COMBUSTION RESEARCH FACILITY

Light-Duty Diesel Combustion

Light-Duty Engine Experiments

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Sandia National Laboratories

Light-Duty Combustion Modeling

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Program Manager: Gurpreet Singh / Leo Breton, DOE EERE-OVT

Project ID: ACE002

Overview

Timeline:

- Project started in 1997 to support DOE/industry advanced engine development projects
- Continuous evaluation of direction through industry feedback

Budget:

- Funded by DOE on a year-by-year basis
  - SNL: $544k
  - UW: $99k
- Additional work / 2nd post-doc funded by GM through October 2014

Barriers addressed:

A: Lack of fundamental knowledge of advanced engine combustion regimes

B, G: Lack of cost-effective emission control

C: Lack of modeling capability for combustion and emission control

Technical targets addressed:

- 40% fuel economy improvement over 2009 baseline gasoline vehicle
- Tier 2, bin 2 emissions
- Emission control efficiency penalty <1%
- Specific cost: $30/kW

Partners:

- Close collaboration with GM and Ford diesel R&D groups
- Ongoing collaboration between SNL / Convergent Science / GM
- Increasing collaboration with industry / national lab partners in Advanced Engine Combustion MOU

Technical / Programmatic Approach

- Develop and disseminate fundamental understanding of advanced combustion processes
- Validate and improve computational modeling capabilities

SNL: Optical Engine (DOE / GM funded)

- Measurement of flow, mixture preparation, ignition, combustion, species
- Emissions and cylinder-pressure analysis
- ***Detailed analysis and result synthesis***

» Common engine platform (GM 1.9L)
» SNL provides validation data
» Regular e-mail communication, teleconferences, joint publications

UW: CFD Simulation (DOE / GM funded)

- Interpretation of experiments
- Model development; optimization methods
- Numerical studies
- ***Supplemental insight beyond exp. data***

» Developing cooperative project plans with ORNL and third-party supplier

Other National Labs (VT program)

- Testing with production engines over the full operating map with various fuels
- Characterization of efficiency and emissions
- ***Application of insights gained from analysis of optical and simulation results***

» CSI - GM - SNL cooperation
» SNL provides validation data
» CSI performs simulations w/ GM 1.9L grid
» Regular e-mail communication, teleconferences, joint publications

Convergent Science (Third-Party)

- Commercial code vendor
- Development of predictive simulation tools using SNL's research results
- ***Direct interface with many OEMS: getting technological insights into the market***

» NDA: sharing of Ford / GM piston geometry for SNL experimental work / UW simulation work

AEC Industry Partners (VT program)

- Ongoing discussions / exchange of info
- ***Crucial support, feedback, and suggestions***

Milestones / Progress

- SNL: balance of experimental work and analysis
  - Experiment: **in-cylinder flow** characterization with particle image velocimetry (PIV)
  - Analysis: **combustion noise reduction** with close-coupled pilot injection; **characterization of in-cylinder flow** asymmetries and assessment of CFD simulations
- UW: computational simulations and analyses
  - **Improved modeling capabilities** and increased computation capacity to address previously observed deficiencies in jet penetration and turbulence modeling
  - Progress towards **understanding swirl vortex development**

		2014										2015		
		Mar	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
SNL	**Experimental work**	High speed imaging; confirm main injection rate shaping trends		PIV setup; measurement technique development		Swirl-plane PIV measurements: measurement of flow fields throughout intake & compression strokes			PLIF: fuel distribution imaging for General Motors			Prepare new stepped-lip piston; develop new break-in procedure; set up for swirl-plane PIV		
SNL	**Analyses**	Analysis of pressure and imaging data; development of theories for noise reduction; development of PIV processing methodology				0-D modeling: test noise reduction theories; continued development of PIV processing techniques			Analysis and publication of PIV data; comparison with 3D-CFD results			Final description of combustion noise reduction mechanism; summary of findings to be presented at ASME 2015		
UW	**CFD Simulation**	Calibration of unsteady gas-jet flow superposition model with ECN spray A				Spray model optimization; assessment of cold-flow simulation results via comparison with PIV results			Principal component analysis; region-based analysis: swirl & turbulence; intake port throttling study			Code optimization for parallel processing; effects of geometry on PCA coefficients, bulk flow, & turbulence parameters		

Relevance of pilot-main dwell investigations

- Multiple injection strategies are necessary to meet emissions, combustion noise, and efficiency targets in light-duty Diesel engines
- Modern fuel injection hardware enables up to 8 injections per cycle, but a fundamental understanding of mixture formation and combustion processes with multiple injection strategies is lacking
- The current focus is on conventional Diesel combustion (not LTC)
- This study focuses on varying the dwell (delay) time between a single pilot of fixed mass and a main injection
- Objective 1: through **optical engine experiments** and **detailed analyses**, develop a deep understanding of how changing pilot-main dwell impacts:
  - Combustion noise *(primary focus of past year's activity)*
  - Fuel injection, mixture preparation, ignition, combustion, pollutant formation
  - Cycle-to-cycle variability
  - Fuel efficiency
- Objective 2: support the **development of advanced computational models** to simulate and analyze the fuel injection, mixing, and combustion processes with multiple injection strategies

Relevance of collaboration with UW and Convergent Science: current work

Reliable validation data is needed to develop and test predictive simulation capabilities

PIV: in-cylinder flow	Mie scattering: liquid fuel penetration	PLIF: fuel-air mixing; pollutant formation	Others

Common platform: GM 1.9L light duty Diesel engine

Convergent Science

- Develop and validate computational simulation tools
- Demonstrate predictive capabilities,best practices for boundary & initial conditions

Deliver predictive computational tools to engineers to improve engine design

University of Wisconsin / SNL

- Develop computational models and analysis capabilities
- Provide additional insight into experimental & numerical results

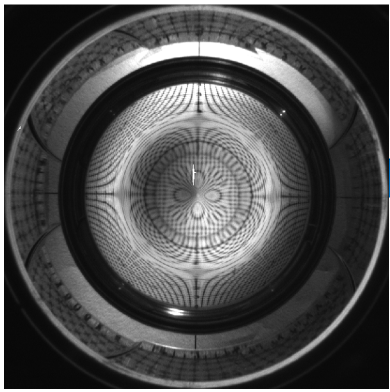
Synthesis of knowledge; development of conceptual models to guide engineers

- Objective: generate high quality swirl plane flow fields; provide data to UW and Convergent Science for validation purposes
  - Improve predictive capability of computational models
  - Improve fundamental understanding of swirl asymmetry near TDC

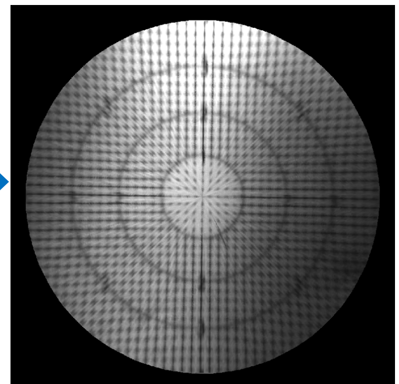
TA: development of a processing methodology for high-quality PIV measurement data

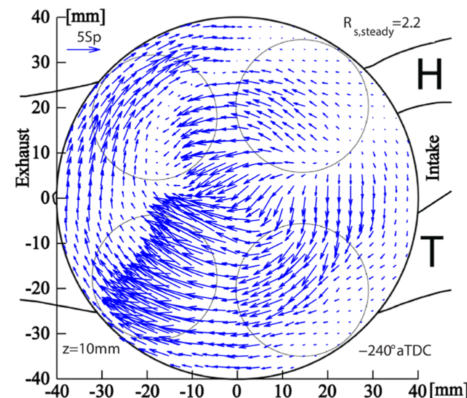
An analytical approach to image processing is key to generating reliable PIV data for computational model validation with a complex piston geometry.

Severely distorted image



Distortion correction

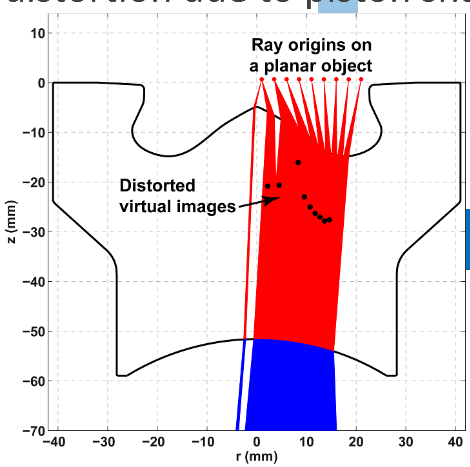




Well resolved flow topology

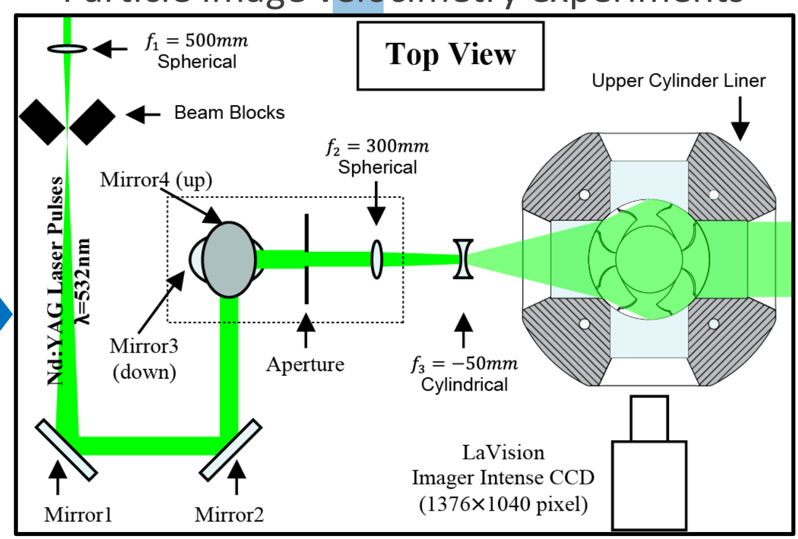
State-of-the-art data quality

Ray tracing: analytical description of image distortion due to piston shape



Velocity error quantification & correction

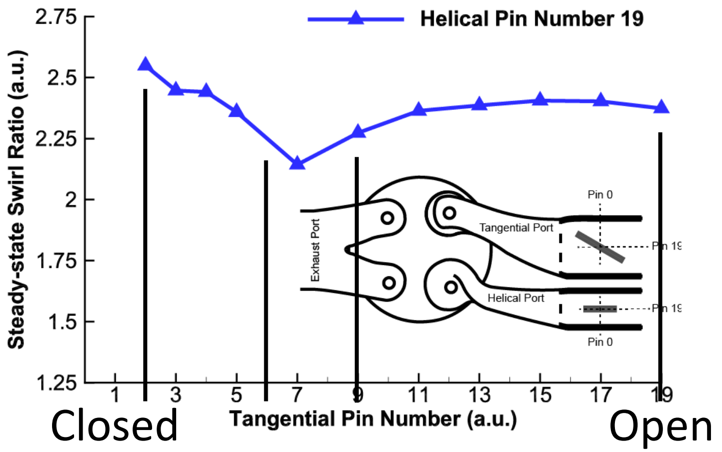
Particle image velocimetry experiments



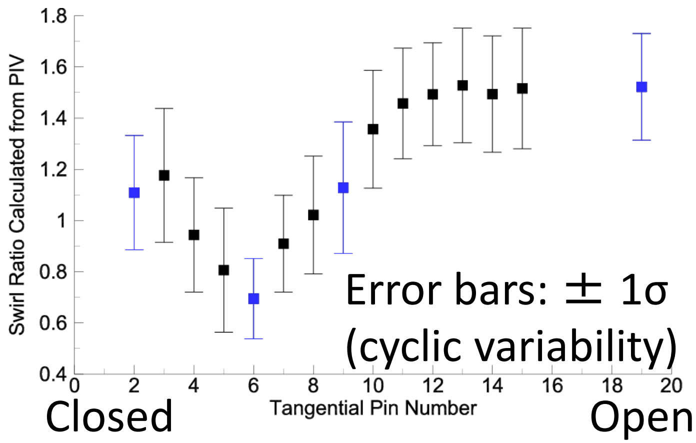
TA: Qualitative agreement between PIV results and flow bench results has been achieved

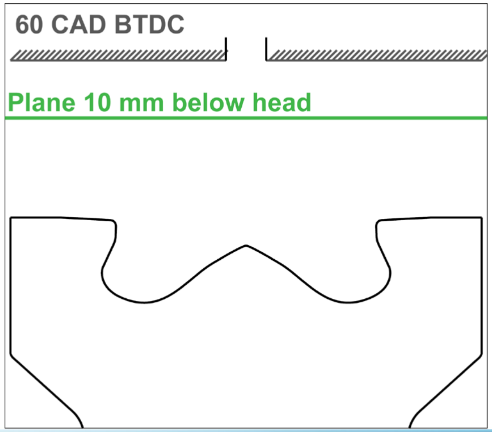
Swirl ratios computed from PIV measurements follow similar trends to swirl ratio trends measured on a steady-state flow bench.

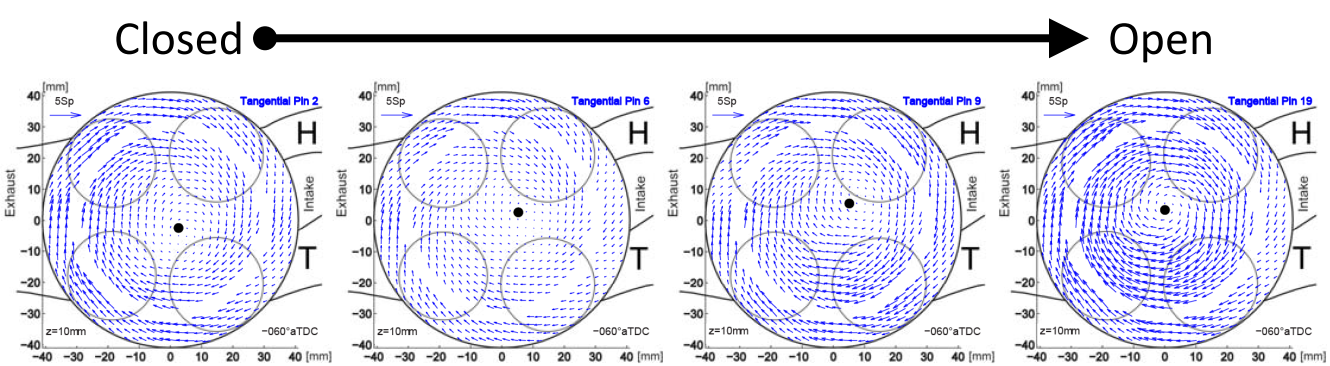
Steady-state flow bench measurement; tangential port throttle sweep



Swirl ratio computed from planar PIV measurement

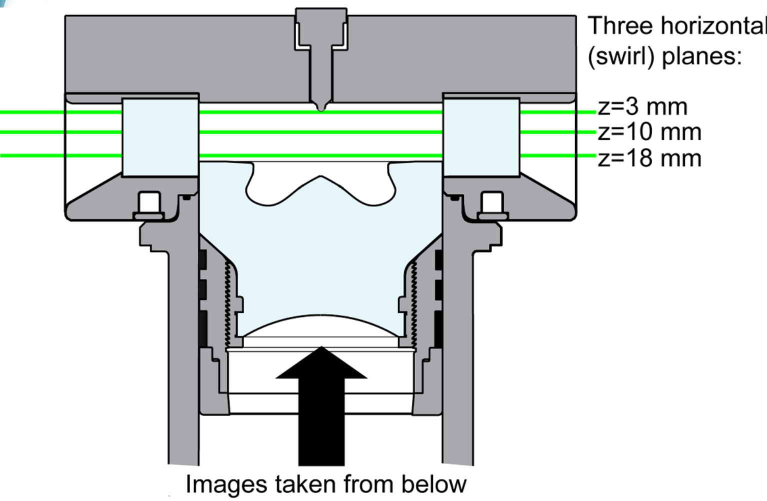






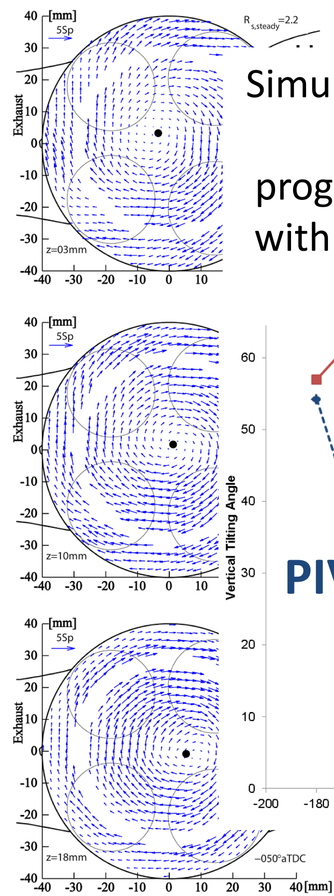
TA: PIV data from SNL have been used to validate simulations from Convergent Science

Simulated velocity fields from Convergent Science predict trends in swirl asymmetry and axis tilt that compare favorably to compression stroke PIV results.

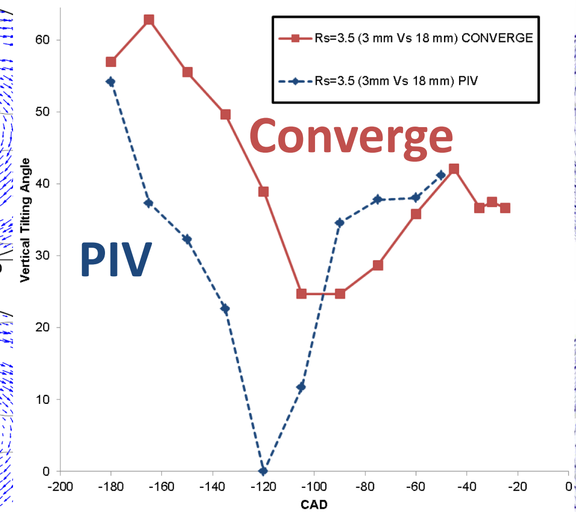


- Steady-state swirl ratio 2.2; images taken at 50 CAD BTDC; motored operation for low load, LTC point
- Swirl center position is computed for measured and simulated data
- Flow asymmetry and swirl axis tilt are well-predicted by the CONVERGE computational model

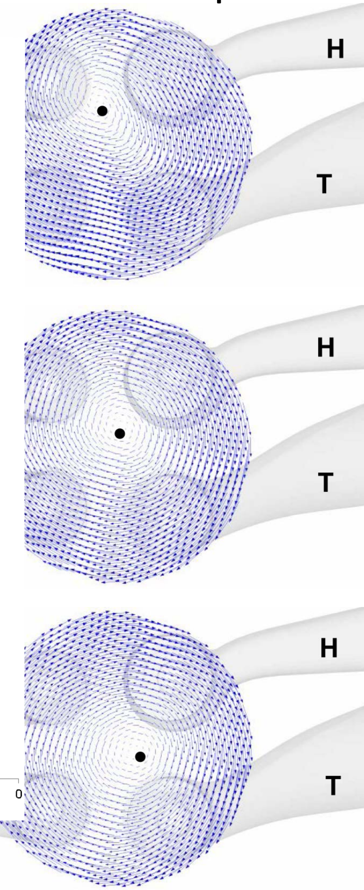
SNL - PIV



Simulation predicts axis tilt as compression stroke progresses; close agreement with experiment near end of compression stroke



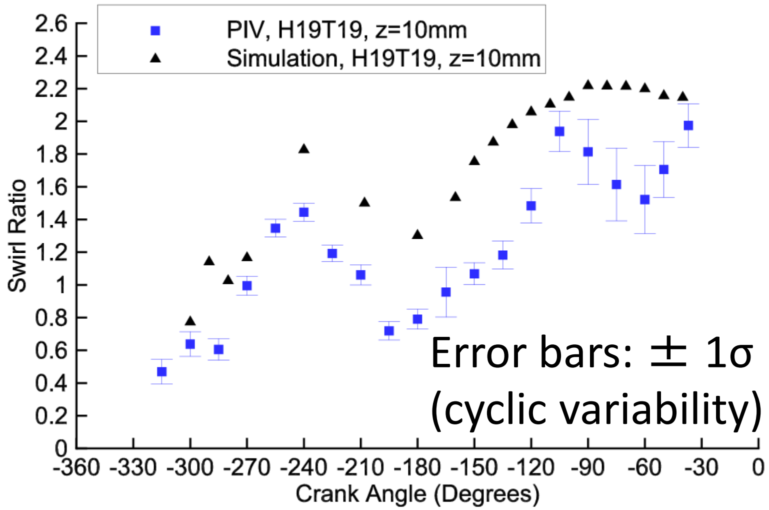
CONVERGE - Computation



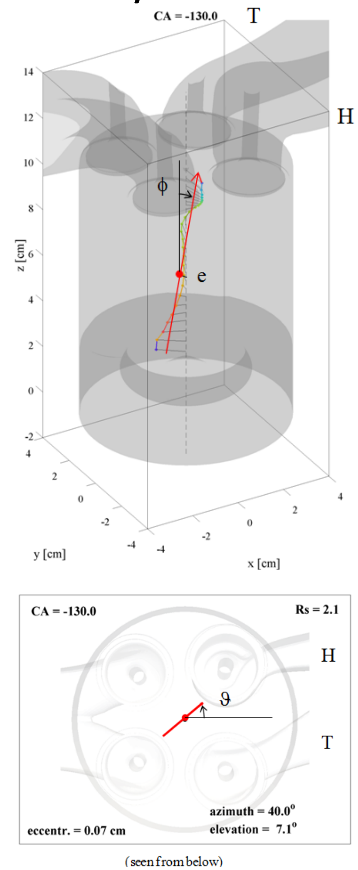
TA: Numerical simulations capture and describe in-cylinder swirling flow (UW)

Computational flow simulations at UW reproduce measured trends; PCA reveals that in-cylinder compression stroke flow resembles a tilted, rotating solid body.

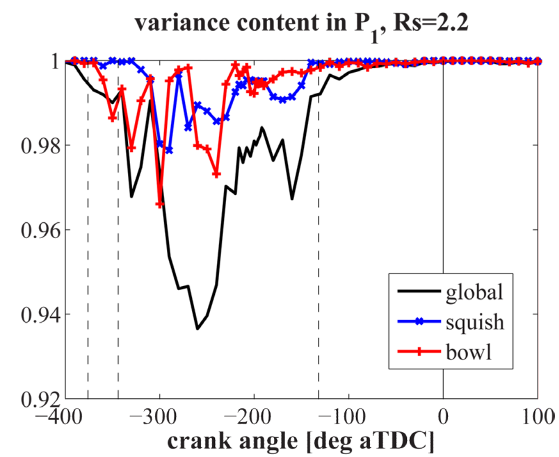
- SNL's PIV results have also been used to validate UW's computational simulations
- The simulated trend in swirl ratio agrees qualitatively with the measured data (see below)
- Principal component analysis (**PCA**) is used to reduce the dimensionality of the complex, evolving in-cylinder flow field



P_1: axis of solid-body rotation

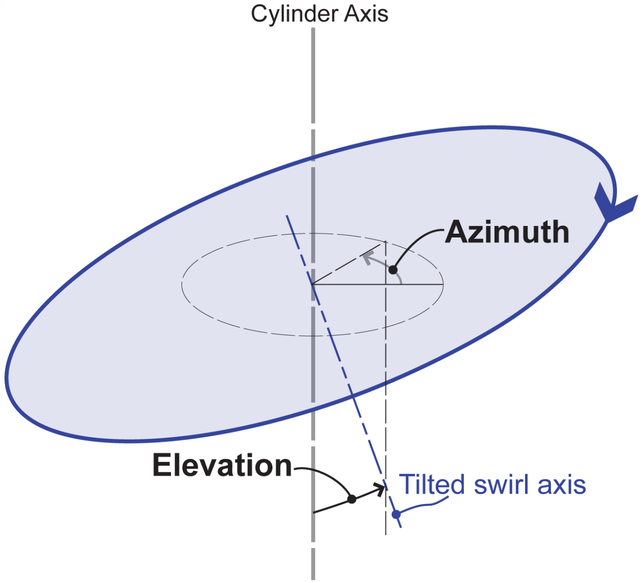


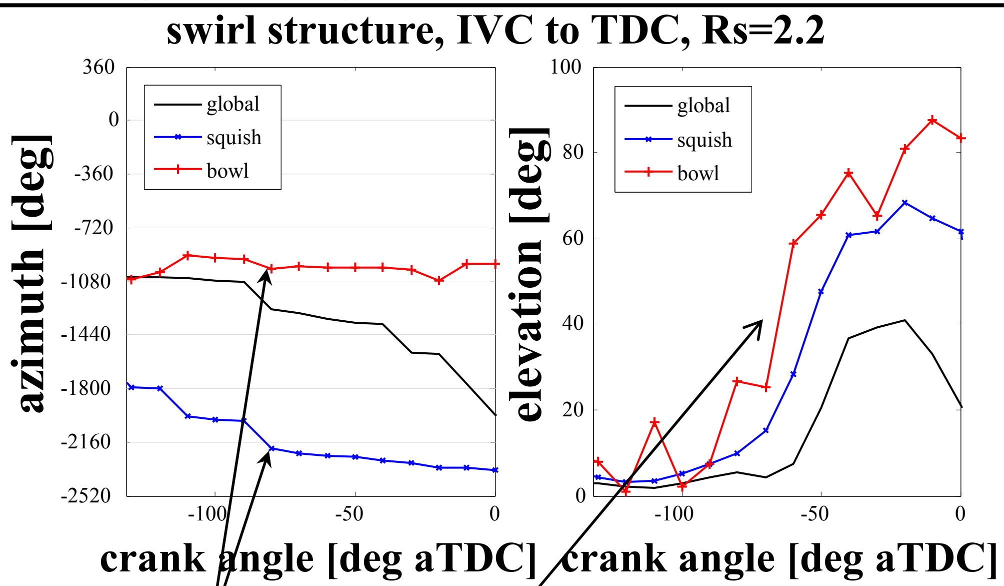
- First principal component: axis orientation with solid body rotation assumption
- First component (P_1) captures most of the variance in the flow field
- During the late compression stroke, the flow field behaves as a solid body



TA: Principal component analysis of simulation results describes swirl vortex evolution (UW)

A simplified representation of the complex swirl vortex provides insight into flow topology changes during the compression stroke.



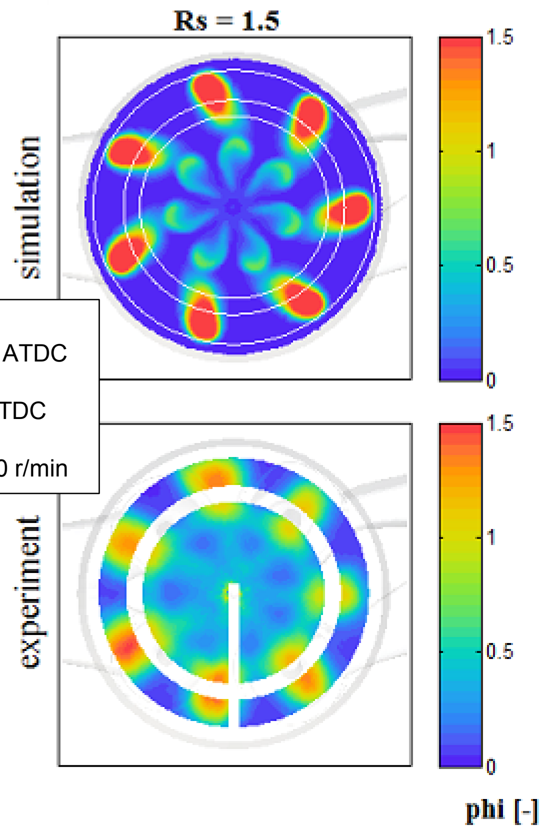


- Vortex precession in bulk of cylinder slows with compression stroke; little precession occurs in the piston bowl
- Increase in swirl axis tilt & vertical velocity components as piston approaches TDC
  - Acts as stored energy that can be dissipated as turbulence
- Swirl tilt behavior is captured qualitatively by both the UW and the Convergent Science simulations

TA: implementation of a full engine grid for more accurate fuel-air mixing predictions (UW)

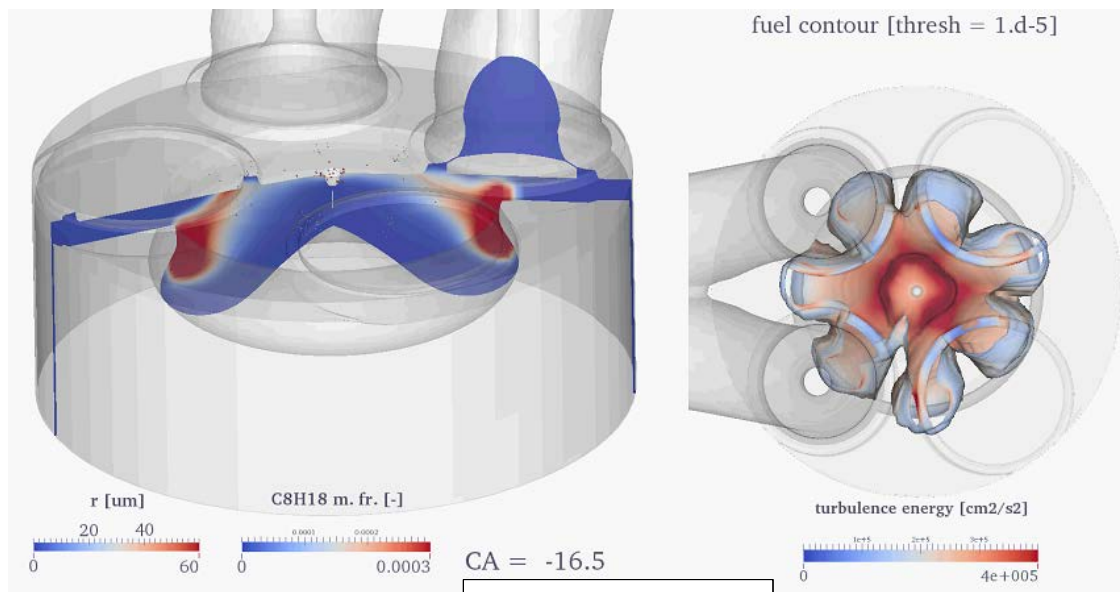
UW full engine simulations now include a calibrated unsteady jet model; they predict asymmetric mixing and jet-to-jet mixing discrepancies.

Previous results with sector mesh: jet penetration, turbulent mixing, and pollutant formation (CO, UHC) not accurately predicted



Squish plane (P1)
SOI = -23.3 CAD ATDC
m_{inj} = 8.8 mg
CA = -10 CAD ATDC
IMEP = 3 bar
eng. speed = 1500 r/min

New capability: 360° mesh / full engine simulation, calibrated unsteady jet spray model; requires parallelization and further code optimization (ongoing); results to be validated with SNL's PLIF images



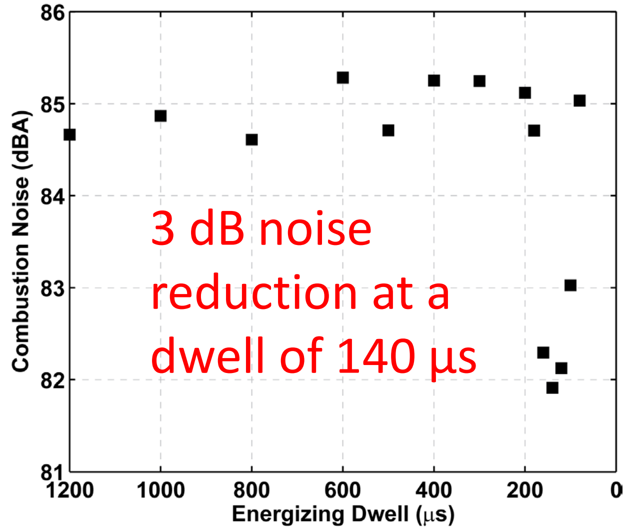
SOI = -23.3 CAD ATDC
m_{inj} = 8.8 mg
CA = -16.5 CAD ATDC
IMEP = 3 bar
eng. speed = 1500 r/min

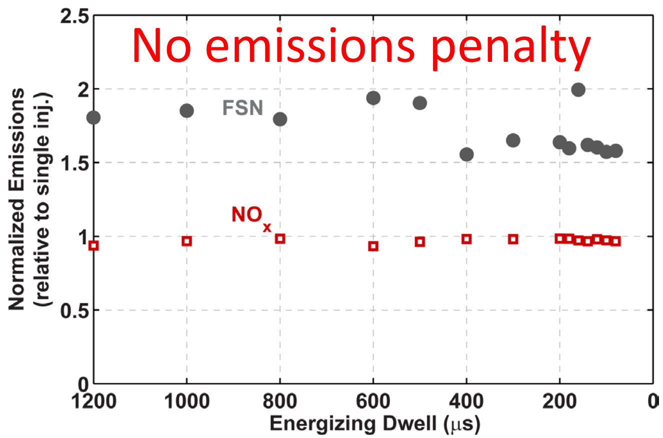
TA: Combustion noise reduction via a close-coupled pilot injection

Combustion noise can be dramatically reduced with a close-coupled pilot injection (energizing dwell < 200 μs) without penalties in emissions (compared to a far pilot).

- **Operating point**:
  - 1500 rpm; 9 bar $IMEP_g$; $COV(IMEP_g) < 2.3\%$
  - Pilot mass: 1.5 mg/str (held constant)
  - $[O_2]$: 19.7% (10.3% EGR)
  - P_{rail}: 800 bar
  - CA50: 13 CAD ATDC
  - T_{TDC}: 925 K (est.)
  - ρ_{TDC}: 21.8 kg/m^3 (est.)
  - Fuel: DPRF58
    (58 vol% heptamethylnonane, 42 vol% n-hexadecane)

- Vary solenoid energizing delay (dwell) between pilot and main injection; maintain load and CA50
  - Energizing dwell: 1200 – 80 μs
  - Operation with short dwells requires an advanced, fast-acting injector



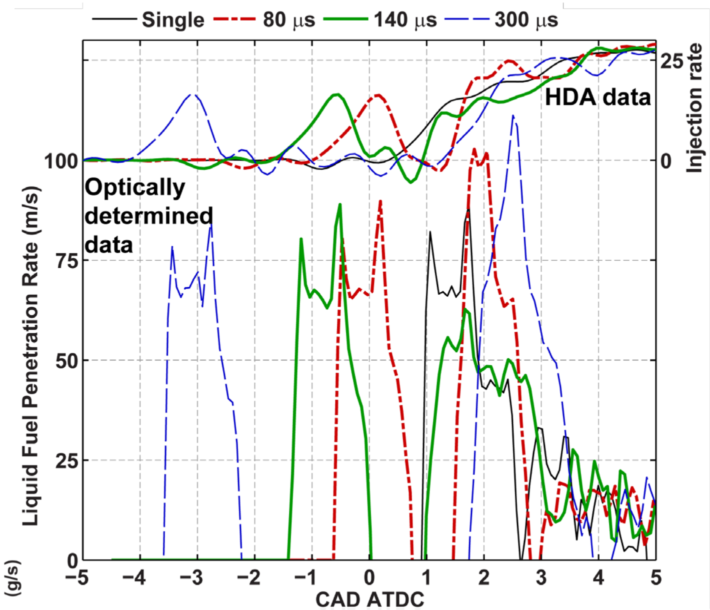


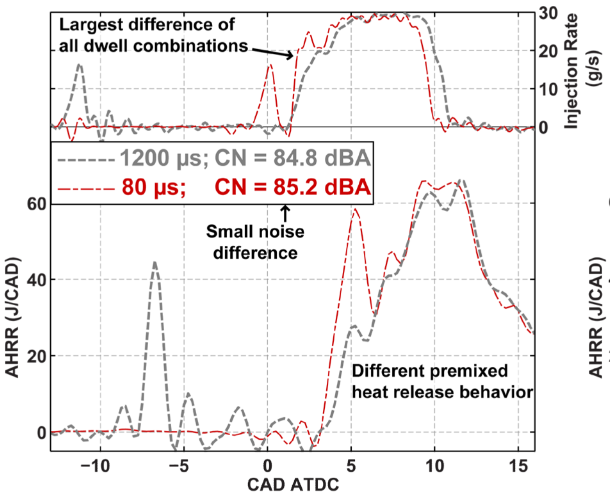
TA: Main injection rate shaping is affected by dwell with a close coupled pilot injection

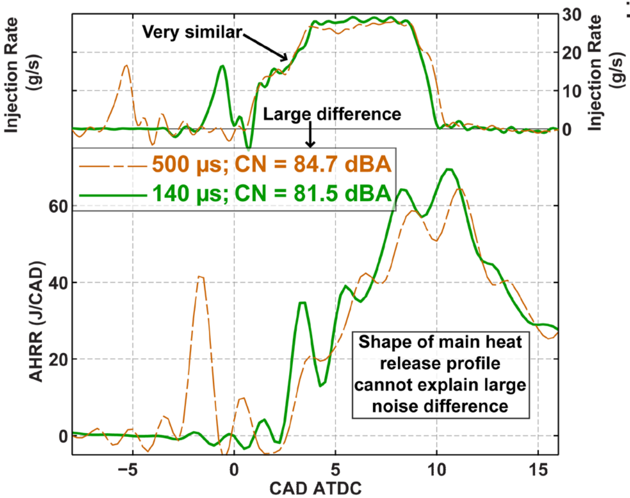
Main injection rate shaping does occur as dwell changes with a close-coupled pilot, but it is not responsible for the reduction in combustion noise.

- **Injection rate measurements:** shape of main injection rise rate is affected by hydrodynamics in the injector & high pressure fuel line as dwell changes: top plot →

- **Optical engine measurements:** a similar trend in main injection rate shaping is observed in the engine with high speed imaging: bottom plot →







- **However:** main injection rate shaping trends do not correlate with noise trends

TA: Detailed analyses - development of a model to understand the noise reduction mechanism

The close-coupled pilot noise reduction mechanism has been captured within a very simple thermodynamic model.

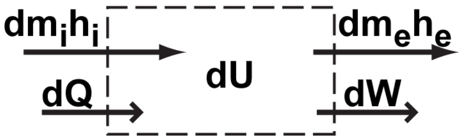
- Development of a 0-D thermodynamic model to capture the combustion noise reduction mechanism
  - Compute combustion noise given a pre-defined heat release profile: (A)
  - Vary phasing of pilot and main heat release profiles to match experiments; compute combustion noise trend (B)

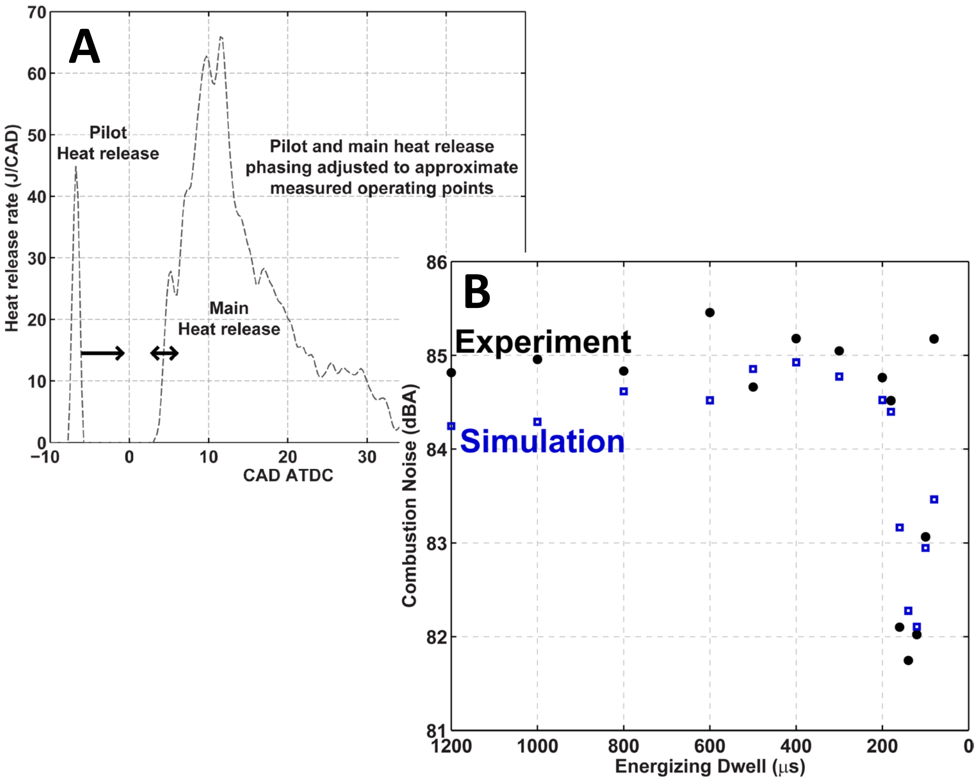
- The combustion noise mechanism is contained within this simple model
  - Confirmation: noise reduction occurs without main injection rate shaping
  - Changes to cylinder-pressure waveform in response to changing heat release phasing are responsible for the noise reduction

$$dm = dm_i - dm_e$$

$$dT = \frac{PdV + VdP}{mR} - T\frac{dm}{m}$$

$$dP = \frac{1}{V}\left[(\gamma-1)dQ - \gamma PdV + \frac{PV}{\gamma-1}d\gamma + (\gamma-1)(dm_i h_i - dm_e h_e)\right]$$

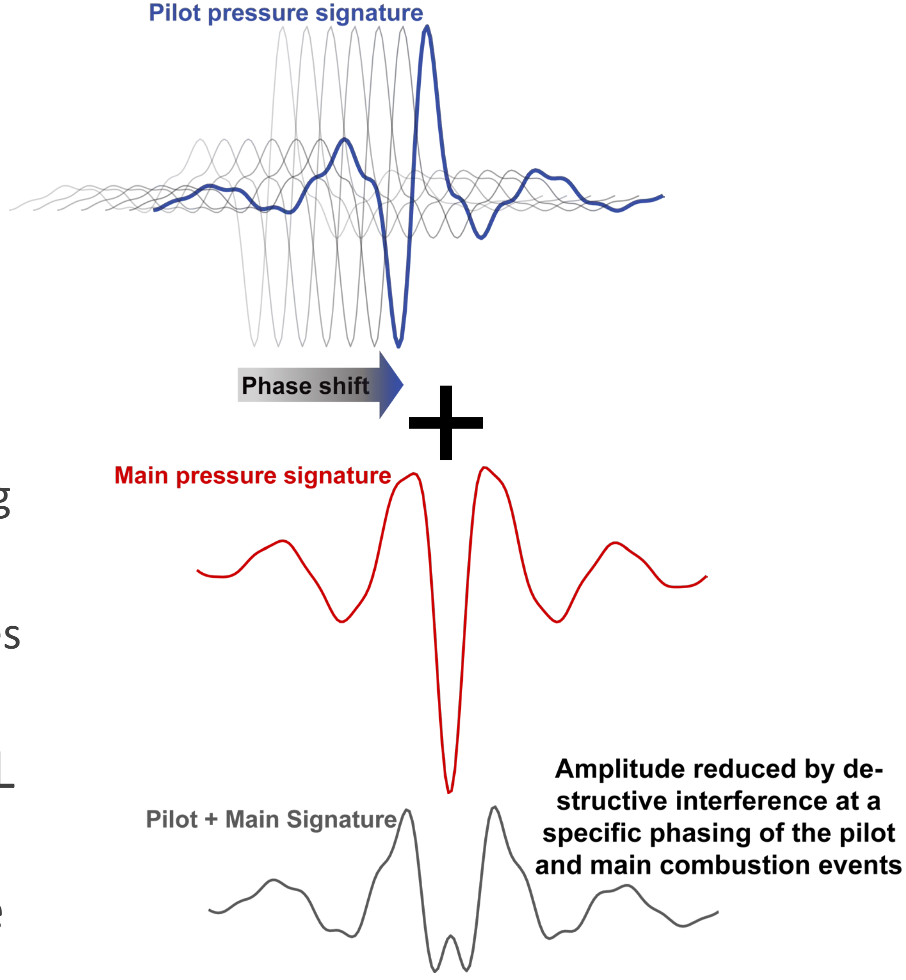




TA: Detailed analyses – an understanding of the close-coupled pilot noise reduction mechanism

Detailed analyses at SNL are revealing the fundamental combustion noise reduction mechanism with a close-coupled pilot injection.

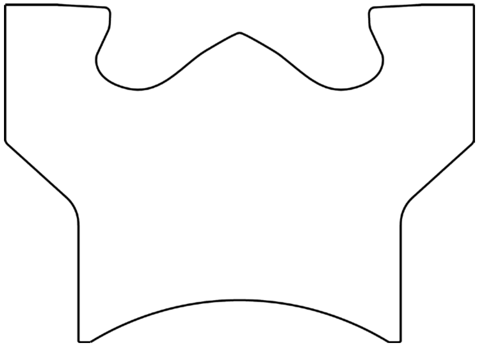
- Detailed analyses demonstrate the destructive interference mechanism responsible for the combustion noise reduction
  - Will be presented at ASME ICEF2015
- Potential of this noise reduction mechanism
  - Enables more efficient combustion phasing
  - May apply to other combustion modes
  - Could help advanced combustion strategies reach the market
- Planned collaborative effort with ORNL to determine this mechanism’s potential over a wider operating range and with other modes of combustion



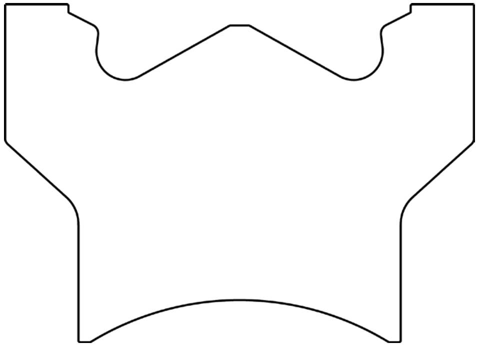
Future work: effects of piston bowl geometry on flow and mixture formation

- Project planned in cooperation with GM & Ford
- Low temperature and conventional combustion
- Planned measurements
  - Swirl plane PIV (Mar – Apr 2015)
    - Generate high quality validation data over the intake and compression strokes for computational models
    - How does bowl geometry affect flow topology?
  - Fuel tracer PLIF (Jul – Oct 2015)
    - Provide updated validation data for computational models using a diesel-like reference fuel
    - How is fuel distribution (in swirl planes) affected by piston geometry / reverse squish flow?
  - Squish flow PIV (Sept 2015 – Mar 2016)
    - Objective: characterize and compare squish and reverse squish flows for both piston geometries
    - Existing experimental techniques have been unsuccessful; new techniques must be developed for swirl-plane and/or tumble plane measurements

Re-entrant bowl used in previous studies



Stepped lip bowl



Future work: multiple injection strategies and beyond

- Close-coupled pilot injections
  - Mixture formation and combustion via fuel tracer PLIF and high speed imaging
  - Simulations at UW – how well can simulations capture mixture preparation, ignition, combustion processes and explain what is observed in the experiments?
  - Developing collaboration with ORNL – explore the potential and impact of a close-coupled pilot injection in a production engine over a wider range of conditions.
- Computational activities at UW
  - Validation of spray predictions with measured data
  - Optimization of code to run in parallel
  - Simulation of flow fields with stepped-lip piston; validation with SNL data
- Longer term contributions
  - Multiple injection strategies to enhance LTC in cold conditions (2016)
    - Can the close-coupled pilot combustion noise reduction mechanism be used to reduce noise and unburned hydrocarbon emissions simultaneously?
  - Development of updated Diesel conceptual models for multiple injection strategies
    - Collaborations within SNL's engine group; it will take time to build this understanding

Responses to reviewers' comments

- More investigation is needed on fuel dependency of injection rate with a pilot injection

  Response: we hypothesize that this phenomenon depends on fuel density and compressibility (see GTP-15-1068). 1-D modeling and line pressure measurements would help confirm this, but detailed geometric data for the injector are not available; further work is not in the scope of near-term plans.
- Cold-start strategies and cold, in-cylinder emission control are of keen interest; close-coupled pilot injections at various rail pressures should be explored for LTC combustion strategies

  Response: agreed. We hope to address cold, LTC operation with multiple injection strategies in 2016.
- More information on control of pressure and temperature near TDC is warranted

  Response: we control intake charge mass flow rates and temperatures. TDC temperature is estimated with a calibrated GT-Power simulation. A fast-response dual thermocouple probe is being developed.
- It is not clear if "robust ignition" correlates with what is acceptable in a real-world engine

  Response: the pilot ignition study does not provide a complete picture; we are interested in understanding how the robustness of pilot ignition influences ignition and combustion of the main mixture field.
- More emphasis by the project team on squish interactions would be of interest

  Response: recent attempts to measure squish flows using PIV were unsuccessful; we are building new plans.
- Nozzle geometry effects on mixture formation and ignition should be investigated

  Response: this will be useful but exceeds our near-term capacity; tentative plans are in place for FY2017.
- The project team should expand work in the future to include non-petroleum fuels

  Response: This is a current topic of interest; we would like to investigate promising advanced fuels in conjunction with advanced combustion strategies. We hope to secure funding to support this effort in 2016.
- Future experiments should address real engine applications and compare different options.

  Response: the close-coupled pilot injection study and the planned collaboration with ORNL should demonstrate progress in this direction, as should the planned piston bowl geometry investigations.

Summary

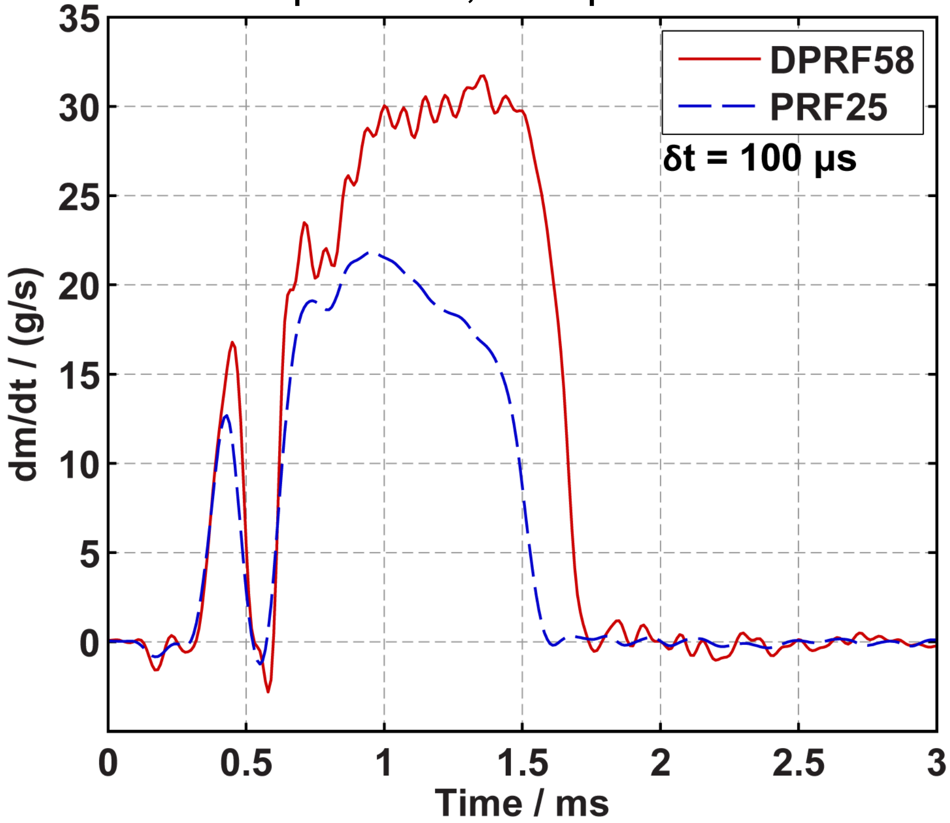
- Relevance
  - Fundamental knowledge of the close-coupled pilot combustion noise reduction mechanism will help engineers manage noise and improve fuel economy (will be presented at ASME ICEF 2015)
  - Generating high quality, experimentally-based, in-cylinder flow field data enables simulation validation and progress towards more accurate, predictive computational capabilities
- Approach
  - Engine experiments augmented with detailed analyses and computational simulations; close cooperation with computational code vendor; strong partnerships with industrial partners
- Technical Accomplishments
  - Developed experimental techniques (PIV) and analytical image distortion correction to generate high quality swirl-plane velocity field data over a wide crank angle range
  - Validated computational simulations with PIV results; verified predictive capabilities of simulation tools
  - Calibrated unsteady jet model; demonstrated ability to predict jet-to jet variations with 360° grid
  - Significant combustion noise reduction achieved with close-coupled pilot injections; thermodynamic modeling and analyses have led to a fundamental understanding of the underlying mechanism
- Collaborations
  - Strong partnership with UW; strong and growing partnerships with industrial partners and other national labs
- Future Work
  - In-depth study of piston bowl geometry (in-cylinder flows and mixture preparation process)
  - Mixture preparation and combustion processes with multiple injections
  - Continued code validation; simulation of bowl geometry effects and multiple injection strategies

Technical Back-Up Slides

Differences in main injection rates with multiple injections for PRF25 and DPRF58

- Severe pressure oscillations with PRF25
  - Low pass filter cutoff frequency decreased to 6 kHz
- Significant differences in main injection behavior
  - Higher rates of injection <u>and</u> longer injection duration for DPRF58
- Injector hydrodynamics
  - Fluid hammer depends on product of fuel sound speed and density ($c\rho$)
  - $c\rho$ is estimated to be ~33% higher for DPRF58 (diesel-like fuel)
  - Fluid hammer likely forces the needle to open further and close later with DPRF58
  - Pressure surge in nozzle would also serve to increase the DPRF58 injection rate during the main injection
  - 1D modeling and fuel line pressure measurements would be necessary to resolve this (not currently planned)

Injection schedule: 310 μs pilot, 100 μs dwell, 278 μs main

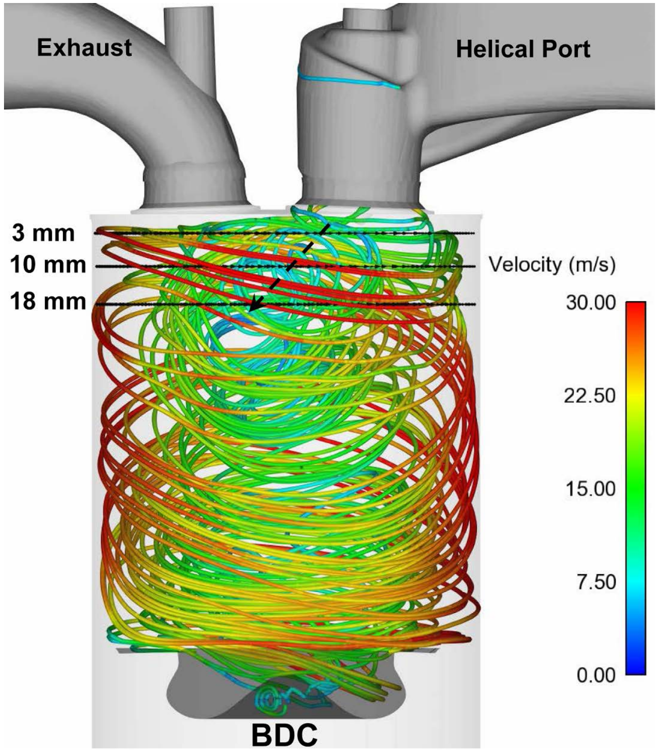


More detail given in 2014 ASME ICEF conference paper and in upcoming Gas Turbines & Power article: GTP-15-1068

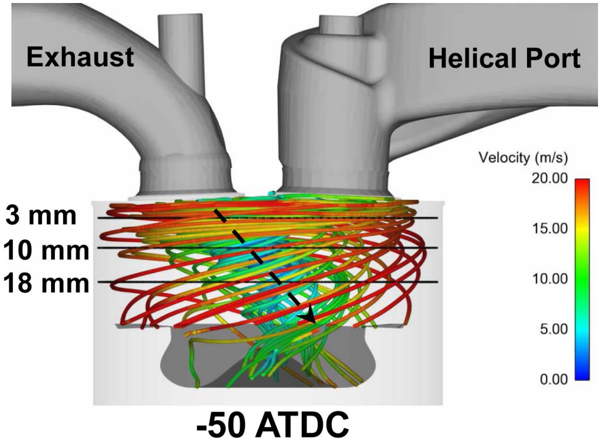
TA: Convergent Science simulations predict trends in swirl axis tilt

Trends in swirl axis tilt agree qualitatively between CSI's computational simulation and SNL's measured data, particularly late during the compression stroke

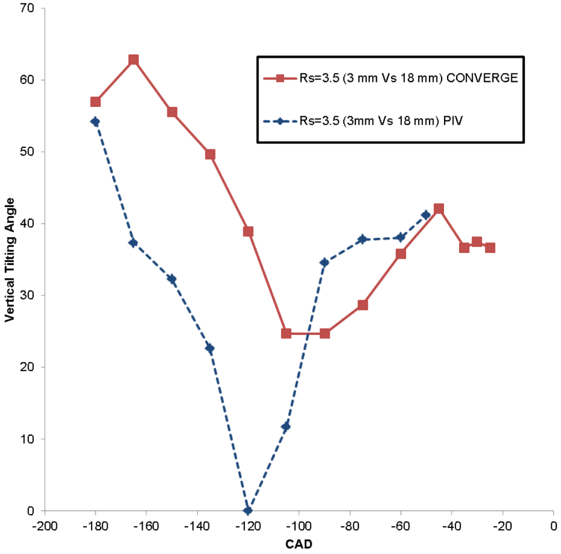
Simulation results reveal a wealth of information that cannot be measured



The swirl axis tilt angle changes and is non-zero during the late compression stroke



Qualitative agreement; close agreement in late compression stroke



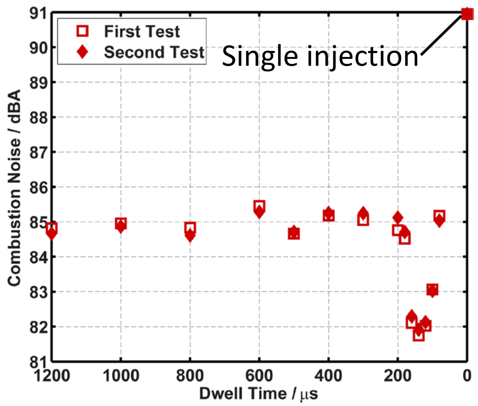
Controlling near-TDC temperatures and pressures

- Intake mass flow rates (and therefore composition) are controlled during engine operation via precisely calibrated critical flow orifices and closed loop pressure controllers.
- The temperature of the intake gases, as well as the intake plenum controlled.
- Operation with the optical engine is inherently transient as a result of the limited run durations. Measurements are taken on a set time schedule (for example, in an 8-minute period, the engine is motored until the flows are stable (approx. 1 min), and at a set time, measurements are taken. After approximately 3 minutes of operation, the engine is stopped for cleaning; data are saved and the next measurement point is set up. The measurements are therefore always taken at the same point in the engine's transient operation;
- Peak cylinder pressure is continuously monitored and highly repeatable from run to run (typically within 20-30 kPa during the measurement period).

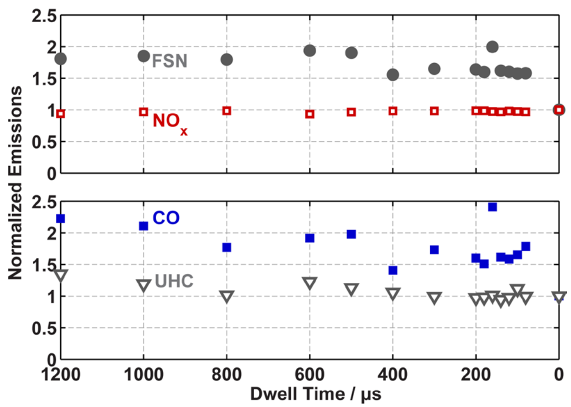
- TDC temperature is estimated using a 1-D model (implemented in GT-Power). The model has been calibrated to match a range of operating conditions.
- We are developing a fast-response twin thermocouple device to measure in-cylinder gas temperatures and validate the 1-D modeling results.

Relevance of close-coupled pilot injection studies

- In Diesel engines, there is very often a tradeoff between combustion noise, emissions, and efficiency
  - Combustion noise is particularly problematic for low temperature combustion (LTC) strategies
  - Excessive combustion noise hinders customer acceptance and market penetration
- Objective: provide a fundamental understanding of the combustion noise reduction with a close-coupled pilot injection for part-load, conventional Diesel operation



Busch et al., IJER 2015



Busch et al., THIESEL 2014

- A working knowledge of this noise reduction mechanism should be an enabler for combustion noise management and improve fuel economy in a variety of applications:
  - Conventional combustion strategies
  - LTC strategies (potentially)
  - Combustion mode switching / dynamic combustion noise behavior (potentially)

Cyclic variability with close-coupled pilot injections

The decrease in noise appears to come with a penalty in cycle-to-cycle variability; planned testing in a close-to-production engine will provide more reliable data.

- With far pilots, COV(IMEP) is very low (~1%)
- At the dwell for minimum noise of 140 µs, COV(IMEP) is near 1.5%
- COV(IMEP) peaks at a dwell of 100 µs just below 2.3%
- These data are taken in a skip-fired optical engine and may not be an accurate representation
- Planned testing at ORNL will demonstrate the variability over a wider range of operating conditions