Expanding the Knock/Emissions/Misfire Limits for the Realization of Ultra-Low Emissions, High Efficiency Heavy Duty Natural Gas Engines

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Annual Merit Review Meeting

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Project ID: FT079

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Project Overview

Timeline

Project Start Date: 5/23/2018

Project End Date: 5/22/2021

Percent Completion: 33%

Barriers

- Goal: Increase brake efficiency to 44% for NG engine
  - Reduced kinetic model to predicted end gas autoignition (EGAI)
  - Advanced controls to maintain controlled EGAI at high BMEP and variable fuel quality.

Budget

Total Project Cost: $1,572,922

Federal = $1,257,633

Cost Share = $315,289

Budget Period 1 Federal: $463,242

Budget Period 2 Federal: $405,149

Budget Period 3 Federal: $389,242

Partners

Project Lead: Colorado State University

Cummins Inc.

Woodward, Inc.

Milestones

Project Tasks, Milestones, and Go/No-Go Decisions	Budget Period 1				Budget Period 2				Budget Period 3			
	2018		2019				2020				2021	
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
1. Validate and Development Modelling Tools				M1.3	GN1	M2.1						
2. CFR Experiments and Modelling		M1.1		M1.2								
3. Combustion Chamber Design						M2.2						
4. Single Cylinder Engine (SCE) Development							M2.3	GN2		M3.1		
5. Control System Development							M3.2					
6. System Optimization - Target 44% Efficiency												M3.3

- Complete   - To Be Completed

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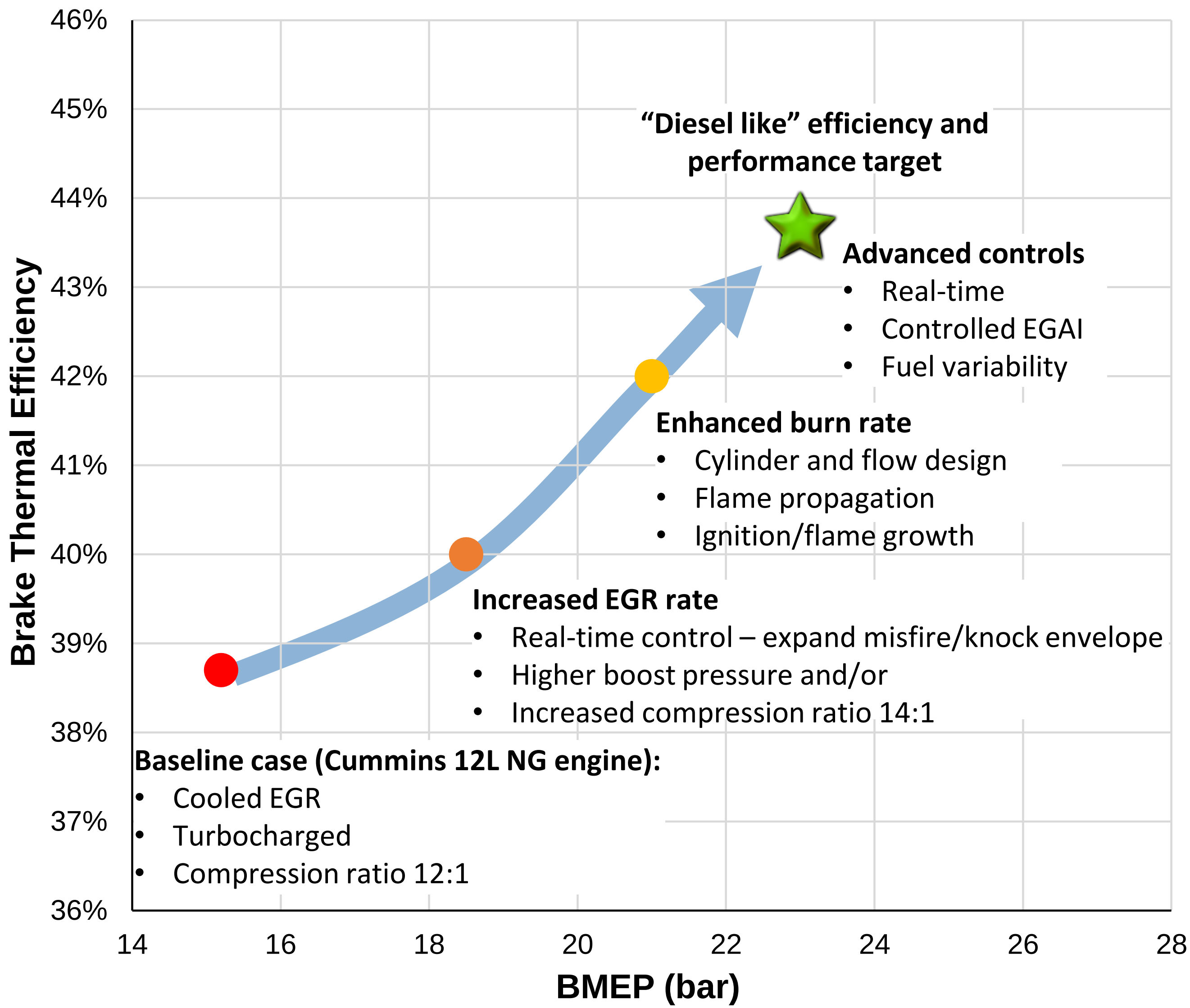
Approach

Engine Configuration to Meet Goal

- Stoichiometric SI, turbocharged
- High levels of cooled EGR
- Combustion chamber design for high burn rate
- Prechamber spark plugs
- Advanced engine controls



Pathway to "Diesel-like" Efficiency and Performance

Technical Accomplishments and Progress

Detailed Parent Mechanism

Detailed Mechanism	Origin	Species	Reactions
Aramco 3.0	National University Ireland Galway	581	3,034
Aramco 2.0	National University Ireland Galway	493	2,714
NUIG NGM II	National University Ireland Galway	229	1,359
Ranzi V1412	Polytechnic University of Milan	115	2,141
GRI Mech 3.0	University California Berkeley	53	325
San Diego	University California San Diego	57	268
USC Mech Version II	University Southern California	111	784

- 7 Detailed parent mechanisms were selected for evaluation
- Mechanisms were designed to predict ignition delay and laminar flame speed of HC species < C5
- Desired performance for Methane, Ethane, Propane natural gas fuels with MN 34-95 and pressured from 5-85 bar
- Reduced mechanism (~50 Species) will be tuned using rapid compression machine (RCM) ignition delay and flame propagation rate data collected at CSU

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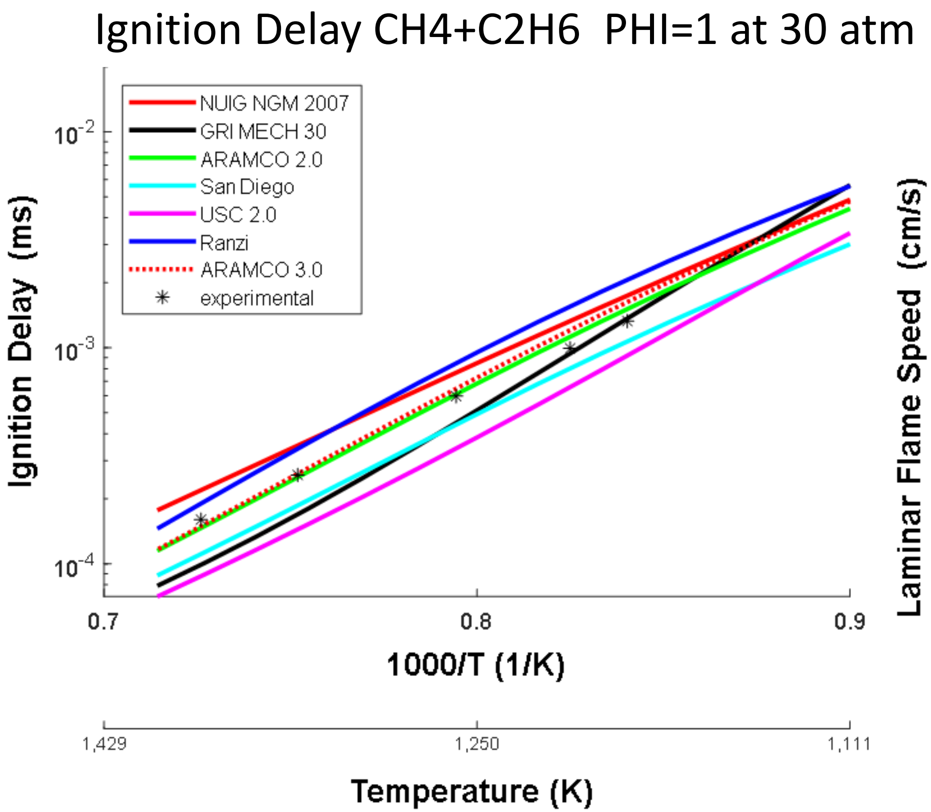
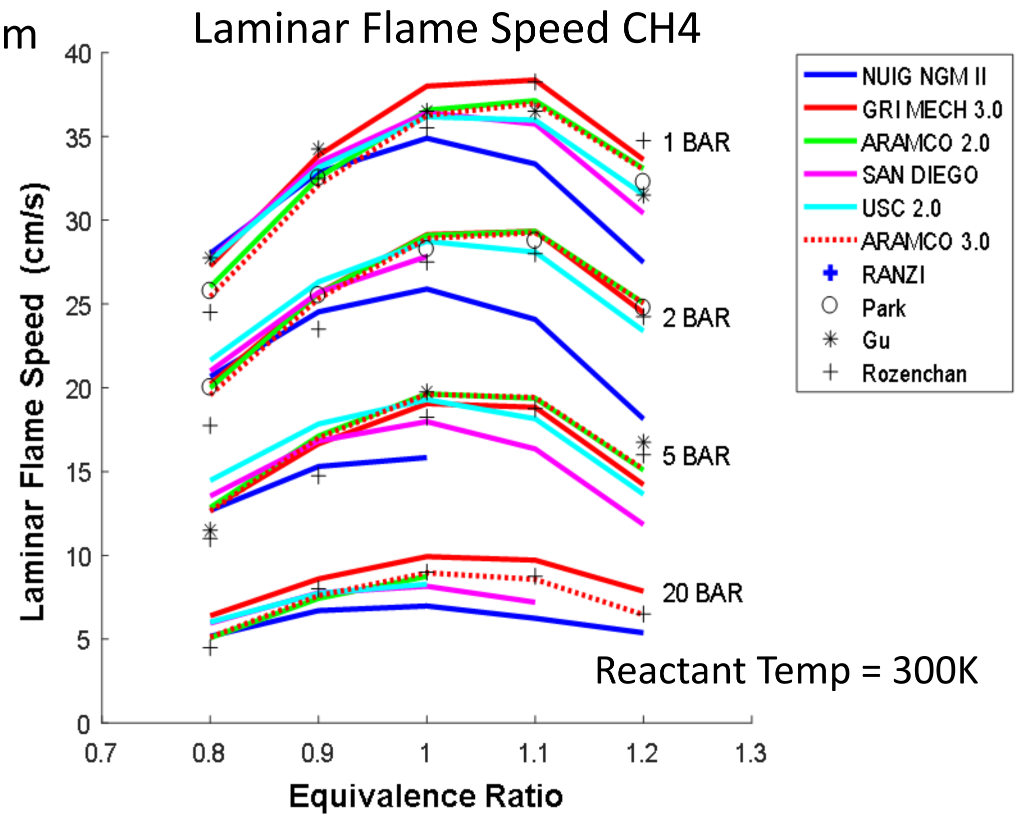
Technical Accomplishments and Progress

Detailed Parent Mechanism Performance





- Ignition delay performance at high pressure with methane-ethane blend. Note good agreement of Aramco mechanisms at elevated pressure to experimental (black stars)
- Laminar flame speed performance of methane . Note good agreement of Aramco mechanisms to experimental points (black markers)
- Selected Aramco 3.0 as parent

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Technical Accomplishments and Progress

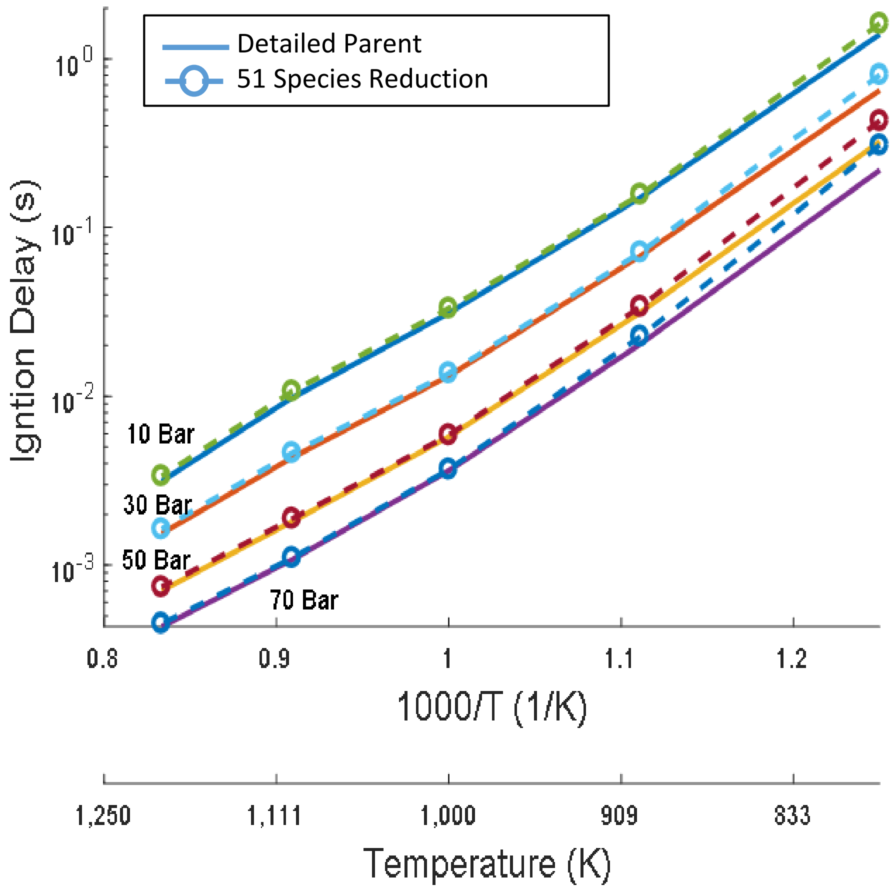
Reduced Mechanism Performance

Tested Fuel Blends

	Dry	Middle	Wet	Propane
Methane	99%	95%	82%	0%
Ethane	0.5%	4%	15%	0%
Propane	0.5%	1%	3%	100%
MN	95	86	68	34

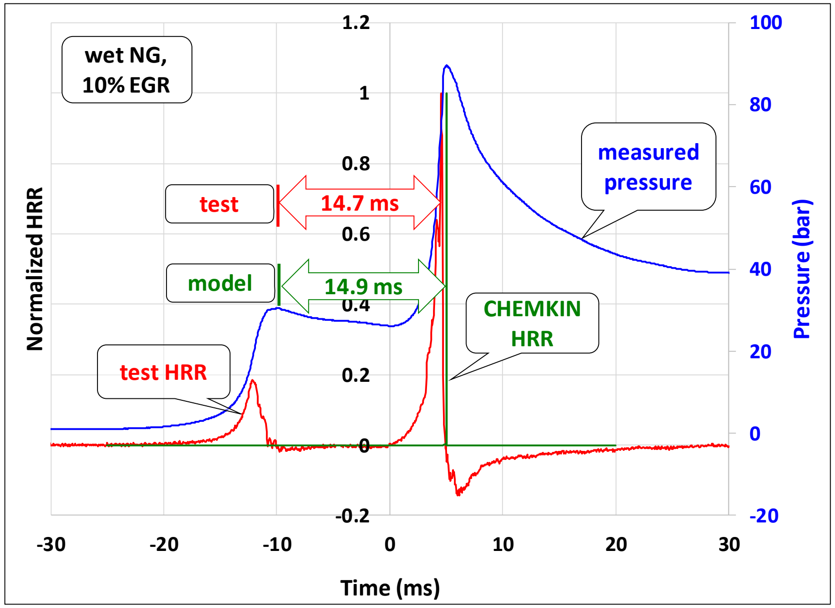
- The detailed mechanism was reduced using Chemkin to create a 51 species mechanism
- Ignition delay was main tuning parameter and benchmarked against detailed mechanism performance (right) for 4 fuel blends shown (above)

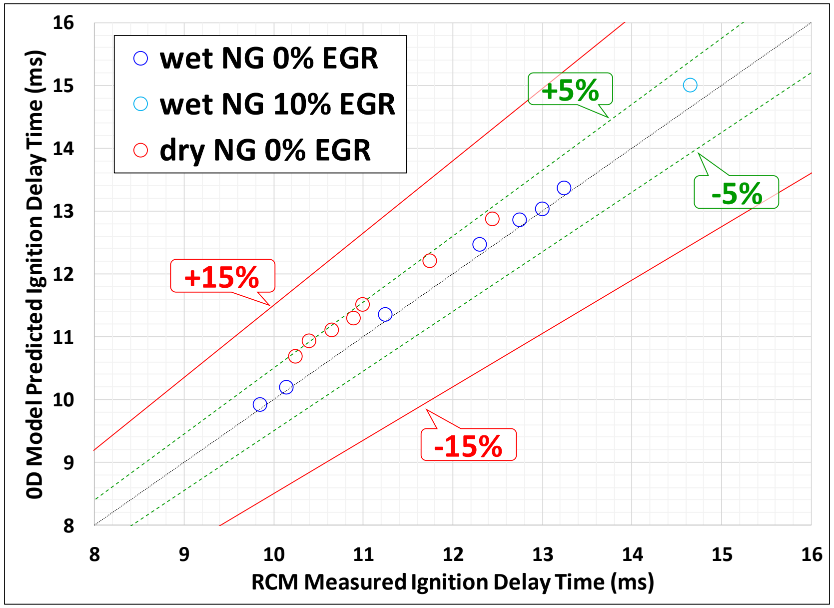
Ignition Delay Performance of Middle NG blend
PHI=1 51 Species Mechanism



Technical Accomplishments and Progress

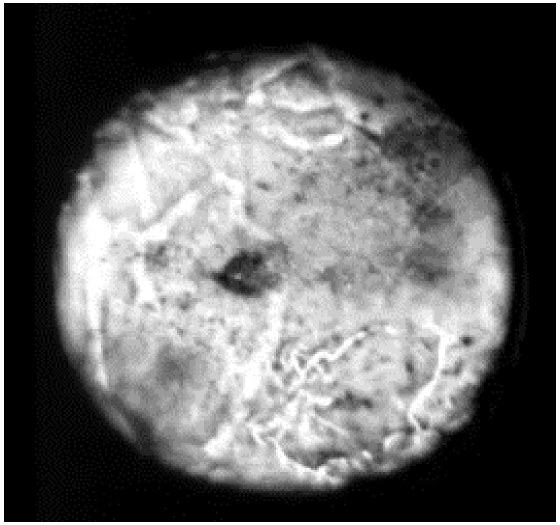
Reduced Mechanism Performance





- Reduced mechanism can reliably **predict autoignition time in 0D CHEMKIN simulations**
- CHEMKIN 0D homogeneous premixed model was used.
- Inputs include measured pressure with time, initial temperature, fuel type, and air/fuel ratio
- **Overall autoignition prediction accuracy within 5%**

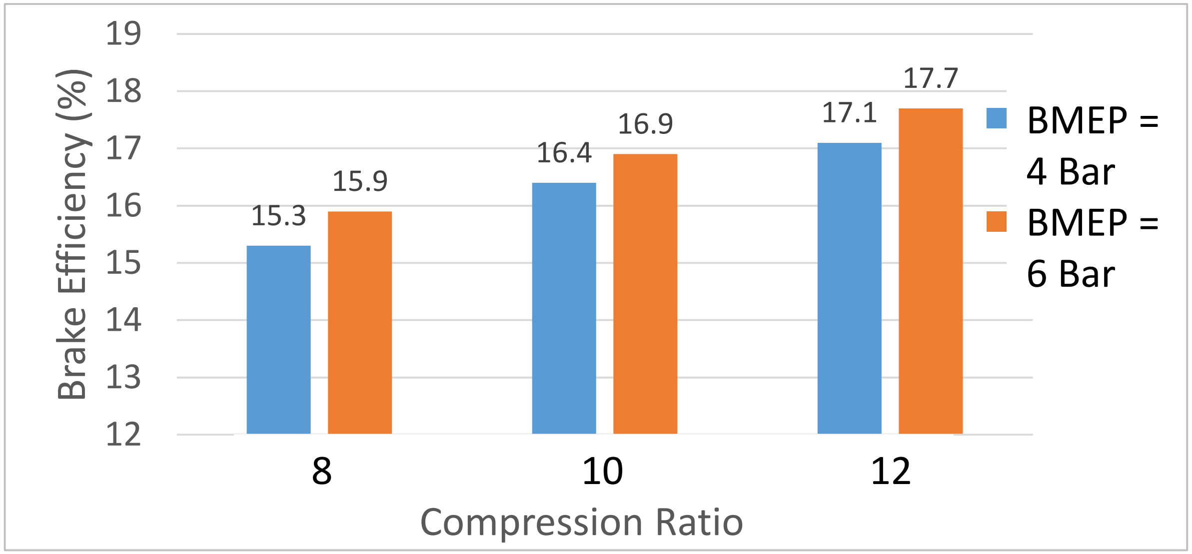
Experiment Specifications: →
Wet Blend Fuel: 82% CH_4, 15% C_2H_6, 3% C_3H_8
Oxidizer/Inert: 21% O_2 / 59% Ar / 20% N_2
Stoichiometric - 0% EGR - Laser-ignition: 10 ms



Technical Accomplishments and Progress

Preliminary Engine Experiments

- Cooperative Fuels Research (CFR) engine upgrades:
    - Woodward Large Engine Control Module (LECM)
    - Dynamic Pressure Sensors
    - Exhaust Gas Recirculation (EGR) Test Cart
    - Fuel Blending System
- Established knock intensities for knock detection method comparison
- Provided baseline engine data for 0D and CFD engine model development



EGR Cart

Cooperative Fuels Research (CFR) Engine

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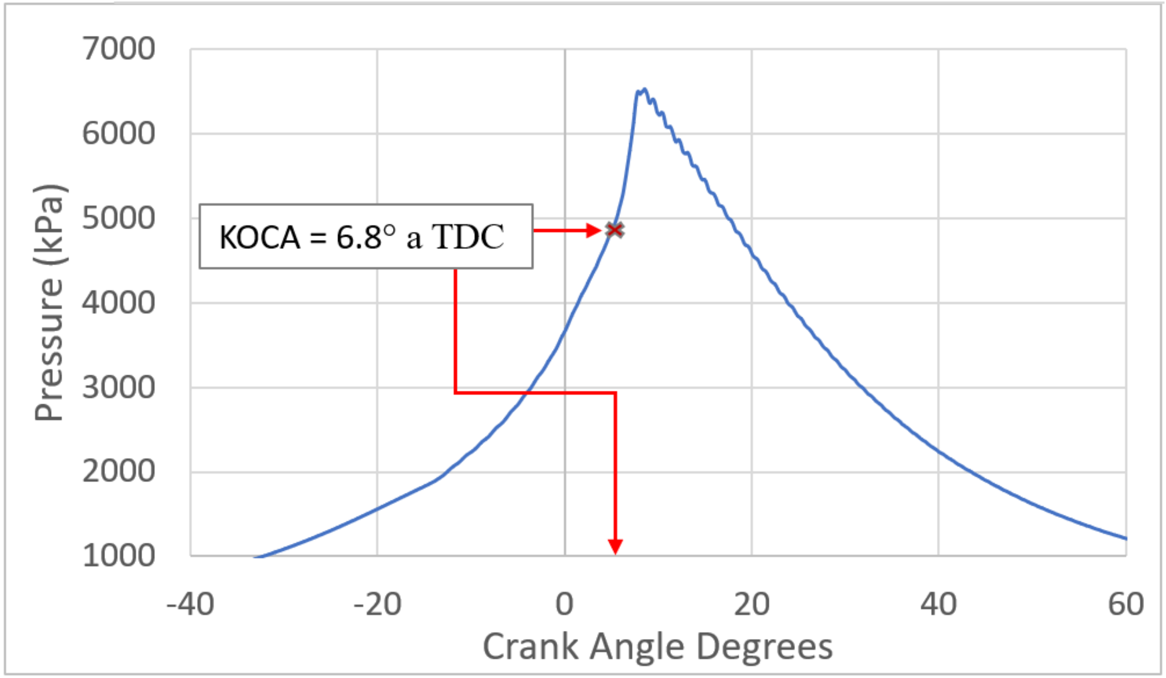
Technical Accomplishments And Progress

Knock Detection Method Quantification

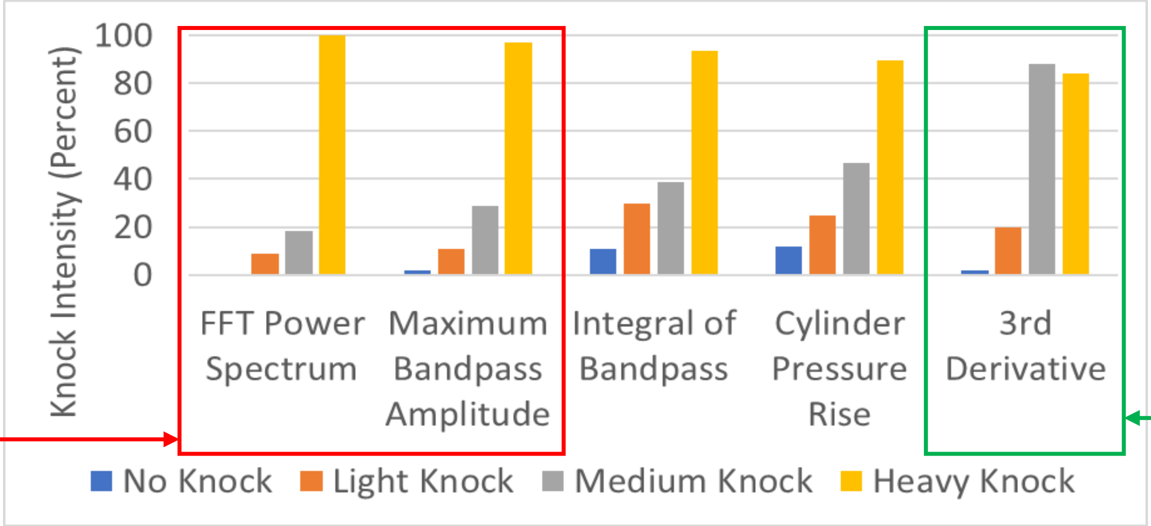
- Explored pressure based knock detection methods

Knock Location and Intensity:

- Necessary for "Controlled End Gas Auto-Ignition"
- Will operate within window of knock onset to light knock



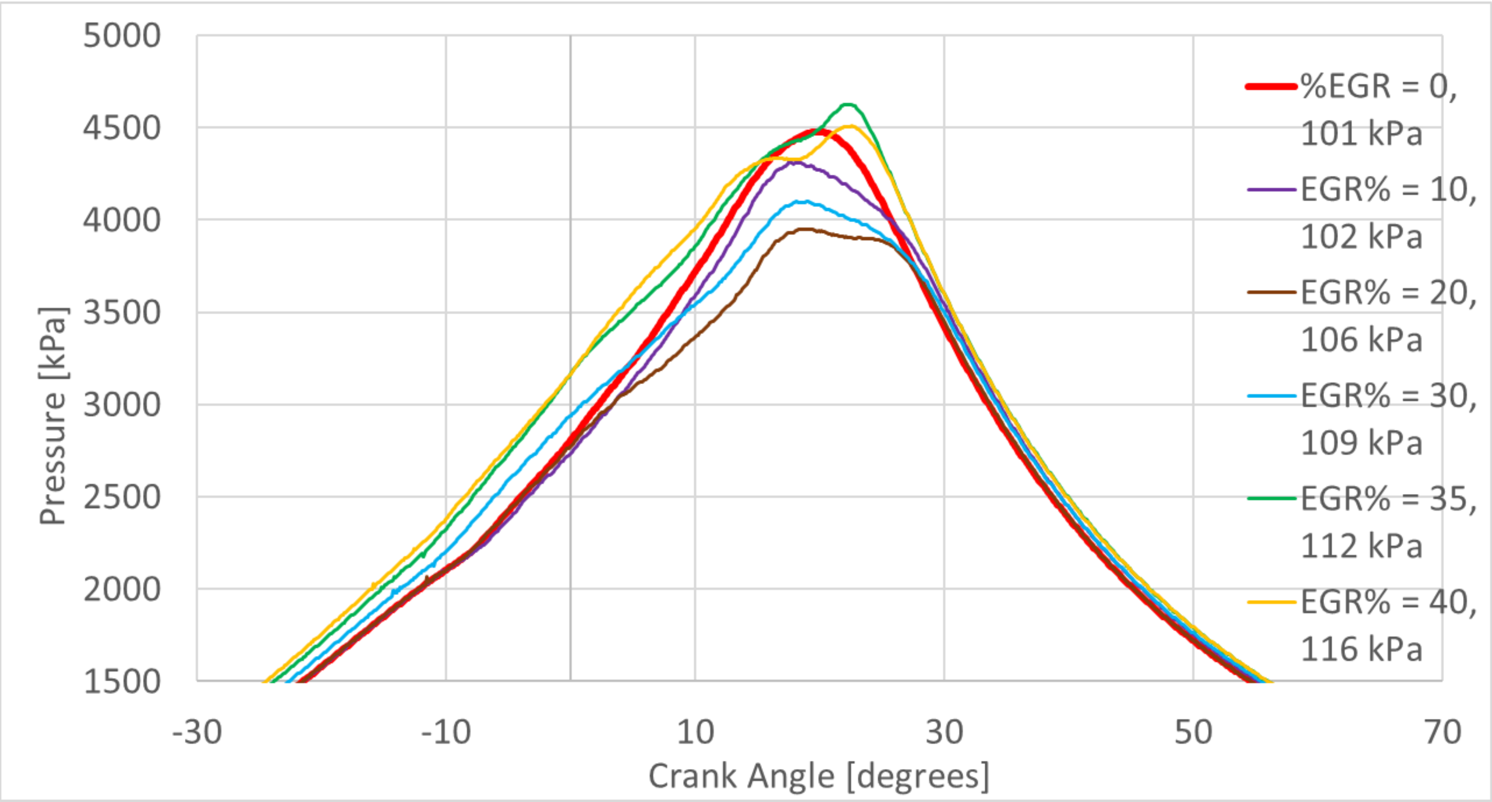
Initial selections for auto-ignition detection



Initial selection for KOCA calculation

Technical Accomplishments and Progress

Exhaust Gas Recirculation Operation on CFR Engine



Phi = 1
IMEP = 8 Bar
RPM = 942
Intake Temp. = 65°C
CA50 = 13.8° aTDC
CR = 11.9

- EGR limit = COV Peak Pressure ≥ 10.0
  - Observed EGR Limit ~ 35%
- Subsequent tests will explore increasing compression ratio (CR) and brake mean effective pressure (BMEP) to improve efficiency

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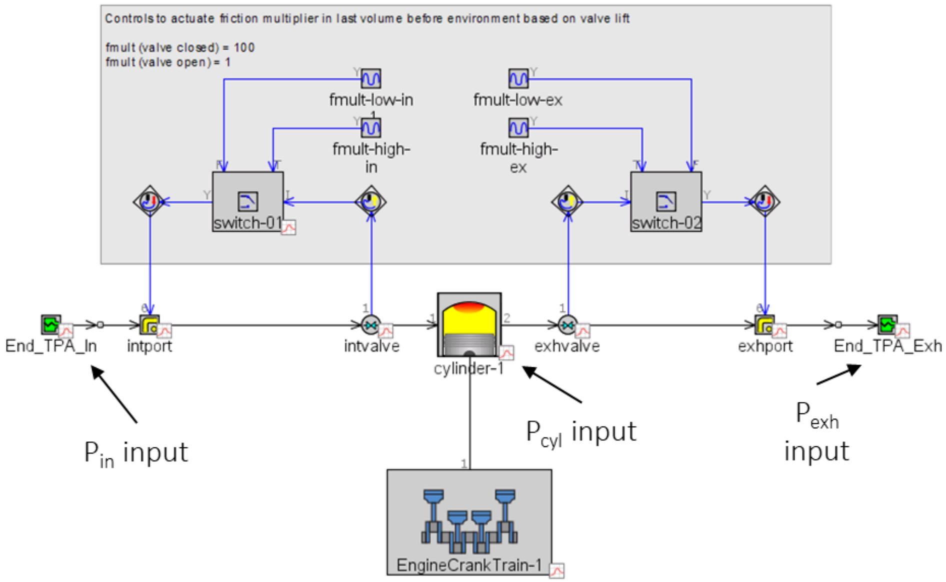
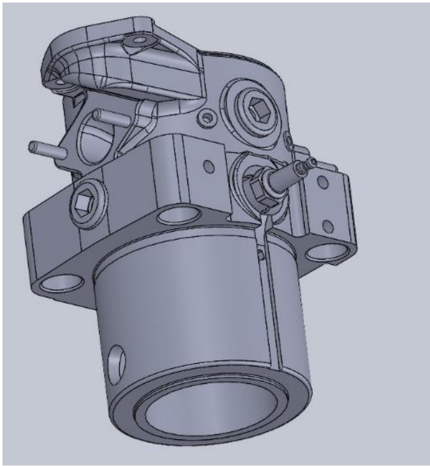
Technical Accomplishments and Progress

CFR Engine Modeling



GT-Power Three-Pressure Analysis Model



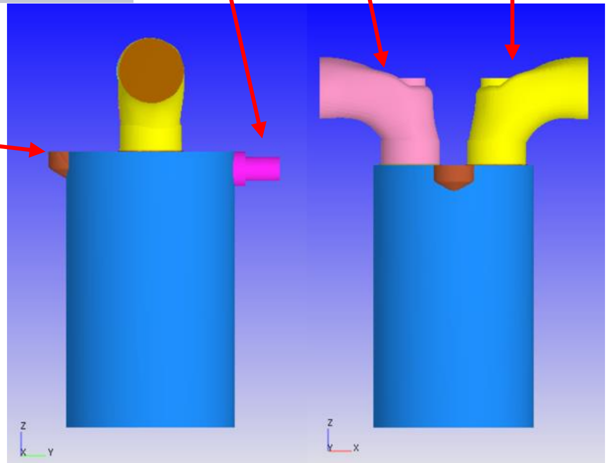
ANL 3D Scanned Model[1] of the CFR Engine

Spark Plug

Intake Port

Exhaust Port

Knockmeter cavity > pressure transducer

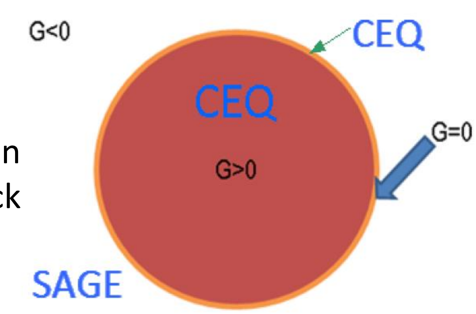


CONVERGE CFD Surface of the CFR Engine

CFD Model using:

- CONVERGE CFD (commercial code)
- RANS RNG k-ε Turbulence Model
- Adaptive Mesh Refinement (AMR)
- Fixed Embedding
- Combustion model: G-Equation + SAGE
  - G-Equation: track flame propagation
  - SAGE: chemical kinetics solver (track autoignition)

Combustion Model[2]



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[1] Pal P. et al. 2018
[2] CONVERGE Theory Manual

Technical Accomplishments and Progress

CFR Engine Modeling

$$s_{l\_ref} = B_m + B_2(\phi - \phi_m)^2$$

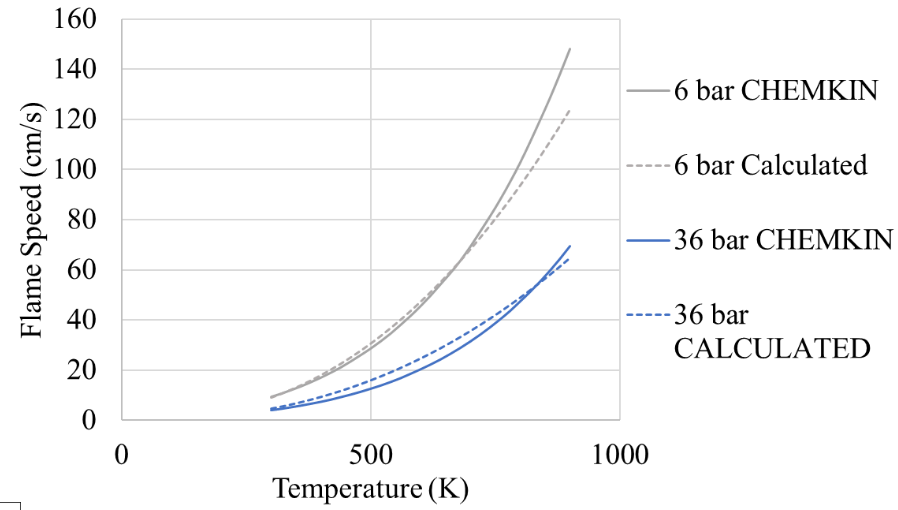
$$s_l = s_{l\_ref}\left(\frac{T_u}{T_{u\_ref}}\right)^{\gamma}\left(\frac{P}{P_{ref}}\right)^{\beta}(1 - 2.1Y_{dil})$$

$$\gamma = a + m(\phi - 1)$$

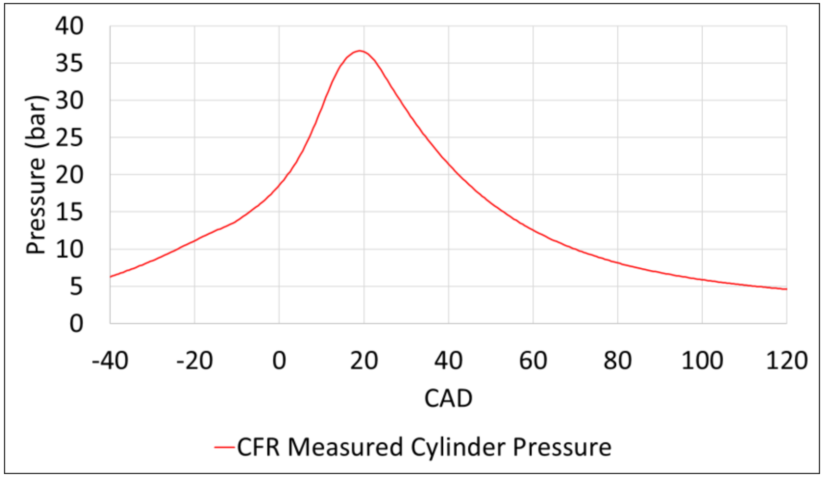
$$\beta = a + m(\phi - 1)$$

*Metghalchi and Keck 1982

Combustion Model Equations for Laminar Flame Speeds



Flame Speeds calculated from implemented combustion model agree with flame speeds calculated using a chemical kinetics solver



Engine conditions at which flame speeds are calculated. Combustion model properly calculates flame speeds at these conditions

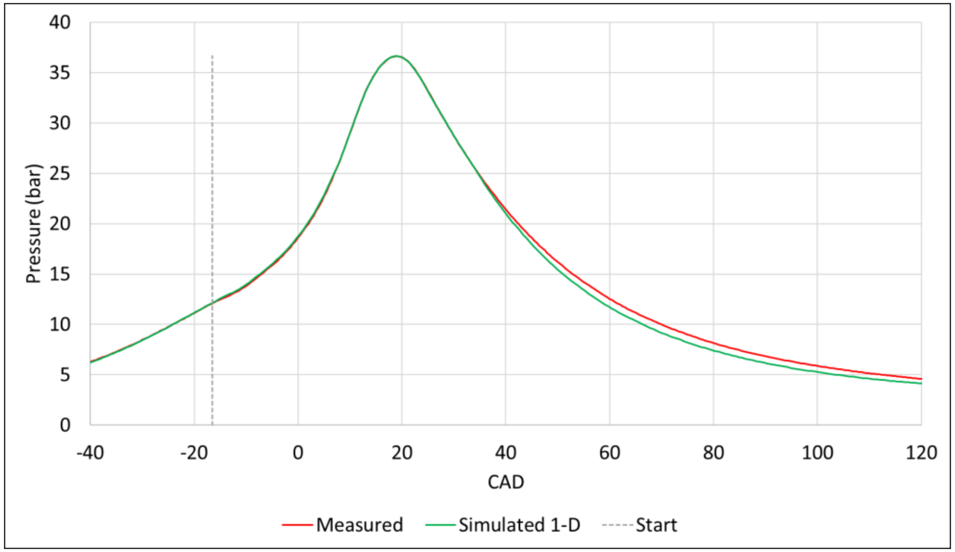
Species	Mol %
CH4	81.9
C2H6	14.28
C3H8	3.485
N2	0.31
MN	**68**

Natural Gas composition used in this work

- Tracks flame speed at engine relevant conditions
- Enable the use of reduced mechanisms to reduce computational cost

Technical Accomplishments and Progress

CFR Engine Modeling

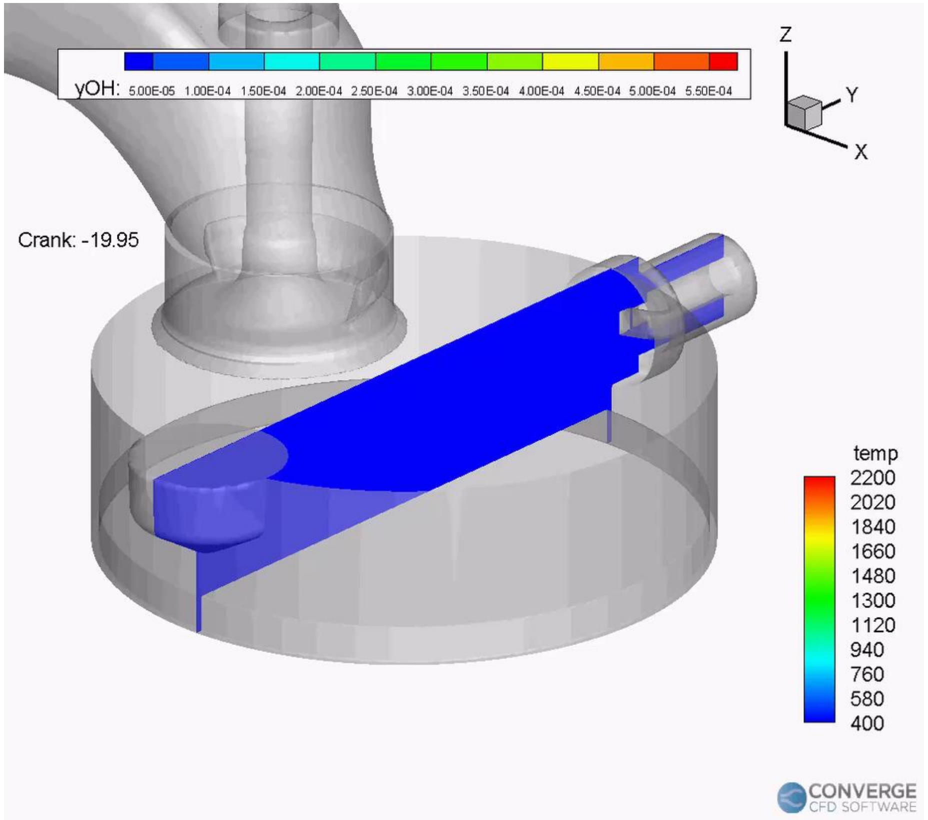


GT-Power TPA Model results closely agree with measured data

GT-Power Performance			
	CFR	**GT-Power**	**Unit**
CA50	10.07	10.50	CAD
gIMEP	8.27	8.13	bar
P_{peak}	39.31	38.70	bar
P_{peak} at	18.83	18.60	CAD
$m_{trapped}$	456.00	468.70	mg/cycle

GT-Power Model Performance results closely predict performance of the CFR Engine

CONVERGE CFD Flame Propagation



CONVERGE CFD Flame Propagation. Enables the study of the influence of engine geometry on turbulence and therefore, engine performance

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Technical Accomplishments and Progress

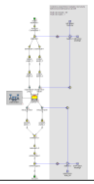
Single Cylinder Engine (SCE) Development

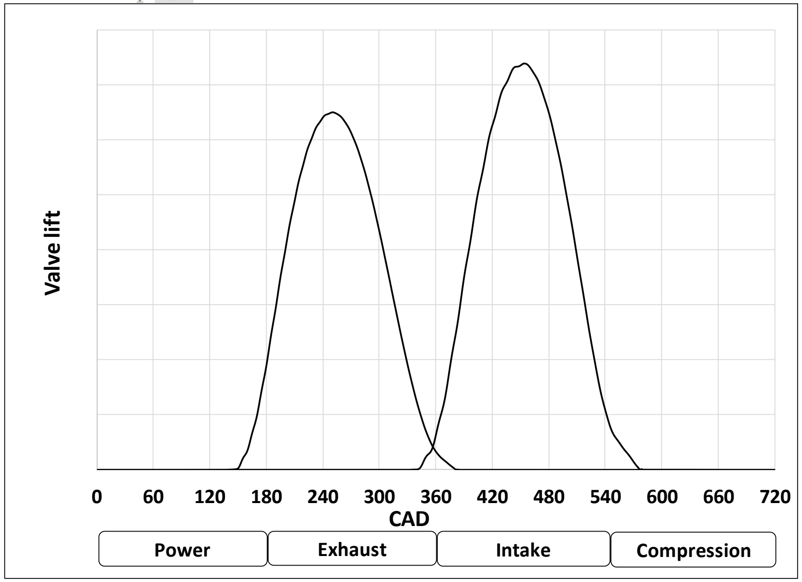
X15 Engine
- Bore x Stroke: 137 x 169 mm
- 2.5 L per cylinder

Parts to remove
- Diesel fuel pump and filter
- Injectors and rails
- ECM
- EGR valve and cooler
- EGR crossover
- Turbocharger

Parts to replace or modify
- Pistons
- #6 cylinder liner
- Camshaft
- Bearings and seals
- Exhaust manifold
- Intake manifold

- GT-Power model is under development
- Simulations utilized to guide design and predict performance





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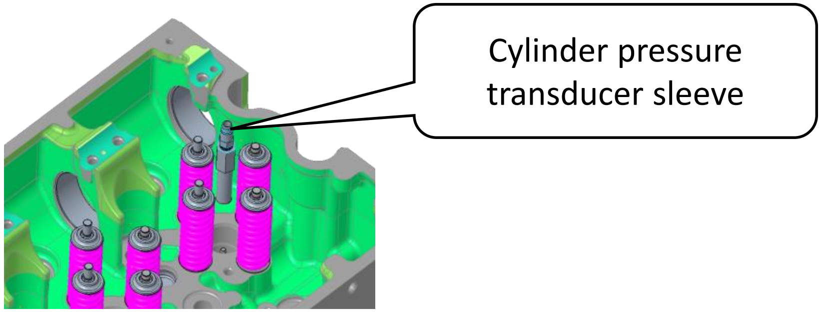
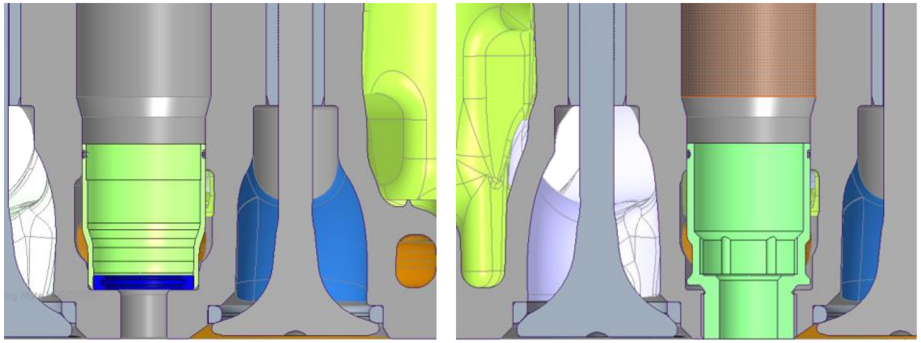
Technical Accomplishments and Progress

Single Cylinder Engine Development

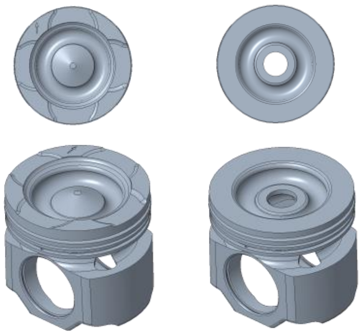
Cylinder pressure transducer (AVL QC34C)



Replace diesel injector with spark plug adaptor



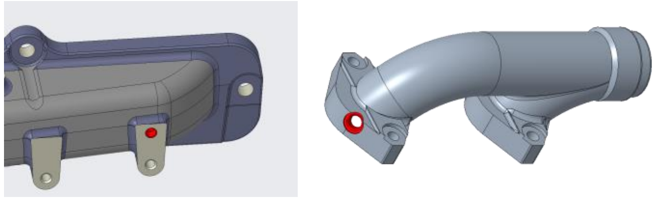
Piston modification



#6

#1-5

IMP and EMP pressure



New camshaft design

Collaboration and Coordination with Other Institutions

Prime Contractor: Colorado State University
PI: Daniel Olsen
Co-PIs: Anthony Marchese, Bret Windom
Students: Jeffrey Mohr, Andrew Zdanowicz, Diego Bestel, Scott Bayliff, Jack MacDonald

Sub-contractor: Cummins Inc.
PI: Hui Xu
Key Contributor: Robin Bremmer

Sub-contractor: Woodward, Inc.
PI: Greg Hampson
Key Contributors: Suraj Nair, Domenico Chiera

- Cummins team responsibilities:
  - Support RCM, CFR, and SCE experiments and modelling technical discussions
  - Build and deliver the SCE, support SCE installation, testing and modelling
- Woodward team responsibilities:
  - Technical guidance for 1-D simulation and CFD modeling and related testing
  - Program, install, and commission Large Engine Control Module (LECM) on CFR and SCE engines

Remaining Challenges and Barriers

Challenges

- Matching of CFR data with CFD, so CFD can be utilized for combustion chamber design for SCE
- Demonstration of controlled EGAI with high compression ratio and high EGR using the Woodward LECM
- Test cell setup for high EGR, advanced controls, and variable fuel composition
- Final fabrication of SCE and commissioning in test cell

Barriers

- No barriers identified at this time

Proposed Future Research

Budget Period 2 (2019-20)

- Complete CFD model validation with CFR and RCM data
- Apply CFD to SCE for combustion chamber design
- Install and commission 2.5 liter SCE at CSU
- Demonstrate baseline NG efficiency of 39% (Go/No-go)

Budget Period 3 (2020-21)

- Complete SCE mapping
- Final programming of LECM algorithm for real-time control
- Selection of final engine configuration and operating parameters
- Demonstration of diesel-like efficiency of 44% on SCE

Any proposed future work is subject to change based on funding levels.

Summary Slide

Approach

- Reduced chemical kinetic mechanism development in support of CFD modeling utilizing CFR engine and RCM
- Develop 2.5 liter SCE configuration: stoichiometric SI, turbocharged, high levels of cooled EGR, combustion chamber design for high burn rate, prechamber spark plugs, advanced engine controls

Technical Accomplishments and Progress

- Production of CFR engine and RCM experimental data for model development
- Development and demonstration of EGR cart on CFR engine
- Development of reduced kinetic mechanism (~50 species)

Next Steps

- Finalize model validation with CFR engine data
- Perform modeling in support of SCE combustion chamber design
- Install and commission SCE at CSU
- Collect baseline performance data