COMBUSTION RESEARCH FACILITY

# HCCI and Stratified-Charge CI Engine Combustion Research


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**May 14, 2013 – 9:30 a.m.**

**U.S. DOE, Office of Vehicle Technologies Annual Merit Review and Peer Evaluation**

**Program Manager: Gurpreet Singh**

**Project ID: ACE004**

*This presentation does not contain any proprietary, confidential, or otherwise restricted information.*

# Overview

## Timeline

- Project provides fundamental research to support DOE/Industry advanced engine projects.
- Project directions and continuation are evaluated annually.

## Barriers

- Increase the efficiency of HCCI (LTC).
- Extend HCCI (LTC) operating range to higher loads.
- Improve the understanding of in-cylinder processes.

## Budget

- Project funded by DOE/VT:
  FY12 – $760k
  FY13 – $740k

## Partners / Collaborators

- Project Lead: Sandia ⇒ John E. Dec
- Part of Advanced Engine Combustion working group – 15 industrial partners
- General Motors – specific collaboration
- Cummins – spark-plug cylinder heads
- LLNL – support kinetic modeling
  – CFD modeling
- Univ. of Michigan – thermal stratification
- Univ. of Calif. Berkeley – CFD modeling
- Chevron – advanced fuels for HCCI
- LDRD – advanced biofuels project

# Objectives - Relevance

**Project objective: to provide the fundamental understanding (science-base) required to overcome the technical barriers to the development of practical HCCI or SCCI engines by industry.**

**FY13 Objectives ⇒ Increased Efficiency, High Loads, Improved Understanding**

- Effects of Gasoline Ethanol Content: Complete investigation of the effects of ethanol content of gasoline on HCCI/SCCI efficiency and load.
- Improve Efficiency of HCCI/SCCI: Determine the potential of raising the compression ratio (CR) to16:1 vs. 14:1 to increase thermal efficiency (T-E) for both premixed fueling and with partial fuel stratification (PFS).
- Thermal Stratification (TS) Imaging: 1) Investigate the effect of piston-top temperatures on TS & cold-pocket distribution. 2) Explore the potential for obtaining thermal boundary-layer (BL) measurements from T-map images.
- Facility Upgrade for spark-assisted HCCI & higher GDI injection pressures.
- Support Modeling of chemical-kinetics at LLNL and TS at the University of Michigan (UM) and General Motors.

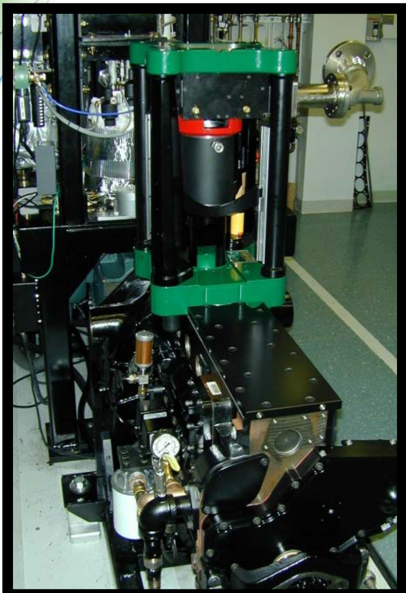
# Approach

- Use a combination of metal- and optical-engine experiments and modeling to build a comprehensive understanding of HCCI/SCCI processes.

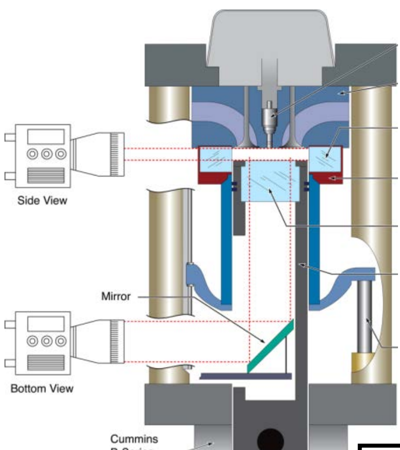
- Metal engine ⇒ high-quality performance data. Conduct well-characterized experiments to isolate specific aspects of HCCI/SCCI combustion.
  - Fuel Effects: Systematically investigate performance for premixed and partially stratified operation with E0, E10, E20, E100, and a high-AKI E0 fuel.
  - Improved efficiency: Install CR = 16 piston and seek the highest-efficiencies and highest-loads for a range of op. conditions. Compare with previous CR = 14 data.
- Optical engine ⇒ detailed investigations of in-cylinder processes.
  - Thermal stratification: Install instrumented aluminum piston top and variable air-jet cooling. Apply PLIF-based thermal imaging to bulk-gas & boundary layer (BL).
- Facility upgrade: Work with Cummins to modify heads for spark plugs, and with GM to obtain a high-pressure (300 bar) GDI injector and driver.
- Computational Modeling: Collaborate with LLNL, UM & GM, and UC-B. ⇒ Support by identifying key trends, providing data, discussion & feedback.
- Combination of techniques provides a more complete understanding.
- Transfer results to industry: 1) physical understanding, 2) improved models.

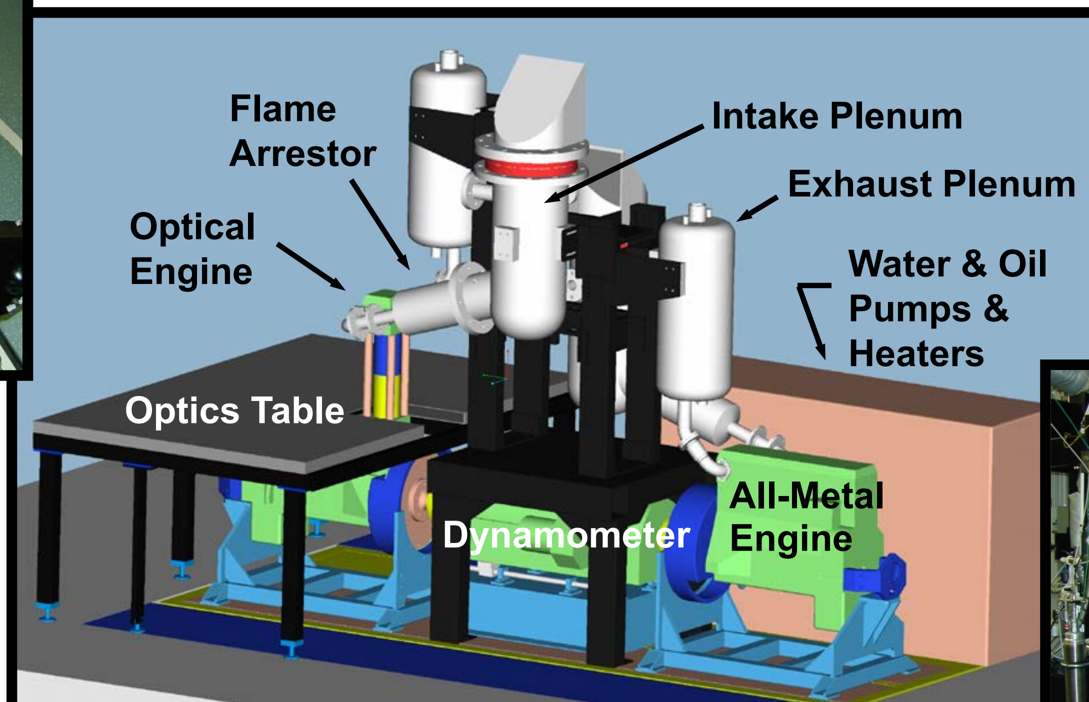
# Sandia HCCI / SCCI Engine Laboratory

- Matching all-metal & optical HCCI research engines.
  - Single-cylinder conversion from Cummins B-series diesel.

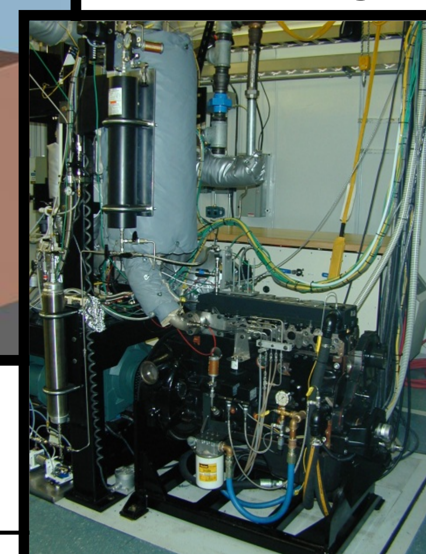


Optical Engine




All-Metal Engine



- Bore x Stroke = 102 x 120 mm
- 0.98 liters, CR=14 & 16

**Unless noted: Ringing ≤ 5 MW/m² & spd = 1200 rpm**
**$NO_x$ & soot emiss. > 10x below US-2010**

# Accomplishments

- Completed evaluation of performance affects of increasing ethanol content of gasoline, from E0 ⇨ E10 ⇨ E20. (Base fuel, E0 ⇒ AKI = 87, regular gas).
  - Evaluated effects on stability, efficiency, high-load limit, and ability to apply PFS.
- ♦ Expanded fuels study to include: **1)** E100 (pure ethanol), and **2)** effects of changing the base fuel composition ⇒ high AKI = 93 distillate fuel (CF-E0).
  - Evaluated performance and compared with ethanol addition.
- Determined the effect of increasing the CR from 14 to 16 on performance for both fully premixed and partially fuel stratified (PFS) operation.
  - Study is about 70% complete ⇒ on track to complete this FY.
- Optical Engine: designed and installed aluminum piston with variable air-jet cooling, & evaluated vignetting/camera-position effects for BL measurement.
  - On track to obtain TS and BL data as planned this FY.
- With Cummins, designed and fabricated spark-plug cylinder heads, and with GM, acquired ignition systems & high-pressure GDI injectors.
- ♦ Conducted a comparative study of Combustion Noise and Ringing Intensity.
- Supported chemical-kinetic & CFD modeling at LLNL, and TS modeling at U. Michigan & GM. Expanded task to include CFD at UC-Berkeley.

# Effects of Gasoline Reactivity and Ethanol Content on Boosted HCCI / SCCI Combustion

- Efforts in HCCI/SCCI are moving toward a greater emphasis on high-load capabilities ⇒ potential for a full-time HCCI/SCCI-LTC engine.
- Important to understand how **fuel reactivity** can improve boosted HCCI performance: 1) stability, 2) efficiency, and 3) high-load capability.
  1. Vary the ethanol content of gasoline: **E0, E10, E20, & E100**.
     > E10 and E20 ⇒ add 10 & 20% ethanol to base fuel **(E0)** ⇒ antiknock index, **AKI = 87**.
     ⇒ Eliminates effect of changes in base-fuel composition, but increases AKI.
  2. Increase the AKI of base fuel with no ethanol.
     > Certification fuel **(CF-E0)** ⇒ a high-octane distillate fuel, **AKI = 93**.
- AKI of E0 base-fuel increases progressively with ethanol content.

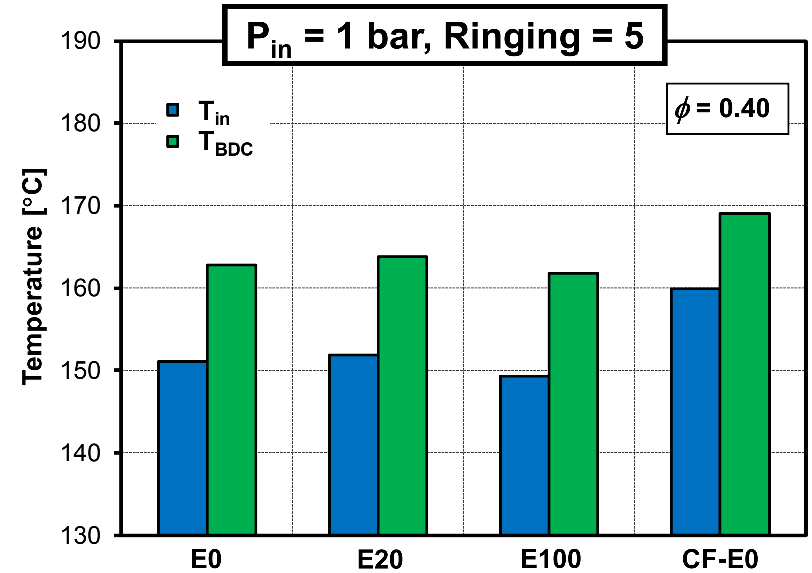
| | RON | MON | AKI SAE 2012-01-1274 | AKI Ethanol – linear blending |
|---|---|---|---|---|
| E0 | 91.0 | 82.7 | 86.9 | N/A |
| E10 | 95 | 86 | 90.5 | 88.2 |
| E20 | 98 | 87.5 | 92.8 | 89.4 |
| E100 | 109 | 90 | 99.5 | N/A |
| CF-E0 | 96.6 | 88.7 | 92.7 | N/A |

**CR = 14 for Fuels Study**

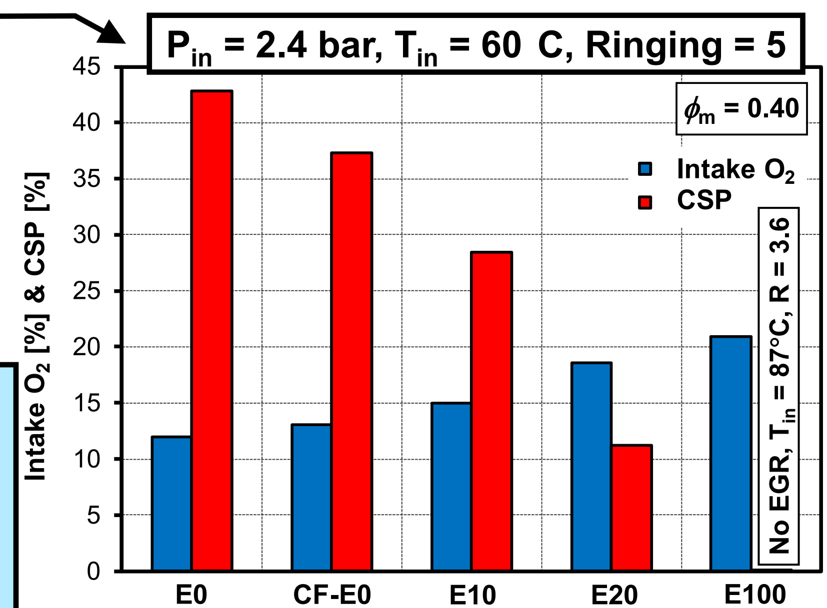
- CF-E0: AKI nearly the same as E20, RON is between E10 and E20.

# HCCI Autoignition Reactivity – Fully Premixed

- Naturally Aspirated:
  - E0, E20 & E100 all autoignite with nearly identical $\mathbf{T_{in}}$ and $\mathbf{T_{BDC}}$.
  - CF-E0 requires ~ 8°C hotter $T_{in}$.



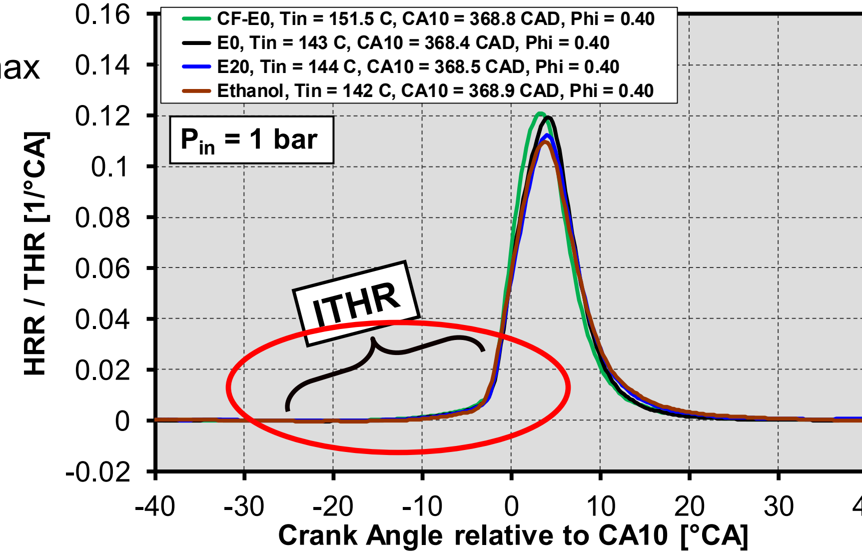

- The autoignition reactivity of all fuels increases with boost.
  - Compensate with reduced $T_{in}$ & EGR.
  - Select $T_{in}$ = 60 C as min. for premixed.
- $P_{in}$ = 2.4 bar, typical boosted behavior **Intake $O_2$** & **CSP** show amt. of EGR.
  - **Intake-$O_2$:** E0 < E10 < E20 < E100
  - Reactivity enhancement with boost is inversely correlated w/ ethanol content.
  - CF-E0 falls between E0 and E10.
    ⇒ Despite AKI ≈ AKI of E20.

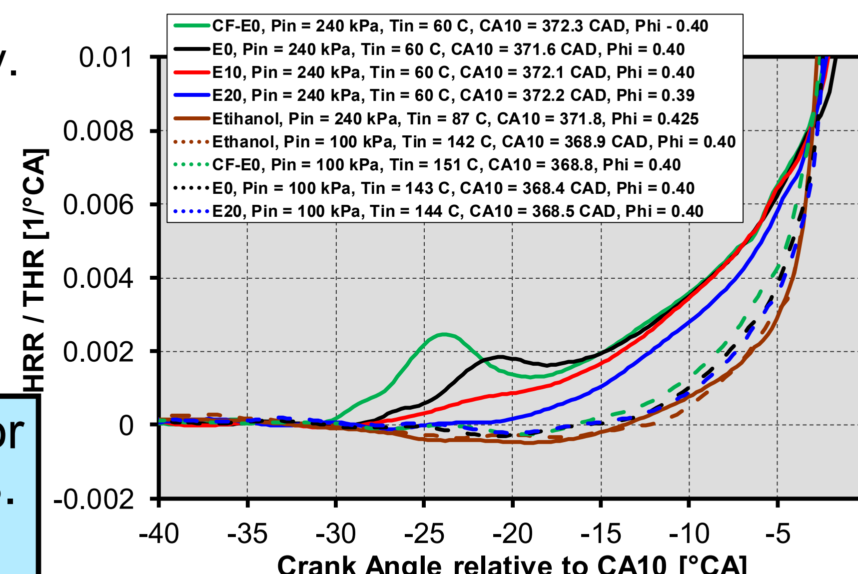



- Ethanol content ⇒ no effect nat. aspir.
  ⇒Strong effect on reactivity for boosted
- CF-E0 less reactive than E0, N.A. & boost
- ON not a good indicator of HCCI reactivity

# Stability – Effect of Fuel Type and $P_{in}$ on ITHR

- Key to high-loads is ability to retard CA50 with good stability to ctrl. $PRR_{max}$
- ITHR keeps $dT/d\theta$ rising despite expansion, giving good stability.
- $P_{in}$ = 1 bar: all fuels show low ITHR.
  - Retard limited to **CA50 ≈ 373 CA**.
- Boosted, $P_{in}$ = 2.4 bar (typical):
  - E0 & CF-E0 show large incr. in ITHR ⇒ good stability to **CA50 ≈ 379 CA**.
  - E100 no change in ITHR, poor stability.
  - E10 similar ITHR to E0.
  - E20 between E0 and E100.
- Amount of ITHR also correlates with $\phi$-sensitivity & ability to apply PFS.




- E0, E10 & CF-E0: expect good stability for high-load boosted oper., premixed & PFS.
- E100: poor stability & E20: in between

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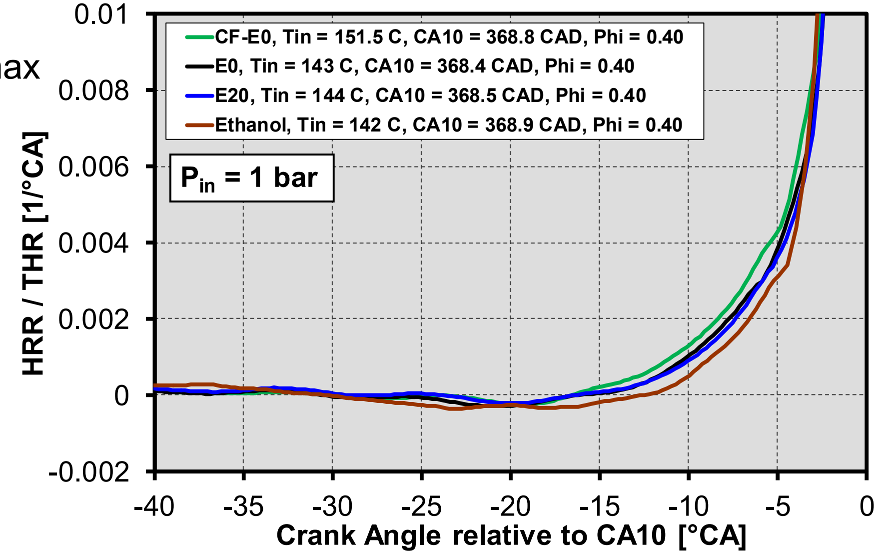


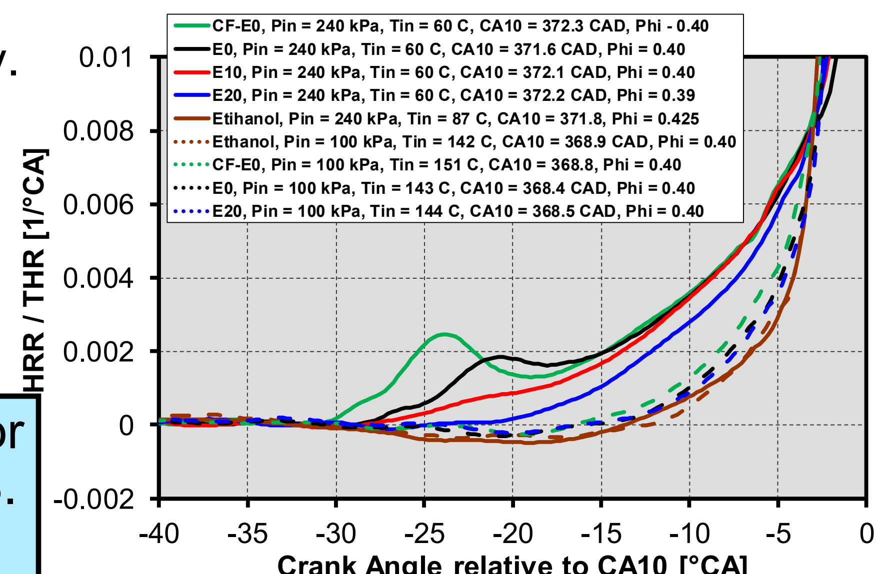


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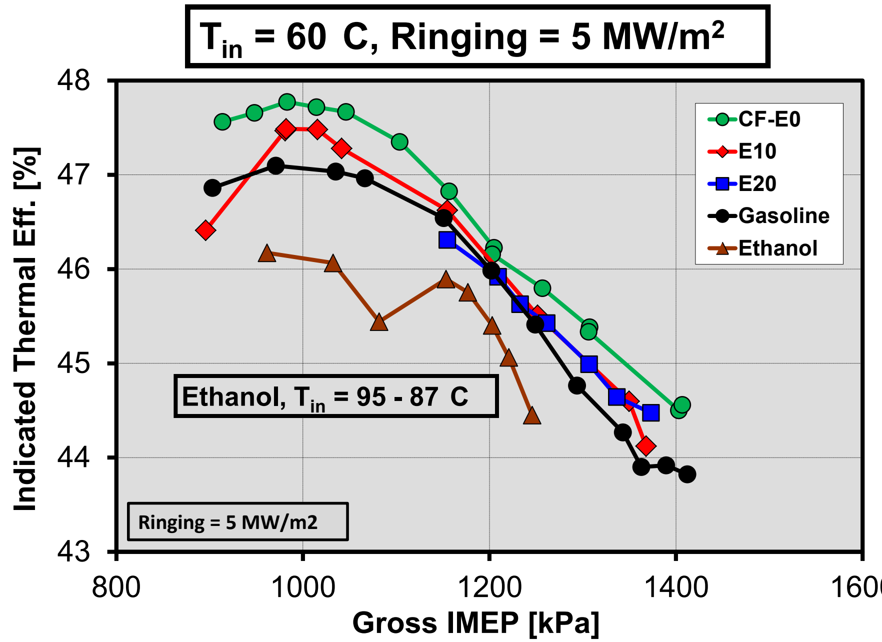
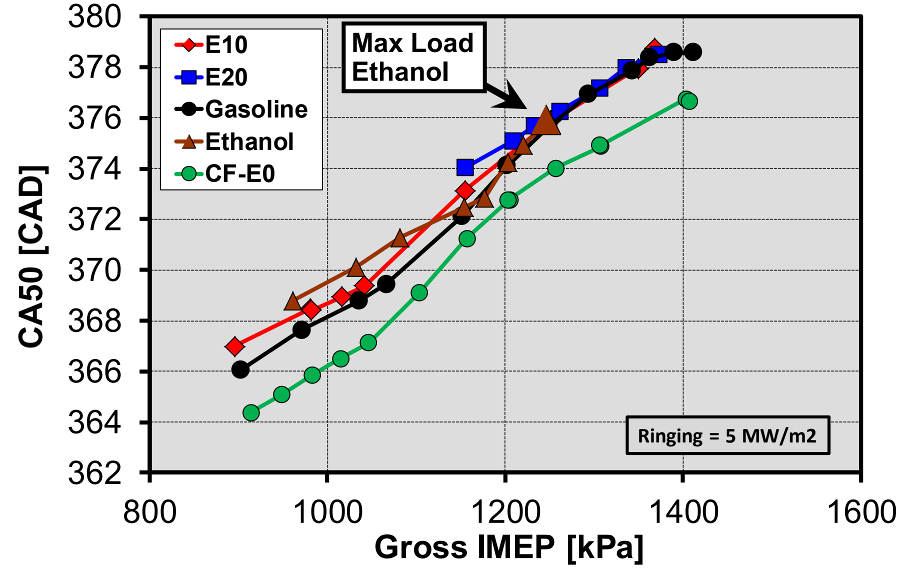
# Efficiency – Premixed Fueling, $P_{in}$ = 2.4 bar

- T-E falls with load due to CA50 retard.
- Indicated Thermal Eff. (T-E) and max. load very similar for E0, E10 & E20.
  - Changes in EGR & C-E tend to cancel.
  - No low loads for E20 – need higher $T_{in}$.
  - E20 max. load & CA50 retard similar despite less ITHR.
- Ethanol requires $T_{in}$ = 95 - 87 C.
  - Lower T-E ⇒ more heat loss & lower γ.
  - CA50 v. load similar, but max. load is less ⇒ low ITHR limits CA50 retard.
  - Much less stable for loads acquired.
- CF-E0 similar load range, higher T-E.
  - Higher sensitivity to TS, slows HR.
  - Allows CA50 to be more advanced.

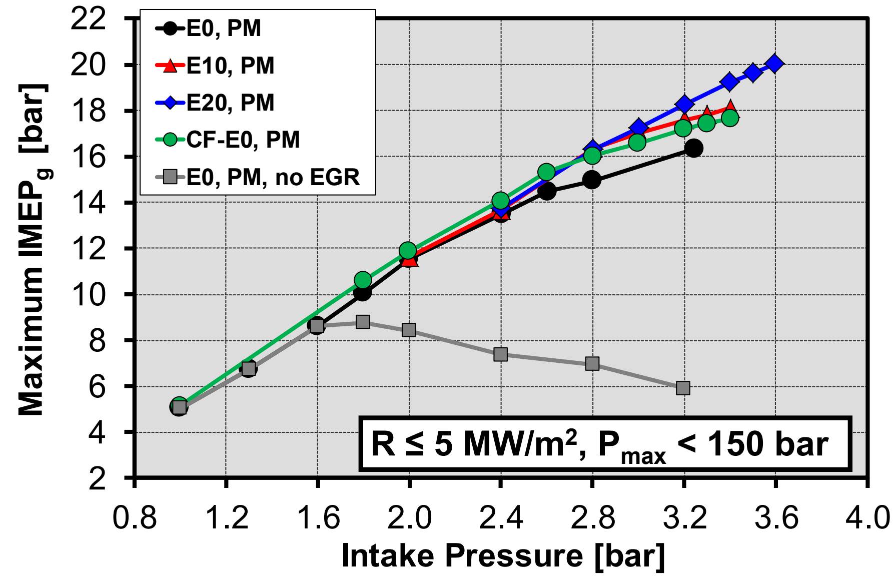


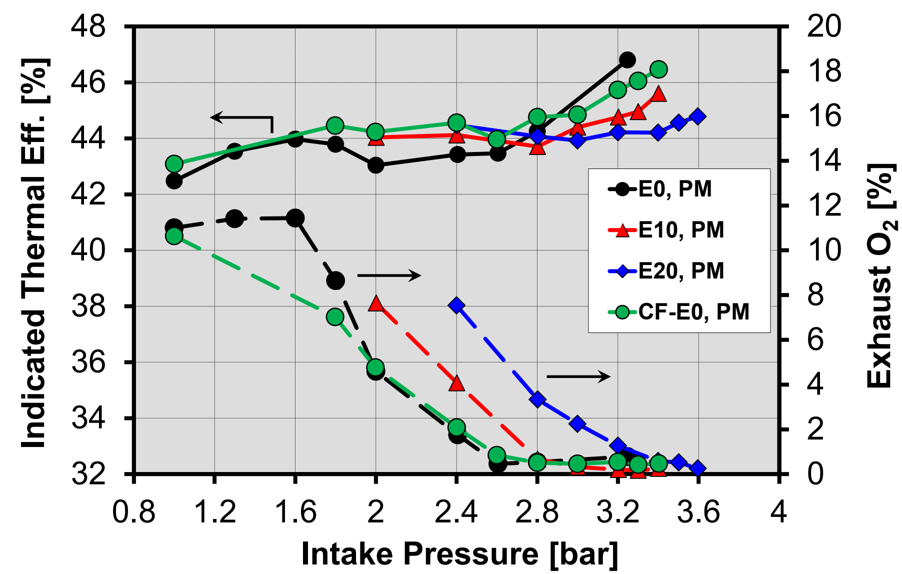




- For premixed fueling, $T_{in}$ & CA50 are the main factors affecting T-E.
⇒ CF-E0 gives a little better T-E.

# High-Load Limit – Premixed (PM)

- Gasoline reactivity increases w/ boost ⇒ use EGR to control CA50.
- **E0**: $O_2$ limited for $P_{in} \geq 2.6$ bar ⇒ Load limit = 16.3 bar $IMEP_g$.
- Blending with ethanol significantly reduces EGR requirement with boost.
  - More air in charge ⇒ higher fueling.
- **E10**: ⇒ $O_2$ limited for $P_{in} \geq 2.8$ bar ⇒ Load limit = 18.1 bar $IMEP_g$.
- **E20**: ⇒ $O_2$ limited for $P_{in} \geq 3.6$ bar ⇒ **Load limit = 20.0 bar $IMEP_g$.**
- **CF-E0**: ⇒ $O_2$ limited for $P_{in} \geq 2.7$ bar ⇒ Load limit = 17.7 bar $IMEP_g$.
- Higher T-E for CF-E0 mainly due to less required CA50 retard for Ring ≤ 5.
- Ringing ≤ 5, ultra-low $NO_X$ & soot.
- High-loads limited by $P_{max} < 150$ bar

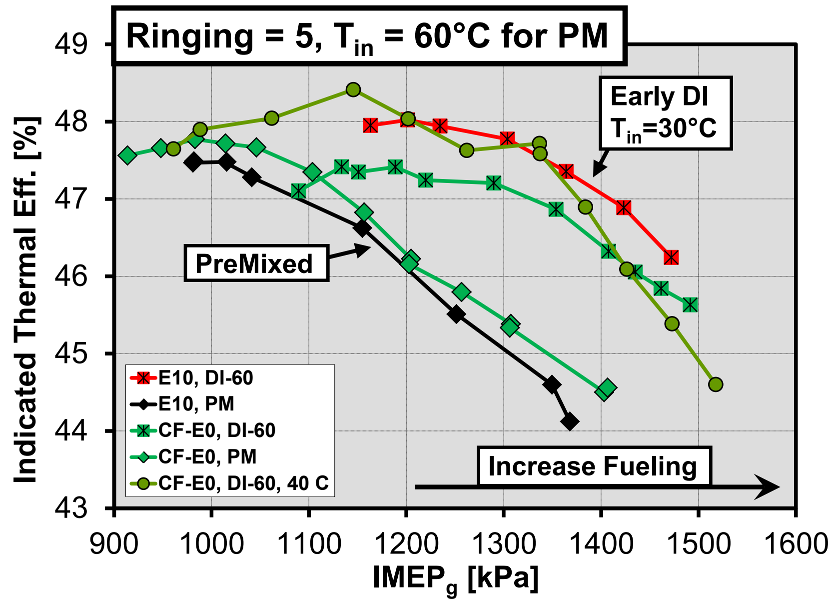


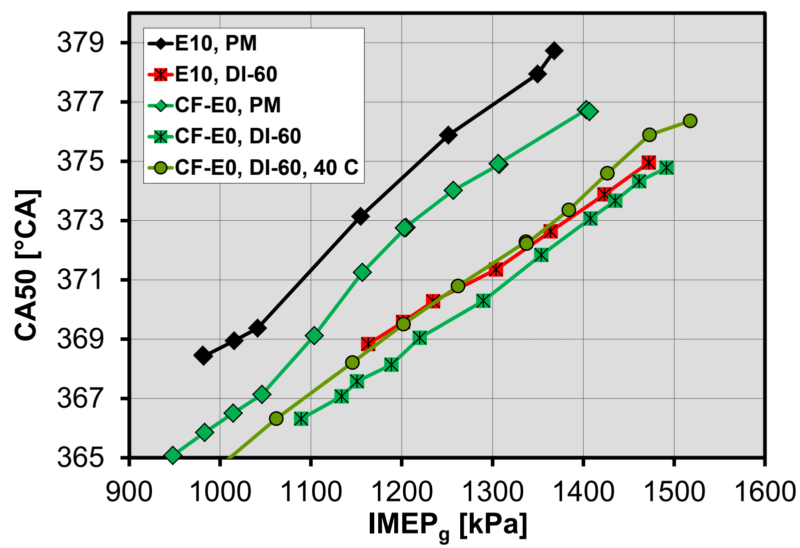



# Fueling Strategies – PM, Std. PFS & Early-DI

## Results for E10 & CF-E0 at $P_{in}$ = 2.4 bar

- With boost, fuel autoignition becomes ϕ-sensitive, so partial fuel strat. (PFS) can reduce HRR.
  - Allows higher loads & more adv. CA50.
  - Std. PFS ⇒ Premix ~90% + late-DI
  - Early-DI ⇒ 100% at 60° CA, & lower $T_{in}$.
    - PLIF images show not fully mixed.
- **E10**: Std. PFS & Early-DI both increase T-E significantly for the same load.
  - Adv. CA50, & early-DI ⇒ lower $T_{in}$ & $T_{peak}$.
  - Also increase max. load compared to PM
  - E0: similar improvements (not shown).
- **CF-E0**: Like E10, Early-DI increases T-E and max. load compared to PM.
  - $T_{in}$ = 30°C, peak T-E of E-DI < PM & E10.
  - $T_{in}$ = 40°C, peak T-E of E-DI > PM & E10
    - **Maximum T-E = 48.4%**, best yet.




- Both fuels, Early-DI PFS significantly improves T-E & increases max. load.

# Fueling Strategies – PM & Early-DI
## Results for E10, E20, & CF-E0 at $P_{in}$ = 2.8 bar

**E20**: requires higher $P_{in}$ for signif. ϕ-sensitivity.

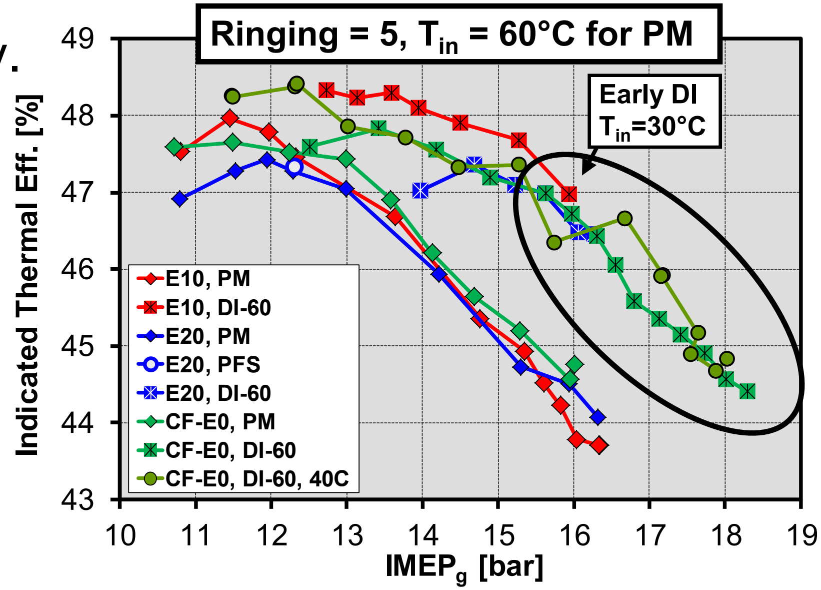
- PM: load sweep similar to $P_{in}$ = 2.4 bar.
- Std. PFS: very unstable ⇒ took only one point ⇒ no improvement.
  - Likely due to low ϕ-sens. with low ITHR.
- Early-DI: same max. load with higher T-E ⇒ due to advanced CA50.
  - Load range limited and lower peak T-E.

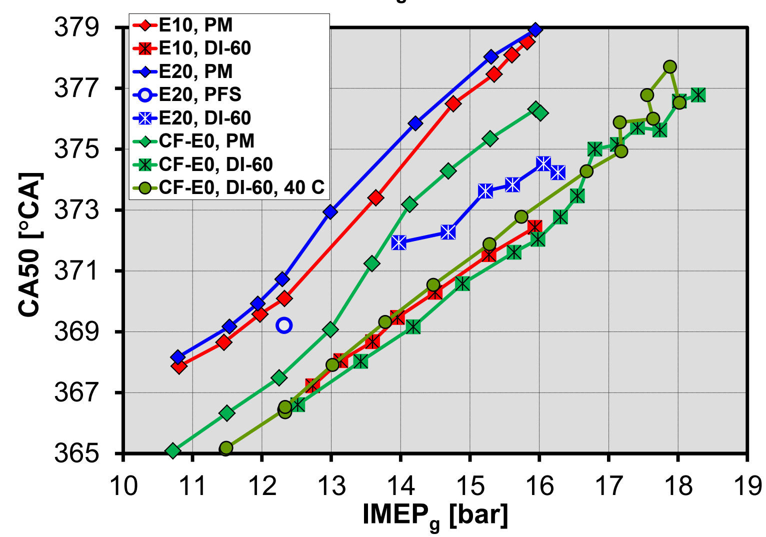
**E10**: PM - very similar to E20.

- Early-DI: Higher T-E than E20 ⇒ adv. CA50.

**CF-E0**: PM - slightly higher T-E ⇒ adv. CA50.

- Early-DI:
  - $T_{in}$ = 30°C: T-E > PM, but < E10 early-DI
  - $T_{in}$ = 40°C: higher T-E at low loads
    - > **Max. T-E = 48.4%**, matches $P_{in}$ = 2.4 bar.
  - Good stability to much higher load than PM.

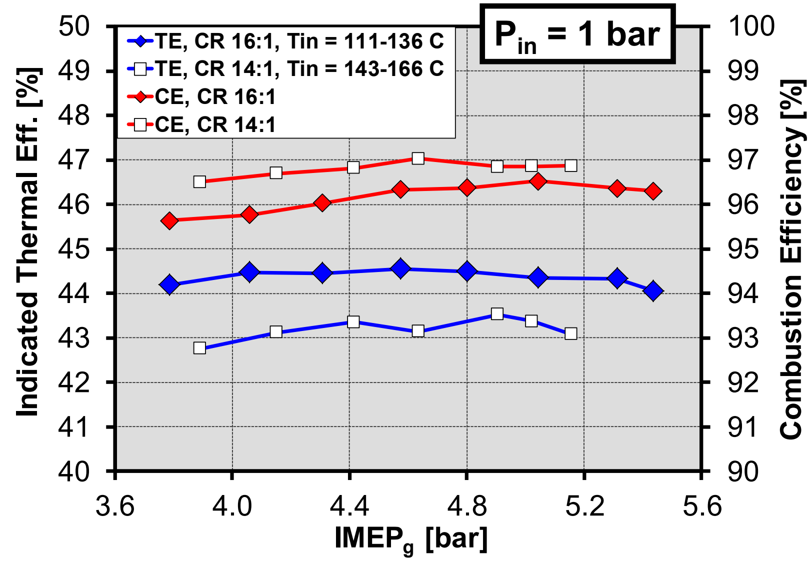


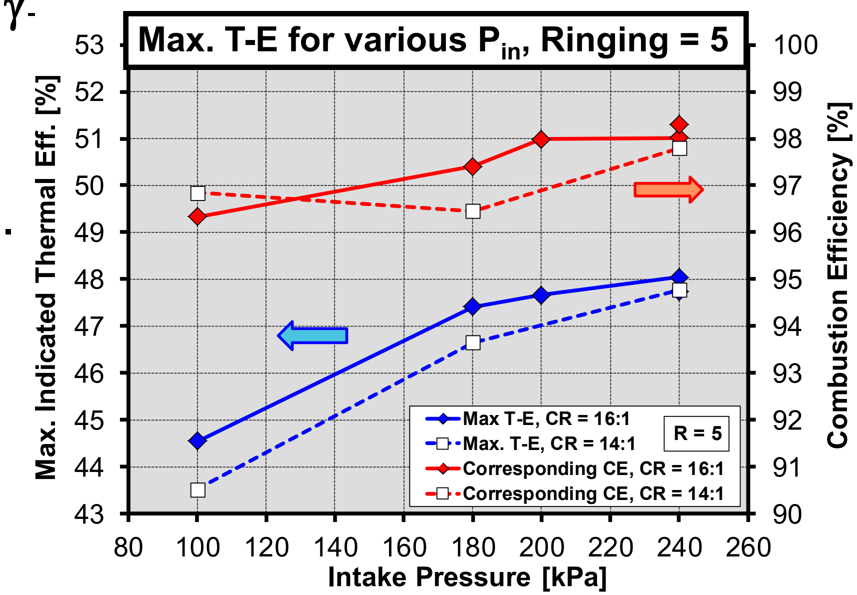

- E20: std.-PFS does not work well, & Early-DI has limited load range ⇒ low ITHR
- Early-DI: increases T-E all fuels, and for CF-E0, gives a large incr. in max. load.

# Increase CR from 14:1 to 16:1 – PreMixed

- Increase the CR from 14:1 to 16:1.
  - Investigate potential for increasing T-E.
  - Evaluate effects on load range
    ⇒ maximum load as a function of $P_{in}$.
  - Premixed and Early-DI PFS fueling.




- Naturally Aspirated: CR 16 has higher T-E.
  - Larger expansion ratio.
  - Lower $T_{in}$, $T_{peak}$ ⇒ less heat loss, higher $\gamma$.
  - C-E lower ⇒ incr. HC (from crevice?)
  - **Higher max. load due to lower $T_{in}$.**

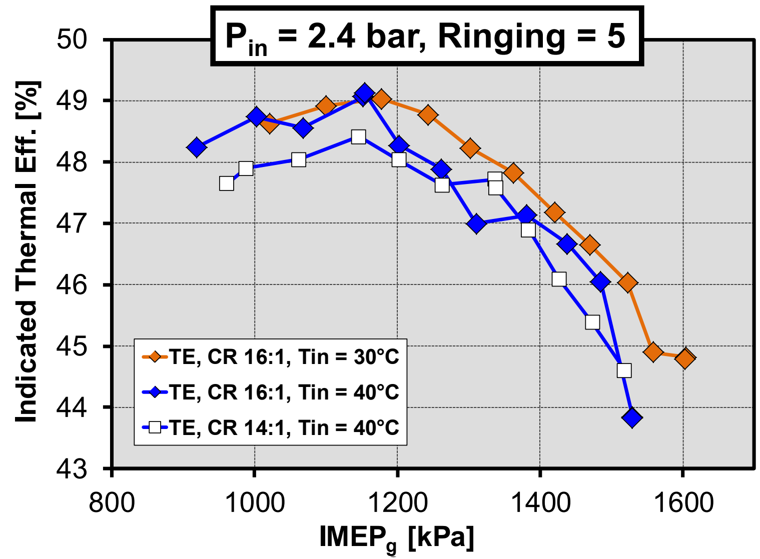


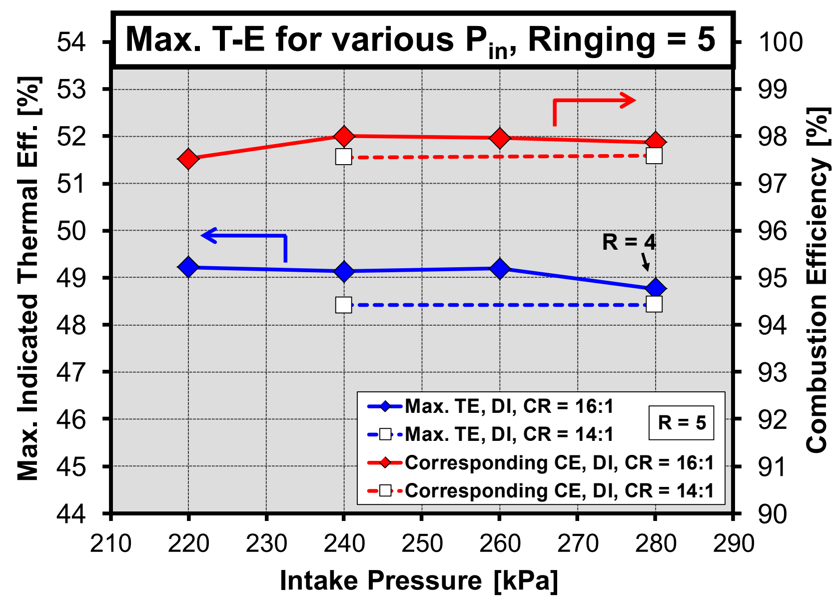

- Boost up to 1.8 bar: T-E higher for CR 16.
  - $T_{in}$ reduced to 60°C, but still zero EGR.
- $P_{in}$ = 1.8 – 2.4 bar: efficiency advantage for CR 16 diminishes, despite better C-E.
  - $T_{in}$ = 60°C for both CRs, but more EGR required for CR =16.

- PreMixed: CR = 16 gives higher T-E, but advantage less w/ boost > 1.8 bar.

# Increase CR from 14:1 to 16:1 – Early-DI

- Early-DI gives higher T-E than PM.
- $P_{in}$ = 2.4 bar, $T_{in}$ = 40°C: CR = 16 gives ⇒
  - Higher T-Es at low loads, $IMEP_g$ < 12 bar
  - About the same T-E for $IMEP_g$ > 12 bar.
  - Load range is similar.
  - Max. **T-E = 49.1%** vs. 48.4 for CR = 14.
- $P_{in}$ = 2.4 bar, $T_{in}$ = 30°C: increases T-E over the load range, but not incr. max. T-E.
  - More advanced CA50 for same $IMEP_g$.
  - Lower $T_{in}$ & $T_{peak}$ ⇒ less heat loss and higher γ.
  - **Higher maximum load.**
- CR=16 gives higher T-E for all $P_{in}$ tested.
  - **Max. T-E = 49.2%** at $P_{in}$ = 2.2 & 2.6 bar, vs. 48.4% for CR=14.
- Combustion efficiency is consistently a little higher with CR = 16.

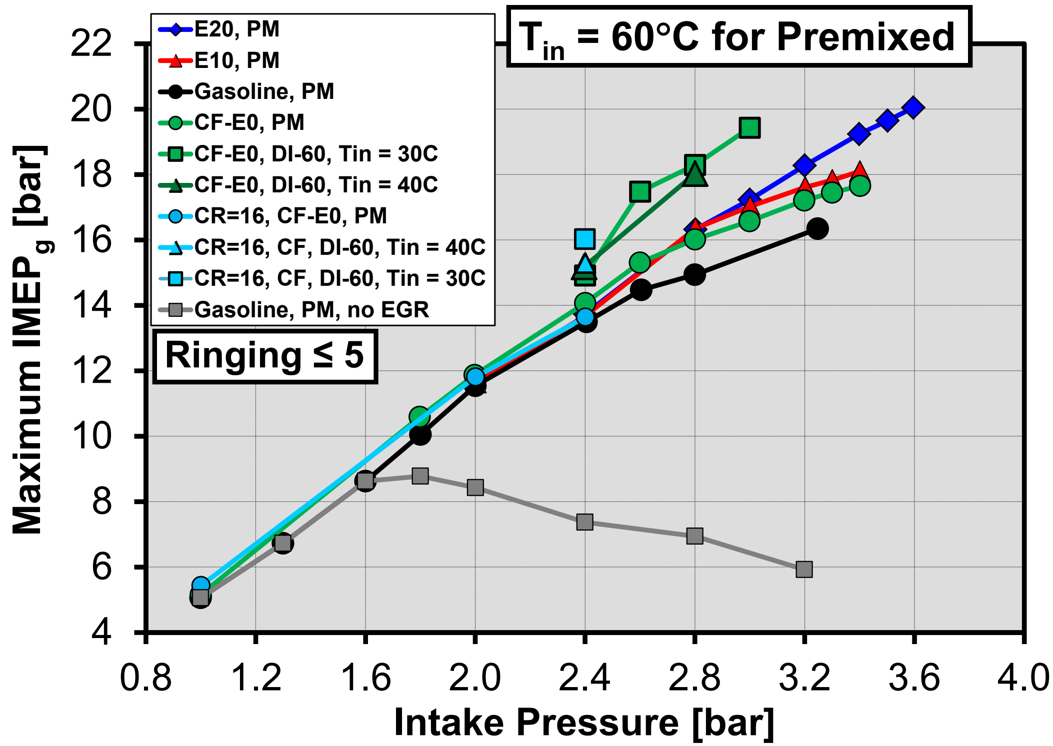



- Early-DI: CR = 16 consistently gives higher T-E, max. = 49.2 vs. 48.4%.

# High-Load Limit – Early DI, CR = 14 & 16

- Early-DI fueling ⇒ higher loads than PreMixed for same boost.
  - Gives benefits of PFS for reducing HRR & $PRR_{max}$, due to incomplete mixing.
  - Allows lower $T_{in}$ = 30 or 40°C ⇒ less EGR required (> $O_2$), more charge mass.



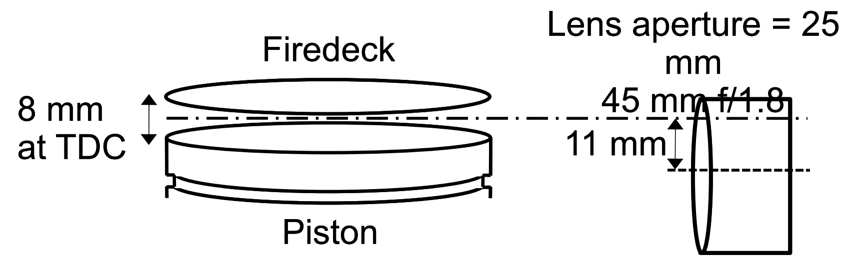

- CF-E0, Early-DI ⇒ $IMEP_g$ = 19.4 bar @ $P_{in}$ = 3.0 bar v. 3.45 bar for E20.
- CR = 16, PreMixed ⇒ Little effect on max. load up to $P_{in}$ = 2.4 bar.
- CR = 16, Early-DI ⇒ Gives highest load at $P_{in}$ = 2.4 bar, $IMEP_g$ = 16.0 bar.

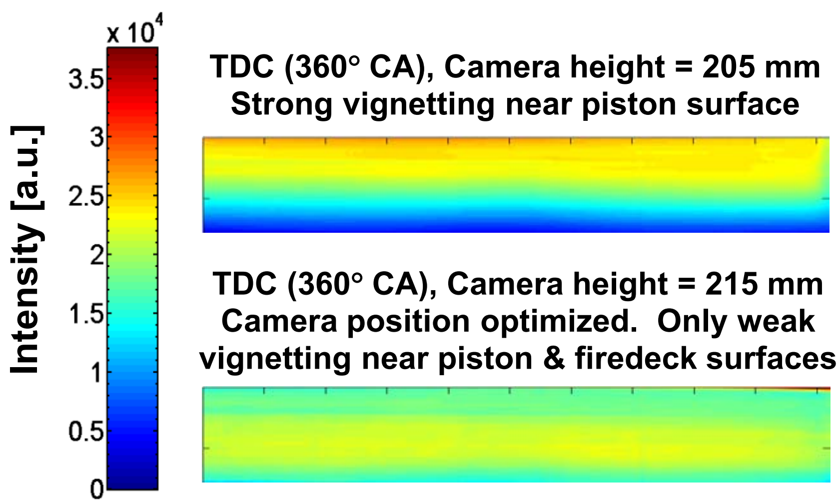
# Imaging of Thermal Strat. & Boundary Layer

**Objectives**: 1) Investigate effect of $T_{piston\text{-}top}$ on bulk-gas TS & cold-pocket location.
2) Potential for thermal BL measurements.

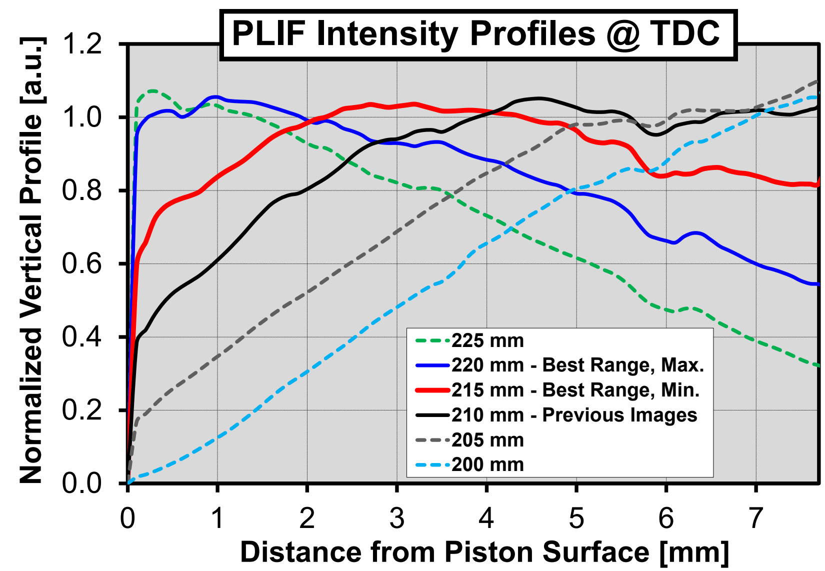
- T-map, PLIF imaging in optical engine.
- Installed aluminum top on ext'd. piston.
  - Instrumented with thermocouples.
  - Variable air-jet cooling from bottom side.
- Imaging BL at piston top is challenging because of piston motion and vignetting.
- Developed vignetting correction technique and selected optimal position.

**Schematic showing why vignetting occurs for side-view imaging near TDC.**

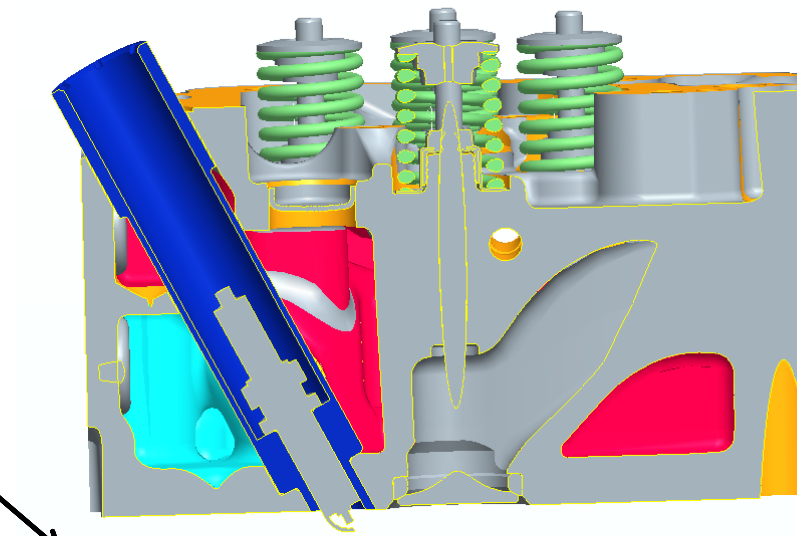



**Vignetting corr. ⇒ normalize by uniform image. Sweep camera height for best profile.**

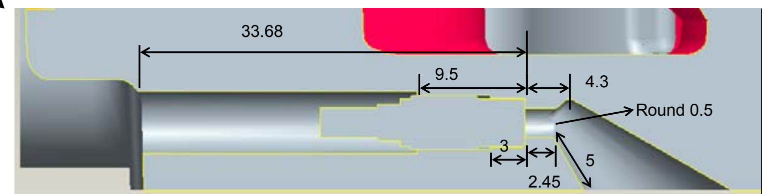


# Facility Upgrade for Spark-Assist and High-Pressure GDI Injectors



## Spark-Plug Head

- Worked with Cummins on design ⇒ Cummins provided heads & machining.
- Machining and installation of spark-plug passage tube are complete.
  - Keep centrally mounted GDI injector.
- Pressure transducer relocated.
- New port design gives low swirl without anti-swirl plate used in current head.




PT mounted horizontally through firedeck

## Spark-Ignition System

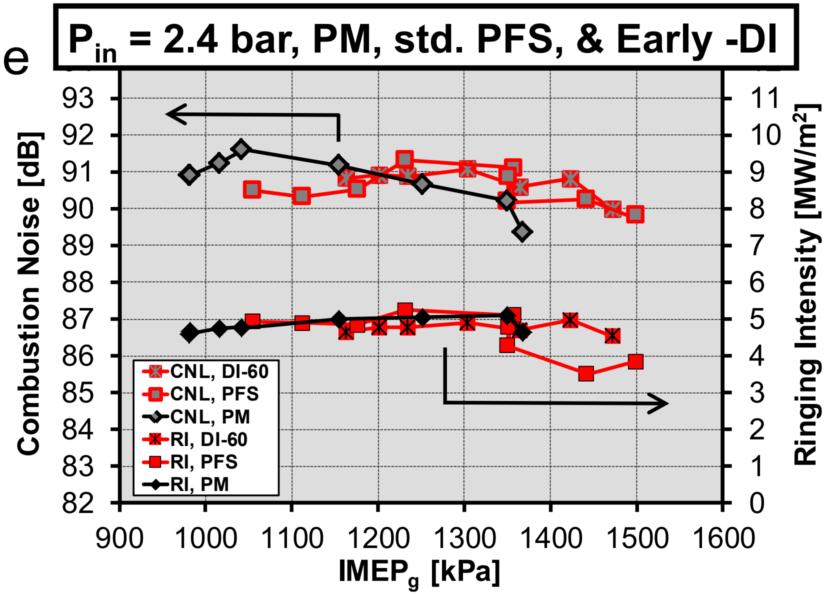
- GM has provided ignition systems.
- Obtained spark plugs, 12 mm threads & 14 mm flats, with dual iridium tips.

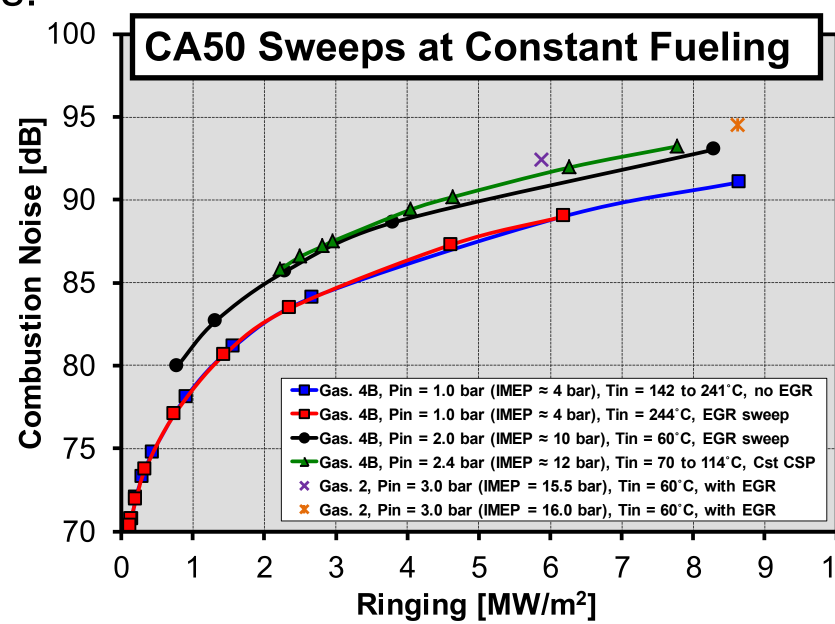
## High-Pressure GDI Injectors

- Discussed injector requirements and performance characteristics with GM.
- GM will supply new-generation Bosch 300 bar GDI injectors and a driver.
- New higher-pressure fuel-supply system designed and parts acquired.

# Combustion Noise vs. Ringing Intensity

- Adapted Matlab® code for combustion noise level (CNL) from UW (SAE 2013-01-1659) to read & analyze our cyl.-pressure data.
- Performed analysis for several datasets.
- 1st example shows fueling sweeps for PM, std-PFS, & Early-DI fueling, with E10.
  - Hold Ringing Intensity ≈ 5 $MW/m^2$ ⇒ most adv. CA50 w/o knock, highest T-E.
  - CNL and Ringing have very similar trends.
- **Ringing of 5 ≈ CNL of 90 – 91 dB.**
- CA50 sweeps show that CNL is reduced by retarding CA50 to reduce Ringing.
  - Only a small reduction in T-E.
- Note that CNL is approx. 3 dB higher for $P_{in}$ = 2.0 & 2.4 bar vs. $P_{in}$ = 1.0 bar.
- Since Ringing > 5 is good indicator of knock, this discrepancy indicates that CNL is likely not a precise indicator of knock.



# Collaborations

- Project is conducted in close cooperation with U.S. Industry through the Advanced Engine Combustion (AEC) / HCCI Working Group, under a memorandum of understanding (MOU).
  - Ten OEMs, Five energy companies, Four national labs, & Several universities.
- LLNL: 1) Support the development of a chemical-kinetic mechanism for gasoline/ethanol blends, Pitz *et al*., and 2) CFD modeling, Flowers, *et al.*
- General Motors: Frequent internet meetings ⇒ in-depth discussions.
  - Provide data to support GM efforts on boosted HCCI & in modeling TS (with UM).
- Cummins, Inc.: Design and fabrication of spark-plug cylinder heads.
- U. of Michigan: Collaborate on modeling and analysis of TS (with GM).
- U. of California - Berkeley: Support CFD modeling of PFS-HCCI.
- Chevron: **Funds-In project** on advanced petroleum-based fuels for HCCI.
- SNL-LDRD: **Funds-In project** on biofuels produced by fungi ⇒ collab. with researchers in basic chemistry (C. Taatjes *et al.*) & Biofuels.

# Future Work

**Increase Efficiency and Loads of Boosted HCCI/SCCI**

- Complete evaluation of performance with CR = 16 over a wider range of operating conditions. ⇒ Also, evaluate potential of a Miller-cycle cam.
- Conduct a comprehensive study of Early-DI-PFS to determine the extent to which its substantial benefits for T-E and load range can be applied.
  - Determine effects of operating cond. & fuel-injection parameters ($P_{inj}$ & DI timing).
  - Expand study to include multiple injections for more-effective fuel stratification.
- Image fuel distributions in optical engine to guide fuel-injection strategies.
- Install spark-plug cylinder heads: 1) determine effects of new intake-port geometry, and 2) initiate studies of spark-assisted CI combustion.

**Thermal Stratification**

- Complete investigation of the effects of piston-top temperature on amount of TS and cold-pocket distribution. ⇒ Also, investigate potential over-mixing.
- Determine the potential for obtaining thermal BL profiles at the piston-top.

**Support of HCCI/SCCI Modeling**

- Continue to provide data, analysis, and discussion to support modeling at LLNL, U. of Michigan, and U. of California-Berkeley.

# Summary

- Conducted an extensive study of the effects of “gasoline-like” fuel composition, including: 1) blending ethanol up to 20%, 2) increasing the AKI of the base fuel from 87 to 93 without ethanol, and 3) pure Ethanol.
- Early-DI-PFS fueling provides substantial benefits when ethanol content ≤ 10%, and for the high-AKI base fuel (CF-E0).
  - Gives higher T-E and higher loads for a given $P_{in}$. ⇒ Allowed **$IMEP_g$ = 19.4 bar at $P_{in}$ = 3.0 bar** vs. $IMEP_g$ = 16.6 bar for PreMixed. ⇒ Ease turbo design.
- Explored the potential benefits of increasing the CR from 14:1 to 16:1.
  - Achieved a **peak T-E of 49.2% for CR 16**, compared to 48.4% for CR 14.
  - No significant penalty in maximum load for $P_{in}$ up to 2.4 bar (using CF-E0).
- Thermal-stratification and boundary-layer (BL) measurements:
  - Installed aluminum piston-top with variable air-jet cooling.
  - Worked out vignetting correction for BL measurements.
- Facility upgrade: 1) worked with Cummins to design and build a “spark-plug” cyl. head, and 2) worked with GM to obtain high-press. GDI injectors.
- Combustion Noise Level (CNL) and Ringing Intensity are generally well correlated for HCCI/SCCI combustion, but the results indicate that CNL may not be a good indicator of knock over the operating range.

# Technical Backup Slides

# Detailed Summary – 1

- Conducted an extensive study of the effects of “gasoline-like” fuel composition, including: 1) blending ethanol up to 20%, 2) increasing the AKI of the base fuel from 87 to 93 without ethanol, and 3) pure Ethanol.
- For Premixed fueling:
  - Ethanol content has almost no effect on autoignition for naturally aspirated operation, but a large effect for boosted operation.
  - For boosted operation with $P_{in} \geq 2.4$ bar, blending with ethanol up to 20% has little effect on the T-E, but CF-E0 gives a slightly higher T-E.
  - Blending ethanol up to 20% is beneficial for extending the high-load limit.
    $\Rightarrow$ Increased maximum load from $IMEP_g$ = 16.3 bar at $P_{in}$ = 3.25 bar for E0 to **$IMEP_g$ = 20.0 bar at $P_{in}$ = 3.6 bar for E20.**
  - For the high-AKI E0 fuel (CF-E0), performance was generally similar to E10.
- Early-DI-PFS fueling provides substantial benefits when ethanol content ≤ 10%, and for the high-AKI base fuel (CF-E0).
  - Gives higher T-E and higher loads for a given $P_{in}$ compared to premixed.
    $\Rightarrow$ Allowed **$IMEP_g$ = 19.4 bar at $P_{in}$ = 3.0 bar** vs. $IMEP_g$ = 16.6 bar for premixed.
    $\Rightarrow$ Beneficial for turbocharger design.
  - Early-DI PFS did not work well with E20 due to instabilities.

# Detailed Summary – 2

- Explored the potential benefits of increasing the CR from 14:1 to 16:1.
  - Typically increased T-E by 0.5 – 0.8 thermal-efficiency percentage units.
  - Achieved a **peak T-E of 49.2% for CR 16**, compared to 48.4% for CR 14.
  - No significant penalty in maximum load for $P_{in}$ up to 2.4 bar (using CF-E0).
- Thermal-stratification and boundary-layer (BL) measurements:
  - Installed aluminum piston-top with variable air-jet cooling.
  - Worked out vignetting correction for BL measurements.
- Facility upgrade: 1) worked with Cummins to design and build a "spark-plug" cyl. head, and 2) worked with GM to obtain high-press. GDI injectors.
- Combustion Noise Level (CNL) and Ringing Intensity are generally well correlated for HCCI/SCCI combustion, but the results indicate that CNL may not be a good indicator of knock over the operating range.