Origin of particle emissions of a new IMO NO_x Tier 2 category cruising ship compliant with European SO_x emission control areas

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Background

Estimations are presently being done of the effects of the new and forthcoming IMO and EU marine emission legislations - with vivid developments of marine engine and after-treatment technologies being on the way - also on aerosol emissions from ships. So far there are no regulatory limits as regards particle emissions, even for the most 'restricted' areas, viz. European emission control areas, ECAs. Only SO_x and NO_x are limited. IMO's Marpol Annex VI Tier 2 requirements for NO_x from 2011 on have made development of new emission generation vessels unavoidable. Also, according to IMO and EU fuel quality enhancement to ≤ 0.1 w-% sulphur from the current ≤ 1 w-% S is implemented in ECAs in 2015. This means either switch from the heavy fuel oil HFO to 'cleaner' fuels like distillates (MGO, MDO) or cleaning the exhaust from SO_x with scrubbing. Technological changes, either new engines or emission abatement by fuel change or after-treatment, have also effects on particle emissions, partly to an unresolved extent. Particle emissions are also affected by engine power change like slow steaming. One reasoning for lacking requirements for particle emission control are estimations e.g. by IMO and by scrubber suppliers that particulate matter will be reduced from 60-75 % to 80-85 %, respectively, together with the adopted SO_x and NO_x emission abatement technologies. This is not proven yet.

In this study fuel quality and engine operational parameter effects on particle emissions of new IMO Tier 2 NO_x emission category ro-ro ferry were investigated. The operational conditions were realistic for a cruising ship including running at normal constant loads as well as transitional loads necessary e.g. in port areas. In addition, changes in emission rates by gradual load increase from 10 % to full 100 % engine power were analysed.

Experimental

Emissions were monitored from one main engine (ME) of the ship. Propulsion system was 4 x 4-stroke derated medium speed MEs (4 x 7600 kW) with turbo-charging and variable valve timing, and 4 auxiliary engines. The ship had a mechanical drive and controllable pitch propellers. Emission formation was governed by engine internal measures, no exhaust after-treatment technologies were applied. The ship used either IMO SECA compatible heavy fuel oil FO380 with 1 % sulphur S or gasoil MGODMA with 0.09 % S. The former is the maximum currently allowed in the Baltic Sea and North Sea and the latter in EU ports.

During dynamic operations of the engine particle number (PN) was monitored with electrical low pressure impactor (ELPI) that records continuously particle number emission and particle sizes over aerodynamic particle size D_a range circa 20 - 10000 nm. Dilution air was heated to 300^{o}C to avoid the highly ambient conditions dependent mode of nucleated volatile particles, which are generated from volatile hydrocarbons and sulphuric acid as the exhaust is cooled down and diluted. Dilution ratio (Dr) ranged 30 – 100. Particulate mass PM was sampled during constant loads batch-wise with

ISO8178:2006 standard (Dr 12-16, T max 52°C) or ISO9096 standard (in-stack, T 220-260°C). Gaseous emissions (NO, NO_2, CO_2, SO_2 etc.) were recorded with FTIR. Shaft power and engine speed of the ME were recorded. Information of the SFOC vs. load and respective exhaust mass flow rates were available.

Results

The continuous particle emissions presented here are for non-volatile accumulation mode particles of size D_a > 55 nm, which are constituted of black carbon (BC), oxides and sulphates of ash elements and non-volatile HCs. These emission constituents are stable, well defined and remain quantitatively unchanged in various sampling conditions. There is also no immediate change in such non-volatile primary emissions when released into air. The difficulty in sampling and monitoring 'total' aerosol emission is due to typical marine exhaust of inferior fossil fuel quality always being strongly a function of sampling or ambient conditions, as inherently it contains high amounts of volatile matter, viz. sulphuric acid, water and low molecular weight hydrocarbons, **Figure 1**. If desired, there exists methodology for describing the 'total particle' emission (solid particles + volatile aerosols); it requires batch sampling, like that according to US EPA201a + EPA202 (in-stack PM + condensable particulate matter).

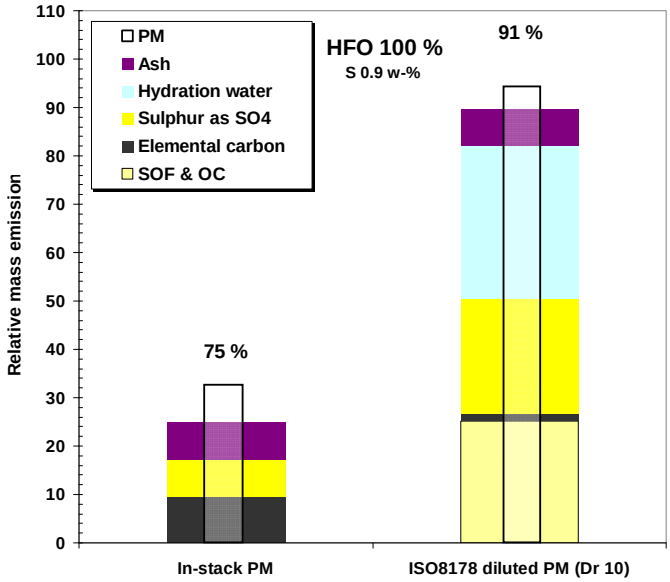

Figure 1 PM emission according to established procedures for power plants (in-stack) and marine propulsion (ISO8178:2006).

The non-volatile PN emission of the Tier 2 ME was very strongly a function of fuel quality, viz. the fuel sulphur (and probably ash) content, and to a much less extent on load (high vs. low). Hence before port approach the mere fuel change from 1 % S to 0.09 % S caused non-volatile particle emission (PN/s) to go down to less than 10 % of the original, without change in cruising load (85 %). Load variations in port operations with low S fuel caused PM to variate 20 -fold up to circa 20 % of the maximum emission with high sulphur fuel and high load.

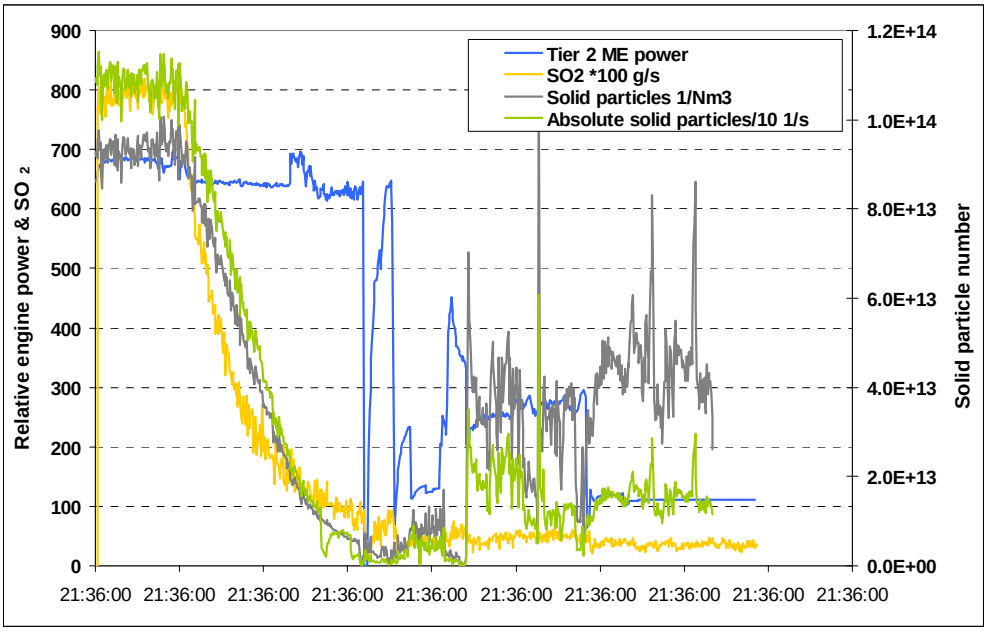

Figure 2 Effect of ME power and fuel change on particle emission in port approach.

Without fuel quality HFO -> MGO change there was no significant change in emission factor (PN/kWh) of accumulation mode particles (D_a > 55 nm) over almost the whole studied power range. Only at ultimately low loads (< 15 %) a slight increase in the emission factor was experienced, **Figure 3**.

Thinking of human exposure to PM in harbor areas, where engine loads may be low, variable, and main engines even turned off, meaningful unit describing particles release is emission per time or per distance, as emission volumes fluctuate, being directly proportional to engine load. An illustration of the effect of engine powering on particle emissions per second is in **Figure 3**. The solid non-volatile particles can be considered as an air quality indicator in attainment areas, and the number release (PN/s) seems to be linearly correlated with engine load in load range 10 – 90 %, as long as fuel is not changed before berthing. As regards cruising ships, it is typical for fuel economy reasons that both main engines and auxiliary engines are operated at relatively high power also close to port, and part of the engines are turned off completely for speed reduction. This means that relatively high amounts non-volatile particles (PN/s) may also be produced in harbors from these ship types.

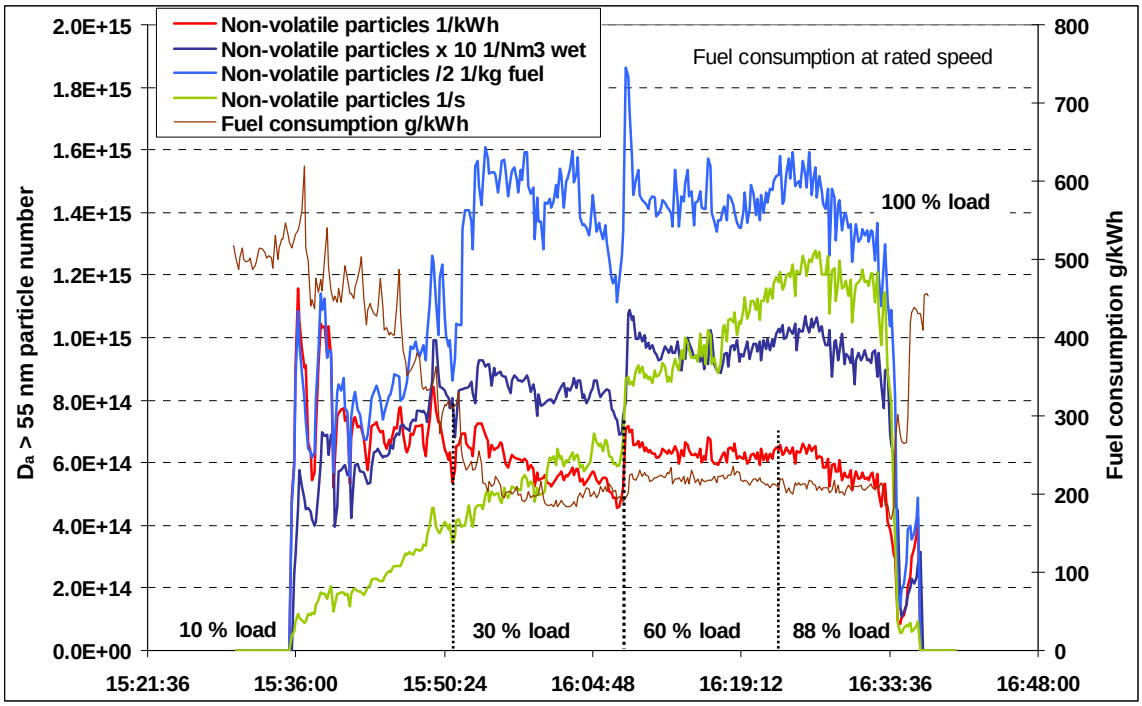

Figure 3 Non-volatile particle emissions (PN/s, PN/Nm^3) and emission factors (PN/kg fuel, PN/kWh) over medium speed marine ME load range 10 – 100 %.

Due to larger size of the lowest load, 10-30 %, particles, **Figure 4**, these may yield some increase in PM mass emissions, compared to smaller particles from higher loads. An estimation of PM mass emission rates at different ME engine loadings of various sea operations is in **Table 1**. Depending on the formed particle size range a density estimate between 1 – 1.6 was used as an average for size distributions. For port approach fuel had been changed to low S MGO.

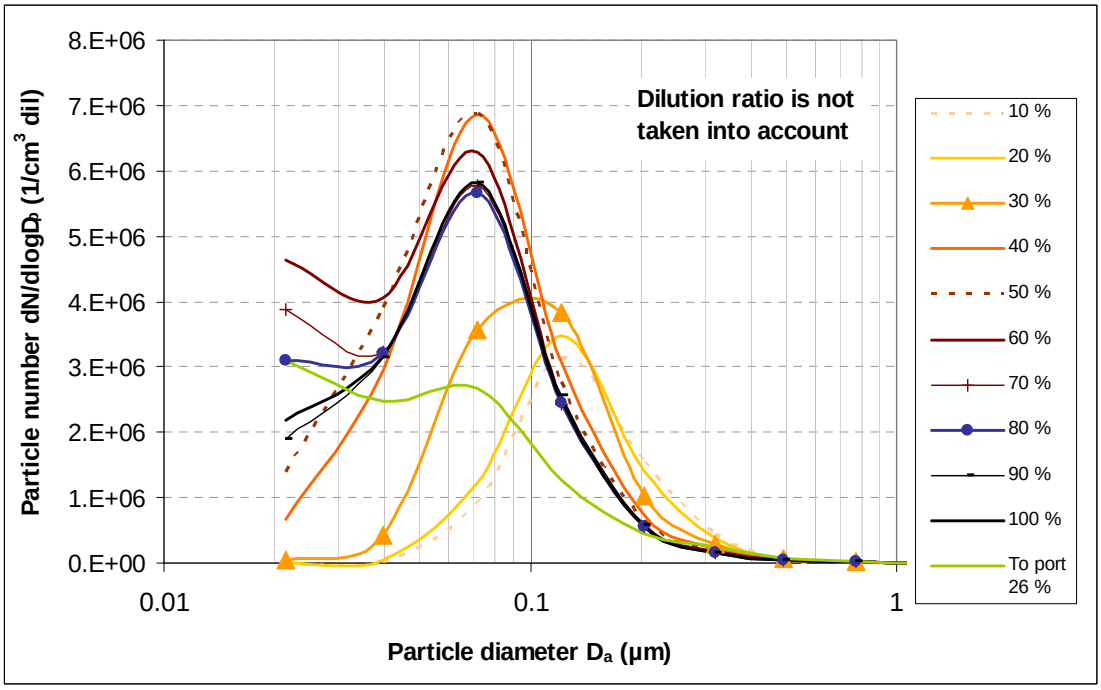

Figure 4 Particle number size distribution (ELPI) at main engine powering range 10 – 100 % with 1.0 % S fuel at sea.

Table 1 Estimated relative PM emissions from the main engine in various phases of cruising.

Load		Sulphur %	Relative non-volatile PM mass emission (ELPI > 55 nm)			
			PM / kWh	PM / Nm^3	PM / kg fuel	PM / s
Low load	< 35 %	1.0	3.7	2.2	2.0	0.80
Slow steaming	35-60 %	1.0	0.93	0.87	1.0	0.54
At sea	60-100 %	1.0	1.0	1.0	1.0	1.0
At sea	92 %	1.0	0.92	0.95	0.84	
Manoeuvring		1.0				
To port	av. 26 %	0.09	0.27	0.16	0.16	0.07

Due to the tightened NO_x emission requirements for Tier 2 vessels from 2011 on implications of NO_x – PM mass trade-off may be expected. Somewhat higher than expected PM emission levels were measured for ISO8178 PM. The in-stack PM emission factor was, however, of the order of same magnitude, 0.2 g/kWh @ 83-100 % load, as found earlier for a respective 'Tier 0' level MS marine engine. As expected there was no synchrony between the hot stack PM (ISO9096) and the diluted and quenched PM (ISO8178) emission rates, the difference was approximately 7-8 fold at the maximum, 0.2 g/kWh vs. 1.5 g/kWh at high cruising loads, respectively.

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Background

Estimations are being done of the effects of the new and forthcoming IMO and EU marine emission legislations – with current developments of marine engine and after-treatment technologies - also on aerosol emissions from ships. By now there is no particle emission control in European emission control areas, ECAs. Only NO_x and SO_x are limited. Stricter regulations are for NO_x from 2011 on (IMO Tier 2), and SO_x will be further limited in 2015 in EU waters. Abatement solutions may be engine, fuel, powering or after-treatment based. Effects on particle emissions are partly unresolved. Expectations of IMO and scrubber suppliers is 60-85 % PM reduction as a by-product of SO_x plus NO_x reduction technologies. This is not proven yet.

In this study fuel quality and engine operational parameter effects on particle emissions of new IMO Tier 2 NO_x emission category ro-ro ferry were investigated. The operational conditions included normal cruising, manoeuvring and transitional loads needed in port areas. Analysed was also gradual load increase from 10 % to full 100 % engine power.

Experimental

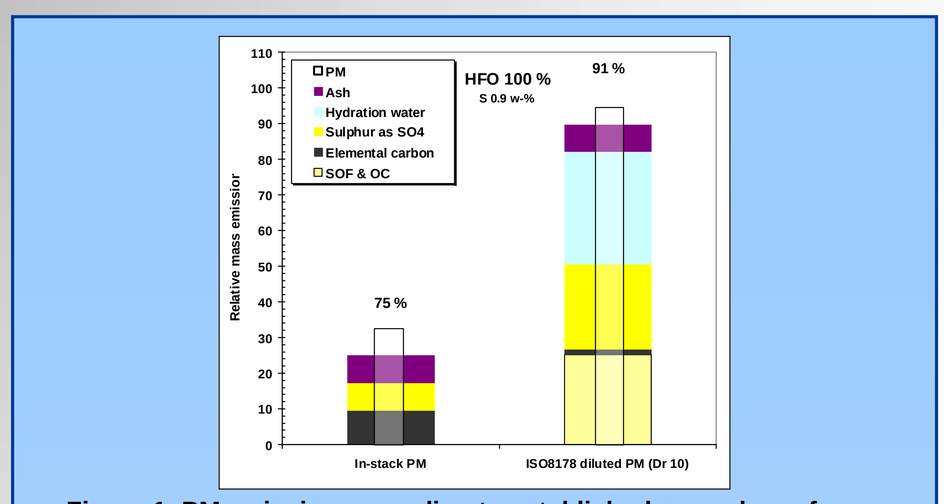
Main engine (ME) was experimented. Propulsion was turbo-charged 4-stroke medium speed MEs (4 x 7600 kW) and 4 auxiliary engines. The ship had a mechanical drive and controllable pitch propellers. Emission formation was governed by engine internal measures, without after-treatment. Fuels were IMO SECA compatible heavy fuel oil HFO with 1 % sulphur S or gasoil MGO with 0.09 % S. The latter is required in EU ports.

Continuous particle number (#) emission was monitored with electrical low pressure impactor (ELPI) over aerodynamic particle size D_a range 20 - 10000 nm. Dilution air was at 300°C to avoid the highly ambient conditions dependent volatile particles, which are generated from hydrocarbons and sulphuric acid in exhaust cooling and dilution. Dilution ratio (Dr) ranged 30 – 100. For particulate mass (PM) ISO8178 standard (Dr 12-16, T max 52°C) or ISO9096 standard (in-stack, T 220-260°C) were applied. Gaseous emissions (NO, NO_2, CO_2, SO_2 etc.) were recorded with FTIR. Shaft power and engine speed were recorded. Information of the SFOC and exhaust mass flow rates were available.

Results

The continuous particle emissions are for non-volatile accumulation mode particles of size D_a > 55 nm, which are constituted of black carbon (BC), oxides and sulphates of ash elements and non-volatile hydrocarbons (HC). Particle mass below this size was negligible. These constituents are stable, well defined and remain quantitatively unchanged in various sampling conditions. The difficulty in sampling and monitoring 'total' aerosol emission is, due to typical marine exhaust from inferior fossil fuel qualities, in being strongly a function of sampling or ambient conditions, as the emission contains also high amounts of volatile matter, viz. sulphuric acid, water and lower molecular weight HCs, **Figure 1**. Ultimately, there exists a rarely used batch-wise methodology for describing the 'total' PM emission at 0°C: US EPA201a + EPA202 (in-stack PM + condensable particulate matter).

The non-volatile particle # emission of the ME was very strongly a function of fuel quality, viz. the fuel S (and probably ash) content, and to a much less extent on load. Before port approach the mere fuel change from 1 % S to 0.09 % S caused non-volatile particle emission (1/s) to go down to less than 10 % of the original, without change in cruising load (85 %), **Figure 2**. Load variations in port operations with low S fuel caused the emission to variate 20 –fold, up to max. circa 20 % of the emission with high S fuel and high load.



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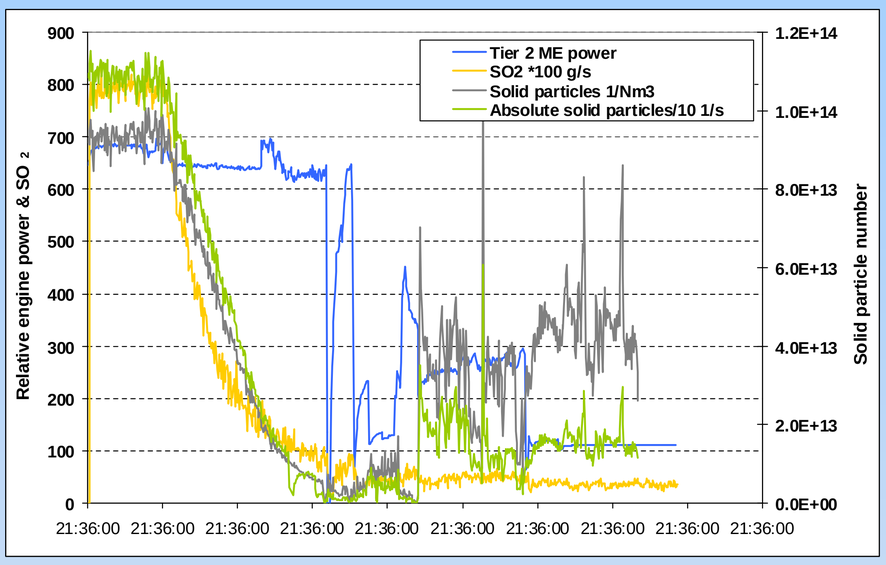

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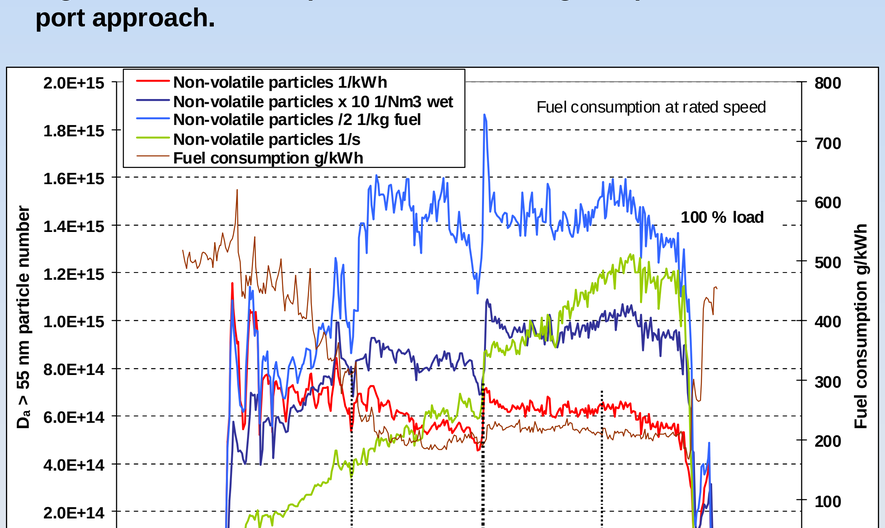

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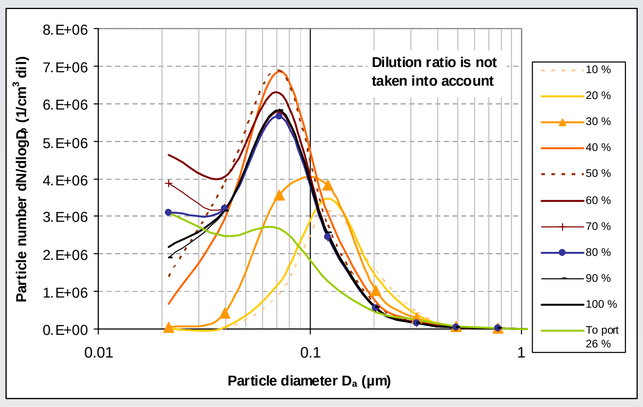

Figure 4. Particle size distributions (ELPI) at main engine powering 10 – 100 % at sea and port approach.

Without fuel change HFO -> MGO there was no significant change in particle emission factor (1/kWh) over almost the whole studied power range. Only at ultimately low loads (< 15 %) a slight increase in the emission factor was experienced, **Figure 3**.

Thinking of human exposure to particles in harbor areas, where engine loads may be variable, meaningful unit describing particles release is emission per time, as emission volumes fluctuate being directly proportional to engine load. An illustration of the effect of engine powering on particle emissions per second is in **Figure 3**. The non-volatile particles are one air quality indicator in human attainment areas; the time based (1/s) was is linearly correlated with engine load in load range 10-90 %, without fuel change before berthing. For cruising ships, it may be beneficial for fuel economy to operate the engines at relatively high power also close to port, part of the engines being off for speed reduction.

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Due to tightened NO_x emission limits for Tier 2 engines in 2011 implications of NO_x – PM mass trade-off may be expected. Somewhat higher than expected PM emission levels were measured for ISO8178 PM. The in-stack PM emission factor was, however, of the order of same magnitude, 0.2 g/kWh @ 83-100 %, as found earlier for a respective 'Tier 0' level MS marine engine. As expected there was no synchrony between the hot stack PM (ISO9096) and the diluted and quenched PM (ISO8178) emission rates, the difference was approximately 7-8 fold at the maximum, 0.2 g/kWh vs. 1.5 g/kWh at high cruising loads, respectively.

Conclusions

1. Throughout load range 15-100 % non-volatile particle emission factor (1/kWh) is quite constant, independent on engine load.
2. Non-volatile particle # emission (1/s) increased linearly with load in load range 10 – 90 %.
3. From health point of view the non-volatile particle emission (1/s) was very low in port areas for the good quality MGO compared with HFO at cruising speeds, reduction being 80-95 %. In low load conditions the reduction merely due to fuel change was circa 60-70 %.
4. Implications of NO_x – PM emission trade-off were seen in the ISO8178 PM emission factor for the Tier 2 engine. The in-stack PM rate was 'as usual', circa 0.2 g/kWh at cruising loads.

Table 1. Estimated relative PM emissions from the main engine in various phases of cruising.

Load		Sulphur %	Relative non-volatile PM mass emission (ELPI > 55 nm)			
			PM / kWh	PM / Nm^3	PM / kg fuel	PM / s
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