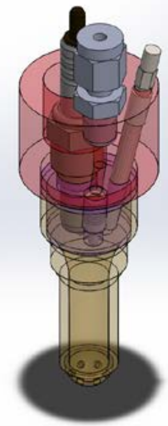
MULTI-MODE COMBUSTION IN LIGHT-DUTY SPARK-IGNITION ENGINES



TOBY ROCKSTROH, ASHISH SHAH

Argonne National Laboratory

Project ID: ACE134

DOE Sponsors: Mike Weismiller, Gurpreet Singh

June 11, 2019

OVERVIEW

Timeline

- Project start: October 2018
- Project end: FY 2021

Budget

- Funding in FY19: $600k

Partners

- Ford Motor Company
- Sandia National Laboratories
- Oak Ridge National Laboratories

Barriers

Improved understanding and further development of low temperature combustion (LTC) strategies for multi-mode (MM) engines

- Narrow Advanced Compression Ignition (ACI) operating range
- Lack of robust engine control strategies for ACI and mode-switching
- Limited understanding of alternative ignition systems for MM engine operation

RELEVANCE

- The Light-duty vehicle corporate average fuel economy (CAFE) regulations for 2025 require a US fleet average **fuel consumption of 54.5 miles per gallon** compared to a 2008 baseline of 25 miles per gallon. **Advanced combustion approaches**, such as low temperature combustion (LTC) are required to meet these targets [1].
- **Low temperature combustion concepts** have been shown to exhibit Diesel like efficiency with low NOx and soot, but high load operation is limited [2].
- **Multi-mode operation** for gasoline engines is an attractive means to improve part-load efficiency while maintaining SI performance at high load.
- The use of **pre-chamber ignition systems** for lean and/or EGR dilute SI combustion have shown promising results [3].
- Recent investigations have highlighted the potential of spark assisted compression ignition **(SACI) using a pre-chamber** [4].
- More insight needed to **characterize combustion behavior** in pre-chambers and investigate pre-chamber assisted compression ignition (PCACI).

1. US DRIVE Advanced Combustion and Emission Control (ACEC) Technical Roadmap for Light-Duty Powertrains, 2018.
2. Sellnau, M., Moore, W., Sinnamon, J., Hoyer, K. et al., SAE Int. J. Engines 8(2):2015, doi:10.4271/2015-01-0834.
3. Bunce, M. and Blaxill, H., SAE Technical Paper 2016-01-0709, 2016.
4. Koch, D., Berger, V., Bittel, A., Gschwandtner, M. et al., SAE Technical Paper 2019-01-0039, 2019.

OBJECTIVES

Maximize the thermal efficiency of light-duty gasoline engines through ACI operation and pre-chamber ignition

- **Evaluate** the constraints of ACI operation and the potential for pre-chamber assisted compression ignition on a GDI engine platform
- **Focus** on advanced combustion systems to improve fuel efficiency and reduce emissions based on ACEC guidelines
- **Research** the combustion behavior in pre-chambers to broaden the knowledge on EGR-dilute SI and ACI operation
- **Develop** robust engine combustion control methodologies:
  - Using conventional ACI operating strategies – intake air heating and boosting, EGR, mixture stratification
  - Evaluate control methodologies by utilizing static autoignition data
  - Develop pre-chamber assisted compression ignition strategies

MILESTONES

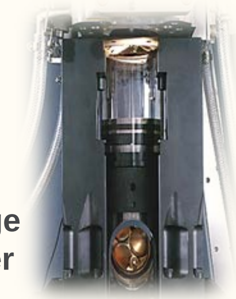
Mo./Year	Description	Status
06/2019	Complete parametric engine control approach study for multi-mode operation with 87 AKI gasoline	On Track
09/2016	Design and implement ACI pre-chamber ignition (PCI) system	On Track
06/2020	*Analyze pre-chamber combustion products in an inert environment and characterize via GC - collaboration with Isaac Ekoto (SNL)*	*Planned*
06/2020	*Commission active pre-chamber ignition system on single cylinder engine*	*Planned*
09/2020	*Characterize the potential of pre-chamber assisted compression ignition on a multi-mode engine*	*Planned*

APPROACH

Argonne NATIONAL LABORATORY

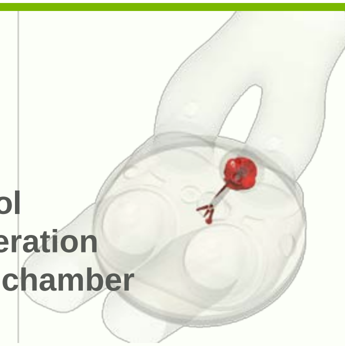
– **Identify ACI operating range and effects of engine control parameters**
– **Formulate engine control methodology for ACI operation using AKI 87 gasoline**
– **Implementation of a pre-chamber ignition system towards enabling pre-chamber assisted compression ignition**

Sandia National Laboratories



PI: I. Ekoto
– **Pre-chamber investigation - Information and data exchange**
– **Characterize ANL pre-chamber combustion products at SNL**

Argonne NATIONAL LABORATORY



PI: R. Scarcelli
– **Describe engine control parameters for ACI operation**
– **CFD simulation of pre-chamber combustion**

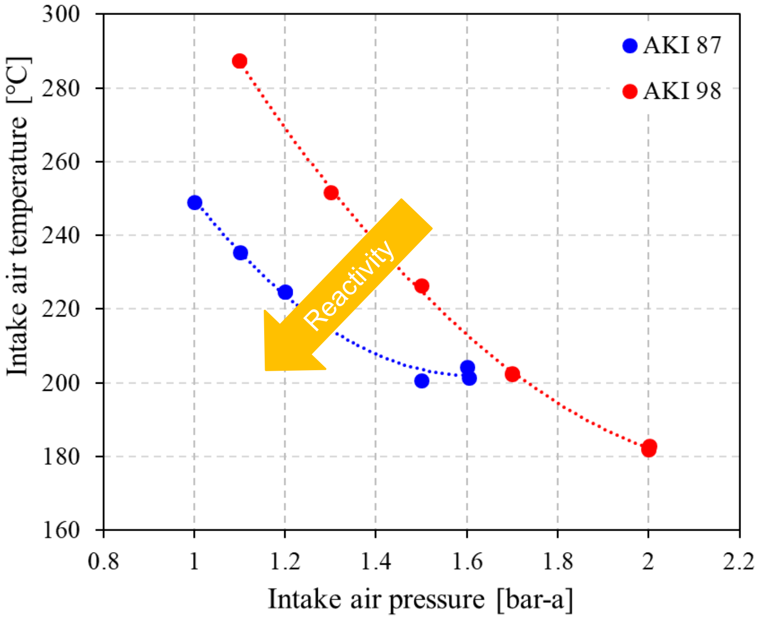
Argonne NATIONAL LABORATORY

PI: S. Goldsborough
– **High fidelity ignition delay data from a rapid compression machine**
– **Characterize combustion behavior at engine-relevant conditions**

ACCOMPLISHMENTS FY19

ACI engine operation

- **Engine operating conditions:**
  - Compression Ratio trade-off to enable SI and ACI operation – CR 11.3:1.
  - qHCCI (no EGR) scoping tests using AKI 87 and AKI 98 highlighted the intake air conditions required to attain low load (~4 bar IMEP) ACI operation.
  - **Significant intake air heating or boosting required to attain ACI operation at SI relevant compression ratios.**
  - Ongoing efforts to characterize the use of hot residuals and partial fuel stratification for low to medium load ACI on a multi-mode engine platform.

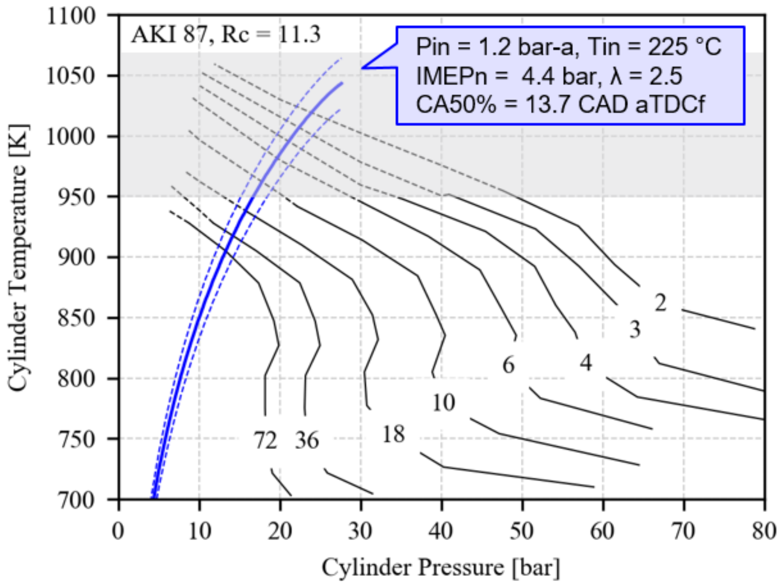


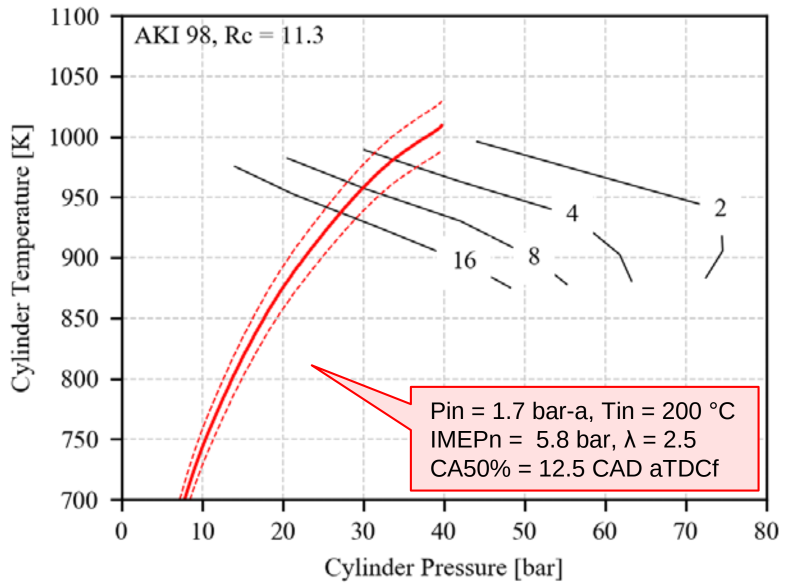
Argonne NATIONAL LABORATORY

ACCOMPLISHMENTS FY19

ACI engine operation

- **Engine operating conditions:**
  - Analysis of autoignition delay characteristics of AKI87 and AKI 97 fuels from RCM experiments at engine relevant operating conditions – Scott Goldsborough (ANL).
    - Contour maps of ignition delays – λ = 2.5, 21% O_2
  - Comprehensive AKI87 ignition delay dataset enabled extrapolation into intermediate temperature chemistry range.
  - Engine compression trajectories suggest start of combustion to correlate with ~ 1.5 ms (AKI 87) and ~ 2 ms (AKI 98), respectively.

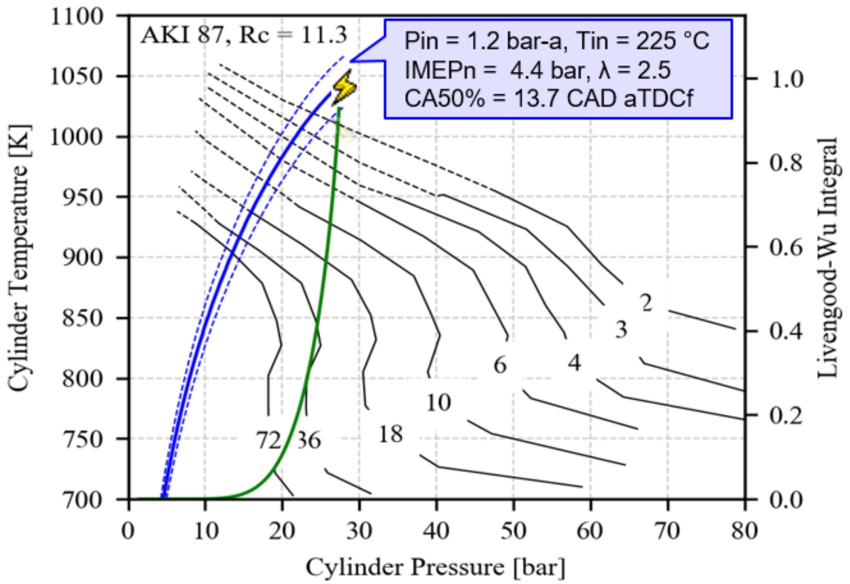




ACCOMPLISHMENTS FY19

ACI Operation using AKI 87

- **Engine operating conditions:**
  - In order to capture the chemical reaction time intervals during compression in the engine, the Livengood-Wu integral can be applied to the AKI87 RCM dataset
    - Start of combustion occurs when the integral reaches unity: $\int \frac{1}{\tau} dt = 1$
    - Uncertainties associates with cylinder temperature estimation
  - Livengood-Wu integral reaches unity at ~ 1045K / 27 bar corresponding to ~ 1.5 ms
  - Continue investigation to assess the potential of a combustion phasing control method over a wider range of ACI operating conditions



ACCOMPLISHMENTS FY19

Pre-chamber design

- **Design considerations:**

Engine Constraints

- Pent-roof head – avoid pre-chamber jet impingement
- Space constraints around M14 spark plug port - 20 degree incline to cylinder vertical axis
- No cooling arrangements in the cylinder head for pre-chamber

Pre-chamber Type

- Active pre-chamber required
- Pre-chamber size constrains gasoline direct injector installation
- Fuel delivery via check valve – well characterized mixture prepared upstream

Pre-chamber design

- Modular design to enable a range of pre-chamber volume and nozzle configurations
- Pre-chamber volume and nozzle geometry range obtained from existing literature, e.g. SAE2011-01-0664, SAE790692

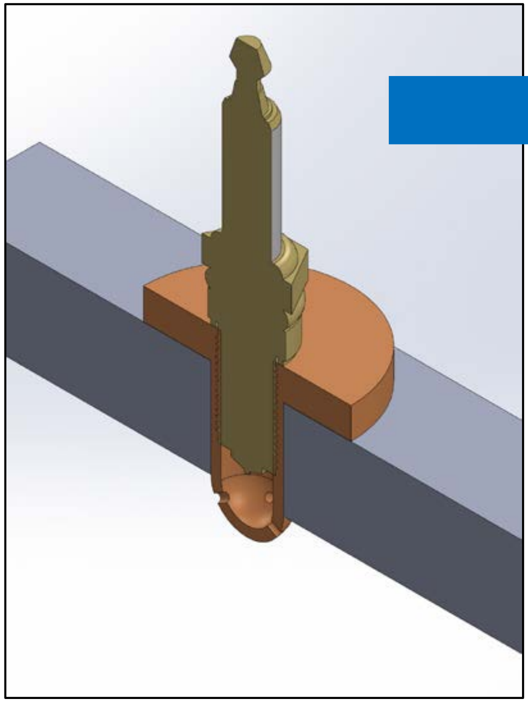
Material selection

- Cost effective and easily machinable
- 4130 Alloy Steel – established track record in pre-chamber gas engine research

ACCOMPLISHMENTS FY19

Pre-chamber design

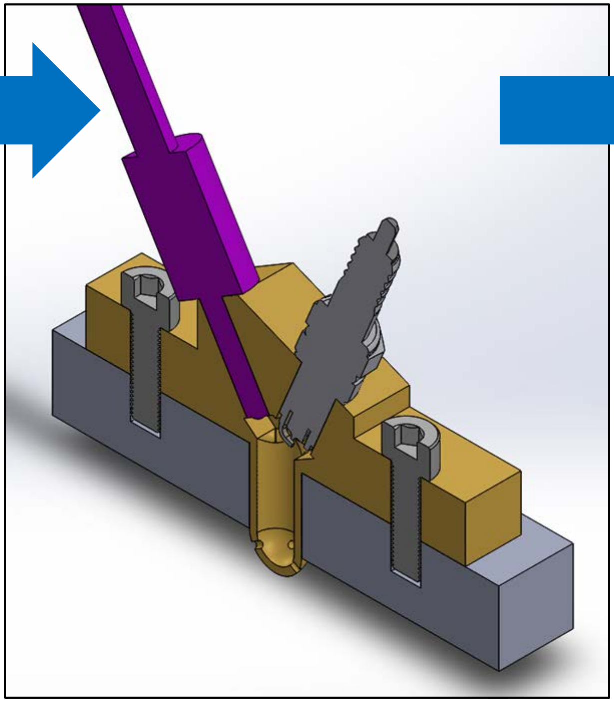
Concept 1 – October 2018



Design considerations
- Central spark plug
- Pre-changer volume and nozzle area flexibility

Constraints
- Cylinder head space constraints
- Passive pre-chamber

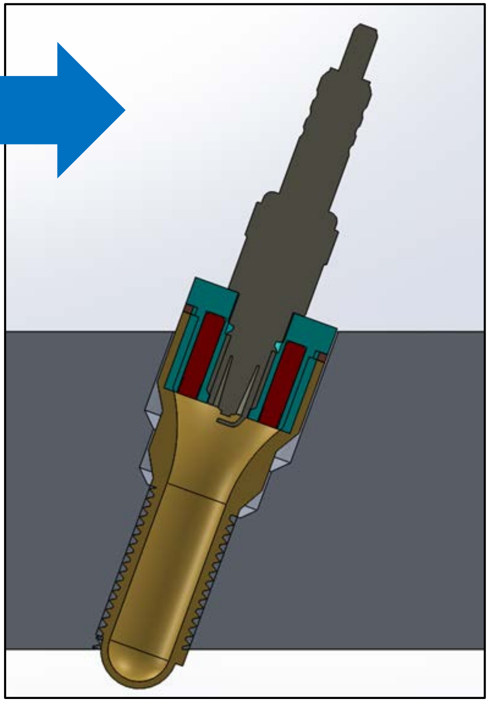
Concept 2 – November 2018



Design considerations
- Active pre-chamber
- Pre-chamber volume and nozzle area fixed

Constraints
- Cylinder head modification required
- Injector matching complexity

Concept 3 – February 2019



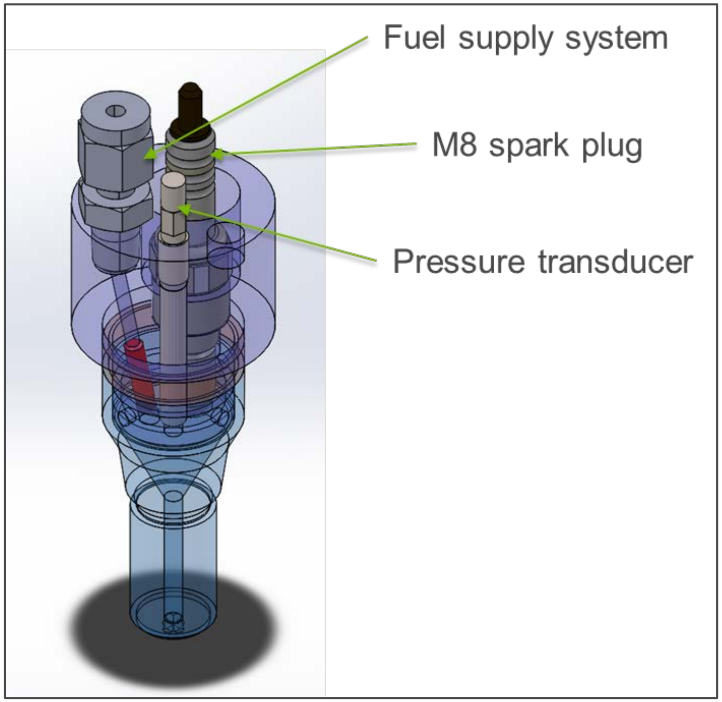
Design considerations
- Active pre-chamber
- Central spark plug
- Multi check-valve fuel delivery

Constraints
- Check valve size constraints – possibility of soot fouling

ACCOMPLISHMENTS FY19

Pre-chamber prototype

Final Concept – March 2019



Prototype – April 2019

Design considerations

- Modular design – separate pre-chamber head and body
- Adapted for spark plug port in existing cylinder head
- Flexibility changing pre-chamber volume and nozzle area
- Air/fuel supply via single check valve

Constraints

- Dimensional restrictions on pre-chamber assembly
- Upstream air/fuel mixture system required

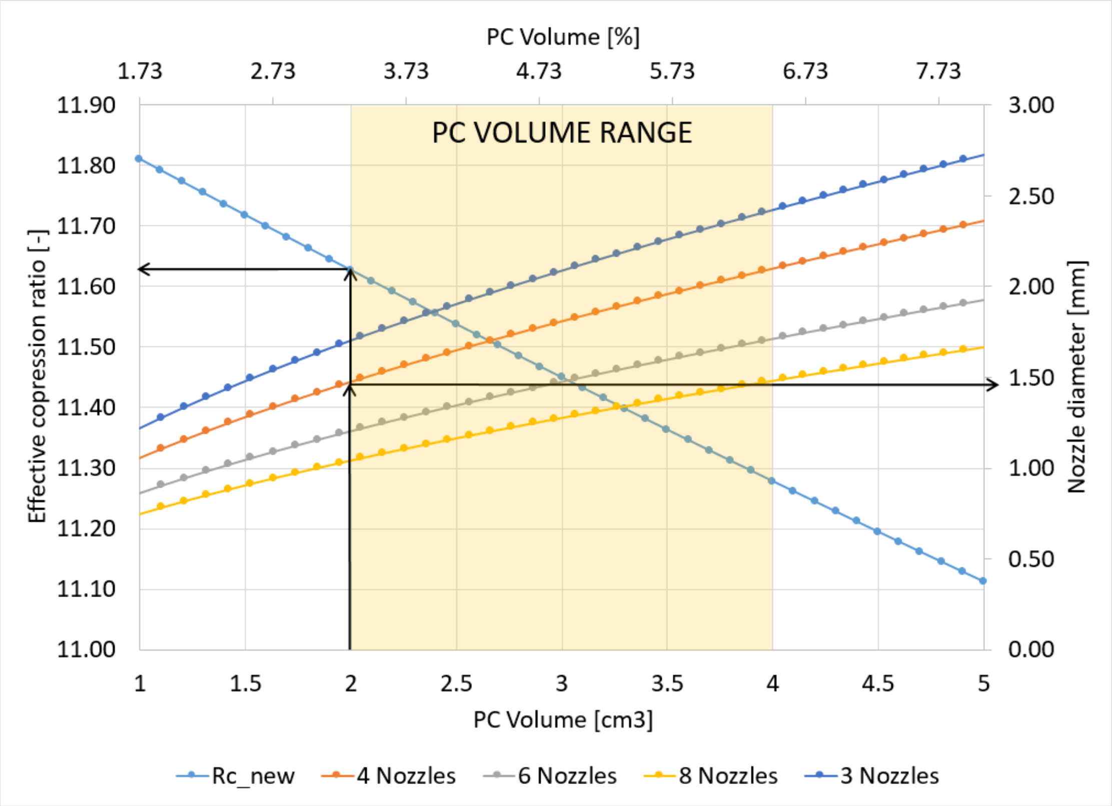
Commissioning

- Installation on single cylinder engine
- Passive pre-chamber operation - air/fuel supply port blocked
- Scoping tests conducted

ACCOMPLISHMENTS FY19

Pre-chamber geometry

- **Chamber volume / nozzle geometry:**
  - Pre-chamber volume configurable from 2 – 4 cm^3 (~3 – 6.5 % of clearance volume)
  - First pre-chamber configuration investigated:
    - 2 cm^3 pre-chamber volume => effective compression ratio of 11.62:1
    - 4 nozzles with 1.5 mm nozzle diameter



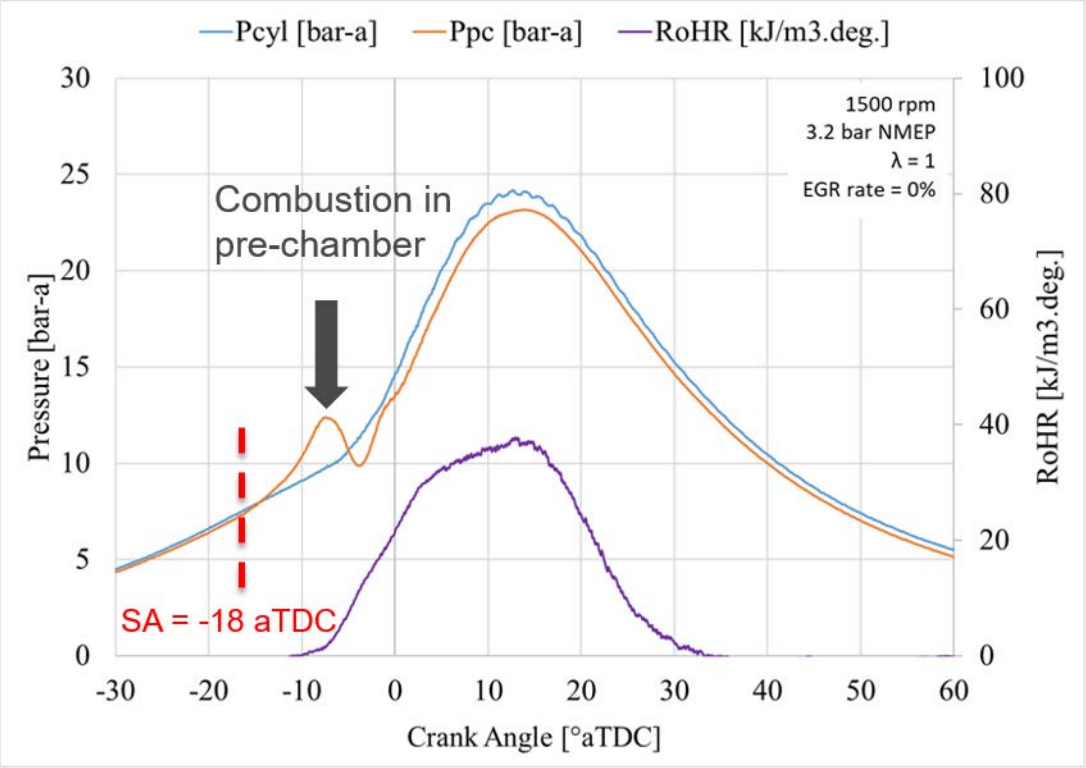
Argonne NATIONAL LABORATORY

ACCOMPLISHMENTS FY19

Pre-chamber combustion

Preliminary scoping test results:

- Engine operation at 1500 rpm – 3.2 bar IMEP
- Successful implementation of a passive pre-chamber
- Ongoing efforts to characterize the light/medium load operating range

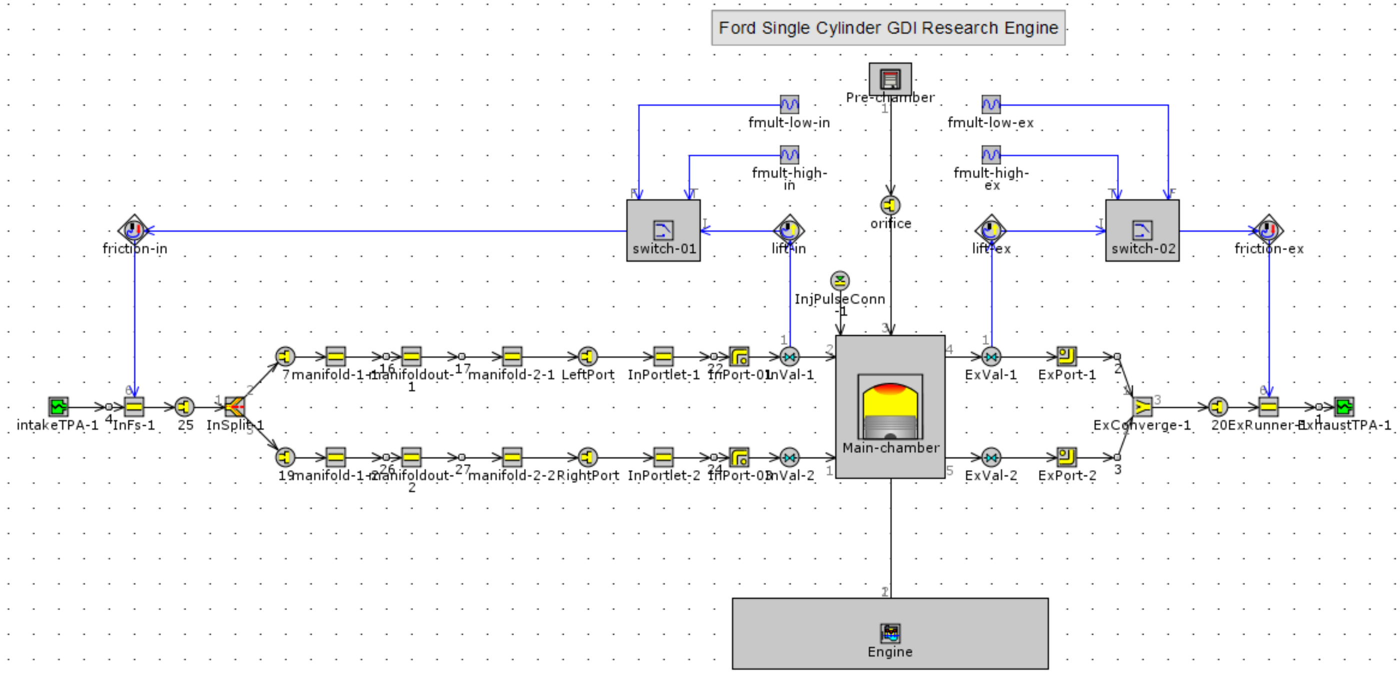


ACCOMPLISHMENTS FY19

Pre-chamber combustion

GT-Power model development:

- Three pressure analysis (TPA) model of the Ford Single cylinder engine
- Implementation of pre-chamber system
- Model validation is ongoing



Argonne NATIONAL LABORATORY

RESPONSE TO REVIEWER COMMENTS

Project# ACE134 “Multi-mode combustion in light-duty spark-ignition Engines” is a new project for FY19 and was not reviewed last year.

COLLABORATION AND COORDINATION

- **Ford Motor Company**
  - Engine hardware support
  - Project guidance with regular conference calls
- **USCAR**
  - Prioritization of research efforts
  - Development of single cylinder engine test protocols
- **Sandia National Laboratory**
  - Data sharing and exchange of ideas on pre-chamber system analysis
  - Characterizing pre-chamber combustion products
- **Light-duty Combustion Consortium**

REMAINING CHALLENGES AND BARRIERS

- The **limited ACI operating range** achievable in multi-mode engine platforms severely **restricts the potential fuel efficiency gains**, and thereby impedes meeting the project objectives in attaining a significant increase in thermal efficiency with respect to the baseline spark ignition engine configuration.

- The **limited fundamental knowledge of pre-chamber combustion systems**, especially for adaption in LTC compression ignition mode, is a significant **barrier for the development and widespread adoption** of such systems.

PROPOSED FUTURE WORK

- **Three-level factorial experimental design – FY19**
  - Assess geometric CR trade-off between ACI and high-load SI
  - Establish an ACI operating map by utilizing engine control parameters
    - RPM, intake temperature, boost pressure, EGR%, φ, SOI

- **Passive pre-chamber system – FY19**
  - Characterize the combustion behavior of a passive pre-chamber system
  - Evaluate lean and EGR dilute operation

- **Active pre-chamber system – FY20**
  - Design and implement an active pre-chamber system
  - Measure the exhaust gas temperatures and emissions under retarded combustion phasing towards cold start strategies with a pre-chamber
  - Sample the pre-chamber combustion products in an inert environment and analyze via GC – collaboration with I. Ekoto (SNL)
  - Investigate the potential of pre-chamber assisted compression ignition

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

SUMMARY

Relevance

- Extend the ACI operating map in multi-mode engines
- Investigate pre-chamber combustion system towards multi-mode engine operation

Approach

- Formulate engine control methodology for ACI operation using regular grade gasoline
- Implementation of a pre-chamber ignition system towards enabling pre-chamber assisted compression ignition

Technical accomplishments

- Establish compression ratio trade-off for ACI operation while maintaining high load SI for regular grade gasoline
- Investigate the potential of an ACI combustion phasing control method utilizing static autoignition delay data
- Design and implement a passive pre-chamber ignition system

Remaining Barriers

- Establish methods to enhance the ACI operating range in a multi-mode SI engine
- Define robust combustion control strategies for ACI operation

Future work

- Characterize the combustion behavior in a passive pre-chamber and evaluate the potential for cold start strategies
- Design and implement an active pre-chamber system
- Investigate the potential of pre-chamber assisted compression ignition

Argonne NATIONAL LABORATORY

THANK YOU. QUESTIONS?