiency (η_o).

The influence of the nitrON® package on the course of the rate of the heat release in the engine cylinder obviously influences the exhaust gas composition, as well.

3.2 Composition of exhaust gases

Due to the nature of the action of the NITROCET50® additive in the nitrON® package (reduction of the auto-ignition delay), the main component of the exhaust gas that was analyzed were nitrogen oxides (NO_x). The mechanism of NO_x and particulate matter (PM) formation shows that a decrease in NO_x concentration in the exhaust gas is usually accompanied by an increase in PM emissions (Fig. 17). As the measurement of particulate matter (PM) is difficult under the conditions of the measurements (on a water resistor), it was replaced with the determination of the degree of smoke opacity using the filtration method.

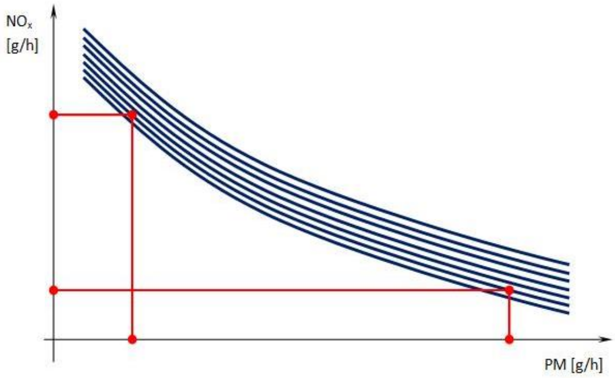

Fig. 17. Diagram of correlation between NO_x and PM emissions [7]

The effect of the nitrON® fuel package on the NO_x concentration in the exhaust gas (with respect to the tested fuels) is shown in Fig. 18. Since, similarly to the hourly fuel consumption FC, the effect of the engine load (points of test F) is greater than the effect of nitrON® on the NO_x concentration in the exhaust gas, then additionally, Fig. 19 shows the percentage changes of this parameter resulting in only from the effect of nitrON® (compared to the base fuel). The graphs show that irrespective of the engine operating point, the addition of nitrON® to the fuel causes a strong reduction of NO_x concentration in the exhaust gas (by several per cent) in relation to the engine fueled with fuel without this additive.

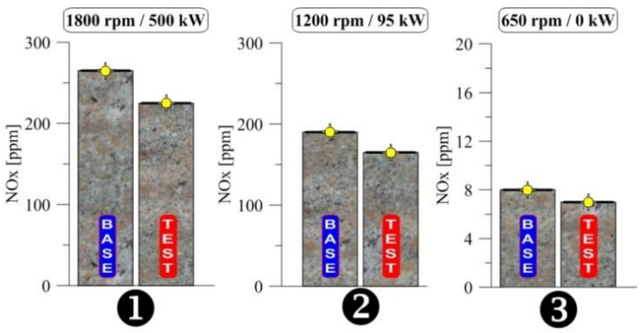

Fig. 18. The concentration of nitrogen oxides (NO_x) of the CAT C27 engine powered by the base fuel (BASE) and the base fuel with nitrON® (TEST), for 3 points of test F (❶❷❸)

Moreover, it should be noted that similarly to the hourly fuel consumption FC, the intensity of the reduction of the concentration of nitrogen oxides NO_x in the exhaust gas of the engine, due to the influence of the nitrON® package, is greater for the bigger engine loads (Fig. 19).

The mechanism of the formation of nitrogen oxides in the combustion process shows that the factors influencing their emission in the exhaust gases of the engine are:

- combustion temperature,
- oxygen availability in the combustion zone,
- reaction time (combining nitrogen with oxygen),
- the presence of reducing substances (eg. unburned hydrocarbons).

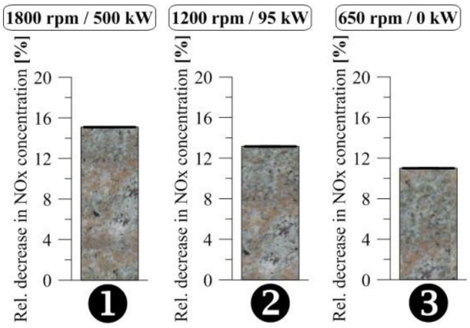

Fig. 19. Relative reduction of nitrogen oxides (NO_x) of the CAT C27 engine powered by the base fuel (BASE) and the base fuel with nitrON® (TEST), for 3 points of test F (❶❷❸)

Under the test conditions, at the same point of test F, only the combustion temperature changes are significant for the case of supplying the engine with test fuel in relation to the fuel supply. This is due to the influence of the nitrON® package on the reduction of the auto-ignition delay (τ_c), confirmed in the tests [2] – Fig. 14. The diagram shows that in the entire load range of the engine used at that time, the addition of nitrON® resulted in a reduction of the auto-ignition delay (compared to the base fuel). In a shorter time between the beginning of injection and the beginning of auto-ignition of the fuel (lower τ_c), a smaller amount of fuel is accumulated in the combustion chamber. In consequence, the auto-ignition of the smaller amount of fuel (until the start of combustion) leads to a less dynamic combustion process.

Consequently, a lower maximum heat release rate in the first, kinetic combustion phase is obtained, which, as is known, results in a lower maximum combustion temperature and a lower concentration of nitrogen oxides in the engine exhaust. For this reason, both in the tests [2, 3] and the studies covered by this publication, the beneficial effect of the nitrON® additive package in the test fuel was found on the reduction of NO_x concentration in the engine exhaust in relation to the base fuel (Fig. 18, Fig. 19).

According to the previous explanation, apart from the analysis of the influence of the nitrON® additive package on the NO_x concentration in the engine exhaust gas, the smoke opacity was also measured. The results of the exhaust smoke test, measured by the filtration method, for the engine powered by the base fuel and the test fuel, are shown in Fig. 20.

As expected and in the diagram shown in Fig. 17, at the points of the engine operation (test F) where the addition of the nitrON® package to the fuel resulted in a reduction of NO_x concentration in the engine exhaust gas, a slight increase in exhaust opacity was also observed. It should be emphasized that the percentage reduction in the concentration of nitrogen oxides in the exhaust gas (due to the use of the nitrON® package) is much greater than the increase in exhaust opacity. This is due to the aforementioned fact that the addition of NITROCET50® in the nitrON® package selectively affects the combustion speed, very intensively reducing the kinetic combustion speed $(dQ_k/d\alpha)_{max}$ right after fuel self-ignition, and only slightly reducing the maximum diffusion combustion speed $(dQ_d/d\alpha)_{max}$. Strong reduction of $(dQ_k/d\alpha)_{max}$ causes a large reduction of NO_x concentration in the exhaust gas. A slight reduction $(dQ_d/d\alpha)_{max}$ leads to a reduction in the amount of burnt-out, previously formed solid particles, which in the overall balance results in a greater emission of particulate matter (PM) and soot in the engine exhaust. This justifies a slight increase in exhaust smoke (as a result of using the nitrON® fuel package), especially at high engine loads.

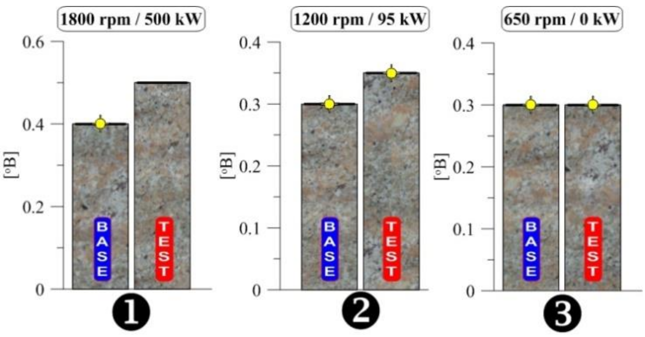

Fig. 20. The degree of the smoke exhaust of the CAT C27 engine powered by the base fuel (BASE) and the base fuel with nitrON® (TEST), for 3 points of test F (❶❷❸)

To sum up, in the overall balance of exhaust emissions, the addition of the nitrON® package to the fuel causes a very large reduction in NO_x concentration in the exhaust gas, at the cost of only a slight increase in exhaust opacity.

4. Conclusions

The conducted tests of the Caterpillar C27 engine of the 6Dg locomotive and the previous tests of the VW 1.9 TDI diesel engine [2, 3, 7], referred to in this article in order to facilitate the cause-effect analysis, authorize the presentation of the following, most important conclusions regarding the impact of the additives used in the nitrON® package on fuel on the parameters of the combustion process in a compression ignition engine (in relation to the base fuel). The addition of NITROCET50® in the nitrON® fuel package mainly resulted in:

1) a strong reduction of NO_x concentration in the exhaust gas (11–15%), which resulted from a significant reduction in the kinetic combustion speed,

2) a slight increase in PM emissions and exhaust smoke (about one percent), which is associated with a slight reduction in the rate of diffusion combustion,

3) a slight reduction in hourly fuel consumption (from one to nearly five percent). Since the calorific value of both tested fuels was the same, the increase in the overall efficiency of the engine, which resulted in a slight reduction in the test fuel consumption, resulted only from the improvement of the combustion process at that time (as well as for the exhaust gas composition). The addition of NITROCET50® in the nitrON® package resulted in an earlier end of combustion (due to earlier fuel self-ignition), which led to a reduction in exhaust heat loss,

4) the increase of the effectiveness of the nitrON® package to the fuel in relation to the reduction of the NO_x concentration in the exhaust gas and the increase in the overall efficiency of the engine together with the increased engine load. This is most likely related to the combustion temperature.

5) as stated in the research [7], there is a possibility of synergistic interaction of the nitrON® package (reducing the speed of kinetic combustion) with the addition of Reduxco® – DAGAS, Poland (increasing the heat of combustion in the diffusion phase) to simultaneously reduce NO_x and PM emissions.

Nomenclature

$(dQ_d/d\alpha)max$	max rate of diffusive combustion
$(dQ_k/d\alpha)max$	max rate of kinetic combustion
$dQ/d\alpha$	rate of heat release
NOx	concentration of nitrogen oxides
FC	hourly fuel consumption
n	engine rotation speed
η_o	overall engine efficiency
η_t	thermall engine efficiency
α_{sc}	start of fuel self-ignition
α_{si}	start of fuel injection
RME	rapeseed methyl ester (FAME)
PM	emission of Particulate Matter
τ_c	self-ignition delay
LC	cetane number
α_{ec}	end of combustion

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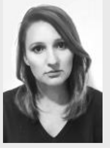

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