Development of Advanced Combustion Strategies for Direct Injection Heavy Duty LPG Engines to Achieve Near-Diesel Engine Efficiency

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Project ID: ACE178

DOE Vehicle Technologies Office Virtual Annual Merit Review (AMR)

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Colorado State University

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Project Overview

Timeline

Project Start Date: 10/1/2020

Project End Date: 12/31/2023

Percent Completion: 46%

Budget

Total Project Cost: $3,670,092

Federal = $3,100,085

Cost Share = $570,007

Budget Period 1 Federal: $1,535,947

Budget Period 2 Federal: $720,176

Budget Period 3 Federal: $843,962

Barriers

- Development of reduced chemical kinetic mechanism for LPG combustion CFD simulation
- Accurate modeling of 2-phase LPG flow for high pressure direct injection
- Stable control of LPG combustion near knock limit – Controlled End-Gas Auto-Ignition (C-EGAI)

Partners

Project Lead:	Colorado State University
Contractual Partners:	Cummins Inc.
	Argonne National Laboratory
Critical Vendors:	Czero Inc.
	Woodward, Inc.

Relevance

- The main project goal is to increase the peak torque efficiency of a 15 liter LPG engine to near-Diesel efficiency (44%)

Key Project Objectives

1. Characterize flame propagation and end-gas autoignition (EGAI) phenomena for LPG/air/EGR mixtures.
2. Develop LPG direct injection (DI) strategies in parallel with a detailed LPG DI spray model.
3. Validate, refine, and utilize tools (CHEMKIN, CONVERGE, GT-Power) for closed cycle engine combustion design.
4. Develop advanced real-time control algorithms for the Cummins X15 single cylinder engine (SCE).

VTO Goals: Advanced Combustion Engines

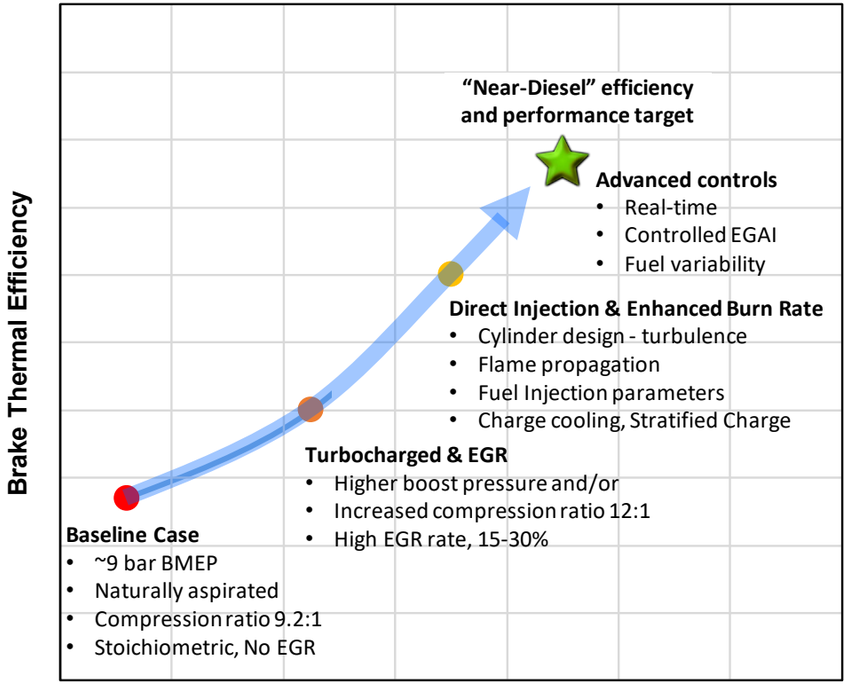
- Early-stage research to enable industry to accelerate fuel diversification through:
  - improved understanding and ability to manipulate combustion processes and,
  - generating the knowledge and insight necessary for industry to develop the next generation of engines for light-and heavy-duty vehicles.

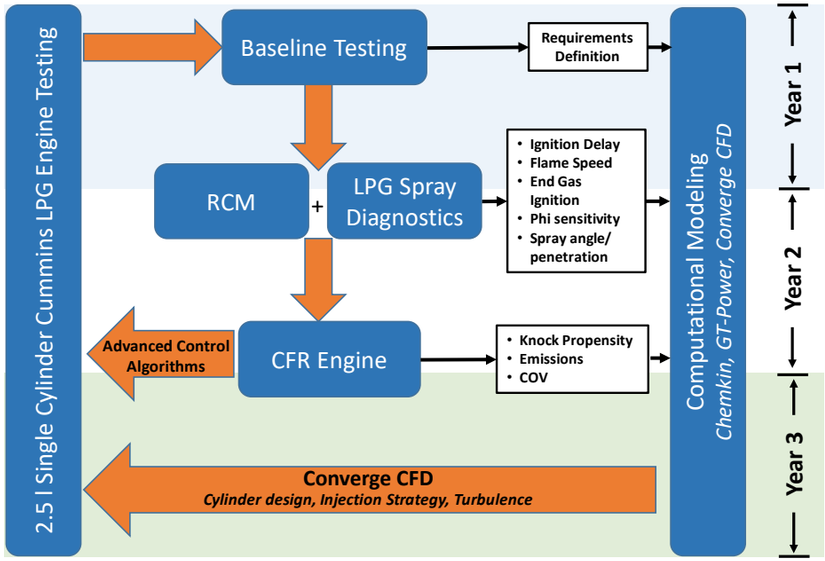
LPG ≡ Liquefied Petroleum Gas

Approach

Project Tasks, Milestones, and Go/No-Go Decisions	Budget Period 1					Budget Period 2				Budget Period 3			
	2020	2021				2022				2023			
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1. Chemical Kinetic Model			M1.1		**GN1**	M2.1							
2. Liquefied Petroleum Gas (LPG) Fuel Injection System			M1.2										
3. Fuel Injection Visualization in High Pressure Spray Chamber (HPSC)							M2.2						
4. Development of Fuel Injection Spray Model				M1.4									
5. Design of Advanced Combustion Strategy				M1.3				M2.3		M3.1	M3.2		
6. LPG Hardware Integration on X15 Cummins Single Cylinder Engine (SCE)							M2.4		**GN2**				
7. System Optimization for Near-Diesel Efficiency on X15 SCE												M3.2	M3.3

- Complete - Ongoing - To Be Completed

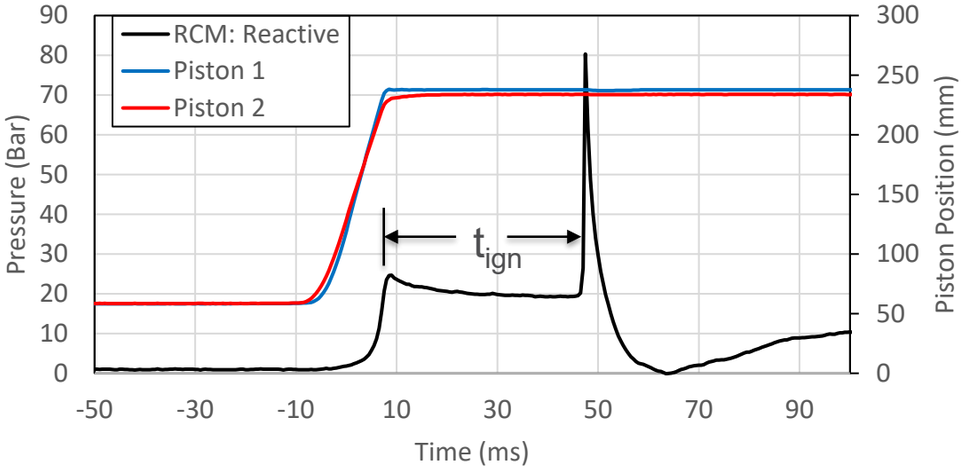


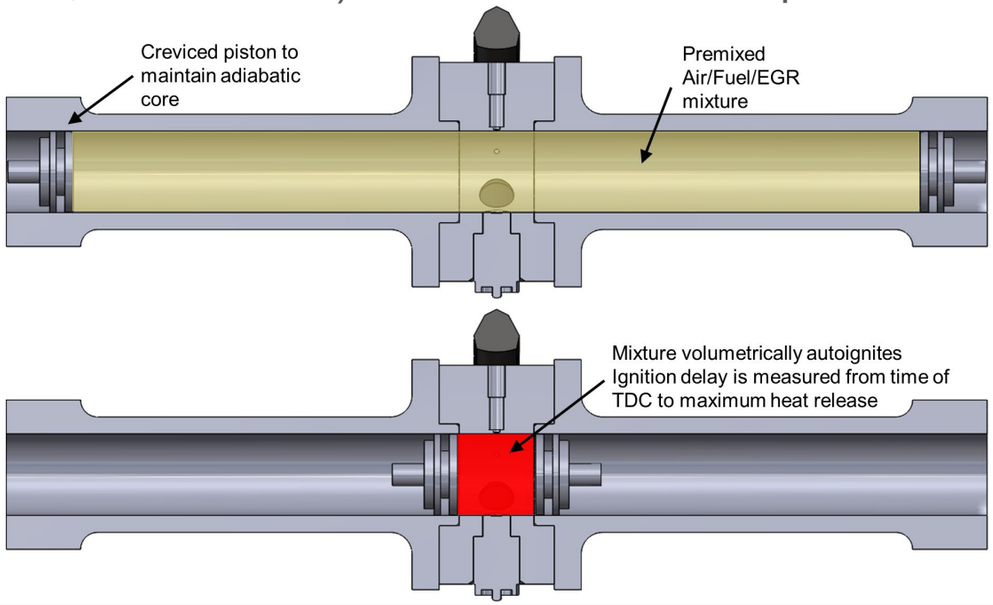


Technical Accomplishments and Progress

Chemical Kinetic Model

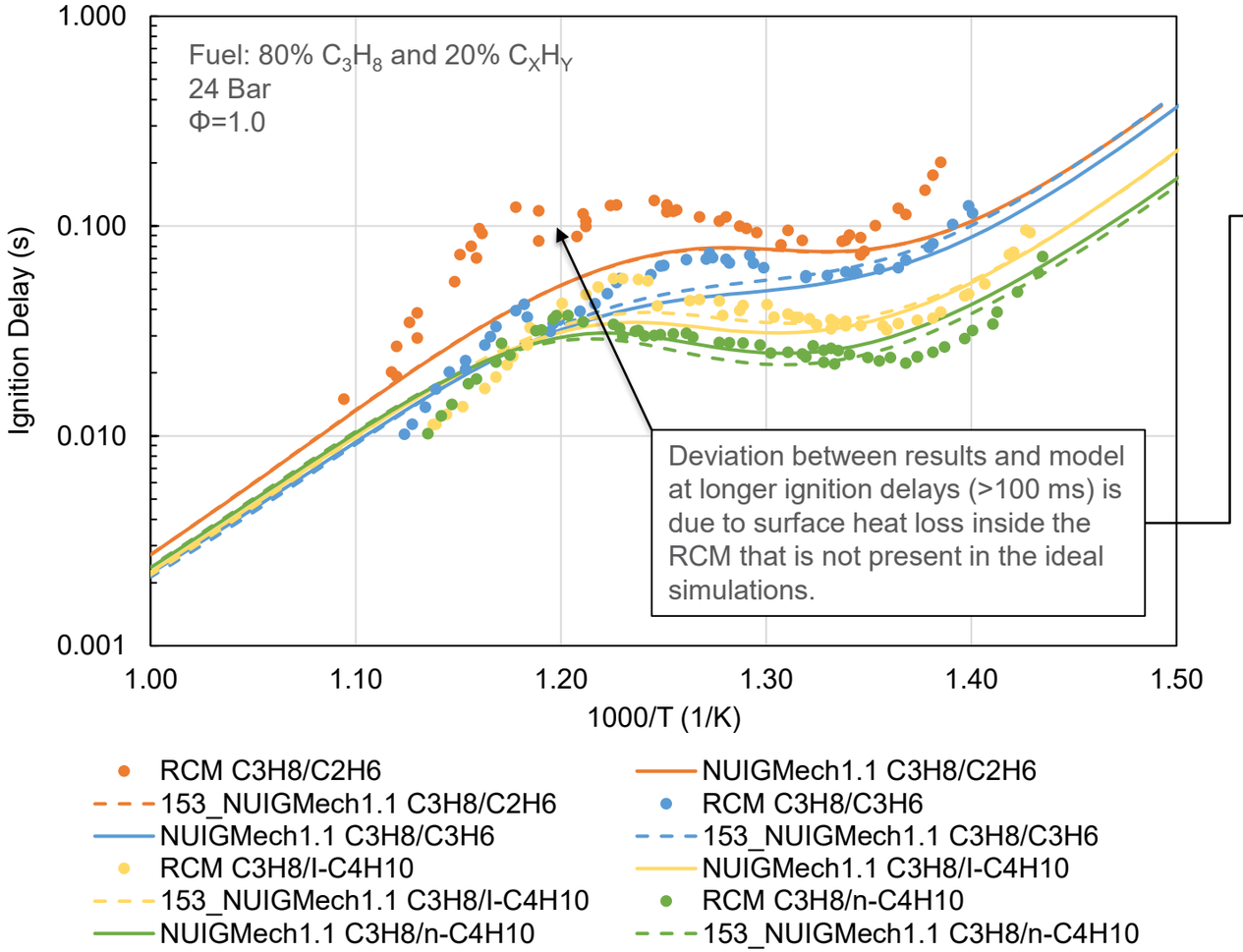
- The rapid compression machine (RCM) can operate in compression ignition or laser spark mode.
- Pressure data inside the RCM is recorded.
- Ignition delay is measured from piston TDC until maximum pressure rise during combustion.
- High speed Schlieren imaging (50,000 fps) is used to record the flame propagation when using laser ignition.
- Models using a reduced (153 species; 1,227 reactions) chemical kinetic mechanism derived from NUIGMech1.1 (2,746 species; 11,279 reactions) were validated with experimental results.

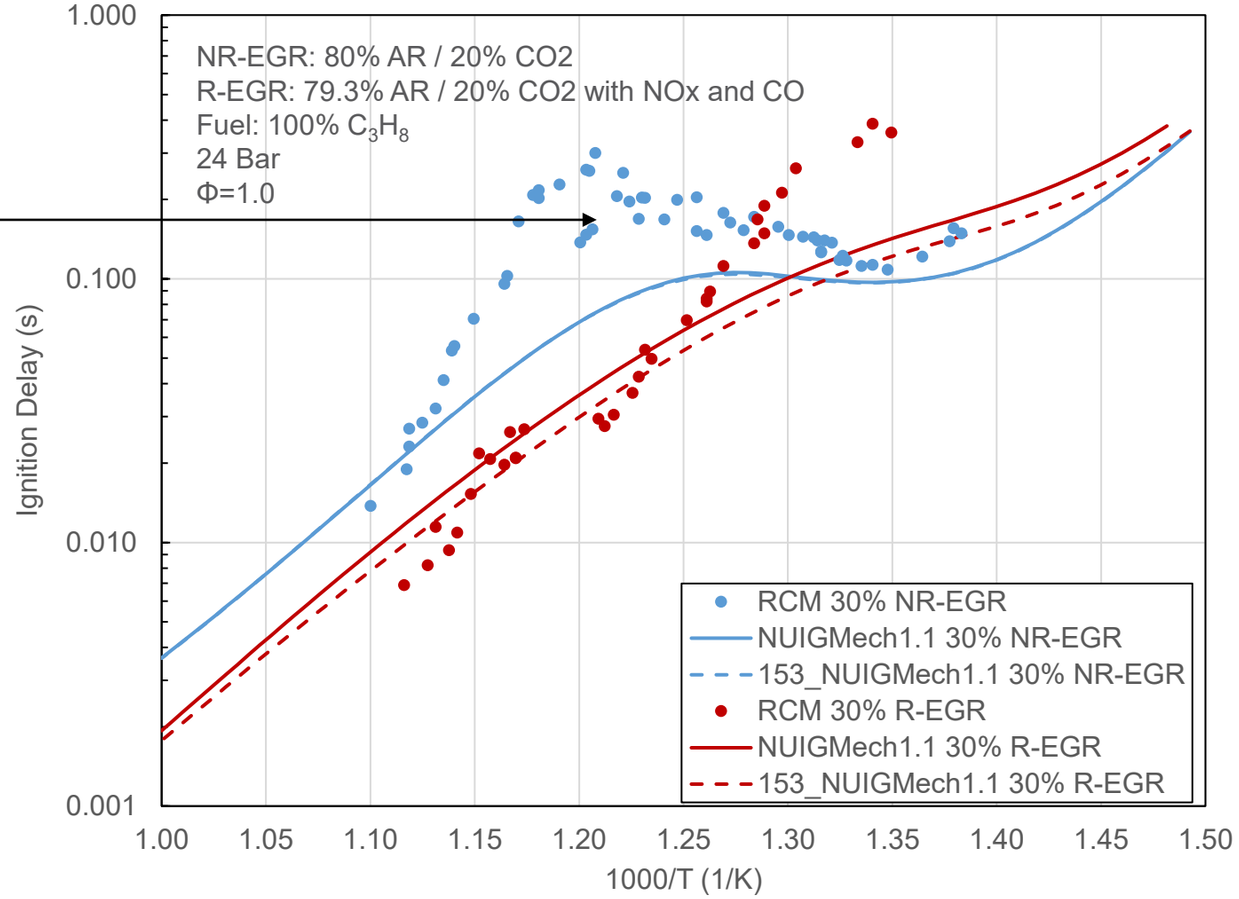




Technical Accomplishments and Progress

Chemical Kinetic Model

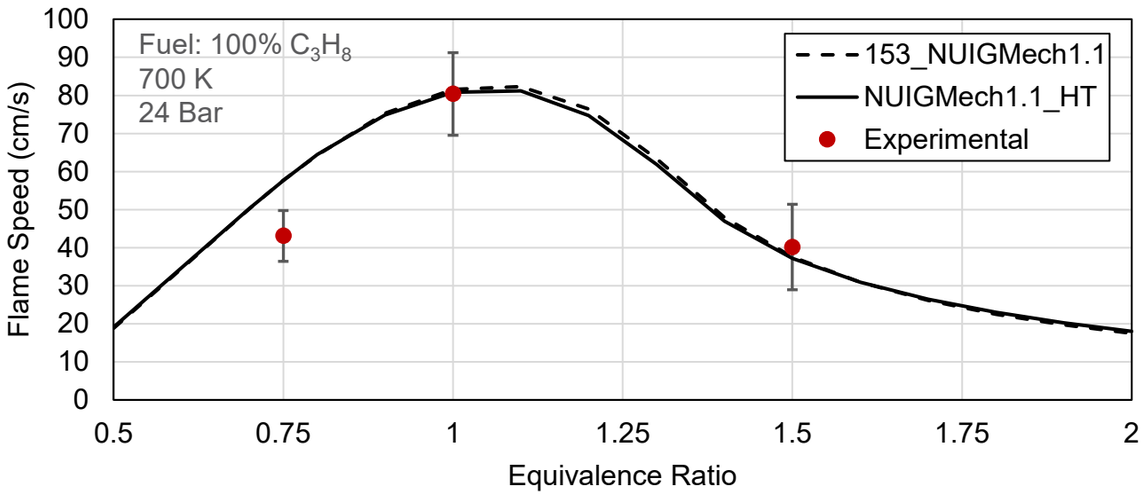


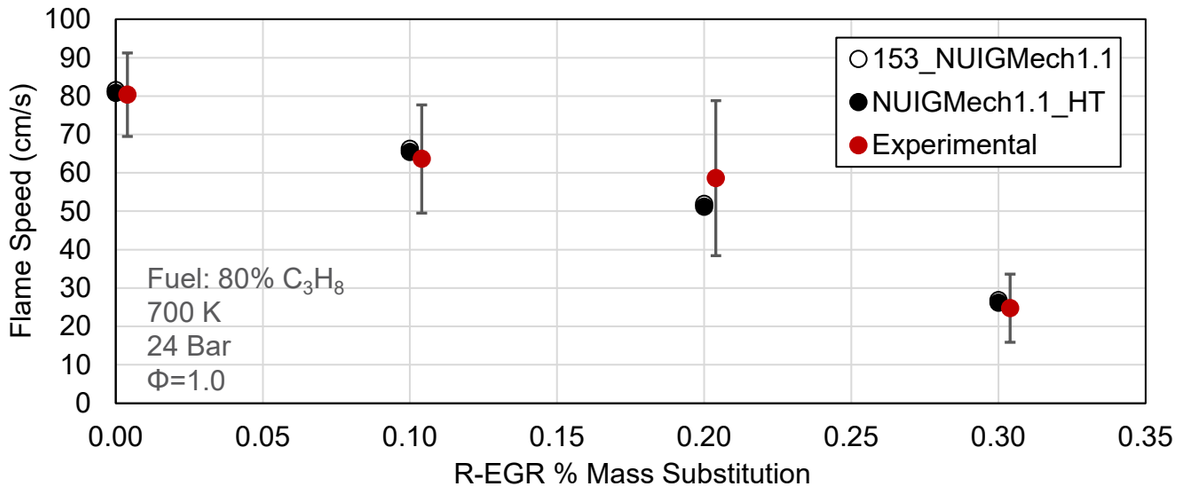


Experimental RCM ignition delay measurements (symbols) and simulated constant volume homogeneous autoignition delay of binary fuel/inert/O_2 (left) and C_3H_8/inert/O2/EGR (right) using NUIGMech1.1 (solid lines) and 153_NUIGMech1.1 (dashed lines).

Technical Accomplishments and Progress

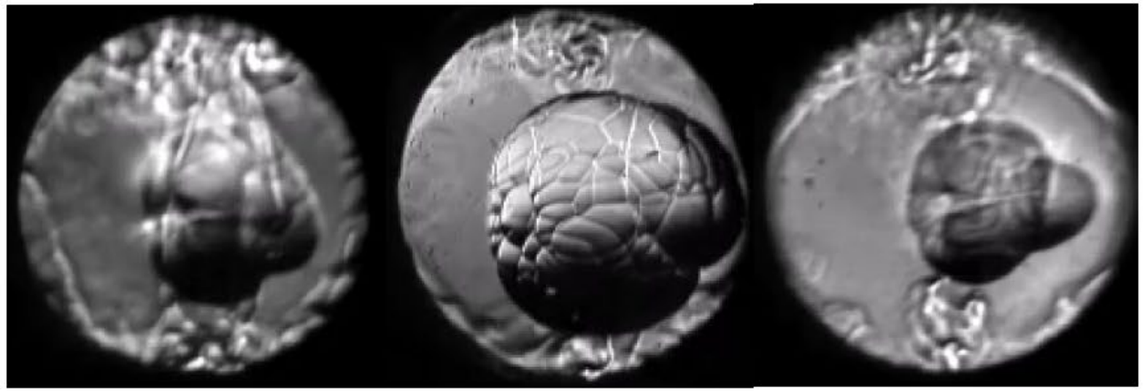
Chemical Kinetic Model





Experimental zero stretch flame speeds (symbols) and simulated 1-D laminar flame speeds using NUIGMech1.1_HT and 153_NUIGMech1.1 for varying equivalence ratio (left) and R-EGR mass substitution (right). Error bars represent standard deviations.

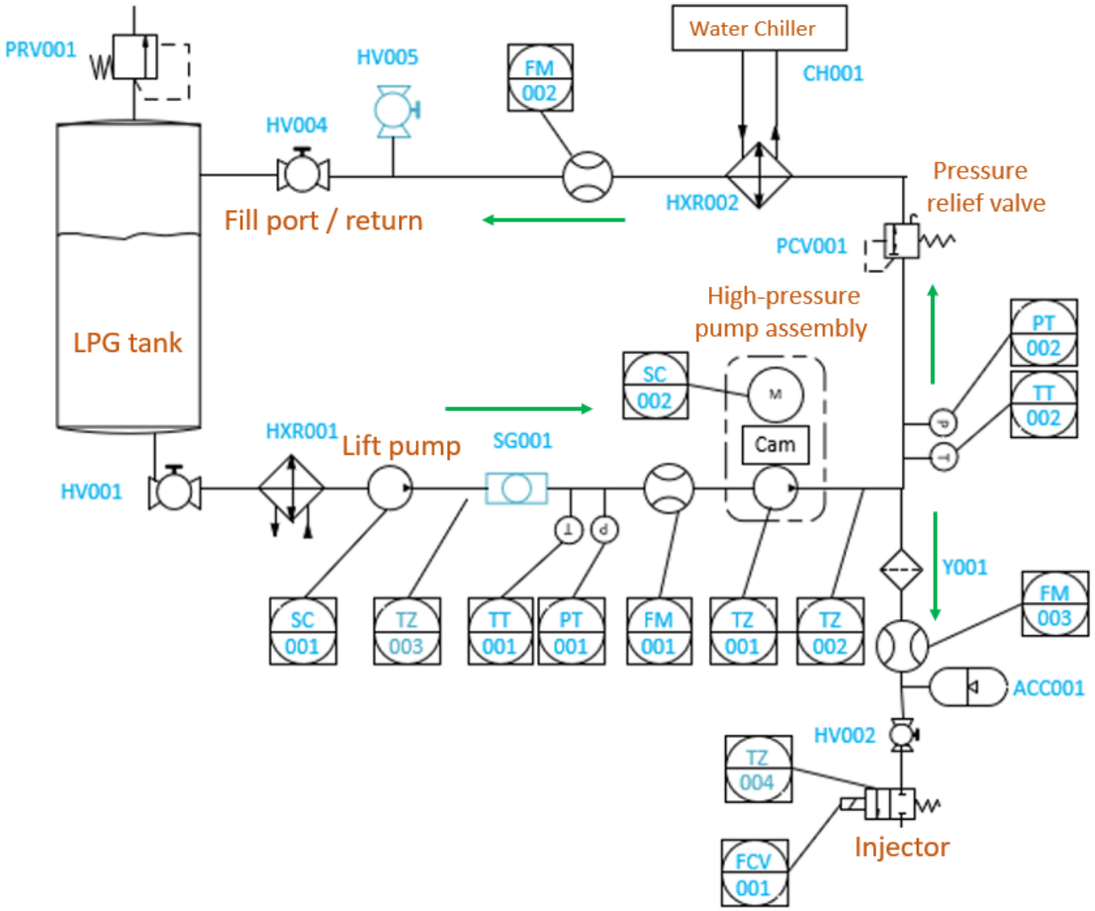
Phi=0.75 Phi=1.0 Phi=1.5



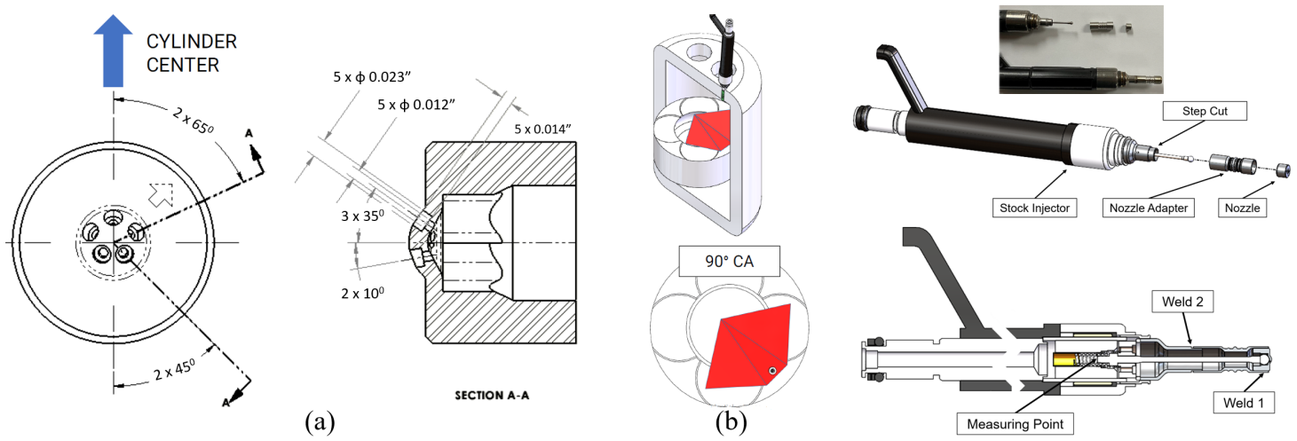
10% R-EGR 20% R-EGR 30% R-EGR

Technical Accomplishments and Progress

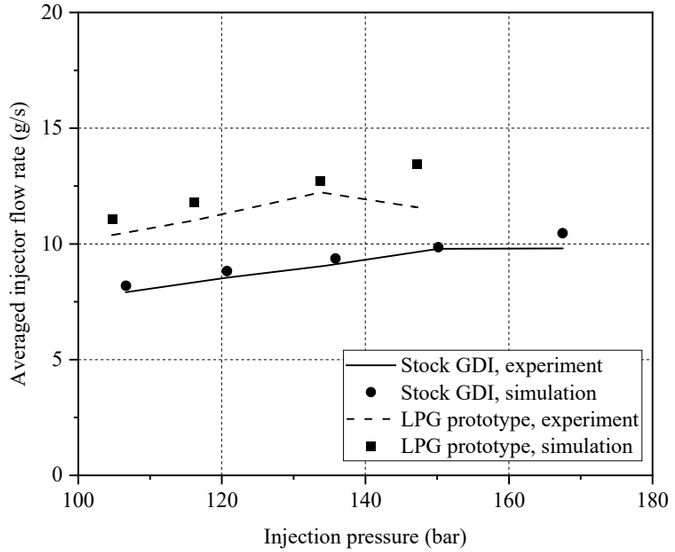
LPG Fuel Injection System



- Designed and developed liquid LPG direct injection fuel delivery system



- New 5-hole LPG prototype injectors developed and tested



- LPG prototype injector achieved higher flow rate than the stock injector

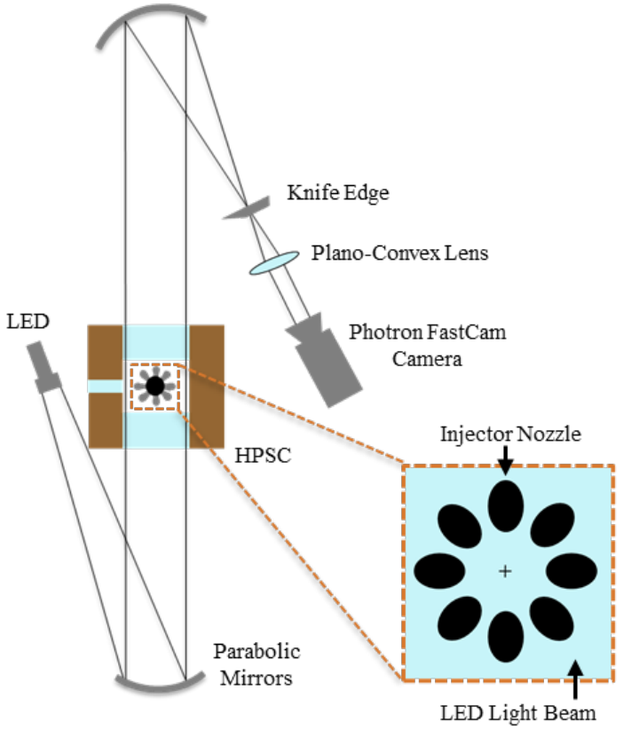
Technical Accomplishments and Progress

Fuel Injection Visualization in HPSC

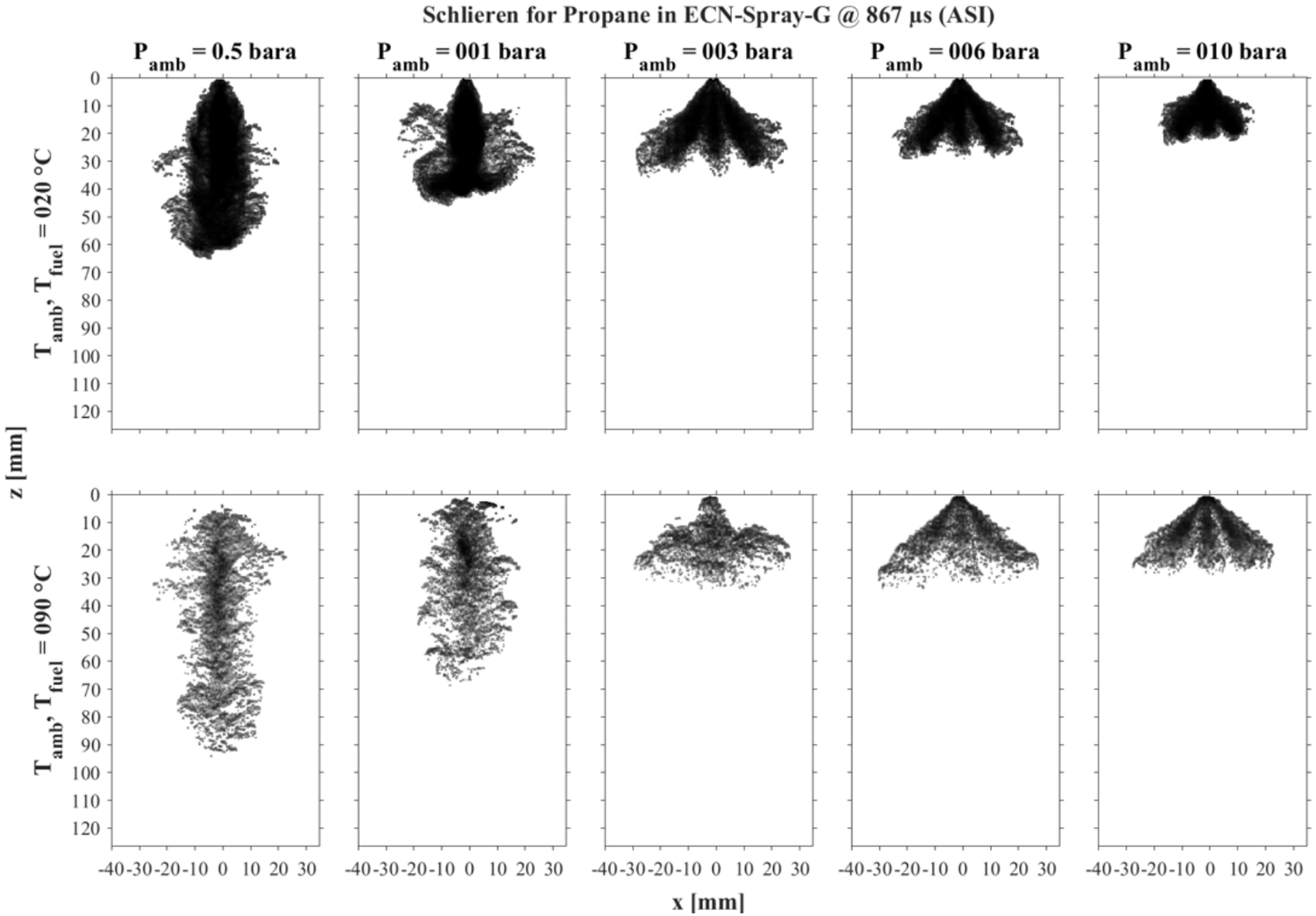
High-Speed Schlieren Setup

Real time - Line of sight, high-speed imaging technique used to visualize the density gradients in the spray.

Measurements: Global Spray Characteristics: Vapor Penetration Length, Width, and Speed.



Spray development sensitive to fuel temperature and chamber pressure



ASI = After Start of Injection ECN = Engine Combustion Network HPSC = High Pressure Spray Chamber

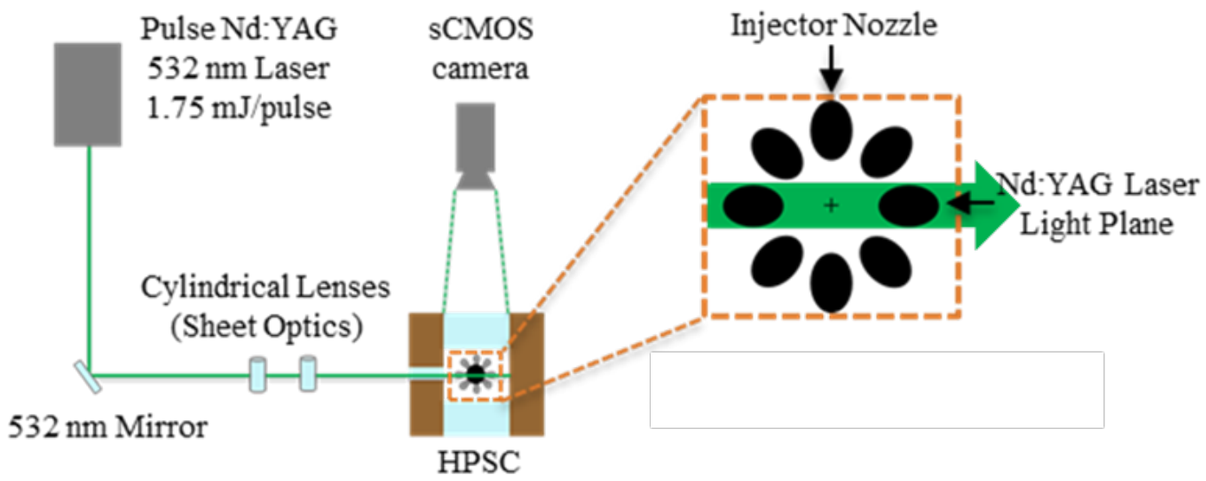
Technical Accomplishments and Progress

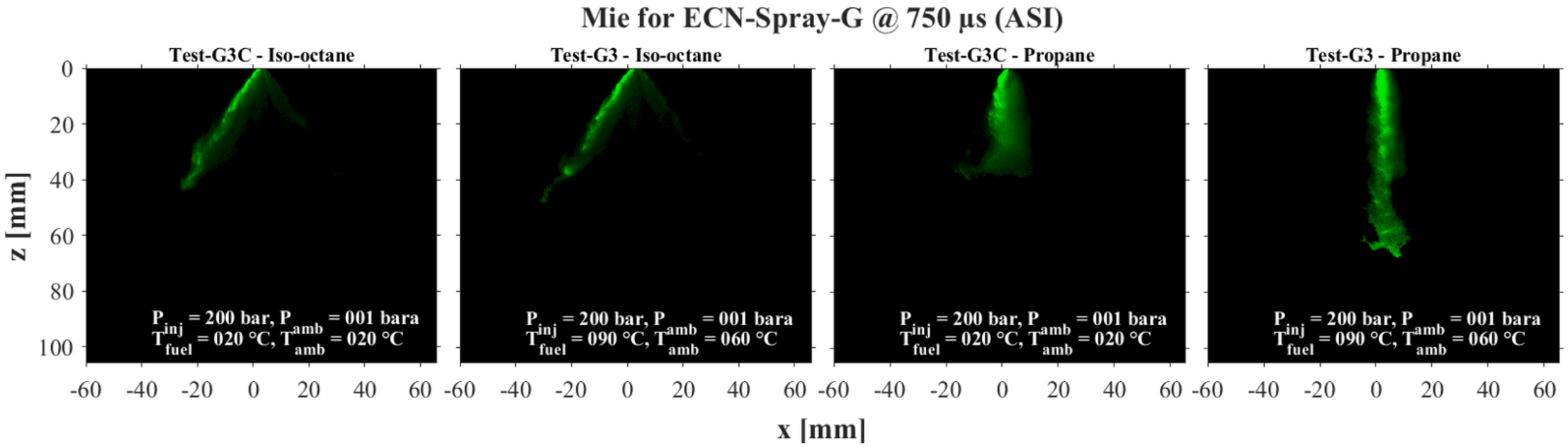
Fuel Injection Visualization in HPSC

Planar Mie Scattering Setup

Elastic light scattering technique used to measure liquid penetration through a medium in a plane

Measurements: Liquid Penetration Length, Jet Width, Angle, Speed

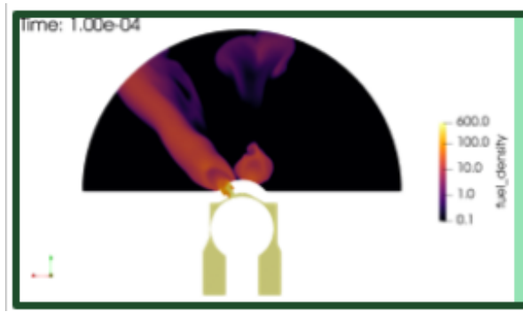




Propane spray development sensitive to fuel temperature

Technical Accomplishments and Progress

LPG Injection and Spray Modeling: Unconventional and vaporizing LPG spray dynamics



High-Fidelity internal nozzle-flow simulations to capture propane under-expanded jet characteristics

- Flash-boiling vaporization is incorporated in the spray phase-change
- Modeling of *catastrophic* breakup regime

Near-Nozzle Spray

- Orifice-specific mass flow rate
- Initial jet dynamics

Far-Field Spray

- Optimized phase-change modeling
- Gas-cooling and fuel mixture distribution

Baseline
Lagrangian-Eulerian Spray Modeling for GDI

Model development

Result
LPG injection and spray model in HPSC

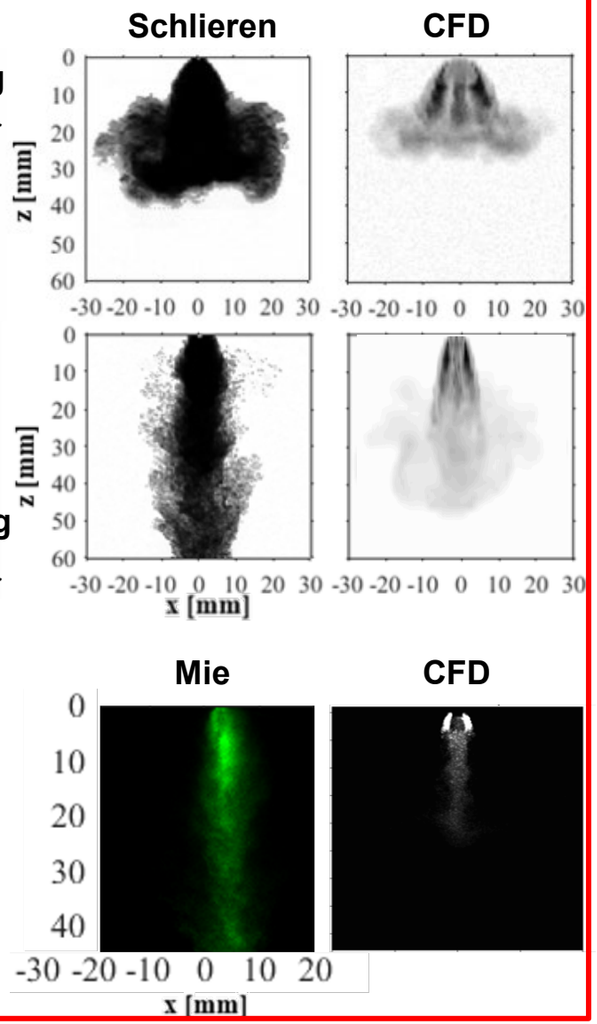
Validated Lagrangian Spray model against HPSC spray data

Mild-Flashing

P_{inj}= 200 bar
T_{fuel}= 293 K
P_{amb}= 1 bar
T_{amb}= 293 K

Flare-Flashing

P_{inj}= 200 bar
T_{fuel}= 363 K
P_{amb}= 1 bar
T_{amb}= 333 K



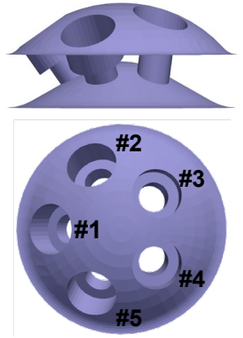
Modeling of LPG Direct Injection for Realistic Engine Applications

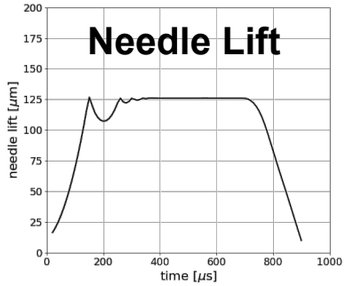
- High-fidelity nozzle-flow simulations are leveraged to inform the spray model
- Lagrangian-Eulerian spray model is compatible with reacting combustion simulations
- Validation range to cover the full range of injection timing and operating conditions

Technical Accomplishments and Progress

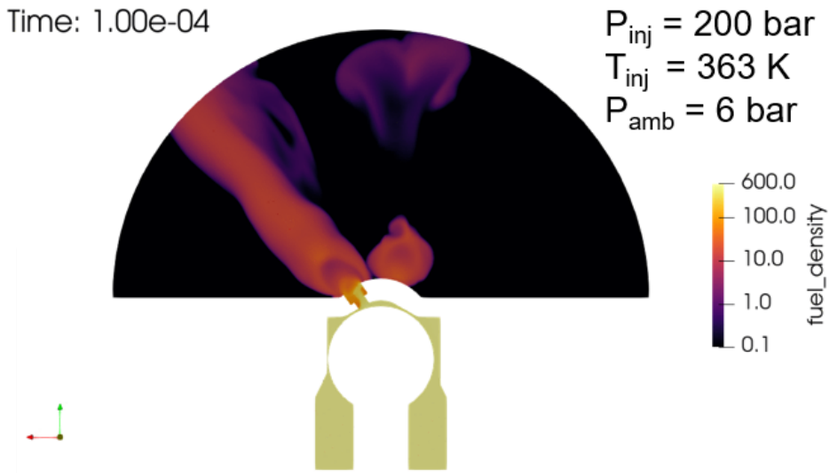
Modeling of new prototype 5-hole counter-bored injector

Injector head

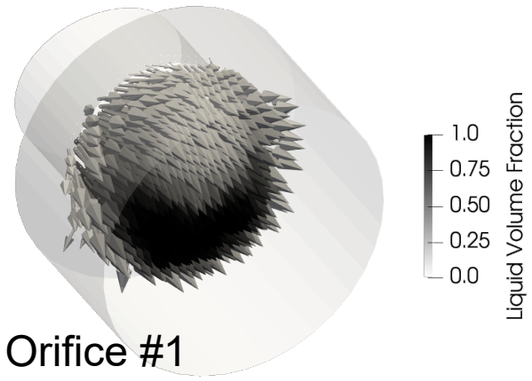




High-fidelity Nozzle-flow simulation of full injection event

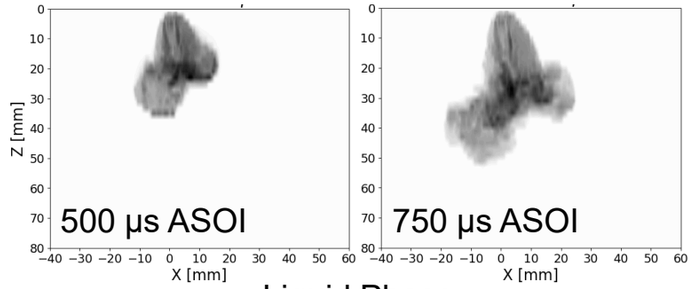


Static Coupling between Nozzle flow and Lagrangian spray

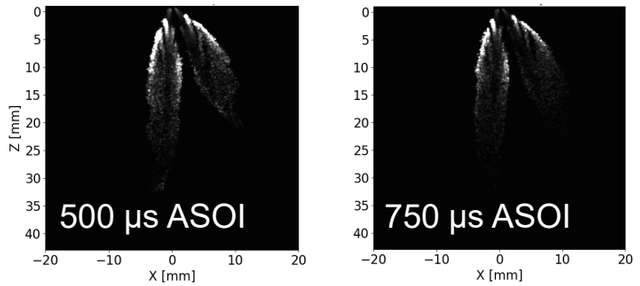


Lagrangian Spray in HPSC

Spray Morphology



Liquid Phase



P_{inj}=200 bar, T_{fuel}=293 K
P_{amb} = 1 bar, T_{amb} = 293 K

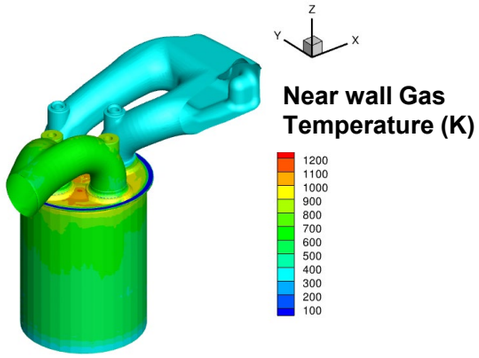
- Fully-coupled simulation of propane jets for engine design purposes
  - Characterization of a new injector behavior + optimized submodel setup definition
  - Spatially- and temporally- resolved initialization of the spray dynamics for flashing sprays
  - Accurate and cost-efficient approach. Compatible with engine combustion modeling

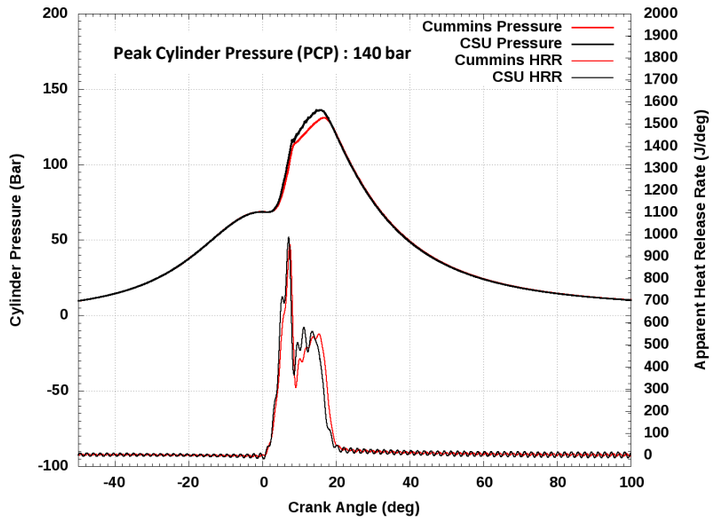
Technical Accomplishments and Progress

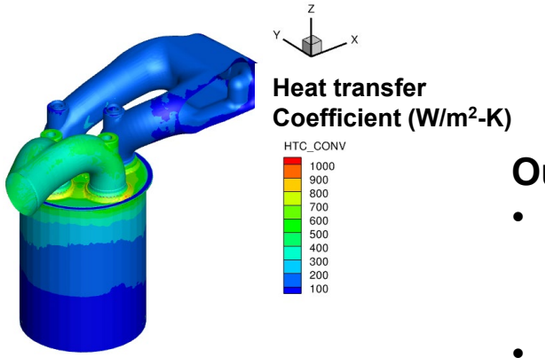
CFD and Structural Analysis

Cylinder Head Status: Design completed, and machining is expected to finish by April 2022.

CFD analysis : Natural Gas (NG) peak load condition was selected to generate the hot boundary conditions for thermal analysis



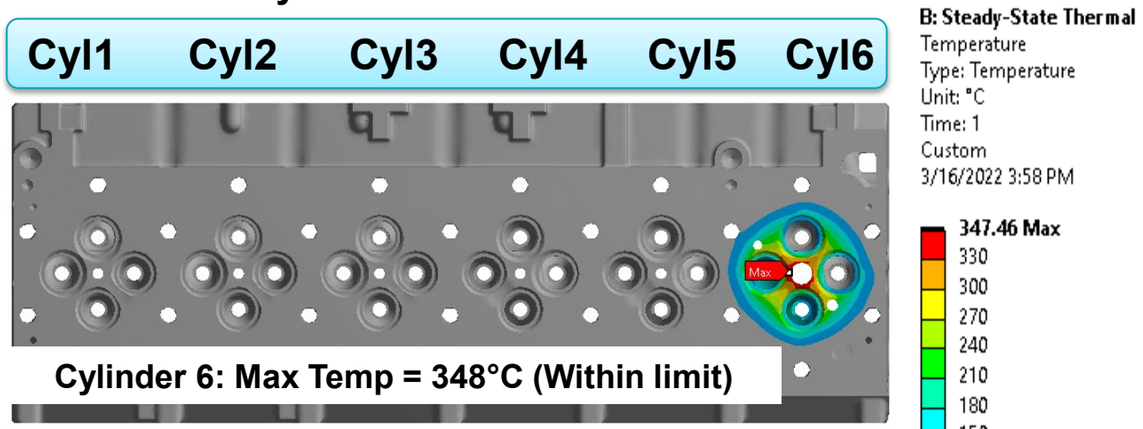




Outcome :

- Predicted the wall heat transfer on combustion faces of X15 at highest thermal conditions.
- CFD combustion data was provided as a boundary conditions for structural analysis.

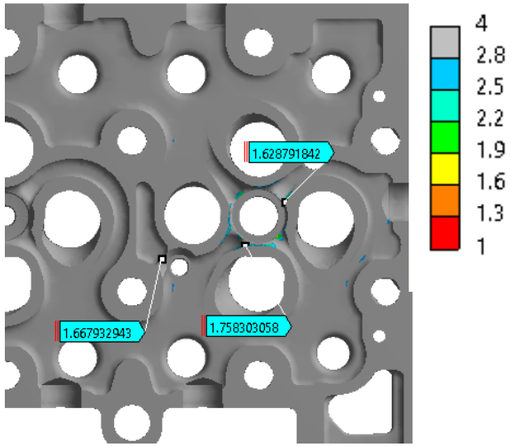
Structural analysis:



Cylinder 6: Max Temp = 348°C (Within limit)

Cyl. 6 ANSYS model :

- Combustion heat input was only applied for Cyl. 6 (combustion face, liner, exhaust and intake faces)
- Stoichiometric NG, 1200 RPM, 18 bar GIMEP



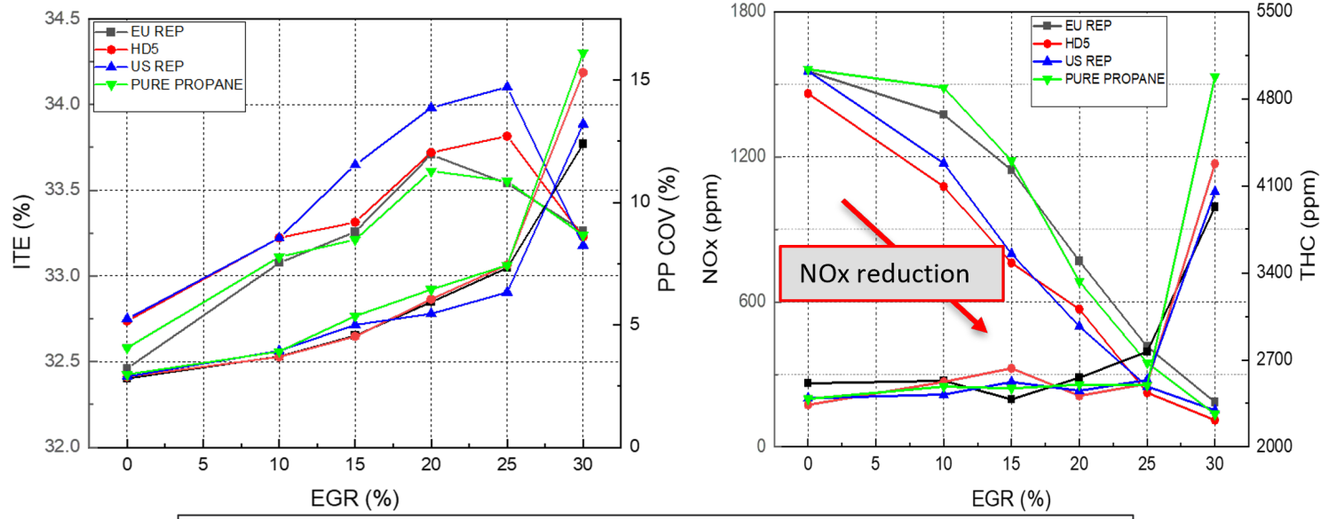
Factor of Strength (FOS)
Durability : 400 hours

Conclusions :

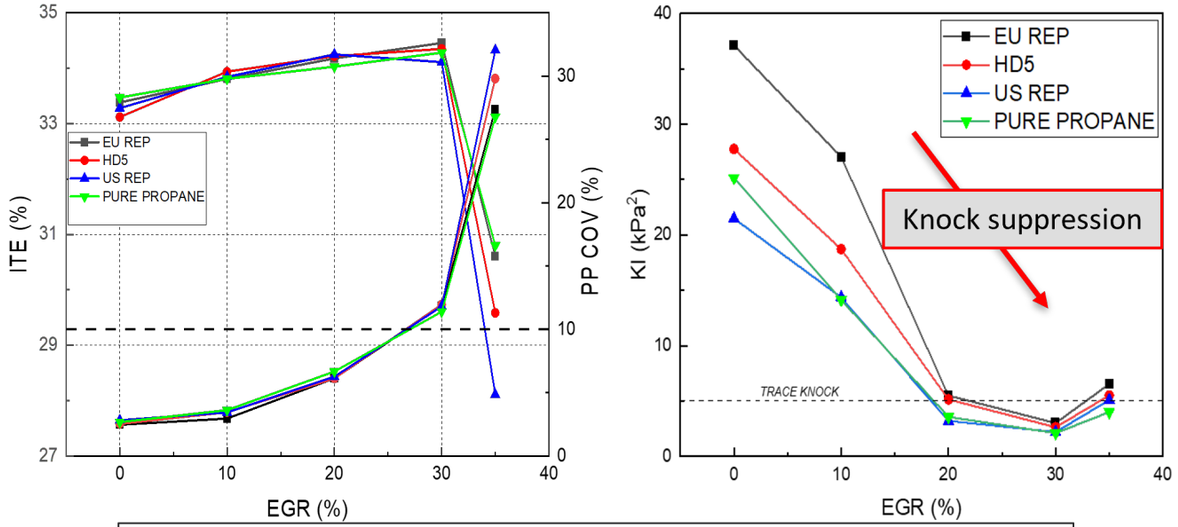
- The predicted temperature and FOS values show that the modified cylinder head is at a low risk of failure.
- The current analysis is done for natural gas inputs and is expected to be conservative. The temperatures (and stresses) will presumably be lower for propane inputs.

Technical Accomplishments and Progress

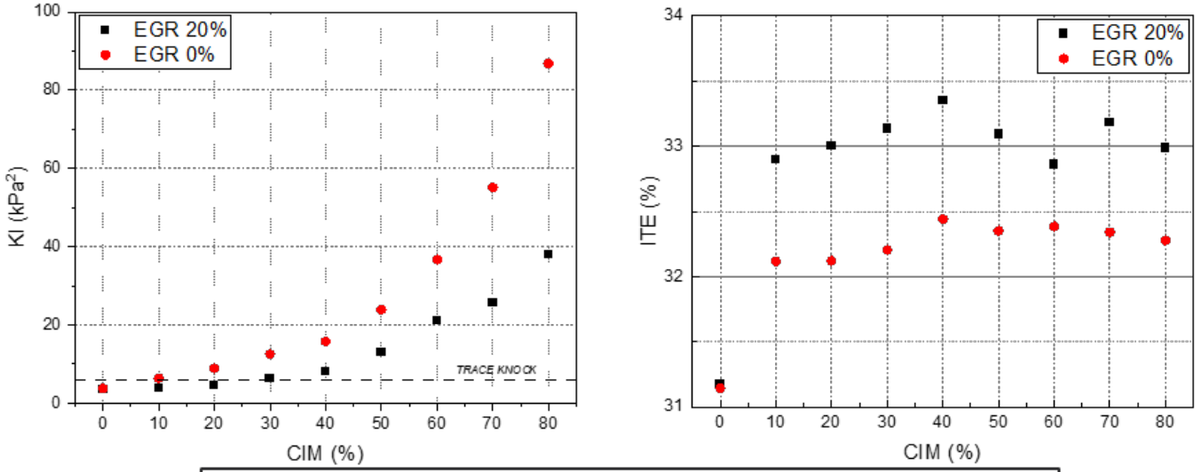
CFR Engine Testing



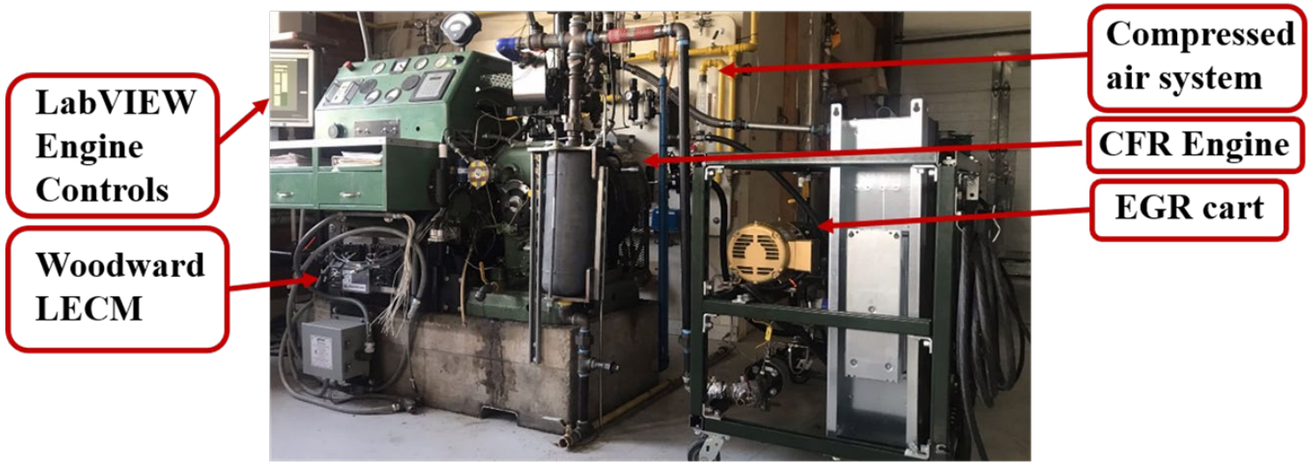
CR: 8:1, CA50: 9^0 ATDC, IMEP: 800kPa, Φ: 1, Speed: 900rpm



CR: 9:1, CA50: 9^0 ATDC, IMEP: 800kPa, Φ: 1, Speed: 900rpm

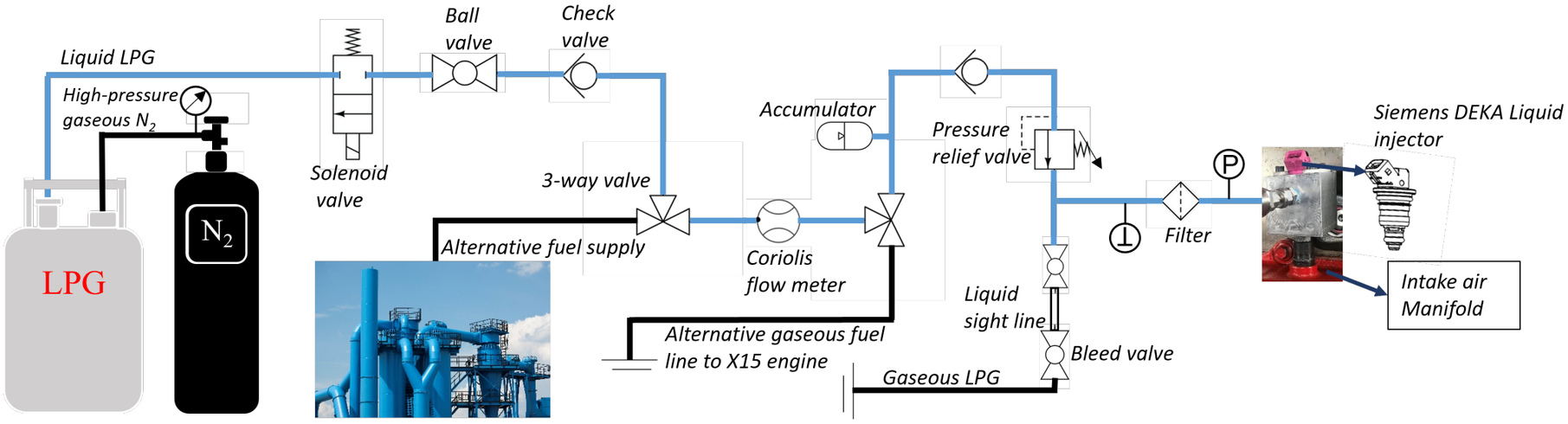


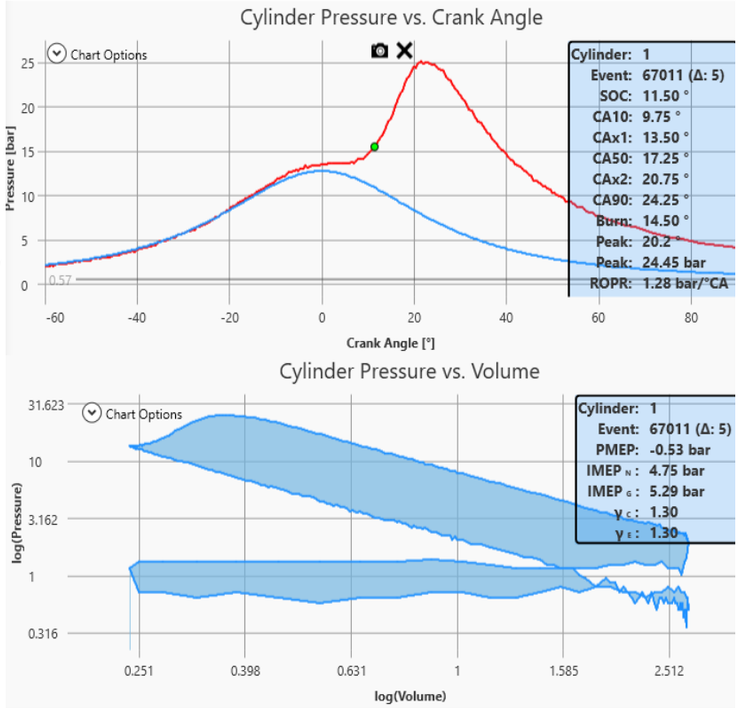
CR 8:1, ST: CIM, IMEP: 1000kPa, Speed: 900rpm, φ: 1

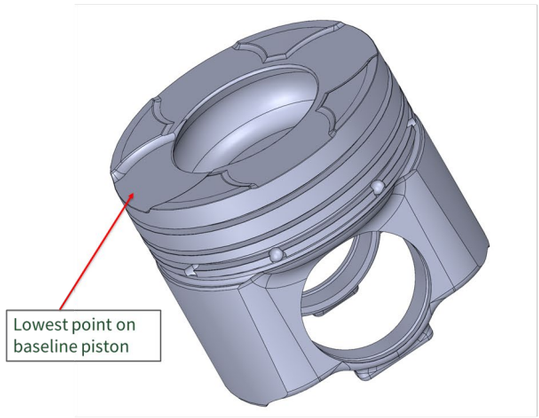


Technical Accomplishments and Progress

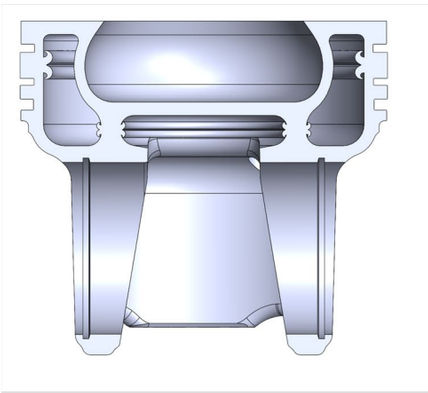
Initial LPG Port Fuel Injection (PFI) Testing on X15 SCE



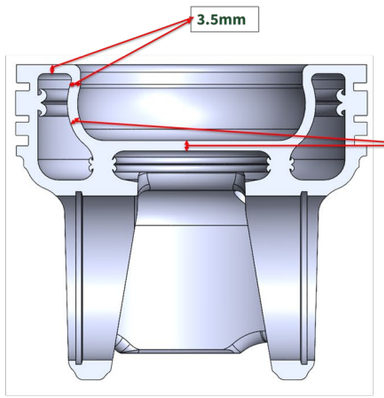




11.5:1 CR Piston



Section: Piston cut at lowest point



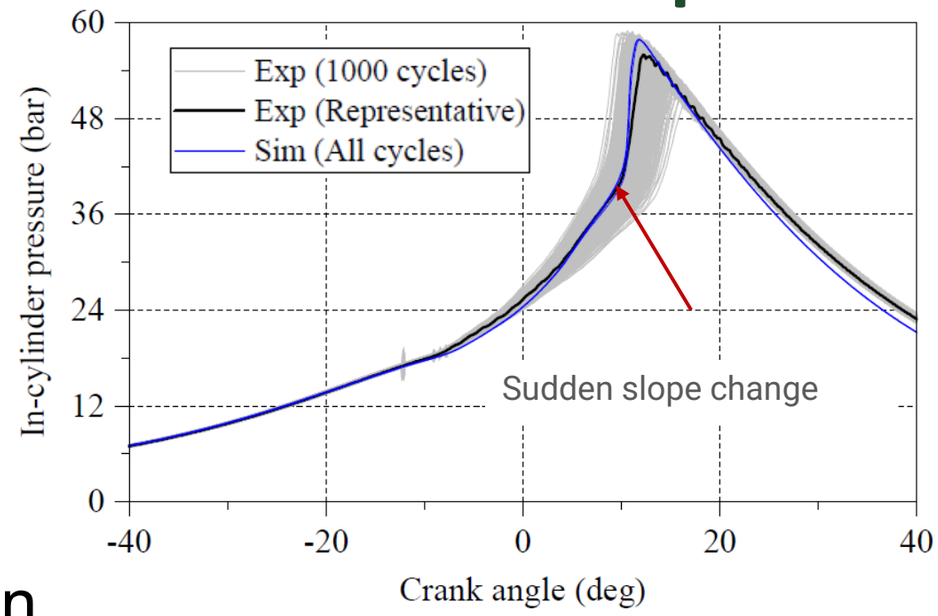
9.3:1 CR LPG Baseline Piston

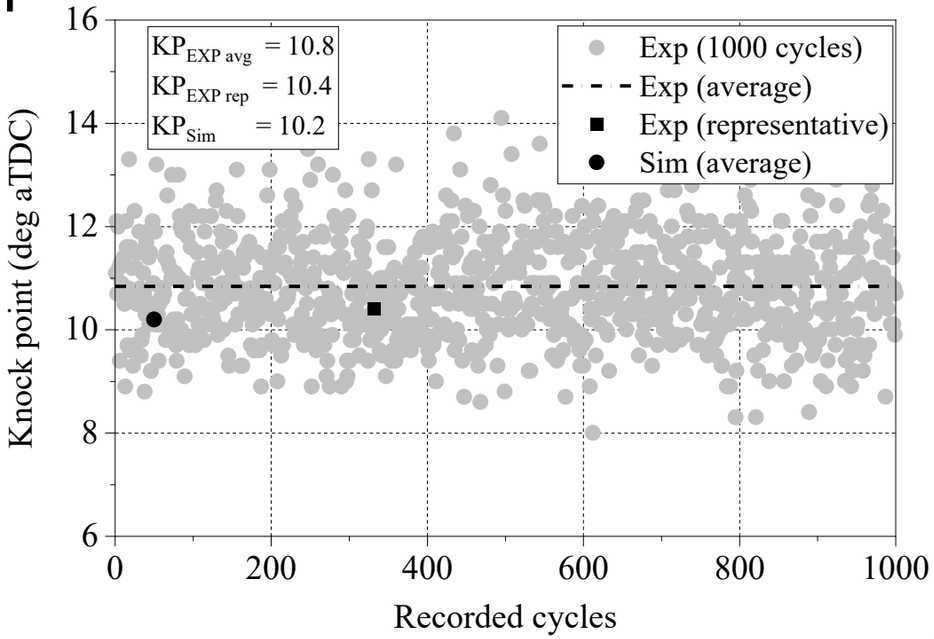
Baseline Piston
PCP ~ 60bar
BMEP ~ 9bar

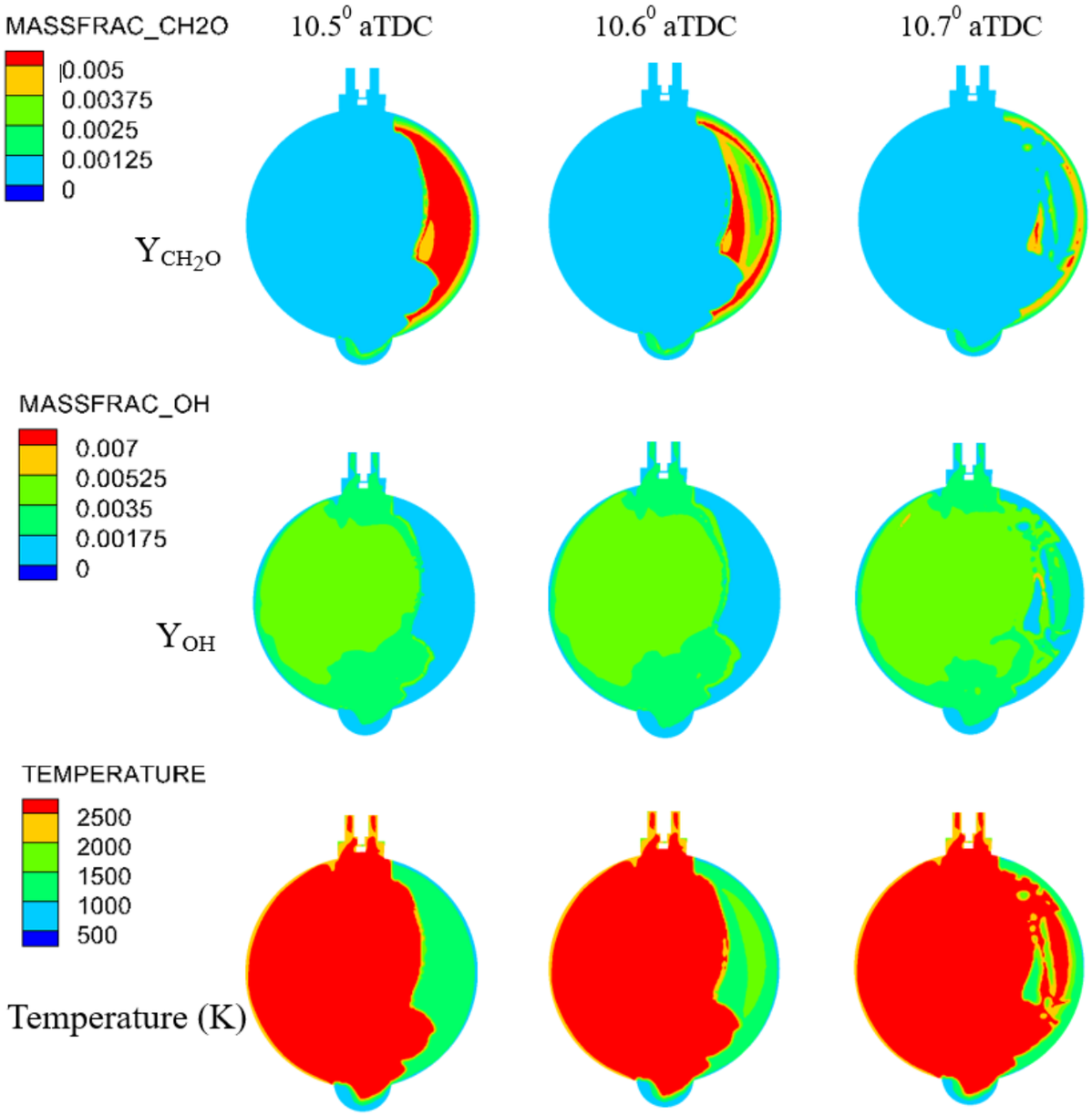
PCP = Peak Cylinder Pressure

Technical Accomplishments and Progress

CFR engine CFD simulation







Collaboration and Coordination

Prime Recipient: Colorado State University
PI: Daniel Olsen
Co-PIs: Anthony Marchese, Bret Windom
Postdoc: Tanmay Kar
Students: Toluwalase Fosudo, Brye Windell, Manav Sharma, Colin Slunecka

Sub-recipient: Cummins Inc.
PI: Hui Xu
Key Contributors: Robert Sperry, Tim Shipp

Sub-recipient: Argonne National Laboratory
PI: Sibendu Som
Co-PI: Lorenzo Nocivelli

- Cummins team responsibilities:
  - Support RCM, CFR experiments and modelling technical discussions
  - Design, fabricate, and deliver the X15 SCE LPG-DI head, and support installation and commissioning
- Argonne team responsibilities:
  - Development and validation of a 3-D CFD spray model for LPG DI
  - Incorporation of the spray model into engine simulation models

Remaining Challenges and Barriers

- Tuning of LPG injection model to match spray imaging results, specifically flash vaporization effects as spray enters cylinder.
- Ensuring LPG remains in liquid phase in the LPG supply system for port injection and direct injection testing on Cummins X15 SCE.
- Injector nozzle design to deliver required fuel mass and facilitate desired in-cylinder fuel distribution and mixing.
- Mechanical integration of modified GDI injector into Cummins X15 cylinder head.
- Development of combustion recipe to achieve near-diesel efficiency.

Proposed Future Research

Budget Period 2 (2022)
Perform X15 SCE baseline testing with liquid LPG port injection
CFD simulations of X15 SCE with LPG direct injection
Fabricate/deliver new Cummins X15 direct injection cylinder head
Operate Cummins X15 SCE with LPG direct injection

Budget Period 3 (2023)
Carry out Large Engine Control Module (LECM) programming to implement new LPG injection strategies
Perform initial Cummins X15 SCE performance mapping of injection strategies, EGR rate, IMEP, and fuel composition
Apply optimization techniques to demonstrate ≥ 44% brake thermal efficiency of SCE operation on LPG

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

Summary

Main project goal: Increase the peak torque efficiency of a 15 liter LPG engine to near-Diesel efficiency (44%)

Accomplishments

Milestone	Description
1.1	Setup RCM for LPG fuel supply and generate pressure vs. time data for variable composition/EGR
1.2	Establish capability to inject LPG through GDI commercial injector
1.4	Completion of initial fuel injection spray model for incorporation into CFD
GN1	Develop reduced mechanism able to predict laser ignited RCM experimental data within ≤15% for realistic fuel variability and EGR
2.1	Demonstrate accurate matching of CFR engine simulation model with experimental data