SAND2020-1394PE

Sandia's New Medium-Duty Diesel Research Engine

and what we're going to do with it

With the generous support of Ford Motor Company, Sandia National Laboratories has constructed a new medium-duty diesel research engine. The engine features a combustion system that very closely mimics current production hardware. All of the engine's auxiliary systems have been successfully commissioned and the engine will be put into operation this month.

Previous research within this project has produced the hypothesis that improved vortex formation will improve peak thermal efficiency and reduce pollutant formation. A dimpled, stepped-lip (DSL) piston design has been conceived to achieve this goal. 1D and 3D models will be created for the new engine to support the development of a DSL-like piston. Experiments with a metal version of this piston will provide a direct test for the hypothesis described above.

Experiments in the small-bore engine indicate that the pilot and main injections may act as critical sources of unburned hydrocarbon emissions during catalyst heating operation. Furthermore, oxygenate blendstocks that either increase or decrease the fuel mixture's reactivity do not appear to enhance the heat-release characteristics of very late post injections. However, the most recent CFD simulation results show a strong sensitivity of the heat-release of late post injections to cetane number. The new research platform provides an opportunity to improve the certainty of boundary conditions for simulations, as well as to expand upon previous experimental findings in a continuously fired engine.

Sandia is working to build on in-house materials science expertise and capabilities to create the foundations of a thermal barrier coating research program. This includes customization of the medium-duty diesel engine to provide in-situ, in-operando piston surface temperature and/or heat flux measurements via an advanced telemetry system. These capabilities will be used to provide foundational understanding of coating property impacts on diesel combustion processes.

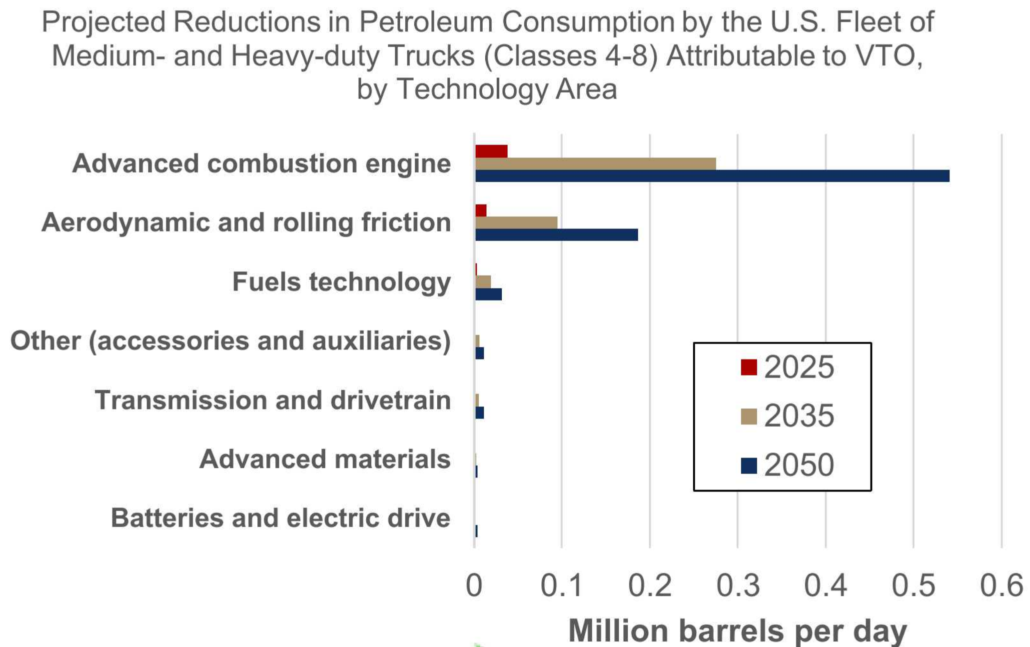
Stephen Busch
Sandia National Laboratories

02/04/2020

AEC MOU Program Review Meeting

Objectives of medium-duty diesel research

- Provide scientific understanding needed to achieve further improvements in efficiency and reductions in emissions
  - Bowl geometry designs to improve mixing – can the state-of-the-art be improved?
  - Catalyst heating operation – critical for getting efficient, compliant engines to market
  - Heat transfer reductions – how much is possible?



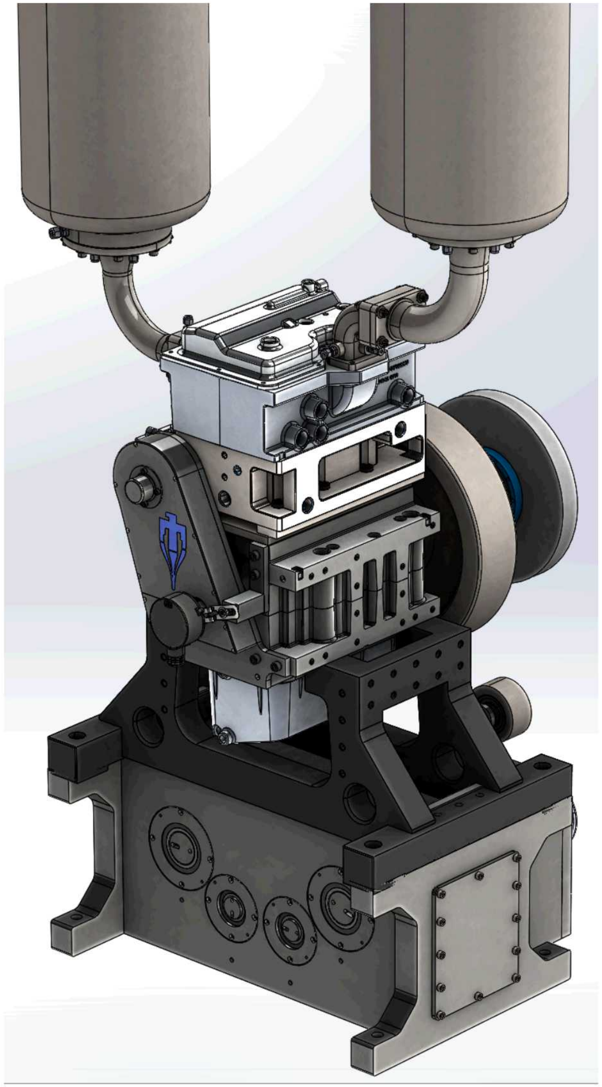
Outline

- Sandia’s new medium-duty diesel engine
- Research plans

Sandia's Medium-Duty Diesel Engine

- Single-cylinder research engine
- Combustion system: Ford 6.7L Scorpion

Bore	99 mm
Stroke	108 mm
Compression ratio	16.2:1
Valves/cylinder	4
Injector	8-hole piezo
Piston bowl shape	Stepped-lip
Max speed	2000 rpm
Max rail pressure	2000 bar
Lubrication system	Dry sump

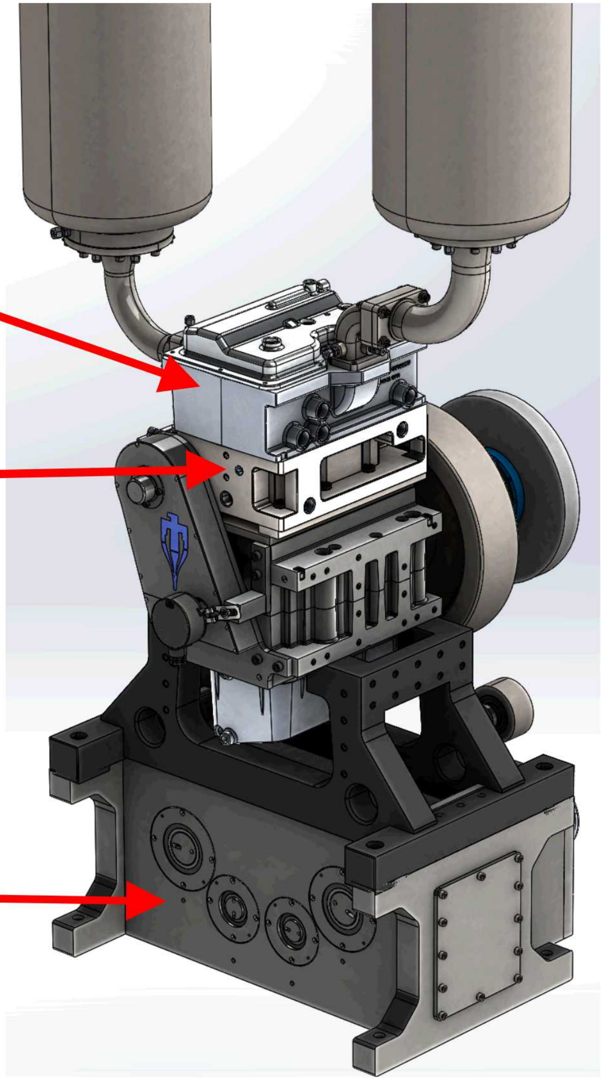


Sandia's Medium-Duty Diesel Engine

Cast aluminum cylinder head

Custom deck adapter facilitates conversion to optical engine

Reconfigurable, belt-driven Lanchester balancing box (1^{st} and 2^{nd} order)



Sandia's Medium-Duty Diesel Engine

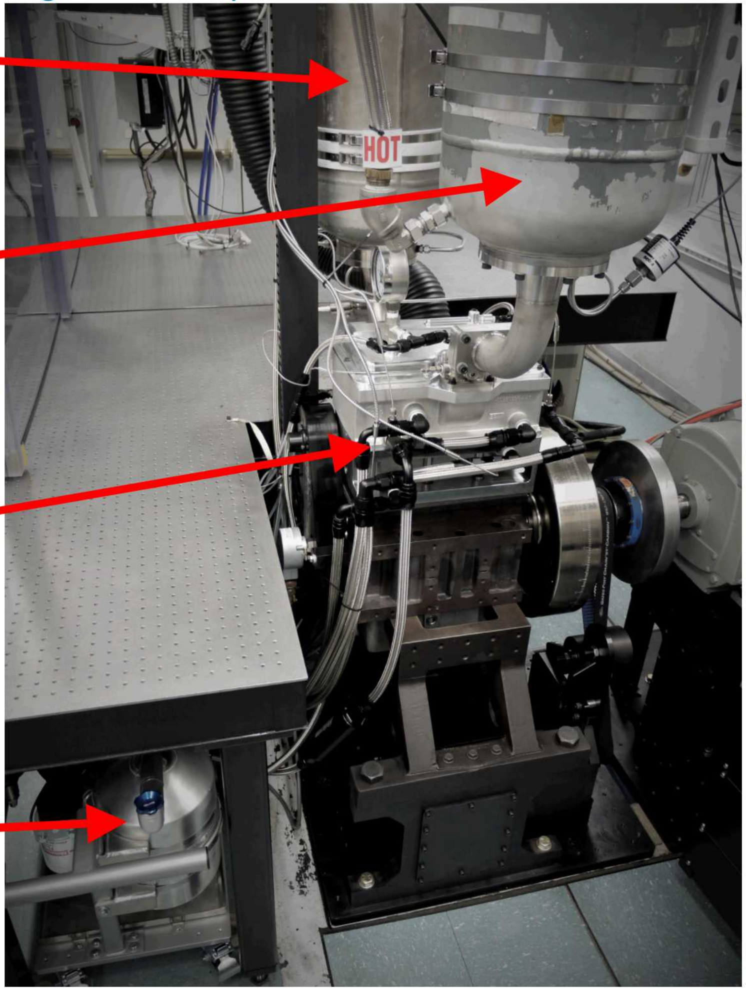
Adjustable exhaust back pressure

Control of intake flow rate, composition, and temperature

Measurement of coolant temperatures and flow rates

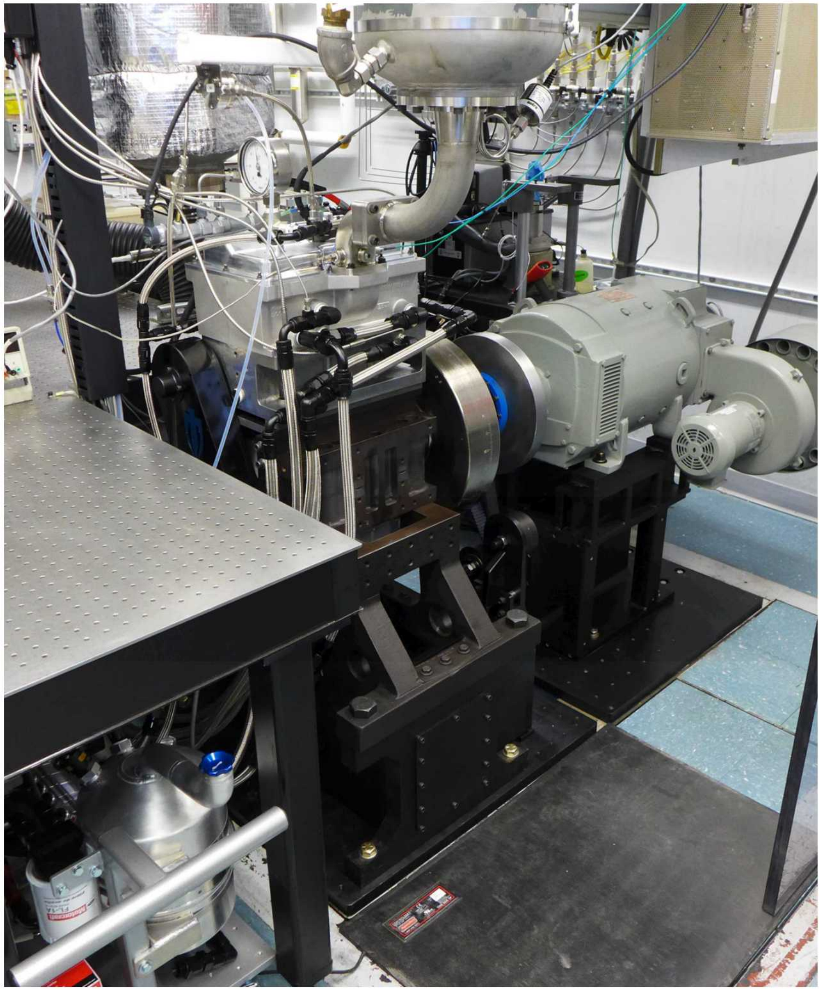
Dry sump lubrication system with electrically driven, five-stage pump

Engine after dry-fit test



Current status

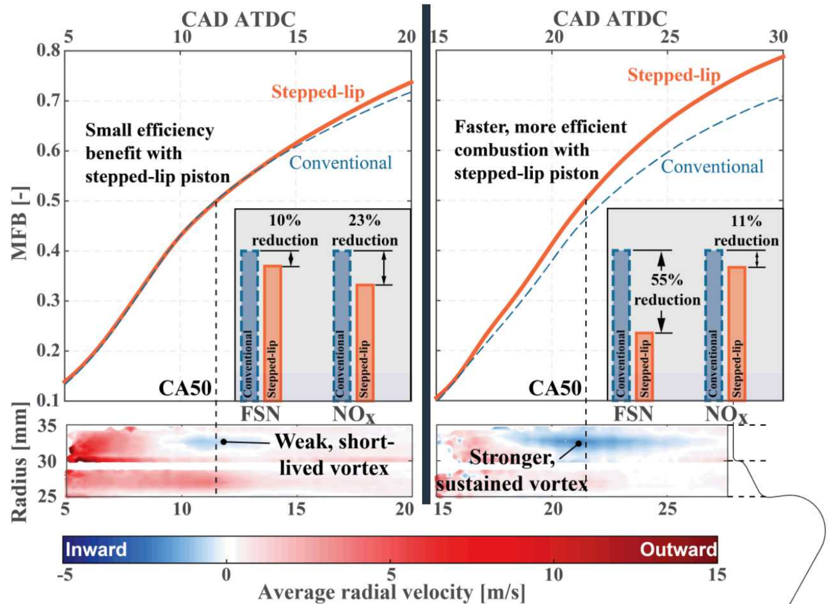
- Engine assembly essentially complete
- Phasing operations complete
    - Crank angle encoder
    - Cam shaft
    - Balancing box
- All auxiliary systems passed initial testing
    - Lubrication
    - Coolant
    - Crankcase ventilation
    - Fuel
    - Dyno
- Break-in procedure to commence next week



Research plans

- Bowl geometry impacts on efficiency and emissions
- Fundamental understanding of catalyst heating operation
- Thermal barrier coating research
- Continued optical measurements

Bowl geometry impacts on efficiency and emissions



Near-TDC injection

- Small difference in rate of mixing controlled heat-release
- Modest soot reduction
- Weak vortex in squish region

Late injection

- Faster, more efficient combustion
- Substantial soot reduction
- Stronger, longer-lived squish region vortex

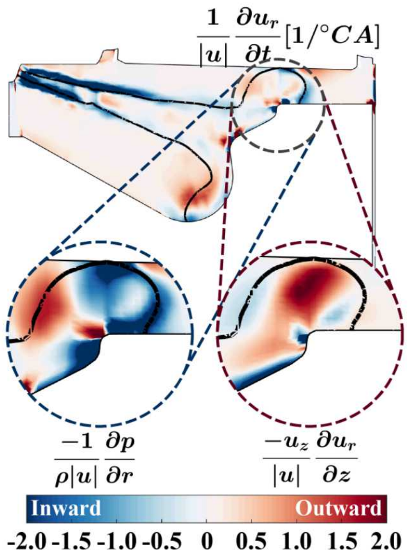
Observation: faster, more efficient mixing-controlled heat-release rates correlate with stronger vortex action.

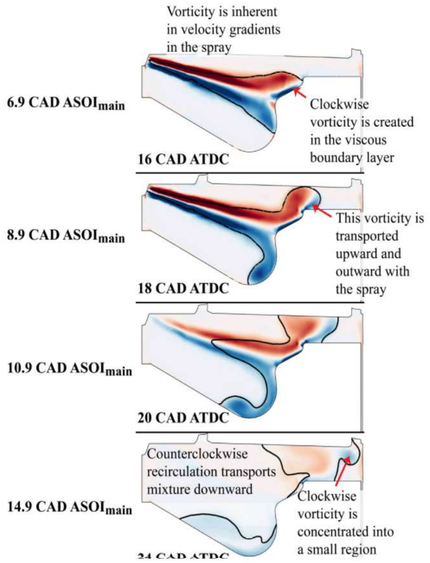
Hypothesis: promoting vortex formation at near-TDC injection timings may be able to improve peak efficiency and air utilization.

CFD simulations provide understanding of turbulent flow evolution in the stepped-lip combustion chamber

3D RANS-CFD simulations (FRESCO)

- Flow, liquid, and spray penetration validated using optical measurements
- Results indicate sensitivity of squish region vortex formation to injection timing → consistent with experiments
- Analysis of results provides understanding of turbulent flow evolution in the squish region





Radial flow evolution

- Inward acceleration: adverse pressure gradient
- Outward acceleration: convection of spray momentum

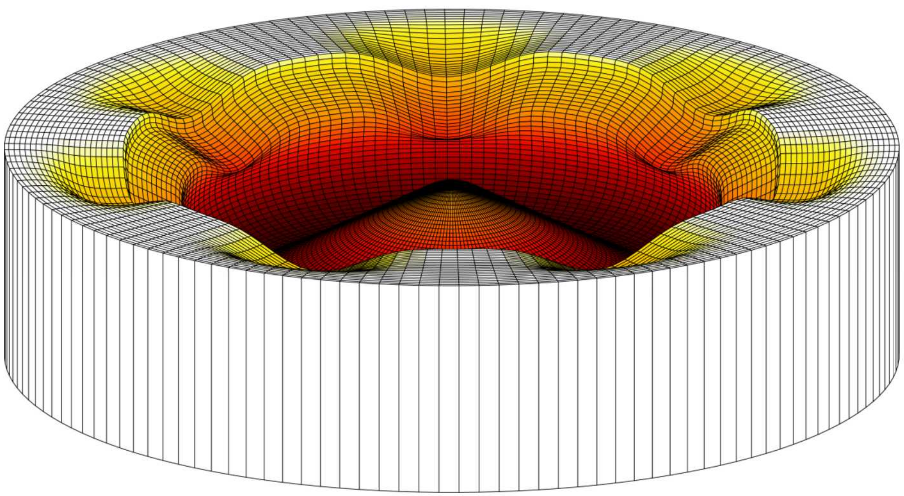
Vorticity

- Inherent in spray
- Forms in shear layer resulting from spray-wall interaction
- Transported up and out into squish region

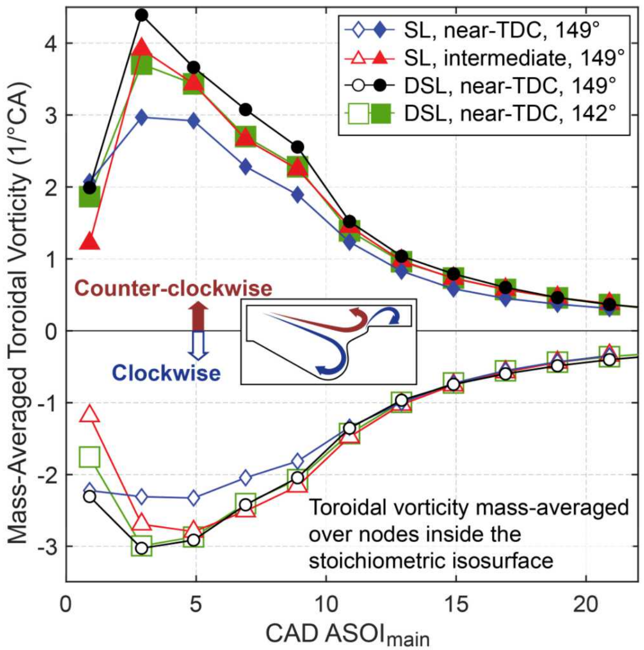
A dimpled, stepped-lip piston is predicted to promote vortex formation

Dimpled, stepped-lip (DSL) piston

- Simulations indicate that the larger space in the squish region supports vortex formation
- Lower impingement position effectively deflects upper portion of spray along step surface



Toroidal vorticity: mass averaged over all nodes contained within the stoichiometric isosurface and plotted as a function of crank angle



This metric captures the global evolution of vorticity, as well as sensitivities to injection timing and bowl geometry

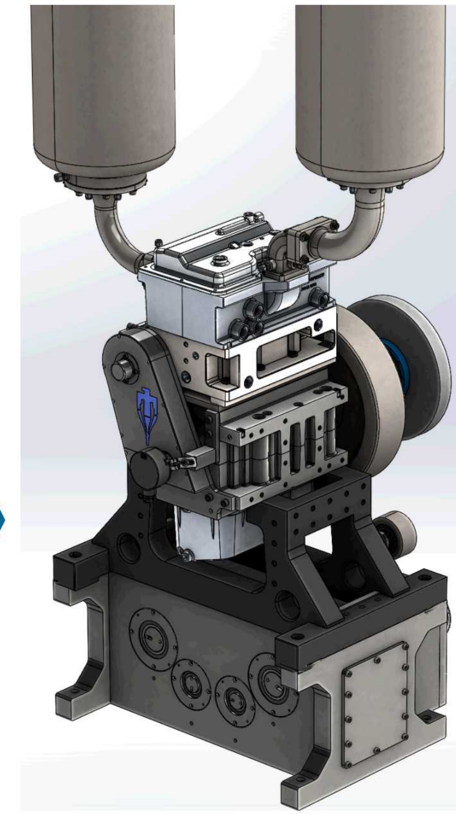
For more detail, see Busch, S., Perini, F., Kurtz, E., “Effects of Stepped-lip Combustion System Design and Operating Parameters on Turbulent Flow Evolution in a Diesel Engine”, SAE International Journal of Engines, in press.

CRF

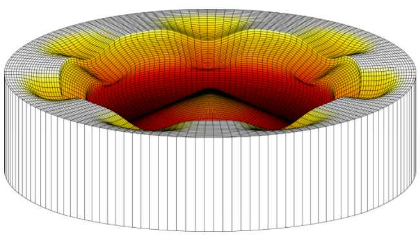
Next steps

- Experiments and simulations have thus far all been done on the small-bore diesel engine (decommissioned)
- A DSL-like piston will be developed using CFD simulations of the new medium-duty diesel engine
  - Generation of 1D model for BCs and 3D mesh for CFD will begin soon
  - The integrated vorticity metric will be used for a limited optimization study before a hardware version of the piston is created

Implementation in medium-duty diesel engine



DSL piston concept

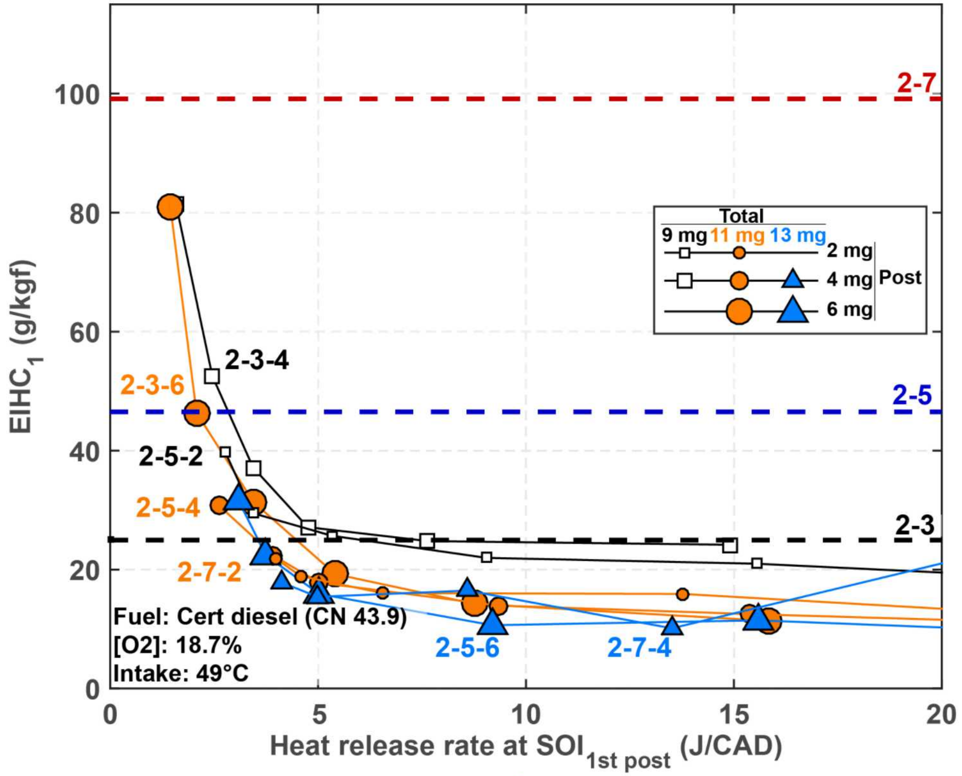


Vorticity-focused optimization strategy

Design development, CFD validation and optimization for medium-duty diesel engine

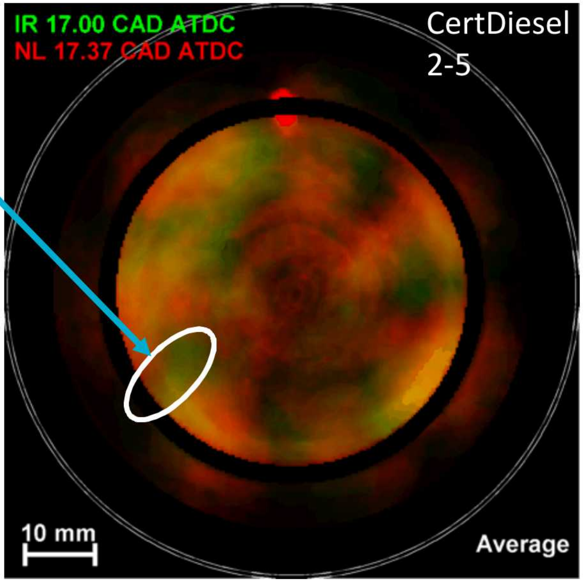
Catalyst heating operation: insights from exhaust emissions data

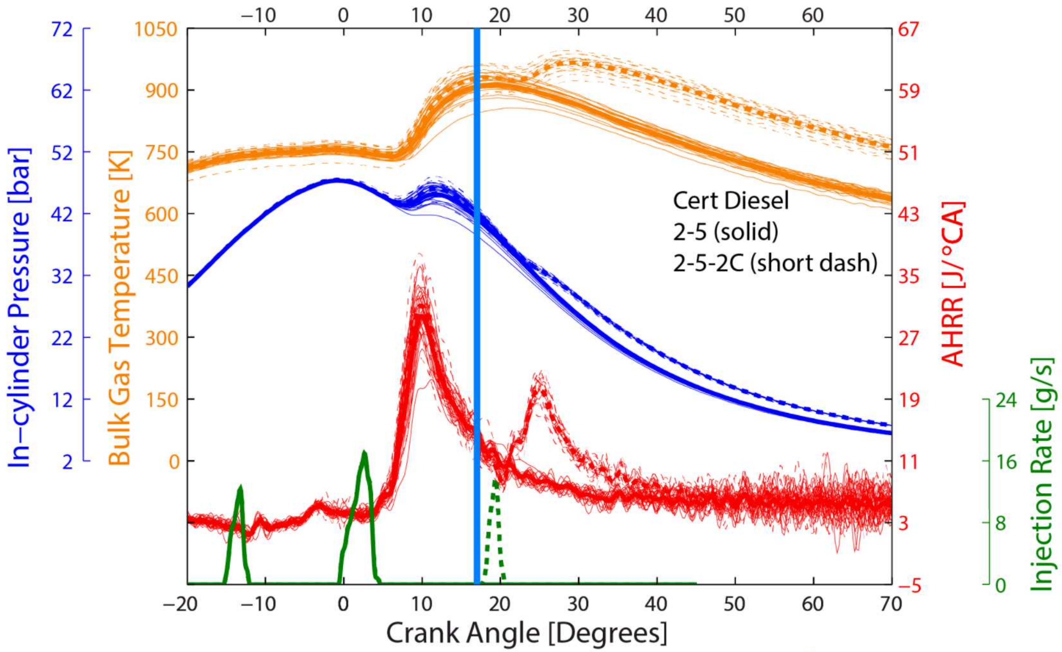
- Addition of even a small post injection typically decreases UHC emissions, particularly as the main injection quantity increases
- **Implication: the pilot and main mixtures are significant sources of unburned hydrocarbons in catalyst heating operation**

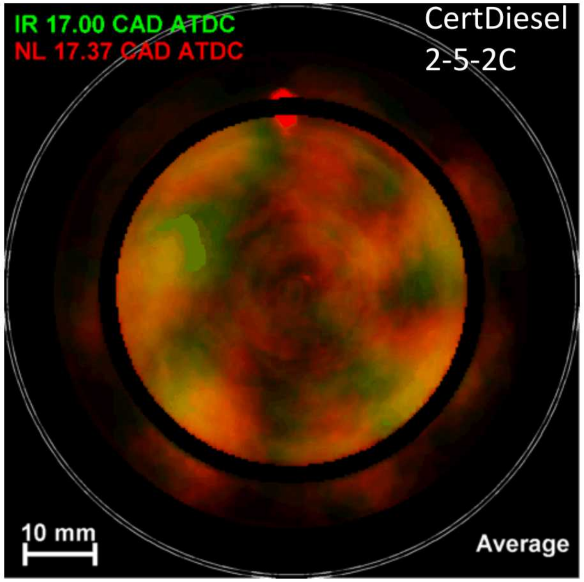


Insight into pollutant formation mechanisms during catalyst heating operation

- IR signal observed in the bowl between spray plumes
  - Consistent with un- or partially-burned fuel: C-H stretch
  - Potential source of unburned hydrocarbons
  - **Hypothesis: over-lean mixture in the bowl fails to react to completion and acts as a source of unburned hydrocarbons**
    - Late post injections may not interact with the bowl contents and may not help oxidize partially burned fuel

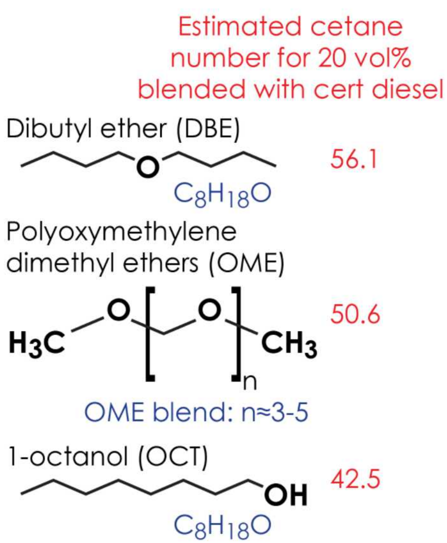


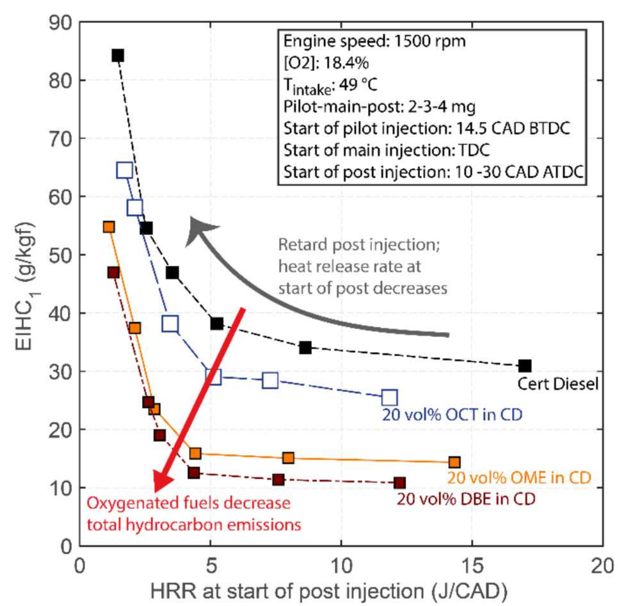


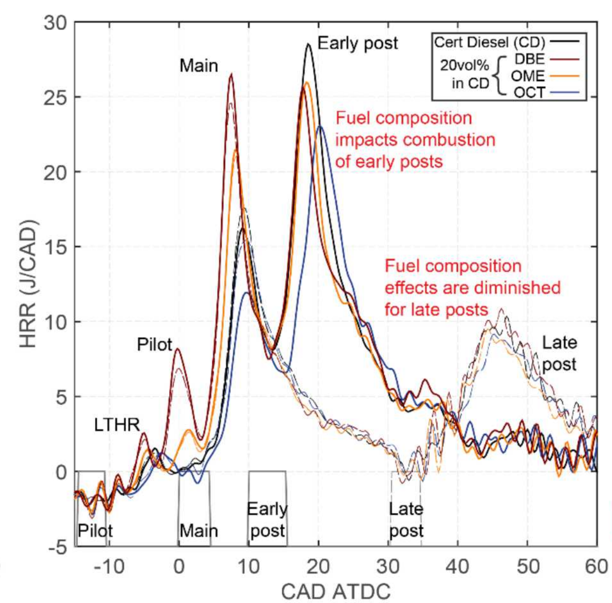


Oxygenate additives decrease UHC emissions, but ignition of late post injections seems insensitive to CN

- Oxygenated additives can significantly reduce total hydrocarbon emissions
  - Ethers do this more effectively than 1-octanol
- Oxygenated additives affect the ignition and combustion of the pilot and main injections, but the impact on the post combustion depends on post injection timing
  - The combustion of late post injections is not significantly affected by post timing
  - Preliminary evidence: oxygenate additives may not promote ignition of late posts

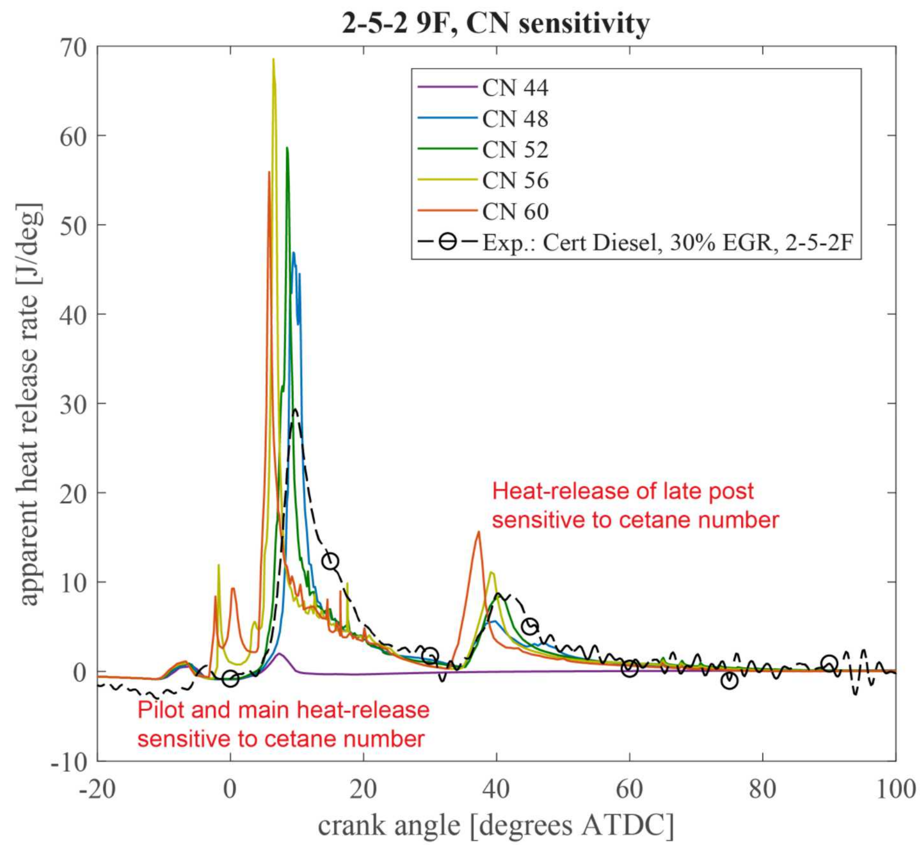






Predicted fuel reactivity effects on ignition of late post injections don't match experimental findings

- Approach: sector mesh-based simulations using FRESCO to provide insight into ignition process of late post injections
- 1D model of small-bore engine not well calibrated for catalyst heating operation
  - Large uncertainty in T_{IVC}
  - Requires adjustment of BCs
- Simulations appear to overpredict the sensitivity of heat-release to cetane number
  - Oxygenate study: heat-release of late posts insensitive to CN over a range of 42.5 – 56.1
- Thorough characterization of the new engine will improve certainty of boundary conditions
  - Are the simulations failing to include important physics?



Next steps

- Characterization of boundary conditions
  - Calibrate GT-Power model to provide more reliable CFD inputs
- Development of catalyst heating strategies in the new engine
  - Variation of pilot injection(s) and the impact on exhaust emissions
  - Quantification of exhaust enthalpy and injection strategy calibration impacts
- CoOptima
  - Verify and expand upon effects of oxygenate blendstocks; isolate cetane number effects from oxygen effects
    - Hexyl hexanoate (HH: CN = 40) and dibutoxymethane (DBM: CN = 70)
- Development of optical engine hardware
  - Improved understanding of ignition and pollutant formation processes (as well as spray-wall interactions and vortex formation for the bowl geometry study)

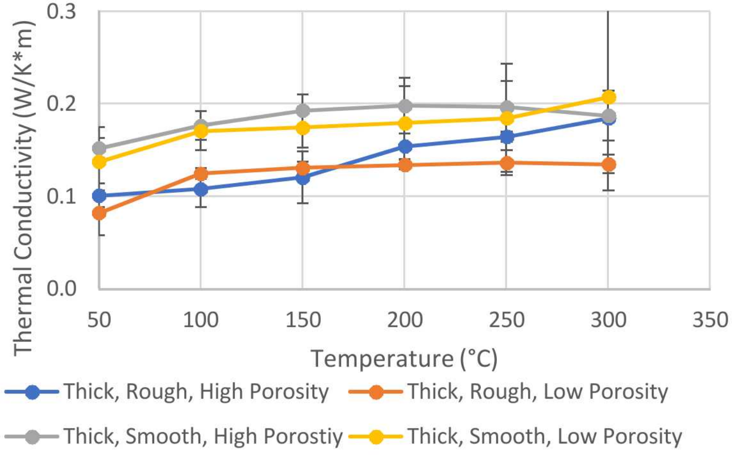
Thermal barrier coating (TBC) research

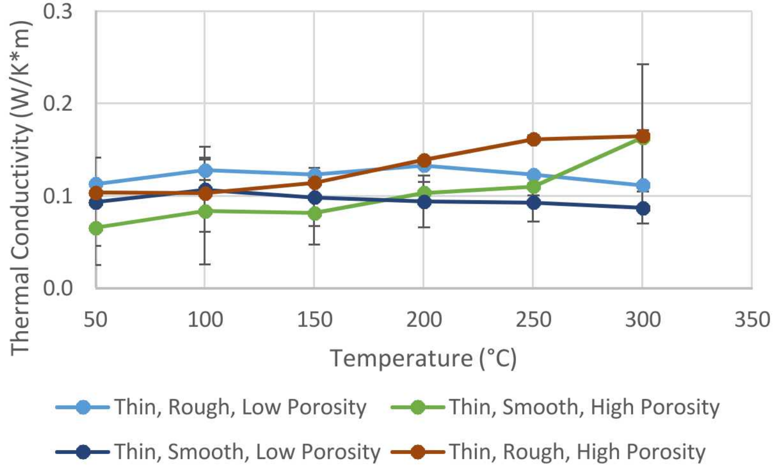
- Many applications of TBCs to piston surfaces can be found in the literature
  - Theoretical efficiency improvement may be as high as 8% using low thermal inertia coatings[1]
  - In practice, efficiency improvements are often very modest or even negative
  - In-depth thermodynamic analyses into efficiency impacts are rare
  - Coating durability remains a significant challenge
- Sandia is building foundational capabilities to perform TBC research
  - Leverage existing materials science expertise to provide accurate, quantitative data on thermophysical properties of coatings
  - Develop medium-duty diesel engine into a TBC research platform
  - Provide fundamental understanding of interactions between coating properties and diesel combustion processes
  - Inform future TBC R&D efforts

[1] Kosaka, H., Wakisaka, Y., Nomura, Y., Hotta, Y. et al., "Concept of "Temperature Swing Heat Insulation" in Combustion Chamber Walls, and Appropriate Thermo-Physical Properties for Heat Insulation Coat," SAE Int. J. Engines 6(1):142-149, 2013, https://doi.org/10.4271/2013-01-0274.

Sample results: very low thermal conductivity has been demonstrated for a potential TBC candidate

- Measured thermal conductivities are very low; near the detection limit
  - Toyota's SiRPA coating: ~0.6 W/mK[1]; partially stabilized zirconia: 0.4-1.2 W/mK[2]
- Coating development continues
  - Goal: durable coatings with variable properties to inform engineering models





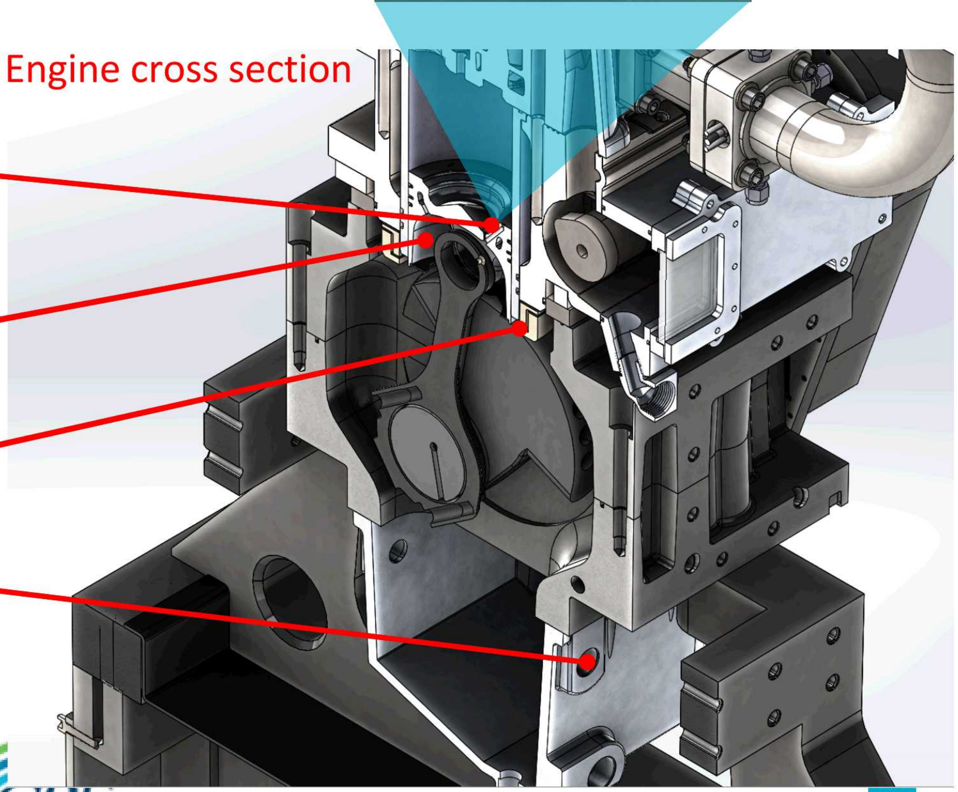
[1]Kawaguchi, A., Iguma, H., Yamashita, H., Takada, N., Nishikawa, N., Yamashita, C., Wakisaka, Y. and Fukui, K., "Thermo-Swing Wall Insulation Technology; - A Novel Heat Loss Reduction Approach on Engine Combustion Chamber." SAE Technical Paper 2016-01-2333, 2016, DOI: https://doi.org/10.4271/2016-01-2333.

[2]Tritt, T.M., ed. *Thermal Conductivity: Theory, Properties, and Applications*, Kluwer Academic/Plenum Publishers, New York: 2010

Developing capabilities for thermal barrier coating research

- Capabilities for fast measurement of piston-surface temperatures and heat fluxes are being developed and are scheduled to be implemented in 2020

- Key components
  - MEMS-based surface temperature and/or heat flux sensors
  - Onboard data acquisition hardware, power receiving antennas, Bluetooth data transmission antenna
  - Magnetic resonant coupling power transmission antennas
  - Bluetooth data receiving antenna



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Thank you for your attention

Your questions and feedback are welcome