Particle Emissions from a Soot Free Engine

Anil Bika, Wei Fang, Luke Franklin, Bin Huang, and David Kittelson
Center for Diesel Research
Department of Mechanical Engineering
University of Minnesota

Cambridge Particle Meeting

18 May 2012

Outline

- Introduction
- Experimental apparatus and procedure
- Dilution sensitivity
- Results
  - Emissions
    - Influence of fuel
    - Influence of thermal processing
    - Volatility measurements
- Conclusions

Soot free and low soot engines / fuels

- Low temperature combustion – there are a variety of so called low temperature combustion concepts including:
  - HCCI, Homogeneous Charge Compression Ignition)
  - PCCI or PCI (Premixed Charge Compression Ignition)
  - RCCI (Reaction Controlled Compression Ignition)
  - *All rely on control of the temperature – mixing history to avoid passing through regions of soot and NOx formation. However only very well mixed, lean HCCI has the potential to completely eliminate soot emissions.*
- There are also fuels that lead little or no soot formation including:
  - Natural gas – if you do it right
  - DME (dimethyl ether) – it is nearly impossible to do it wrong
- But all of these processes and fuels still emit PM, especially in the nanoparticle range
- ***The work presented here is for a converted Diesel engine running HCCI with ethanol, gasoline, and hydrogen fuels***
- ***Number and mass emissions of particles were of the same order as those from contemporary Diesel engines without aftertreatment but the particles were nearly all volatile***

Why are we interested?

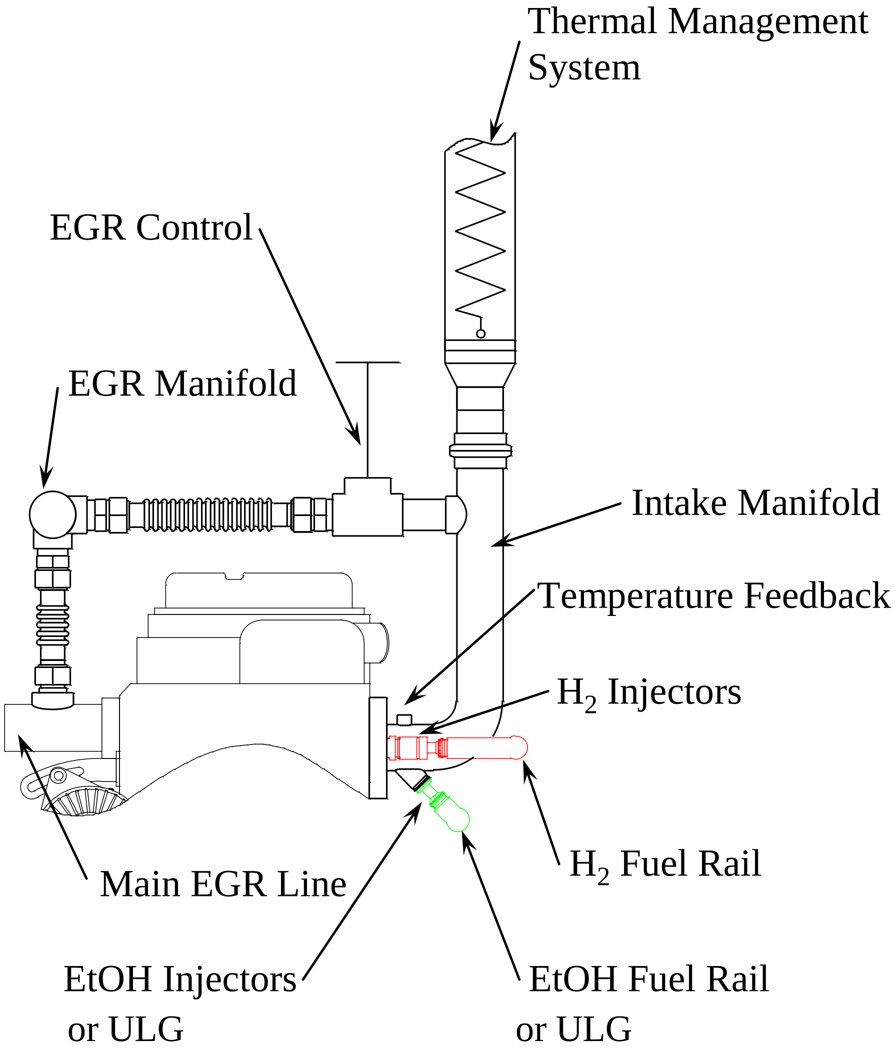
- To determine the source PM emissions from low temperature combustion
    - Engine modifications to minimize emissions
    - Identification of appropriate aftertreatment, exhaust temperatures are low
- To examine the use of soot free engine combustion to improve our understanding of the contribution of lubricating oil PM emissions
    - Oil and related ash emissions impact performance of exhaust filters
    - Typically emissions under fired conditions are much lower than under motored conditions
    - Emissions related to heat release rate and internal cylinder temperatures and pressures and their influence on lubricating oil evaporation and atomization
    - Very sensitive to engine conditions and history

Outline

- Introduction
- Experimental apparatus and procedure
- Dilution sensitivity
- Results
  - Emissions
    - Influence of fuel
    - Influence of thermal processing
    - Volatility measurements
- Conclusions

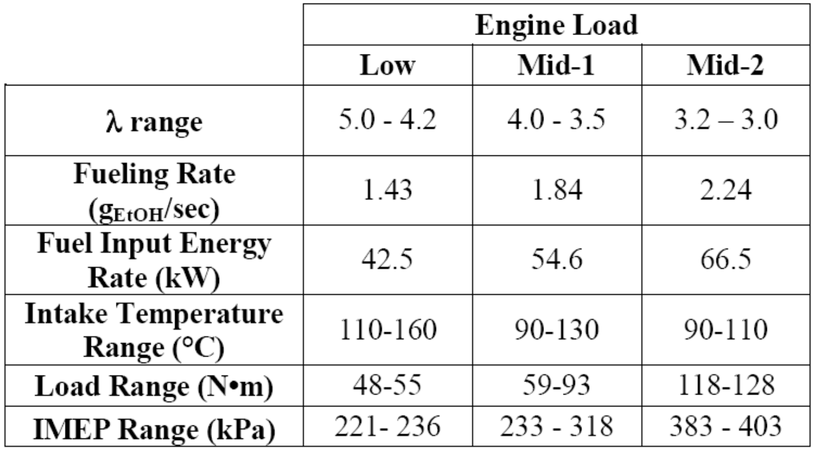
Engine modifications for HCCI

- The test engine is a modified 2005 Isuzu 4 cylinder, 5.3 L, medium-duty Diesel engine.
- Turocharger and aftercooler removed
- Common rail Diesel fuel injection not used
- Primary fuel ethanol or unleaded gasoline preheated to improve atomization
- Independent control of EGR, air temperature, hydrogen, ethanol or unleaded gasoline
- Closed loop controlled thermal system capable of maintaining temperatures of 150 °C
- Intelligent Controls IC 5620 engine management system used for fuel injector control



Test conditions

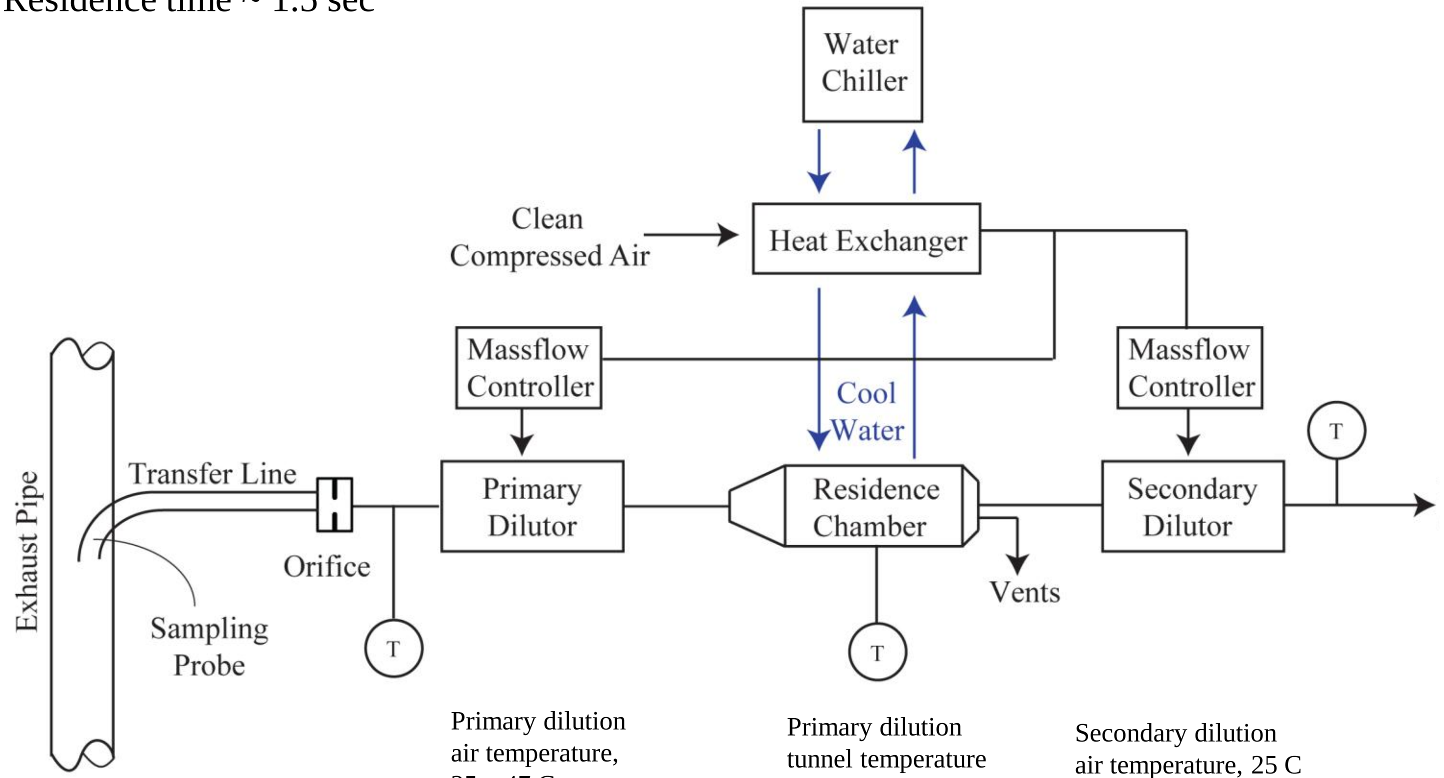
- Engine combustion was controlled in three ways
  - Variable intake temperature
  - Variable EGR rate
  - Changing fuel blend by substituting H_2 for ethanol
  - Variable intake temperature motoring
- Engine speed was varied from 1200 to 2000 rpm but most tests were done at constant engine speed of 1500 rpm
- The table below shows variable temperature test conditions for ethanol tests
- Variable EGR and fuel blending test were done at essentially same load and equivalence ratio ranges
- Tests with gasoline and hydrogen have been done mainly in the low and mid-1 range with intake air temperature control



	Engine Load		
	Low	**Mid-1**	**Mid-2**
λ range	5.0 - 4.2	4.0 - 3.5	3.2 – 3.0
Fueling Rate (g_{EtOH}/sec)	1.43	1.84	2.24
Fuel Input Energy Rate (kW)	42.5	54.6	66.5
Intake Temperature Range (°C)	110-160	90-130	90-110
Load Range (N•m)	48-55	59-93	118-128
IMEP Range (kPa)	221- 236	233 - 318	383 - 403

Sampling and dilution system

Dilution ratios, primary = 18 early work, 15 later work, secondary = 15
Residence time ~ 1.5 sec



Nano SMPS,
other instruments

Primary dilution
air temperature,
25 – 47 C

Primary dilution
tunnel temperature
25 – 47 C

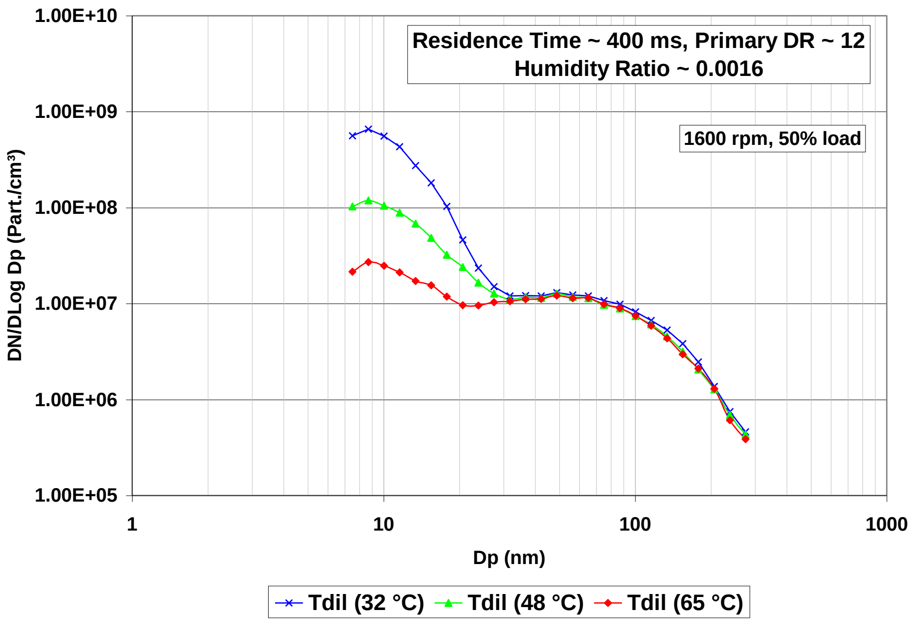
Secondary dilution
air temperature, 25 C

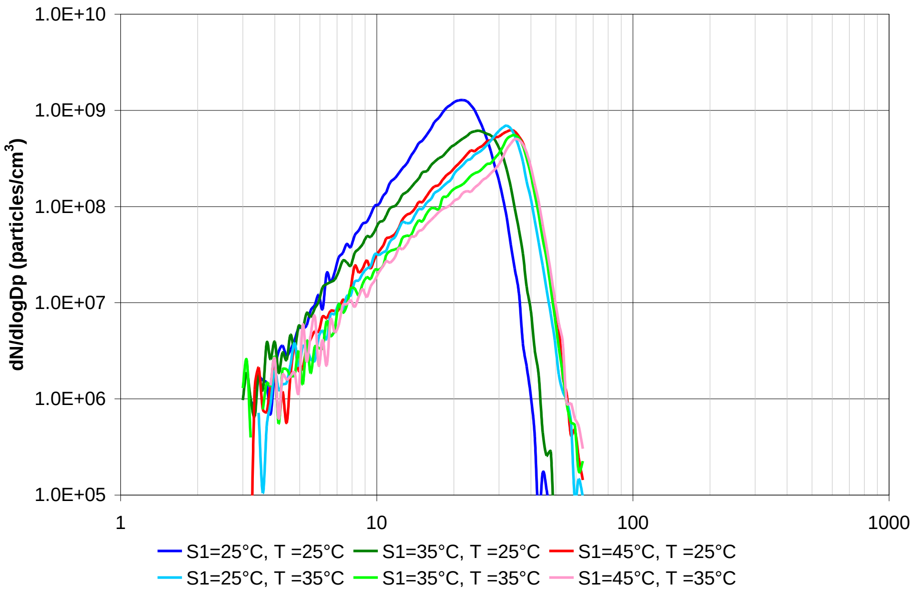
Outline

- Introduction
- Experimental apparatus and procedure
- Dilution sensitivity
- Results
  - Emissions
    - Influence of fuel
    - Influence of thermal processing
    - Volatility measurements
- Conclusions

Nanoparticle formation is very sensitive to dilution conditions - comparison with Diesel dilution sensitivity

The sensitivity to dilution temperatures is similar the that observed with Diesel nanoparticles. Our first set of experiments were done with primary tunnel and dilution air temperatures, 35 and 35 C, respectively, recently we have moved to 47 and 25 C to make the tunnel temperature compliant with EPA filter sampling temperature.

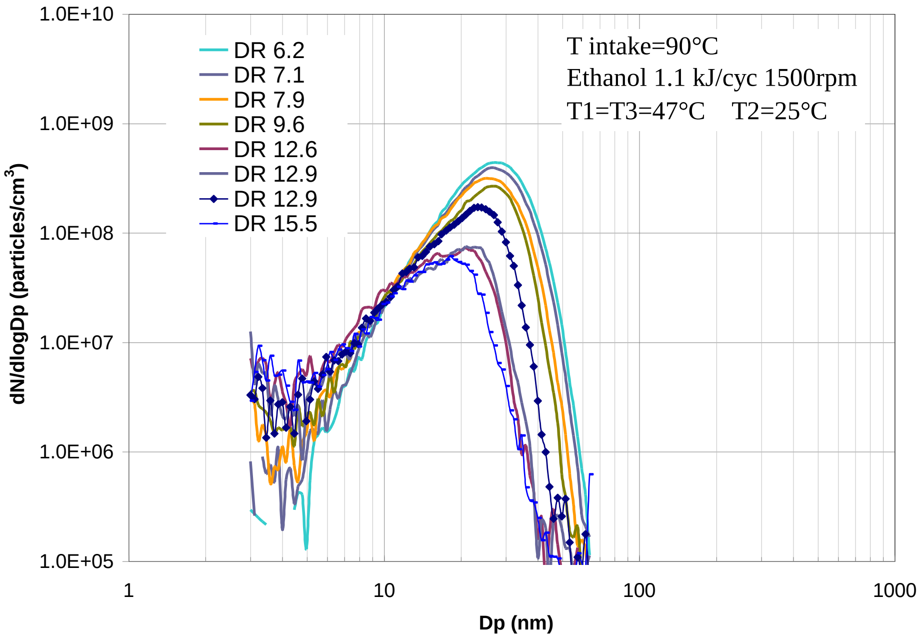


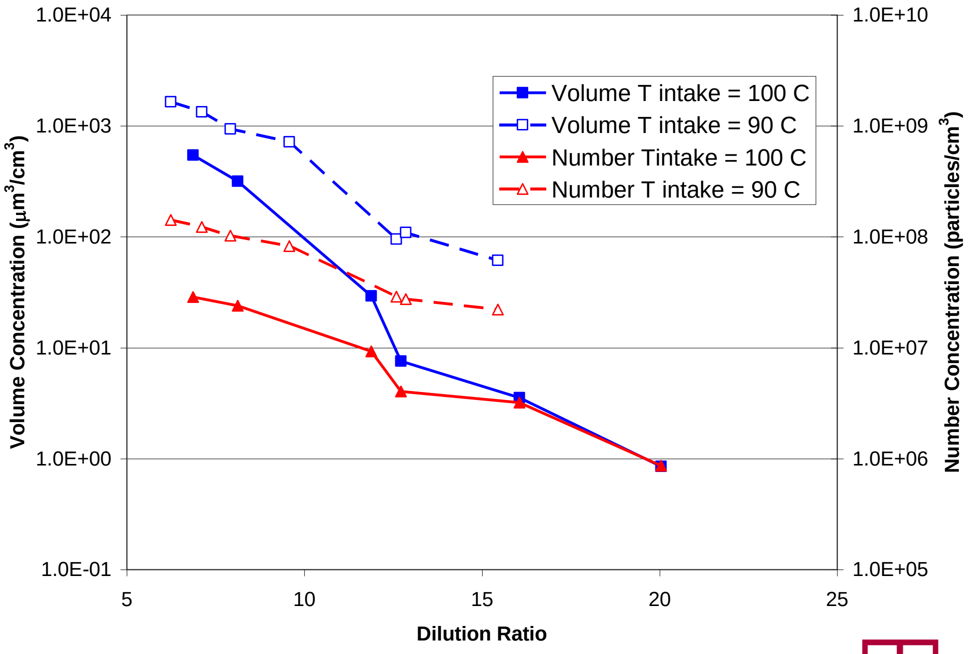


Abdul-Khalek, I., D.B. Kittelson, and F. Brear. 1999. “The Influence of Dilution Conditions on Diesel Exhaust Particle Size Distribution Measurements,” SAE Paper No. 1999-01-1142, 1999.

Further examination of dilution sensitivity showed strong dependence on dilution ratio

- We decided to standardize first stage dilution temperature – which is the critical one, to 47 C
- Both total number and total volume are very sensitive to dilution conditions but volume is most sensitive due to effect of both changing number and size
- There is no stable region for DR but the curve is “relatively” flat at DR = 15 so that is where we have mainly tested

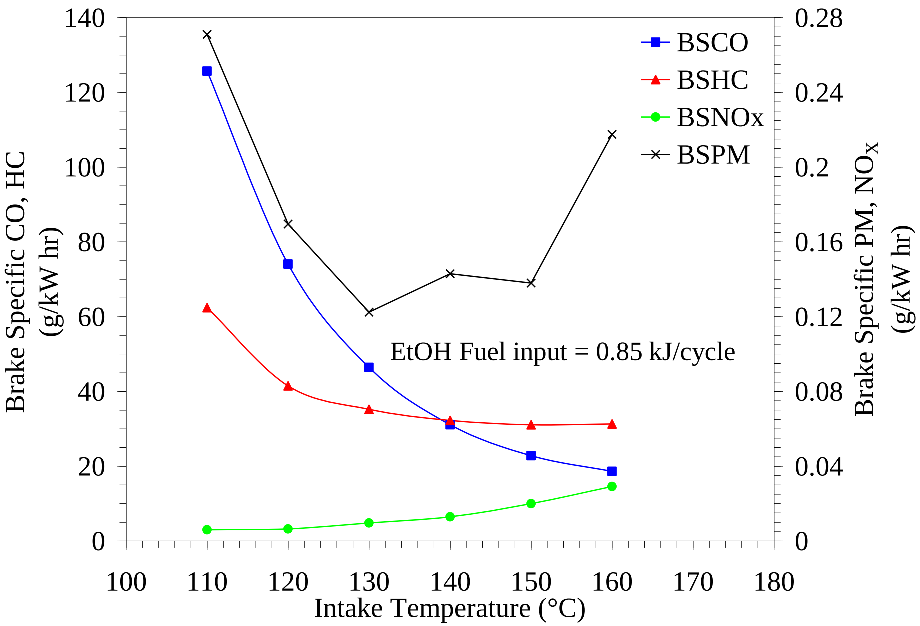


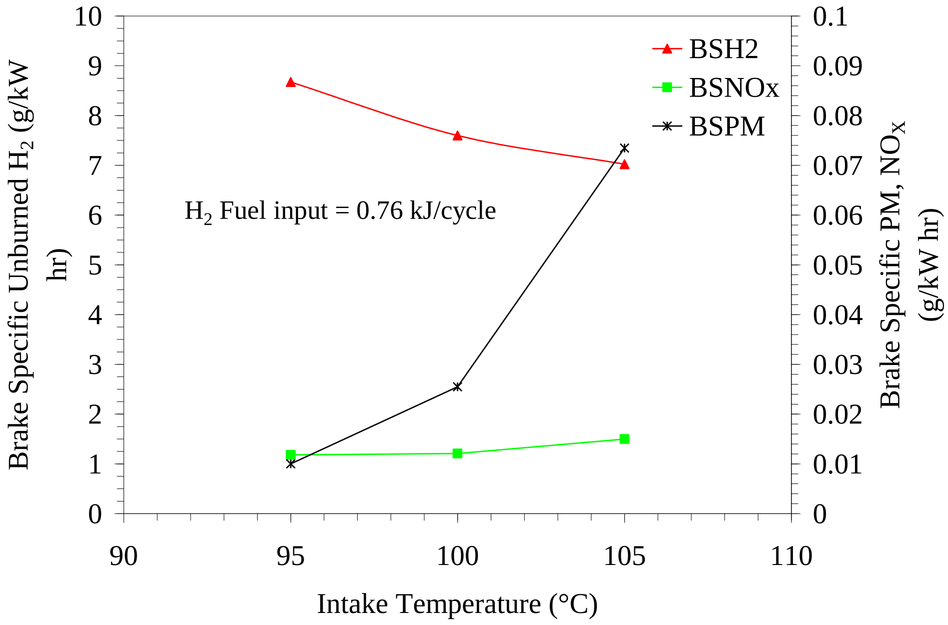


Outline

- Introduction
- Experimental apparatus and procedure
- Dilution sensitivity
- Results
  - Emissions
    - Influence of fuel
    - Influence of thermal processing
    - Volatility measurements
- Conclusions

Influence of intake temperature (ignition timing) on emissions with pure ethanol and hydrogen fuels



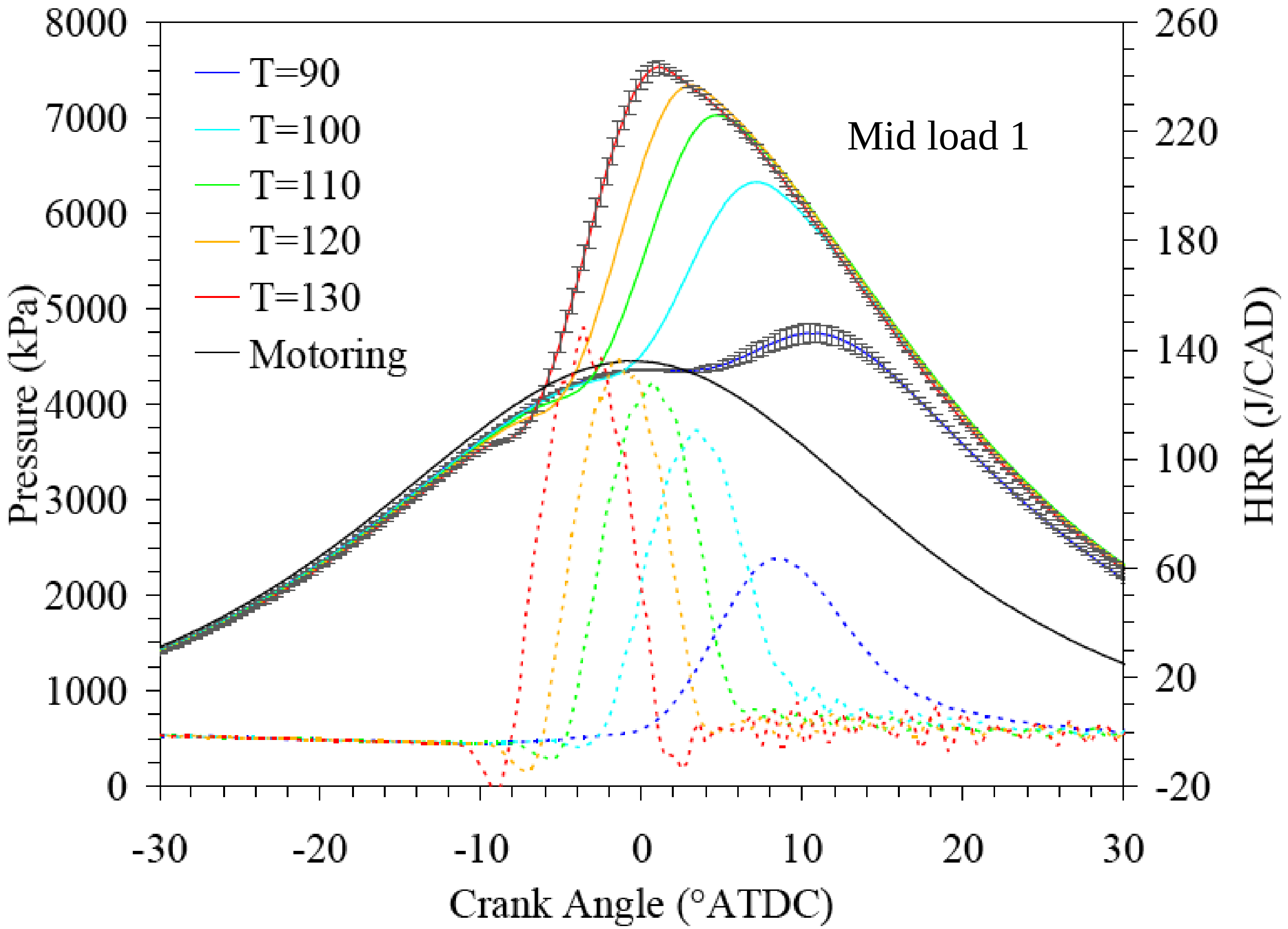


- In these tests maximum IMEP was achieved at inlet temperatures of 130 and 100 °C for ethanol and hydrogen, respectively
- Very low NOx emissions, < 0.02 g/kWh
- Surprisingly high PM emissions, but nearly 100% volatile
- EtOH has higher PM than H_2 but we believe this is mainly due different burning rates and average in-cylinder temperatures influencing oil evaporation and atomization

Outline

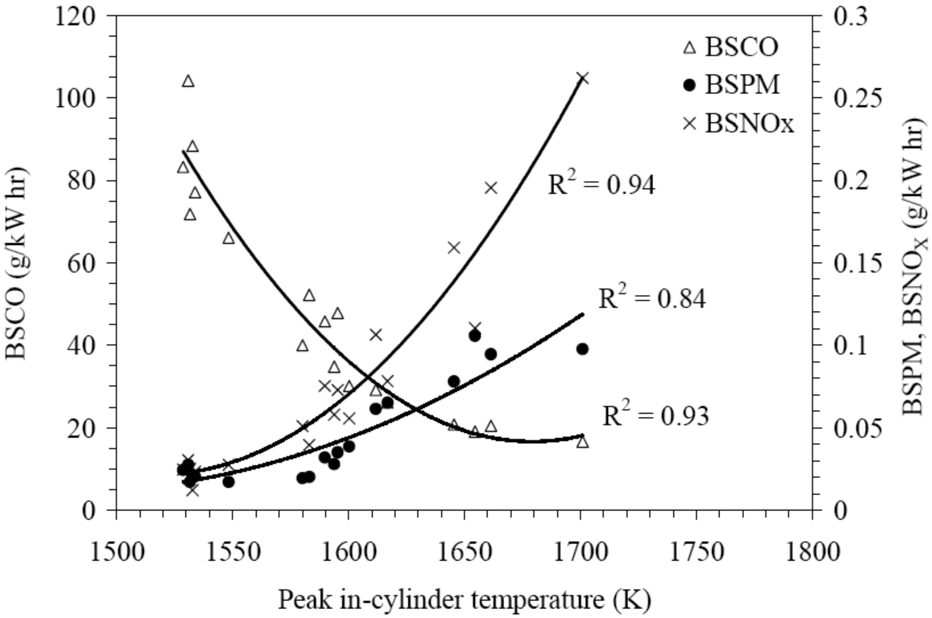
- Introduction
- Experimental apparatus and procedure
- Dilution sensitivity
- Results
  - Emissions
    - Influence of fuel
    - Influence of thermal processing
    - Volatility measurements
- Conclusions

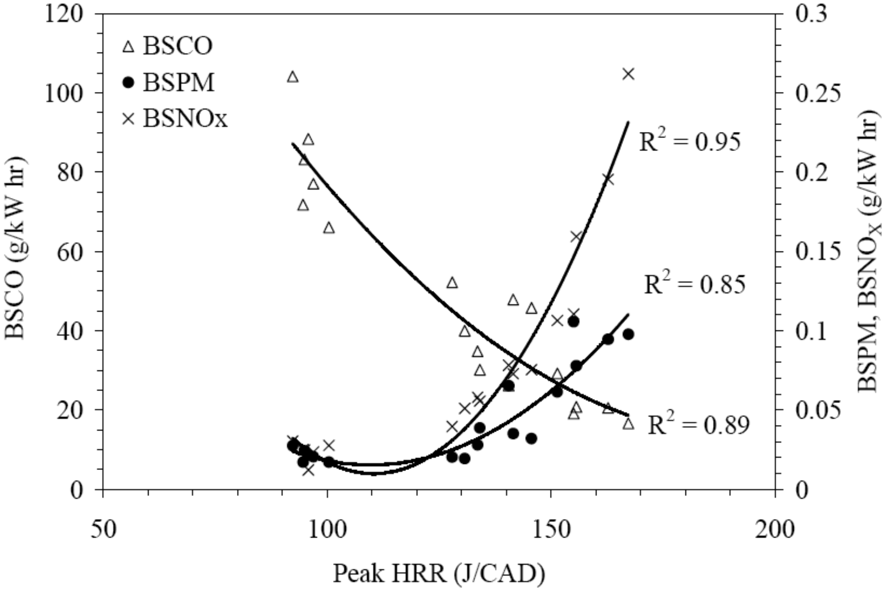
In cylinder pressure measurements were used to calculate bulk temperatures, cycle work, and heat release rate



Dependence of PM and other pollutants depend upon combustion conditions, thermal processing

In Diesel engines there is usually a strong positive correlation between CO and PM formation and an inverse relation between NOx and PM, here the opposite trend is apparent.

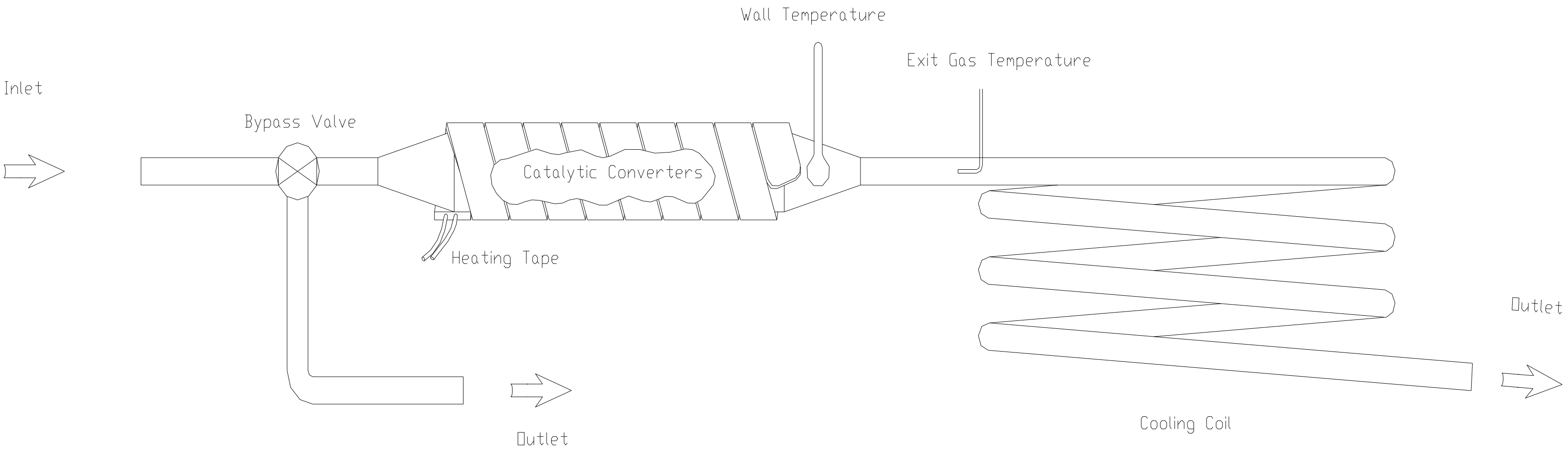




Outline

- Introduction
- Experimental apparatus and procedure
- Dilution sensitivity
- Results
  - Emissions
    - Influence of fuel
    - Influence of thermal processing
    - Volatility measurements
- Conclusions

A catalytic stripper was used to differentiate volatile and solid particles

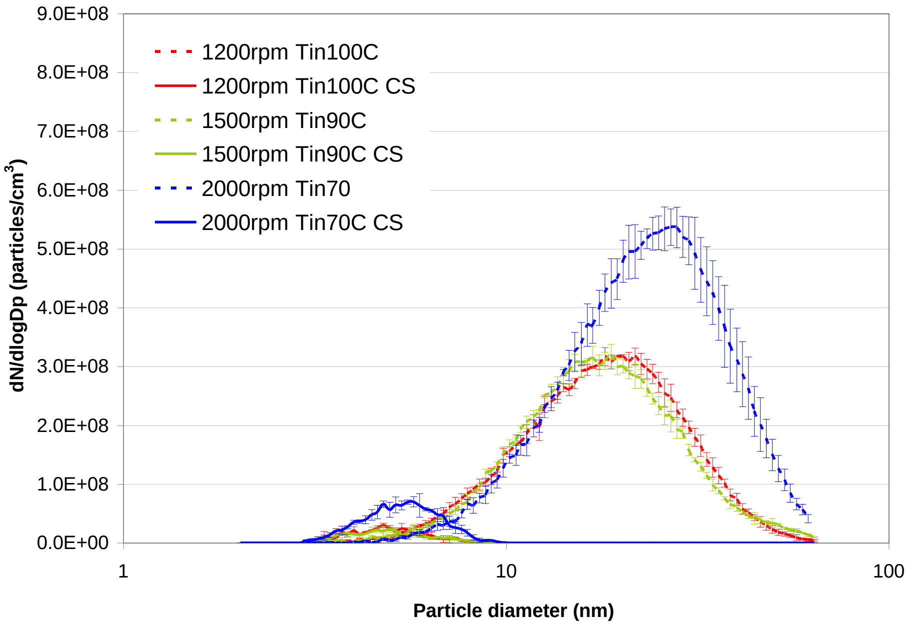


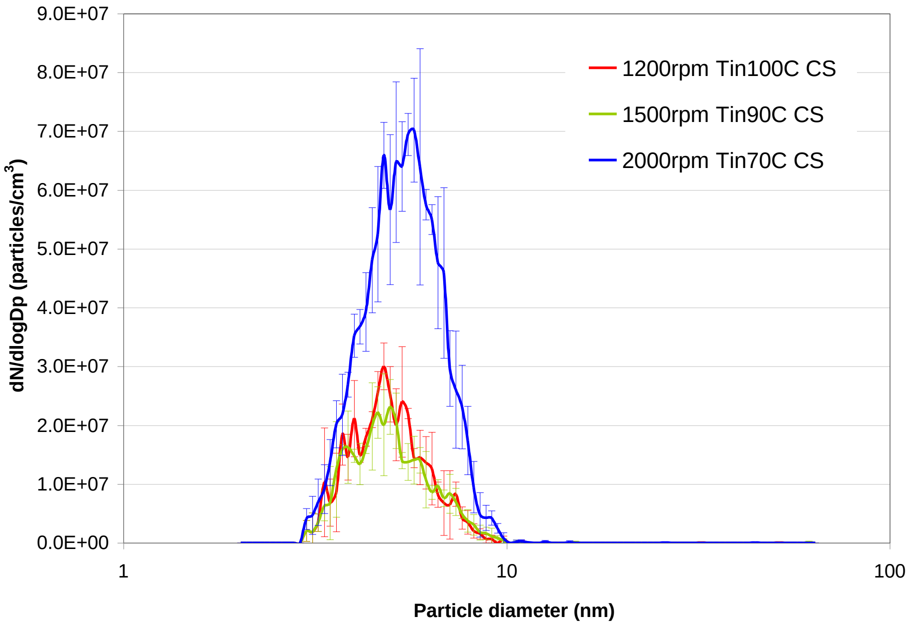
- Recent stripper design
  - Stripper consists of a 2 substrate catalyst* followed by a cooling coil
  - The first substrate removes sulfur compounds
  - The second substrate is an oxidizing catalyst
  - Diffusion and thermophoretic losses present but well defined

*Catalysts were provided by Johnson-Matthey

Kittelson, D. B.; Watts, W. F.; Savstrom, J. C.; Johnson, J. P. Influence of catalytic stripper on response of PAS and DC. *J. Aerosol Sci.* ***2005***, *36*, 1089–1107.

Measurements of solid particles with catalytic stripper (CS)

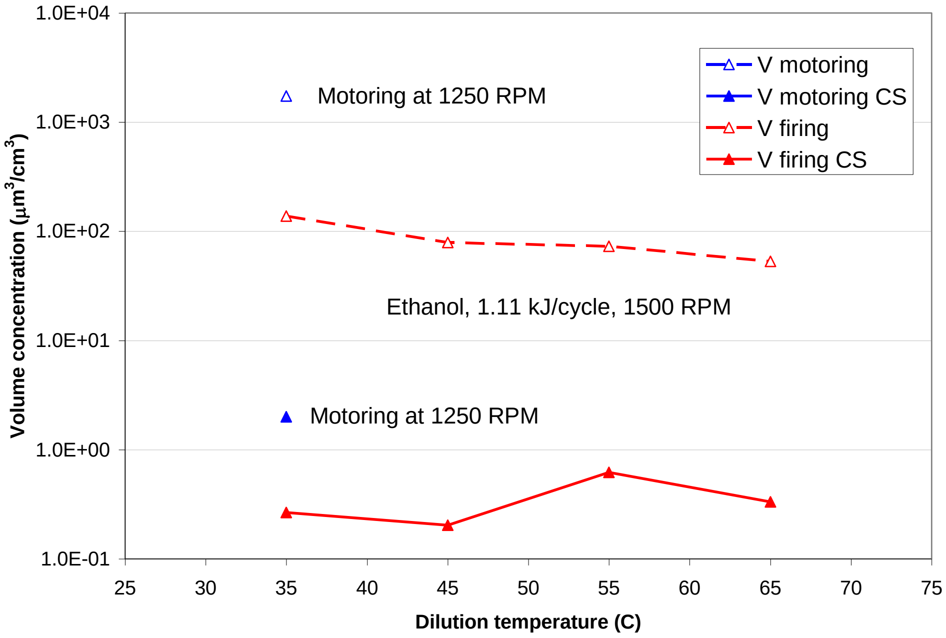


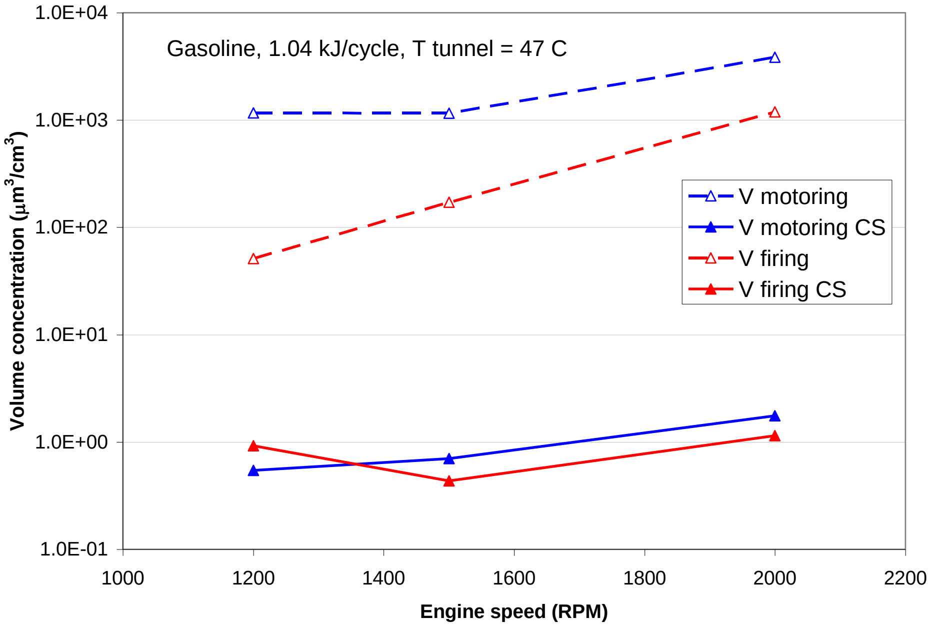


- Right plot shows solid fraction on 10x expanded scale
- Very small solid fraction present
- Depends upon speed, load, temperature – thermal processing

Total and solid particle volume emissions, motoring and firing

- Gasoline produces slightly higher total and solid emissions than ethanol
- Particle emissions are usually much lower under fired conditions than under motored conditions – hot motoring does not give reliable estimates of lube oil related particles
- Particles are more than 99% volatile





Tandem DMA used for detailed volatility measurements

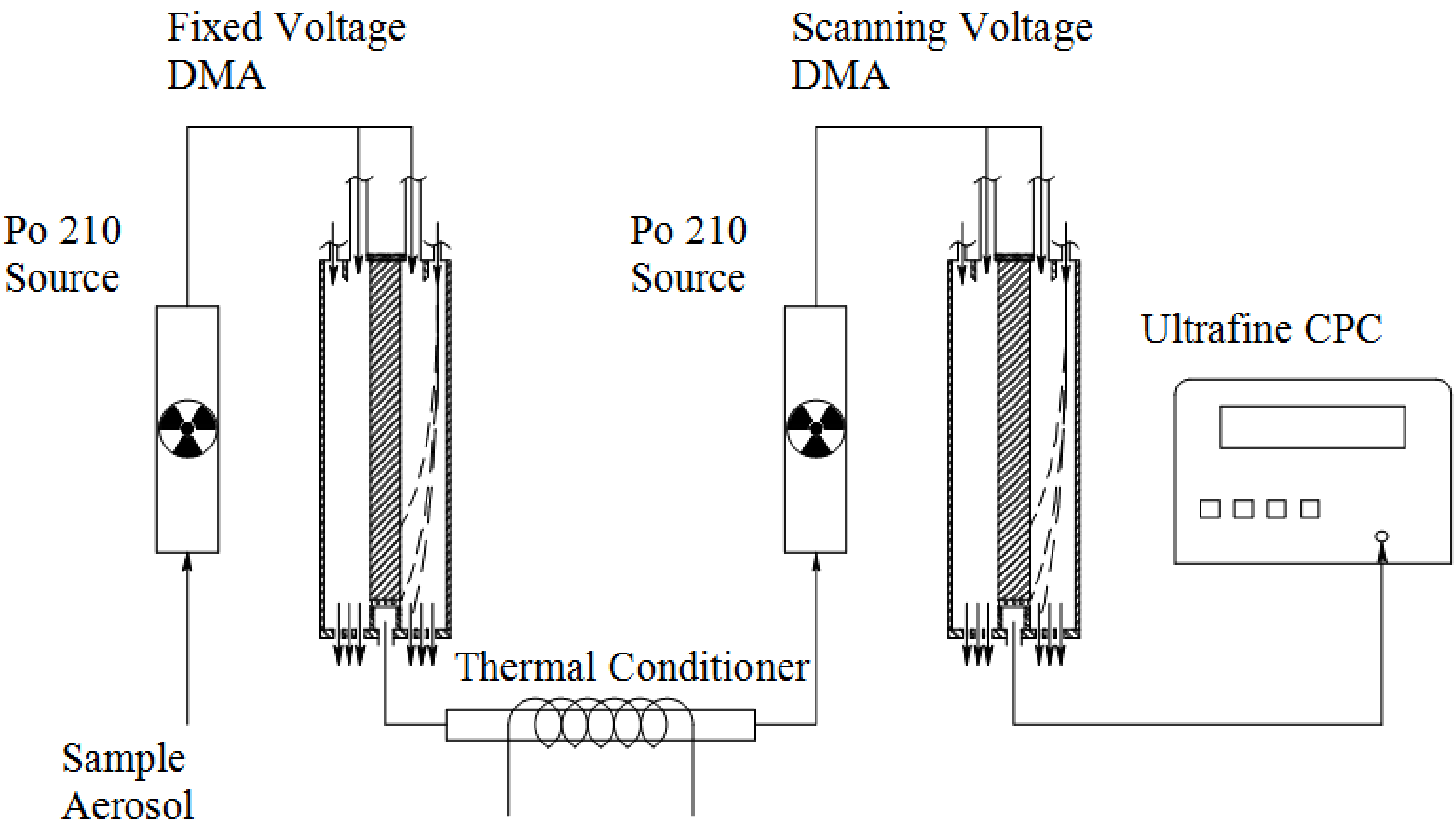
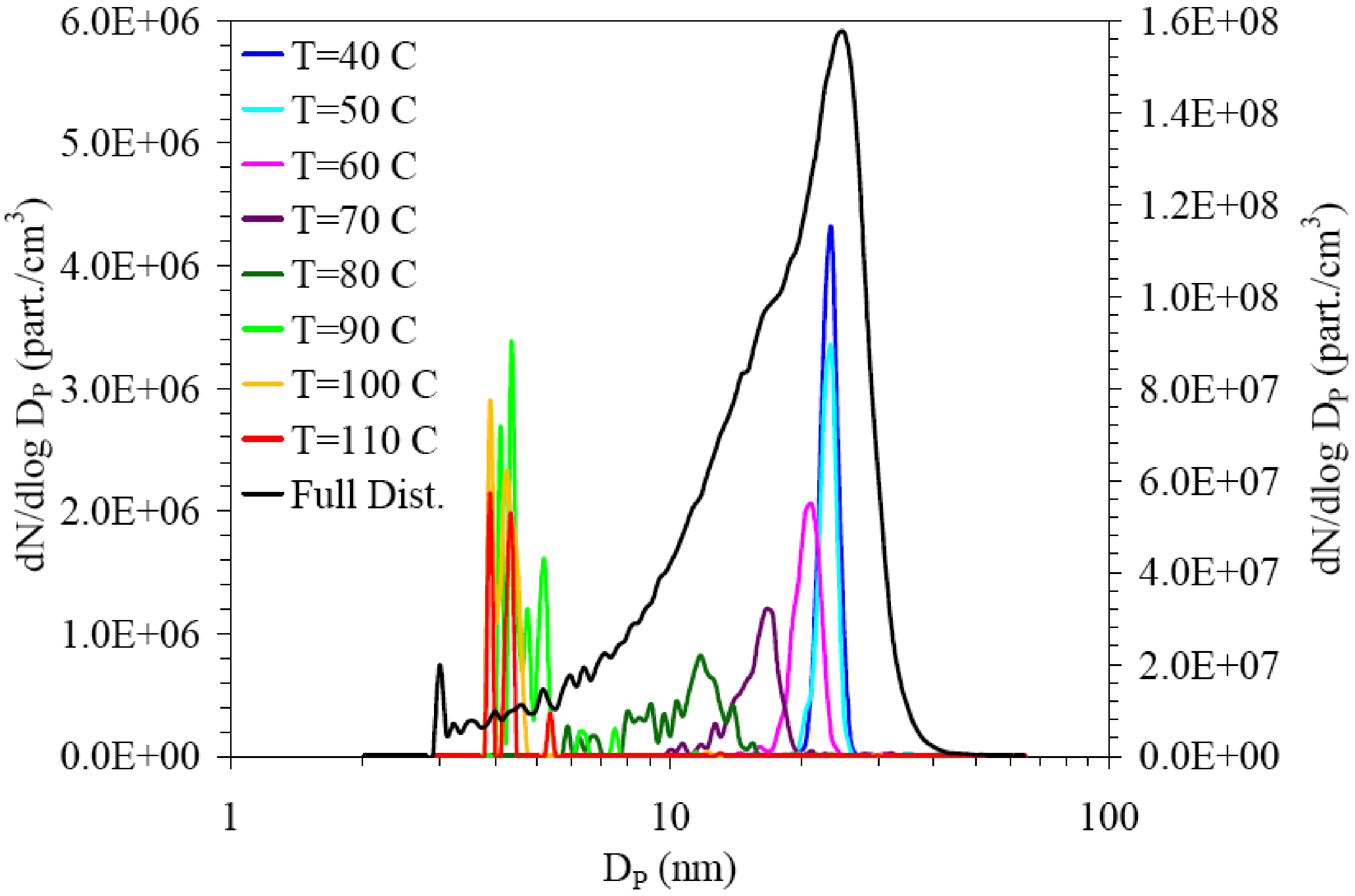


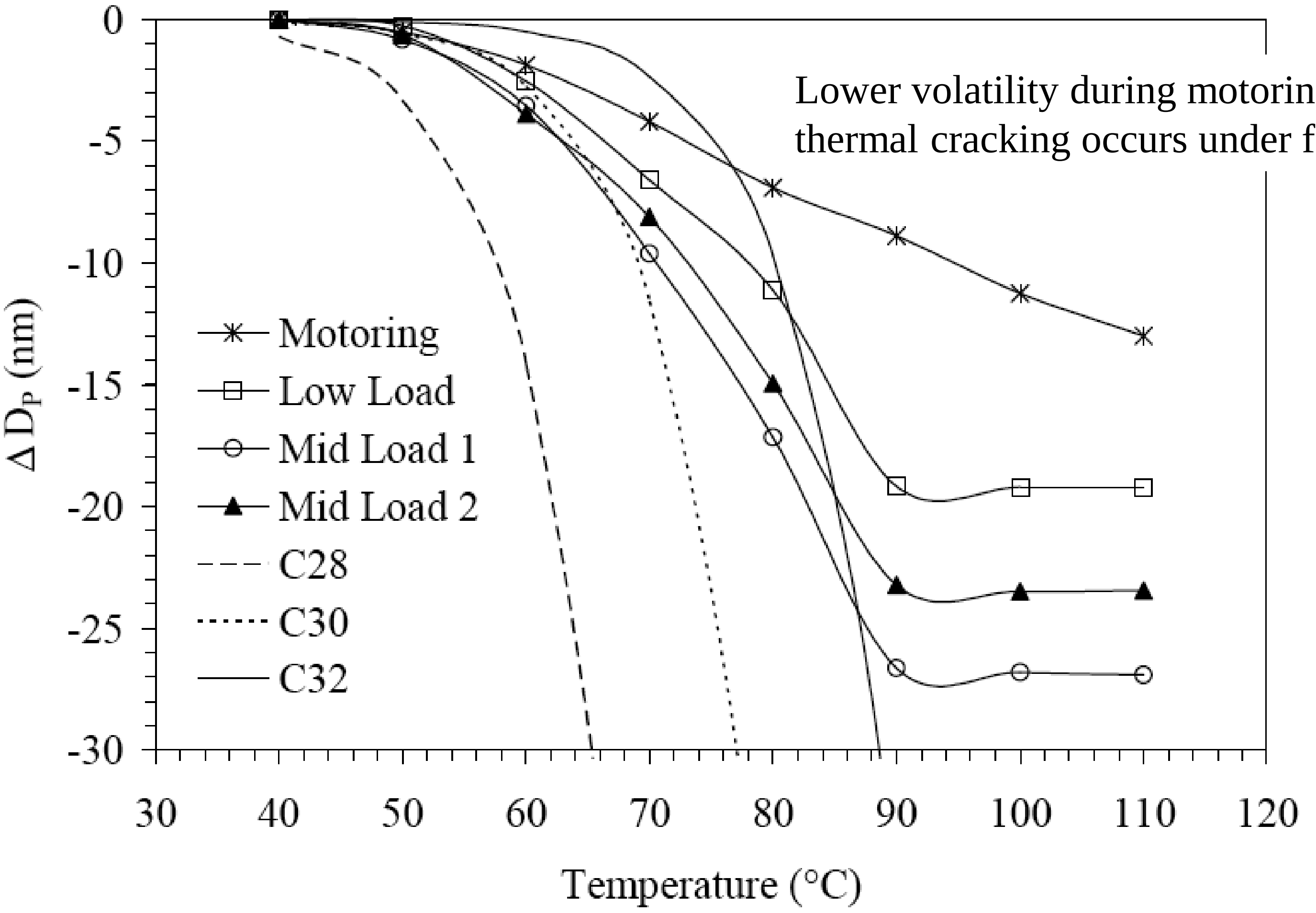
Figure 11: TDMA Apparatus

Tandem DMA measurements of particle volatility



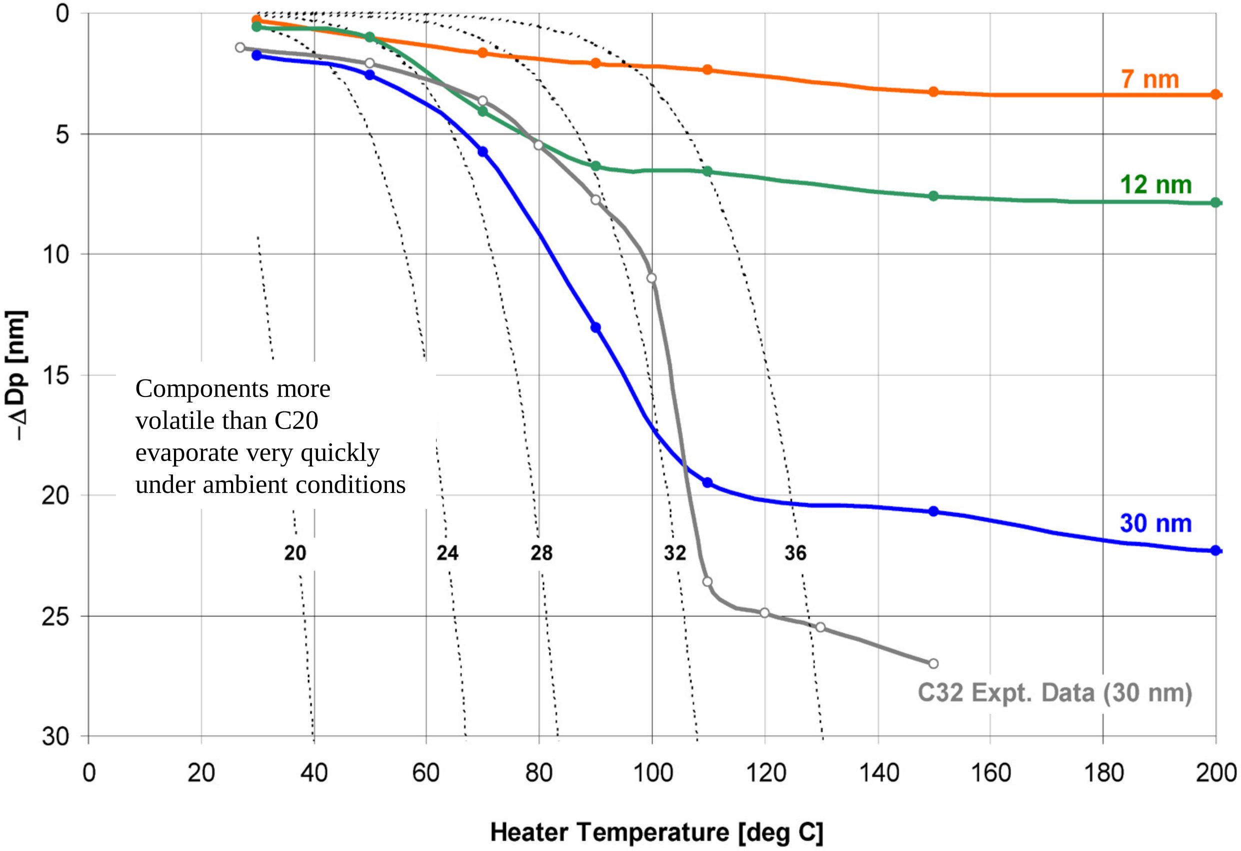
Light load, ethanol fuel, no EGR

Evaporation profiles for fired conditions are similar to C30 – C32 normal alkanes.



Lower volatility during motoring suggests thermal cracking occurs under fired conditions

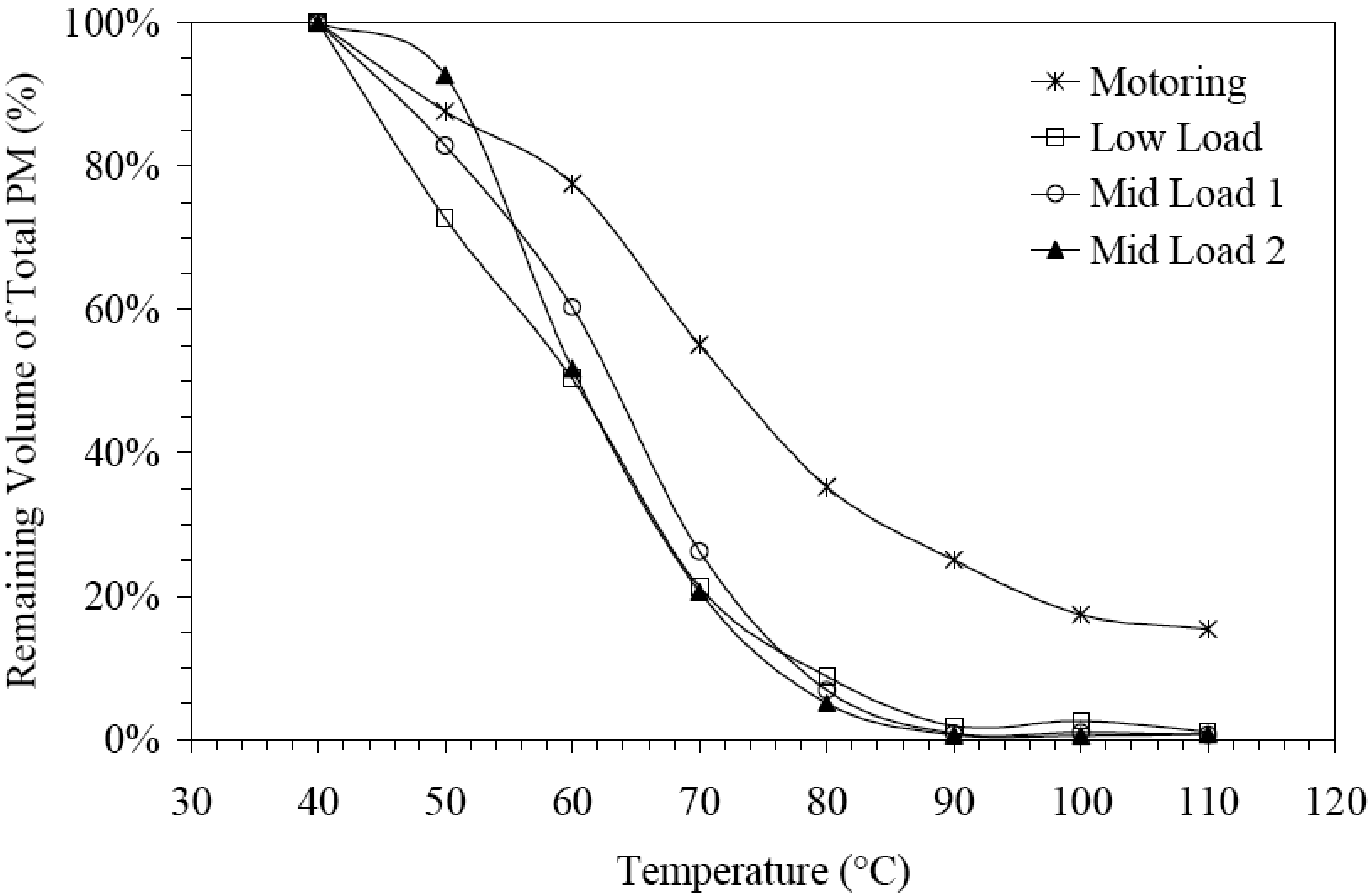
Evaporative shrinkage of n-alkanes and Diesel nanoparticles. Diesel nanoparticles behave like C28-C32 – lube oil?



Components more volatile than C20 evaporate very quickly under ambient conditions

Sakurai, Hiromu, Herbert J. Tobias, Kihong Park, Darrick Zarling, Kenneth S. Docherty, David B. Kittelson, Peter H. McMurry, and Paul J. Ziemann, 2003. “On-Line Measurements of Diesel Nanoparticle Composition, Volatility, and Hygroscopicity,” Atmospheric Environment 37 1199–1210.

Nearly all the volume (and mass) of these particles is volatile



Outline

- Introduction
- Experimental apparatus and procedure
- Dilution sensitivity
- Results
  - Emissions
    - Influence of fuel
    - Influence of thermal processing
    - Volatility measurements
- Conclusions

Conclusions – PM emissions from pure HCCI

- Significant mass and number emissions observed
  - Most of material between 10 and 50 nm
  - Nearly all volatile
  - Particle emissions strongly associated with in-cylinder thermal history
  - Significant particle formation even with pure H_2 fuel
    - Particles apparently formed from thermal processing of lube oil
    - Should explore other lube oil formulations and oil vaporization / atomization mechanisms
  - It is likely that most of these particles could be removed by an oxidizing catalyst at sufficiently high exhaust temperatures
- It is likely that particle formation mechanisms will be similar in other non-sooting engine / fuel concepts like other low temperature combustion modes, and engines running on DME, CNG, H_2
- Lube oil related particles are one of the last remaining problems to be understood as we move to ever cleaner engines and combustion systems

Questions?

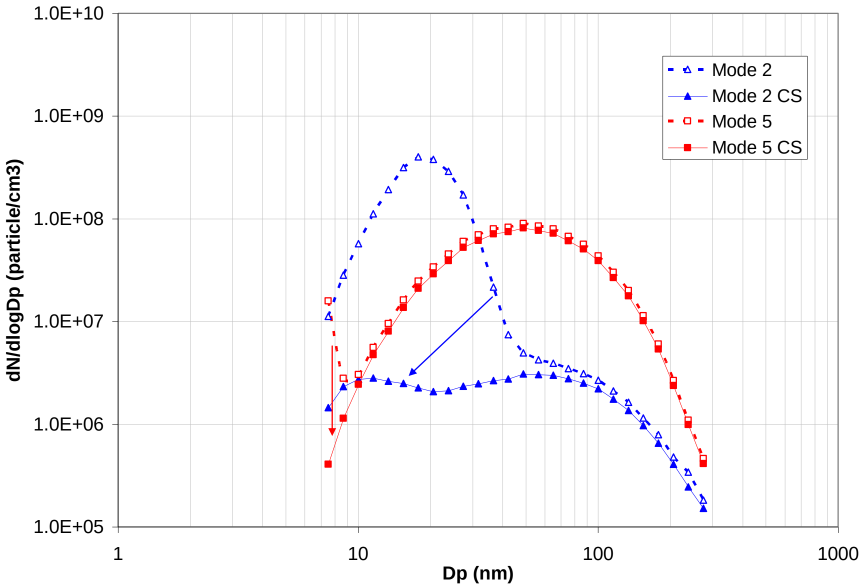
Additional slides

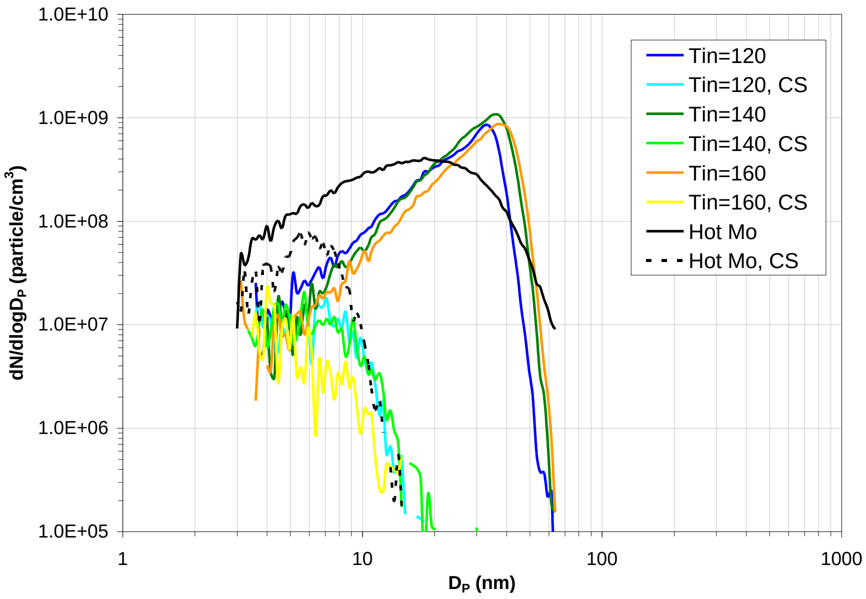
Related work on HCCI particle emissions

	Kaiser *et al* (2002)	Price *et al* (2007)	Misztal *et al* (2009)	Zinola & Lavy (2009)
Engine	DI, Intake heating, CR=15.2:1,	DI, 19 valve timings, λ=1 only,	Mixed hot/cold intake streams, variable valve timing	2.2 liter, DI, CR=14:1, boost, cool/hot EGR mixing
Fuel	Gasoline	Gasoline	Gasoline	low sulfur(<10ppm) diesel, CN =56.1
Instrumentation	SMPS, 2 stage dilution	DMS500	DMS500	SMPS 3071A ,with 3022 CPC
Findings	-Mid load HCCI yielded more and larger accum. mode PM than DISI operation	-HCCI showed more accum. mode PM and less nucl. mode PM than DISI	-Increased EGR-decreased total PM -Lack of dilution monitoring/control reported	-NO_2:NO_X ≈12-17% -VOF 75-90% for low load HCCI -no nucleation mode PM present -no dilution conditions reported

Solid particle measurements

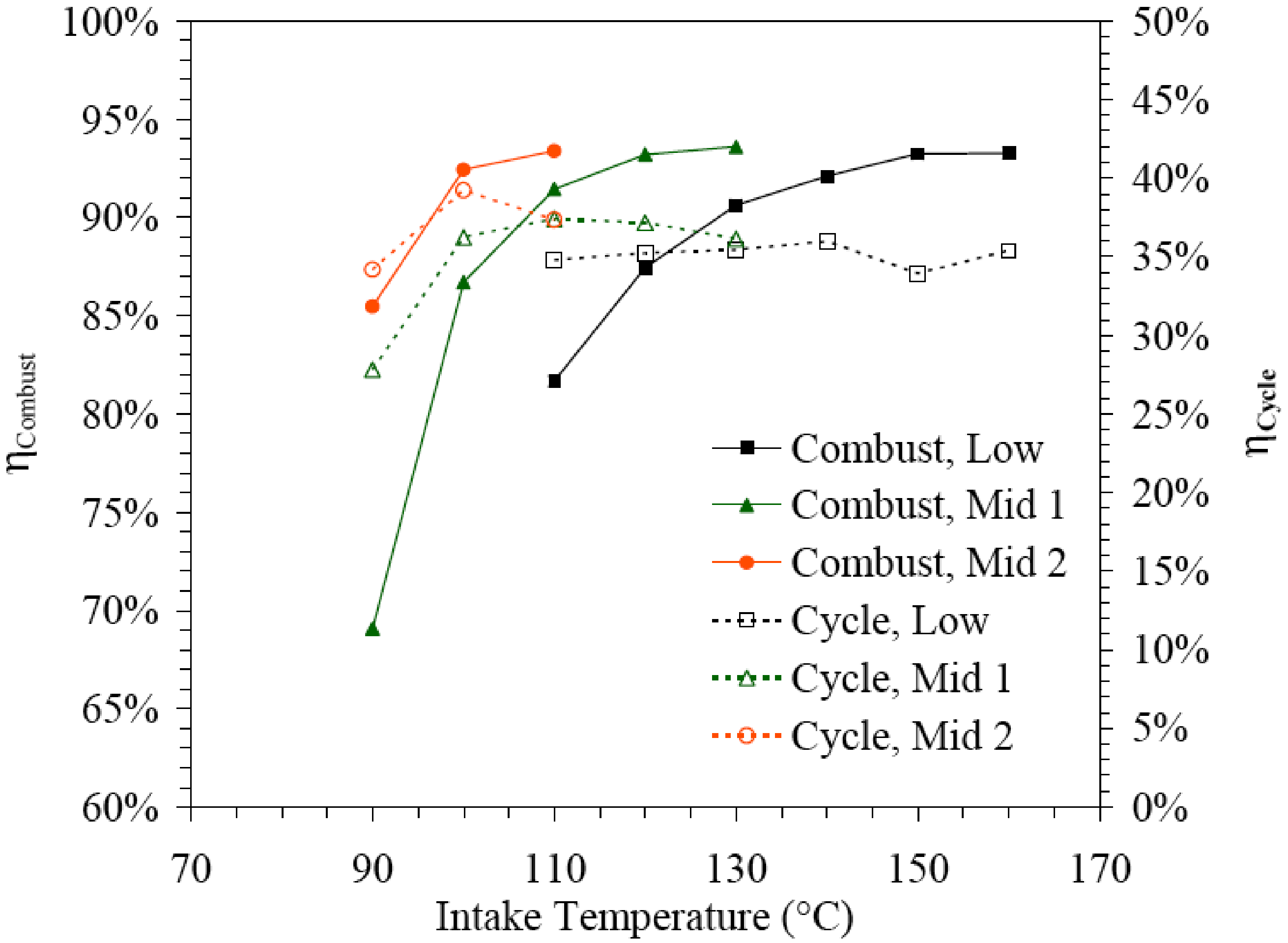
Comparison with solid particles from a modern Diesel. HCCI nucleation mode particles much smaller but in higher concentration.



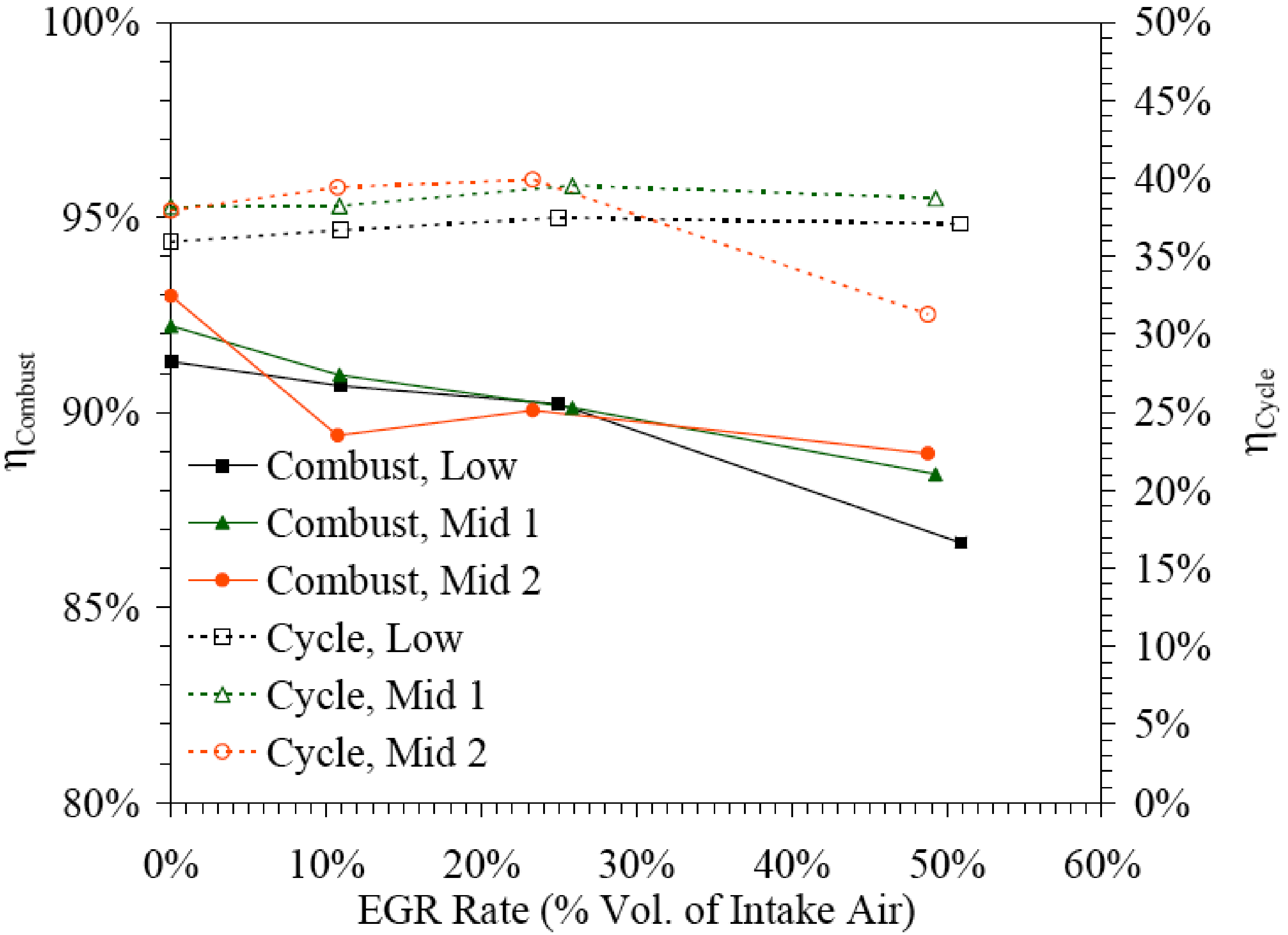


Additional combustion data

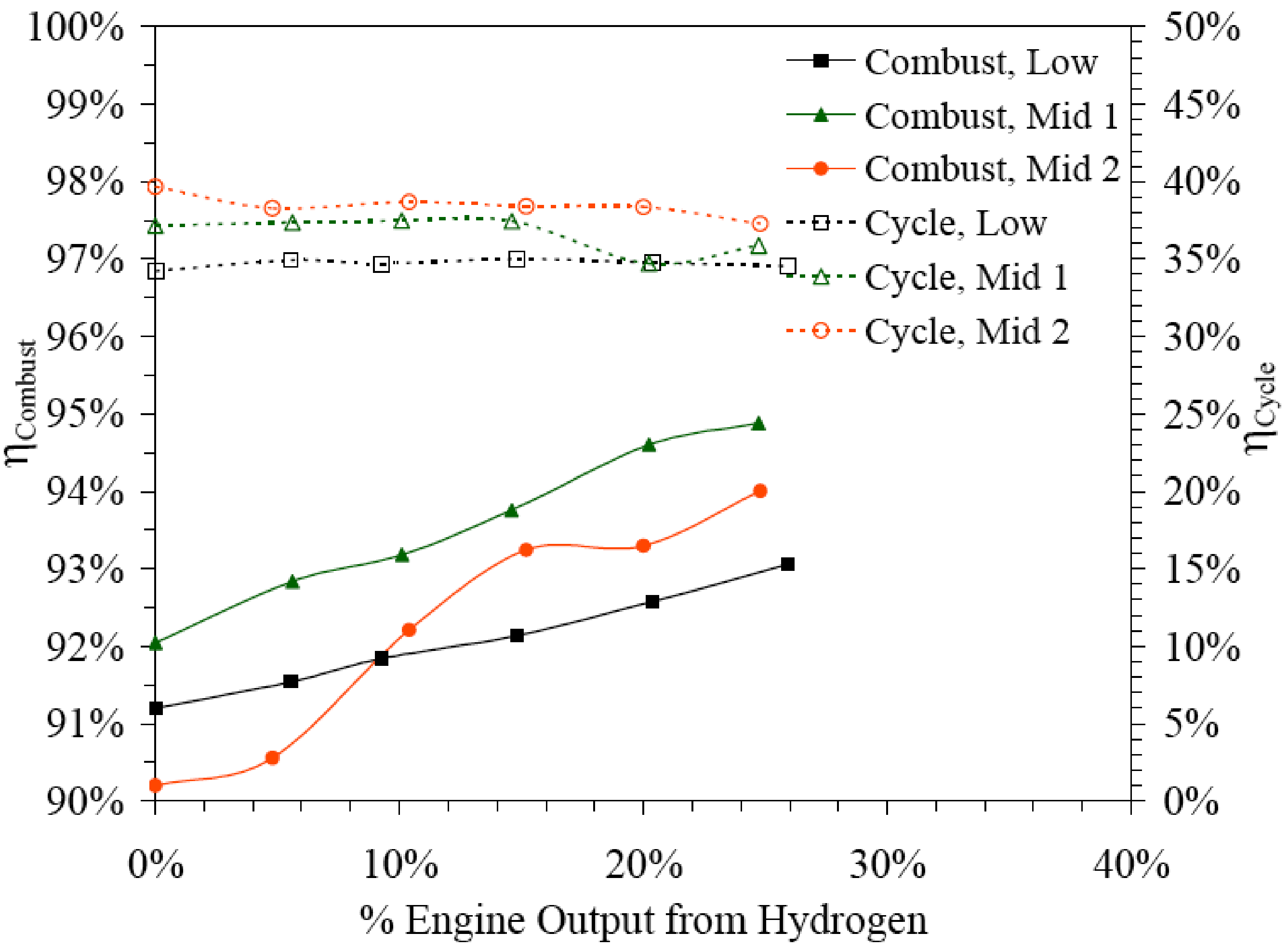
Typical engine performance, cycle efficiency and combustion efficiency, ethanol fuel



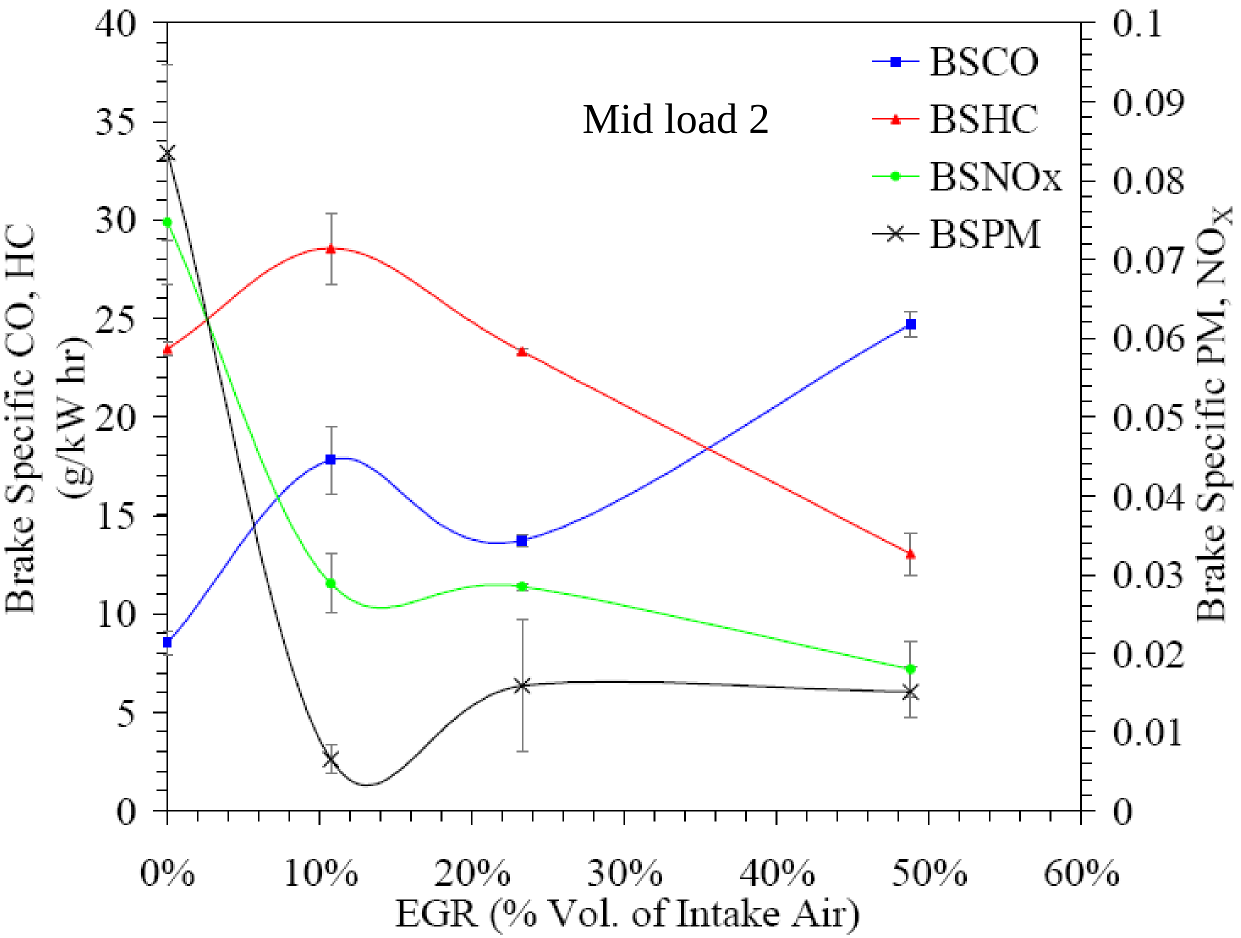
Changing EGR rate at constant load changes combustion timing and efficiency



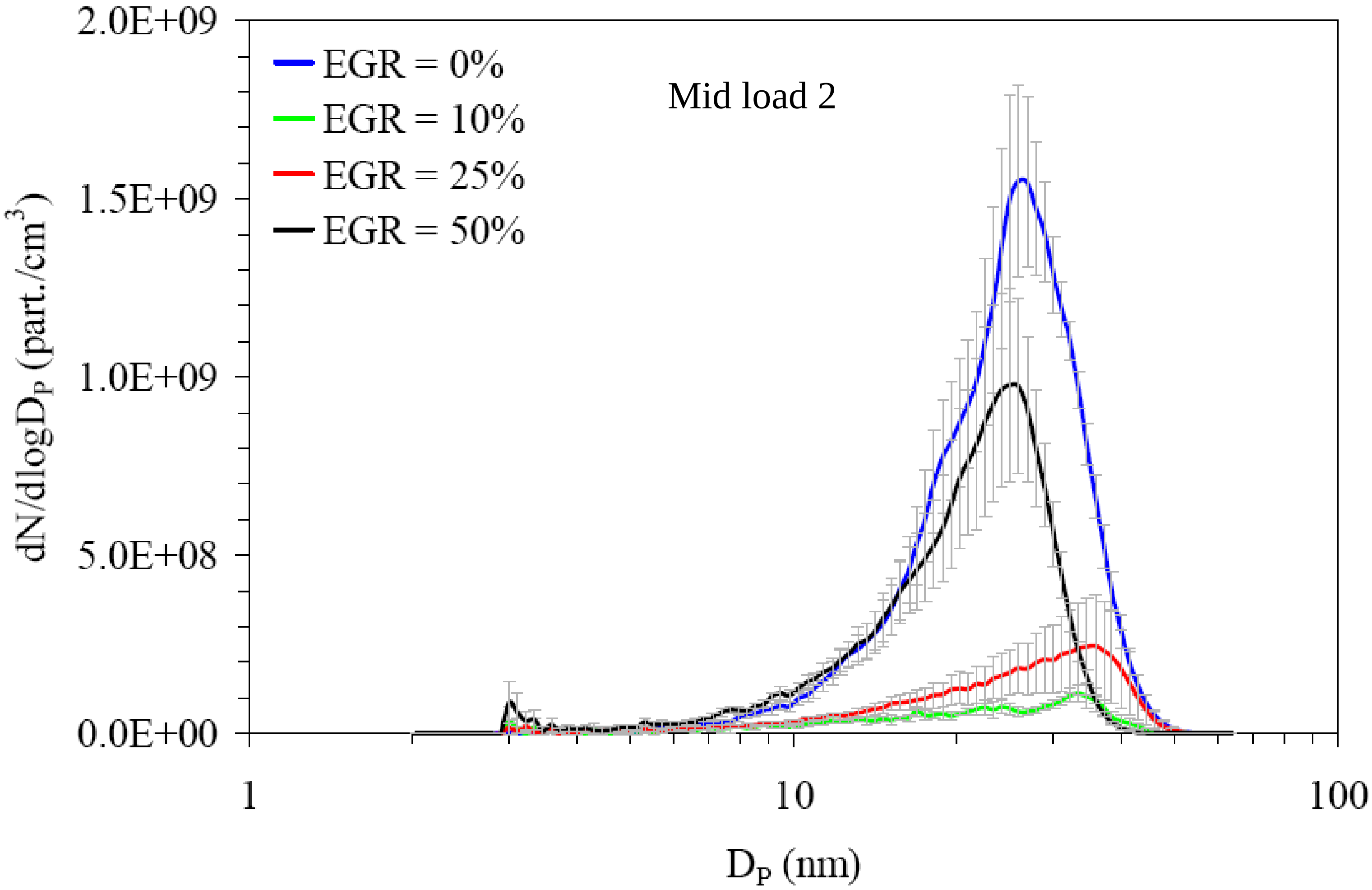
Changing H_2 rate at constant load changes combustion timing and efficiency



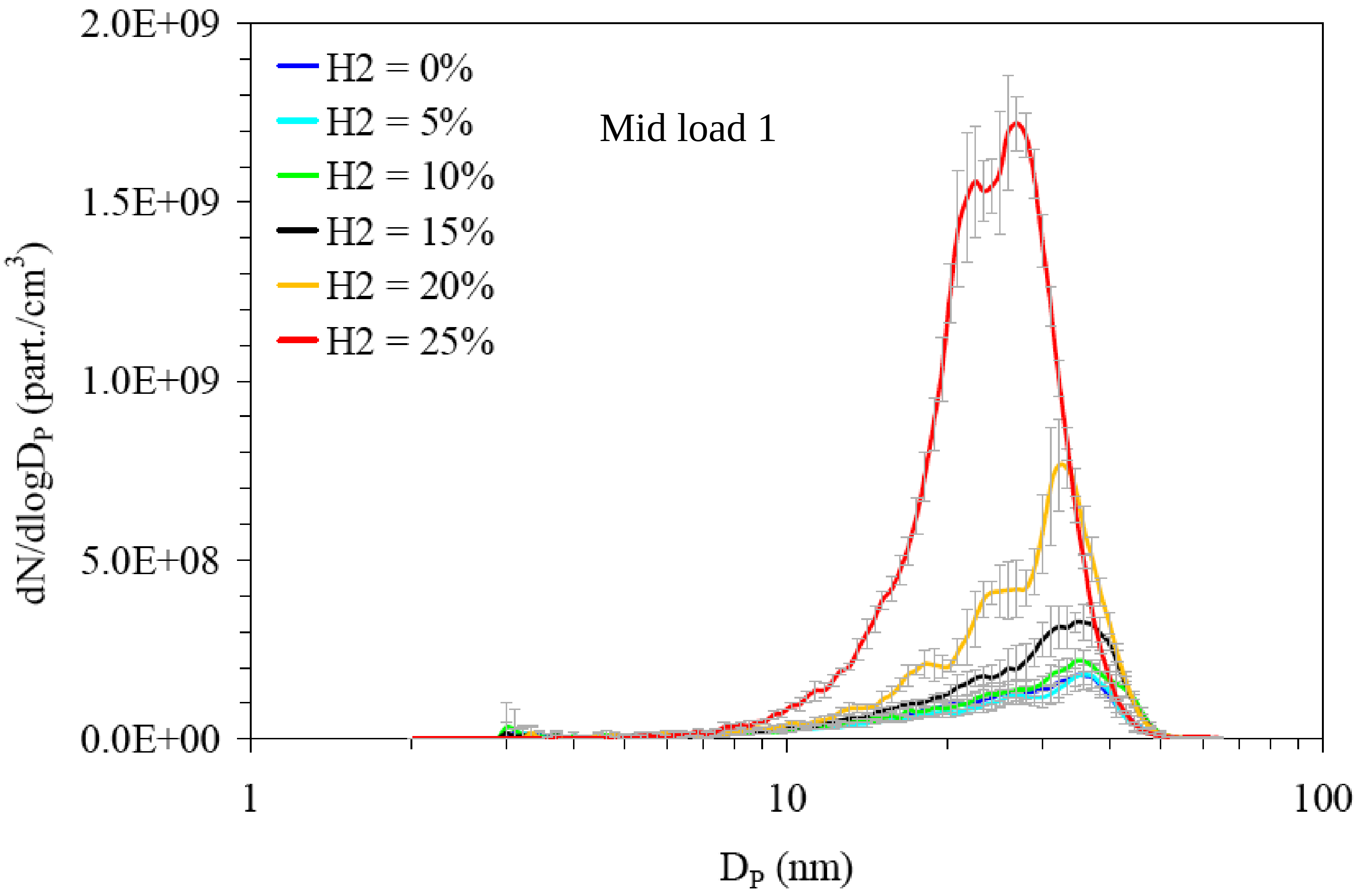
Influence of EGR on emissions



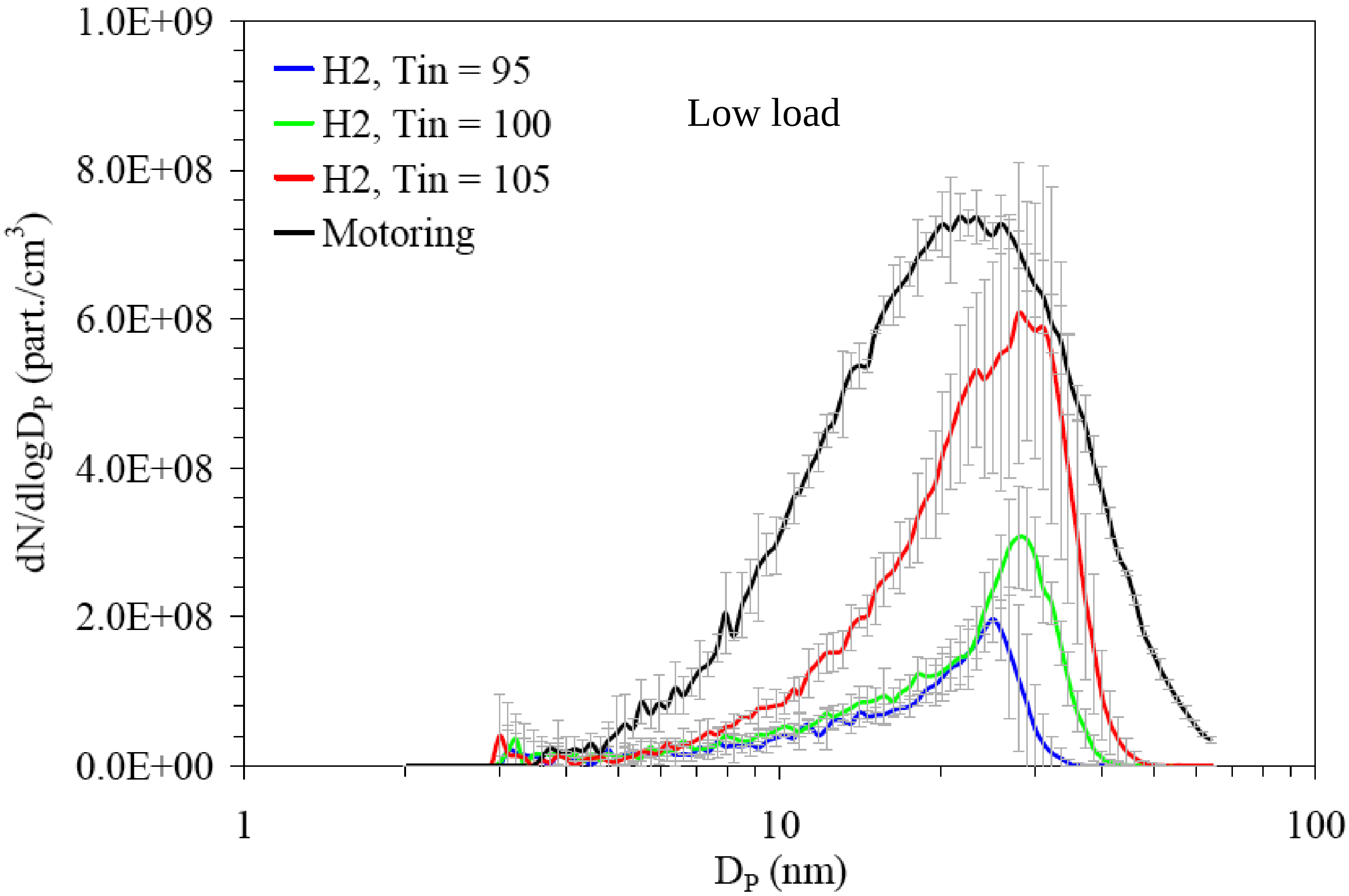
The particle size distribution is unimodal and in the nucleation mode range – concentrations decrease with EGR



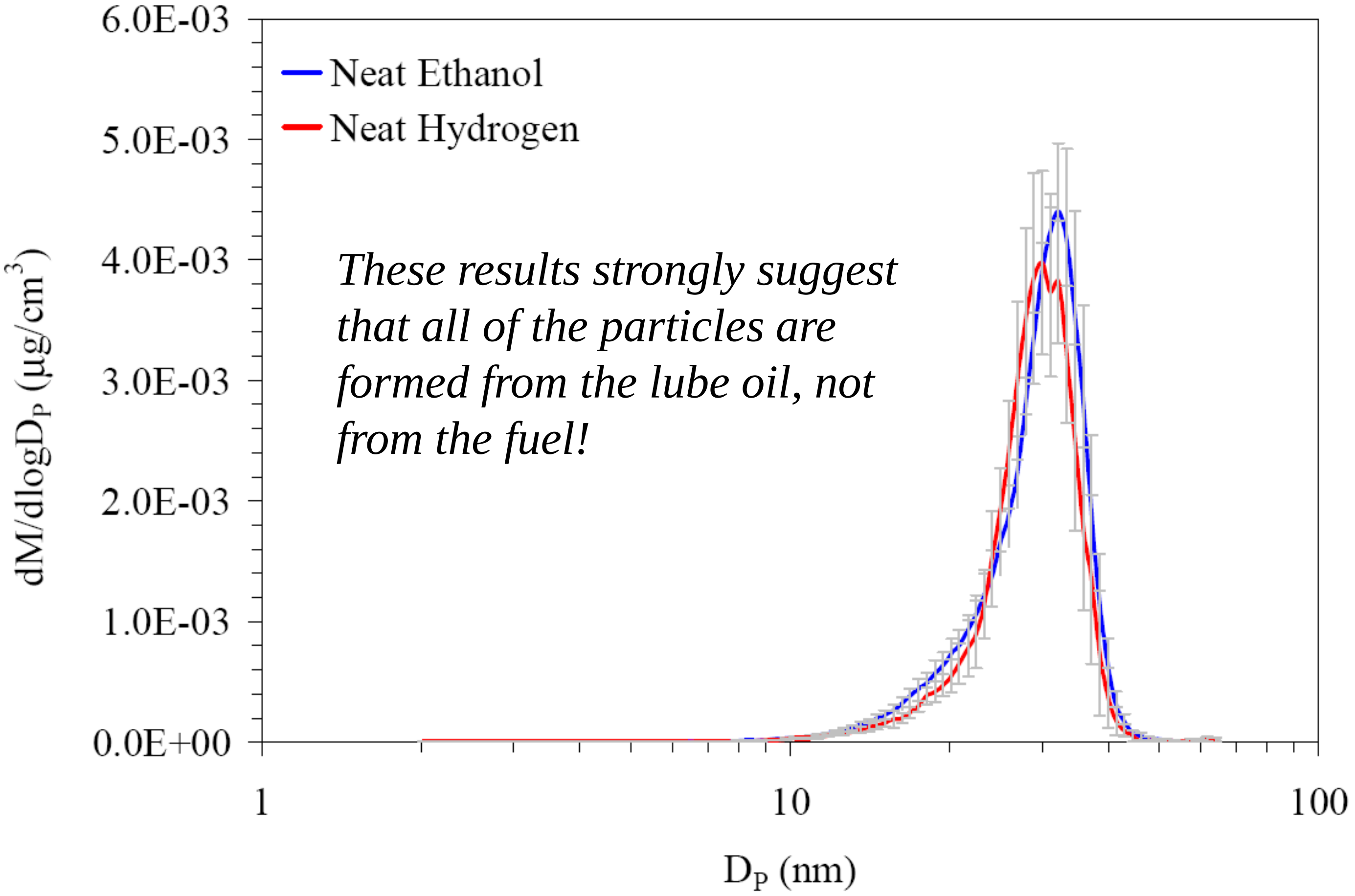
The particle emissions increase with increasing H_2 addition at constant load



For pure H_2 particle concentrations increase with inlet temperature, hot motoring result also shown



PM formation with ethanol and pure H_2 fuels, matched combustion conditions



These results strongly suggest that all of the particles are formed from the lube oil, not from the fuel!