

Particulate emissions from aromatic containing fuels

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Introduction

Reduced Sulphur limits in SECA region [1]. Interest to study the effect of aromatics.

Previous experiments showed a decrease in PM emission (mass and number) when adding aromatics (contrary to expectations) [2]. Why?

Hypothesis: More premixing => less PM formation



Objectives

- To explain findings from previous results (multi-cylinder) [3]
 - Using single cylinder research engine (Euro IV calibration) and pressure trace analysis
 - Using ignition improver to further isolate the effect of aromatics in the fuel
- To increase understanding of PM emissions (= formation – oxidation)
 - Variation in pre-mixing by varying rail pressure and EGR

Figure 1. Comparison Low Load (A25)

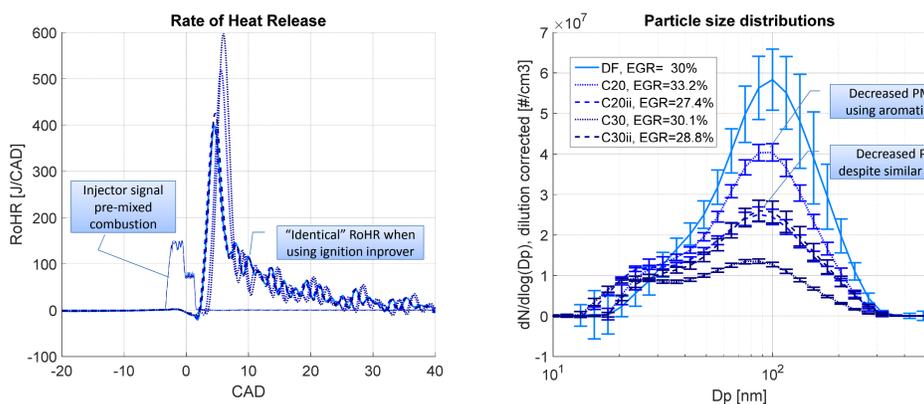


Figure 3. Variation in P_{inj} with EGR (Medium Load, B50)

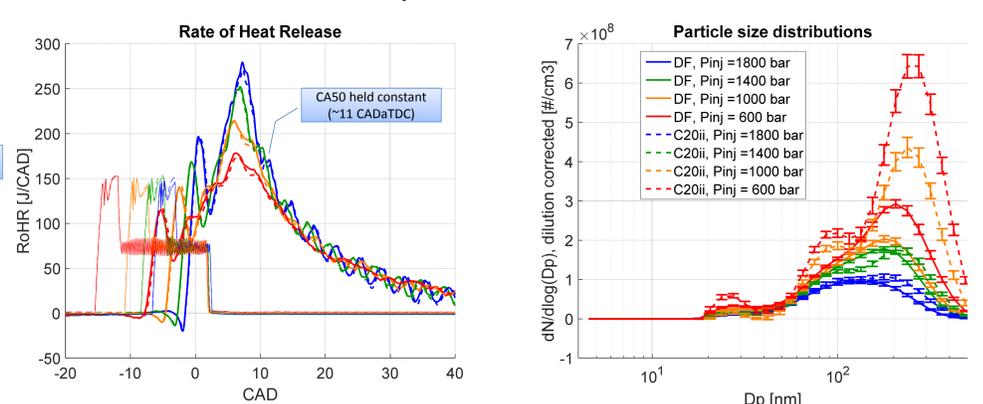


Figure 2. Comparison High Load (C75)

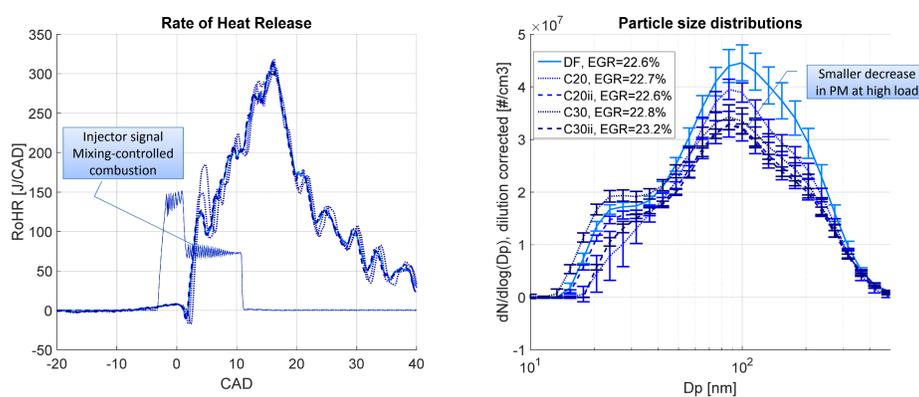


Figure 4. Variation in P_{inj} without EGR (Medium Load, B50)

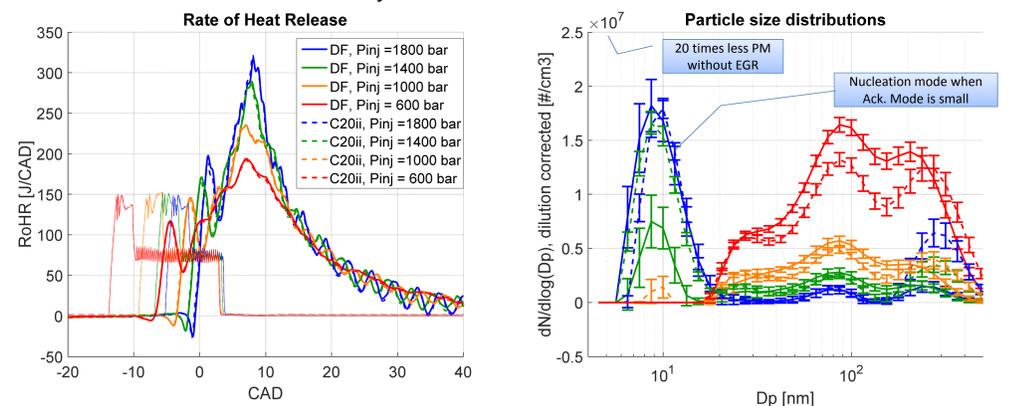
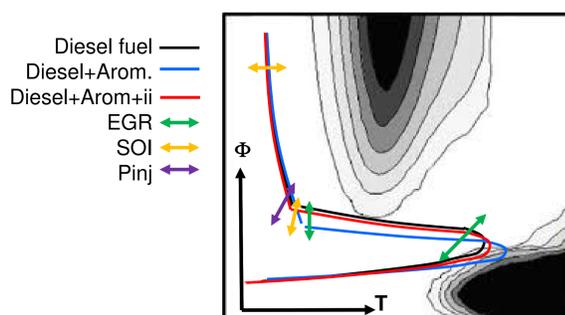


Figure 5. Conceptual model



Engine: 1 cyl (2 dm³), Operation points: A25 (low load 1200rpm, 78Nm), B50 (medium load, 1500rpm, 146Nm), C75 (high load, 1800rpm, 196Nm). Common rail fuel single injection (600 - 1800 bar)
Fuels: Low sulfur diesel fuel (DF), Aromatics (Caromax 28), ignition improver (2EHN)
Properties Caromax28 (Diesel fuel): mono-Ar: 24% (5%), di-Ar: 68% (0.1%), poly-Ar <0.02% (0.04%), density: 985 kg/m³ (815 kg/m³), ibp/fbp 230/290 °C (184/290 °C)
Sampling system: Dekati 4000, dilution factor by NO_x analysis
Thermodenuder (250 °C), correction factor by diffusion loss measurements (NaCl)
PM instrument: DMS 500 (Cambustion), primary dilutor not used, secondary dilutor =1 (not used)

References

- [1] IMO, MARPOL Annex VI and NTC 2008 with guidelines for implementation 2013 edition, International Maritime Organization, London, United Kingdom, 2013.
- [2] Maria Zetterdahl, et al., Impact of aromatic concentrations in marine fuels on particle emissions., 2016. in manuscript.
- [3] Tankai Zhang, et.al., An Experimental Study on the Use of Butanol or Octanol Blends in a Heavy Duty Diesel Engine, SAE International Journal of Fuels and Lubricants, 8 (2015).

Conclusions

- The use of ignition improver reduces PM emissions using aromatic fuel blends.
- The reason is improved pre-mixing, here enabled by high injection pressures
 - Plausible reasons include lower equivalence ratio "per molecule", higher density & lower viscosity. To be explored in future studies.

Poster summary

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Background:

PM emissions are increasingly important, especially for marine applications. As the legislations for fuel sulphur content is introduced in the SECA region, the focus was turned into the effects of aromatics. Aromatic fuel is known to increase PM emissions, but preliminary tests of drop-in aromatics in a marine diesel engine resulted in lower PM emissions. The objective in this presentation is to further investigate the interplay between fuel properties and the engine operations in order to try to explain the lowered PM emissions.

Experimental:

A single cylinder diesel engine (displacement 2 dm³) was used with different fuel mixtures. Standard low sulphur diesel and an aromatic fuel mixture (Caromax-28) at two levels (20% and 30%) were used in combination with ignition improver (Cepro 100, 2-ethylhexyl nitrate), to adjust the cetane number (CN). In total five different fuels were prepared. The engine was run at four different load points selected from a stationary driving cycle (only three load points presented in this poster). In order to further investigate the effect of combustion and fuels on PM emissions, variations in rail pressure and EGR were made.

The PM emissions were sampled from the exhaust pipe using a dilution system (Fine particle sampler 4000, Dekati) and supplementary NO_x measurements to derive dilution factors. The extracted flow was also passed through a thermodenuder to reduce the volatile components of the PM emissions. A DMS500 (from Cambustion) was used to record the particle size distributions. Separate experiments using NaCl nanoparticles at the same number concentration were used to derive the diffusion losses in the system.

Results:

In figure 1 and figure 2, two load points are illustrated. One low load (A25, 1200rpm, 78Nm) and one high load ("C75", 1800rpm, 186Nm). In the left panels, the Rate of Heat Release (RoHR) together with the injector signal is displayed. In the right panels, the corresponding particle size distributions (psd) are shown.

- When comparing the different fuels without ignition improver, the lowered emissions could be explained by the increased degree of pre-mixed combustion (lower cetane number) as expected. The RoHR is delayed for the aromatic fuels and is larger in magnitude. The increased ignition delay will make the fuel more mixed before combustion and soot formation is decreased. Furthermore, the more intense combustion will increase the soot oxidation and further contribute to lower PM emissions as can be seen in the psd plots.
- When comparing the rate of heat release (RoHR) for the fuels with same cetane number (by use of ignition improver), the RoHR curves were very similar. This means that the cylinder-global phenomena were very similar between the different fuels. However, the PM emissions for aromatic containing fuels were constantly lower (especially for the low load case) and the reason was assigned to the local phenomena of soot formation not visible on the RoHR (measuring cylinder-global phenomena, including soot oxidation).

To further investigate the "unexpected" results of lower PM emissions upon addition of aromatics, the rail pressure was reduced in steps of 400 bar (1800 bar, 1400 bar, 1000 bar and 600 bar) while keeping the CA 50 constant (to approx. 11 CADatdc), see figure 3. Only one load point was investigated (B50) and only two fuels compared (diesel fuel and 20% aromatics with ignition improver).

- When investigating the RoHR (left panel), the final phase of the combustion is very similar and the injection were advanced to get the same combustion phasing. Since the main combustion

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commences about at the end of injection, the degree of pre-mixed combustion (first peak in the RoHR) is increased as the rail pressure is reduced and as the injection timing is advanced.

- When studying the PSD, it can be seen that the aromatics gives about the same PM emissions for high injection pressures (1800 bar, 1400 bar). However, for lower injection pressures, the aromatics gives higher PM emissions.

When analyzing replicate experiments, it became clear that the PM emissions were very sensitive to EGR (not shown) and since the EGR could not be exactly controlled, the experiments were repeated without EGR, still while keeping CA 50 constant (approx. 10 CADaTDC).

- When studying the RoHR, similar to the EGR-case (figure 3) the main combustion start at the end of injection. The higher injection pressure, the more rapid combustion (high peak in RoHR). The rapid combustion for high injection pressures is also manifested in the ringing phenomena due to high peak pressures.
- The PSD without EGR (right panel, figure 4) are significantly different. The PM emissions are one order of magnitude smaller and nucleation mode particles are observed. The nucleation mode particles appear only at high injection pressures and dominates over the accumulation mode particles. Persistently, the aromatic fuels give less accumulation mode compared to diesel whereas for high injection pressure, the difference vanishes (even somewhat more nucleation mode for aromatic fuels). The nucleation mode particles at high injection pressures indicate that the residence time in the flame front (at conditions favorable for soot formation) is of importance and can be used as a future indicator during engine calibration e.g. for engine manufacturers.

Discussion, Conclusions

- By using ignition improver, the RoHR analysis showed very similar combustion (cylinder global phenomena) for the different fuels containing varying amounts of aromatics.
 - This indicates that differences are due to local phenomena in the flame front, i.e. the difference is in the soot formation (rather than differences in soot oxidation)
 - The PM emissions were lower for aromatic fuels in contrast to “common belief”. The reasons for better pre-mixing for aromatic fuels can be different and future investigation will try to pin-point the most plausible explanation, (see Figure 5). Possible explanations include:
 - Lower molecular weight of aromatics (compared to diesel fuel) will make use of less oxygen in the air, hence lower equivalence ratio and less soot formation
 - Physical properties such as density, viscosity and surface tension may also influence the spray break-up and contribute to a lower equivalence ratio. Furthermore, the influence of cavitation inside the nozzle may vary depending on fuel properties.
- The trend of lower PM emissions for aromatic fuel could be “broken” by a different injection strategy (here: rail pressure):
 - When P_{inj} is sufficiently high, the effect of efficient pre-mixing (and hence shorter residence time at soot formation conditions) is dominating over increased soot formation due to presence of aromatic compounds (pre-cursors in soot formation).
 - When P_{inj} is lower (toward more traditional injection pressures found in older diesel engines), the increased soot formation due to aromatics dominates over increased pre-mixing.
- By changing the operating conditions to exclude EGR, the comparison was improved and furthermore, the existence of nucleation mode particles could further help understand the fate of the soot formation.

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Supplementary results

The emission values for the experiments presented in the figures are given in the tables below

Fuel mixtures	density	CN
	[kg/m ³]	[-]
DF	815.2	52.8
DF+20%Caromax	849.16	43.5
DF+20%Caromax+2EHN	854.254	52.9
DF+30%Caromax	866.14	39.0
DF+30%Caromax+EHN	866.14	52.0

data, Figure 1 (load Point A25)	EGR	SOI	CA50	Pinj	NOxSp	COSp	HCSp	PMSp	PNCorr
	%	CADbTDC	[CADaTDC]	[bar]	[g/kWh]	[g/kWh]	[g/kWh]	[g/kWh]	[/cm ³]
DF_A25	30	4.52	9.1	1800	1.35	1.15	0.27	0.03	3.4e+07
C20_A25	33.2	4.52	8.4	1800	1.21	1.45	0.28	0.01	2.4e+07
C20ii_A25	27.4	4.52	8.8	1800	2.04	0.78	0.15	0.01	1.8e+07
C30_A25	30.1	4.52	7	1800	2.01	1.14	0.19	0	1.1e+07
C30ii_A25	28.8	4.52	8.9	1800	1.91	1.03	0.26	0.02	1.7e+07

data, Figure 2 (load Point C75)	EGR	SOI	CA50	Pinj	NOxSp	COSp	HCSp	PMSp	PNCorr
	%	CADbTDC	[CADaTDC]	[bar]	[g/kWh]	[g/kWh]	[g/kWh]	[g/kWh]	[/cm ³]
DF_C75	22.6	4.5	17.5	1800	1.61	0.43	0.08	0.07	3.6e+07
C20_C75	22.7	4.5	17.4	1800	1.72	0.41	0.1	0.08	2.9e+07
C20ii_C75	22.6	4.5	17.5	1800	1.77	0.41	0.08	0.11	2.7e+07
C30_C75	22.8	4.5	17.6	1800	1.77	0.42	0.1	0.08	3.1e+07
C30ii_C75	23.2	4.5	17.3	1800	1.76	0.4	0.1	0.12	2.6e+07

data, Figure 3 Pinj, with EGR	EGR	SOI	CA50	Pinj	NOxSp	COSp	HCSp	PMSp	PNCorr
	%	CADbTDC	[CADaTDC]	[bar]	[g/kWh]	[g/kWh]	[g/kWh]	[g/kWh]	[/cm ³]
DF_P1800	27.2	7.8	10.8	1800	1.45	1.04	0.07	0.17	6.5e+07
DF_P1400	28.4	9.55	10.8	1400	1.22	1.5	0.07	0.36	1.1e+08
DF_P1000	26.8	12.1	11.1	1000	1.34	1.91	0.05	0.69	1.3e+08
DF_P600	25.7	16.65	11.3	600	1.35	2.9	0.05	1.59	1.7e+08
C20ii_P1800	29.7	7.8	10.9	1800	1.21	1.19	0.07	0.24	7.5e+07
C20ii_P1400	29.2	9.55	10.7	1400	1.23	1.54	0.08	0.47	1.1e+08
C20ii_P1000	28.5	12.1	11.1	1000	1.21	2.28	0.08	0.92	2.2e+08
C20ii_P600	27.8	16.65	12.6	600	1.18	3.53	0.06	2.29	3.3e+08

Figure 4 Variations in injection pressure, without EGR

data, Figure 4 Pinj, without EGR	EGR	SOI	CA50	Pinj	NOxSp	COSp	HCSp	PMSp	PNCorr
	%	CADbTDC	CADaTDC	bar	[g/kWh]	[g/kWh]	[g/kWh]	[g/kWh]	[/cm ³]
DF_P1800noEGR	0.5	6.4	10	1800	9.18	0.27	0.11	0	6.1e+06
DF_P1400noEGR	0.9	8	10.5	1400	8.18	0.32	0.12	0.01	3.4e+06
DF_P1000noEGR	0.2	10.45	10.5	1000	7.54	0.41	0.12	0.01	4.4e+06
DF_P600noEGR	0.9	15	10.7	600	6.45	0.58	0.13	0.05	1.4e+07
C20ii_P1800noEGR	0.7	6.4	9.9	1800	9.87	0.26	0.1	0	6.7e+06
C20ii_P1400noEGR	0.6	8	10.4	1400	8.93	0.31	0.11	0	6.7e+06
C20ii_P1000noEGR	0.6	10.45	10.4	1000	7.89	0.39	0.13	0.01	4.4e+06
C20ii_P600noEGR	0.5	15	11.2	600	6.93	0.56	0.13	0.07	1.3e+07