Particle number emissions of offroad engines in NRSC and NRTC using the EC standardised PMP measuring method

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Introduction

On January 1st, 2009, with the amendment of the Federal ordinance on air protection (OPair) concerning the section construction machines a particle number limit value was introduced for the first time in Switzerland. In the OPair only emission limit values for particle mass (PM10 mass concentration of aerosol particles with an aerodynamic diameter D ≤ 10 µm) were legally stipulated so far. However, diesel engines emit a high number of ultrafine soot particles (D < 300 nm) which, regarding to their mass, only account for a minor part of PM10. Though there are a number of studies which point to the specific toxicity of this particle fraction. In order to minimise the emission of soot particles dangerous to health the particle number is now also limited by the OPair.

With the revision of the ordinance on air protection a limit value of 1×10^{12} particles/kWh for particle number emission in the section construction sites was defined. This limit value comes into force at staggered intervals: On 1 January 2009 for new construction machines with a capacity of at least 37 kW. Until 1 May 2010 machines of this capacity class with year of construction 2000 or later have to be retrofitted according to the OPair. From 1 May 2015 this limit value will also be in force for construction machines set into operation before year 2000. For new-built machines of the capacity class 18 to 37 kW the new regulations are valid from year of construction 2010.

These regulations differ from EU legislation. It is decided to introduce the measurement of particle number emissions of passenger cars in the EU countries, but the measurement method still has to be defined. With EURO-5 a particle number limit value will be introduced gradually. In the year 2009 an intercomparison performed by various laboratories took place for test bench homologations to investigate a measuring method according to PMP (Particle Measurement Programme) guidelines[1] for heavy-duty vehicles. On the international level, in the section offroad engines neither by the EU nor by UNECE (United Nations Economic Commission for Europe) efforts are undertaken to investigate a measuring method to determine particle number emission not to mention the proposal of a limit value.

The objective of this investigation was to obtain emission data of a construction machine equipped with a VERT certified particle filter (VERT: Curtailing emissions of engines in tunnel sites, a project to investigate technical methods to diminish Diesel particle emissions from deployed engines). On an engine test stand it was surveyed whether the new particle number limit value of 1×10^{12} particles/kWh can be maintained during typical offroad cycles. The test engine was operated in the NRSC (Non-road steady-state cycle) and NRTC (Non-road transient cycle) according to the directive 97/68 EC[2]. Measurements were performed in July 2008.

Acknowledgements

This work was supported by the Swiss Federal Office for the Environment (FOEN) and performed at the engine test stand of Liebherr Machines S.A. in Bulle, Switzerland.

References

1 UNECE, World Forum for Harmonization of Vehicle Regulations, Regulation No. 83. Agreement concerning the adoption of uniform technical prescriptions for wheeled vehicles, equipment and parts which can be fitted and/or be used on wheeled vehicles and the conditions for reciprocal recognition of approvals granted on the basis of these prescriptions.
Weblink: http://www.unece.org/trans/main/wp29/wp29regs/r083r3a2e.pdf

2 Directive 97/68 EC of the European Parliament and of the Council of 16 December 1997. On the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery.
Weblink: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1997L0068:20090807:EN:PDF

PARTICLE NUMBER EMISSIONS OF OFFROAD ENGINES IN NRSC AND NRTC USING THE EC STANDARDISED PMP MEASURING METHOD

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INTRODUCTION

On January 1st, 2009, a particle number limit value of 1×10^{12} particles/kWh was introduced for the first time in Switzerland for the section construction machines in the Federal ordinance on air protection (OPair). This regulation differs from EU legislation. It is decided to introduce the measurement of particle number emissions of passenger cars in the EU countries, but the measurement method still has to be defined. With EURO-5 a particle number limit value will be introduced gradually.

The objective of this investigation was to obtain emission data of a construction machine equipped with a VERT certified particle filter (VERT: Curtailing emissions of engines in tunnel sites, a project to investigate technical methods to diminish Diesel particle emissions from deployed engines). On an engine test stand it should be surveyed if the new particle number limit value of 1×10^{12} particles/kWh can be maintained during typical offroad cycles.

EXPERIMENTAL

Measurements of particle number concentrations emitted by a construction machine were performed according to the EC-standardised PMP measuring method[1] at an engine test bench of the company Liebherr Machines S.A. in Bulle. Liebherr provided an offroad engine with a VERT certified particle filter (Figure 1). Specifications of test engine, fuel and exhaust aftertreatment are given in Tables 1-3.

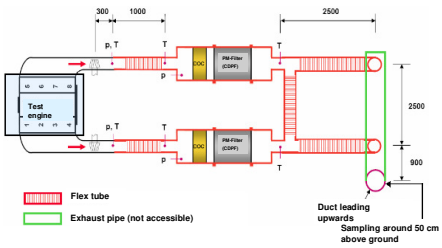

Figure 1. Test bench setup.

Table 1. Specifications of the tested engine.

Manufacturer	Liebherr Machines S.A.
Engine Type	V8 (D9508)
Power	500 kW
Rated speed	1900 1/min
Exhaust emissions	Stage IIIB
Equipment	CR fuel injection system, E-AGR, two-stage charging
Oil	AVIA 10W40 Low ash
Fuel	According to EN-590

Table 2. Specifications of the fuel (according to European standard EN.590).

Density (at 15 °C)	820 – 845 kg/m³
Viscosity (at 40 °C)	2.00 – 4.50 mm²/s
Flash point	> 55 °C
Cloud point	< -10 °C
Cold filter plugging point	CFPP maximum -20 °C
Carbon residue (on 10 % distillation residue)	Maximum 0.30 %
Ash content	Maximum 0.01 %
Sulfur content	Maximum 50 mg/kg
Water content	Maximum 200 mg/kg
Cetane index	At least 46.0

Table 3. Exhaust aftertreatment.

Diesel Oxidation Catalyst (DOC)	
Manufacturer	Emitec
Material	Metal (Type E) 400 cpsi
Dimension of the substrate (Ø × L)	289 ×120 mm
Coating	Without precious metal
Diesel Particle Filter (DPF)	
Manufacturer	Corning
Material	DuraTrap® CO 100 cpsi / 17 mil
Dimension of the substrate (Ø × L)	12"× 13"
Coating	With precious metal

Aerosol samples were taken from the exhaust pipe leading upwards (Figure 1). The instrumentation for the particle number measurement was compliant to PMP (according to UNECE, World Forum for Harmonization of Vehicle Regulations, Regulation No. 83). The exhaust gas was first diluted with an MD 19-2E rotating disk diluter (Matter Engineering). Then the aerosol was led through a thermo conditioner (ASET 15-1, Matter Engineering) heating the sampling probe to 300 °C in order to evaporate volatile components. In the secondary dilution system the aerosol sample was further diluted and therefore cooled down to a temperature of < 35 °C according to PMP. An Engine Exhaust Condensation Particle Counter (EECPC 3790, TSI) recorded particle number concentrations.

Exhaust emission measurements for the offroad engine equipped with a particle filter were performed in the NRSC (Non-road steady-state cycle) and NRTC (Non-road transient cycle) according to the directive 97/68 EC[2].

The **NRSC test** is a stationary test for diesel engines installed in non-road machinery. Once the prescribed operating conditions are attained, the amounts of exhaust emissions will be examined with the warmed up engine. The test cycle consists of a number of speed and torque modes which cover the typical operating range of diesel engines (see also Table 4).

The **NRTC test** is a dynamic test for diesel engines installed in non-road machinery. It reflects typical operating conditions of diesel engines and lasts 20 minutes. According to the directive the cycle is performed twice, first as cold start cycle (engine and aftertreatment systems are stabilised at room temperature of 20 to 30 °C) and then as hot start cycle commencing immediately after the completion of the cold start cycle.

Table 4. Particle number emissions of the three NRSC tests subdivided into the individual modes.

Mode	Speed	Load	Particle number emission		
			NRSC 01	NRSC 02	NRSC 03
	[min⁻¹]	[Nm]	[Particles/kWh]	[Particles/kWh]	[Particles/kWh]
1	2000	2380	1.29E+10	7.72E+09	9.38E+09
2	2000	1800	1.58E+10	5.29E+09	6.18E+09
3	2000	1200	2.78E+09	4.19E+09	6.70E+09
4	2000	240	3.12E+09	6.23E+09	1.19E+10
5	1500	3100	1.64E+10	5.08E+09	8.70E+09
6	1500	2373	1.61E+11	5.16E+09	4.98E+09
7	1500	1582	1.55E+10	3.52E+09	4.82E+09
8	600	93	1.06E+12	5.47E+09	6.12E+09
Variance			3.67E+11	1.27E+09	2.45E+09

Both test cycles were run three times to assess the statistic significance of the results. In addition, particle number emissions of the test engine were measured without a downstream particle filter in one NRTC and one NRSC. Particle number emissions of the 500 kW test engine were calculated based on standard conditions for temperature and pressure (P = 101.3 kPa, T = 273 K).

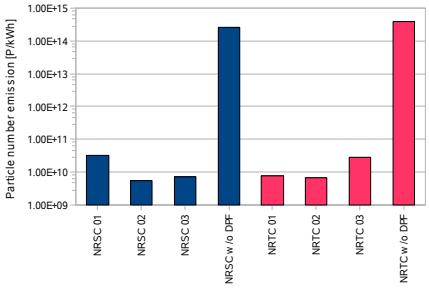

Figure 2. Results of the test cycles with and without particle filter.

RESULTS

From figure 2 it can be seen that in the NRSC as well as in the NRTC two measurements were close to each other while the third cycle provided clearly higher particle number emissions. In the NRSC one measured value differs from the other two measurements by the factor of 5.1, in the NRTC the factor amounts to 3.8. The higher average in the NRTC 03 appeared at a phase of strongly increased particle number concentrations at relatively constant speed (around 1800 min⁻¹) and load (around 2000 Nm) in the middle of the cycle.

Without a diesel particle filter the 500 kW test engine emitted particle numbers in the range of 2.5×10^{14} P/kWh (NRSC) and 3.8×10^{14} P/kWh (NRTC). With DPF an average of approximately 1.5×10^{10} P/kWh was measured for both test cycles (Table 6). These values correspond to a filter collection efficiency of 99.995 %.

In summary, it can be concluded that the measurement results of both test cycles, NRSC and NRTC, were very close to each other. But within the cycles noticeable differences regarding particle number emission (until factor 5) were found. The statistical spread of the measurements could be narrowed down, but to obtain a more reliable statistical analysis more measurements would be required. Particle number emissions of the offroad test engine equipped with a Corning diesel particle filter were in the range of 1.5×10^{10} P/kWh and therefore clearly below the new particle number limit value of 10^{12} P/kWh defined by the OPair.

Table 5. Results of the NRSC and NRTC test cycles.

Test cycle	Particle number emission engine out	Particle number emission	Filter collection efficiency
	[Particles/kWh]	[Particles/kWh]	[%]
NRSC 01		3.28E+10	99.987
NRSC 02		5.59E+09	99.998
NRSC 03		7.35E+09	99.997
NRSC without DPF	2.50E+14		
NRTC 01		7.74E+09	99.998
NRTC 02		6.84E+09	99.998
NRTC 03		2.76E+10	99.993
NRTC without DPF	3.83E+14		

Table 6. Final result of the particle number emission of a 500 kW engine equipped with diesel particle filter (mean value of three measurements).

Test cycle	Particle number emission	Variance	Filter collection efficiency	Variance
	[Particles/kWh]	[Particles/kWh]	[%]	[%]
NRSC	1.52E+10	1.50E+10	99.994	0.006
NRTC	1.41E+10	1.17E+10	99.996	0.003

ACKNOWLEDGEMENTS

This work was supported by the Swiss Federal Office for the Environment (FOEN).

REFERENCES

1 UNECE, World Forum for Harmonization of Vehicle Regulations, Regulation No. 83. Agreement concerning the adoption of uniform technical prescriptions for wheeled vehicles, equipment and parts which can be fitted and/or be used on wheeled vehicles and the conditions for reciprocal recognition of approvals granted on the basis of these prescriptions. Weblink: http://www.unece.org/trans/main/wp29/wp29regs/r083r3a2e.pdf

2 Directive 97/68 EC of the European Parliament and of the Council of 16 December 1997. On the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery. Weblink: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1997L0068:20090807:EN:PDF