Effect of Diesel Fuel Temperature on the Nitrogen Oxides Emission from a Compression-Ignition Engine

Mirosław Czechlowski[1*], Weronika Gracz[2], Damian Marcinkowski[2], Wojciech Golimowski[3], Jakub Mazurkiewicz[1]

[1] Faculty of Agronomy and Bioengineering, Poznań University of Life Sciences, ul. Wojska Polskiego 28, 60-637 Poznań, Poland

[2] Department of Biomass processing Technologies, Institute of Technology and Life Sciences, ul. Biskupińska 67, 60-463 Poznań, Poland

[3] Wroclaw University of Economics and Business, Department of Agricultural engineering and Quality Analysis, ul. Komandorska 118/120, 53-345 Wrocław, Poland

* Corresponding author's e-mail: m.czechlowski@up.poznan.pl

ABSTRACT

The research aimed at analysing the influence of the diesel oil temperature on the NO_x emission level. The tests were carried out on a test stand equipped with a 9.5 kW multi-fuel compression-ignition engine. The setup constitutes an experimental cogeneration unit discharging the produced energy into the power grid. The measurements were carried out under the D1 test procedure provided by ISO 8178–4 for testing engines operating at a constant speed. As a result of statistical analysis of the results obtained, significant differences were found in the u specific values of the nitrogen oxides emission gained for particular phases of D1 tests, when the engine was fed with diesel fuel of different temperatures. The results obtained confirmed the possibility of limiting the specific emission of NO_x only when the engine is running at 75% of its nominal torque. An increase in the NO_x emissions was recorded for the remaining loads.

Keywords: compression-ignition engine, NO_x emissions, fuel temperature

INTRODUCTION

Internal combustion engines are still used as the primary source of propulsion for mobile machines; simultaneously, they are also responsible for the emission of toxic air pollutants. One of the most harmful compounds present in the exhaust gas corresponds to nitrogen oxides (NO_x). As a result of the improved efficiency of diesel engines, achieved by increasing the pressure and temperature in the cylinders, the NO_x concentration in the exhaust gases also increased significantly. The use of exhaust gas aftertreatment systems reducing the emission of particulate matter (PM) and NO_x has become obligatory, enforced by the combustion emission standards adopted in the USA and Europe [Blakeman et al. 2003]. The first solutions used to reduce the NO_x emissions were the exhaust gas recirculation (EGR) systems [Kouremenos, Hountalas, and Binder 2001; Hountalas et al. 2006; Kono, Kobayashi, and Takeda 2005]. Due to the increasingly restrictive regulations, the reduction of the NO_x emissions has been the subject of many ongoing studies. As a result, it was found that the catalysts for exhaust gas purification or biofuels used instead of conventional fuels are effective methods for reducing the emission of harmful gases [Hochhauser 2009; Johnson 2014].

The use of catalysts with platinum (Pt) and rhodium (Rh) coatings has yielded very good results under stabilized conditions, even in the presence of sulphur. The NO_x reduction efficiency reached 80% [Uekusa et al. 2003]. Different configurations of several serially operating catalysts were studied. They have been proven to work at low exhaust temperatures below 200°C, which is difficult to achieve with traction engines

[Tsukamoto et al. 2012]. Adsorption catalysts are deactivated over time by filling them with the molecules separated from exhaust gases. This problem has been solved by using a catalytic diesel particulate filter (CDPF), which cleans itself automatically as a result of a richer fuel mixture (Colliou et al. 2004). Another solution for the maintenance-free catalyst is a selective catalytic reduction (SCR), which requires atomisation of the urea solution (AdBlue) in the exhaust gas. Urban cycle tests showed a 60% NO_x reduction efficiency achieved by SCR [Saito et al. 2003]. The concept of combining the SCR catalysts with DPF was also developed. A new catalytic system called CRDPF was tested. The advantage of this solution is the high efficiency and versatility of systems for various types of diesel engines [Conway et al. 2005, Hosoya et al. 2007]. An alternative to the use of the AdBlue solvent is an NSR system with afterburning of the exhaust gas in a catalytic system, using an additional dose of fuel. Positive results have been obtained, but this solution generates an increase in the fuel consumption [Tsumagari et al. 2006]. One of the maintenance-free solutions that do not require additional catalyst power is the DPNR system. Its efficiency of 99% NO_x reduction has been confirmed in D1 simulation tests for power generators [Parthiban and Jain 2019, Ohashi et al. 2008].

Another solution is to modify the fuel or replace it with the fuels from renewable sources. Adding water in the form of emulsion with the fuel, or injecting it directly into the cylinder, results in a significant reduction in the nitrogen oxide emissions [Hountalas et al. 2006]. The replacement of diesel fuel by rapeseed oil methyl esters (RME) in an engine equipped with NSR/DPNR/Oxidation catalysts has increased the NO_x emissions [Kawano et al. 2006]. This result was confirmed by other tests carried out on the engines not equipped with NO_x reducing catalysts [Veltman, Karra, and Kong 2009]. Moreover, the use of FAME-type biofuels from various oils, including waste cooking oils (WCO) results in an increase in the NO_x emission [Okamoto et al. 2010, Gysel et al. 2014]. In the case of replacing the diesel fuel by untreated rapeseed oil and hydrogenated rapeseed oil (HVO), the NO_x emissions also increased with the rise in engine load. At the same time, a decreasing proportion of NO_2/NO_x [Czerwinski et al. 2008, Mizushima et al. 2012] and NO/NO_x were observed [Wu et al. 2017].

The use of efficient exhaust aftertreatment systems generates additional costs in the production and subsequent operation of engines. These costs, particularly in the case of the units with relatively low horsepower, may be difficult for buyers to accept. At the same time, the introduction of alternative fuels does not bring the expected results. For these reasons, the study aimed at changing the parameters of the diesel fuel injected into the cylinder of the diesel engine was undertaken. The first modification applied involved preheating the fuel and assessing the effect of the temperature changes on the level of emitted NO_x. The study is inspired by the results indicating a reduction in the NO_x emissions from diesel engines using pre-heated biofuels, such as vegetable oils, animal fats and vegetable oil esters [Kleinová et al. 2011; Ranjith, Velmurugan, and Thanikaikarasan 2019].

MATERIALS AND METHODS

Test bench and procedures

The tests were carried out using the ATMX 2000 engine dynamometer, which is a laboratory cogeneration unit equipped with Yanmar 2TNV70-ASA engine (Fig. 1). The engine is a naturally aspirated, two-cylinder unit with indirect injection and a displacement of 570 cm^3. The engine uses a head with pre-combustion chambers, and its nominal power is 10.2 kW achieved at 3600 rpm. The setup is controlled by an automatic control and measurement system operated by Parm PC software. The electricity produced by the setup during the tests was transferred to the electrical grid through an inverter system.

The VARIOplus Industrial exhaust gas analyser manufactured by MRU was used to measure the concentration of nitrogen oxides (NO and NO_2) in the exhaust gas. The device is equipped with a heated probe wire to ensure correct measurements. The measurement of NO and NO_2 concentrations is performed by the analyser using electrochemical sensors. The measurement of the exhaust gas flow is carried out by means of a Pitot tube placed in a measuring exhaust channel of known diameter. The ranges of the measured values are listed in Table 1.

The measurements were carried out according to ISO 8178–4 standard, following the D1 test intended for stationary engines operating at
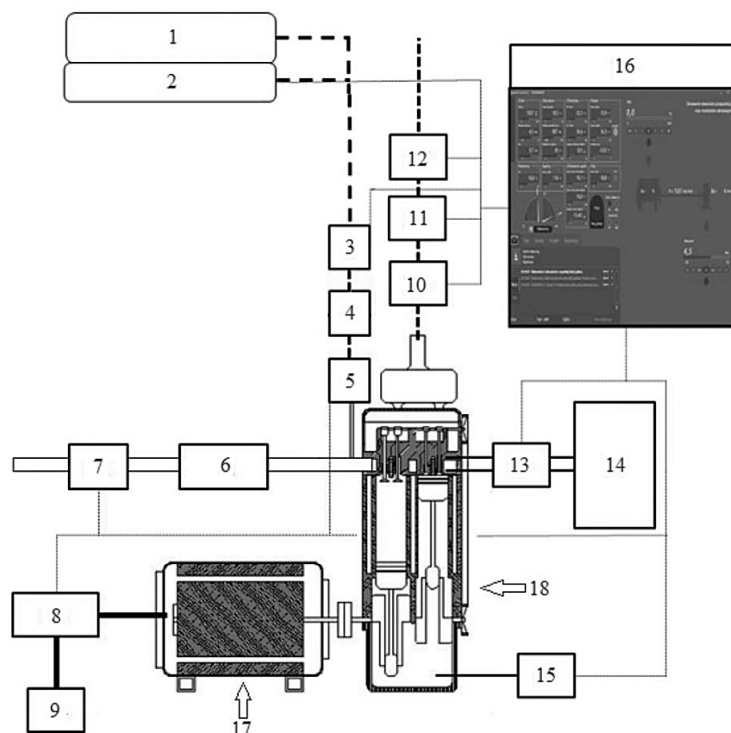
Fig. 1. Test bench: 1 – diesel oil tank, 2 – alternative fuel tank, 3 – fuel mass flowmeter, 4 – fuel temperature control system, 5 – fuel temperature sensor, 6 – air filter, 7 – temperature, pressure and humidity measurement, 8 – electric control and measurement system, 9 – electrical grid, 10 – exhaust gas temperature sensor, 11 – exhaust gas analyzer, 12 – exhaust gas volume flowmeter, 13 – heat measurement, 14 – cooling system, 15 – oil temperature sensor, 16 – measurement and control system, 17 – asynchronous electric motor, 18 – Yanmar 2TNV70-ASA engine [own elaboration based on Gracz 2018]

a constant speed. The D1 test consists of three measurement phases during which the engine operates under the corresponding load: 50%, 75% and 100% of the nominal torque. For the Yanmar 2TNV70-ASA engine and the cogeneration unit nominal speed of 3000 rpm, these load levels correspond to torques of 14.0, 21.0 and 28.0 Nm, respectively. Each phase of the D1 test lasts 10 minutes. The measurement is carried out for the last 3 minutes of the phase, and a period of 7 minutes before the start of data recording is designed to stabilise the engine parameters. During each measurement, the data on the concentrations of nitrogen oxides were recorded 35 times, with sampling every 5 s.

The measurements were taken three times, each time carrying out a D1 test for a different temperature of fuel supplied to the engine. The following fuel temperatures were used during the tests: 20, 40 and 55ºC. These temperatures are achieved by heating the fuel with a laboratory heat exchanger. It was supplied with water of appropriate temperature prepared by a laboratory thermostat with a microprocessor controller. The fuel temperature measurement was carried out using a temperature sensor installed directly in front of the injection pump. This sensor is connected to the measuring system of the dynamometer.

During the research, Ekodiesel ULTRA diesel oil, produced by the Polski Koncern Naftowy Orlen, was used as engine fuel. This fuel meets the requirements of the standard PN-EN 590 and may contain up to 7% bio-components.

Table 1. Selected measuring ranges of the VARIOplus Industrial exhaust gas analyser

Measured parameter		Measuring range	Measuring error
NO	nitrogen oxides (II)	0 – 1000 ppm Overload 5000 ppm	± 5 ppm or 5% < 1000 ppm 10% > 1000 ppm
NO_2	nitrogen oxides (IV)	0 – 200 ppm Overload 1000 ppm	± 5 ppm or 5% < 200 ppm 10% > 200 ppm
Exhaust gas flow speed		1 – 100 m/s	± 1 m/s or 3% measured value

Data processing

The analysis of the obtained results had to be started with determining the total concentration of nitrogen oxides in the exhaust gases. To this end, the values obtained for the NO and NO_2 concentrations must be added together by the following equation:

$$S_{NO_{xi}} = S_{NO_{2i}} + S_{NO_i} \qquad (1)$$

where: S_{NOxi}– total concentration of NO_x [mg/nm^3],
S_{NO2i} – NO_2 concentration in the exhaust [mg/nm^3],
S_{NOi} – NO concentration in the exhaust [mg/nm^3].

Second, the average values of total NO_x concentration were determined for each phase of the D1 test.

$$\overline{S_{NO_x}} = \frac{\sum S_{NO_{xi}}}{n} = \frac{S_{NO_{x1}} + S_{NO_{x2}} + .. + S_{NO_{xn}}}{n} \qquad (2)$$

where: $\overline{S_{NO_x}}$ – average of the total NO_x concentration from each phase of the D1 test [mg/nm^3],
$S_{NOx1}, S_{NOx2, ..,} S_{NOxn}$ – total concentration of NO_x values for each data record [mg/nm^3],
η – number of records stored for each test phase.

For the values obtained using the above-mentioned procedure, the Fisher test was carried out to confirm that the averages of the aggregated NO_x emissions obtained for different fuel temperatures differ statistically significantly. To this point, homogeneity of variance tests and variance analysis were performed. Then, detailed hypotheses were made. The null hypothesis, assuming that the averages do not differ significantly from each other, and the alternative hypothesis indicating significant differences in average values:

$$H_{0ii'}: \mu_i - \mu_{i'} = 0 \qquad i, i' = 1,2,3 \qquad (3)$$

$$H_{1ii'}: \sim H_{0ii'} \qquad i \neq i' \qquad (4)$$

The next step in the emission assessment, according to ISO 8178–4, was to compare the obtained average cumulative NO_x concentration values with the power generated by the engine during each phase of the D1 test. This resulted in specific emissions expressed in g·(kWh)$^{-1}$.

The calculations were carried out using the following formula:

$$N_{NO_X} = \frac{\overline{S_{NO_x}} \cdot \dot{V}}{P \cdot 1000} \qquad (5)$$

where: N_{NOx} – NO_x specific emissions [g·(kWh)$^{-1}$],
$\dot{V}$ – exhaust gas volume flow [nm^3·h^{-1}],
P – engine power [kW].

The final result of the D1 test is a weighted average of the NO_x emissions from all test phases calculated using the equation below:

$$N_{NO_xD1} = \overline{S_{NO_x50\%}} \cdot W_{50\%} + \overline{S_{NO_x75\%}} \cdot \\ \cdot W_{75\%} + \overline{S_{NO_x100\%}} \cdot W_{100\%} \qquad (6)$$

in which weighting factors $W_{50\%}$; $W_{75\%}$ and $W_{100\%}$ take values: 0.30; 0.50 and 0.20; respectively.

All the above-mentioned calculations, except the Fisher test, were made using the Microsoft Excel 2016 spreadsheet. The statistical tests were carried out using the Statistica 13.1 software package.

Finally, it was assumed that both: the specific emissions from the individual phases of test D1 and the final results of the weighted average from the whole test will be the basis for the assessment of the effect of the fuel temperature on the NO_x emissions.

RESULTS

As it was mentioned earlier, the tests were carried out for three temperatures of fuel supplied to the engine injection system (20, 40 and 55°C) and for three different levels of engine load (50, 75 and 100% of nominal torque). In total, nine measurement cycles were performed. The results were divided into three groups, depending on the engine torque load. For the data from each group, the average total NO_x emissions from each phase of the D1 test were determined and then the Fisher test was performed. In all 3 cases, with the assumed level of significance λ=0.05, the obtained statistic values prevented assuming the null hypothesis, with equal average values of NO_x emissions, as true. This allowed assuming an alternative hypothesis – that the average NO_x emission values are statistically significantly different – as true. On this

basis, it can be concluded that the changes in the temperature of the fuel supplied to the engine injection system have a significant impact on the NO_x emissions.

The statement above allowed for a more accurate assessment of the impact of the fuel temperature changes on the NO_x emissions. For this purpose, the results of the specific emission from the individual phases of the D1 test are shown in Figure 2. The first conclusion, which naturally appears when analysing the graph below, is that the changes in the fuel temperature have a much smaller effect on specific NO_x emissions than the changes in engine load. This is because the increase in the engine load from 50% to 100% results in reducing the specific NO_x emissions almost in half.

On the other hand, only one case of a positive influence of the fuel temperature increase on the NO_x emissions was found. It occurred when the engine was running at a load corresponding to 75% of the nominal torque. In this case, the increase in the fuel temperature from 20 to 55°C has reduced the specific NO_x emissions from 10.18 g·(kWh)$^{-1}$ to 9.86 g·(kWh)$^{-1}$, which corresponds to a change of just over 3%. For the other two torque loads, the temperature increase resulted in a proportional escalation in the NO_x emissions. Thus, for a load of 50%, an increase in the fuel temperature from 20 to 55°C caused a rise in the emissions of 0.09 g·(kWh)$^{-1}$, or 0.6% in relative terms. The intensification in

the NO_x emissions associated with increasing fuel temperature while the engine is running at full load is much more noticeable. In this case, a temperature increase of 35°C resulted in a rise in specific emissions of 0.95 g·(kWh)$^{-1}$. In relative terms, this corresponds to an increase in emissions of almost 14%.

Since the final results of the D1 test are most influenced by the phase in which the engine runs at 75% load, it is still necessary to analyse the averaged results, as shown in the diagram below. Moreover, in the case of these results, the increase in specific NO_x emissions associated with higher engine fuel temperatures is clearly visible. However, in reality, it ranges between 0.14 and 0.20 g·(kWh)$^{-1}$, which means an increase does not exceed 2.0%.

The results obtained during the course of the research indicate that the achievements of previous experiments, which confirmed the possibility of reducing NO_x emissions by preheating the biofuel supplied to the engine, cannot be directly transferred to the engines fuelled with standard diesel oil. [Kleinová et al. 2011; Ranjith, Velmurugan, and Thanikaikarasan 2019]. However, comparing the obtained results of specific emission with the results of the works on a similar subject [Pielecha 2001, Piaseczny and Władyka 2008], it can be concluded that the influence of diesel oil preheating on the NO_x emissions is determined by the engine design and power achieved from 1 dm^3 of displacement.
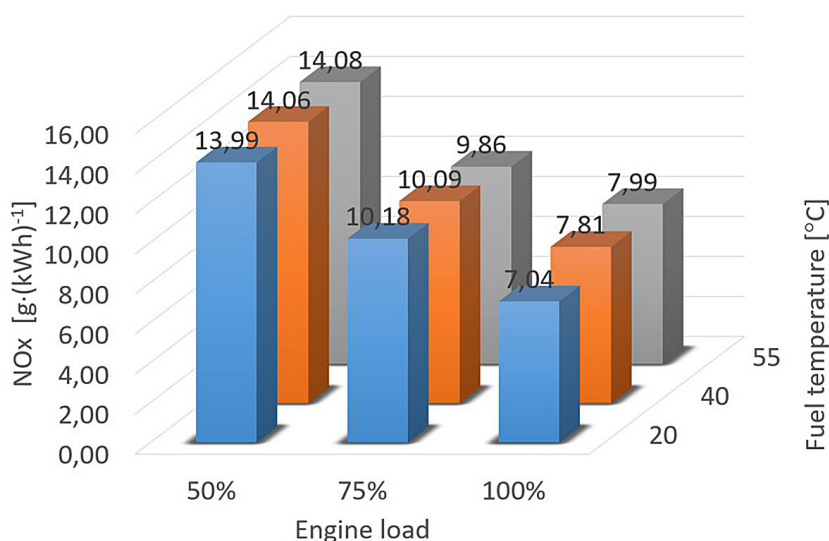

Fig. 2. Changes in specific NO_x emissions from individual phases of the D1 test according to ISO 8178–4 caused by variations in engine fuel supply temperature and load
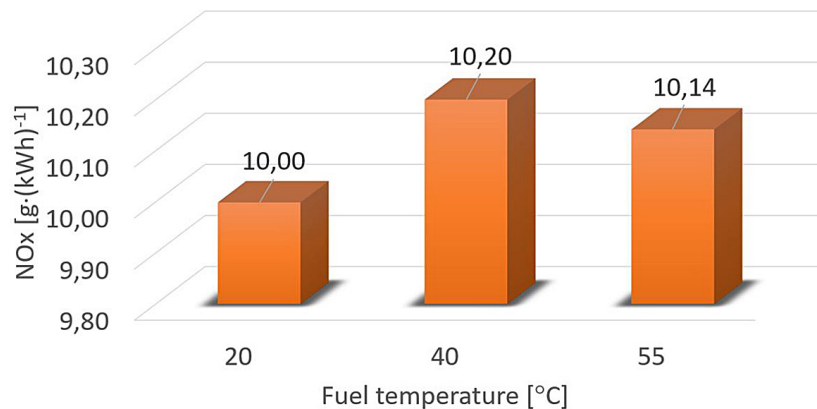
Fig. 3. Specific NO$_x$ emissions from the D1 test according to ISO 8178–4 obtained at different fuel temperatures.

CONCLUSION

On the basis of the results obtained, the following can be stated:

1. Regardless of the temperature of the diesel fuel supplied to the engine injection system, an increase in the engine load results in a significant reduction in specific NO$_x$ emissions.

2. Only when the engine was running at a load of 75% of the nominal torque, the beneficial effect of an increase in the fuel temperature on the NO$_x$ emissions was found. However, the increase in the fuel temperature from 20°C to 55°C resulted in a reduction of NO$_x$ by only 3%.

3. When the engine was running with both a lower and a higher load, an increase in the fuel temperature resulted in a simultaneous rise in specific NO$_x$ emissions, even by 14%.

4. On the basis of the above, it must be concluded that preheating of diesel oil cannot be an effective method of reducing the NO$_x$ emissions from the engines running on standard diesel fuel.

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