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## Effects of alternative marine diesel fuels on the exhaust particle size distributions of an off-road diesel engine.

**Author:** Ovaska, Teemu; Niemi, Seppo; Sirviö, Katriina; Nilsson, Olav; Portin, Kaj; Asplund, Tomas

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# 1 Effects of alternative marine diesel fuels on the exhaust particle size 2 distributions of an off-road diesel engine

3 Teemu Ovaska <sup>a,\*</sup>, Seppo Niemi <sup>a</sup>, Katriina Sirviö <sup>a</sup>, Olav Nilsson <sup>a</sup>, Kaj Portin <sup>b</sup>, Tomas Asplund <sup>b</sup>

4 <sup>a</sup> School of Technology and Innovations, University of Vaasa, P.O. Box 700, FI-65101 Vaasa, Finland

5 <sup>b</sup> Wärtsilä Corporation, FI-65101 Vaasa, Finland

6 \* Corresponding author: [teemu.ovaska@uniwaasa.fi](mailto:teemu.ovaska@uniwaasa.fi)

7

## 8 HIGHLIGHTS

- 9 • Renewable naphtha-light fuel oil blend decreased the accumulation mode particles
- 10 • The blend emitted either less or more particles than light fuel oil depending on load
- 11 • Circulation-origin marine gas oil and kerosene generated a high total particle number

12

## 13 KEYWORDS

14 Diesel engine, exhaust particle number, alternative fuel, light fuel oil

15

## 16 ABSTRACT

17 The main objective of this study was to find out how alternative fuels affect the exhaust gas particle  
18 size distribution. The fuels are later intended for marine applications. Along with low-sulfur marine light  
19 fuel oil (LFO), a high-speed off-road diesel engine was fueled by circulation-origin marine gas oil (MGO),  
20 rapeseed methyl ester (RME), crude tall oil derived renewable diesel (HVO), the 20/80 vol.-% blend of  
21 renewable naphtha and marine LFO, and kerosene. Particle size distributions were measured by means of  
22 an engine exhaust particle sizer (EEPS), but soot, gaseous emissions and the basic engine performance were  
23 also determined. During the measurements, the 4-cylinder, turbocharged, intercooled engine was run  
24 according to the non-road steady cycle complemented by an additional load point. The engine control  
25 parameters were kept constant, and any parameter optimization was not made with the studied fuels.

26 Relative to baseline LFO, both naphtha-LFO blend and RME reduced particle numbers above the size range  
27 of 50 nm. Circulation-origin MGO and kerosene generated a high total particle number (TPN), most likely  
28 due to their higher sulfur contents. MGO and RME were beneficial in terms of carbon monoxide (CO) and  
29 hydrocarbon (HC) emissions while nitrogen oxide (NO<sub>x</sub>) emissions were the highest with RME. The  
30 differences in smoke emission were negligible.

31

## 32 **1. Introduction**

33 International shipping produces 5–10% of the total global sulfur emissions [1]. Along with the oxides  
34 of sulfur (SO<sub>x</sub>) and particles, the carbon dioxide (CO<sub>2</sub>) and NO<sub>x</sub> emissions, have also to be reduced  
35 significantly in order to inhibit the pollution of the earth atmosphere. As an act for the pollution inhibition,  
36 the emissions of shipping are considerably regulated worldwide via the MARPOL Annex VI convention of  
37 the International Maritime Organization (IMO). These regulations aim to progressively reduce the  
38 emissions of SO<sub>x</sub> and NO<sub>x</sub>. Even outside the Sulfur Emission Control Areas (SECAs), fuel sulfur content  
39 has to be under 0.5% in 2020. [2].

40 Marine sulfur emissions originate mainly from large marine diesel engines, where heavy fuel oil  
41 (HFO) is widely combusted. As a residual fuel, HFO has high sulfur and ash contents. The high sulfur  
42 content and other fuel characteristics have also been reported to affect the marine exhaust particle emissions.  
43 [3,4].

44 Diesel engine exhaust particles form the size distribution with two distinctive particle modes;  
45 accumulation mode and nucleation mode [5,6,7,8]. The particle mean diameters in nucleation mode are  
46 under 50 nm [9], whereas the mean diameter range in soot mode is 50–500 nm [5,10]. Particle number (PN)  
47 and mass emissions can be decreased through developing the engine design, exhaust gas after treatment  
48 systems, and fuels. Compared to new engine designs or after treatment solutions, alternative liquid fuels  
49 can be taken in use relatively rapidly by the operators. Alternative fuels can also offer immediately  
50 realizable air quality improvements, and in addition to a SO<sub>x</sub> emission decline, the low sulfur content of  
51 these new fuels is beneficial for the performance of diesel particulate filters (DPF) [11,12]. Filters, and even

52 more efficient emissions reduction technologies are needed soon. For the first time, the new emission stage  
53 (Stage V) also has the limits for the exhaust particle number emissions of the off-road engines, including  
54 inland waterway vessels. This regulation of the European Commission and the Council comes gradually  
55 into effect within 2019–2020. [13].

56 Ship owners can meet the emission regulations, especially the IMO's SO<sub>x</sub> limitation, by using low-  
57 sulfur fuel oils, liquefied natural gas (LNG), or exhaust gas scrubbers. Likely therefore, the low-sulfur fuel  
58 oils and other alternative fuel options are going to be used increasingly instead of HFO. Light fuel oils,  
59 such as marine diesel oil (MDO) or MGO, are already used in small vessels and the marine auxiliary diesel  
60 engines of large ocean-going ships. In Finland, for example, low sulfur marine fuels and LNG have been  
61 substitutes for bunkered HFO already for a certain time. [1,14,15].

62 Sustainable and affordable alternative liquid fuels are, however, also needed for the compression  
63 ignited (CI) engines. Florentinus et al. [16] assessed qualitatively the technical compatibility of various  
64 biofuels in marine engines. Mono-alkyl-esters of long-chain fatty acids, i.e. fatty-acid methyl esters  
65 (FAME), di-methyl ether (DME), straight-, and hydrotreated vegetable oils (SVO, HVO) are suitable liquid  
66 fuels for both high-speed and medium speed engines [16]. Moreover, Finnish HVO, as studied e.g. by [17],  
67 could also be a potential option for medium speed engines.

68 Moreover, the US Army Single Fuel Forward Policy raised interest to study jet fuels in CI engines  
69 which are used in different kind of military vehicles. The aircraft gas turbine engines have been previously  
70 run with Jet Propellant 4 (JP-4) fuel which has been replaced by the low sulfur JP-8 fuel, similar to kerosene-  
71 based Jet A-1 fuel of the commercial aviation. Jet A-1 fuel has been identified to have same kind of  
72 properties than diesel fuel oils (DFO) or low-sulfur LFO. [18]

73 However, the alternative fuel option has to also be compatible with the other systems in ship. With  
74 e.g. FAME, several issues have to be considered, like a tendency to oxidation during long term storage,  
75 affinity to water and risk of microbial growth, degraded low temperature flow properties, and material  
76 deposition on exposed surfaces, including filter elements. The problems may arise especially with over  
77 20 vol.-% blends of FAME. [16]. Kerosene-based jet fuel has typically lower cetane number and viscosity

78 compared to LFO, MGO or MDO used in the CI engines in marine and land-use applications. Low cetane  
79 number extends the length of the ignition delay, which affects the combustion timing. Extended delay leads  
80 to the changes of cold-starting performance, combustion noise level, and exhaust emissions. Due to low  
81 fuel viscosity, the fuel injection system performance can deteriorate and the fuel pump wear and leakage  
82 may occur. [18].

83 This paper presents how the selected alternative marine fuels affected exhaust gas particle size  
84 distributions in the study which was the first stage of a large marine fuel research project. Circulation-origin  
85 marine gas oil (MGO) and a blend of renewable naphtha and marine light fuel oil (LFO) were selected to  
86 this study because both fuels are novel marine fuel options. Both could meet the sustainability and  
87 affordability goals set by the ship owners. Along with these fuels, the other studied low-sulfur fuels were  
88 LFO, rapeseed methyl ester (RME), crude tall oil derived renewable diesel (HVO), and kerosene. High-  
89 speed engine experiments were conducted before going to medium-speed engine tests. Alongside the  
90 exhaust gas particle number and size distributions, the exhaust smoke, gaseous emissions and basic engine  
91 performance were determined. The blend fuel contained 20 vol.-% of naphtha and 80 vol.-% of LFO  
92 whereas neat LFO was used as the reference fuel. The high-speed off-road diesel engine was driven  
93 according to the non-road steady cycle (NRSC) plus at one additional load point. During the experiments,  
94 the default engine control parameters were kept constant, and no parameter optimization was applied with  
95 the studied fuels.

96

## 97 **2. Experimental setup**

### 98 *2.1. Engine and fuels*

99 The experiments were performed with a diesel engine installed in a test bed and loaded by an eddy-  
100 current dynamometer. The running cycle was the ISO 8178 C1, added by the 25% load point at intermediate  
101 speed.

102 The 4-cylinder test engine was a turbocharged, intercooled (air-to-water) off-road diesel engine,  
103 equipped with a common-rail fuel injection system. The displacement of the engine was 4.4 dm<sup>3</sup> (bore 108

104 mm, stroke 120 mm) and the rated power 101 kW. The engine was not equipped with any exhaust gas after-  
 105 treatment devices. The engine lubricating oil was Valtra Engine CR-4 10W-40.

106 In addition to baseline LFO, the effects of naphtha-LFO blend, MGO, HVO, RME, and kerosene on  
 107 the exhaust gas particle size distribution were investigated. Naphtha-LFO blend contained 20 vol.-% of  
 108 naphtha. Naphtha was a side-product of wood-based renewable diesel production. MGO was a Finnish  
 109 marine fuel produced from recycled lubricating oils. Kerosene was Jet A-1 type aviation fuel. For the fuels,  
 110 cetane number, density, sulfur content and kinematic viscosity at 40 °C were analyzed by the fuel laboratory  
 111 of the University of Vaasa. Table 1 shows the all analyzed fuel properties. The values for the fuel  
 112 polyaromatic content are based on the available literature in Table 1. Based on the information received  
 113 from the fuel supplier, naphtha may contain negligible traces of polyaromatic compounds. Nevertheless,  
 114 the polyaromatic content of naphtha-LFO blend can still be assumed to meet the SFS-EN 590:2013  
 115 standard.

116

## 117 2.2. Analytical procedures

118 The particle number and size distribution, soot, gaseous emissions and residual oxygen content were  
 119 measured in the laboratory conditions and sampled from the raw engine exhaust. The air mass flow rate  
 120

121 **Table 1.** Fuel specifications.

Parameter	Method	LFO	MGO	RME	HVO	Naphtha-LFO	Kerosene	Unit
Cetane number	EN 15195	52	68	53	65	51	41	-
Density (15 °C)	EN ISO 12185 / ASTM D7042	827	843	883	813	805	787	kg/m <sup>3</sup>
Sulfur content	EN ISO 20884 / EN ISO 20846	8.3	< 100	< 5	< 5	6.8	1000	mg/kg
Kin. viscosity (40 °C)	EN ISO 3104 / ASTM D7042	1.84	7.69	4.49	3.5	1.37	0.94	mm <sup>2</sup> /s
Polyaromatics		< 8 <sup>a</sup>	0.9 <sup>b</sup>	0 <sup>c</sup>	0.2 <sup>d</sup>	< 8 <sup>a</sup>	< 26.5 <sup>e</sup>	wt.-%

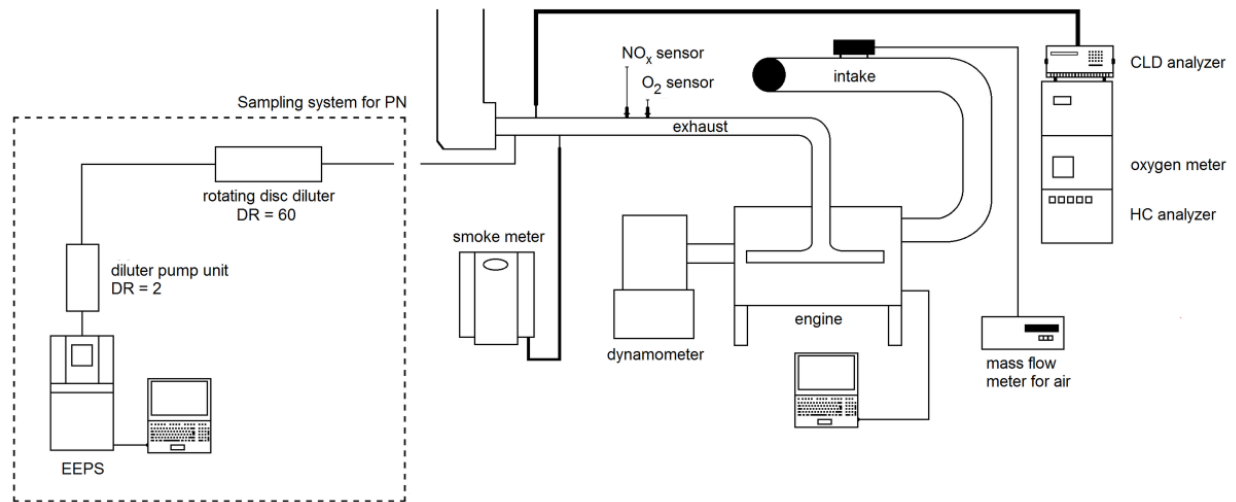
122 <sup>a</sup> The maximum allowable polyaromatic content of the fuel standard EN590 [19].

123 <sup>b</sup> Analyzed by the fuel supplier.

124 <sup>c</sup> [20].

125 <sup>d</sup> [17].

126 <sup>e</sup> The maximum allowable polyaromatic content of the fuel manufacturer [21].



127

128 **Fig. 1.** Experimental setup.

129

130 was measured from the intake air duct of the engine. Each day before the measurements, the analyzers were  
 131 calibrated manually once a day according to the instructions of the instrument manufacturers. The  
 132 experimental setup is in Fig. 1.

133 The particles from a size range of 5.6 to 560 nm were measured by an engine exhaust particle sizer  
 134 (EEPS, model 3090, TSI Inc.), for which the sample flow rate was adjusted at 5.0 l/min. The “SOOT”  
 135 inversion was applied in the EEPS data processing [22]. The exhaust sample was first diluted with ambient  
 136 air by a rotating disc diluter (RDD) (model MD19-E3, Matter Engineering AG). The dilution ratio used in  
 137 the RDD was constant 60. The exhaust aerosol sample was conducted to the RDD and a dilution air was  
 138 kept at 150 °C. The diluted sample (5 lpm) was further diluted by purified air with a dilution ratio of 2.  
 139 Thus, the total dilution ratio was 120.

140 The particle number (PN) was recorded consecutively three times. Each recording was one-minute  
 141 long. One-minute stable time periods were chosen for the results recordings of the PN and particle size  
 142 distributions. The averaging interval of 2 seconds was used for every period. The average PN values,  
 143 calculated from the recordings, were multiplied by the dilution ratio of the exhaust sample. The uncertainty

144 of the PN measurement was approximated by calculating the standard deviation of the PN averages, taken  
 145 from each one-minute recording. The recorded smoke value was the average of three consecutively  
 146 measured smoke numbers (model 415S, AVL). Nitrogen oxides (NO<sub>x</sub>), hydrocarbons (HC) and carbon  
 147 monoxide (CO) were measured by an Eco Physics CLD 822Mh, J.U.M. VE7, and Siemens Ultramat 6,  
 148 respectively.

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

153

### 154 2.3. Experimental matrix and running procedure

155 The measurements were conducted according to the eight-point test cycle C1 of the ISO 8178-4  
 156 standard, known as NRSC, Table 2. The rated speed of the engine was 2200 rpm and the intermediate speed  
 157 was chosen to be 1500 rpm. Additionally, the measurements were taken at 25% load (3.2 bar) at  
 158 intermediate speed. With the low-viscosity kerosene, the default engine control parameters made the engine  
 159 running possible only at intermediate speed. Because no engine parameter optimization was applied during  
 160 the experiments, the additional load point was chosen to gather more information about the effects of  
 161 kerosene on the exhaust particle size distribution. An eddy-current dynamometer of model Horiba WT300  
 162 was employed to load the engine.

163

164 **Table 2.** Experimental matrix [23].

Point	1	2	3	4	5	6	7	8
Speed	Rated				Intermediate			Idle
Load (%)	100	75	50	10	100	75	50	0
Torque (Nm)	351	263	176	35	450	338	225	0
BMEP (bar)	10.0	7.5	5.0	1.0	12.9	9.7	6.4	0



165 A canister of 30 liters was used as a fuel tank. After the tests with each fuel were completed, the fuel  
166 filter was emptied, and the engine was run with new fuel for 10 minutes. At each load point, the intake air  
167 temperature was adjusted at 100 °C downstream the charge air cooler to also ensure proper ignition for low  
168 cetane fuels. The temperature was controlled manually by regulating cooling water flow to the heat  
169 exchanger. Before the recordings, it was waited that the engine had stabilized, the criteria being that the  
170 temperatures of coolant water, intake air and exhaust were stable. The length of the measurement period  
171 was not tied to a certain time.

172 The particle number and size distribution were recorded continuously at each load point. For each fuel,  
173 engine warm up and measurements were performed in an exactly similar way.

174

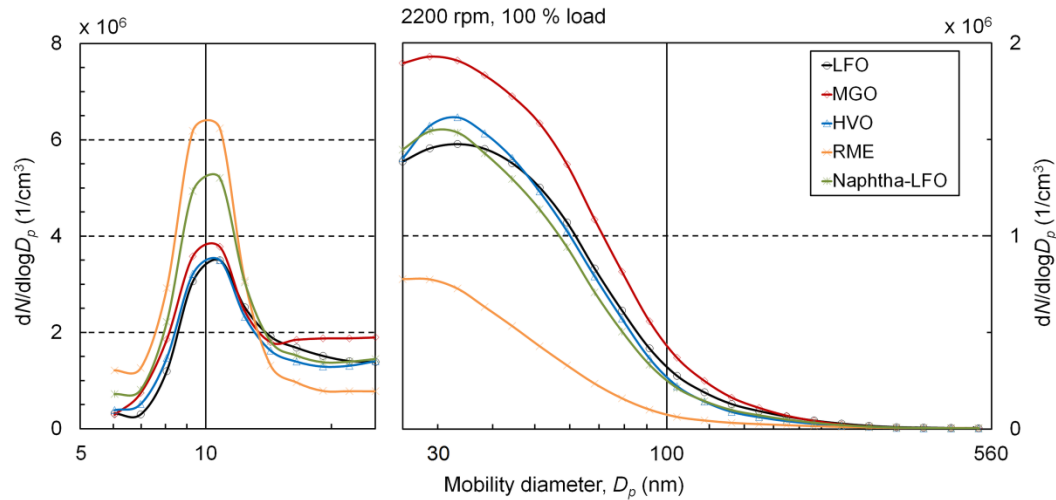
### 175 **3. Results**

#### 176 *3.1. Particle size distributions*

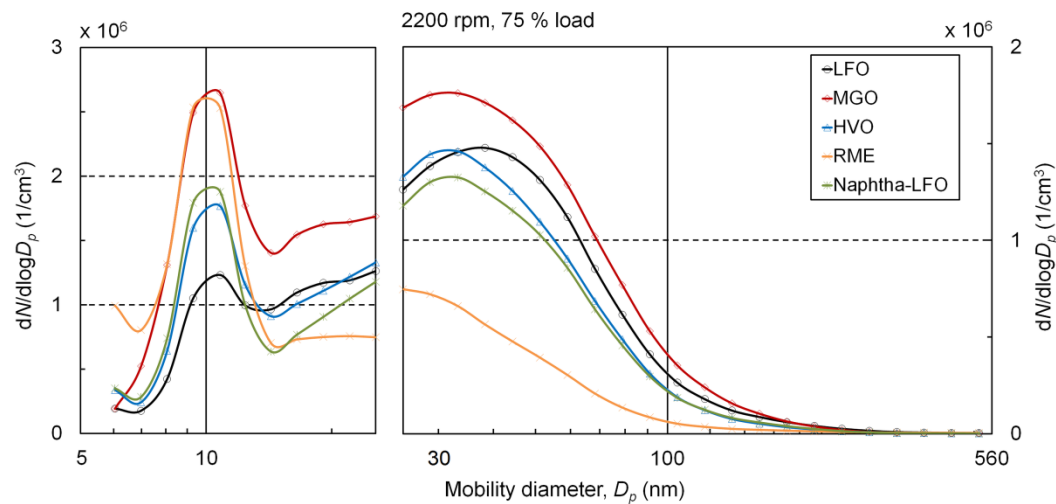
177 Generally at rated and at intermediate speed, naphtha-LFO blend and RME reduced particle numbers  
178 within the size range of 37 to 200 nm compared to LFO while kerosene and methyl ester showed higher  
179 particle numbers within the size range of 8–13 nm than the other fuels. At this range, HVO was favorable  
180 at intermediate speed and at low idle. Below, the distributions are examined more thoroughly at certain  
181 loads.

182 Fig. 2 shows the particle size distributions at full load at rated speed. The distribution was bimodal,  
183 like at many other loads, one peak being detected at a particle size of 10 nm and the other within a size  
184 range of 30 to 60 nm. At the size of approx. 10 nm, the least particles were observed with HVO and LFO.  
185 Between 14 and 340 nm, the smallest particle numbers were recorded with RME, while MGO produced the  
186 highest PN.

187 At 75% load at rated speed, a bimodal distribution was also detected with all fuels, Fig. 3. While the  
188 particle number was clearly the lowest for LFO at 10 nm, RME emitted the least particles within the size  
189 range of 37 to 260 nm, as at full load. MGO emitted a high PN within the entire size range. The nucleation  
190 mode particles were also high with RME.

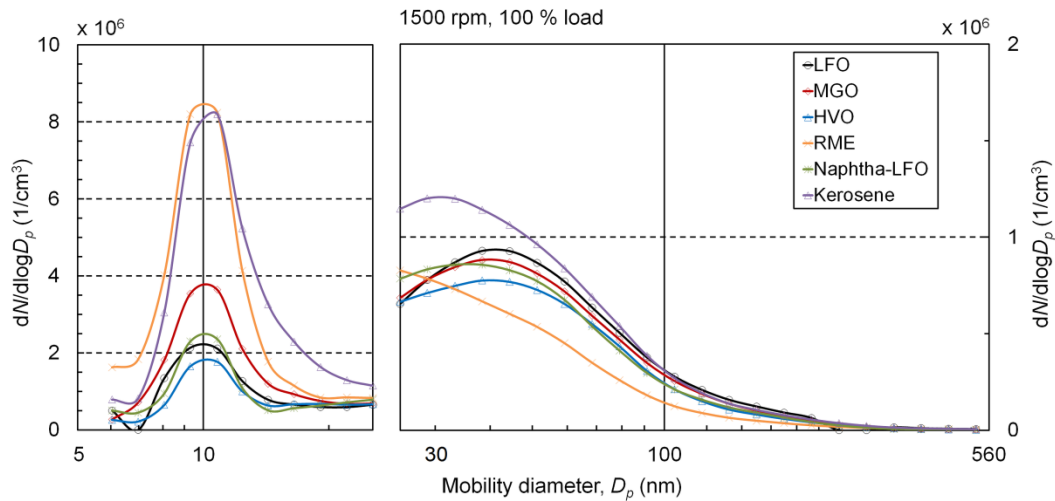


191  
 192 **Fig. 2.** Exhaust particle size distributions at full load at rated speed for different fuels. It should be noted  
 193 that the left and right scales of the y axes are different.  
 194

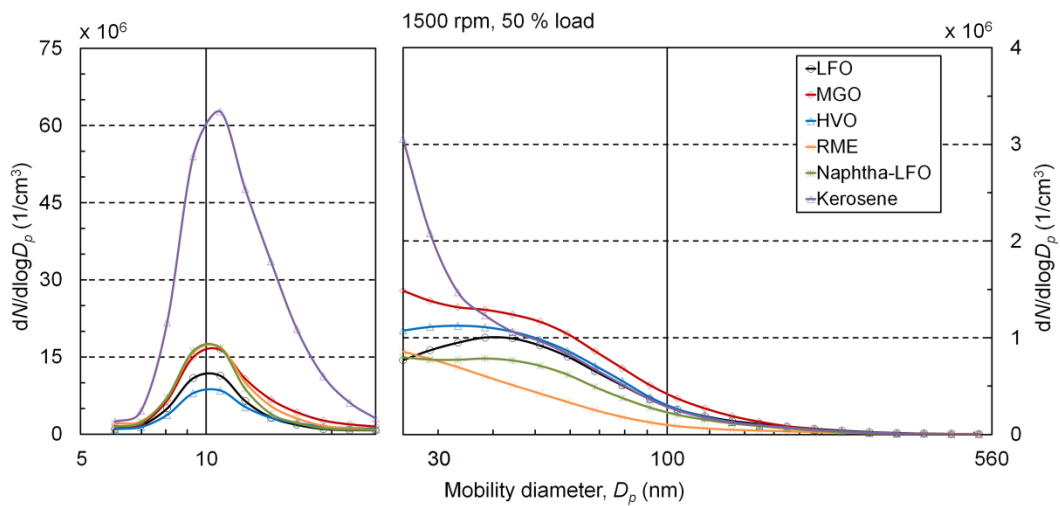


195  
 196 **Fig. 3.** Exhaust particle size distributions at 75% load at rated speed for studied fuels. Please note the  
 197 different scales of the y axes.  
 198

199 For full and half loads at intermediate speed, the particle size distributions are illustrated in Figs. 4 and  
 200 5. Again, there was one peak at a particle size of approx. 10 nm and the other within the size range of 30 to  
 201 60 nm. The least particles between 37 and 260 nm were detected with RME.



202  
 203 **Fig. 4.** Exhaust particle size distributions at full load at intermediate speed for different fuels. Please note  
 204 the different scales of the y axes.  
 205



206  
 207 **Fig. 5.** Exhaust particle size distributions at half load at intermediate speed for studied fuels. Please note  
 208 the different scales of the y axes.  
 209

210 As at rated speed, the use of naphtha-LFO blend reduced again particle numbers within the size range  
 211 of 37 to 200 nm compared to neat LFO. At full load, RME and kerosene produced the most particles at the  
 212 size category of 10 nm while HVO showed the lowest PN. At this category at half load, the PN was far the

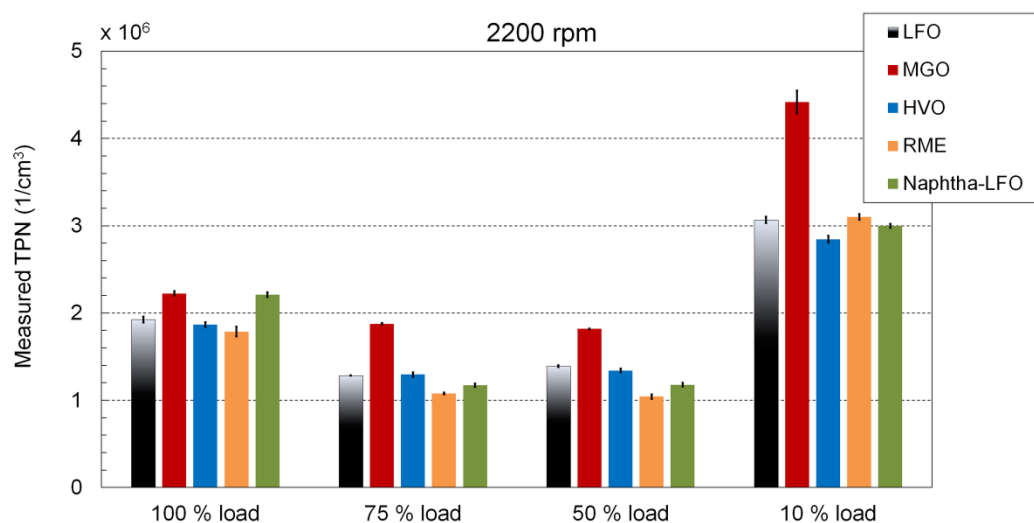
213 highest with kerosene and again the lowest with HVO. At intermediate speed, relative to other fuels, the  
214 MGO results were slightly more favorable than at rated speed.

215 Both at rated and intermediate speeds, the biggest differences in the PN emissions were detected at  
216 the particle size of approx. 10 nm, either HVO or LFO generating mostly the lowest particle numbers.  
217 Kerosene, only used at intermediate speed, produced often the highest amount of particles at 10 nm. At  
218 intermediate speed, the distribution shapes differed from those at rated speed since the peaks between  
219 30 and 60 nm were now much lower compared to those at approx. 10 nm.

220 The measured total particle number (TPN, from 5.6 to 560 nm) is shown at rated speed in Fig. 6 and  
221 at intermediate in Fig. 7. For all fuels at rated speed, the TPN decreased when the load decreased from full  
222 to 75% load and remained then almost constant at half load. It increased, however, when the load decreased  
223 further, being clearly the highest at 10% load.

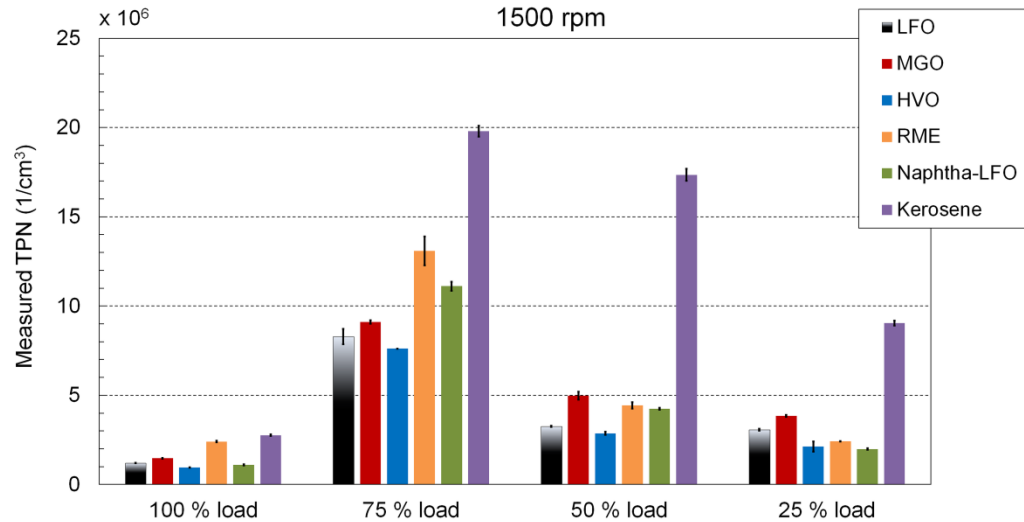
224 At full and 10% loads, the TPN were the lowest when HVO was used. At other loads at rated speed,  
225 RME had the lowest TPN. As a whole, naphtha-LFO blend was very competitive with neat LFO. MGO  
226 generated the highest TPN at all loads at rated speed.

227



228

229 **Fig. 6.** Measured TPN at rated speed.



230

231 **Fig. 7.** Measured TPN at intermediate speed.

232

233 At intermediate speed, the TPN was at the lowest at full and the highest at 75% load. The TPN  
 234 decreased when the load decreased from 75 to 25%. Regardless of load, HVO generated the lowest TPN  
 235 whereas kerosene showed the highest. At some loads, naphtha-LFO generated a higher TPN than LFO, at  
 236 other loads a lower one. MGO resulted again in a somewhat higher TPN than LFO.

237 The measured TPN was divided into two categories depending on how many of the particles out of  
 238 TPN were detected below or above the size category of 23 nm. The shares of the particles above the size of  
 239 23 nm were calculated for the fuels, Table 3. At full load at rated speed, 40% of the particles were detected  
 240 above the size of 23 nm, and thus, 60% below. The lowest average share of the particles above 23 nm was  
 241 detected with RME, and the highest share with HVO. At 75% load at intermediate speed, the shares of the  
 242 particles above 23 nm were only 4.3–5.8%.

243

### 244 3.2. Gaseous emissions and smoke

245 Table 4 shows the brake specific emissions of HC, NO<sub>x</sub>, and CO and smoke number ranges. In general,  
 246 MGO and RME were favorable in terms of CO and HC emissions while NO<sub>x</sub> emissions were the lowest

247 with HVO. The smoke numbers were altogether minor with all fuels. Due to the intended use of an SCR  
 248 catalyst, high NO<sub>x</sub> tuning of the test engine had most likely a decreasing effect on smoke.

249

250 **Table 3.** The share of particles larger than 23 nm out of the TPN for all fuels at different loads.

Speed Load (%)	Rated				Intermediate			Idle
	100 %	75 %	50 %	10 %	100 %	75 %	50 %	0 %
LFO	40	59	58	57	44	5.6	17	7.2
MGO	44	48	51	36	34	5.5	15	8.0
HVO	41	50	55	53	46	5.8	21	22
RME	18	27	34	30	15	4.5	7.2	20
Naphtha-LFO	33	53	57	55	43	4.3	10	7.9

251

252 **Table 4.** Cycle-weighted brake specific emissions of HC, NO<sub>x</sub> and CO and smoke number ranges from  
 253 lowest to highest within the NRSC cycle with different fuels. The specific PN emission was determined  
 254 over the size range of 5.6–560 nm.

	HC (g/kWh)	NO <sub>x</sub> (g/kWh)	CO (g/kWh)	Smoke (FSN)
LFO	0.24	9.3	0.33	0.014–0.038
MGO	0.16	9.3	0.28	0.014–0.033
HVO	0.20	8.9	0.32	0.013–0.031
RME	0.12	10.8	0.30	0.005–0.015
Naphtha-LFO	0.29	-	0.36	0.011–0.031

255

#### 256 4. Discussion

257 In the present study, all particle size distributions measured from the exhaust gas of the high-speed  
 258 off-road diesel engine had a bimodal shape. This common shape of engine-out size distributions has also  
 259 been observed both in on-road and laboratory conditions in case of heavy-duty diesel truck [24], light-duty  
 260 diesel [7], natural gas buses [25], direct-injected gasoline vehicle [26,27] and off-road diesels [17,28–30].

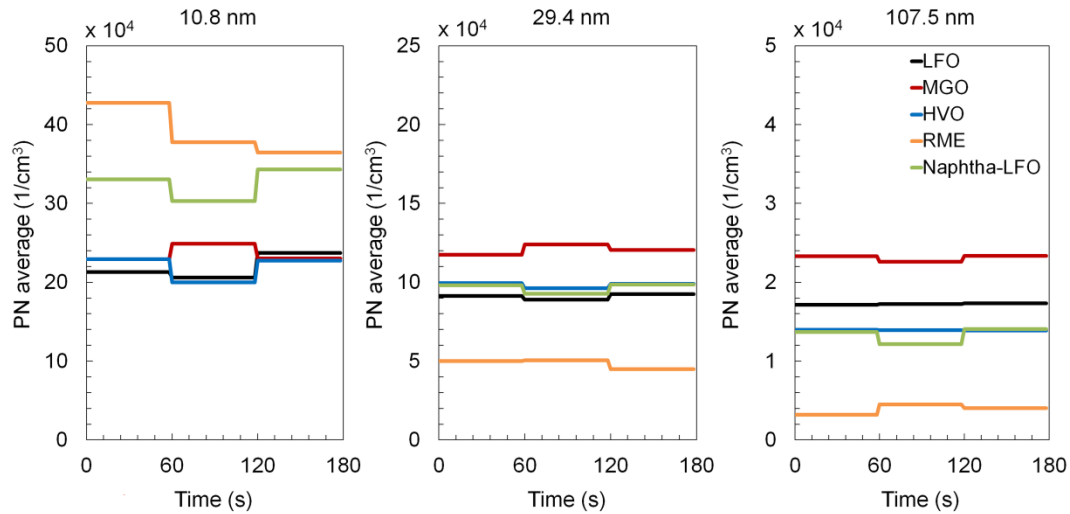
261 Moreover, Ntziachristos et al. [31] detected bimodal particle size distributions in the exhaust gas of a  
262 medium-speed marine diesel engine when LFO was used at low load.

263 The nucleation mode particles have a non-volatile core which is considered to initiate in the cylinder  
264 or in the tailpipe [9,32]. The most of the nucleation mode particles are believed to form during dilution of  
265 the exhaust gas. Their formation has been reported to be sensitive to the engine parameters [33], fuel and  
266 lubricant oil characteristics [34], exhaust after-treatment [35], and dilution conditions such as dilution ratio,  
267 temperature and relative humidity of the dilution air [36]. However, Rönkkö et al. [9] reported that their  
268 formation was insensitive to the fuel sulfur content, dilution air temperature, and relative humidity of  
269 ambient air.

270 Nucleation, condensation and coagulation may change the particle size distribution during the exhaust  
271 gas sampling [37]. In this study, the exhaust gas sample was diluted at two stages in order to decrease the  
272 particle concentration of the sample for the EEPS. The first dilution was made with heated air (150 °C) in  
273 order to prevent the condensation of ambient moisture to sampling lines. However, the first dilution was  
274 not sufficiently hot to the prevention of nucleation mode formation. According to Vaaraslahti et al. [38],  
275 the nucleation mode evaporates completely when an exhaust sample is heated enough. Thus, the authors of  
276 this paper believe the nucleation mode formation could have been avoided if a thermodenuder [39] was  
277 adopted during the PN measurement.

278 Unlike the nucleation mode, the accumulation mode is not sensitive to dilution conditions. [35,40]  
279 Accumulation mode particles are formed in the cylinder, when either the fuel or the remnants of lubricating  
280 oil do not burn completely during combustion.

281 Despite the complex nature of nucleation mode, the PN averages calculated from the EEPS scans were  
282 found to remain fairly constant, mostly, and be repetitious in this study. The variation of the particle  
283 numbers between the three consecutive one-minute EEPS scans can be seen in Fig. 8. The average values  
284 were calculated from the recordings of those three EEPS measurement channel, where the PN peaked with  
285 different fuels at full load at rated speed.



286

287 **Fig. 8.** The variation of the average particle number between the three consecutive one-minute EEPS scans  
 288 at the three EEPS channels (10.8 nm, 29.4 nm and 107.5 nm).

289

290 The physical properties of the liquid fuel tend to control fuel spray characteristics while the fuel  
 291 composition determines the pathways of chemical reactions during combustion [11]. Besides the fuel sulfur  
 292 content, particle formation is also influenced by other fuel characteristics such as the fuel density [41,42],  
 293 viscosity [43,44], and cetane number [45,46]. The start of injection is determined by the fuel density,  
 294 viscosity, and compressibility. After the injection has started, fuel cetane number determines the moment  
 295 when combustion starts. Higher fuel density and viscosity lead to an advanced start of injection. A higher  
 296 cetane number leads to a shortened ignition delay plus advanced combustion. [47]. Too viscous fuel  
 297 increases pumping losses in the injection system and the injection pressure at the pump end may increase  
 298 when conventional in-line pumps are adopted. All this may cause disruptions in the combustion process.  
 299 [48,49]. Higher fuel density and viscosity may lead to incomplete combustion due to poor fuel atomization.  
 300 Therefore, the soot emission will increase. [50].

301 In this study, MGO had the second highest density and highest viscosity, which may partly explain  
 302 why MGO generated the highest TPN at all loads at rated speed even though the cetane number was quite  
 303 high. At intermediate speed with kerosene, on the other hand, the lowest density and viscosity did not



304 compensate for the effect of the lowest cetane number on clearly the highest TPN. RME had the highest  
305 density and second highest viscosity, but the particle numbers within the size range of 37 to 200 nm were  
306 still the lowest. However, RME contained approx. 10% oxygen which usually results in lower soot and thus  
307 lower accumulation mode particles. Naphtha-LFO blend had a slightly lower cetane number and kinematic  
308 viscosity than LFO but a clear difference at density that might explain the reduced particle numbers within  
309 the size range of 37 to 200 nm relative to LFO.

310 During the combustion, the aromatic content of fuel has a role as precursors of particulates [51–53]  
311 although researchers have received divergent results about the effect of the fuel aromatic content on PM  
312 emission [42]. Zetterdahl et al. [53] reported that an increase in the aromatic concentration in low-sulfur  
313 diesel fuel led to decreased or unchanged number of particles emitted. However, Talibi et al. [54] concluded  
314 that the increasing number of methyl branches on the aromatic ring results in an increased PN, and Peña et  
315 al. [55] found that the sizes of primary particles decreased with the addition of methyl group(s) on the  
316 aromatic ring. The concentrations of aliphatics and oxygenated groups in soot particles were also decreased.  
317 They suggested that the combustion of aromatic fuel, if aliphatic chains are present, tends to produce soot  
318 with a compact nanostructure. Due to the same propensity, the content of amorphous, oxygenated, and  
319 aliphatic carbonaceous materials in the soot may decrease. Therefore, the reactivity with oxygen decreases  
320 too. [55]. Nabi et al. [50] concluded that exhaust particle number and mass emission was higher with MGO  
321 compared to diesel fuel due to the higher C/H ratio in MGO. Therefore, they assumed that the aromatic  
322 content of MGO would also be higher. This expectation was based on the study of Kalligeros et al. [56],  
323 who stated that aromatics increase the fuel C/H ratio.

324 In this study, despite the complex nature of nucleation mode PN formation, the favorable PN results  
325 of HVO at the size category of 10 nm are assumed to be caused by the almost zero content of polycyclic  
326 aromatic hydrocarbons. On the other hand, the difference in PN at the size 10 nm between MGO and  
327 reference fuel LFO cannot be explained by the polyaromatics. The kinematic viscosity of MGO was not  
328 much higher than it was for the other fuels, and the content of the polycyclic aromatic compound of MGO  
329 was 0.9 wt.-%. This is lower than for LFO for which the maximum allowable content of the polyaromatics

330 is 8 wt.-% [19]. MGO (< 100 mg/kg) and kerosene (1000 mg/kg) contained, however, more sulfur than  
331 other fuels, kerosene considerably more. Because a higher content of sulfur was available before  
332 combustion, more sulfur oxides, mainly SO<sub>2</sub> and a small fraction of SO<sub>3</sub>, were present after fuel burning  
333 especially in the case of kerosene. The nucleation mode of particles may be caused by sulfuric acid  
334 originating from reaction between SO<sub>3</sub> and water vapor [9,38,57,58]. Therefore, the high PN of MGO and  
335 especially of kerosene at the size 10 nm was assumed to be caused by the same reaction and thus due to the  
336 higher sulfur contents of these fuels.

337 Unlike HVO, RME produced often the most nucleation mode particles. This result is in line with the  
338 several studies of other researchers [44,59–61]. Heikkilä et al. [59] suggested that the relatively high share  
339 of nucleation mode particles with RME may be due to its content of viscous, high boiling point molecules,  
340 triglycerides and glycerol. Moreover, RME also contains ash forming elements, such as alkali metals and  
341 metalloids that may contribute significantly to the formation of the nucleation mode particles.

342 The accumulation mode particles, however, were reduced with RME most likely due to oxygen  
343 bounded in mono-alkyl-ester molecules. Thus, the more complete combustion was enabled and the more  
344 effective soot oxidation was promoted during RME usage compared the usage of other fuels in this study  
345 [62,63]. Nyström et al. [64] detected a lower PN around the peak values of 75–116 nm when a high-speed  
346 off-road diesel engine was fueled with RME compared to low-sulfur diesel fuel. Earlier studies have also  
347 been reported how RME and other FAMEs, either as neat or the blending component, have the similar  
348 decreasing effect on accumulation mode particle numbers [59,65,66].

349 The present study was intended for being able to prepare experiments with a medium-speed engine  
350 carefully. In a later study, some of the current fuels were used in a medium-speed engine. Significant  
351 combustion differences exist as large marine engines has higher stroke-to-bore ratio compared to smaller  
352 high-speed engines. Furthermore, large marine engines are operated with lower engine speeds and higher  
353 air-to-fuel ratios than the small engines in land use. High stroke-to-bore ratio, and low engine speed gives  
354 more time for fuel to combust which promotes soot oxidation. [31]. As presented by Ntziachristos et al.  
355 [31], use of the LFO fuel in a marine engine may result to much lower specific mass emissions of particles

356 compared to the emission limitation intended for road vehicles at some loads. Therefore, the presented PN  
357 reductions may be presupposed when the fuels of this study are later intended for marine applications. No  
358 parameter optimization was applied with the studied fuels at this first stage to be able to compare the fuels  
359 first without any modifications. At the next stages, parameters have to be optimized.

360

## 361 **5. Conclusions**

362 This study concentrated on working out how different alternative off-road engine fuels affect the  
363 exhaust particle size distributions of a high-speed diesel engine. The examined fuels were a blend of  
364 renewable wood-based naphtha and marine low-sulfur LFO, circulation-origin MGO, RME, HVO, and  
365 kerosene. LFO worked as baseline fuel. The measurements were performed according to the NRSC test  
366 cycle. Based on the obtained results, the following conclusions could be drawn:

367

- 368 • A bimodal shape was detected in all particle size distributions.
- 369 • Considering the complex nature of nucleation mode PN formation, no consistent conclusions could be  
370 drawn concerning the particle numbers under the size category of 50 nm.
- 371 • Except at idle, the particle numbers above 50 nm were the lowest with RME most likely due to oxygen  
372 bounded in mono-alkyl-ester molecules.
- 373 • Relative to LFO, both naphtha-LFO blend and RME reduced particle numbers above 50 nm-at rated and  
374 intermediate speeds.
- 375 • Circulation economy based MGO generated the highest total particle number (TPN) at all loads at rated  
376 speed, most likely due to the higher fuel sulfur content. At intermediate speed, still higher TPN values  
377 were recorded for kerosene, the sulfur content of which was higher by one order of magnitude relative  
378 to MGO.
- 379 • In terms of TPN at intermediate speed, renewable HVO was more beneficial than LFO. At rated speed,  
380 the HVO results were quite similar to those of LFO.

- 381 • Concerning the TPN as a whole, the blend of renewable naphtha and LFO was competitive with LFO.  
382 At some loads, the blend emitted more particles, at other loads less than LFO.
- 383 • MGO and RME were favorable in terms of CO and HC emissions while the lowest NO<sub>x</sub> emissions were  
384 recorded with HVO.
- 385 • Smoke emission was negligible for all fuels.

386

### 387 **Declarations of interest**

388 None.

389

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396

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