Impact of Fuel Properties on the Combustion of Late Post Injections used for Aftertreatment Thermal Management

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Background and Motivation:

- Heavy-duty engines are equipped with aftertreatment systems to treat engine-out pollutants: oxides of nitrogen (NOx), carbon monoxide (CO), and hydrocarbons (UHC)
- Aftertreatment components must be operated at sufficiently high temperatures to achieve high conversion efficiency (>90%)
- Number of fuel injections and their timing are tuned to increase exhaust enthalpy (i.e., temperature and pressure) by delaying combustion phasing late into the expansion stroke
  - This results in reduced combustion efficiency and stability and increase fuel consumption

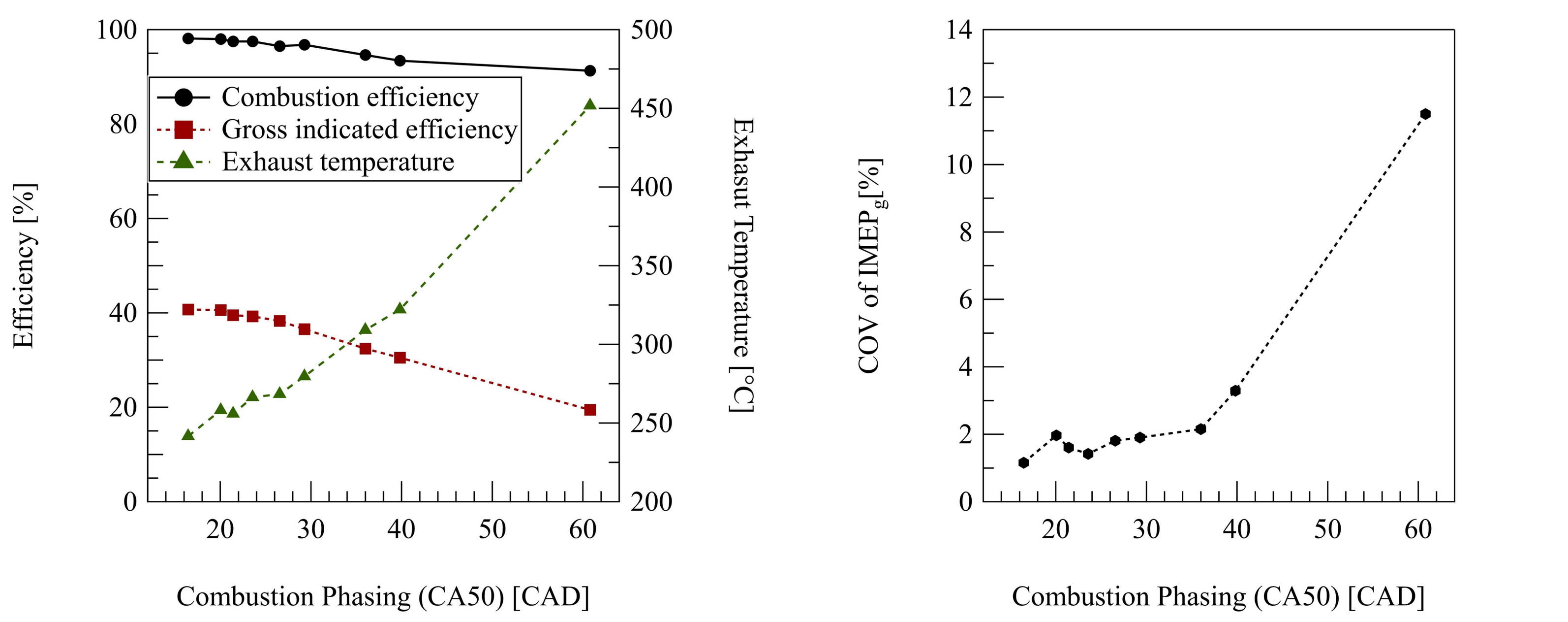

Figure 1. Left: Thermal efficiency, combustion efficiency, and exhaust temperature. Right: coefficient of variation of gross indicated mean effective pressure ($IMEP_g$) as a function of combustion phasing (CA50).

Objective:

- Overall Objective: Design a mono-ether bioblendstock derived from catalytic conversion of biomass (2nd generation) to be blended with conventional diesel fuel
  - Bioblendstocks have reduced carbon footprint which can help reduce carbon intensity of heavy-duty diesel engines to meet future greenhouse gas regulations
- To facilitate the fuel design, the impact of fuel volatility (boiling point), chemical reactivity, and oxygen content on aftertreatment thermal management operation was investigated

Methods:

Test Cell:

- Light-duty single-cylinder research test cell was used for all engine experiments
- Instrumented test cell allows precise control of operating and boundary conditions

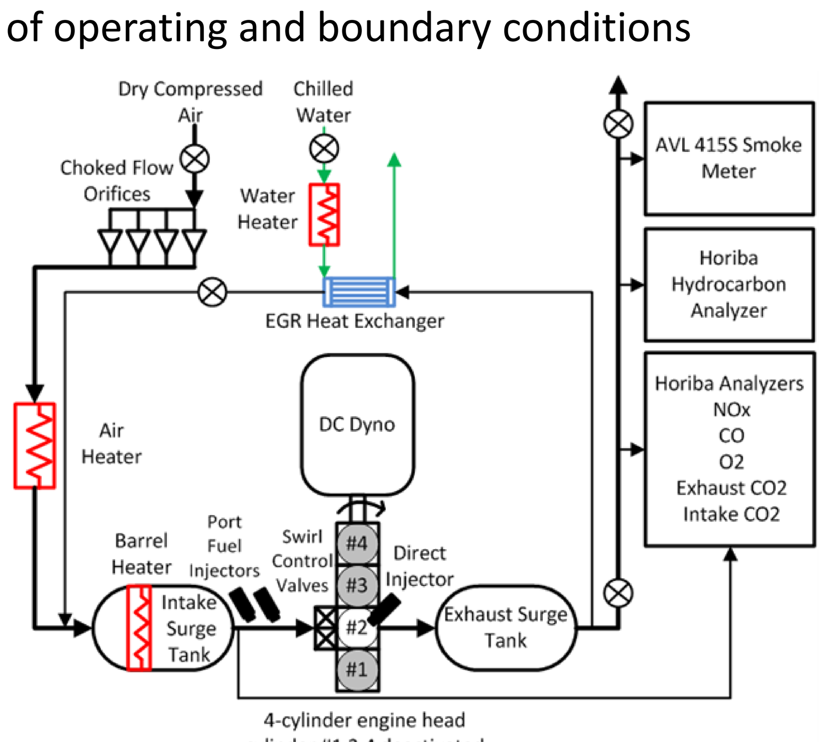

Figure 2. Light-duty test cell layout.

Table 1. Engine geometry details.

Parameter	Units	Value
Connecting Rod Length	mm	145
Bore x Stroke	mm	82 x 90.4
Displacement	L	0.475
Compression Ratio	-	17:1
IVO/IVC	CAD	350°/ -138°
EVO/EVC	CAD	122°/-346°

Table 2. Operating parameters

Parameter	Units	Value
Engine Speed	RPM	1500
Engine Load ($IMEP_g$)	kPa	300
Intake Temperature	K	328
Intake Pressure	kPa	100
Exhaust Gas Recirculation	%	30
Injection Pressure	MPa	50
Pilot SOI/DOI	CAD/ms	-14/0.32
Main SOI/DOI	CAD/ms	1/0.34
Oil Temperature	K	328

Operating Conditions:

Triple-injection strategy representative of aftertreatment thermal management operation

- Timing and duration of first two injections (pilot and main) held constant as timing of last (post) injection was retarded in the expansion stroke (see Table 2 for operation parameters)

Fuels:

- **Baseline fuel:** Ultra-low sulfur #2 diesel certification fuel
- Two binary blends were used to investigate the effect of boiling point and chemical reactivity (cetane number) of the fuel
  - **Binary blends:** 1. Iso-octane and n-heptane; primary reference fuels (PRFs)
    2. Farnesane (2,6,10-trimethyldodecane)-Heptamethylnonane (2,2,4,4,6,8,8-heptamethylnonane (FAR-HMN)
- Mono-ether bioblendstock composition represented by three mono-ethers components: di-butyl ether (65 vol. %), di-hexyl ether (33 vol. %), and di-isopentyl ether (2 vol. %)

Table 3. Fuel property information. ED stands for Ether-Diesel.

Parameter	Units	#2 diesel	PRF 0	FAR-HMN	ED CN 44	ED CN 54	Ether Blend
Cetane Number (CN)	-	42	56	45/56	44	54	-
Density	kg/m^3	854	687	772	852	838	778
Normal Boiling Point	K	442-606	371	523	427-606	419-605	414-501
Viscosity (313 K)	cSt	2.509	0.496	2.96	-	-	-
Lower Heating Value	MJ/kg	42.62	44.5	43.6	42.36	41.78	38.96
Molecular Weight	g/mol	204	100	215	199	187	145
H/C	-	1.84	2.28	2.13	1.86	1.91	2.22
O/C	-	0.0	0.0	0.0	0.0022	0.0076	0.0353
AFR_{st}	-	14.54	15.13	14.93	14.43	14.17	12.94
% diesel	v/v	100	0	0	92	75	0

Results:

Fuel volatility:

Measurements with PRF (CN 56) and FAR-HMN (CN 56) used to investigate the impact of fuel volatility (boiling point) on the combustion of late post injections

- Similar ignition delay was observed at matched injection timing
- Minimal impact of volatility on combustion phasing and combustion stability (Figure 3)
  - Some deviation was observed at the most retarded injection timing, but combustion was highly unstable to draw any valid conclusions
- No significant difference in engine-out emissions was observed

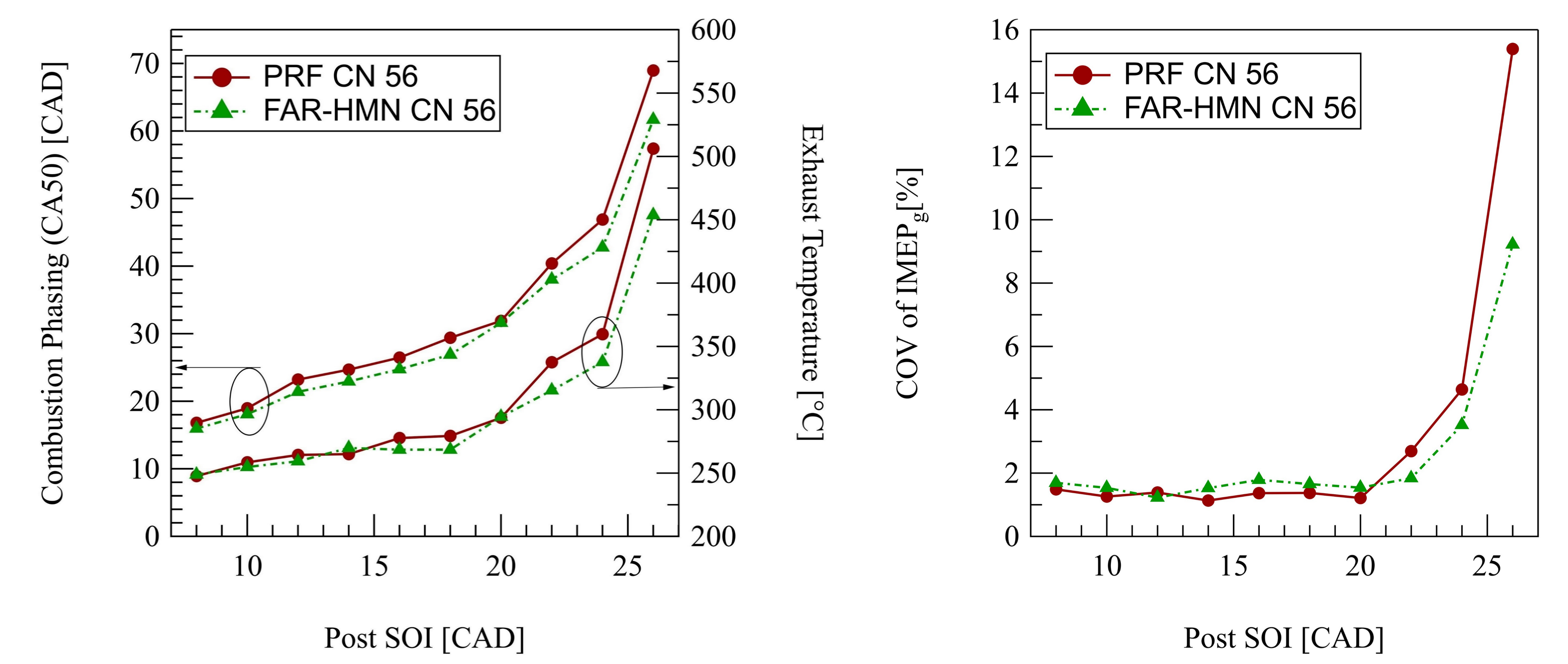

Figure 3. Left: combustion phasing (CA50) and exhaust temperature; right: coefficient of variation of indicated engine load ($IMEP_g$) as a function of post-injection timing

Reactivity of the Fuel:

Measurements performed with FAR-HMN CN 45, and CN 56 were used to investigate the impact of reactivity on the last post injection combustion

- Higher cetane number fuel had shorter post-injection ignition delay and advanced combustion phasing and decreased duration, which improved combustion stability at late injection timings
- Combustion and thermal efficiency for the higher CN fuel are increased at late injection times

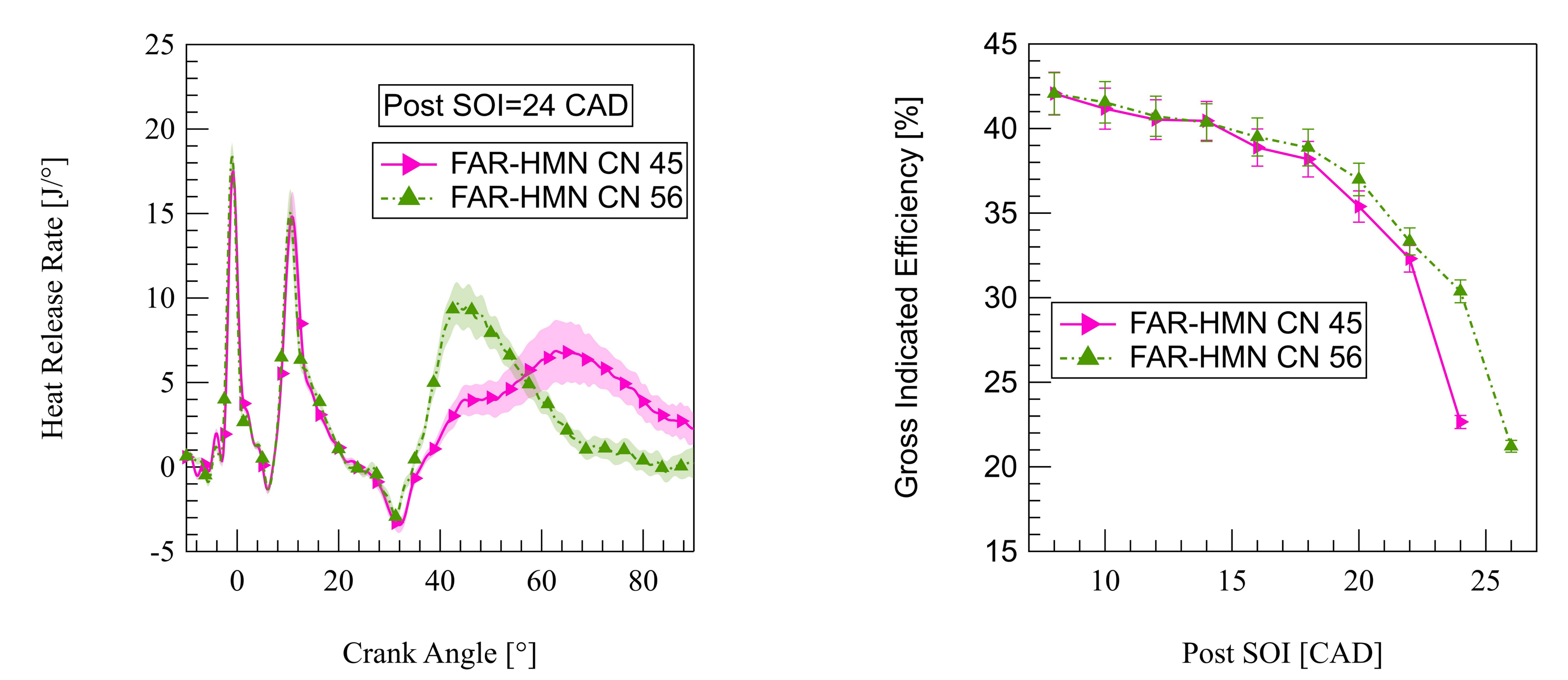

Figure 4. Left: heat release rate at post SOI=24 CAD; right: gross indicated efficiency as a function of post-injection timing.

Mono-ether Bioblendstock:

Measurements using ether-diesel blends (CN 44 and CN 54), and the pure ether blend (CN>100) allowed the performance of mono-ether diesel blends to be investigated

- Increased reactivity of the fuel significantly reduced the ignition delay and combustion duration of the post-injection, as shown in Figure 5
- For late post injections, higher CN fuels were observed to have better combustion stability and decreased combustion duration leading to more complete combustion
- At matched exhaust temperature ($T_{exhaust}$= 300°C), better thermal and combustion efficiency were achieved for fuel blends with bioblendstocks components, as shown in Figure 5

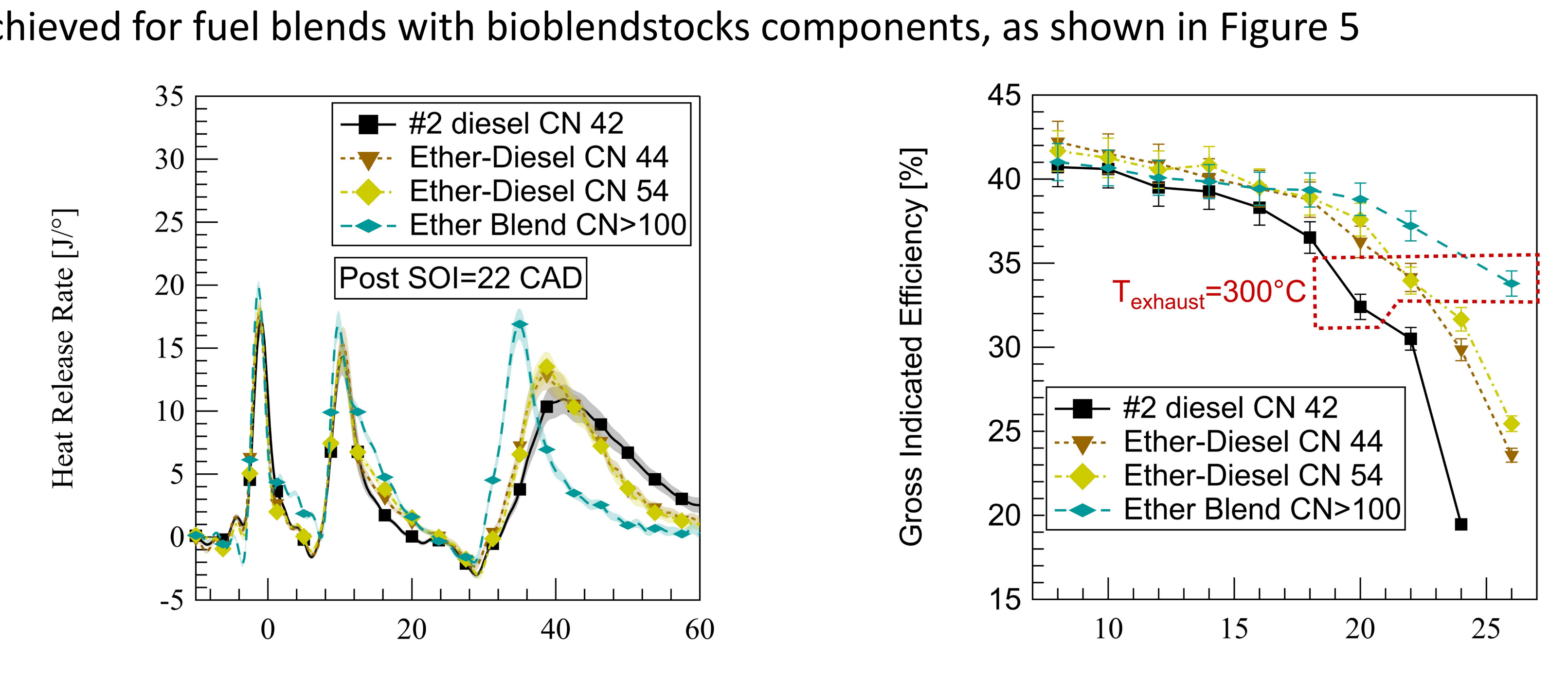

Figure 5. Left: heat release rate at post SOI =22 CAD; right: gross indicated efficiency as a function of post-injection timing.

Conclusions and Future Work:

- Effect of volatility was not significant on engine operation. While increasing chemical reactivity of the fuel improved combustion stability and thermal efficiency at late injection timings
- Using high-cetane mono-ether bioblendstocks can potentially reduce engine-out emission and fuel penalty during aftertreatment thermal management operation

Future Work: Engine experiments will be coupled with chemical kinetic simulations to investigate the effect of overmixing of fuel leading to the formation of fuel lean pockets at late injection timings. Measurements using blends of di-butyl ether and HMN at different CNs will be used to study the effect of chemical reactivity in extending the bounds of post-injection timing

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