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REDUCTION OF NOx EMISSION OF A DIESEL ENGINE WITH A MULTIPLE INJECTION PUMP BY SCR CATALYTIC CONVERTER

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Abstract

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This paper deals with reduction of NOx-emission of a diesel engine with multiple injection pump by SCR catalytic converter. Main aim of the measurement was the detection of SCR catalyst converter efficiency. Tests were realized at the Research and Development workplace of Zetor Tractor a.s. Used engine was equipped with a multiple injection pump with electromagnetic regulator of a fuel charge. During the experiment selective catalytic reduction and diesel particulate filter were used as an after treatment of harmful pollutants reduction. Testing cycle of the eight-point test was chosen and Non-Road Steady Cycle (NRSC) was maintained according to 97/68/EC directive. Results confirmed the dependencies between temperatures of SCR catalyst and exhaust gases and the volume of exhaust gases on efficiency of SCR catalyst. During the operation load of the engine, selective catalytic reduction reached efficiency over 90 %. Used after treatment system is suitable for reduction of harmful pollutants according to the Tier 4f norm.

Keywords: SCR catalytic converter, reduction efficiency, temperature of exhaust gases

INTRODUCTION

Combustion in the cylinder of a diesel engine is physic-chemical complex process based on oxidation and reduction reactions. Fuel is burned under the rapid changes of a pressure and a temperature due to presence of the air oxygen. Mutual side reactions are in progress during the combustion process. As a result of burning of the air, various components are created in a different physical state. Combustion process is affected by thermal, shape and vortices characteristics of combustion engine and especially by method and quality of a fuel injection. According to former analysis, exhaust gases content consist up to 160 constituents (Bauer *et al.*, 2013). Exhaust gases can be divided into several categories. One of the classifications is into harmful and harmless substances. Elements such as N_2, O_2, H_2O and CO_2 belong to harmless category. Carbon dioxide is in this class because it is a final product of complete combustion. In the other hand this chemical composition is classified as a greenhouse gas (Vlk, 2003). It is estimated that combustion engines are responsible for more than 19 % of global production CO_2 emissions (Mustafa and Havva, 2009). Exhaust gases contain also harmful substances which are product of incomplete combustion process. Highest priority is devoted to carbon monoxide and unburned hydrocarbons (paraffin, olefin and aromatic hydrocarbons), partly burnt hydrocarbons (aldehyde, ketones), fission products (acetylene, ethylene, hydrogen and soot), carbon oxides NOx (nitric oxide, nitrous oxide and nitrogen dioxide) and also particulate matter (Čupera *et al.*, 2010). Amount of aforementioned substances is very small (diesel engine – 0.1 %), but due to their toxicity and negative impact on the Environment and human health are these substances monitored and their production is limited. Emission limits set the maximum allowance of monitored components of gaseous emissions and particulate matter amount in exhaust gases. They are established by country-specific government. Acceptance and formation of emission limits is directly affected by international organizations. Emission limits for tractors are determined according to engine power spectrum and for the validity period with usage of international unit of measurement $g.kWh^{-1}$. Among restricted and monitored amounts belongs carbon monoxide, hydrocarbons resp. volatile organic compounds HC, slurred particles PM and carbon monoxide NOx. European designation for emission limits Stufe, Phase or Etape is used. Tier is a designation for emission limits in the USA. (Bauer *et al.*, 2013)

There are many of harmful emissions influencing agents. Thermal, shaped and vortex properties of combustion chamber are one of the main one. Also the method and quality of injection process falls into the same category. Despite the usage of modern concepts of internal combustion engines, possibility of achieving of the appropriate emission standards without additional treatment of exhaust gasses is possible. Oxidation catalytic converter and selective catalytic reduction or exhaust gas recirculation with particles filter are one of the main methods for exhaust gases after treatment (Šmerda and Čupera, 2011). SCR technology is widely used with trucks, buses and coaches, agricultural and construction machinery, but nowadays car manufactures using this concept in passenger cars concept. These catalysts are used for reduction of NOx. Former reduction of nitrogen oxide was difficult and problematic. The most significant pollutants of diesel engines are NOx (Macek and Suk, 1996). Chemical reactions in SCR catalyst are initiated with the aid of reducing agent of ammonia NH_3. Nitrogen oxides are transformed into N_2 and H_2O. Reducing agent is delivered as a urea, respectively mixture of carbonic acid diamide with demineralized water. Amount of urea in demineralized water is 32.5 % (Bauer *et al.*, 2013).

The aim of the realized measurement was finding of nitrogen oxides reduction effectiveness with diesel engine equipped with multiple injection pump with SCR technology after treatment.

MATERIALS AND METHODS

The measurement was realized at the workplace of Research and Development of Zetor Tractors a.s. company. The engine was fitted with multiple injection pump with electromagnetic regulation of fuel charge. The combustion chamber was undivided and formed in the piston. During the measurement selective catalytic reduction (SCR) and diesel particulate filter (DPF) were used as an after treatment for harmful pollutants reduction of exhaust gases. Other selected parameters of the engine are available in Tab. I.

Measurement methodology – Non-road steady cycle (NRSC)

The measurement methodology is specified in annex 3 of Directive 97/68/EC, which relates to measures against the emission of gaseous and particulate pollutants from internal combustion engines of non-road mobile machinery. The directive defines gaseous pollutants as a carbon monoxide, total hydrocarbons and nitrogen oxides. Particulates are defined as all material retained on the defined filtration device after diluting the exhaust gases by clean filtered air. The temperature of the diluted exhaust gas has to be maintained between 315K (42 °C) and 325K (52 °C) immediately upstream of the filter holders. The test shall be carried out with the engine mounted on a test bench and connected to a dynamometer. The test cycle consists of a number of speed and torque (load) modes, which cover the typical operating range of

I: *Selected parameters of measured engine (manufacturer's data)*

Manufacturer	Zetor
Type	Z 1717
Nominal power [kW / HP] – ECE 24 R 03	103 / 140
Fuel system	multiple injection pump
Intercooling	air/air
Number of cylinders (disposition)	4 (inline engine)
Number of valves	16
Volume [cm3]	4,156
Nominal engine revolutions [rpm]	2,200
Idle [rpm]	800
Compression ratio	17
Fuel	diesel
Maximum torque [Nm]	585
Cooling	fluid
Emission standard	STAGE IV

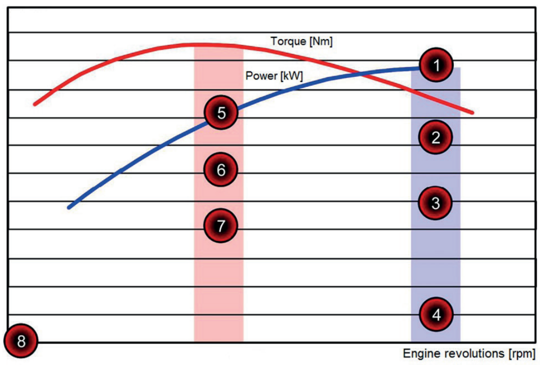
II: *Test cycle of the eight-point test for emissions measurement of the tractor engine*

Number of the point (mode)	Engine revolutions	Load percentage[2]	Weighting Factor
1	nominal	100	0.15
2	nominal	75	0.15
3	nominal	50	0.15
4	nominal	10	0.1
5	intermediate[1]	100	0.1
6	intermediate[1]	75	0.1
7	intermediate[1]	50	0.1
8	idle	-	0.15

[1] revolutions at maximum torque, which must be between 60 % and 75 % of nominal engine revolutions
[2] maximum of available torque at certain rpm

diesel engines. The test shall be performed in order of the mode numbers 1–8 as set out below in table II. The NRSC is identical with cycle C1 according to the norm ISO 8178-4 for engines of off-road vehicles with variable load and engine revolutions. The sampling has to be in certain time range. Each point has its weight expressed by Weighting Factor (WF), which indicates discharged amount of the sample. Measured values of the emissions are multiplied by WF.

Engine has to be warmed up before each measurement. Warming up of the engine and the system shall be at maximum speed and torque in order to stabilize the engine parameters according to the recommendations of the manufacturer. The conditioning period should also prevent the influence of deposits from a former test in the exhaust system. The example of a distribution of measuring points is illustrated by Fig. 1.



1: *Example of measuring points distribution in the NRSC (Čupera et al., 2010)*

During each mode of the given test cycle after the initial transition period, the specified speed shall be held to within ± 1 % of rated speed or ± 3 rpm, which is greater, except for low idle which shall be within the tolerances declared by the manufacturer. The specified torque shall be held so that the average over the period, during which the measurements are being taken, is within ± 2 % of the maximum torque at the test speed. For each measuring point a minimum time of 10 minutes is necessary. The gaseous exhaust emission concentration values shall be measured and recorded during the last three minutes of the mode. The particulate sampling and the gaseous emission measurement should not commence before engine stabilization, as defined by the manufacturer, has been achieved and their completion must be coincident. The time of the stabilization was 3 minutes and was monitored temperature of engine oil.

Quantity of nitrogen oxide was measured in front of and behind the SCR catalytic converter. Nitrogen oxide content behind the SCR converter was measured each 7, 8, 5 and 10 minute of the test. From these values, mean value was obtained. Temperature sensing was realized behind the turbo charger, in front of and behind the diesel particulate filter, in front of urea injector and behind the SCR catalytic converter.

Used equipment:

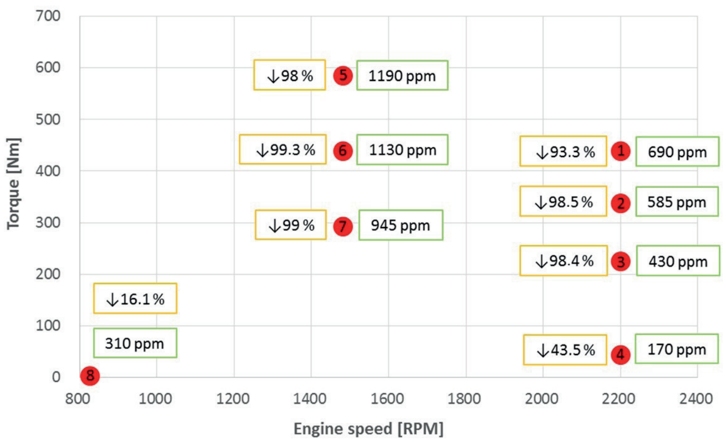
- electromagnetic eddy current dynamometer Schenck W230,
- device for measurement of NOx emissions – NO analyser Rosemnout Model 955 chemiluminiscence detector (CLD) principle, measuring range 10 – 10 000 ppm,
- thermocouples for temperature measurement of exhaust gases.

RESULTS AND DISCUSSION

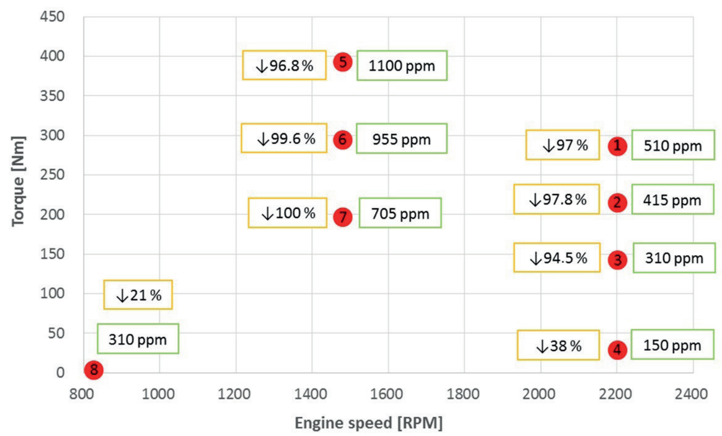
As has been mentioned in introduction, main goal of the measurement was to determine the nitrogen oxide reduction efficiency. Results from 8-point test during the full fuel charge are plotted in Fig. 2. Red points represent achieved engine torque in specific rpm and engine load. Measured quantities of nitrogen oxide in front of SCR catalytic converter are highlighted in green box. Values in orange boxes represent calculated efficiency of NOX reduction. Calculation was obtained from measured amounts of NOx in front of and behind the SCR catalytic converter.

Production of nitrogen oxide is highly dependent on the combustion temperature. Highest production of NOx (especially NO) takes place at high engine load which is accompanied by high combustion temperature (Macek and Suk, 1996). High combustion temperatures are reached during the maximum load of the engine. This phenomenon is confirmed by Fig 2. In the area of high engine load nitrogen oxides levels reaches higher values than in low engine load. After the injection of urea into the exhaust manifold and subsequent chemical reaction of ammonia with exhaust gases, significant NOx reduction occurs. During the 50 % of engine load, NOx emissions decrease by more than 90 %. Because of significant NOx reduction, high consumption of AdBlue reducing agent is assumed. Reduction of NOx is not significant on the opposite site of the Fig. 2. This area represents low engine loads. Main reason of this behaviour is the temperature of exhaust gases or rather temperature in SCR catalytic converter which is the one of the main parameters directing the NOx reduction. Highest efficiency of NOX reduction is reached if the temperature of SCR catalytic converter is between 450 °C and 500 °C. This theory is supported by Kobayashi and Miyoshi (2007) studies, dealing with efficiency of SCR catalyst at different operating temperatures.

During the monitoring of the engine with multiple injection pump, temperature of exhaust gases between DPF and SCR catalytic converter reached value in point 4 and 8 only 190 °C and 131 °C. Temperature behind the catalytic converter fluctuated between 183 °C and 225 °C. This was the reason why catalytic converter couldn't reach efficient temperature and process of SCR catalyst couldn't convert nitrogen oxides and ammonia to water vapour and harmless nitrogen. Residual ammonia was released into the environment which. This state would have a negative impact on healthcare and the Environment because



2: *Results of 8-point test with highlighted amounts of NOx and calculated efficiency of NOx reduction in relevant regimes of the engine with full fuel charge*



3: *Results of 8-point test with highlighted amounts of NOx and calculated efficiency of NOx reduction in relevant regimes of the engine with 60 % fuel charge* the ammonia is classified as a toxic and harmful substance (Integrated Pollution Register, 2015).

Top temperature of SCR catalyst is also important for optimal efficiency of reduction process. If the temperature exceeds a certain limit (about 500 °C), decrease of reduction efficiency occurs. Due to high temperatures of exhaust gases in SCR catalytic converter, parallel reactions will start. This leads to imperfect reactions of NH3 and nitrogen oxides. Also high injection of urea brings free ammonia leakage. This leads to formation of dangerous compounds which may clog active surface of the catalytic converter and reduce its effectiveness (Javed *et al.*, 2007; Radivojevic, 1998). AdBlue dosing is regulated not only by the content of NOx before and after catalytic converter, according to the engine mode and current fuel consumption, but also by the temperature of exhaust gases. Amount of AdBlue injection is in the range between 0.1 to 10 % of current fuel consumption (Bauer *et al.*, 2013).

Fig. 3 represents the results of 8-point test at 60 % of fuel charge. Description of the graph in Fig.3 is the same like previous graph in Fig. 2.

Results from the measurement with 60 % of fuel charge are matched with the results with 100 % of fuel charge. High value of NOx reduction efficiency is reached at higher engine loads (over 50 %). Conversely, due to the low combustion temperature, respectively low temperature of SCR catalytic converter (in points 4 and 8), the efficiency of conversion reached very low value. This was caused by low temperature of exhaust gases in front of SCR catalytic converter (183 °C and 118 °C in front of it and 174 °C and 188 °C behind it).

CONCLUSION

Tractor engines must fulfil increasingly more stringent emission limits. These limits are the one of the conditions for the passing of homologation tests which are necessary to bring the tractor to the market. The most complicated component of exhaust gases are carbon oxides (NOx) and particulate matter (PM).

This article deals with reduction of NOx with a usage of selective catalytic reduction (SCR) because sufficient fulfilling of the emission norm requires technical equipment for after treatment of exhaust gases. Results confirmed that SCR catalytic converter significantly reduces NOx content depending on not only amount of the exhaust gases and engine regime, but especially on temperature of exhausts, respectively on the temperature of SCR catalytic converter. Measurement was aimed on the most widely used engine regime, where NOx reduction is efficient and sufficient for compliance with the specified emission limits.

Results also show possibility of fulfilment of the NOx limits which are listed in the currently stringent emission standards Stage IV, respectively Tier 4f with multiple injection pump, which can nowadays seem to be obsolete. For this purpose, injection pump regulator must have been upgraded from mechanical to electrical one which provides more precise engine management. This technical solution is required because of urea injection and SCR system incorporation into the exhaust manifold for after treatment of exhaust gases. Indisputable advantages of multiple injection pumps are less prone to the fuel cleanliness, simpler design compared to the modern electronic fuel injection systems of Common Rail type making their usage justified.

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