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Mixed-mode Diesel HCCI with External Mixture Formation: Preliminary Results

Shawn Midlam-Mohler, Yann Guezennec, **Giorgio Rizzoni**

The Ohio State University

Center for Automotive Research

Michael Bargende, Simon Haas

FKFS, Universität Stuttgart

rizzoni.1@osu.edu

http://car.eng.ohio-state.edu

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Outline

1. Mixed-mode HCCI/DI concept
2. Experimental results in single-cylinder engine
3. Future Work

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1. Mixed-mode HCCI technologies

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Basic concept

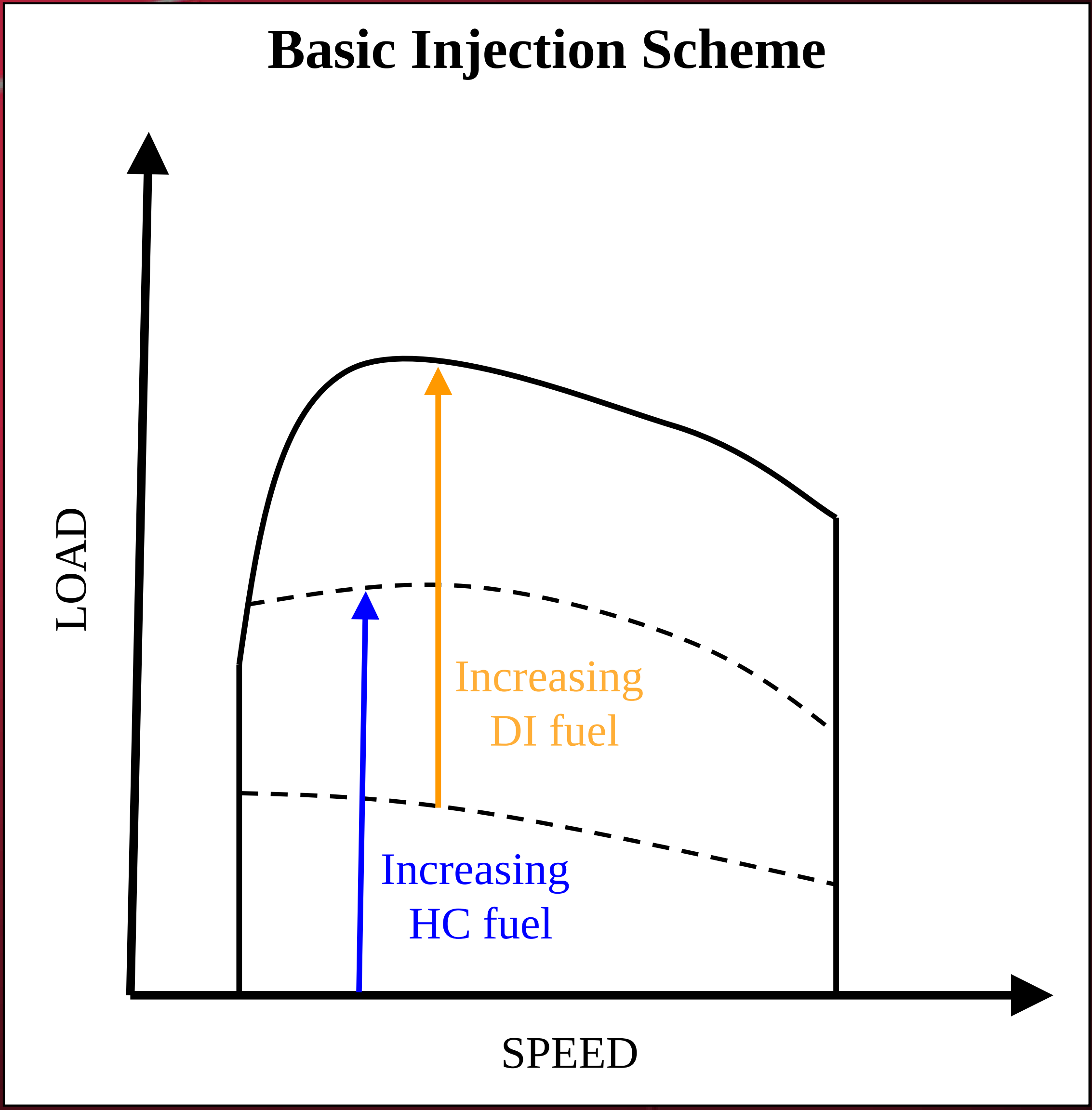
- Single fuel system: Diesel
- Two injection systems
  - Port/manifold injection – low pressure atomizer system
  - Direct injection - high-pressure injection system
- Atomizer system delivers fuel as a pre-mixed lean homogeneous mixture in the cylinder.
- Homogeneous charge ignites due to compression, or alternatively due to triggering from direct injection pulse
  - Allows more control over HCCI SOC

Characteristics

- Small droplet size (< 1μm mean diameter) allows rapid evaporation during compression stroke, removing the need for intake air heating (leading to higher CR).
- EGR and valve actuation control (based on models of combustion delay and reaction rates) permits SOC control.
- Direct injection supplements the reaction with additional fuel as a function of load for high-torque output.

Engine Operation

- Low load
  - Main torque from homogeneous charge (HC) fuel
  - Direct Injection (DI) mainly for ignition
- Mid load
  - Increasing HC fuel
  - Increasing DI fuel
- High load
  - Max HC fuel
  - Increasing DI to full load



Diesel HCCI Methods

- External Mixture Formation
  - Port-Injection/Fumigation: fuel is injected in the intake air as it enters the cylinder
- Internal Mixture Preparation
  - Early In-Cylinder Injection: Fuel is injected in the cylinder well in advance of TDC
  - Late In-Cylinder Injection: Fuel is injected in the cylinder near TDC

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HCCI combustion with External Mixture Preparation

- Advantages:
  - Utilizes turbulence at intake port to promote mixing; very homogenous charge
  - For mixed mode combustion, the conventional direct injection fuel system can be optimized for *just direct injection* operation; it does not have to be a compromise between the different requirements of HCCI injection and DI injection.
- Disadvantages:
  - Diesel fuel difficult to atomize with conventional atomization techniques
  - Wall wetting can lead to high HC and smoke emissions and oil dilution

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Generation 1 Atomizer

Maximum Power Consumption	320 W
Maximum Flow Rate	20 mL/min
Environmental Temperature Limits:	
Lower	Tested to -5 deg. C with no loss of performance
Upper	Not evaluated; no problems are expected
Physical Dimensions	1” x 1” x 4”
Fuel Pressure Requirement	< 40 psi
System “warm-up time”	5 seconds
Power source	12 VDC

Atomization Quality

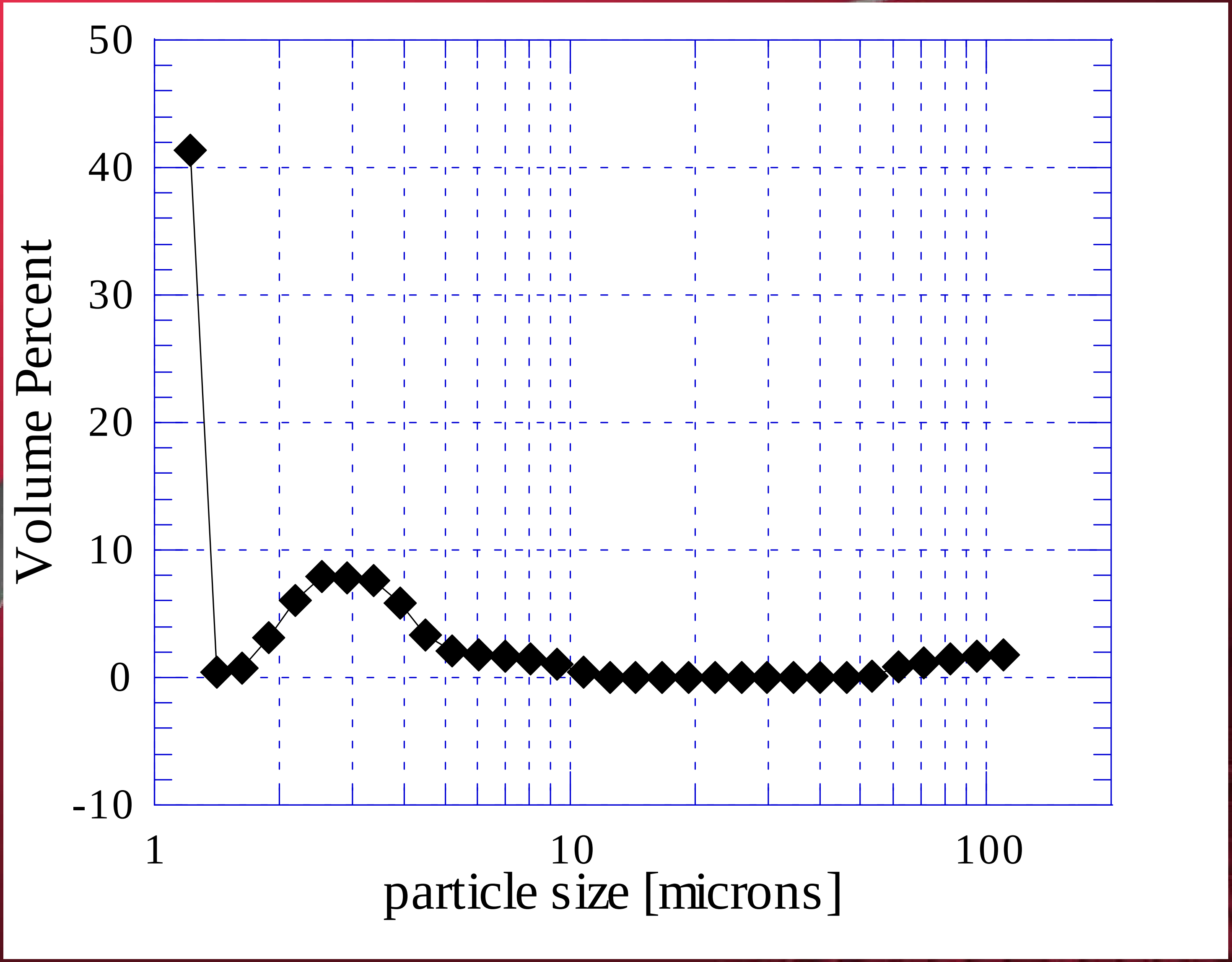
T = 0 min.

T = 2 min.

T = 8 min.

2 mL of diesel in a 2 L flask at room temperature

Droplet Size Distribution



Sample Combustion Quality

10 kW premixed, diesel flame, AFR = 16 burning at atmospheric conditions

The fine atomization allows for spark ignition of diesel fuel

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Generation 2 Atomizer

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Status of the Technology

- Patent pending
- Gen. 3 prototypes available for testing in September 2003
  - Technology is still under development
  - Current system is suitable for laboratory testing
- Improvements to be made in:
  - Reducing power consumption
  - Improving flow rate control
  - Reducing size
- Cost to mass produce has not been evaluated
  - Estimated to be between the cost of a gasoline port fuel injector and a direct injection diesel fuel injector

The atomizer and HCCI mixture preparation

- Low momentum particles follow air streamlines
  - Minimal wall impingement = low wall wetting
    - Lower HC, smoke, and reduced oil dilution
  - Mixing properties are very good in turbulent flows
- Can effectively atomize diesel fuel at low temperatures
- Suitable for injection of water- in- diesel emulsion

2. Single-cylinder engine experiments

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Experimental study

- Conducted in collaboration with Forschungsinstitut für Kraftfahrwesen und Verbrennungsmotoren, *FKFS*, Universität Stuttgart (Prof. M. Bargende).
- Single cylinder engine in controlled environment
- First round of tests completed in Spring 2003.

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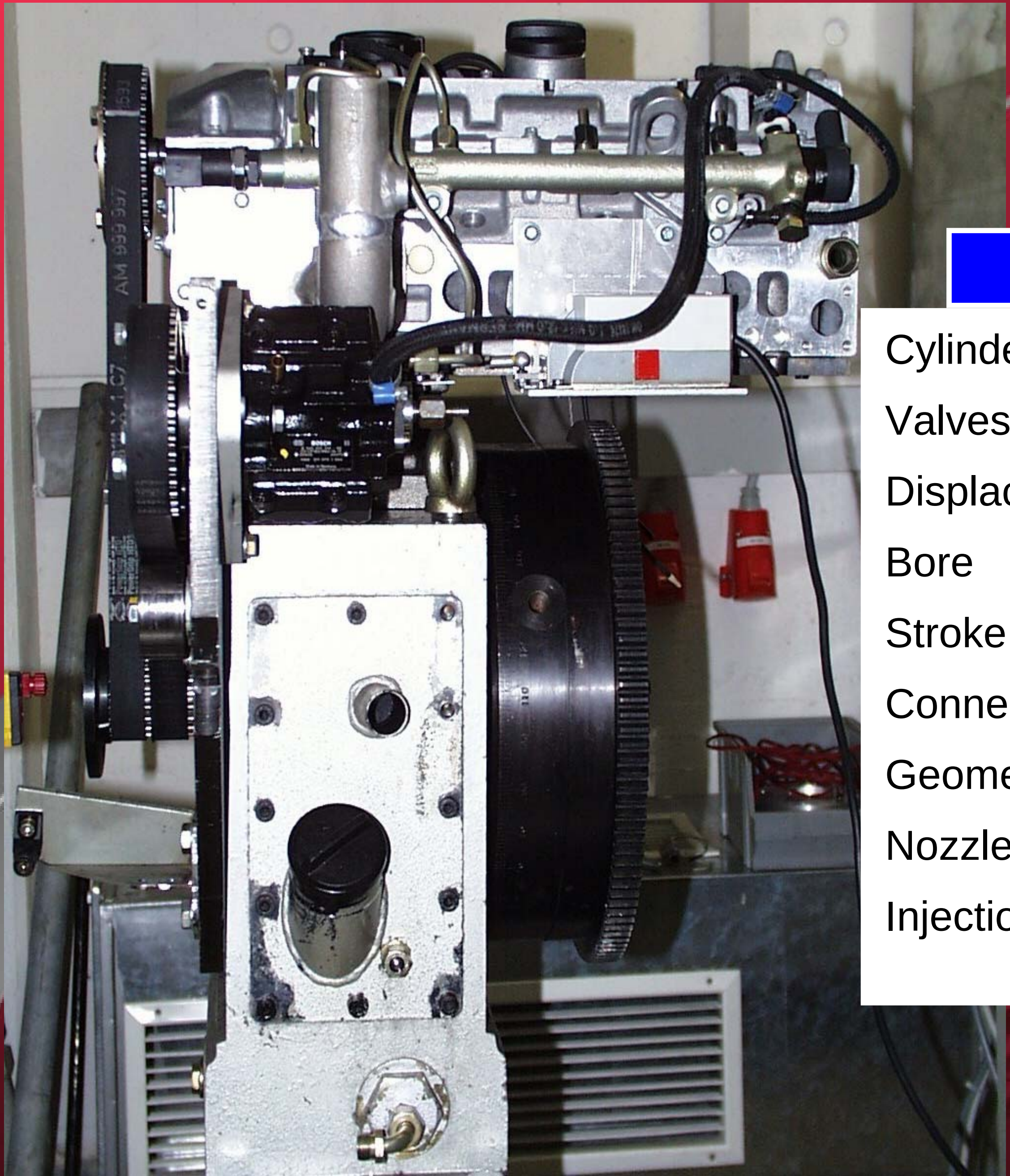
Single-cylinder engine



Single-Cylinder Engine OM 611	
Cylinders	1
Valves	4
Displacement	537,7 cm^3
Bore	88,0 mm
Stroke	88,4 mm
Connecting Rod	149 mm
Geometric CR	18 : 1
Nozzle Type:	6 Holes
Injection System:	Common Rail System 1350 bar

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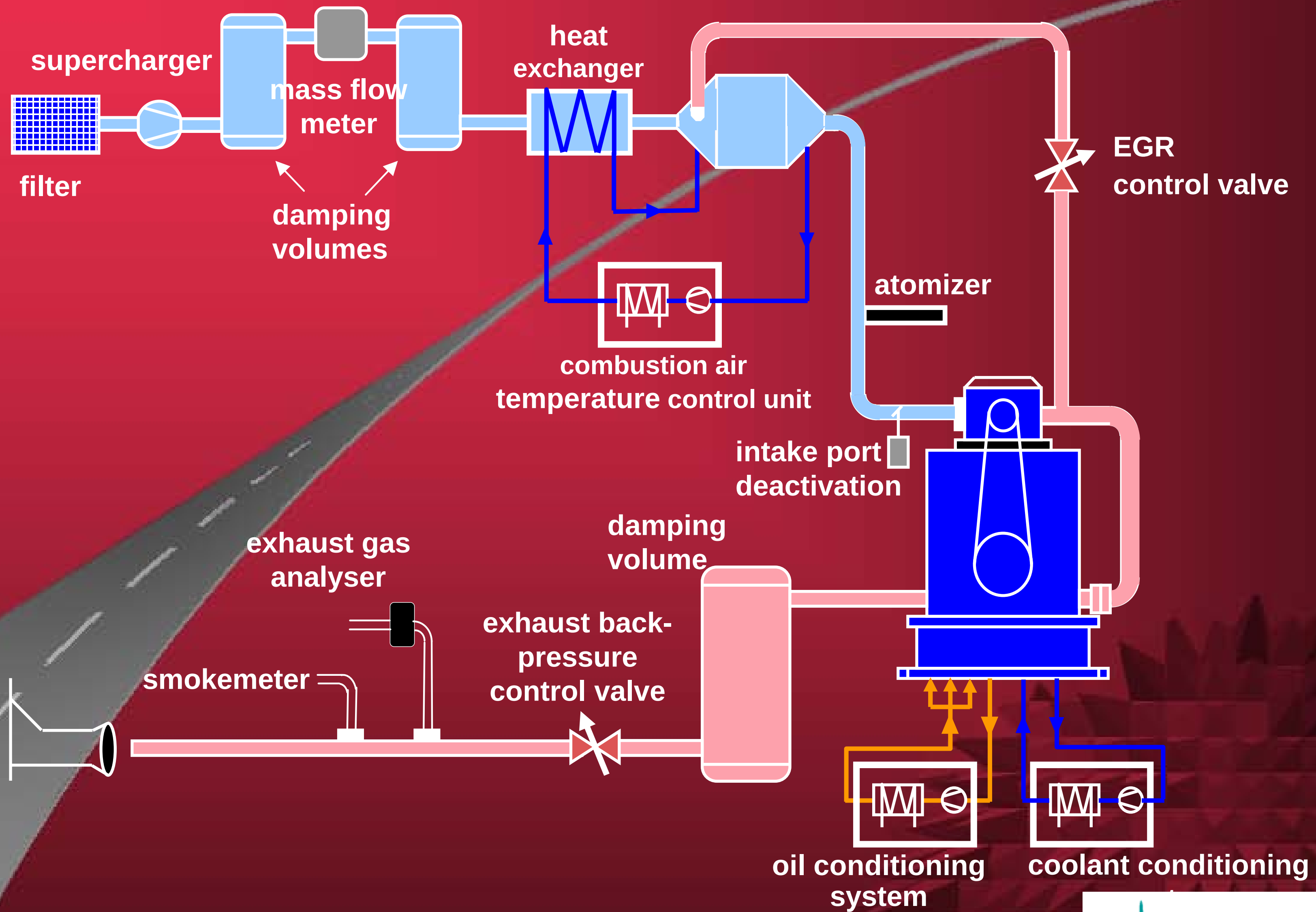
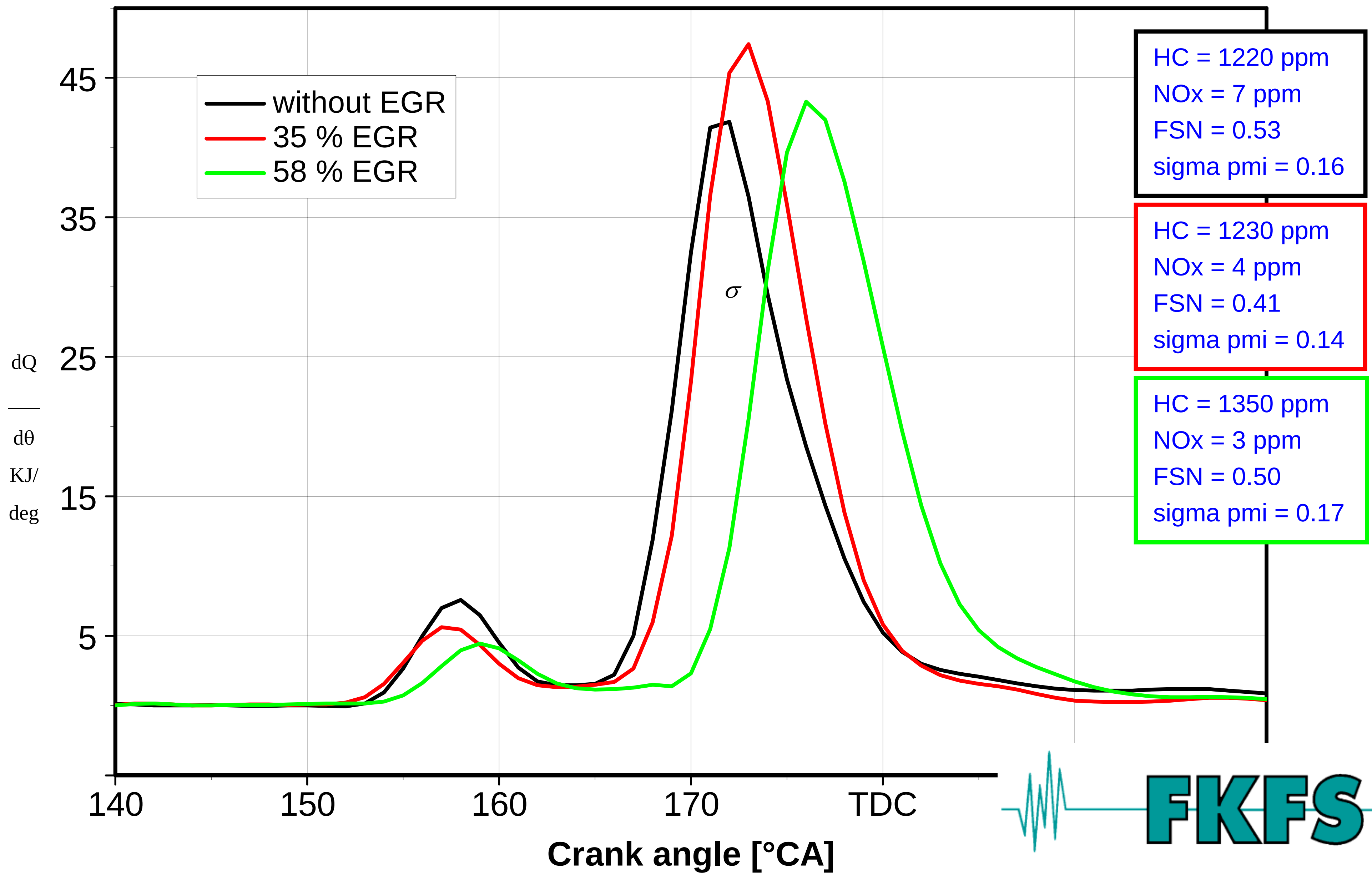
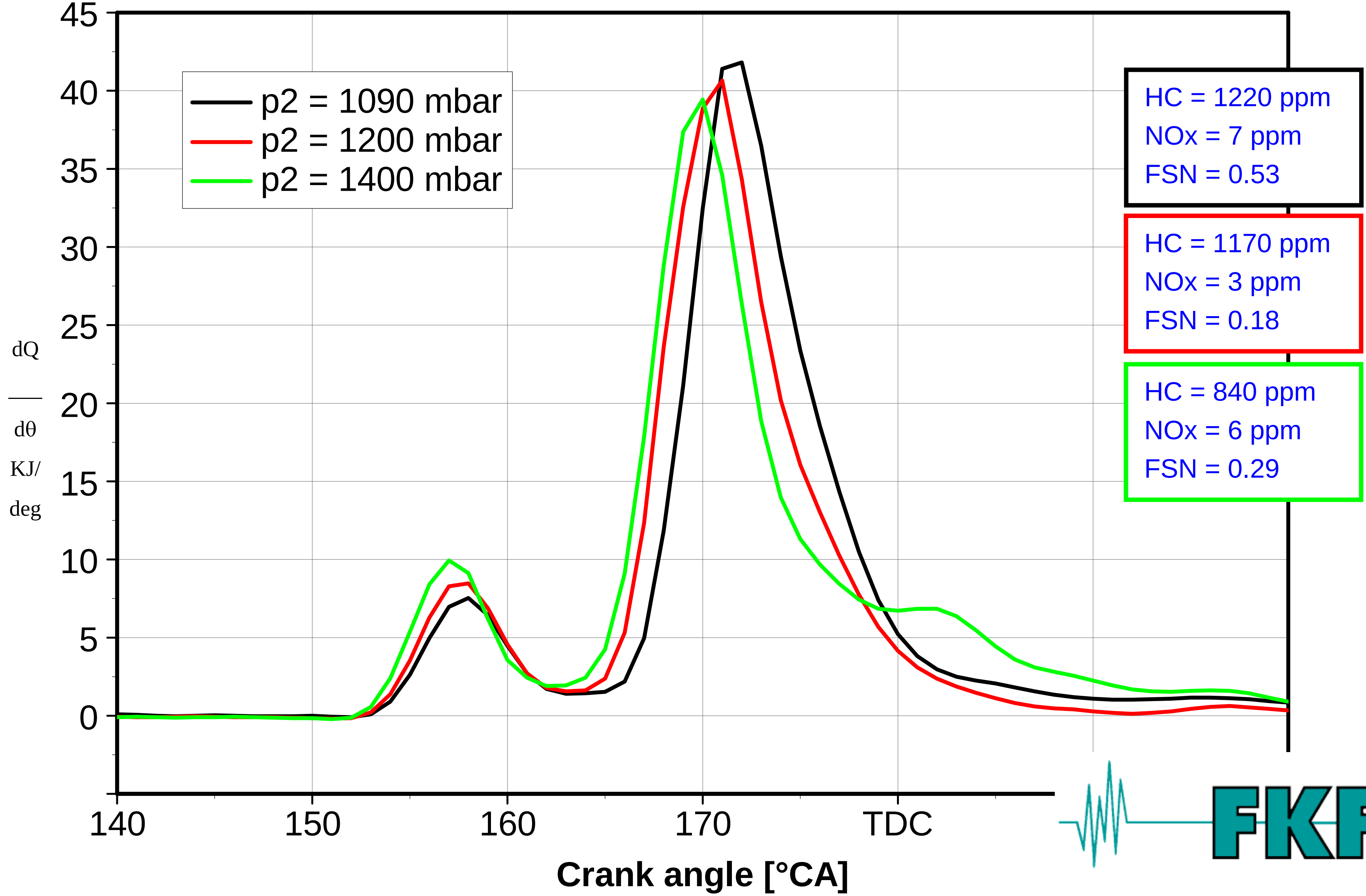
Single-Cylinder Test Cell at FKFS



Effect of uncooled EGR



Effect of Boost Pressure



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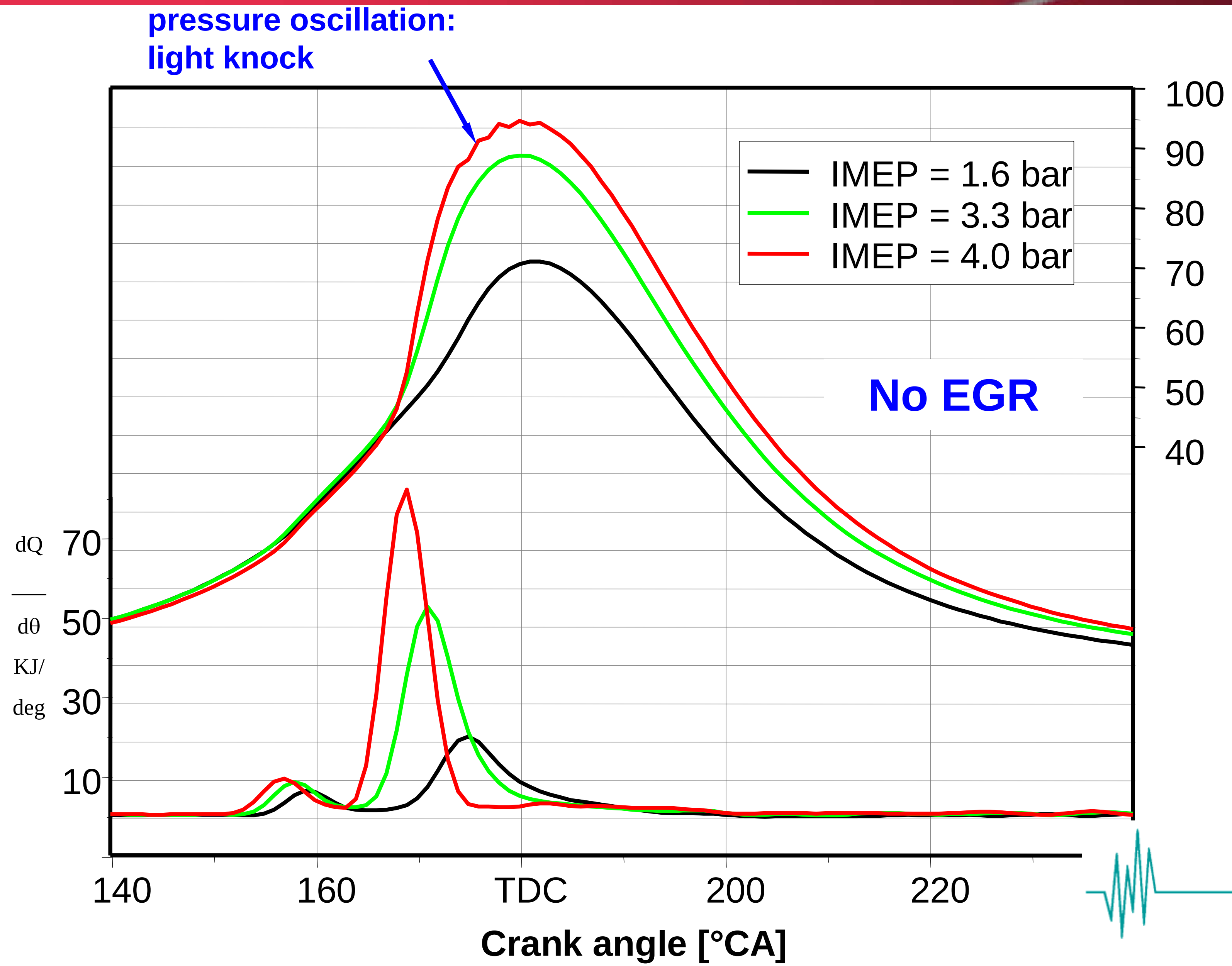
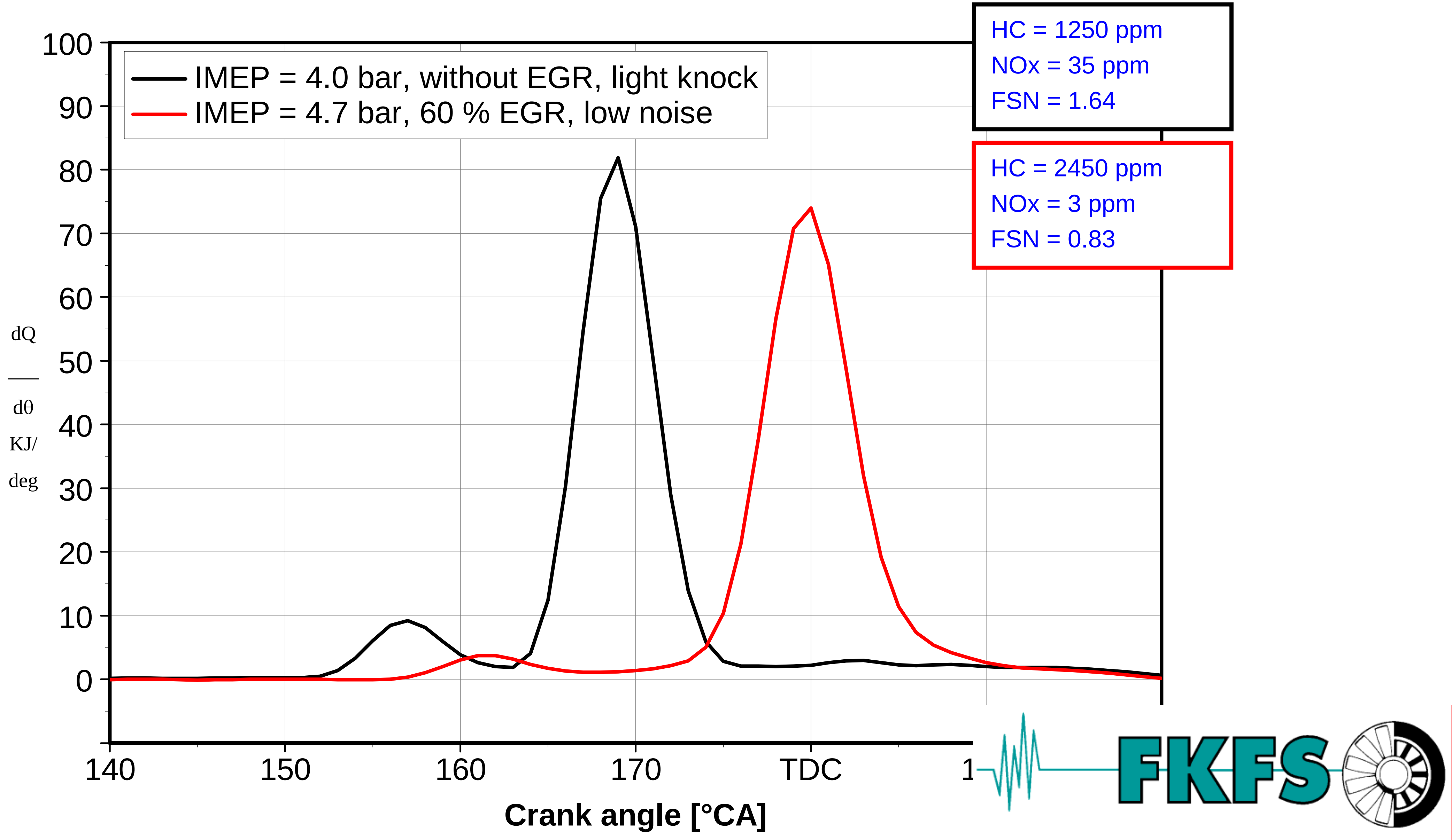
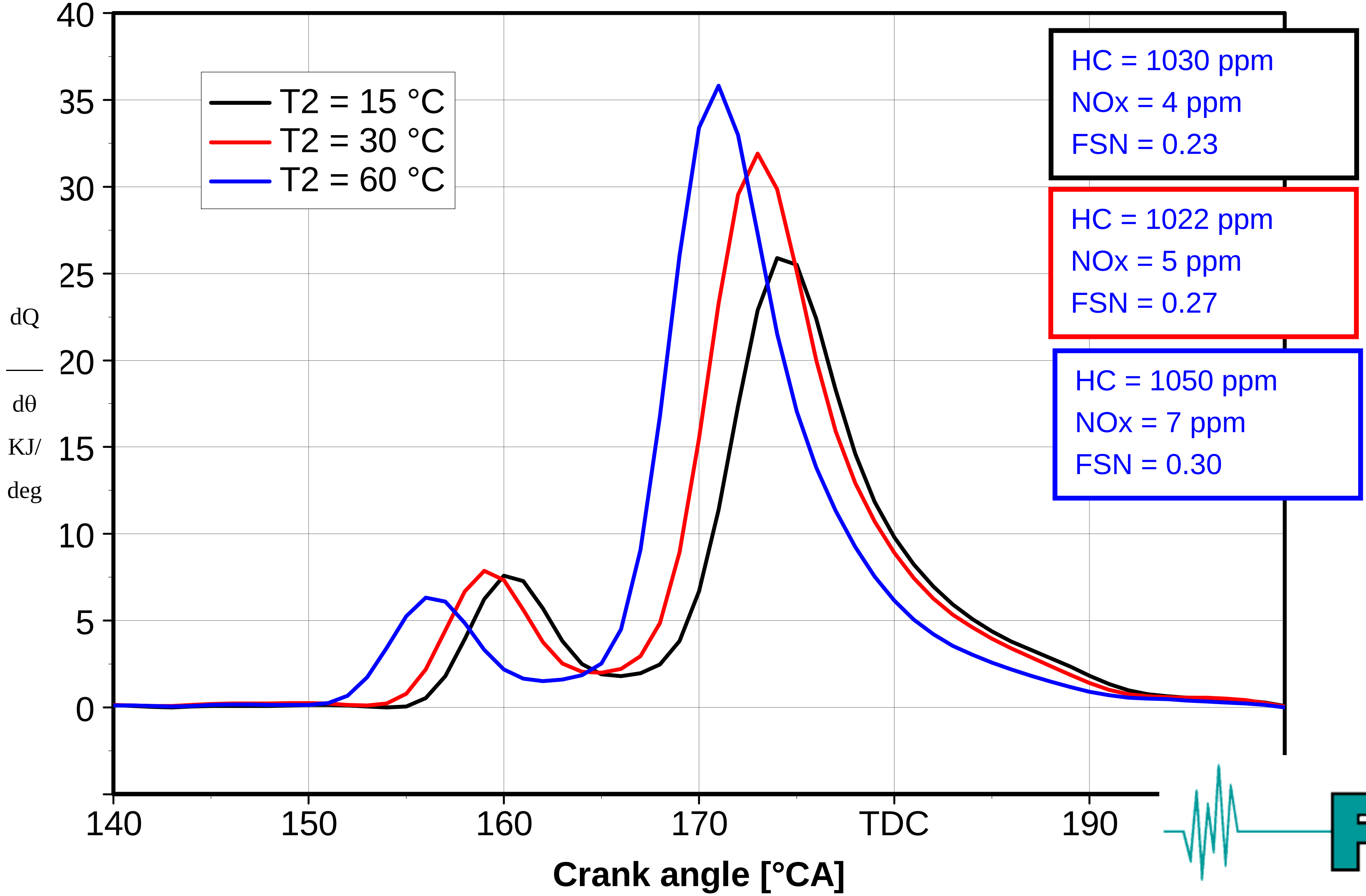
Effect of AFR Increase on IMEP



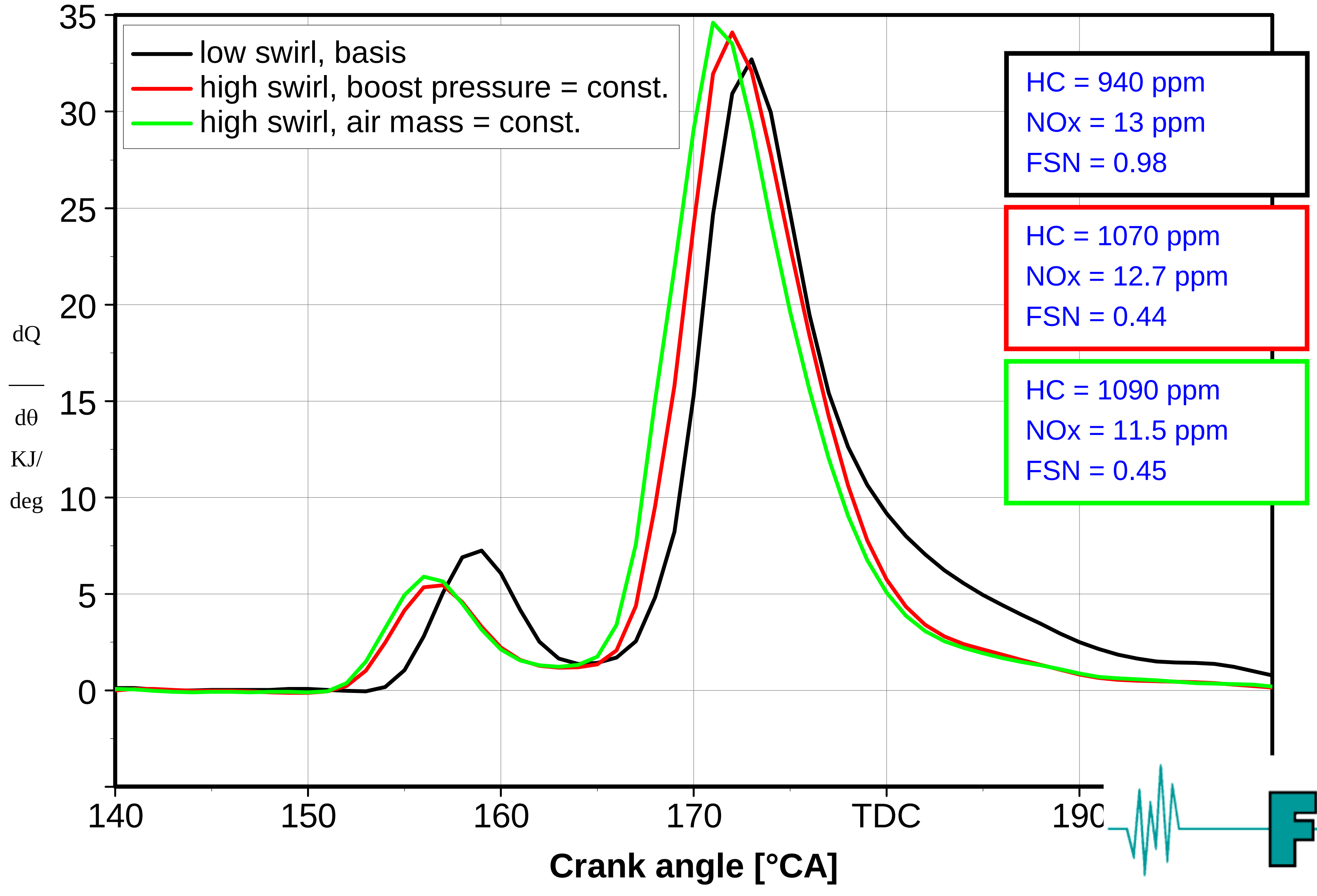
Extension of Load Range



Effect of Intake Air Temperature



Effect of Swirl
(Intake-Port Deactivation)



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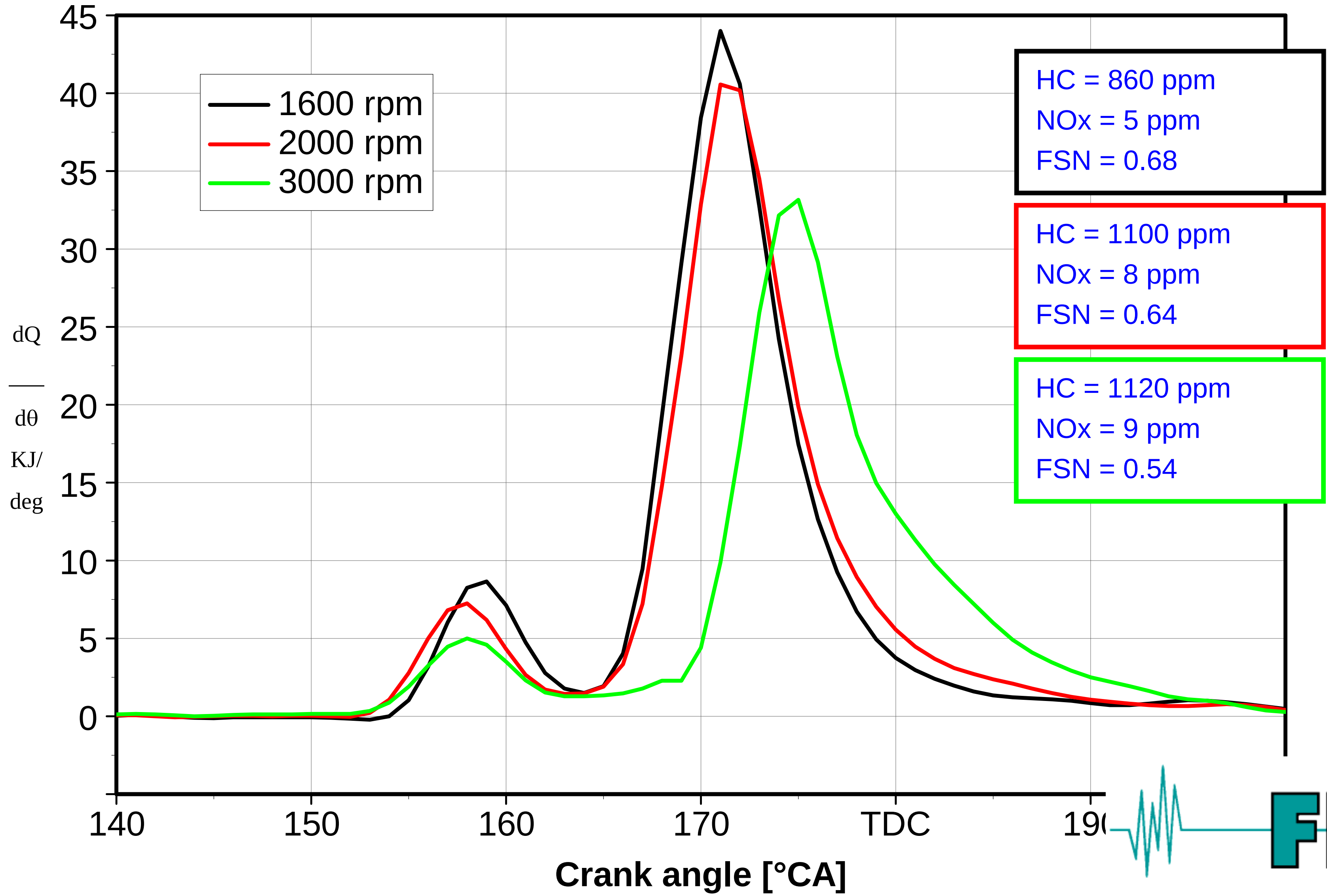
Effect of Engine Speed
(Crank Angle Domain)



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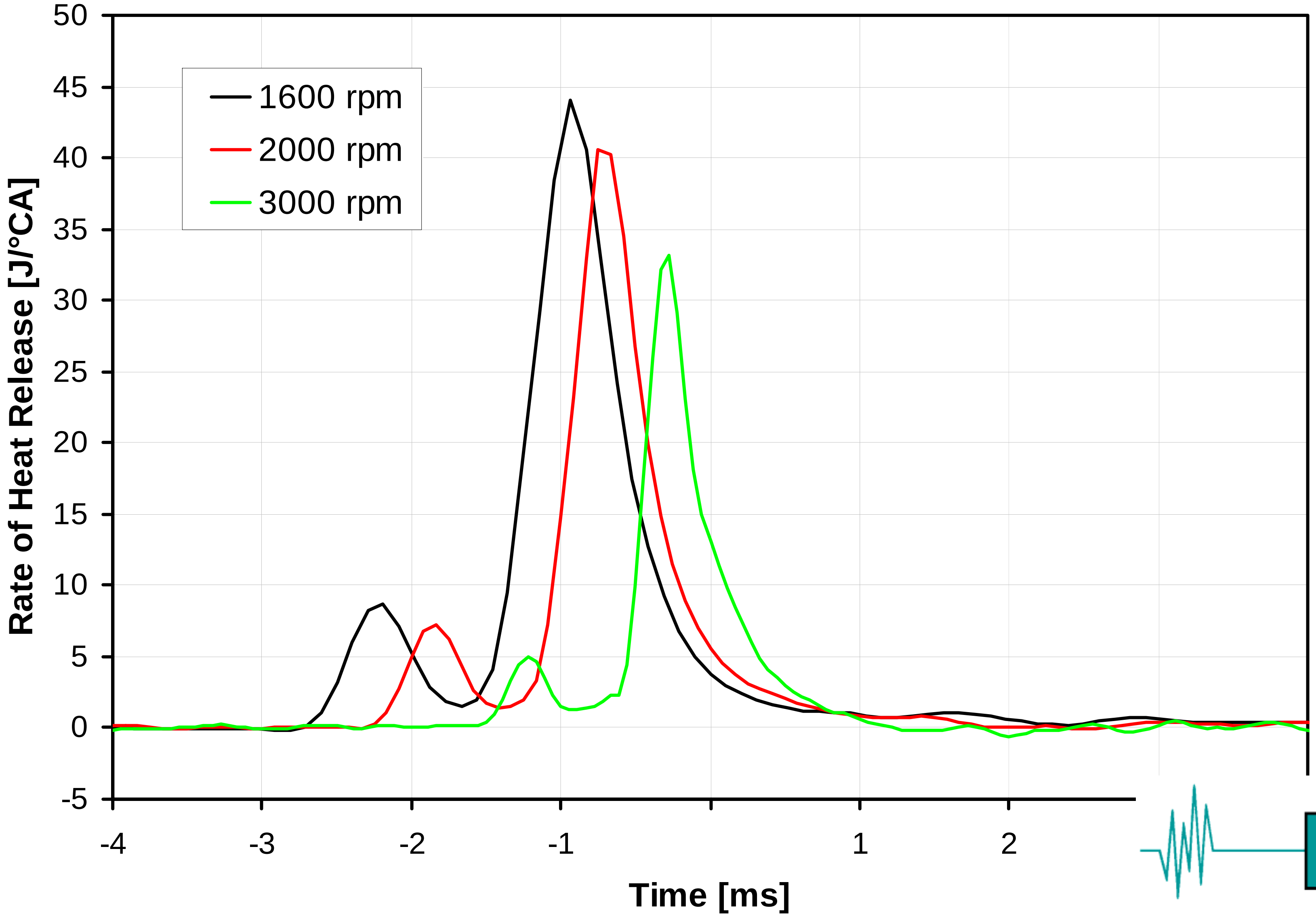
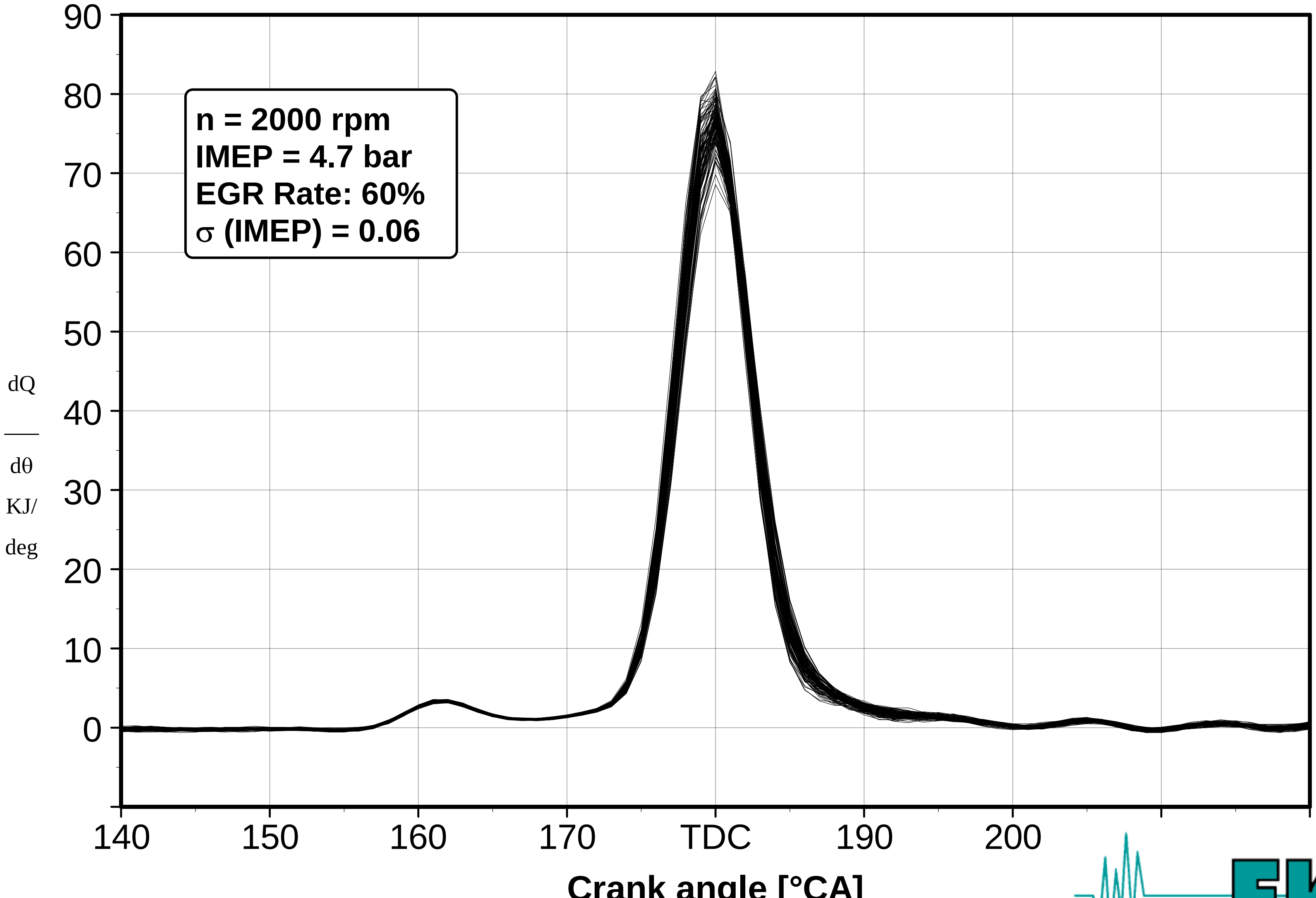
Effect of Engine Speed
(Time Domain)



Cyclic variability (100 cycles)



Goals for atomizer development

- Generation Three Atomizer with:
  - Flow rate sufficient to fuel a single cylinder HCCI engine at at all engine speeds
  - Closed loop fuel control system with high bandwidth control
  - 50% reduced power consumption
  - Appropriate packaging for port injection
- Development of a detailed thermo-fluid dynamic model of the atomizer system to support the above efforts

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3. Future work

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Atomizer characterization

- Proposed work in collaboration with Pacific Northwest National Laboratory (Dan Imre, Alla Zelenyuk-Imre):
  - Characterize the physical and chemical properties of the spray formed by the Ohio State novel atomizer.
    - Radial and axial variation in droplet size distributions and number concentrations will be measured as a function of an array of controllable atomization parameters: flow rate, electrical current, fuel type, fuel viscosity, ambient pressures and temperatures, etc.
    - These data will provide information on the kinetics of spray propagation, coagulation, and gas to particle partitioning to yield predictive relationships between atomizer operation and spray properties.
- Similar collaborations with Sandia, ORNL?

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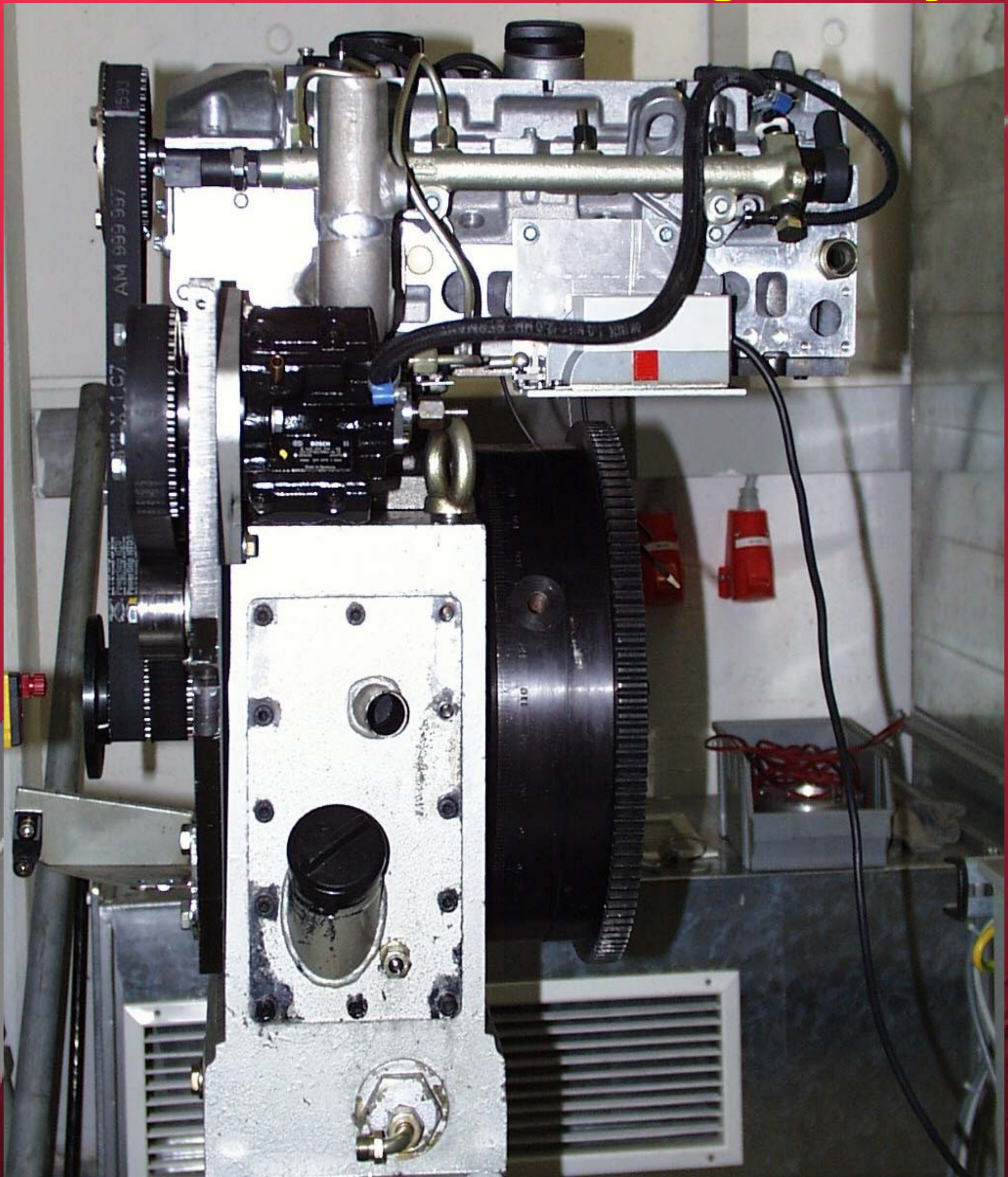
Additional single-cylinder engine tests



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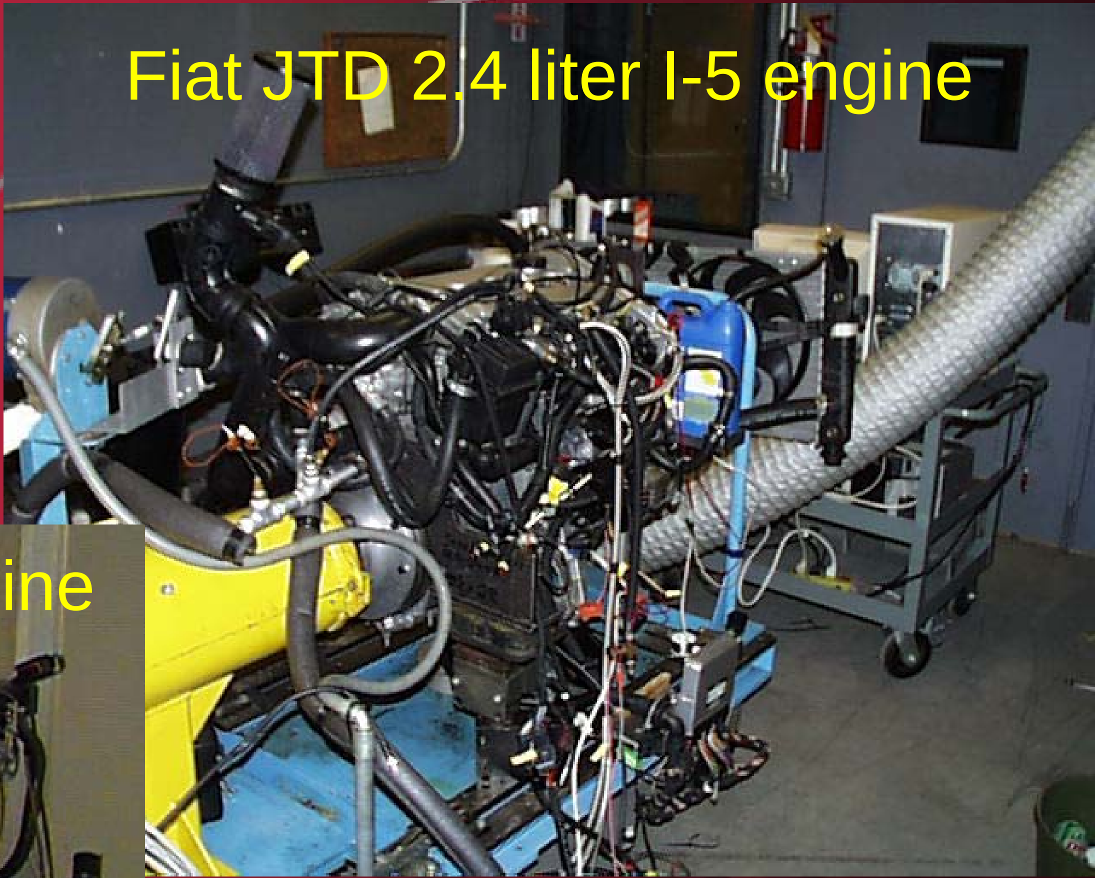
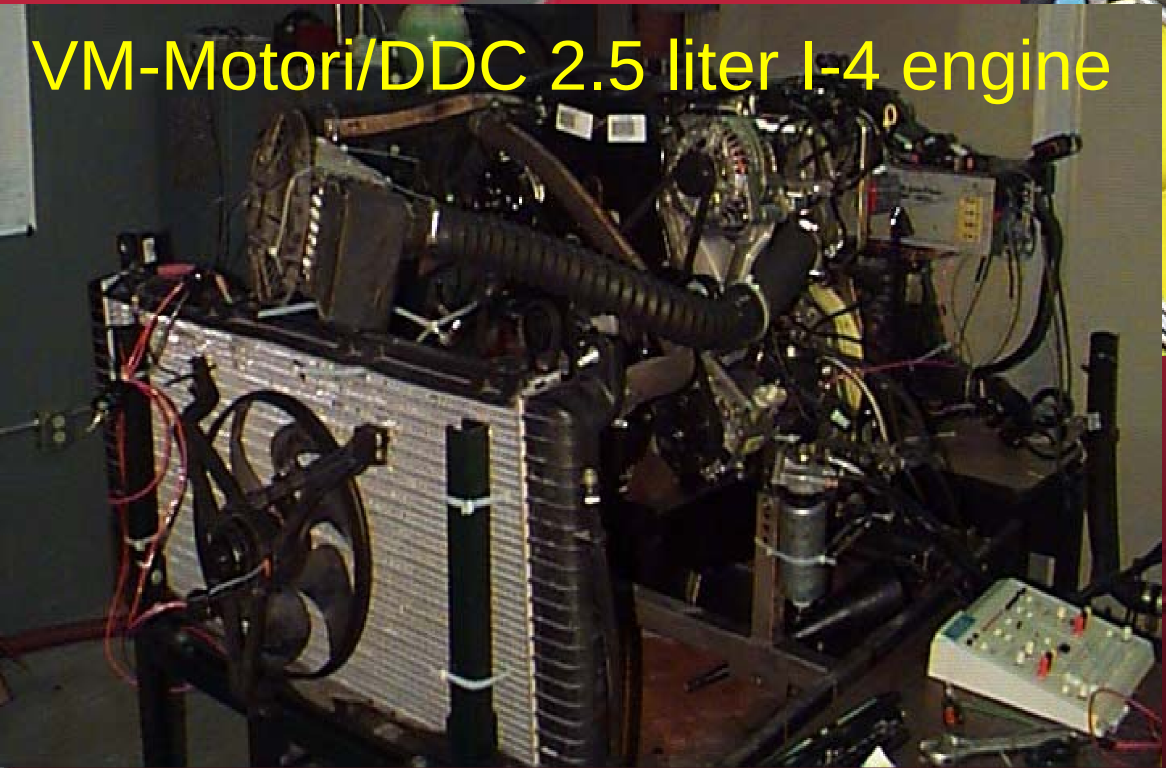
Multi-cylinder engine tests

- Implementation on a multi-cylinder, direct-injection engine in engine test cell.
- Investigation of steady state engine characteristics with mixed mode HCCI.
  - Torque production, emissions, fuel consumption



Fiat JTD 2.4 liter I-5 engine



VM-Motori/DDC 2.5 liter I-4 engine

Vehicle tests

FutureTruck 2004, Ford Motor Co.
Michigan Proving Ground, Romeo, MI