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

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Project ID: FT098

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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:	18%

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

- A comprehensive understanding of intake airflows, fuel sprays, and combustion.
- Limited EGR-diluted operating range for high load knock mitigation.
- Advanced control systems to perform real-time control near knock limit.

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

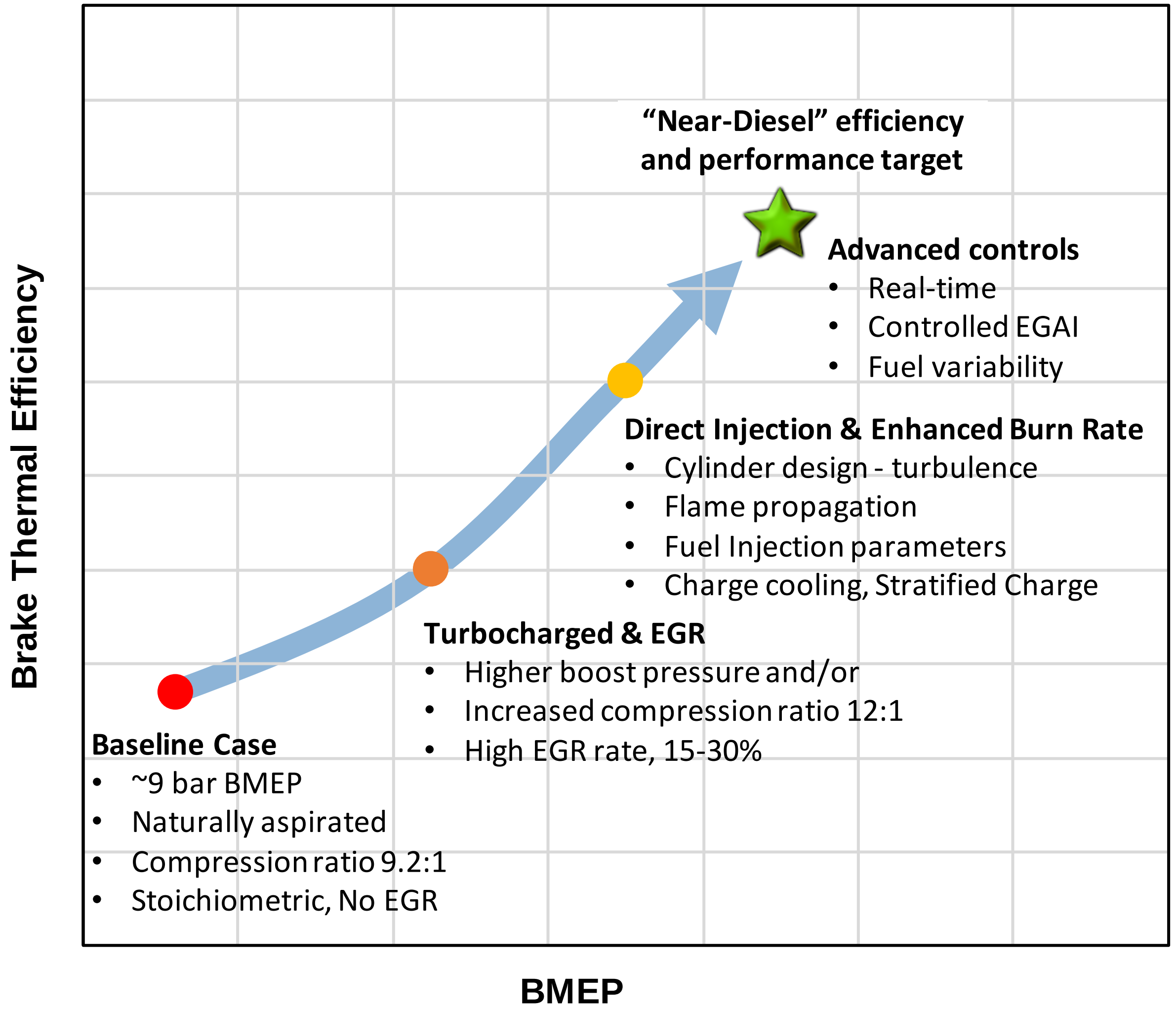
- Early-stage research to enable industry to accelerate fuel diversification through:
  - improved understanding and ability to manipulate combustion processes and,
  - generating the knowledge and insight necessary for industry to develop the next generation of engines for light-and heavy-duty vehicles.

LPG ≡ Liquefied Petroleum Gas

Approach

Engine Configuration to Meet Goal:

- Stoichiometric SI, turbocharged
- High levels of cooled EGR
- Combustion chamber design for high burn rate
- LPG Direct Injection
- Advanced engine controls



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)				M1.3			M2.2						
4. Development of Fuel Injection Spray Model				M1.4									
5. Design of Advanced Combustion Strategy								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

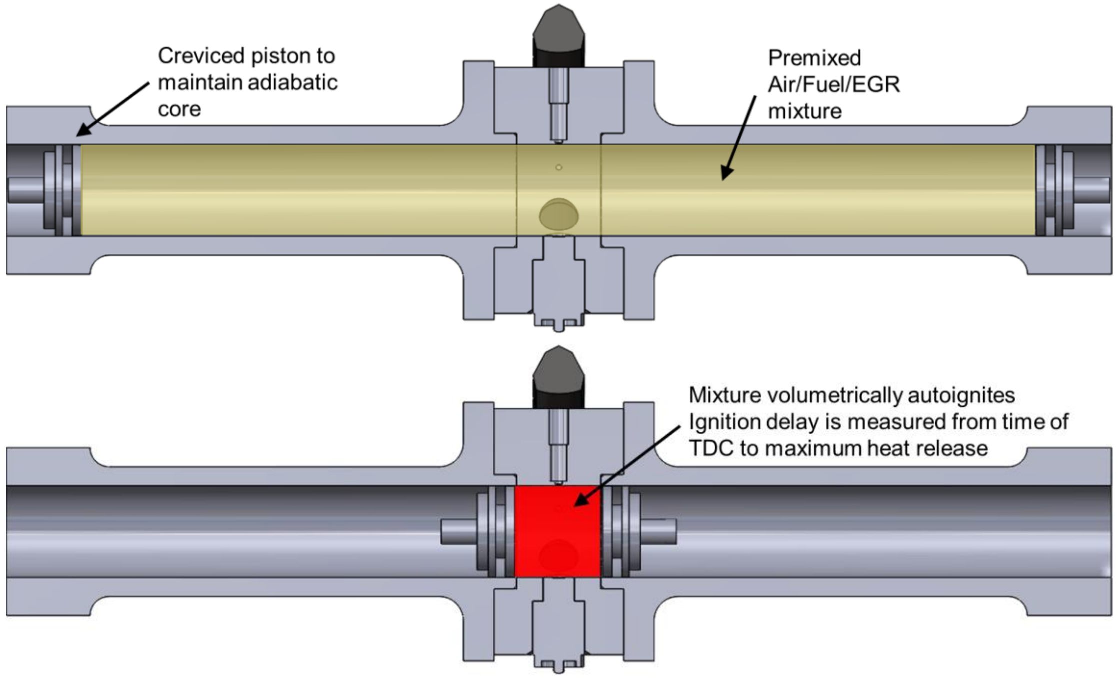
- Complete   - Ongoing   - To Be Completed

SI ≡ Spark Ignition; BMEP ≡ Brake Mean Effective Pressure; EGR ≡ Exhaust Gas Recirculation; EGAI ≡ End Gas Auto-Ignition; RCM ≡ Rapid Compression Machine; LPG ≡ Liquefied Petroleum Gas; CFD ≡ Computational Fluid Dynamics

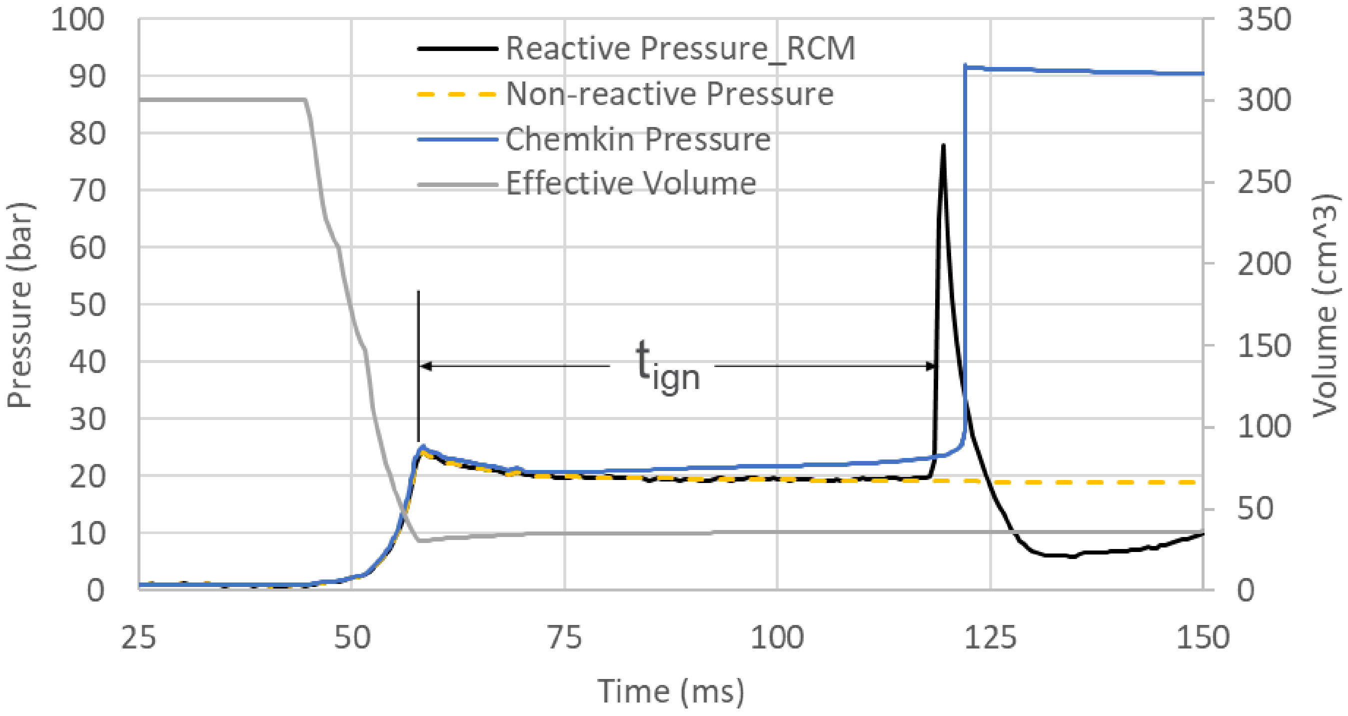
Technical Accomplishments and Progress

Chemical Kinetic Model

- The rapid compression machine (RCM) can operate in compression ignition or laser spark mode
- Compression duration is approximately 8.5 ms to reach a top dead center (TDC) volume of 30.0 cm^3
- Ratio of N_2/Ar in the inert gas is used to adjust temperature at piston TDC
- Initial pressure is varied to maintain TDC pressure of ~24 bar



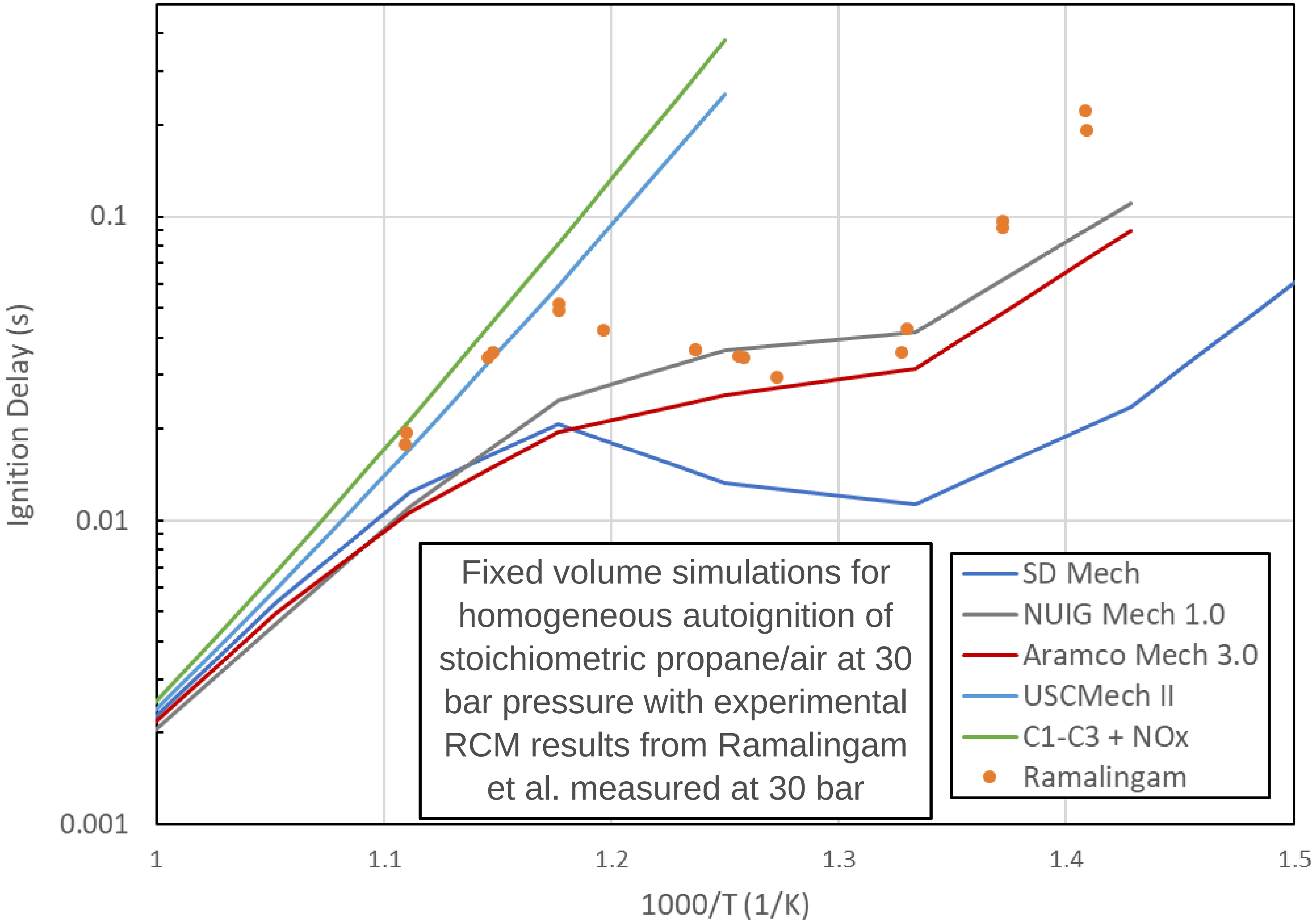
- Data is recorded using a high-speed pressure transducer
- Ignition delay is measured from piston TDC until maximum pressure rise during combustion
- Pressure data can be converted to an effective volume profile for each RCM initial condition for use in variable volume Chemkin simulations



Technical Accomplishments and Progress

Chemical Kinetic Model

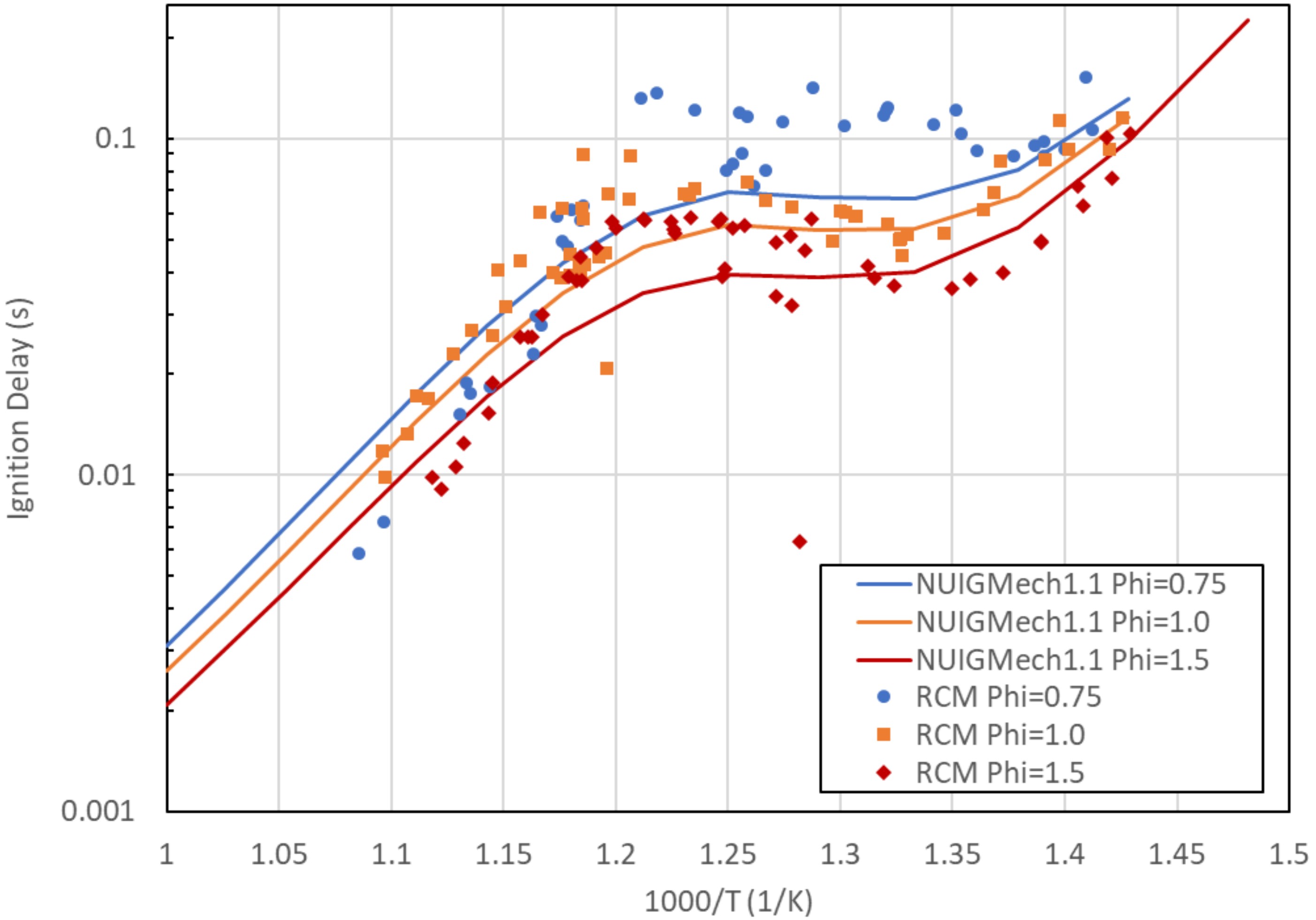
Detailed Mechanism	Origin	Species	Reactions
AramcoMech3.0	NUI Galway	581	3,034
NUIGMech1.1	NUI Galway	2,746	11,279
San Diego	UC San Diego	58	268
USC Mech v. 2.0	University Southern California	111	784
C1-C3 + NOx Mechanism	Polytechnic University of Milan	159	2,459



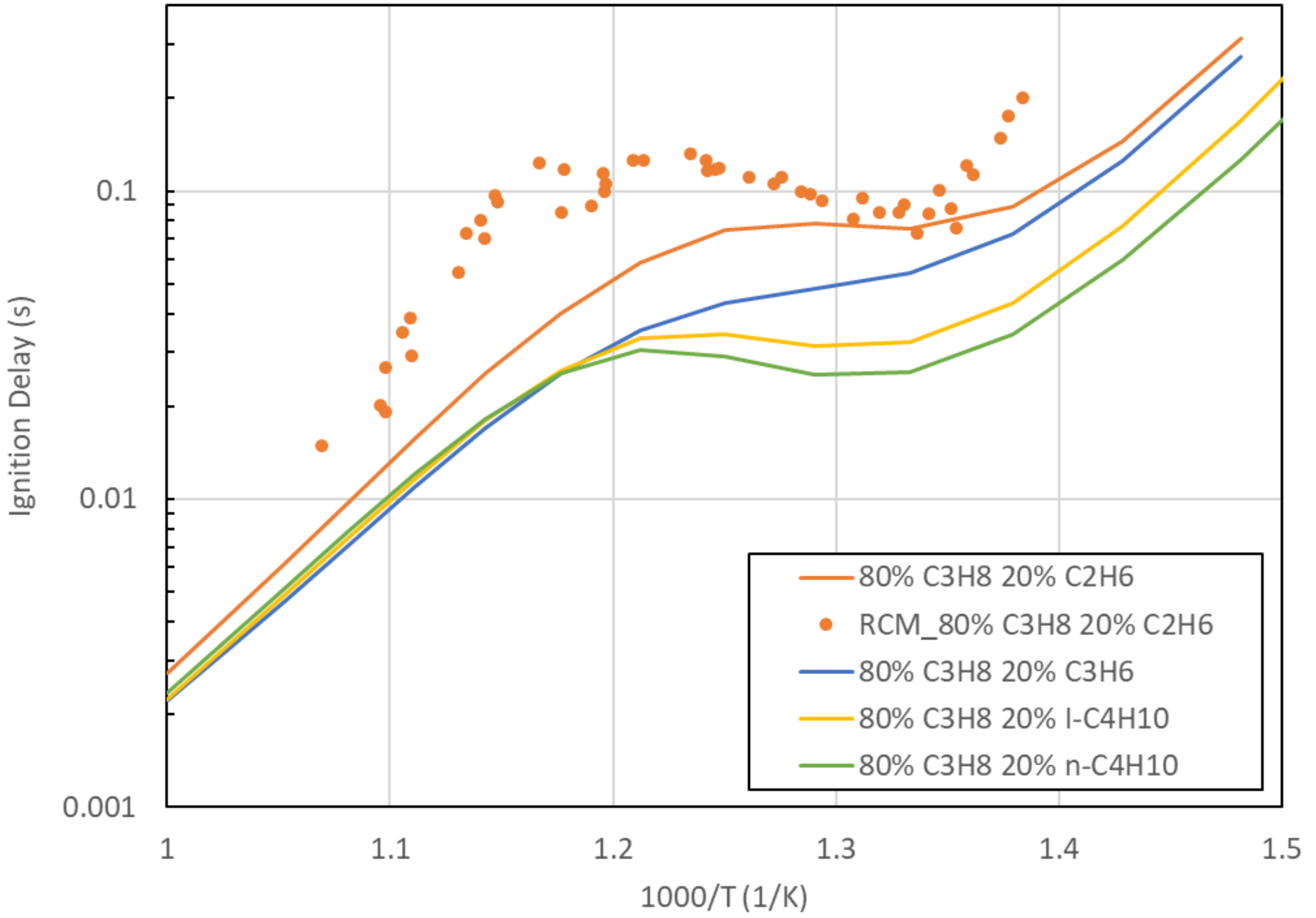
Ramalingam, A., Fenard, Y., Heufer, A., 2020, "Ignition Delay Time and Species Measurement in a Rapid Compression Machine: A Case Study on High-Pressure Oxidation of Propane", Combustion and Flame, Volume 211, Pages 392-405.

Technical Accomplishments and Progress

Chemical Kinetic Model



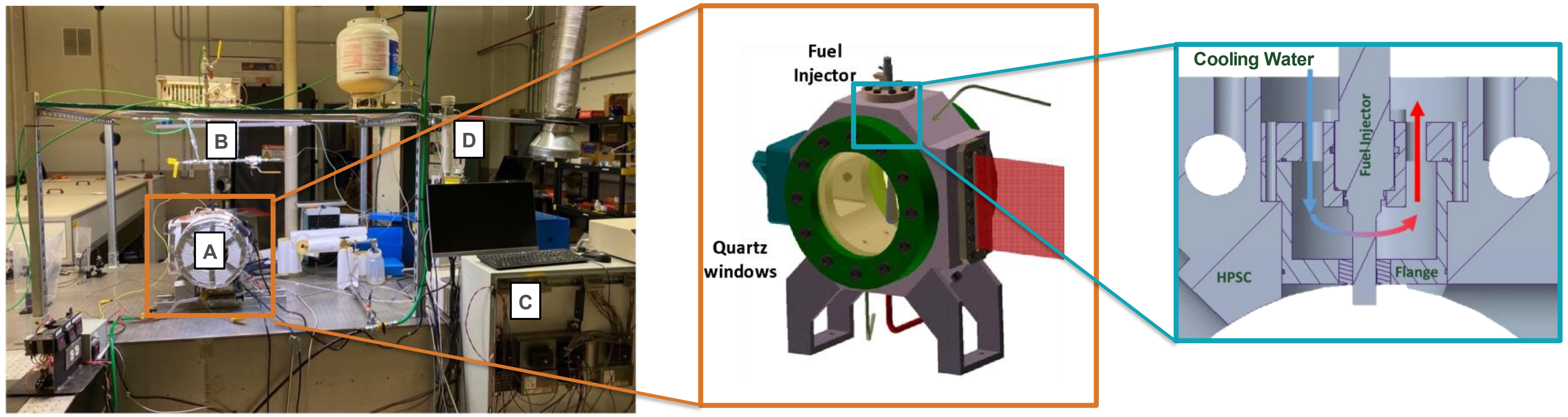
RCM ignition delay measurements (symbols) and simulated fixed volume homogeneous autoignition delay (lines) of C_3H_8/O_2/inert at 24 bar pressure and varying equivalence ratio using NUIGMech1.1 chemical kinetic mechanism.



RCM ignition delay measurements (symbols) and simulated fixed volume homogeneous autoignition delay (lines) of binary fuel/O_2/inert at 24 bar pressure using NUIGMech1.1 chemical kinetic mechanism.

Technical Accomplishments and Progress

Fuel Injection Visualization in HPSC



i) ii) iii)

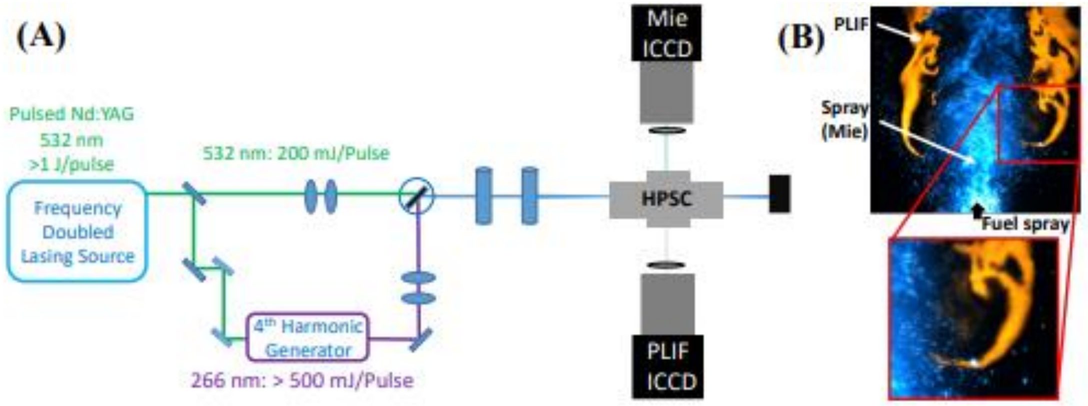
i) HPSC Setup Assembly, ii) HPSC Solid Model, and iii) Fuel Injector Cooling Jacket Flange. Here:
A) HPSC, B) Fuel Injector and Accumulator, C) Woodward's Large Engine Control Module, and D) Syringe Pump

Control Parameter	HPSC Capabilities
Fuel	Propane, Iso-octane, LPG Blends
Fuel Injector	BMW EU6, ECN's Spray-G, Delphi
HPSC Temperature	293 K – 393 K
HPSC Pressure	0.05 psig – 150 psig
Injector Temperature	283 K – 393 K
Injector Pressure	1000 psi – 5000 psi
Injection Duration	500 – 1500 μs

Control Capabilities of the Boundary Condition Parameters of the HPSC Setup Assembly.

Imaging Techniques :

- **High-Speed Schlieren** : Overall Spray Behavior (Penetration length, Angle, and Speed)
- **Mie Scattering** : Liquid Penetration Length
- **Planar Laser Induced Fluorescence** : Vapor Penetration Length using Acetone tracer



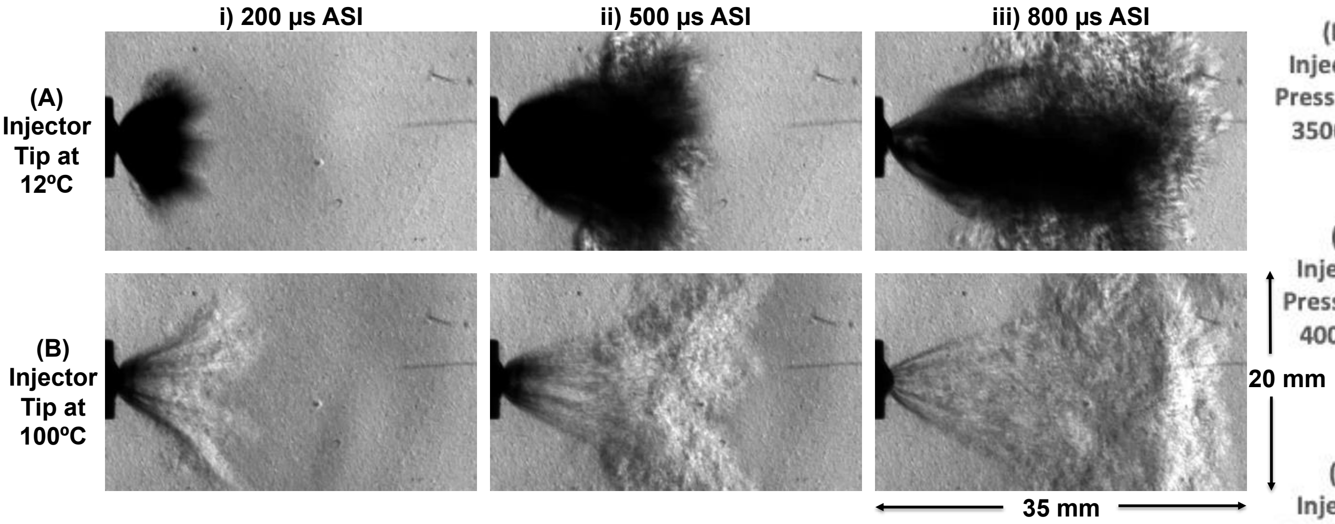
a) Optical configuration for simultaneous PLIF/Mie Scattering, and b) resulting images for Jet Fuel [1].

[1] Windom, B., et al. (2020) Proceedings of the Combustion Institute

Technical Accomplishments and Progress

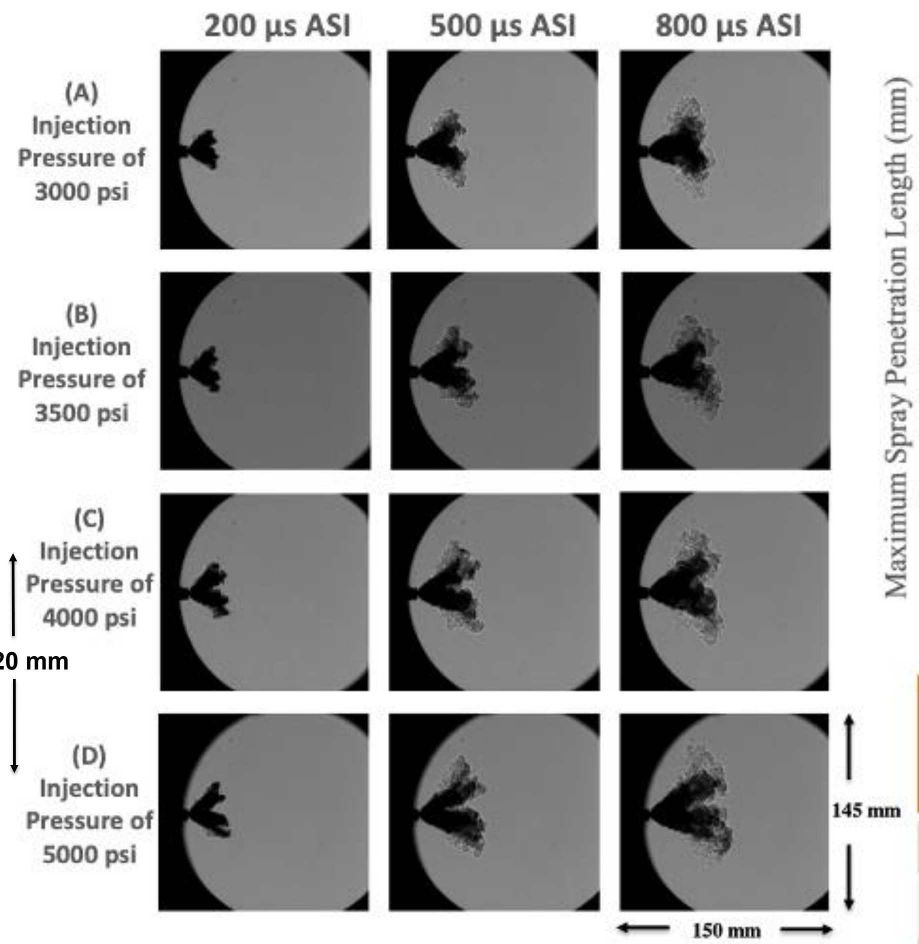
Fuel Injection Visualization in HPSC

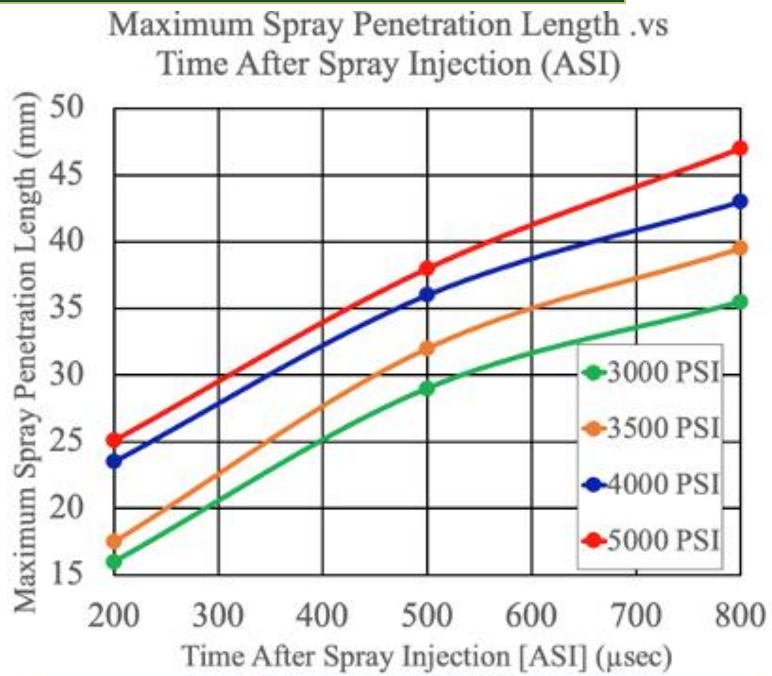
Spray development sensitive to fuel temperature



Schlieren Images for propane at HPSC temperature of 100 ºC, HPSC pressure of 15 psi, injection pressure of 1000 psi, and injector tip temperatures as mentioned above for Bosch HDEV 5.2 EU6 Injector.

Schlieren imaging capable of quantifying key spray behaviors



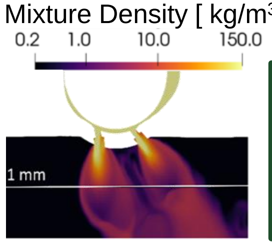


Injection Pressure	Average Spray Angle	Average Penetration Speed
A) 3000 psi	85.85°	92.6 m/sec
B) 3500 psi	81.87°	101.2 m/sec
C) 4000 psi	86.75°	113.6 m/sec
D) 5000 psi	80.57°	124.6 m/sec

Figure: Schlieeren Images for prpane STP conditions for HPSC, fuel temperature of 20 °C, at a fuel pressure and timing as mentioned aboveand corresponding spray measurments for BMW EU6

Technical Accomplishments and Progress: LPG Injection and Spray Modeling

Challenge: LPG undergoes **extreme vaporization** and can reach **supercritical mixing** conditions



High-Fidelity internal nozzle-flow simulations to capture propane under-expanded jet characteristics[2]

Flash-boiling vaporization[4] is incorporated in the spray phase-change process

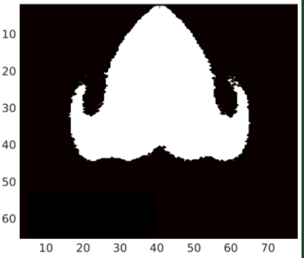
Hypothesis: pure propane as a LPG surrogate

Baseline (subcritical fuel)
Lagrangian-Eulerian (L-E) Spray Modeling for GDI[1]

Model development

LPG injection and spray model in Constant Volume Chamber

Implementation in Engine Reacting Environment

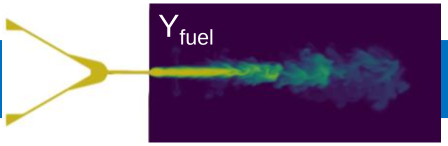


One-Way Coupling (OWC)
The Lagrangian parcels properties are initialized off-line on the basis of the higher-fidelity simulation results[3] and can capture the plume interaction

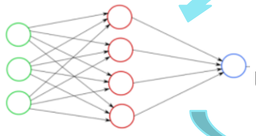
Non-ideal Equation-of-State (EoS) to represent the gaseous phase

Validation and correction against HPSC spray data

Supercritical fuel injection and mixing
The L-E framework is informed or replaced with a Machine Learning-based solution of real-fluid non-ideal EoS for supercritical mixing and implemented in the CFD software



NIST REFPROP



T, p, y_i
on-line User Defined Function
$\rho,\mu,\lambda,c_v,c_p,U,h$
CONVERGE™ CFD software

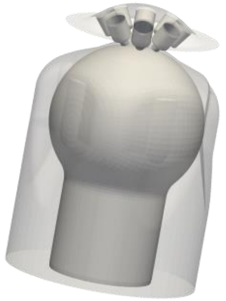
1. Nocivelli, L., et al. (2020), *Analysis of the Spray Numerical Injection Modeling for Gasoline Applications*. SAE Technical Paper 2020-01-0330.
2. Guo, H., et al. (2021), *Numerical study on spray collapse process of ECN spray G injector under flash boiling conditions*. Fuel.
3. Nocivelli, L. et al. (2019), *Effect of ambient pressure on the behavior of single-component fuels in a gasoline multi-hole injector*. ASME-ICEF 2019.
4. Adachi, M., et al., (1997). *Characterization of fuel vapor concentration inside a flash boiling spray*. SAE Technical Paper 970871.

Nozzle-flow simulations capture the multi-phase under-expanded sub-critical jet behavior

Software	CONVERGE v3.0
Turbulence	Large Eddy Simulation – dynamic structure
Two-phase flow	Mixture model – Compressible fluid Homogeneous Relaxation Model (HRM)
Mesh spacing	160 µm base mesh - 10 µm in the nozzle/sac 20 µm via Adaptive Mesh Refinement in the chamber* ~12M cells at quasi-steady flow
Lift	constant needle lift to 50 µm

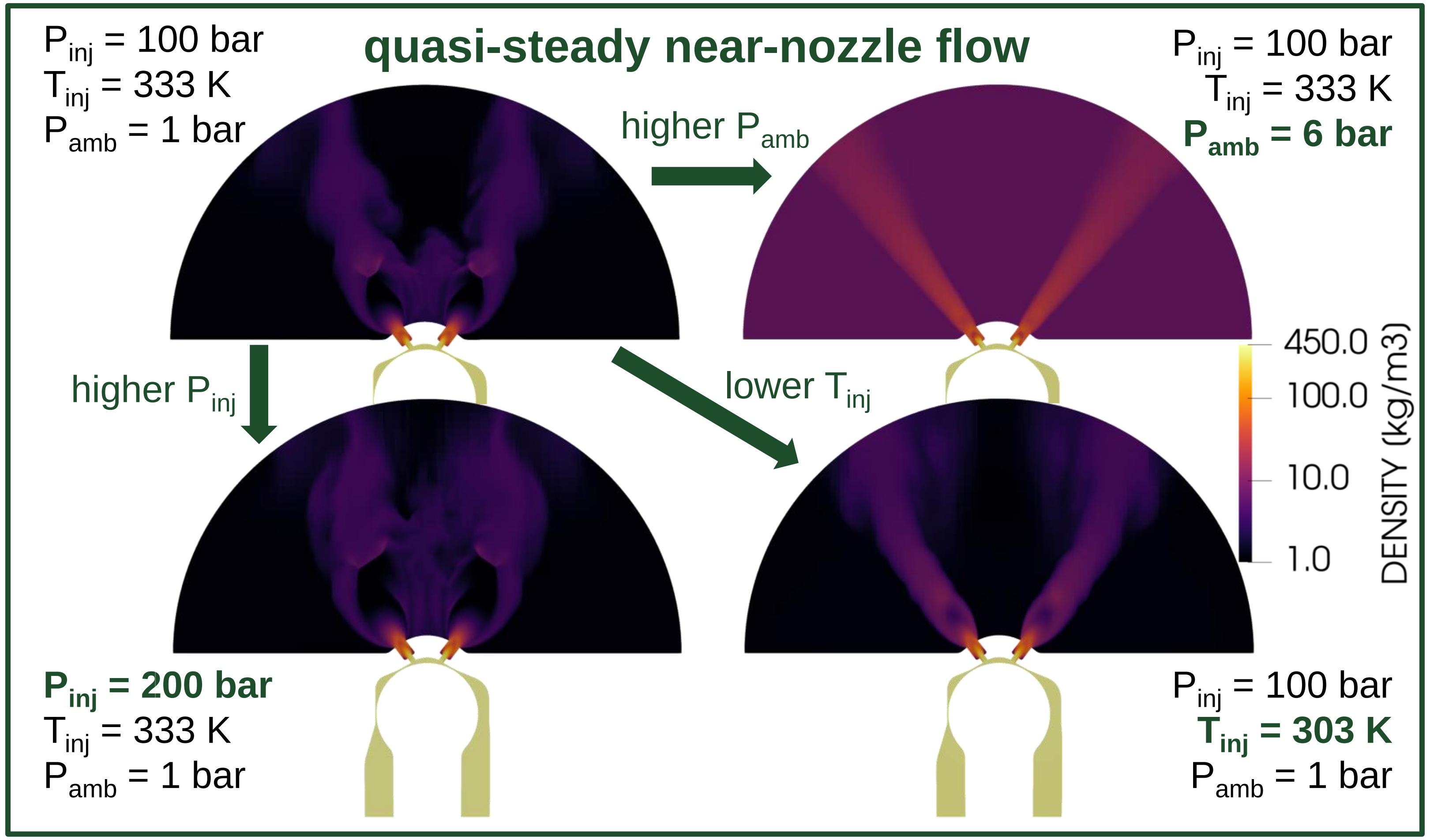
Sensitivity study on injection and ambient conditions

Engine Combustion Network's Spray-G injector



https://ecn.sandia.gov/gasoline-spray-combustion/computational-method/mesh-and-geometry/

fuel	Pure propane
P_{inj} [bar]	100 – 200
T_{inj} [K]	303 – 333
P_{amb} [bar]	1 – 6
T_{amb} [K]	300



- The competition between the vaporization and the plume expansion drives the spray development
- Back-pressure P_{amb} and fuel temperature T_{inj} guide the expansion and flashing propensity of propane
- P_{inj} determines the characteristic flow-through time-scale modifying the plume-plume interaction dynamics

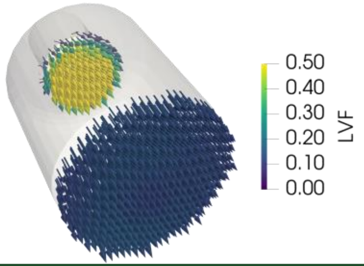
* Nocivelli, L., et al. (2020), *Comparison Between a Center-Mounted and a Side-Mounted Injector for Gasoline Applications: A Computational Study.* ASME-ICEF 2020.

Technical Accomplishments and Progress: Propane Injection for Engine Simulations

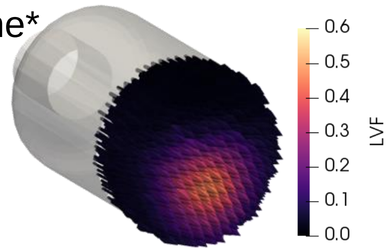
One-Way Coupling of the nozzle flow results at the hole outlets allows the L-E spray to reproduce plume-collapse

Two-phase Nozzle-flow results
Propane jet core is disrupted already at the c-bore exit

Propane
P_{inj} = 100 bar
T_{inj} = 333 K
P_{amb} = 1 bar

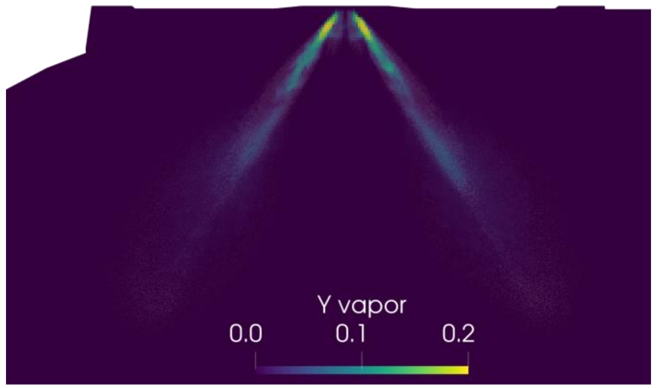


Flashing iso-octane*
P_{inj} = 200 bar
T_{inj} = 363 K
P_{amb} = 0.5 bar



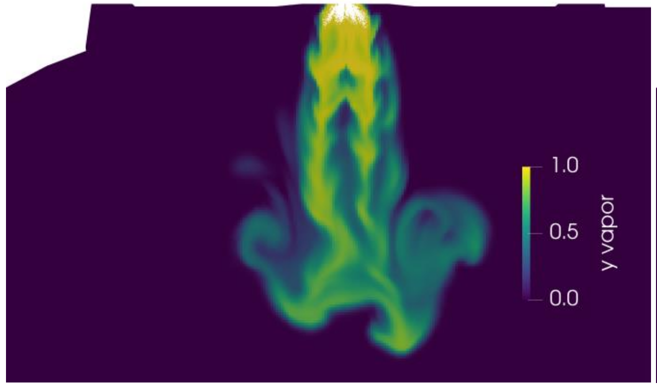
L-E simulation in the HPSC environment at quasi-steady flow

iso-octane
standard spray initialization

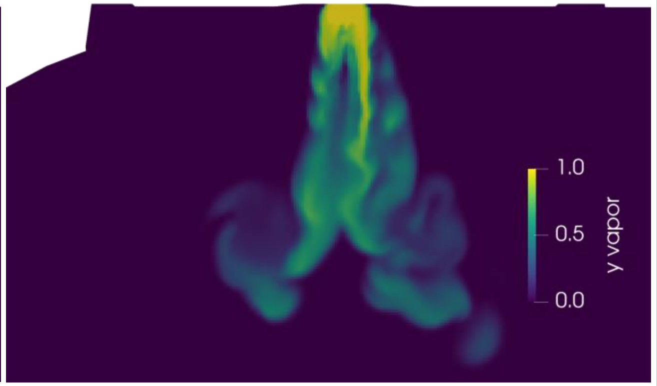


propane

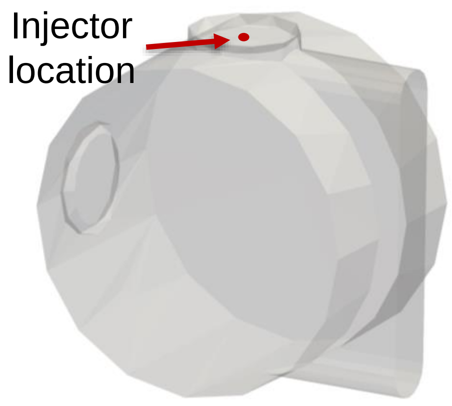
Informed spray initialization



informed spray initialization
with flash boiling vaporization



HPSC domain



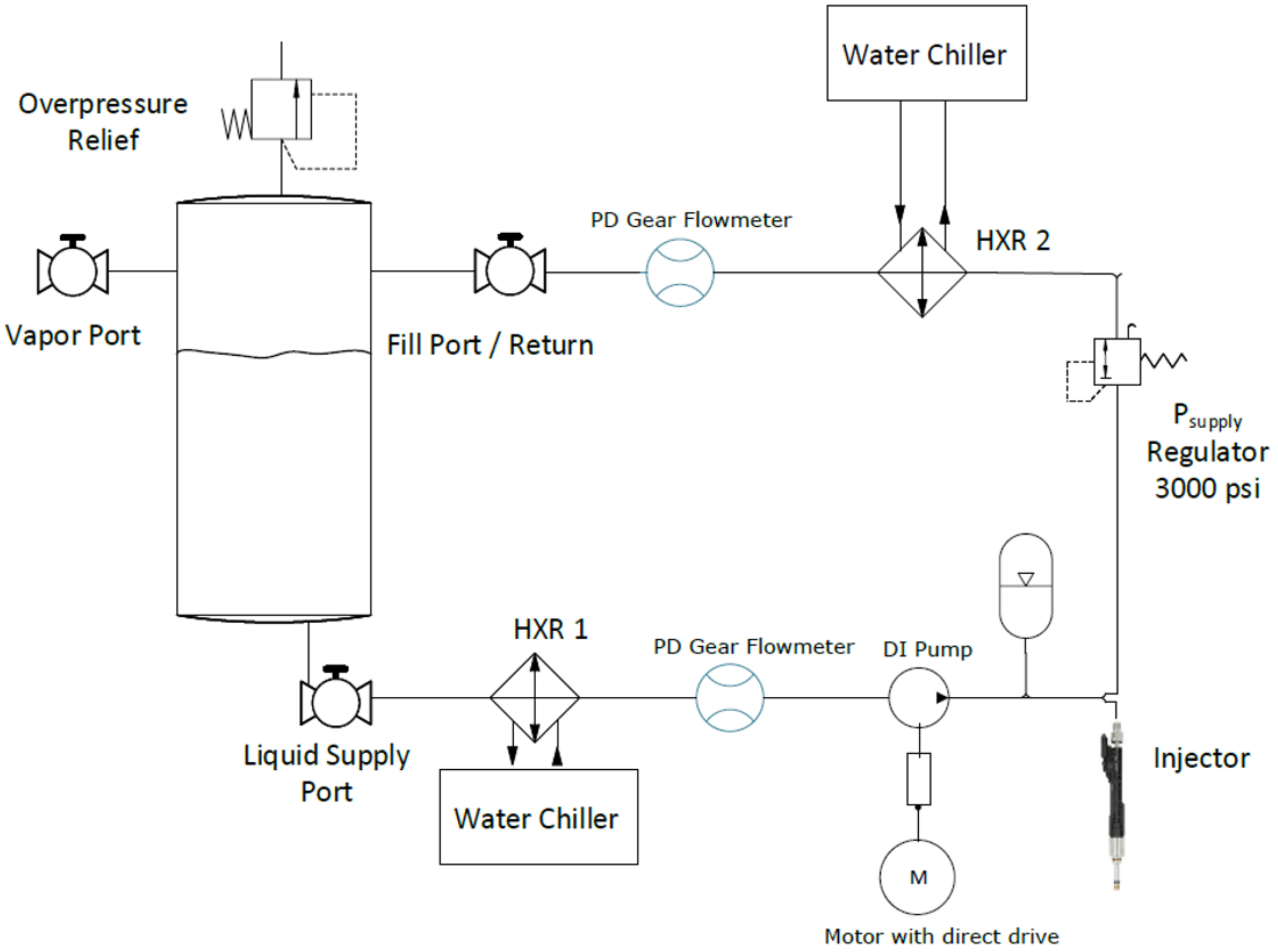
First coupled simulation of propane jets in engine-sized domains

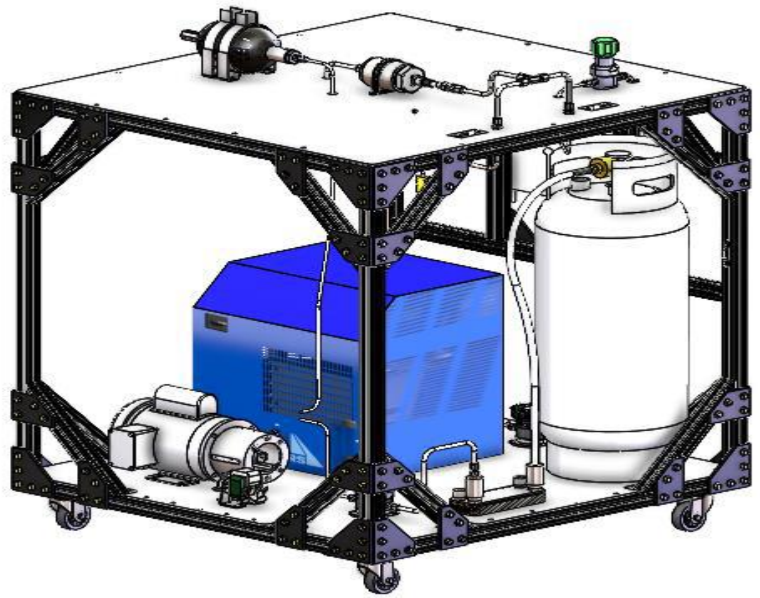
- Smaller initial droplet size to represent the effect of the flash-boiling on the jet atomization
- At the counter-bore outlet the axial momentum of the spray is disrupted, resulting in a sudden interaction of the spray plumes
- The plume collapse and the vaporization rate drive the axial penentration of the spray

* Nocivelli, L., et al. (2020), *Analysis of the Spray Numerical Injection Modeling for Gasoline Applications*. SAE Technical Paper 2020-01-0330.

Technical Accomplishments and Progress

LPG Fuel Injection System



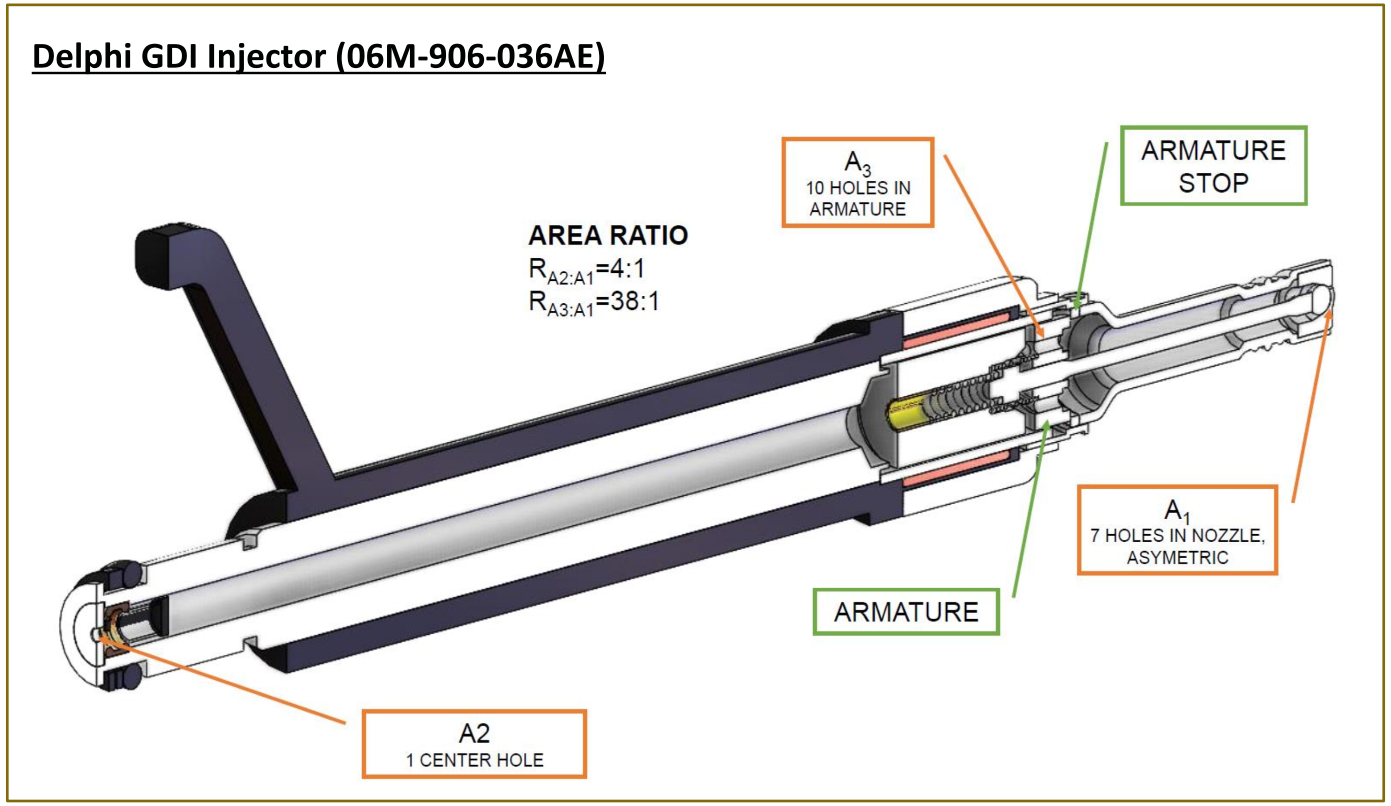


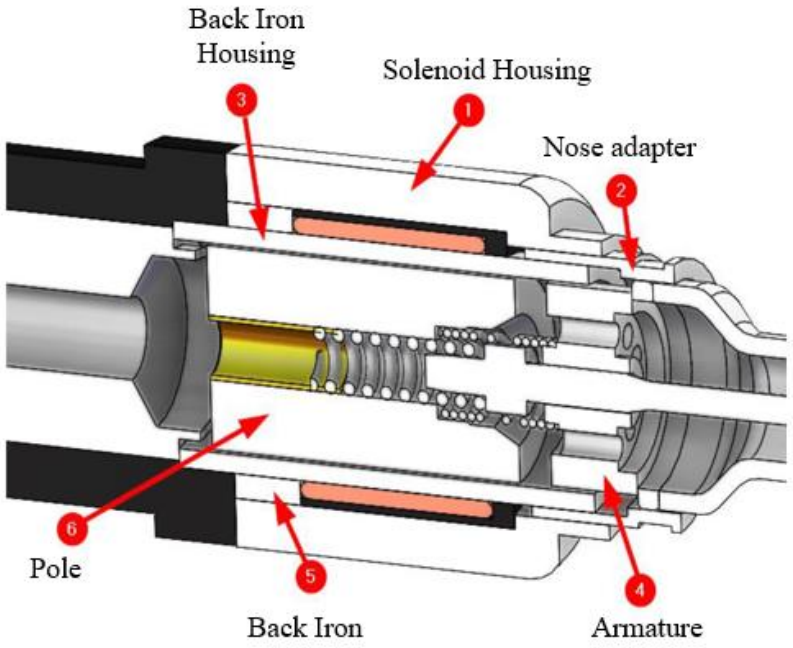
- Fuel delivery system supplying LPG in *liquid state* and at *max pressure of 3000 psi*
- Simulink model predicting flow conditions and assessing *components selection*
- Utilization of GDI system components for compatibility and availability

Parts	Descriptions
Injector	Delphi GDI 06M-906-036AE (2019 Audi Q8 Quattro Prestige)
Fuel Pump	Bosch GDI pump 0261520083 (to be driven directly by Motor)
Flowmeter	Macnaught gear flowmeter, max flow 100 LPH
Control System	LECM (Motohawk controller)

Technical Accomplishments and Progress

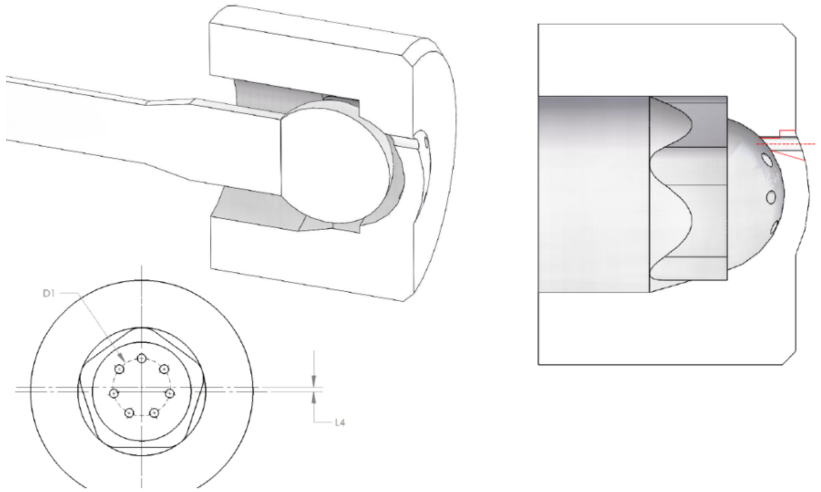
LPG Fuel Injection System





Metallurgy of injector magnetic components

- Delphi injector selected due to its larger internal flow passage and suitable construction for reassembly
- Metallurgical inspection of coil and armature to determine the proper current profile for injector control
- Laser scanning of base injector internals to understand nozzle geometry for future modifications
- Simulink model of injector to guide internal flow area modification and nozzle design

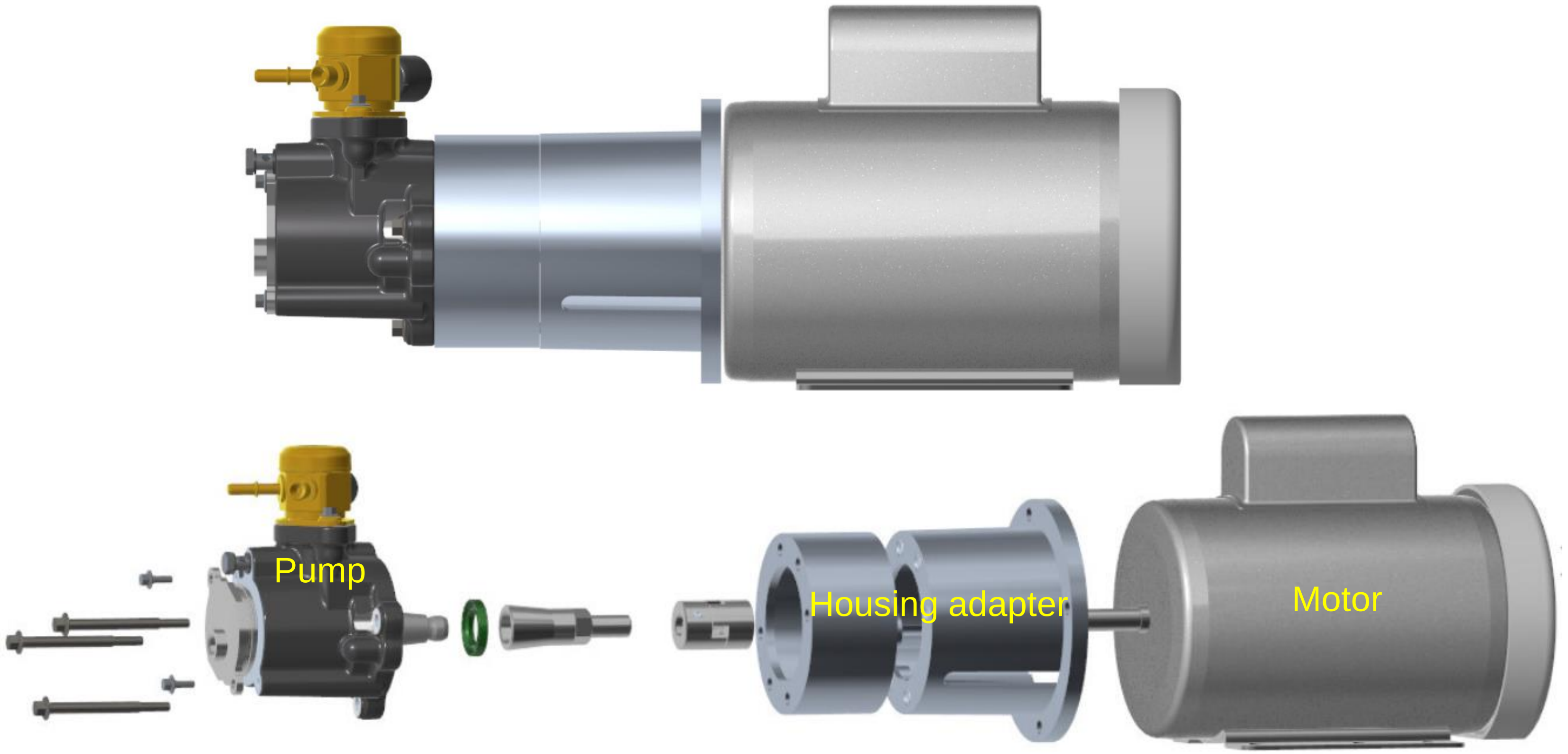


Metrology of injector nozzle geometry

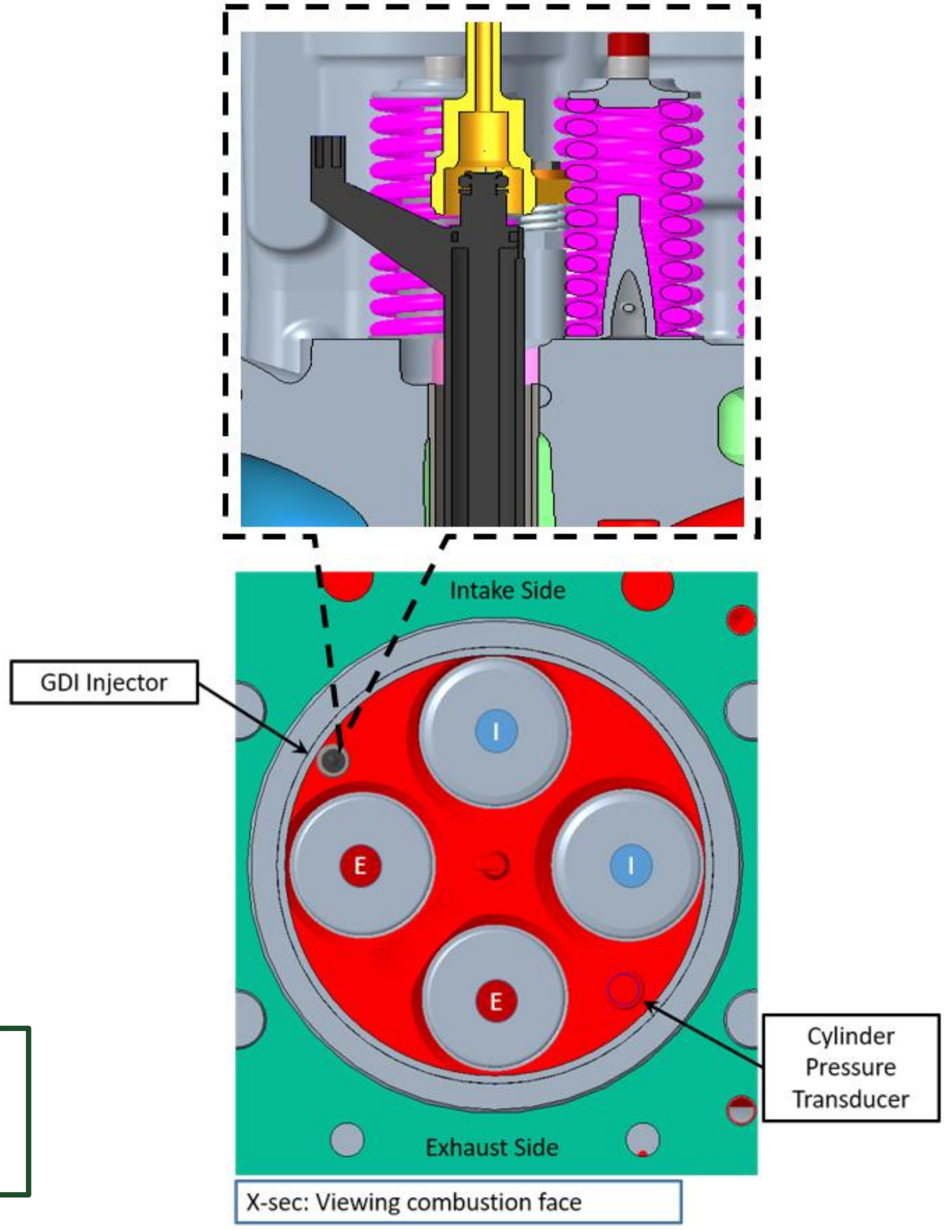
Technical Accomplishments and Progress

LPG Hardware Integration on X15 Cummins SCE

Pump-Motor Assembly



Injector Packaging

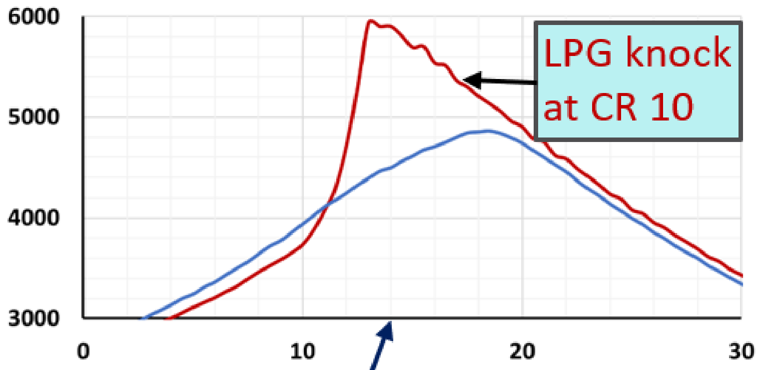


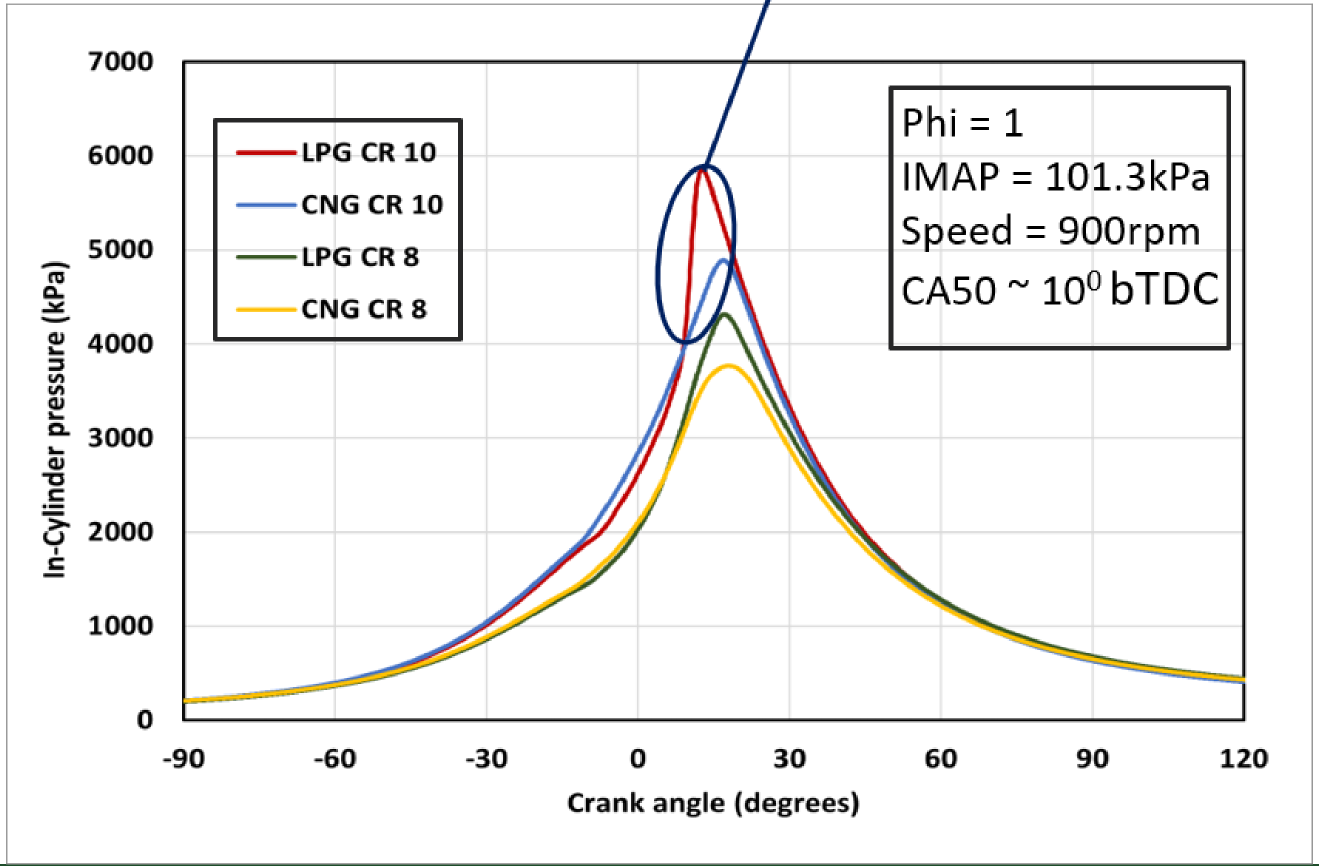
- Design of pump-motor assembly for delivering LPG at high pressure to the injector
- Packaging of Delphi injector in the cylinder head of X15 engine based on available space and accessibility

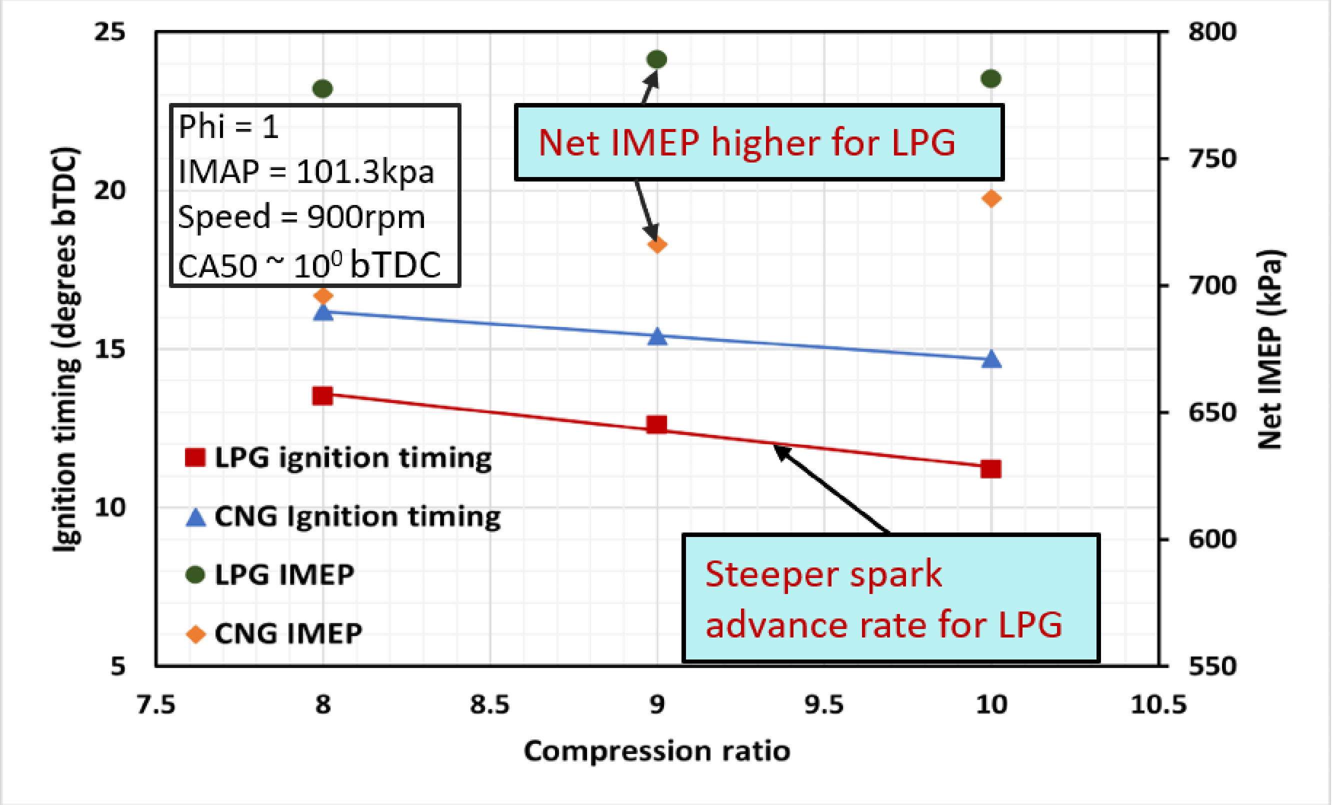
Technical Accomplishments and Progress

CFR Engine LPG Testing

- CFR Engine data for chemically pure LPG vs compressed natural gas (CNG)







IMAP ≡ Intake Manifold Air Pressure, Phi ≡ Equivalence Ratio, CA50 ≡ Crank Angle at 50% Burned LECM ≡ Large Engine Control Module

Collaboration and Coordination with Other Institutions

Prime Recipient: Colorado State University
PI: Daniel B. 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 Contributor: Robert Sperry

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

- Cummins team responsibilities:
  - Support RCM, CFR experiments and modelling technical discussions
  - Build 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

Challenges

- Development of reduced chemical kinetic mechanism for LPG
- Operation of Gasoline Direct Injection (GDI) hardware on LPG
- Injector nozzle design to deliver required fuel mass for heavy duty engine
- Integration of GDI injector into Cummins X15 cylinder head
- Achieve complete mixing of LPG in cylinder via direct injection

Barriers

- No barriers identified at this time

Proposed Future Research

Budget Period 1 (2021)
Complete RCM experiments and finish development of reduced kinetic mechanism
Finish LPG DI bench test setup and characterize DI hardware
Complete generation of CFD validation data in CFR engine
Finish LPG fuel injection spray model

Budget Period 2 (2022)
Validate CFD simulations using CFR engine data
Develop preliminary LPG direct injection strategies in HPSC
Initial simulations of X15 SCE with LPG direct injection
Receive new Cummins X15 cylinder head with direct injection
Operate Cummins X15 SCE with LPG direct injection

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
- Utilize CFD simulations to develop LPG combustion strategy
- Demonstrate final solution on 2.5 liter SCE: stoichiometric SI, turbocharged, high levels of cooled EGR, combustion chamber design for high burn rate, direction injection, advanced engine controls

Technical Accomplishments and Progress

- Performed testing in RCM to support development of reduced chemical kinetic mechanism for LPG
- Developed LPG direct injection hardware test rig design
- Generated method for adapting off-the-shelf GDI injectors for heavy duty engine LPG operation
- Created initial simulation model for high pressure LPG direct injection, supporting 2-phase flow regime

Next Steps

- Complete budget period 1 tasks, including
  - Completion of RCM experiments
  - Collect premixed LPG engine data on CFR and X15
  - Assembly/fabrication of LPG direct injection bench test setup
  - Finalize reduced chemical kinetic mechanism (~100 species)