On the correlation of black carbon, filter smoke number and PM related elemental carbon measured at large medium speed 4-stroke Diesel engines

Keywords: Black carbon, elemental carbon, particulate matter, Arctic ice, international shipping, combustion aerosols, measurement, characterization, chemical composition, carbonaceous particles.

Motivation

Black carbon (BC) emissions from ships are widely unknown and different assumptions on emission factors for BC from ships can be found in the literature [Lack], [Agrawal]. BC absorbs light efficiently and thus has a high global warming potential. Furthermore BC, as deposited on ice and snow, accelerates melting by a decreased albedo effect. Correlations are missing between different measurement procedures, determining different states of "carbon" content in the exhaust gas of large medium speed Diesel engines. Therefore further investigations have been performed at MAN Diesel & Turbo SE and measurement data are presented from different measurement campaigns and with different fuels.

Methods

Unfortunately no distinct definition for BC exists. The term BC is used when light absorbing optical properties of atmospheric aerosols are meant. BC has been measured by multi angle absorption photometer (MAAP) and compared with well established and proven methods of particulate matter (PM) measurement according to ISO-8178 in combination with chemical analysis of the PM constituents and with filter smoke number (FSN) measurement according to ISO-10054. Measured values of the 2 optical-physically methods MAAP and FSN and the analytic-chemically method for PM will be compared.

The model 5012 MAAP by Thermo Scientific was used to measure atmospheric BC by optical light adsorption of ambient atmospheric aerosols through a combination of transmittance, measuring the aerosol extinction, and reflectance, measuring the aerosol scattering, at multiple detection angles. This principle avoids issues related to diffuse back scatter and enhanced adsorption by other components as black carbon like sulfates or secondary organic aerosol [Petzold]. The instrument has been employed in a measurement setup downstream of a controlled dilution system as described in [Lauer].

The smoke meter 415S G002 by AVL was used to measure the FSN of Diesel exhaust soot. The blackening of a filter caused by the soot content is evaluated by calculation from the optical reflectance of the blackened filter relative to a clean filter. The FSN corresponds to the concentration of soot and can be expressed by a correlation equation according to [AVL]

$$\text{"soot"}(mg/m^3) = \frac{1}{0.405} \times 4.95 \times FSN \times e^{(0.38 \times FSN)} ,$$

which has been explicitly established for this instrument.

The 472 smart sampler modular GEM140 by AVL was used to measure PM collected on quartz fiber filters for subsequent chemical characterization. The sampled PM constituents have been analyzed for elemental carbon (EC) and organic carbon (OC) by a thermo-graphic method on the basis of VDI-2465/2. The method has been described in [Lauer] as well.

The typical fuel used in marine transport is residual heavy fuel oil (HFO). Marine gas oil (MGO) has been used as a reference for future fuels used in emission controlled areas (ECA) like the Baltic Sea. Moreover renewable fuels have been used to demonstrate very low "carbon" emissions, due to improved soot oxidation during combustion by the oxygen content of these fuels. Characteristic values of the investigated fuels are listed in table 1.

Fuel	HFO	MGO	Palm oil	Animal fat	Sunflower oil	Soya bean oil
Origin	fossil	fossil	renewable	renewable	renewable	renewable
Category	residual	distillate	vegetable	animal	vegetable	vegetable
Viscosity [mm²/s]	719 @50°C	2,6 @40°C	29 @50°C	31 @50°C	23 @50°C	23 @50°C
Density @ 15°C [kg/m³]	982	838	916	914	924	923
Hydrogen [% mass]	10.45	12.72	11.00	11.20	11.00	11.20
Carbon [% mass]	86.94	87.08	77.30	77.00	78.30	78.10
Oxygen [% mass]	n.a.	n.a.	11.50	11.60	10.50	10.50
Sulfur [% mass]	2.17	<0.1	7.2 ppm	2.8 ppm	1.4 ppm	<0.1
Nitrogen [% mass]	0.42	<0.1	n.a.	n.a.	n.a.	n.a.
Ash [% mass]	0.017	0.0011	0.0016	0.0017	<0.001	<0.001
Lower heat value [kJ/kg]	40,435	42,966	37,144	37,292	37,268	37,264

Table 1: Main fuel characteristics

Measurements have been performed on a serial 8L21/31 medium speed 4-stroke Diesel engine and a single cylinder test engine 1L32/44 as listed in table 2.

Type	Bore	Stroke	Speed	Power
Serial engine	21 cm	31 cm	1000 rpm	215 kW/cyl
Test engine	32 cm	44 cm	750 rpm	400 kW/cyl.

Table 2: Main engine data

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Results

Table 3 summarizes the measured emissions of EC, BC and soot. Additionally conversion factors f_{PF} from emissions per kWh to emissions per kg of fuel is given. BC emission factors for all loads from the fossil fuels range from 0.0045 to 0.238 g/kg fuel. In general the highest emissions occur at 10% engine load.

Fuel	Engine load [%]	EC [mg/kWh]	BC [mg/kWh]	FSN [-]	Soot [mg/kWh]	f_{PF}
HFO	100	21	4.8	0.04	2.76	4.72
	75	13	10.1	0.12	9.24	4.70
	25	15	22.9	0.20	19.42	3.55
	10	94	126	0.36	101.72	1.89
Palm oil	100	10	1.2	0.01	0.69	4.35
	75	8	1.6	0.02	0.38	4.35
	25	14	5.9	0.09	0.96	3.28
	10	65	33	0.33	19.22	1.81
Animal fat	100	8	1.1	0.01	0.66	4.34
	75	8	1.9	0.01	0.75	4.33
	25	10	4.8	0.02	1.91	3.34
	10	34	25.5	0.05	11.83	1.88
Soya bean oil	100	18	1.9	0.01	0.69	4.34
	75	15	3.3	0.01	0.70	4.32
	25	22	6.8	0.03	2.94	3.31
	10	87	45.7	0.06	15.03	1.83
Sun-flower oil	100	24	1.7	0.01	0.67	4.38
	75	19	1.8	0.01	0.74	4.29
	25	22	5.2	0.03	2.93	3.32
	10	77	23.9	0.08	19.01	1.88
MGO	100	8	0.9	0.01	0.67	5.05
	75	7	1.3	0.02	1.50	5.00
	25	12	4.3	0.09	9.04	3.75
	10	62	32.5	0.33	84.89	2.06

Table 3: Emission and conversion factors from emission per kWh to emission per kg of fuel

After careful evaluation of each measurement data, none of the values could be excluded as outlier. Nevertheless the wide scatter band which should not be neglected, reasonable correlations can be found in diagrams 1 and 2 between EC and BC or soot in mg/kWh. As can be seen by the potential regression lines, the EC from PM measurement is always overestimated compared to FSN and MAAP. In contrast to this in diagram 3 MAAP only slightly overestimates BC compared to FSN's soot and shows a quite good correlation with R^2 of 0.86.

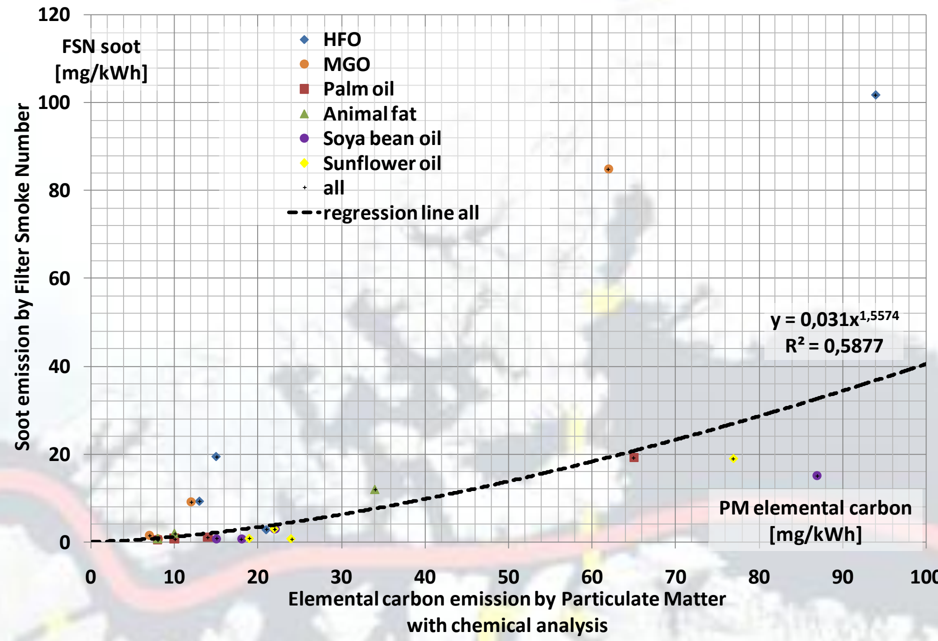

Diagram 1: Correlation between EC and Soot

Conclusions

It could be successfully demonstrated that reasonable correlations are possible between different measurement procedures, determining different states/definitions of "carbon" content in the exhaust gas of large medium speed 4-stroke Diesel engines. With regard to the ongoing discussion on the impact of emissions of BC from international shipping on the Arctic, emission factors for EC, BC and soot have been presented. BC emission factors for fossil fuels in this study correspond to the value given in [Agrawal]. With regard to the simplicity of the direct FSN measurement method compared to the MAAP or PM measurement, which requires either controlled high dilution of the exhaust gas or additional chemical analysis, the correlation between soot and black carbon appears acceptable.

Results

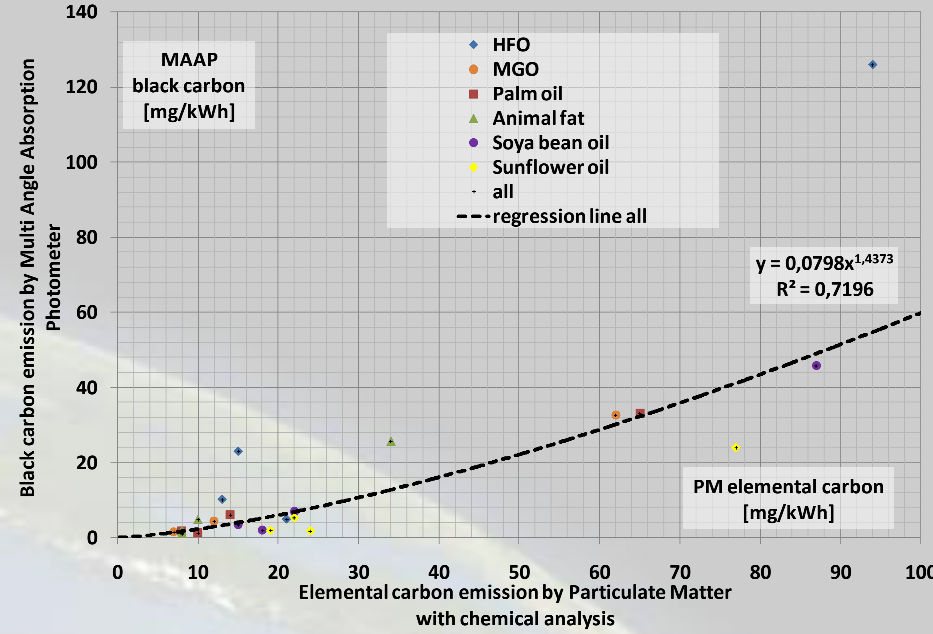

Diagram 2: Correlation between EC and BC

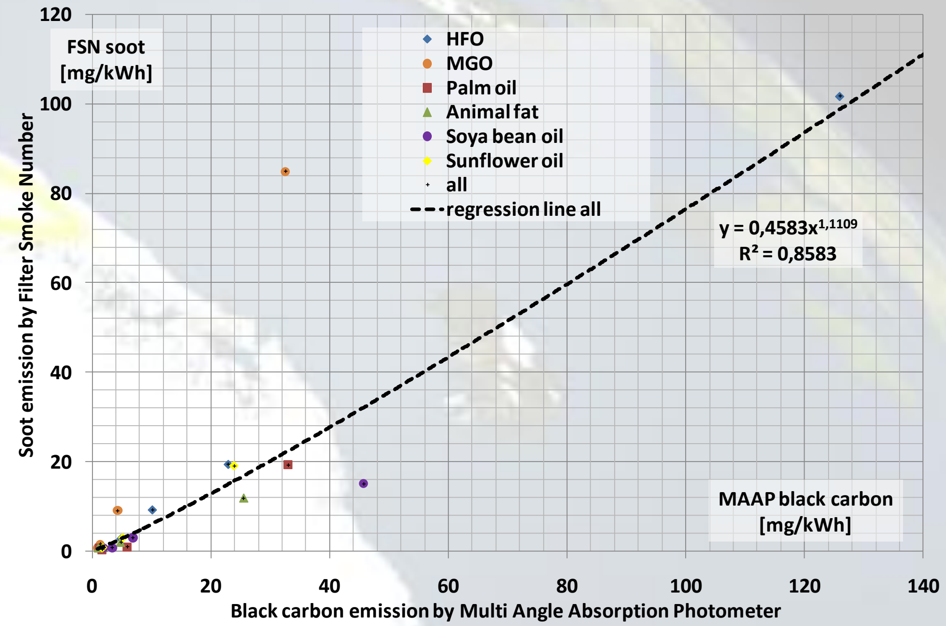

Diagram 3: Correlation between BC and Soot

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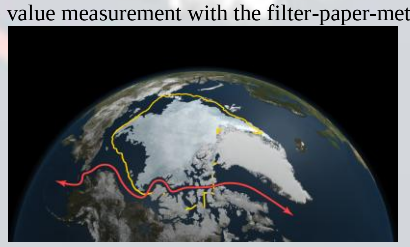

Arctic Ice Minimum by Earth Observatory Images: NASA Goddard Space Flight Center, 09.09.2011.