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Exhaust particle size distributions of a non-road diesel engine in an endurance test

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Abstract. The main objective of this study was to find out how the non-road diesel engine running period of 500 hours affects the exhaust particle size distribution. By means of an engine exhaust particle sizer (EEPS), particle number was measured before the endurance test and after 250 and 500 hours of engine operation. The size distributions were determined at full and 75% loads both at rated and at intermediate speeds. The soot, gaseous emissions and the basic engine performance were also determined and lubricating oil was analysed a few times during the running period. A blend of low-sulphur fossil diesel and soybean methyl ester (B20) was used as fuel in the 4-cylinder, turbocharged, intercooled engine which was equipped with a diesel oxidation catalyst (DOC) and a selective catalytic reduction (SCR) system. All emissions were measured downstream the catalysts. During the 500 hours of operation, the particle number increased considerably within an approximate size range of 7 to 30 nm. Between the initial and final measurements, no notable differences were observed in the particle number emissions within a particle size range of 50 to 200 nm. The copper content of lubricating oil also increased significantly during the 500 hours' experiment. One possible reason for the substantial increase in the nucleation mode particle number was assumed to be copper, which is one of the metallic elements originating from engine wear. The engine efficiency was almost equal, and the differences both in smoke and hydrocarbon emission were negligible throughout the 500 hours' experiment.

Key words: particle number, exhaust aftertreatment, B20, blend fuel, soybean methyl ester.

INTRODUCTION

Some of the combustion products of diesel engines have long been recognized as harmful pollutant emissions that affect the air quality, human health, and climate change. Both the gaseous and particulate emissions are regulated worldwide.

The emission legislation has been met by exploiting different engine design, aftertreatment system, and fuel technologies. All these technologies are needed gradually during 2019–2020 when the new emission stage (Stage V), regulated by the European Commission and the Council, comes into force. The regulation also limits the particle number (PN) emissions of the non-road diesel engines. (EU Regulation 2016/1628). The new PN limitation enforces the usage of diesel particulate filters (DPF) along with the possible catalyst devices in the near future.

Diesel engine exhaust contains non-volatile particles which form the size distribution with two distinctive particle modes; soot mode and core (nucleation) mode. (Kittelson, 1998; Rönkkö et al., 2006; Filippo & Maricq, 2008; Lähde et al., 2010). The formation of the core mode particles is considered to initiate in the cylinder. Soot particles are formed in the cylinder, when either the fuel or the remnants of lubricating oil do not burn completely during combustion. The particle mean diameters in nucleation mode are under 40 nm, whereas the mean diameter range in soot mode is 20–100 nm.

The particles with mean diameters of less than 2.5 μm or 10 μm are often reported to be adverse to human health. In addition, the concentrations of black carbon and nanosized particles < 100 nm may cause health risks. (Oberdörster et al., 2005; Janssen et al., 2011). The smallest particles can deposit onto the lungs and may penetrate into the cardiovascular and even cerebrovascular system via respiratory organs. (Anderson et al., 2012; Oravisjärvi et al., 2014).

Reliable operation of a diesel engine is ensured when the engine is capable of running without failures. When the engine is run with the same fuel in the constant ambient conditions, one can assume that heterogeneous air/fuel mixture preparation during the ignition delay, fuel ignition quality, residence time at different combustion temperatures, and expansion duration are equal. Therefore, the emission formation mechanisms and the resultant concentrations of the different emission species in the exhaust will be the same.

However, mechanical wear of the engine also affects the non-volatile particle number of diesel exhaust in long-term use. The wear metals, such as Fe, Al, Cu, Zn, Co, and Ni, are found among the exhaust particle ash content. (Agarwal, 2005; Dwivedi et al., 2006; Sarvi et al., 2011; Sharma & Murugan, 2017).

This study examined how the non-road diesel engine running period of 500 hours affects the exhaust particle size distribution. A blend of low-sulphur fossil diesel and soybean methyl ester (B20) was used as fuel in the high-speed non-road engine which was equipped with a diesel oxidation catalyst (DOC) and a selective catalytic reduction (SCR) system. The particle number were measured before the endurance test and after 250 and 500 hours of engine operation at full and 75% loads both at rated and at intermediate speeds. The soot, gaseous emissions and the basic engine performance were determined as well. During the experiments, the engine control parameters were kept constant.

MATERIALS AND METHODS

The experimental measurements were performed by the University of Vaasa (UV) at the internal combustion engine (ICE) laboratory of the Technobothnia Research Centre in Vaasa, Finland.

Engine

The test engine was a 4-cylinder non-road diesel engine equipped with a common-rail injection system. The new, turbocharged, intercooled engine was equipped with a DOC and a urea-based SCR system. During all the measurements, emissions were recorded downstream the catalysts.

The test engine was installed in a test bed and loaded by means of an eddy-current dynamometer of model Horiba WT300. The main engine specification is given in Table 1.

Fuel and lubricating oil

Fuel used during the endurance test was a blend of low-sulphur fossil diesel and soybean methyl ester (B20). The fuel consisted of 20 vol.-% soybean methyl ester (SME) and of 80 vol.-% commercial low-sulphur diesel fuel oil (DFO).

Table 1. Main engine specification

Engine	AGCO POWER 49 AWI
Cylinder number	4
Bore (mm)	108
Stroke (mm)	134
Swept volume (dm^3)	4.9
Rated speed (rpm)	2,100
Rated power (kW)	103
Maximum torque with rated speed (Nm)	462*
Maximum torque with 1,500 rpm (Nm)	583*

*conformable to measured torques obtained with B20 fuel.

The commercially available Valtra Engine CR-4, 10W-40 (ACEA E9, API CJ-4) was used as lubricating oil in the engine. Lubricating oil was analysed after the operating hours of 0, 207, 357 and 553. The analysing results of the lubricating oil have been reported earlier by Sirviö et al. (2016).

Analytical instruments

The adopted measurement instruments are listed in Table 2. Before the measurements, the analysers were calibrated manually once a day according to the instructions of the instrument manufacturers. The arrangement of the test bench and measurement devices is seen in Fig. 1 in which temperature sensors are abbreviated to TS.

During the measurements, the particles from a size range of 5.6 to 560 nm were recorded by using the engine exhaust particle sizer (EEPS), for which the sample flow rate was adjusted at 5.0 L min^{-1}. The 'SOOT' inversion was applied in the EEPS data processing. The exhaust sample was first diluted with ambient air by means of a rotating disc diluter (RDD) (model MD19-E3, Matter Engineering AG). The dilution ratio used in the RDD was constant 60 during the measurements. The exhaust aerosol sample was conducted to the RDD and a dilution air was kept at 150 °C. The diluted sample (5 L min^{-1}) was further diluted by purified air with a dilution ratio of 2. Thus, the total dilution ratio used in particle size distribution measurements was 120. In this way, mainly the non-volatile particle fraction 150°C is measured by the EEPS.

Three-minute stable time intervals were chosen for the results recordings of the particle number (PN) and particle size distributions. The average values, calculated from the recordings, were multiplied by the dilution ratio of the exhaust sample.

The recorded smoke value was the average of three consecutively measured smoke numbers.

Table 2. Measuring equipment

Parameter	Device	Technology
Particle number and size distribution	TSI EEPS 3090	spectrometer
Hydrocarbons	J.U.M. VE7	HFID
Smoke	AVL 415 S	optical filter
NO_x	Eco Physics CLD 822 M h	chemiluminescence
NO_x, λ	WDO UniNO_x sensors	ZrO_2-based multilayer
O_2	Siemens Oxymat 61	paramagnetic
Air mass flow rate	ABB Sensyflow P	thermal mass

The sensor data were collected by means of software, made in the LabVIEW system-design platform. In addition to the gaseous emissions, the systems recorded the temperatures of cooling water, intake air and exhaust gas plus the pressures of the intake air and exhaust gas. The engine control parameters were followed via WinEEM4 engine management software, provided by the engine manufacturer.

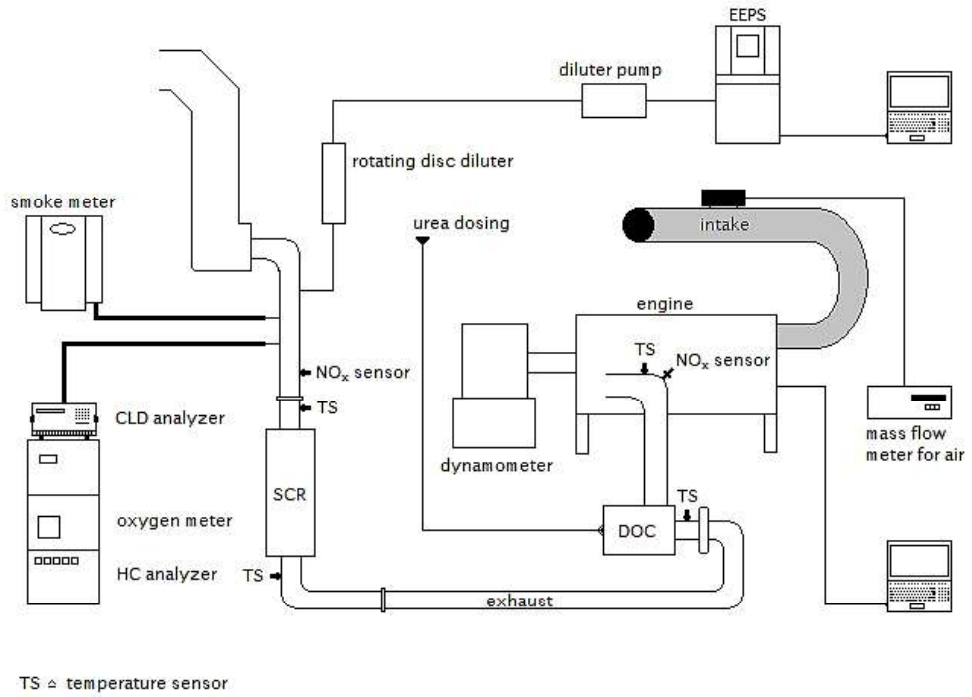

Figure 1. Experimental set-up.

Based on the measured hydrocarbon (HC) concentrations, the brake specific emissions of HC were calculated according to the ISO 8178 standard.

Experimental matrix and running procedure

Before the endurance test of 500 running hours, the baseline performance and emissions measurements were performed with a new engine installation. Thereafter, the engine was daily operated according to a defined running procedure consisting of sequential load points which were supposed to represent the actual use of the engine as

accurately as possible. After 250 hours of engine operation, the performance and emissions measurements were repeated, as they were after 500 hours.

The measurements were conducted at full and 75% loads both at rated and at intermediate speeds. The rated engine speed was 2,100 rpm and the intermediate speed 1,500 rpm.

Before the measurements, the intake air temperature was adjusted at 50 °C downstream the charge air cooler when the engine was run at full load at rated speed. The temperature was controlled manually by regulating cooling water flow to the heat exchanger. After this initial adjustment, the temperature was allowed to change with engine load and speed.

During the measurements, the engine was run with urea dosing, the alpha ratio being 0.95.

Before the recordings at each load point, it was waited that the engine had stabilized, the criteria being that the temperatures of coolant water, intake air and exhaust were stable. The length of the measurement period was not tied to a certain time.

All measurement values were recorded once at each load point.

Daily operation

The daily running cycle between the measurements is given in Table 3. The engine was run by an autopilot-system which was implemented into the LabVIEW platform. The autopilot system made it possible to regulate the dynamometer automatically.

Table 3. Daily cycle of the endurance test

Point	Speed (rpm)	Load (%)	Torque (Nm)	Duration (min)
1	1,000	0	0	15
2	1,300	14	75	15
3	1,600	21	123	15
4	1,800	29	175	30
5	2,000	40	214	15
6	2,100	51	236	15
7	1,900	60	346	15
8	1,700	49	293	15
9	1,500	30	175	30
10	1,200	25	127	15

RESULTS AND DISCUSSION

Particle size distributions

Generally, the PN increased considerably within an approximate size range of 7 to 30 nm during the 500 hours of engine operation. Between the initial and final measurements, no notable differences were, however, observed in the PN emissions within a particle size range of 50 to 200 nm.

Fig. 2 shows the particle size distributions at full and 75% loads both at rated and intermediate speeds. For both speeds and loads, a bimodal shape was detected for the distributions. One peak was detected at a particle size of ca. 10 nm and the other at ca. 32–60 nm. At the initial measurements, the lowest quantity of particles was observed within the size ranges of 7–15 nm and 24–86 nm regardless of the engine speed or load.

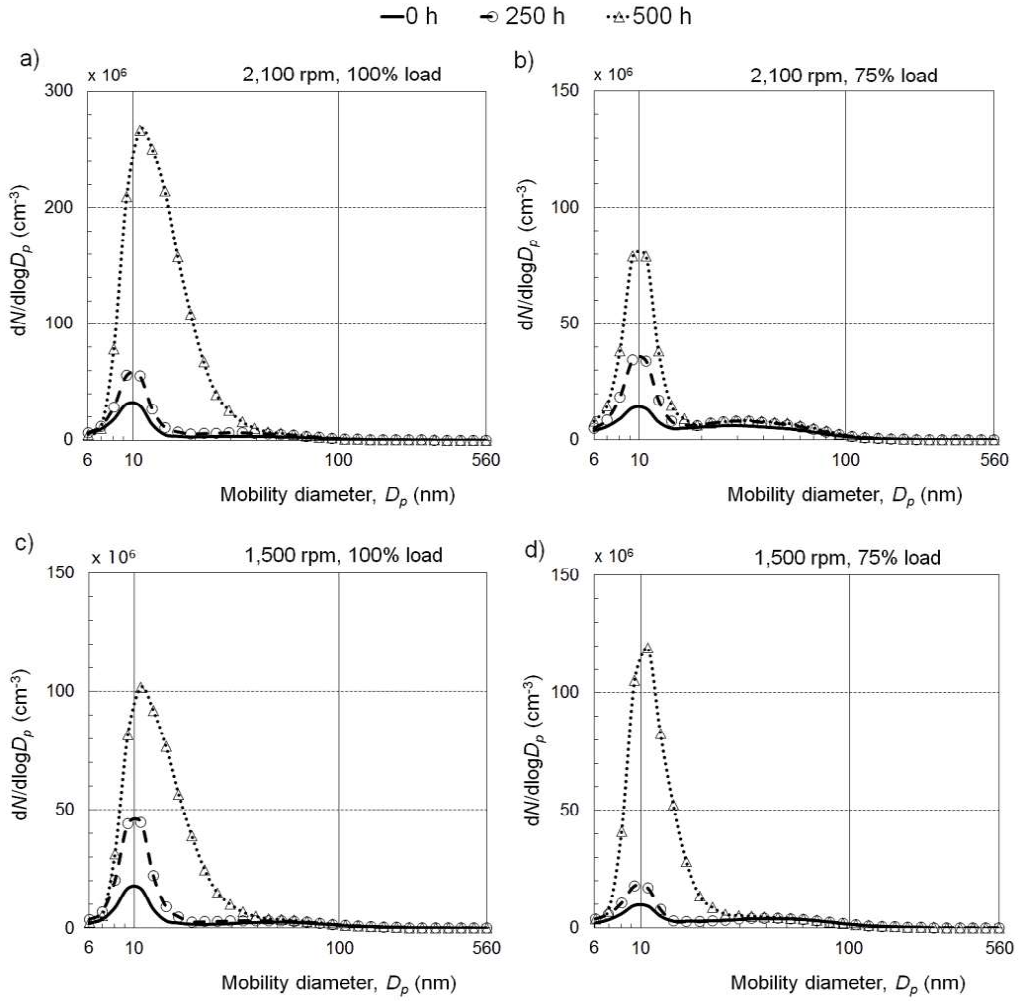

Figure 2. Effect of running period of 500 hours on the exhaust particle size distribution a) at full and b) 75% load at rated speed, and c) at full and d) 75% load at intermediate speed.

After 250 hours' operation, the number of particles under 154 nm increased compared to the baseline apart from at intermediate speed at 75% load where the PN between 86–200 nm decreased. The greatest PN was detected at the size category of 10 nm. At rated speed, the PN was here 1.9-fold at full load and 2.5-fold at 75% load compared to the baseline. At intermediate speed at full and 75% load, the PN was 2.7-fold and 1.8-fold, respectively, at this size category.

After the 500 hours' operation, the PN increased within the size range of 7–200 nm compared to baseline. The highest particle numbers of this study were recorded within the size range of 8–42 nm. The PN peaked again at the size category of 10 nm. Now, at rated speed, the PN was 9.0-fold at full load and 5.9-fold at 75% load compared to the baseline. At intermediate speed at full and 75% load, the PN was 6.1-fold and 13-fold, respectively.

Usually, the initiation of the nucleation is assumed to be sulphur driven. First, when sulphur from fuel and lubricating oil burn in the cylinder, sulphur dioxide is formed. In

the oxidation catalyst, sulphur dioxide of exhaust gas can be converted to sulphur trioxide under high exhaust temperatures. (Giechaskiel et al., 2007) Thus, the nucleation mode of particles downstream the SCR catalyst may be caused by sulphuric acid originating from reaction between sulphur trioxide and water vapor (Vaaraslahti et al., 2004; Arnold et al., 2006; Rönkkö et al, 2007; Biswas et al., 2008). However, the sulphur content of fuel or lubricating oil were not observed to change during the study.

Sirviö et al. (2016) observed that the copper concentration in lubricating oil increased significantly from 49 to 420 ppm between the oil analysis hours of 357 and 553. Copper is one of the metallic elements originating from engine wear. However, the contents of other wear metals, such as lead, did not increase, as would have been probable in the case of damage in bearings or other engine parts (Sirviö et al. 2016).

Schumacher et al. (2005) fuelled an on-road truck diesel engine with the different blends of hydrogenated soybean ethyl-ester. During the first 50,000 miles of operation, 2–3 lubrication oil samples were taken. The samples contained the high levels of copper which were suggested to originate from a copper oil cooler.

For this paper, one possible reason for the substantial increase in the nucleation mode particle number was assumed to be copper which originated from the break-in of a new oil cooler.

Fig. 3 illustrates the effect of the operation time on the measured total particle number (TPN, from 6 to 560 nm), where linear interdependences are presented by using the PN data from each load point.

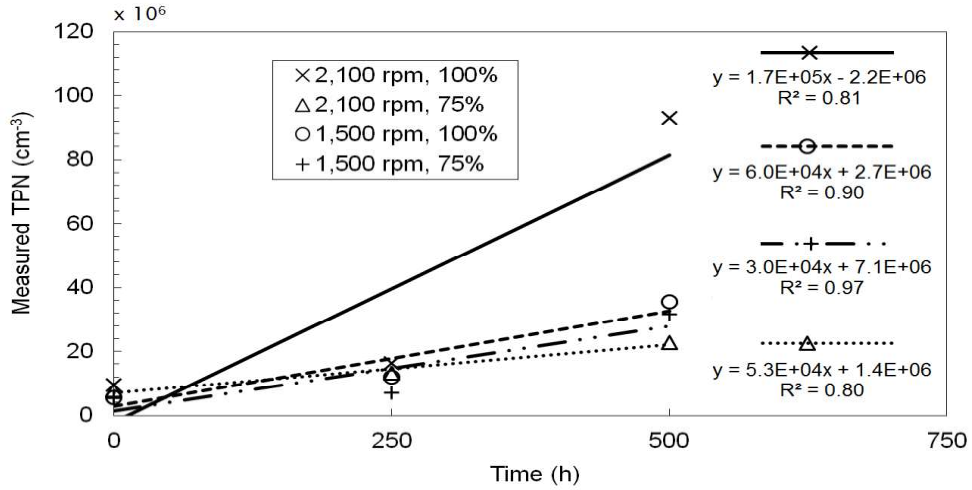

Figure 3. Measured TPN as a function of the operation time.

All correlations were positive irrespective of the engine speed or load. For the presented interdependences, the values of squared correlation factors were between 0.80–0.97.

In general, the total particle numbers were the smallest at the initial measurement and far the highest after 500 hours of engine operation. The least TPN were detected always at intermediate speed at 75% load, whereas the highest TPN were recorded every time at rated power.

HC emissions and smoke

The brake specific HC emission was minor throughout the 500 hours of engine operation, Fig. 4. At rated speed, the HC emission varied from 0.01 to 0.02 g kWh^{-1}, and at intermediate speed from 0.006 to 0.009 g kWh^{-1}. The engine was equipped with a DOC, which reduce the HC concentration of exhaust by promoting the chemical oxidation of HC. Therefore, the HC emission was almost negligible at both loads and speeds.

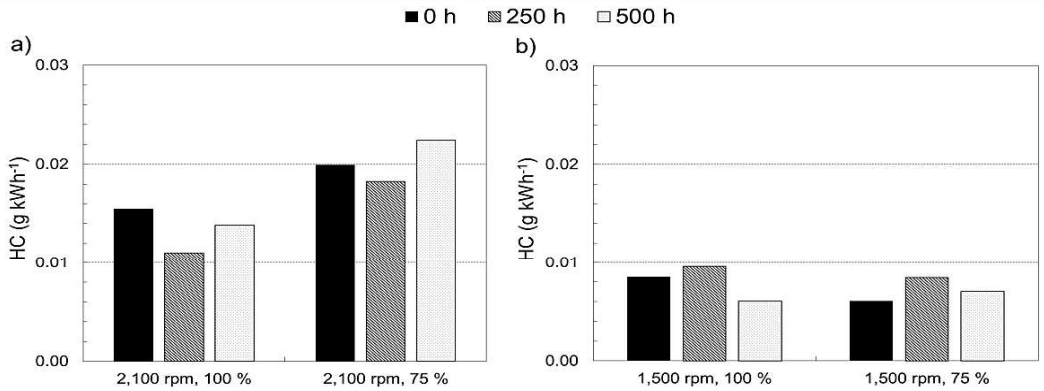

Figure 4. Brake specific HC emissions a) at full and 75% load at rated speed, and b) at full and 75% load at intermediate speed.

Fig. 5 depicts the smoke emissions. Both at rated and at intermediate speed, the smoke was very low, the FSN readings varying from 0.020 to 0.064. No reliable conclusion can be drawn from the smoke emission.

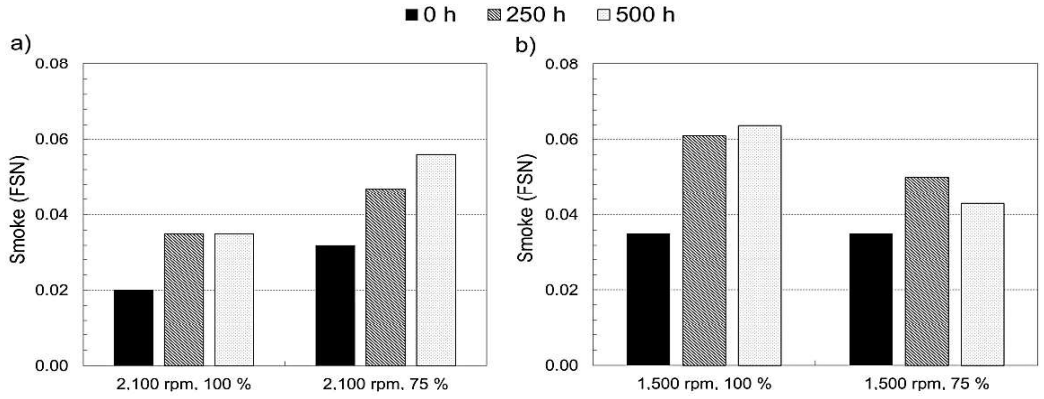

Figure 5. Exhaust smoke a) at full and 75% load at rated speed, and b) at full and 75% load at intermediate speed.

When comparing either the HC or smoke emissions, the differences were negligible, and no clear trend was detected during the 500 hours' operation. The notable increase of PN within an approximate size range of 7 to 30 nm during the 500 hours of engine operation cannot be explained by means of the HC or the smoke emissions.

Performance

The engine efficiency was almost constant at all loads, Fig. 6. At different load points, the efficiencies varied only by 0 to 0.3 percentage points.

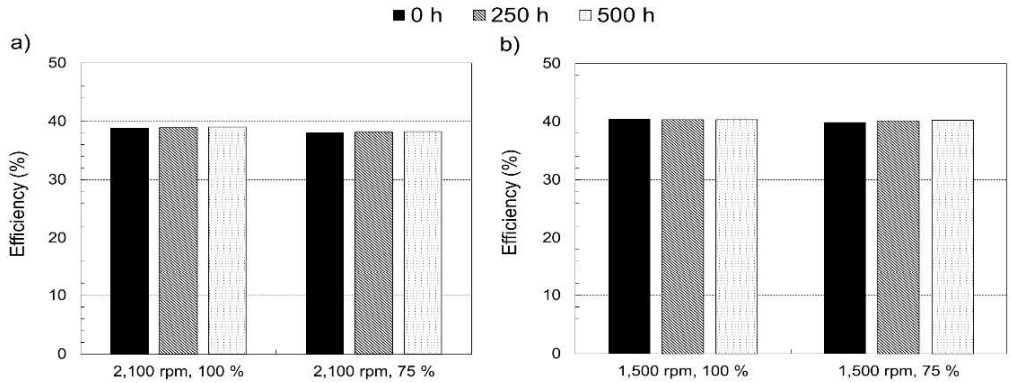

Figure 6. Engine fuel conversion efficiency a) at full and 75% load at rated speed, and b) at full and 75% load at intermediate speed.

CONCLUSIONS

1. During the 500 hours of engine operation, the particle number increased considerably within an approximate size range of 7 to 30 nm
2. No notable differences were observed in the particle number emissions within a particle size range of 50 to 200 nm
3. The correlations between the measured TPN and operation time were positive irrespective of the engine speed or load
4. The engine efficiency remained almost constant, and the changes both in smoke and hydrocarbon emissions were negligible.

The regular change interval for the lubricating oil filter of the non-road diesel engine used in the current study is 500 hours. As a next study, the experiment period could be extended to 1000 hours. Then, the main interest would be the effect of the extended period on the particle number and size distribution, after the oil filter change.

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REFERENCES

Agarwal, A.K. 2005. Experimental investigations of the effect of biodiesel utilization on lubricating oil tribology in diesel engines. *Proc. Inst. Mech. Eng. Part D: J. Automobile Eng.* **219**(5), 703–713.

Anderson, J.O., Thundiyil, J.G. & Stolbach, A. 2012. Clearing the air: a review of the effects of particulate matter air pollution on human health. *J. Med. Toxicol.* **8**(2), 166–175.

Arnold, F., Pirjola, L., Aufmhoff, H., Schuck, T., Lähde, T. & Hämeri, K. 2006. First gaseous sulphuric acid measurements in automobile exhaust: Implications for volatile nanoparticle formation. *Atmos. Environ* **40**(37), 7079–7105.

Biswas, S., Hu, S., Verma, V., Herner, J.D., Robertson, W.H., Ayala, A. & Sioutas, C. 2008. Physical properties of particulate matter (PM) from late model heavy-duty diesel vehicles operating with advanced PM and NO_x emission control technologies. *Atmos. Environ.* **42**(22), 5622–5634.

Dwivedi, D., Agarwal, A.K. & Sharma, M. 2006. Particulate emission characterization of a biodiesel vs diesel-fuelled compression ignition transport engine: A comparative study. *Atmos. Environ* **40**(29), 5586–5595.

EU Regulation 2016/1628. 2016. Regulation of the European Parliament and of the Council on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery. Accessed 26.1.2018.

Filippo, A.D. & Maricq, M.M. 2008. Diesel nucleation mode particles: Semivolatile or solid?. *Environ. Sci. Technol.* **42**(21), 7957–7962.

Giechaskiel, B., Ntziachristos, L., Samaras, Z., Casati, R., Scheer, V. & Vogt, R. 2007. Effect of speed and speed-transition on the formation of nucleation mode particles from a light duty diesel vehicle. *SAE Tech. Pap.* 2007-01-1110.

Janssen, N.A., Hoek, G., Simic-Lawson, M., Fischer, P., Van Bree, L., Ten Brink, H., Keuken, M., Atkinson, R.W., Anderson, H.R., Brunekreef, B. & Cassee, F.R. 2011. Black carbon as an additional indicator of the adverse health effects of airborne particles compared with PM10 and PM2. 5. *Environ. Health Perspect.* **119**(12), 1691.

Kittelson, D.B. 1998. Engines and nanoparticles: a review. *J. Aerosol Sci.* **29**(5–6), 575–588.

Lähde, T., Rönkkö, T., Virtanen, A., Solla, A., Kytö, M., Söderström, C. & Keskinen, J. 2010. Dependence between nonvolatile nucleation mode particle and soot number concentrations in an EGR equipped heavy-duty diesel engine exhaust. *Environ. Sci. Technol.* **44**(8), 3175–3180.

Oberdörster, G., Oberdörster, E. & Oberdörster, J. 2005. Nanotoxicology: an emerging discipline evolving from studies of ultrafine particles. *Environ. Health Perspect.* **113**(7), 823.

Oravisjärvi, K., Pietikäinen, M., Ruuskanen, J., Niemi, S., Laurén, M., Voutilainen, A., Keiski, R.L. & Rautio, A. 2014. Diesel particle composition after exhaust after-treatment of an off-road diesel engine and modeling of deposition into the human lung. *J. Aerosol Sci.* **69**, 32–47.

Rönkkö, T., Virtanen, A., Vaaraslahti, K., Keskinen, J., Pirjola, L. & Lappi, M. 2006. Effect of dilution conditions and driving parameters on nucleation mode particles in diesel exhaust: Laboratory and on-road study. *Atmos. Environ* **40**(16), 2893–2901.

Rönkkö, T., Virtanen, A., Kannosto, J., Keskinen, J., Lappi, M. & Pirjola, L. 2007. Nucleation mode particles with a nonvolatile core in the exhaust of a heavy duty diesel vehicle. *Environ. Sci. Technol.* **41**(18), 6384–6389.

Sarvi, A., Lyyränen, J., Jokiniemi, J. & Zevenhoven, R. 2011. Particulate emissions from large-scale medium-speed diesel engines: 2. Chemical composition. *Fuel Process. Technol.* **92**(10), 2116–2122.

Schumacher, L.G., Peterson, C.L. & Van Gerpen, J. 2005. Engine oil analysis of biodiesel-fueled engines. *Appl. Eng. Agric.* **21**(2), 153–158.

Sharma, A. & Murugan, S. 2017. Durability analysis of a single cylinder DI diesel engine operating with a non-petroleum fuel. *Fuel* **191**, 393–402.

Sirviö, K., Niemi, S., Katila, T., Ovaska, T., Nilsson, O. & Hiltunen, E. 2016. B20 fuel effects on engine lubricating oil properties. In: *The 28th CIMAC World Congress on Combustion Engine Technology* Helsinki, Finland, Paper No.: 025, pp. 1–8.

Vaaraslahti, K., Virtanen, A., Ristimäki, J. & Keskinen, J. 2004. Nucleation mode formation in heavy-duty diesel exhaust with and without a particulate filter. *Environ. Sci. Technol.* **38**(18), 4884–4890.