Homogeneous Charge Compression Ignition (HCCI) engines generate power via compression ignition of highly dilute premixed fuel and air. This low temperature combustion strategy gives simultaneous ultra low emissions of NO_X and soot. However difficulties in fully oxidizing CO and hydrocarbons may result from these low in cylinder temperatures. Although HCCI engines are frequently assumed to have negligible amounts of particulate matter (PM) in the exhaust stream, recent research has shown otherwise, most notably, high number concentrations of volatile nucleation mode particles. The work presented here seeks to characterize particulate emissions and explore their formation in these types of engines.

A major obstacle faced by HCCI technology is the absence of a physical event with which combustion timing can be controlled. Combustion timing is dependant entirely on the temperature and pressure history of the charge and the fuel properties. The test apparatus was designed to explore select mechanisms of combustion timing control. Based on a production 4 cylinder diesel engine, the apparatus maintains stock cylinder geometry and valve timings. External modifications were made to allow precise and individual cylinder control of intake temperature, EGR rate, and fuel flow. A port fuel injection system was used employing both a liquid and a gaseous fuel injector for each cylinder. The primary fuel for the research was 200 proof ethanol. The gaseous injectors were used to provide hydrogen for the supplemental hydrogen fueling and pure hydrogen HCCI experiments.

Both gas and particulate emissions data were collected. Standard gaseous emissions instrumentation was used along with a laser gas analyzer for hydrogen emissions. Particulate emissions were collected via a 2 stage dilution tunnel operating with stage one and stage two dilution ratios of roughly 18:1 and 15:1 respectively. Dilution temperatures were held at 35°C for stage one air, 25°C for stage two air, and 35°C for the tunnel walls. Dilution tunnel residences times were near 1.5 seconds. Clean, dry dilution air was used for all work. A Scanning Mobility Particle Sizer (SMPS) was used to size classify and count particles in the range of 2-64 nm. In order to ensure no particles were above this size range, an Engine Exhaust Particle Sizer (EEPS) was employed intermittently examining a size range from 5.6 to 560 nm. No significant particle number concentrations were found above 64 nm. Figure 1 summarizes the relationships between combustion parameters and emissions for all of the work conducted.

Initial ethanol HCCI experiments were conducted using intake temperatures to optimize power output at three fixed fueling rates and 1500 RPM. The fueling rates corresponded to low load (53 Nm), mid load 1 (90 Nm), and mid load 2 (125 Nm) conditions.

In order to explore fuel blending to control combustion timing, experiments were conducted using ethanol as the primary fuel with supplemental hydrogen addition. The engine power output was maintained constant with hydrogen energy fractions ranging from 0 to 25%. At low loads brake specific emissions showed little dependence on percent hydrogen energy. Combustion analysis showed little change in start of combustion, burn duration, peak cylinder temperatures, and peak heat release rates at the lower loads but at higher loads increased proportions of hydrogen energy advanced combustion, increased in-cylinder temperatures, and increased peak heat release rates.

This led to increases in total particulate and NO_X emissions, and decreases in CO and HC emissions.

Experiments using a TDMA (Tandem Differential Mobility Analyzer) with a thermal conditioning stage were conducted to explore the volatile fraction of particles from ethanol HCCI combustion. The engine was operated at 1500 RPM and the same three loads as in previous experiments. At the low load, mid load 1, and mid load 2 conditions particle number concentration modes of 24 nm, 34 nm, and 31 nm were found at concentrations of $5x10^7$, $5x10^7$, and $1x10^8$ particles/cm^3 respectively. Thermal stage temperatures ranging from 40° to 110° C were used and particle volume reductions of nearly 98% were observed heating to 90°C for all load conditions. From this it can be concluded that nucleation mode particles formed during HCCI combustion are primarily composed of volatile components. The same TDMA experiments were conducted with the engine operating in a motoring mode at 1500 RPM with 120°C intake air. Particles generated during motoring had a mode around 25 nm and total number concentrations were on the order of $3x10^8$ part /cm^3. Much higher volume fractions remained throughout the same thermal stage temperature range with particles generated during motoring. At temperatures of 110°C, only 85% of total particle volume was lost.

A final set of experiments using pure hydrogen fuel were conducted to confirm the role of lubricating oil in the formation of particulate emissions from fully premixed HCCI combustion. Significant number and mass emissions of nucleation mode particles were observed for pure hydrogen HCCI combustion. The engine was operated at 1500 RPM with a 54 Nm load. Three intake temperatures were swept through at a constant fueling rate in order to optimize the engine output with intake temperature. Number concentration modes ranged from 22 to 28 nm with total concentrations on the order of $6x10^7$ to $1x10^8$ particles/cm^3. Total mass concentrations ranged from 130 to 1000 $\mu g/m^3$. As in the cases with ethanol HCCI, advancing combustion led to increased cylinder temperatures giving increased total mass and number particulate emissions.

In summary, it has been shown that significant numbers of nucleation mode particles are produced from fully premixed HCCI combustion of ethanol and hydrogen. The properties of these particles suggest they are formed from lubricating oil and are highly sensitive to the thermal and temporal history of the combustion event.

	PM Total Mass ($\mu g/m^3$)	**BSPM (g/kW hr)**	**BSFC (g/kW hr)**	**BSHC (g/kW hr)**	**BSCO (g/kW hr)**	**BSNO$_X$ (g/kW hr)**
Peak Temp (K)	↑	↑	↕	↓	↓	↑
Peak HRR (J/CAD)	↑	↑	↕	↓	↓	↑
SOC, CA 10 (ºATDC)	↓	↓	↕	↑*	↑*	↓
MFB 50 (ºATDC)	↓	↓	↕	↑*	↑*	↓

* Except when EGR is employed to control combustion phasing

Figure 1: Correlation matrix of emissions trends and combustion properties for fully premixed HCCI combustion of ethanol and hydrogen

Nanoparticle Emissions from an Ethanol Fueled HCCI Engine

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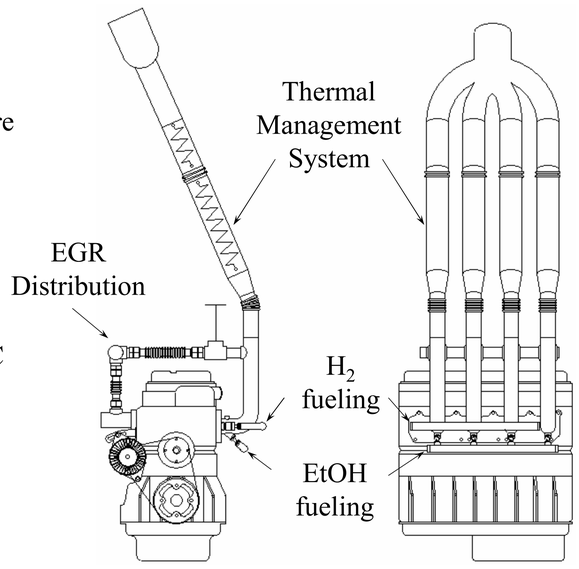
Research Goals

- Investigate the formation of PM in a non-sooting engine
- Gain further understanding of the formation mechanisms of HCCI emissions, both gas phase and particulate
- Isolate primary contributors to PM emissions in HCCI engines
- Understand the routes through which PM emissions are formed
- Explore the roles fuel blending could play in start of combustion control in HCCI engines
- Create a link between combustion phenomena and emissions

Experimental

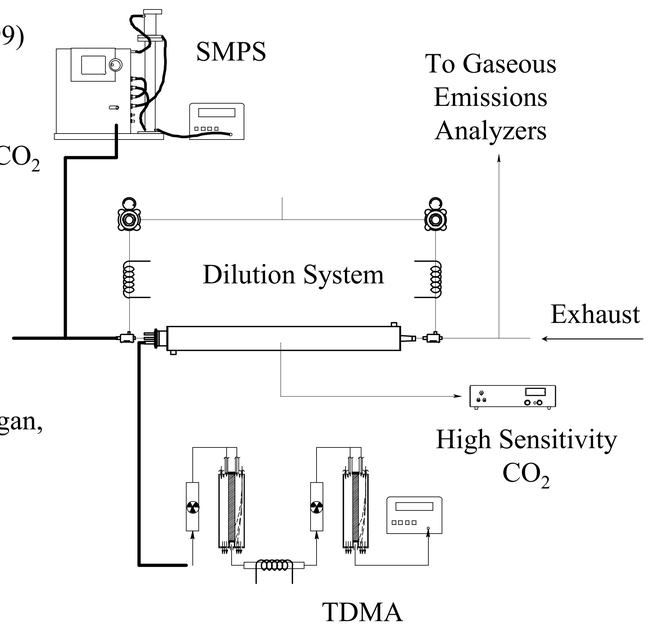
Apparatus

- Modified 5.2 liter, 4-cylinder, Isuzu Diesel engine
- Independent control of intake air temperature to each cylinder from 25° to 160°C
- Multipoint ethanol and hydrogen injection
- Fully premixed fuel and air
  - Preheated ethanol to 60° - 70°C
  - Intake air temperatures from 90° - 160°C
  - Injection timing on closed intake valve
- Manually tuned EGR distribution
- Fully instrumented for monitoring in-cylinder pressure in each cylinder
- Engine coupled to DC dynamometer



Emissions Measurement

- 2 stage micro dilution system (Abdul-Khalek, 1999)
  - Stage 1
    - Temperature: 35°C
    - Dilution Ratio: 15:1 ~ 20:1, monitored via CO_2
  - Stage 2
    - Temperature: 25°C
    - Dilution Ratio: 19:1
  - Tunnel Temperature: 35°C
- Particle counting and sizing via an SMPS
  - Scanning Mobility Particle Sizer (Wang & Flagan, 1990)
  - Mobility diameters from 2 – 64 nm
- Particle volatility measurements
  - TDMA techniques, with thermal conditioning (Orsini *et al*, 1999, Sakurai *et al*, 2003)
- Gas Phase emissions measurements via; CLD (NO_X), NDIR (CO & CO_2), FID (HC), laser gas analysis (H_2), FTIR (18 species)



Experimental Conditions

- Initial experiments optimized intake temperatures for maximum IMEP at three fixed fueling rates for ethanol HCCI
- Research into EGR as a SOC control was also conducted and is reflected in the conclusions
- Hot motoring emissions were also measured at 1500 RPM and 120°intake temperature, the data is shown for reference with the hydrogen HCCI emissions

	Pure Hydrogen HCCI		
	Low Load - Constant Fueling		
Intake Temperature (°C)	**95°**	**100°**	**105°**
Speed (RPM)	1500	1500	1500
Load (Nm)	52	54	52
IMEP (kPa)	228	231	227
λ	5.09	5.06	4.97
Fuel	H_2	H_2	H_2

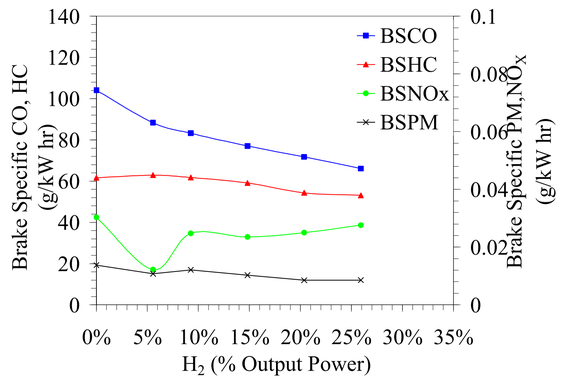
	Ethanol : Hydrogen HCCI	
	Low Load	Mid Load - 2
% Output Energy from H_2	**0-25 %**	**0-25 %**
Speed (RPM)	1500	1500
Load (Nm)	53	125
IMEP (kPa)	225-231	383 - 402
λ	4.35 - 4.42	2.98 - 3.11
Fuel	EtOH , H_2	EtOH , H_2
Intake Temperature (°C)	130 °C	95 °C

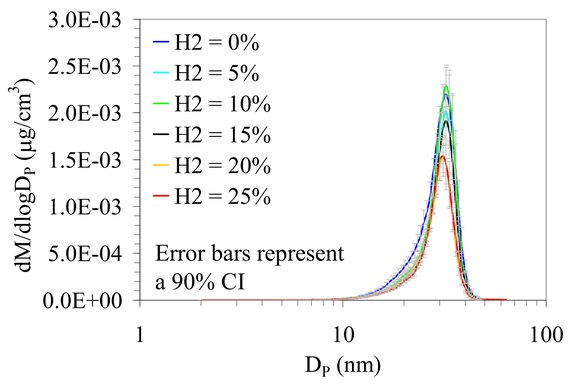
	TDMA Experiments		
	Low Load	Mid Load - 1	Mid Load - 2
TDMA Thermal Stage Temp. (°C)	**40 - 110°**	**40 - 110°**	**40 - 110°**
Speed (RPM)	1500	1500	1500
Load (Nm)	55	93	128
IMEP (kPa)	236	318	403
λ	4.3	3.5	2.8
Fuel	EtOH	EtOH	EtOH
Intake Temperature (°C)	130 °	110 °	100 °

Results

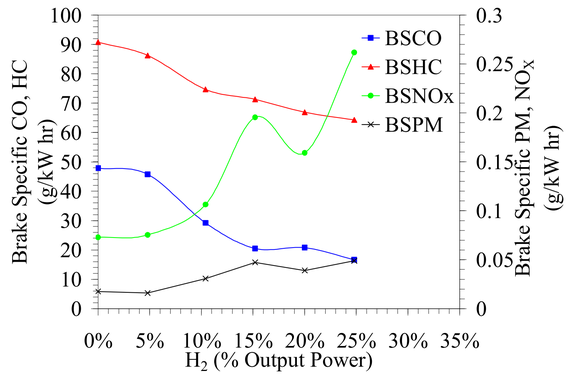
Ethanol HCCI with Supplemental Hydrogen Fueling

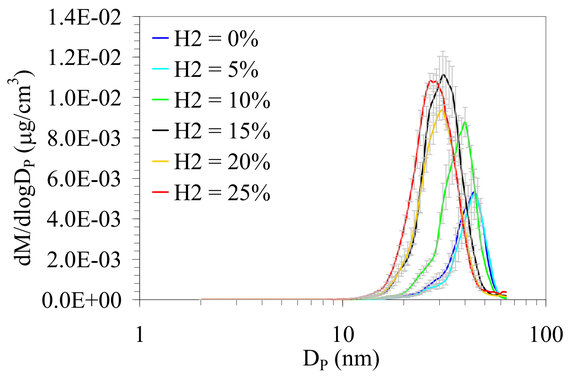
Low Load, Constant Engine Output, Varying H_2 Energy





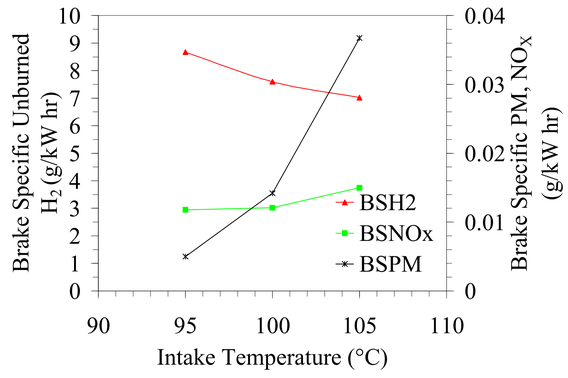
Mid Load-2, Constant Engine Output, Varying H_2 Energy

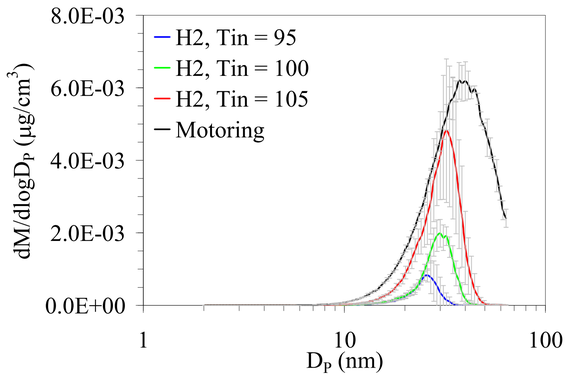




Pure Hydrogen HCCI

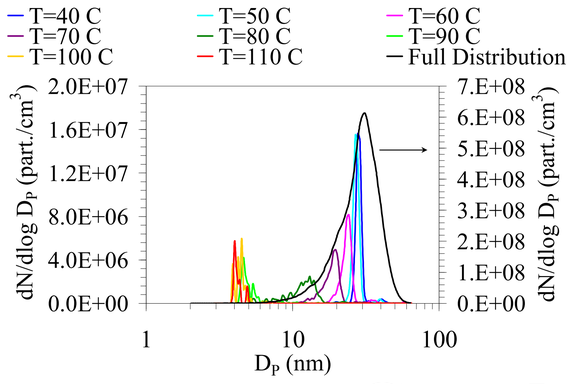
Low Load, Constant Fuel Flow, Varying Intake Temperature



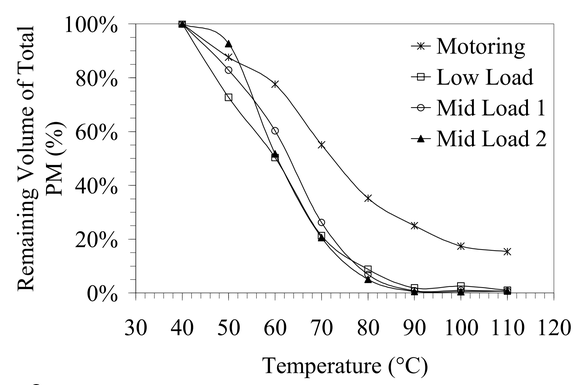


TDMA Results for Ethanol HCCI

Representative dN/dlogD_P data, Mid load 1



Evaporation Profiles, 4 loads



Conclusions

- Significant concentrations of volatile nucleation mode particles are formed during fully premixed ethanol and hydrogen HCCI combustion
- Properties of the particles suggest they are formed from lubricating oil and are highly sensitive to the thermal and temporal history of the combustion event
- Multiple strategies show advancing SOC also increases in cylinder temperature, leading to increased PM production

↑: Emissions characteristic correlates positively with combustion parameter

↓: Emissions characteristic correlates negatively with combustion parameter

↕: Emission characteristic shows an optimization point to combustion parameter

	PM Total Mass (µg/m³)	**BSPM (g/kW hr)**	**BSFC (g/kW hr)**	**BSHC (g/kW hr)**	**BSCO (g/kW hr)**	**BSNOx (g/kW hr)**
Peak Temp (K)	↑	↑	↕	↓	↓	↑
Peak HRR (J/CAD)	↑	↑	↕	↓	↓	↑
SOC, CA 10 (°ATDC)	↓	↓	↕	↑*	↑*	↓
MFB 50 (°ATDC)	↓	↓	↕	↑*	↑*	↓

* Except when EGR is employed to control combustion phasing

Acknowledgments:

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