PCCI Combustion for the Reduction of CO_2, NO_X, and Soot Emissions with Bio-Alcohols and Aerospace Fuel Blends

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Background

Emissions Reduction

- Premixed Charged Compression Ignition (PCCI) is an advanced Low Temperature Combustion (LTC) technique that is used to reduce the formation of NO_X and Soot emissions within the cylinder rather than with an exhaust aftertreatment system (Diesel Particulate Filters, Catalytic Converts, and Def Fluid, etc…) [1,2].
  - PCCI utilizes both a low reactive fuel (gasoline, ethanol, or n-butanol) and a high reactive fuel (ULSD, S-8, Jet-A, etc…) to increase the ignition delay and prolong combustion duration in order to reduce peak in-cylinder temperatures for lower NO_X formation and provide a more homogeneous air/fuel mixture within the cylinder for the reduction of Soot.
  - In PCCI, low reactive fuels are Port Fuel Injected (PFI) into the intake manifold to create a stratified equivalence ratio within the cylinder.

Objective

Premixed Charge Compression Ignition (PCCI) combustion in a compression ignition engine with the usage of an Aerospace fuel additive (S8) to ULSD could be advantageous for the reduction of both NO_X and Soot emissions.

Preliminary Work

Several fuel property studies were conducted in order to gain insight on the effects the various fuels utilized would have on combustion. It was observed in the Figures and tables below that S8 in ULSD had a positive effect on spray droplet size (Sauter Mean Diameter (SMD)) and viscosity as both were reduced by a significant quantity with 90% of the sprays volume (Dv90) being reduced by 20 µm meters and viscosity @ 40°C by 0.5 cP.

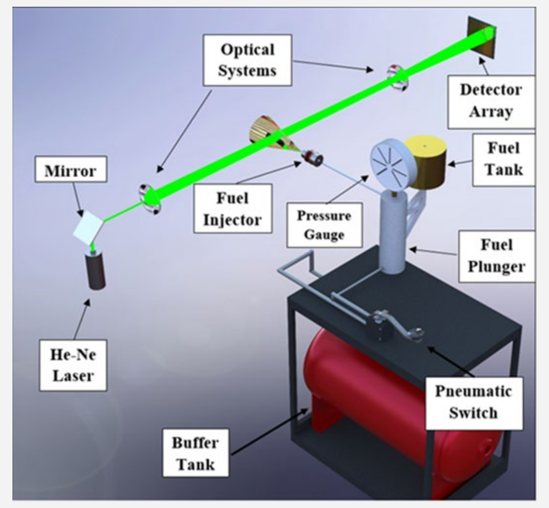

Figure 1: Mie Scattering Apparatus [3]

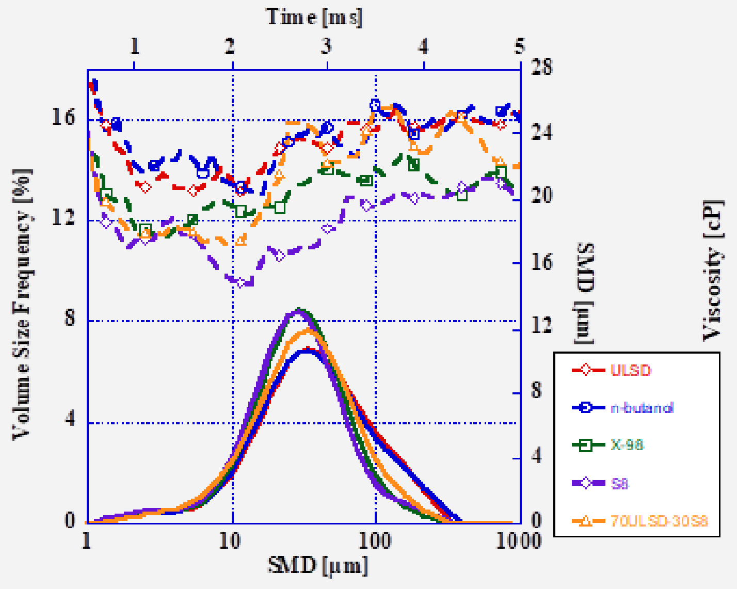

Figure 2: Spray Development

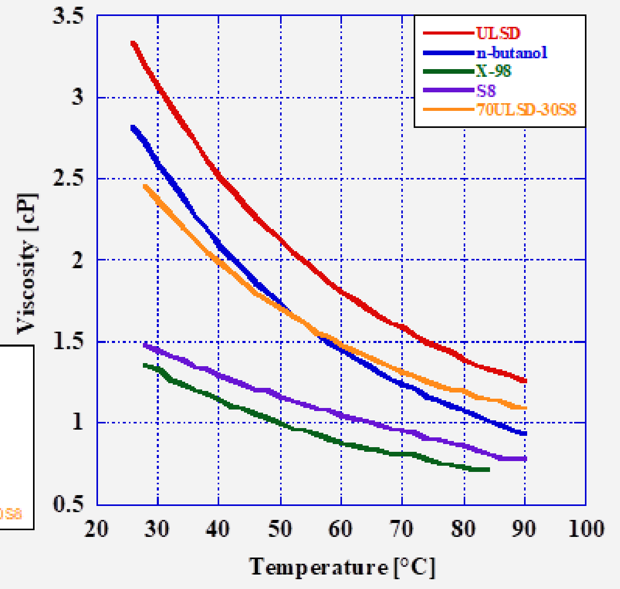

Figure 3: Viscosity Vs Temperature

Table 1: Fuel Thermo-Physical Properties

	ULSD #2	S8	70ULSD-30S8	X-98	n-Butanol
GHV [MJ/kg]	46.81	45.60	47.70	27.14	35.16
LHV [MJ/kg]	42.60	41.50	43.41	24.70	32.00
Density [g/mL]	0.85	0.76	0.82	0.79	0.81
Octane	NA	NA	NA	111.50	96.00
DCN	43.99	61.58	46.30	8.00	16.40
PAC ID	4.04	2.73	3.73	NA	40.16
PAC CD	5.66	3.93	5.26	195.00	81.25
Viscocity @ 40°C [cP]	2.52	1.30	1.99	1.15	2.09
Dv (10) [µm]	12.29	11.06	19.97	24.80	12.23
Dv (50) [µm]	37.89	30.40	55.88	65.33	34.17
Dv (90) [µm]	120.54	85.94	98.37	91.02	88.21
%V < 10 µm	0.09	0.12	0.11	0.08	0.08
% O2	-	-	-	0.35	0.22

Methodology

- A 1.1 L horizontal single cylinder experimental compression ignition engine was utilized to study the effects of adding S8 to ULSD would have on PCCI combustion's NO_X and Soot emissions in comparison to PCCI with 100% ULSD. Conventional Diesel Combustion (CDC) was utilized as a baseline for this study, the engine was operated at 1500 RPM with an indicated load of 4 Bar, a common rail pressure of 800 Bar, and an Exhaust Gas Recirculation (EGR) rate of 25% for CDC and PCCI combustion. PCCI tests were conducted with either 98% Ethanol (X-98) or n-butanol Port Fuel Injected (PFI) at a rate of 35% mass fuel rate.
- The Direct Injection (DI) fuel utilized for CDC and ULSD PCCI tests consisted of 100% ULSD#2, whilst PCCI tests with 70ULSD-30S8 utilized a fuel blend consisting of 70% by mass ULSD and 30% S8 for the DI fuel. The tables and figure included below contain the engine's specifications and Injection timing/duration, and the experimental apparatus utilized for this study.

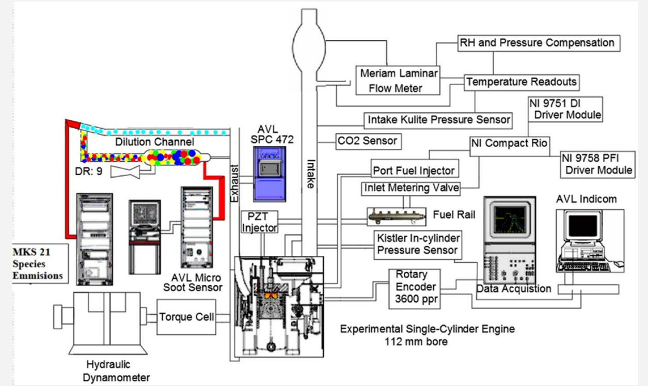

Figure 4: Experimental Apparatus [4]

Table 2: Engine Specifications

Peak Power	17kW @ 2200 RPM
Peak Torque	77.5 Nm @1400 RPM
Bore X Stroke	112 mm x 115 mm
Displacement	1.1L
Compression Ratio	16:1
Piston Geometry	Bowl in piston
DI Injection Nozzle	7 orifices x 0.115mm
Cooling system	Water
Valves per cylinder	2
PFI pressure	2.8 bar
PFI Timing	340° BTDC

Table 3: Injection Timing

	CDC	ULSD PCCI NBU	ULSD PCCI E98	70ULSD-30S8 PCCI NBU	70ULSD-30S8 PCCI E98
SOI-1 timing	17° BTDC	60° BTDC	60° BTDC	60° BTDC	60° BTDC
SOI-1 duration	0.79 ms	0.35 ms	0.35 ms	0.35 ms	0.35 ms
SOI-2 timing	-	12° BTDC	9° BTDC	8° BTDC	10° BTDC
SOI-2 duration	-	0.41 ms	0.32 ms	0.33 ms	0.32 ms

Results and Findings

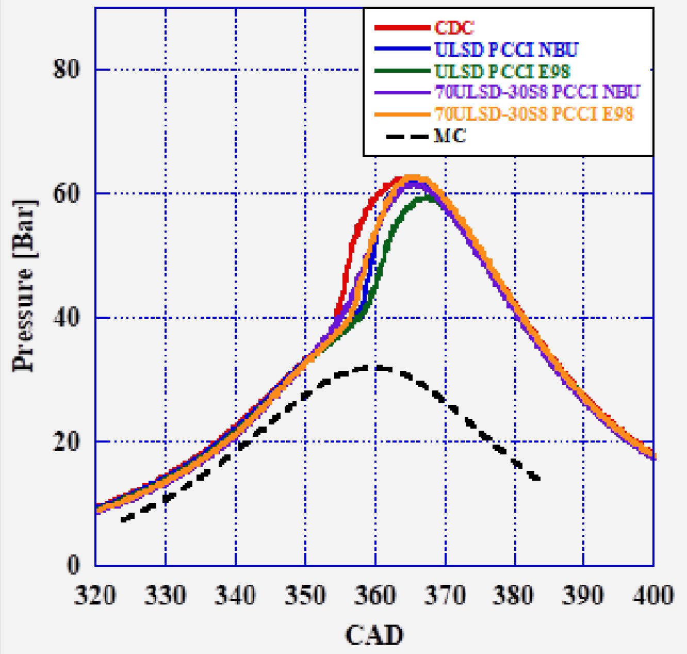

Figure 5: In-Cylinder Pressure

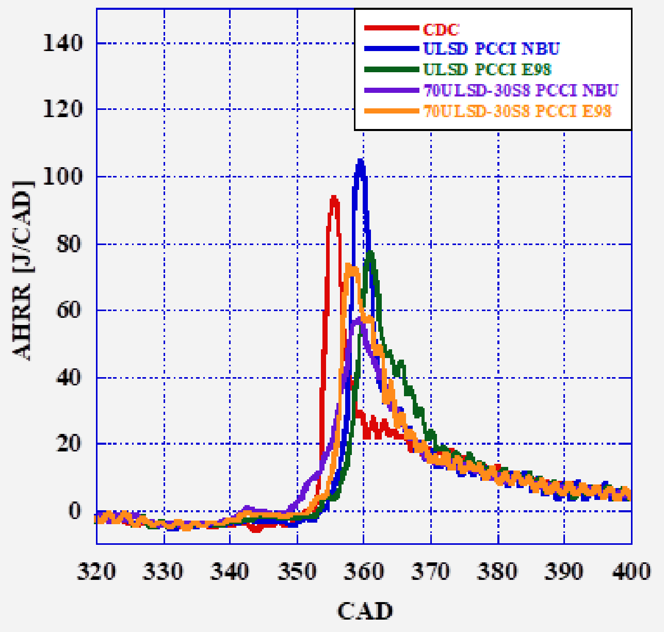

Figure 6: Apparent Heat Release Rate

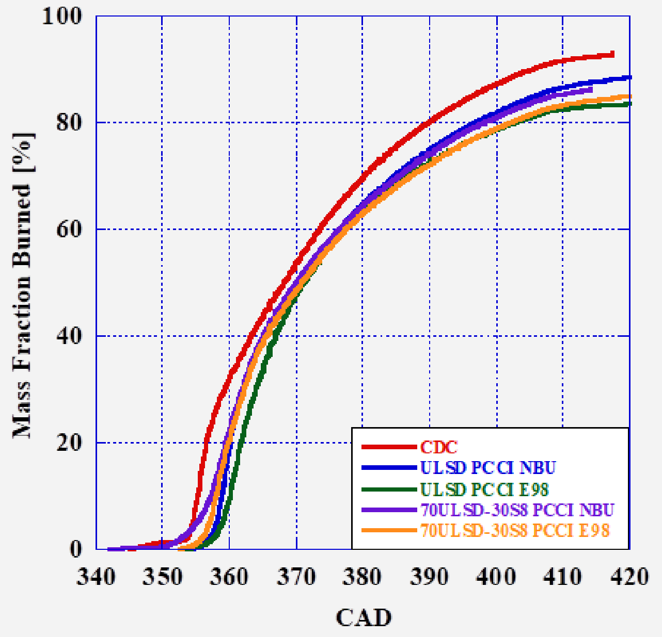

Figure 7: Mass Fraction Burned

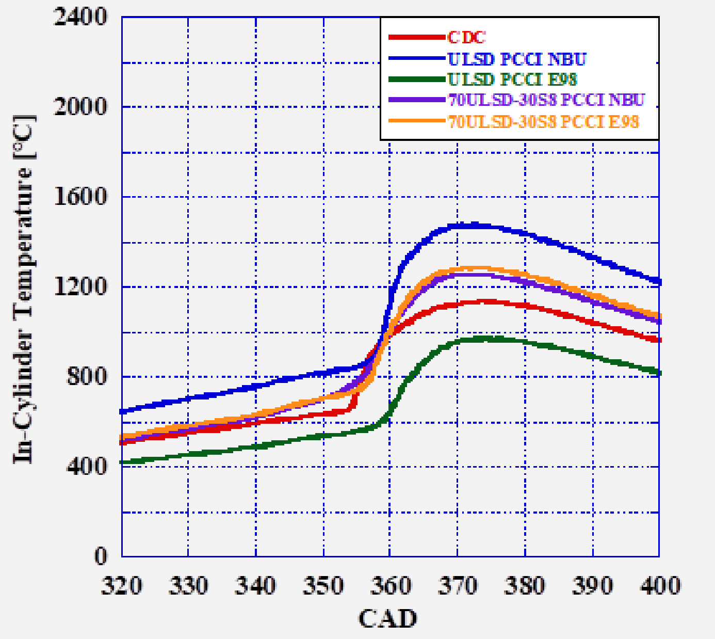

Figure 8: In-Cylinder Temperature

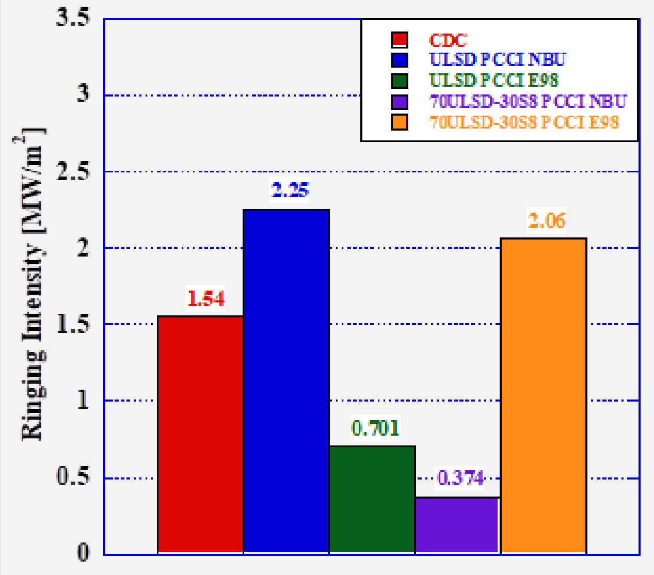

Figure 9: Ringing Intensity

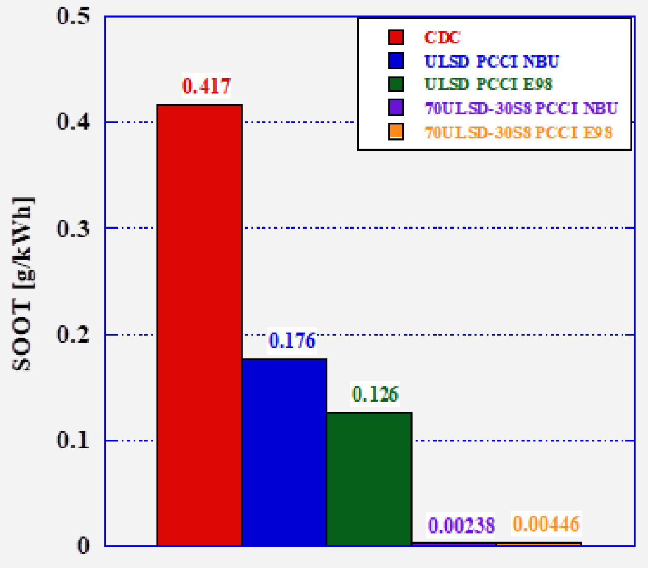

Figure 10: Soot Emissions

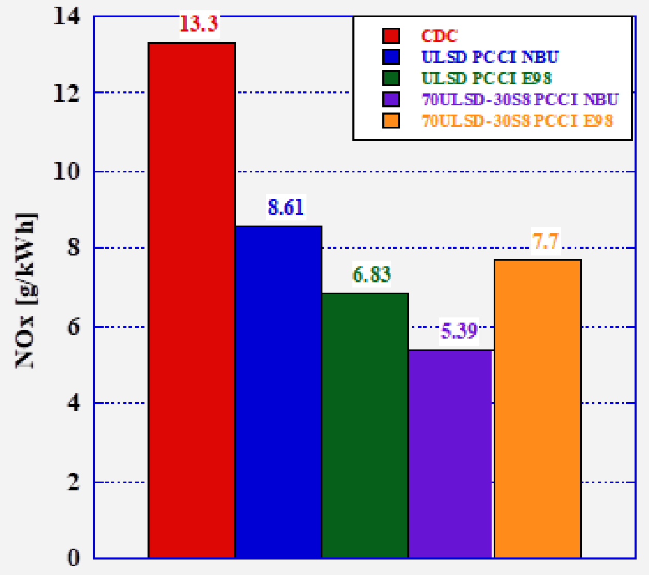

Figure 11: NO_X Emissions

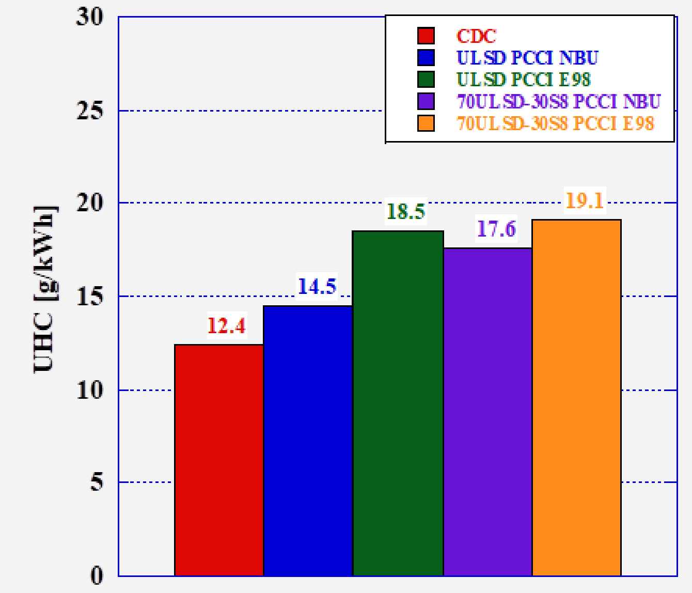

Figure 12: Unburnt Hydrocarbon Emissions

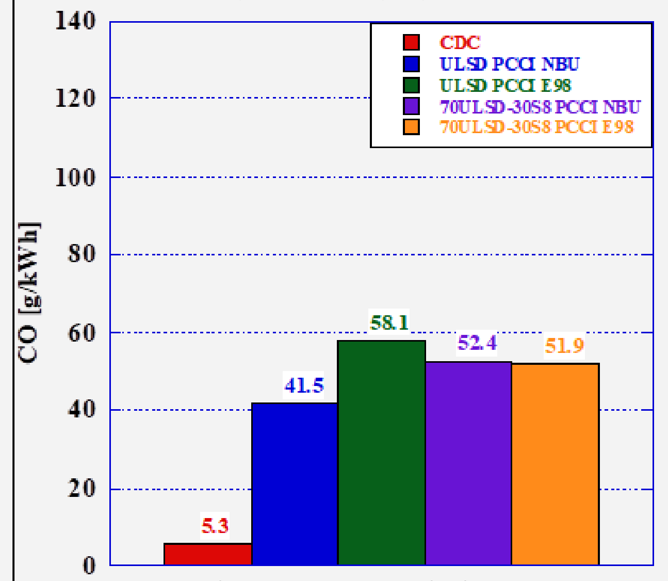

Figure 13: CO Emissions

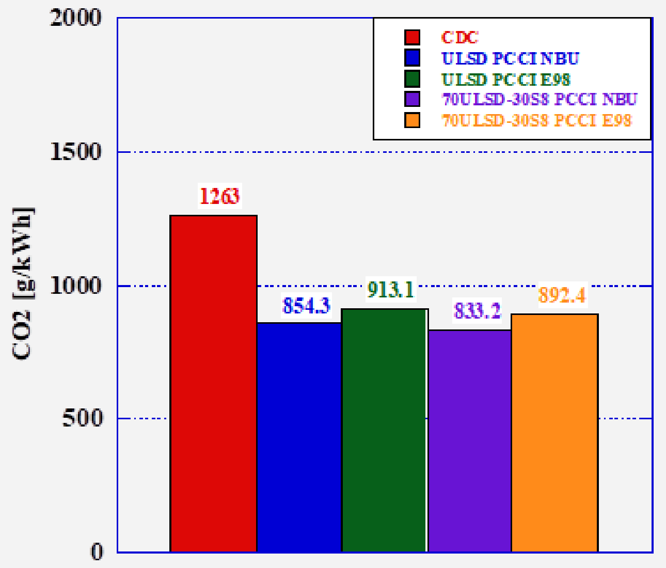

Figure 14: CO_2 Emissions

- Soot emissions for PCCI with 70ULSD-30S8 were reduced by as much as 99.43% (0.00238 g/kWh)with ethanol.
- NO_X emissions for PCCI was reduced by as much as 59.47% (5.39 g/kWh) by 70ULSD-30S8 with n-butanol.
- With further optimization of injection timing and boost, reductions for UHC and CO emissions can be achieved as well.

Discussion

- It was observed that peak In-cylinder pressures were similar for CDC, ULSD PCCI NBU, 70ULSD-30S8 E98, and 70ULSD-30S8 NBU with a max deviation of 1.30 bar whilst ULSD PCCI E98 had the lowest Peak pressure at 59.42 Bar.
- In-cylinder temperatures where only reduced for ULSD PCCI E98 (by 165°C) whereas all other PCCI tests conducted had higher peak temperatures than CDC with the fuel blend PCCI tests having similar peak temperatures for n-butanol and ethanol tests. The increase in In-cylinder temperatures for all PCCI tests conducted except for ULSD PCCI NBU is a result of an increase in the pressure rise rate and the location of the maximum pressure rise occurring closer to TDC.
- Although In-cylinder temperatures were increased for all but one PCCI tests conducted, it was observed that PCCI with either ULSD as its DI fuel or the 70ULSD-30S8 fuel mixture, NO_X emissions were reduced by at least 4.69 g/kWh (ULSD PCCI NBU) from CDC with 70ULSD-30S8 PCCI NBU having the greatest reduction of 7.91 g/kWh from CDC. The decrease in NO_X emissions despite the increase in temperature could be as a result of better air/fuel mixing at the DI injection site creating a lower temperature diffusion flame as a result. In addition, Soot emissions are also reduced substantially due to the oxygenated low reactive fuels (n-butanol and ethanol) providing oxygen for richer regions of the diffusion flame. The addition of 30% S8 by mass to ULSD further lowers the soot emissions of PCCI due to the beneficial spray atomization characteristics of S-8 assisting ULSD in creating fewer larger spray droplets at the site of injection [5].
- However, due to the late combustion phasing of PCCI (at a CA50 of 9-11 °BTDC) as observed in the Mass Fraction Burned graph in Figure 8, less fuel is able to combust in time and led to the increase in CO and Unburnt Hydrocarbon (UHC) observed in Figures 12 and 13. This could be mitigated in a future study with the usage of boost to decrease the combustion delay of PCCI.

References / Acknowledgments

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