Micro-jet Enhanced Ignition with a Variable Orifice Fuel Injector for High Efficiency Lean-burn Combustion

P.I.: Chia-Fon Lee
University of Illinois Urbana-Champaign

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Project ID: ACE096

Overview

Timeline

- Project start: 10/1/2014
- Project end: 09/30/2016
- 70% complete

Barriers

- Lack of cost-effective emission control
- Energy efficiency and cost

Budget

- Total project funding
  - DOE share: $672k
  - Contractor share: 170k
- FY 2015 funding: $366k
- FY 2016 funding: $306k

Partner

- QuantLogic Corporation

QuantLogic, Focussing on Advanced Fuel Injection & Clean Combustion

Relevance

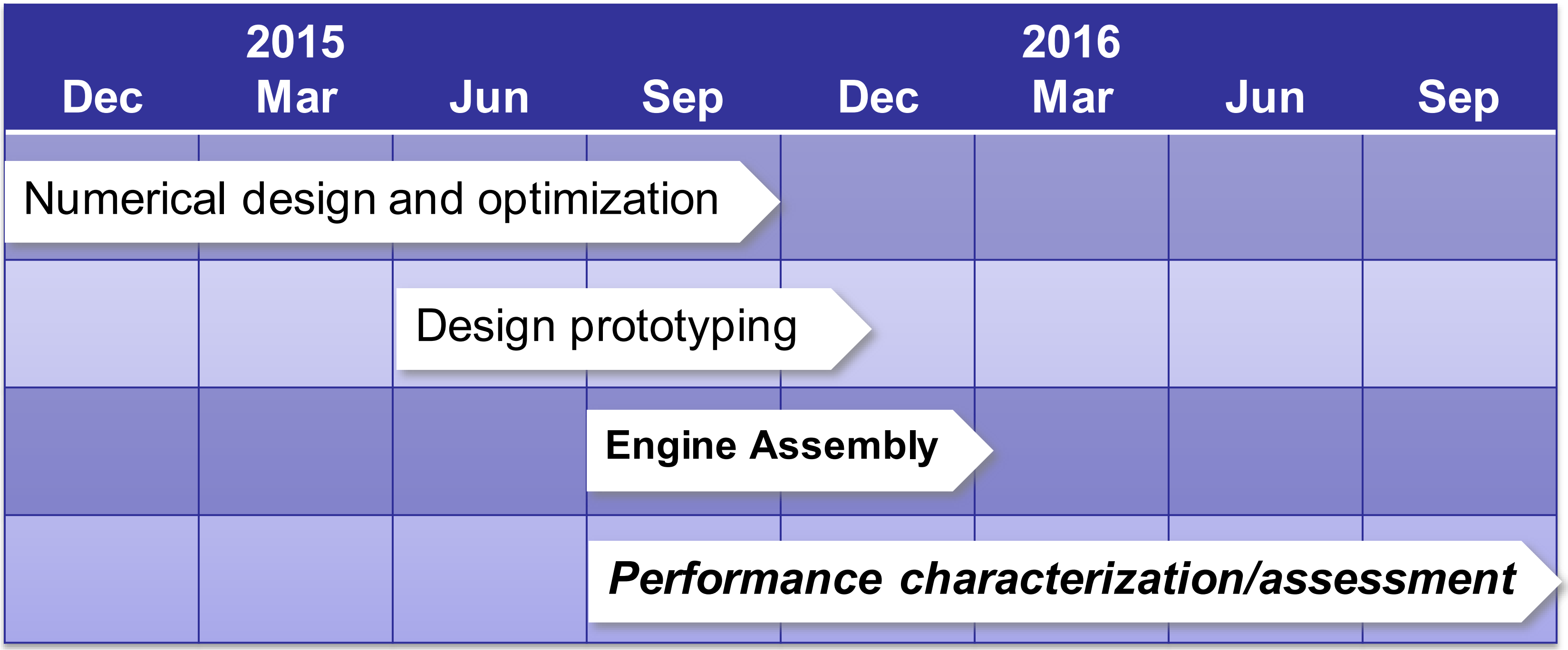
- **Overall Objective:** Improve the performance of gasoline direct injection (GDI) engines through stratified charge mode with the micro-jet enhanced ignition and embedded micro-chamber (MJEI-EMC) system.
  - Address the issues of hydrocarbon emission and wall heat loss due to fuel wall impingement in conventional spark ignition (SI) engines.
  - Design a new injector and piston bowl geometry easily adaptable to existing SI engines.

- **Objectives:** (October 2014 – March 2016)
  - Computationally optimize and manufacture variable orifice injector and micro-chamber embedded piston bowl.
  - Optical engine construction and assembly.

Milestones

Date	Milestones	Status
Dec 2014	Initial model integration	Complete
Mar 2015	Fuel injector nozzle optimization	Complete
Jun 2015	Fuel injector manufacture	Complete
Sep 2015	Spray measurement (imaging, velocity, drop size)	Complete
Dec 2015	Installation of the injection system and micro chamber	Complete
Mar 2016	Air-fuel mixing process measurements	Complete
Jun 2016	In-cylinder combustion measurements	On track
Sep 2016	Optimized condition computation and experiments for injection and combustion	On track

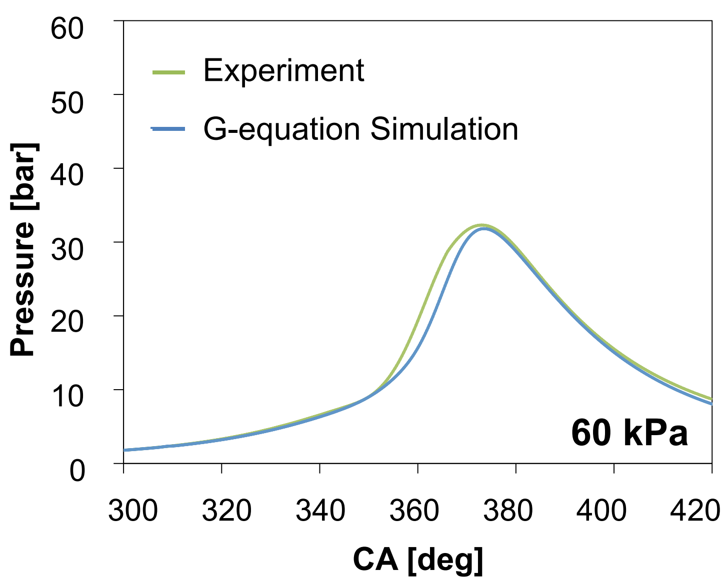
Approach/Strategy

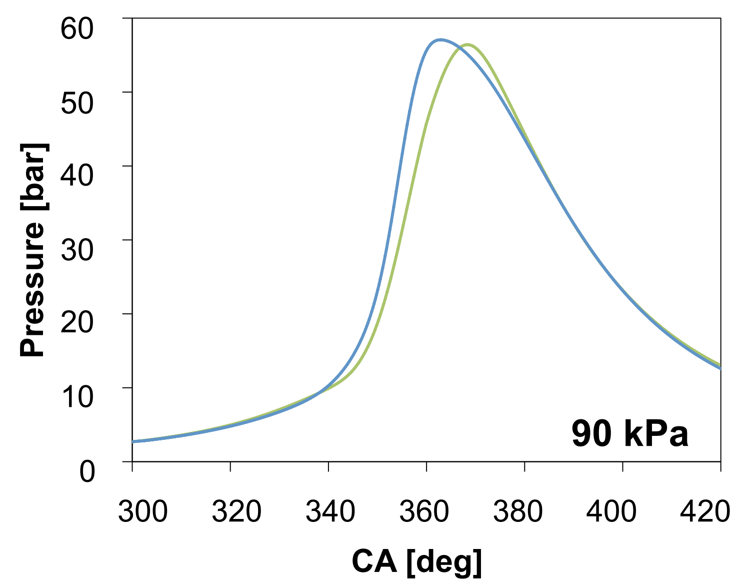


- Design parameters: Injector geometry and control; piston geometry.
- Optimization criteria: combustion emission and efficiency.
- Adaptability is taken into consideration in the design process to reduce the potential cost of utilizing the final product in existing designs.

FY2015 Technical Accomplishments

- Optimization workflow development.
  - Open-source genetic algorithm, playdoh, was utilized.
  - Target function: $$f = k_{perf}\frac{w_{i,ref}}{w_i} + \frac{Y_{NOx}}{Y_{NOx,ref}} + \frac{Y_{soot}}{Y_{soot,ref}} + \frac{Y_{CO}}{Y_{CO,ref}} + \frac{Y_{HC}}{Y_{HC,ref}}$$
- Combustion model development.
  - Built computationally efficient G-equation in KIVA-3V to model combustion.





Optimization Considerations

- Variable orifice injector geometry design.
  - Injection angles.
  - Number of injection holes.
  - Injection hole size.

- Micro-chamber embedded piston head geometry design.

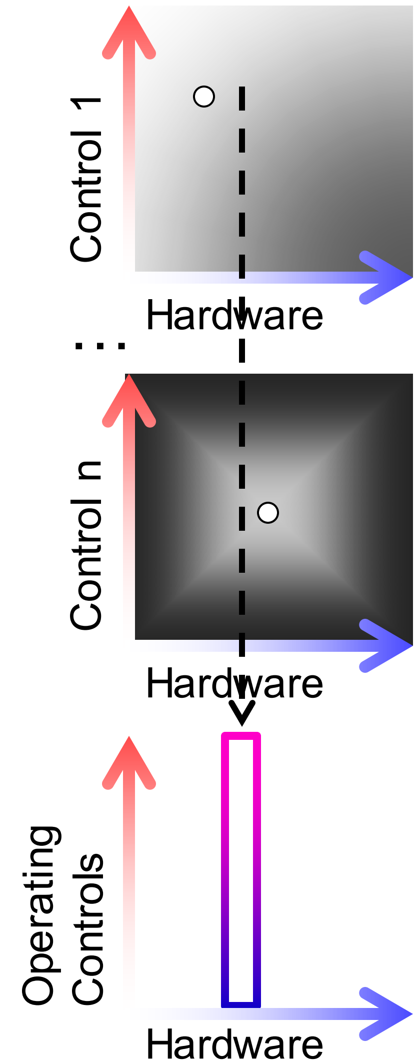
- Operation control parameters.
  - Injection timing, injection duration, spark timing.
  - Variable for different operation conditions.
  - Optimized independently for each individual operation condition.
  - Coupled with hardware (injector and piston geometry) optimization process iteratively.

Optimization Workflow

1
- Optimize the hardware parameters and control parameters for each operation condition

2
- Compromise among operation conditions and make decision on the hardware parameters

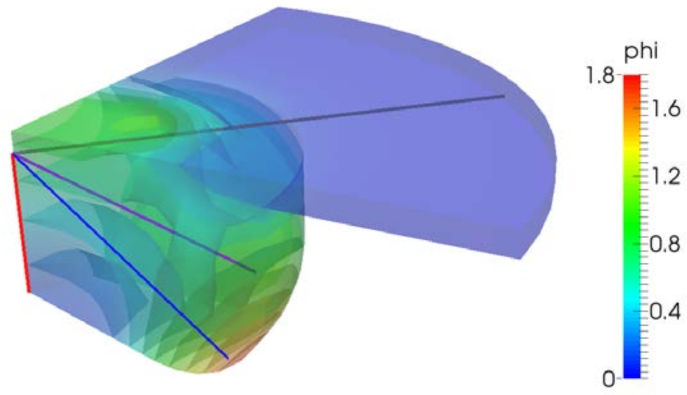
3
- Re-optimize the control parameters independently for each operation condition



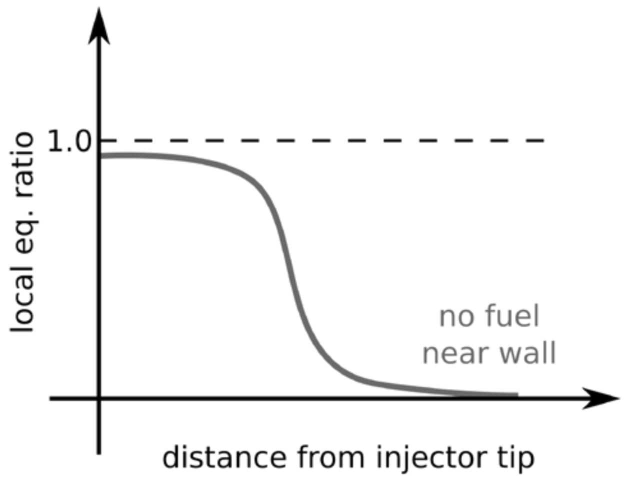
Goals of Injection Optimization

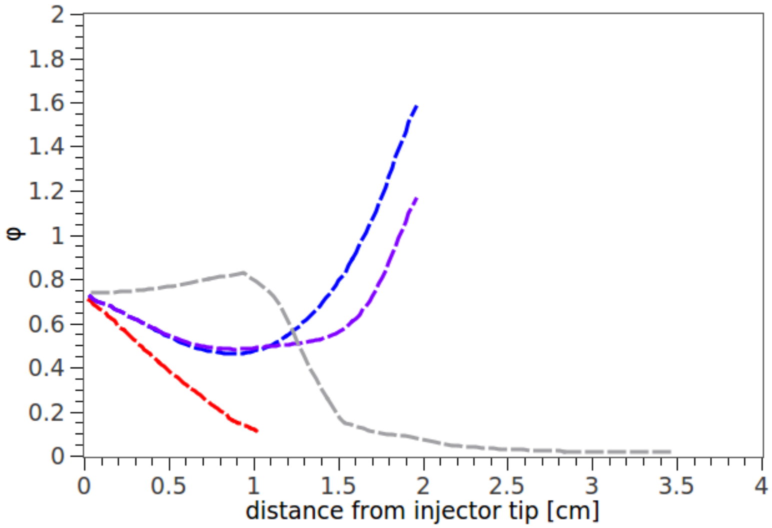
<u>Create Stratified Charge</u>

- Core: near stoichiometric
  - Fast flame propagation
  - Robust ignition
- Outer region: lean
  - Low HC emission
  - Low heat loss

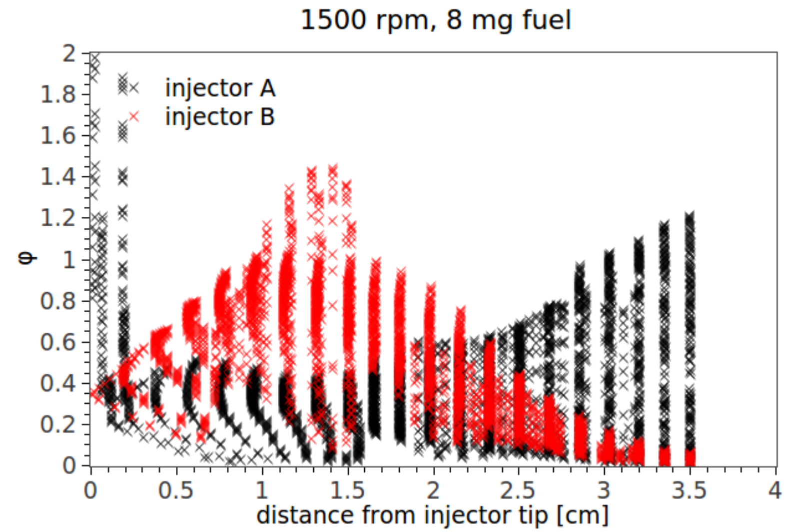


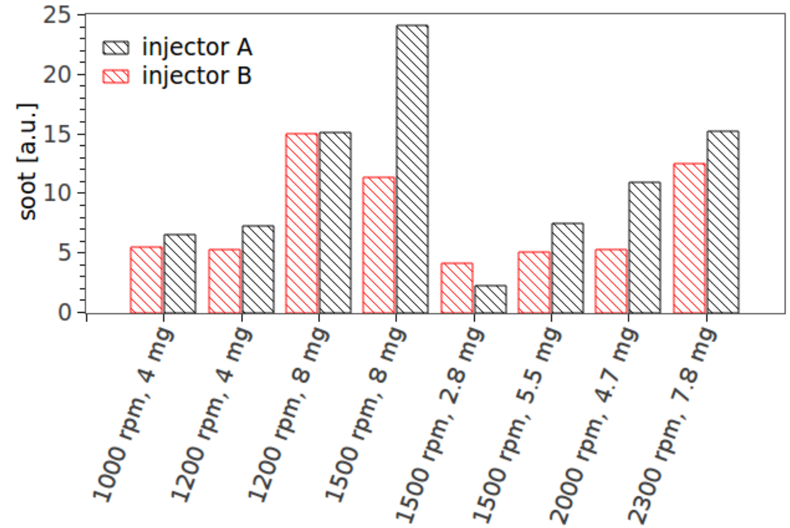
Geometry for demonstration purposes only

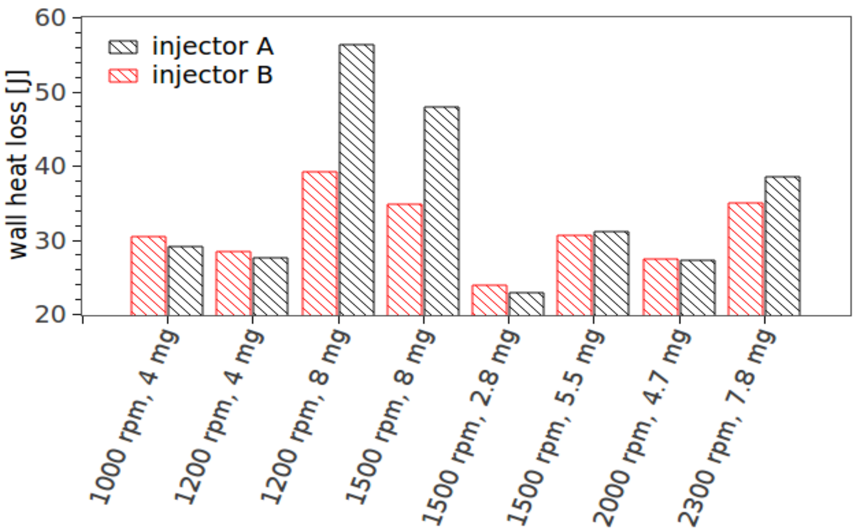


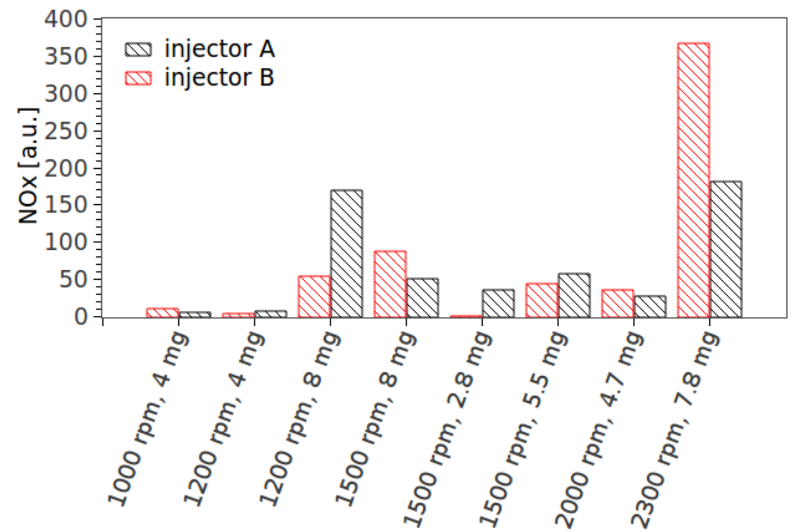


Existing (A) versus Optimized (B) Design



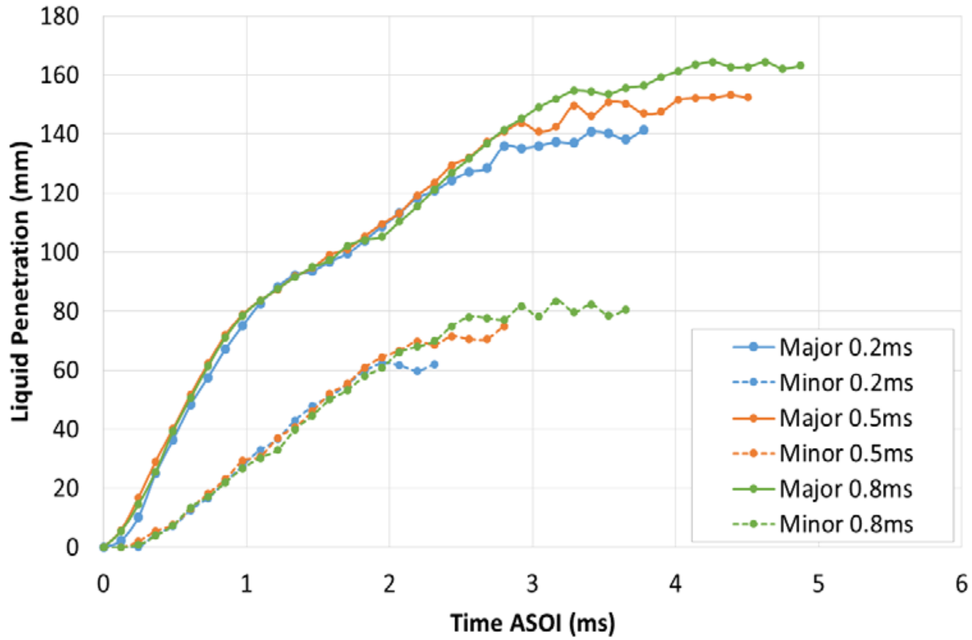


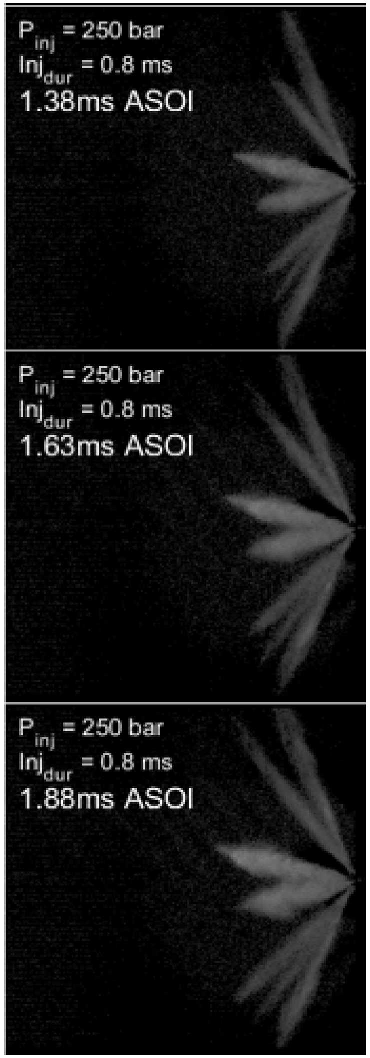


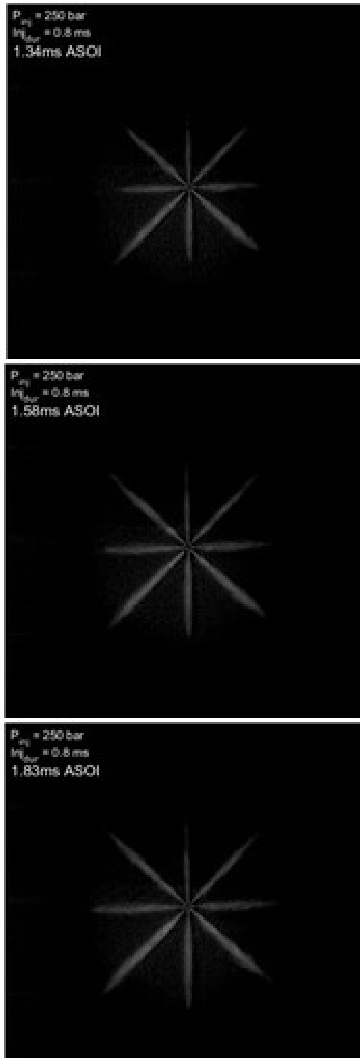


FY2015 Technical Accomplishments

- Injector design prototyping.
  - Measured Injection velocity, penetration and droplet size distribution for comparison with numerical predictions.



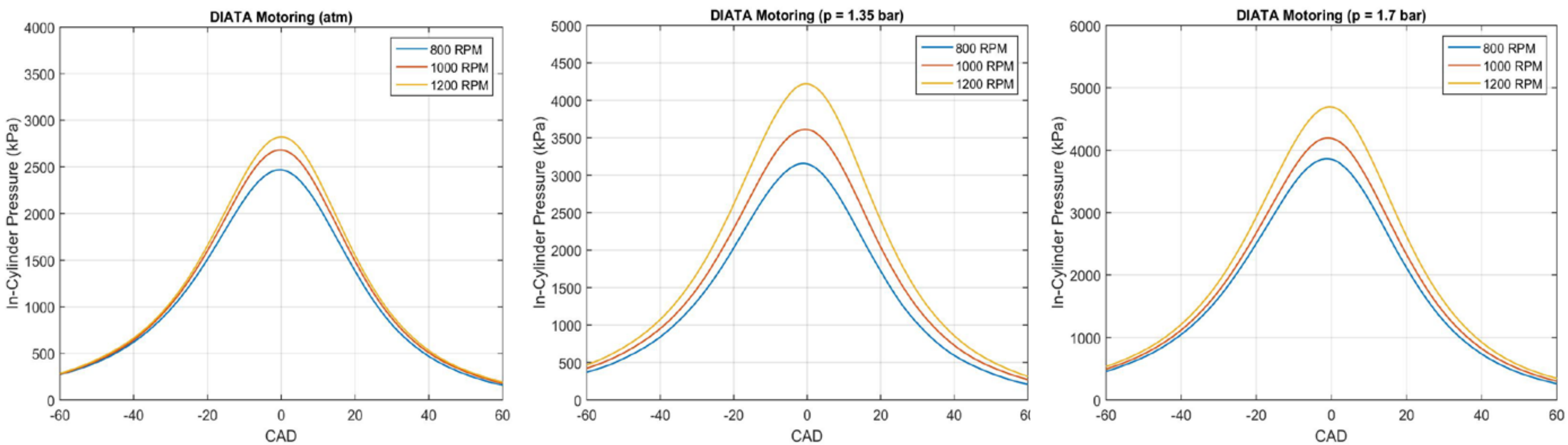




FY2015 Technical Accomplishments

- Optical piston head manufacturing.
  - Optical material: Dynasil 1100 fused silica.

- Optical engine modification and assembly.
  - Ford DIATA single cylinder engine modified from compression ignition to spark ignition application.
  - New spark plug, optical piston and optical windows.

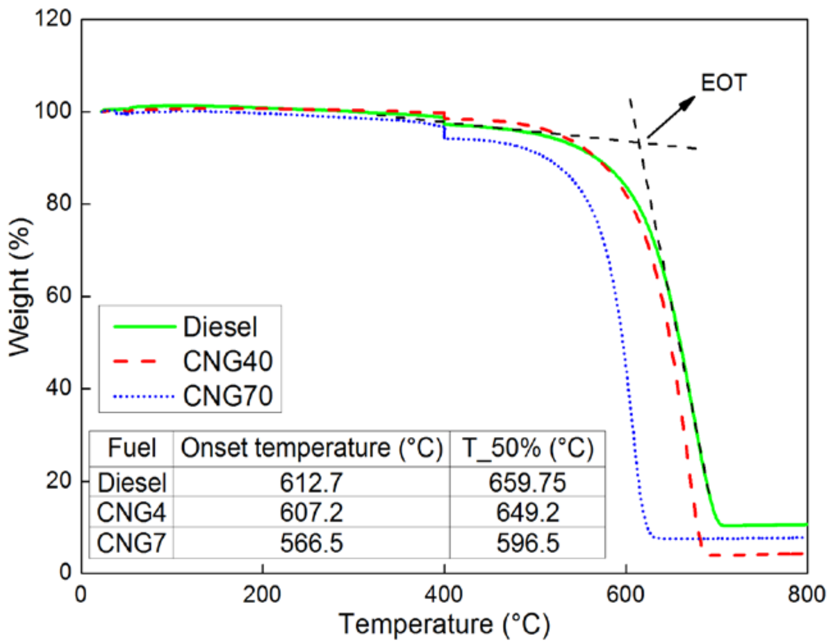


FY2015 Technical Accomplishments

Soot Emissions Characterization

Thermo-gravimetric Analyzer

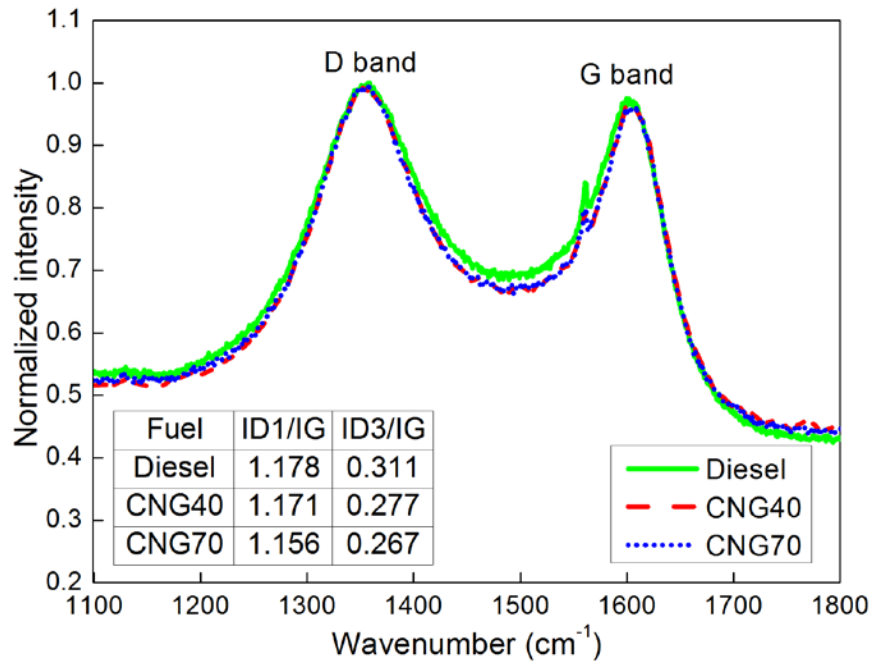
(Soot oxidation reactivity)



Fuel	Onset temperature (°C)	T_50% (°C)
Diesel	612.7	659.75
CNG4	607.2	649.2
CNG7	566.5	596.5

Raman Spectroscopy

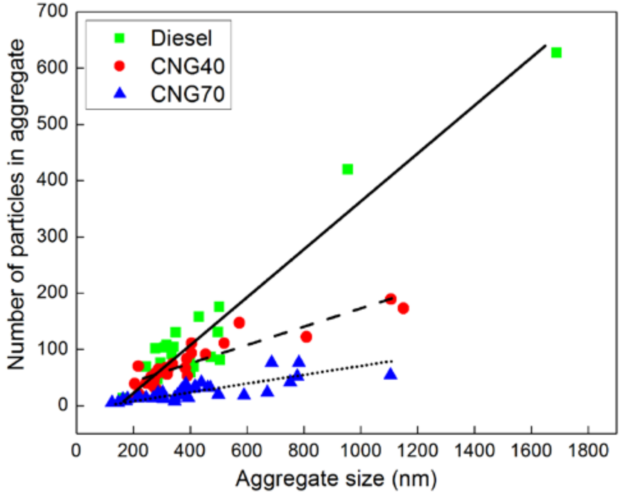
(Soot graphitic nature/impurities)

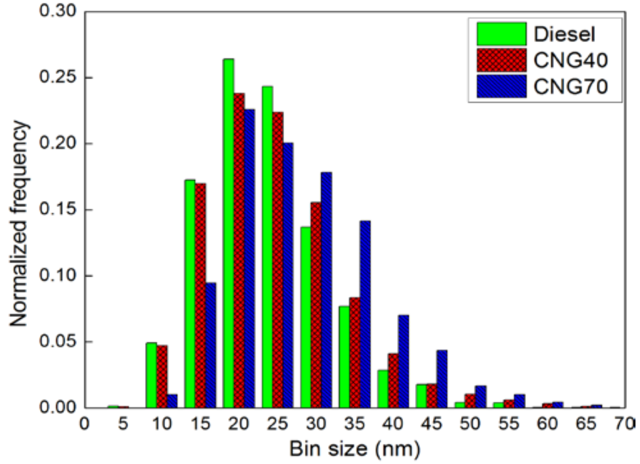


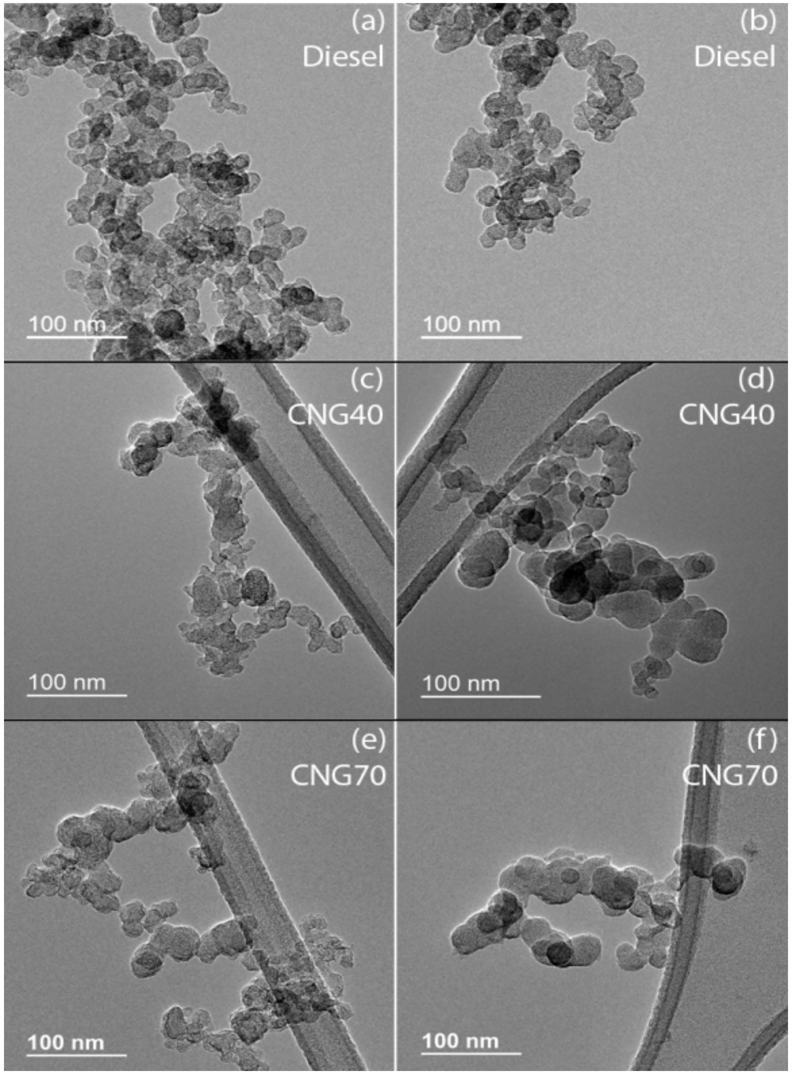
Fuel	ID1/IG	ID3/IG
Diesel	1.178	0.311
CNG40	1.171	0.277
CNG70	1.156	0.267

Soot Emission Characterization

Transmission Electron Microscopy
(Soot morphology)



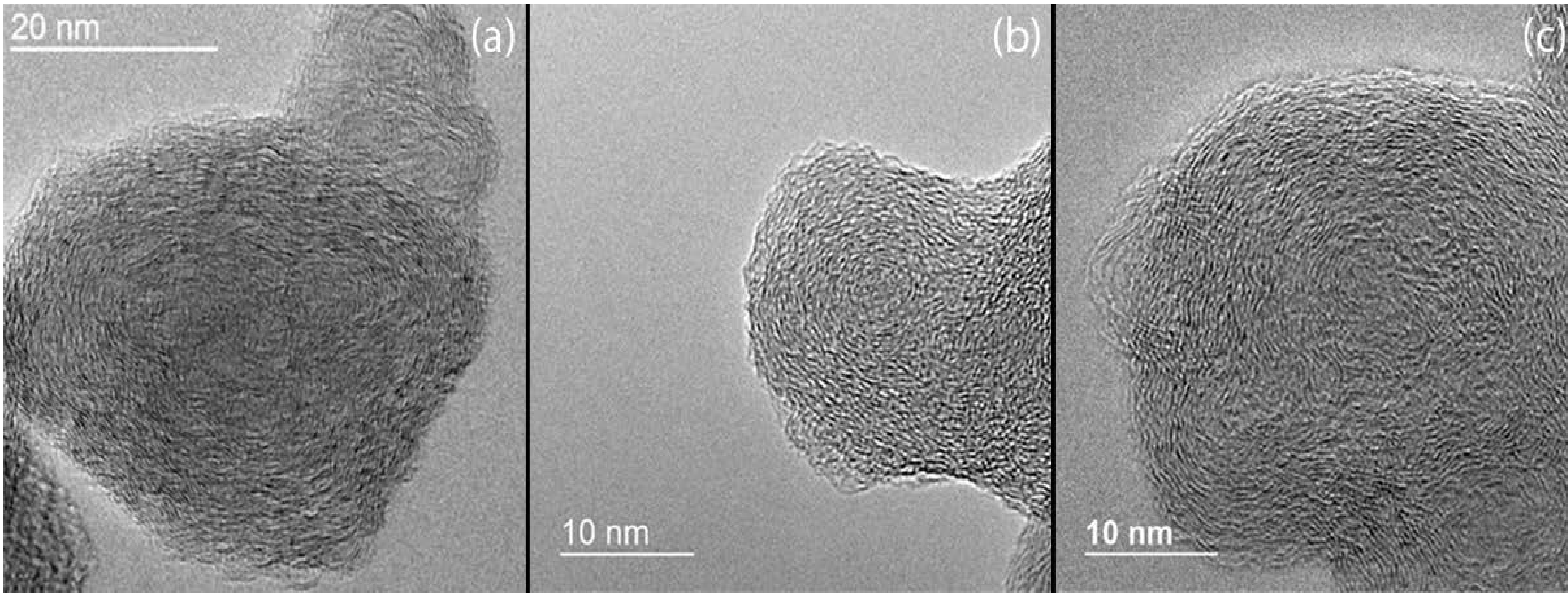




Soot Emission Characterization

High Resolution Transmission Electron Microscopy

(Soot nanostructure)



Diesel CNG40 CNG70

Responses to Previous Year Reviewers' Comments

- This project is a new start.

Partnership/Collaboration

QLC QuantLogic, Focussing on Advanced Fuel Injection & Clean Combustion

- QuantLogic Corporation – Project Subcontractor
  - Manufactured the fuel injector based on the optimized design.

Remaining Challenges and Barriers

- Secure proper lasers to perform laser diagnostics for combustion characterization.
  - The cost for repairing and servicing existing lasers is high, and acquiring new lasers would require a sizeable fund.

- Fine-tune engine simulation model to match experimental results.
  - Identify key model parameters for adjustment.
  - Reconcile the differences between experiments and simulations within the boundary of uncertainties.
  - Determine initial and boundary conditions for simulations based on experimental observations.

Proposed Future Work

Remaining of the Year

- Ongoing: Compare measurement results with model predictions and fine-tune the model accordingly.

- [Q3 Milestone] Complete in-cylinder combustion measurement.
  - Combustion imaging (natural flame luminosity).
  - Laser diagnostics for emissions and combustion efficiencies.

- Obtain soot characteristics in stratified GDI combustion.

- [Q4 Milestone] Re-optimize injection and combustion strategies numerically based on experimental hardware configuration, and test these strategies through optical engine experiments.

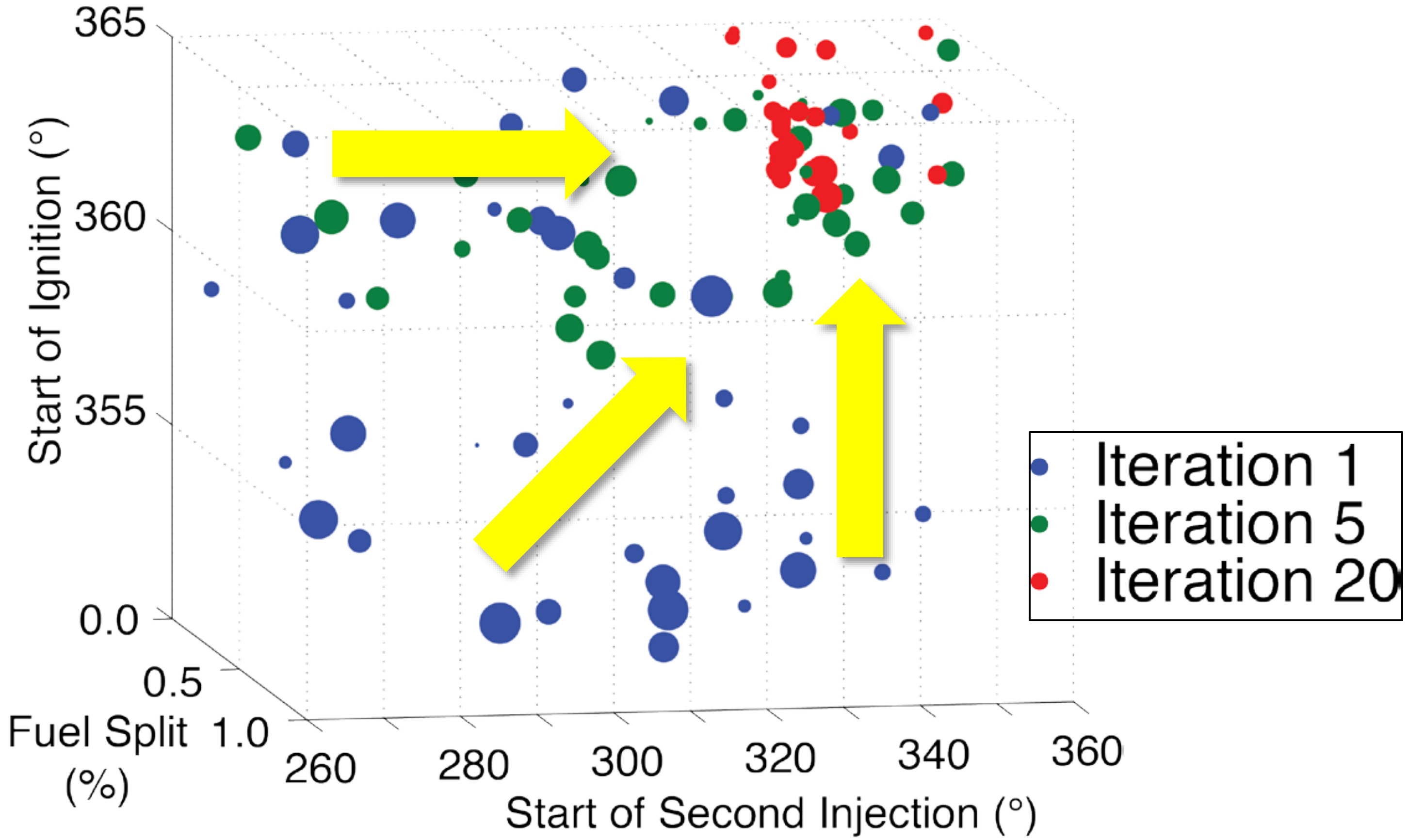
Summary

- Coupling optimization algorithm, playdoh, with engine simulation model, KIVA-3V, to design MJEI-EMC system was a success.
- The optimization process clearly demonstrated the capability of stratified charge to improve GDI engine performance, by minimizing wall impingement.
- Variable injection timing and injection angles were both key design parameters in reducing engine combustion emissions wile increasing efficiencies.
- Data collection of MJEI-EMC system combustion characteristics is set to complete by the end of the year, along with corresponding optimized control parameters based on numerical simulations.

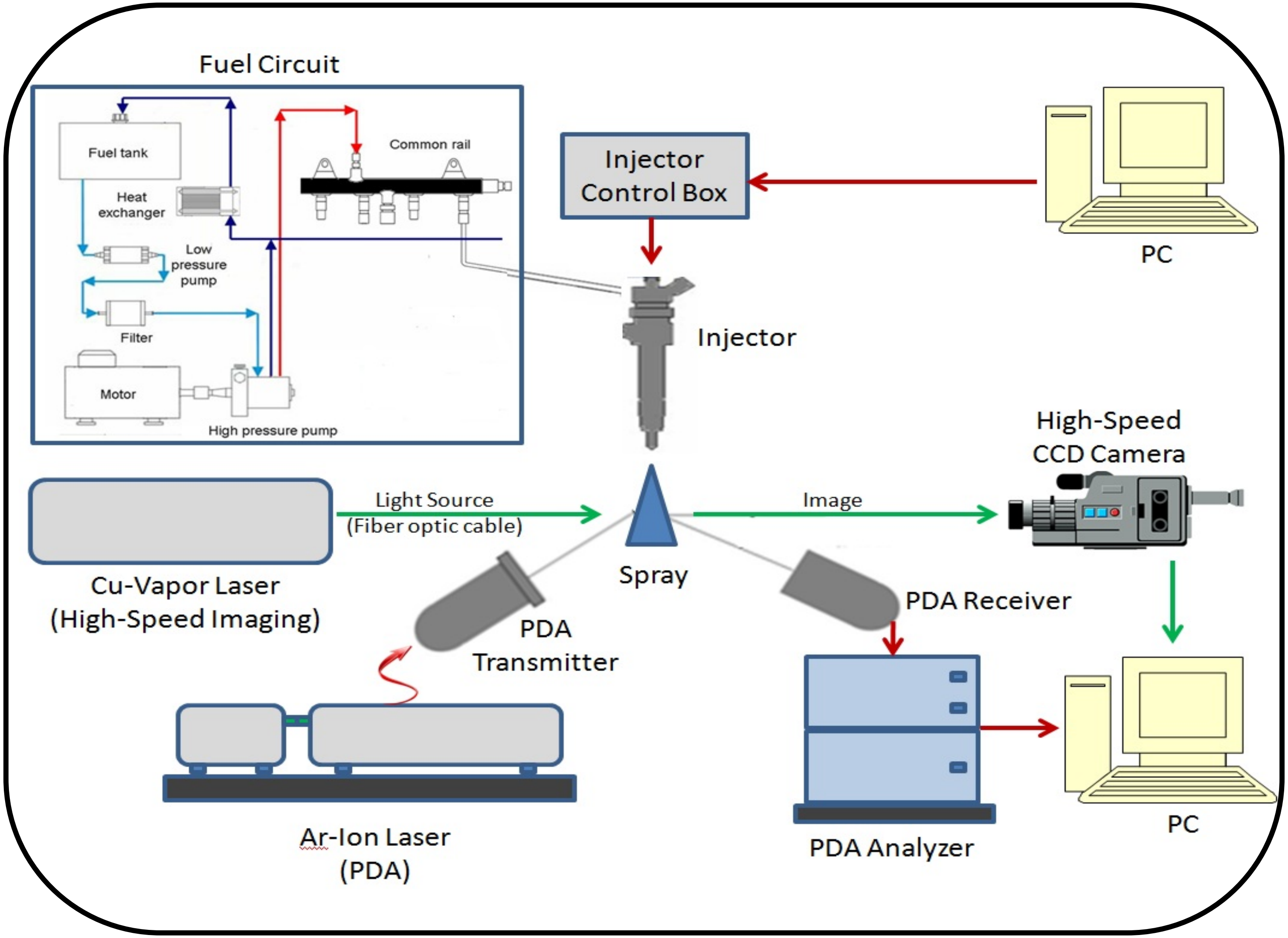
Technical Back-Up Slides

Optimization Process

- Optimized control parameters converge over several generations of iteration by minimizing the target function.

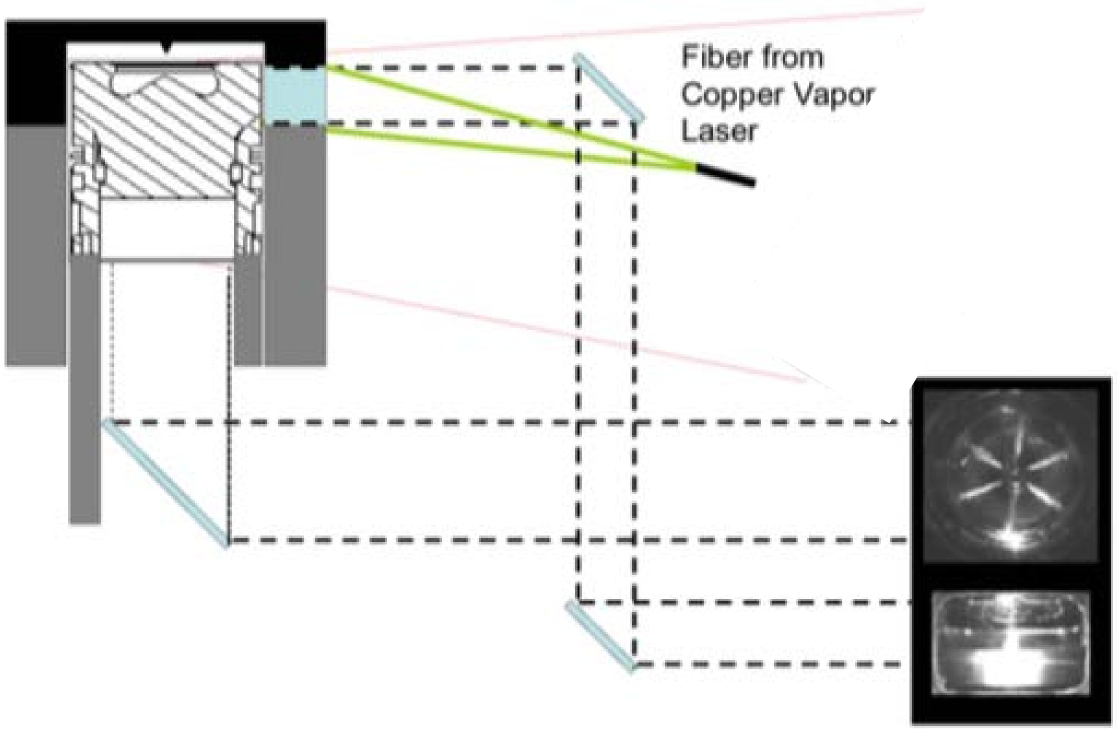


Pray Characterization Setup



Optical Engine Spray Imaging

- Mie-scattering setup for spray imaging inside the engine using copper vapor laser (piston shape shown for illustration purposes only).



Optical Engine Assembly

- Optical piston installed on engine (left) and view through mirror into optical piston before cylinder head installed (right).