Low-Temperature Gasoline Combustion (LTGC) Engine Research

– Previously known as HCCI / SCCI –

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June 9, 2015 – 12:00 p.m.

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

Program Managers: Gurpreet Singh & Leo Breton **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 LTGC / HCCI.
- Extend LTGC / HCCI operating range to higher loads.
- Improve the understanding of in-cylinder processes.

Budget

- Project funded by DOE/VT:
  FY14 – $720k
  FY15 – $680k

Partners / Collaborators

- Project Lead: Sandia ⇒ John E. Dec
- Part of Advanced Engine Combustion working group – 15 industrial partners
- General Motors – in-depth collaboration
- Cummins – spark-plug cylinder heads
- LLNL – support kinetic modeling
- Univ. of Calif. Berkeley – CFD modeling
- Univ. of Melbourne – biofuels & analysis methods
- Chevron – advanced fuels for LTGC

Objectives - Relevance

<u>Project objective</u>: to provide the fundamental understanding (science-base) required to overcome the technical barriers to the development of practical LTGC / HCCI engines by industry.

<u>FY15 Objectives</u> ⇒ Increased Efficiency, High Loads, Improved Understanding

- <u>Energy-Loss Distribution</u>: Determine magnitude of loss terms (heat transfer, combst. inefficiency, exhaust) & how they change with operating conditions. ⇒ *Understand the Trade-offs to Improve the Thermal Efficiency*

- <u>DI Partial Fuel Stratification (DI-PFS) for improved Thermal Efficiency (TE)</u>: Systematically evaluate the TE gains possible with DI-PFS for both single and double direct injections ⇒ including various injection strategies for double DI (<u>multi-year task</u>).

- <u>Fuel-Distribution Imaging</u>: Apply PLIF imaging in optical eng. to understand how GDI strategies affect ϕ-distribution, to help optimization (<u>multi-year task</u>)

- <u>Performance mapping with new low-swirl head</u>: Compare TE and load range for new cylinder head with data from old head at selected conditions.

- <u>Support Modeling</u>: Chemical-kinetics at LLNL & CFD at UC-Berkeley & GM.

Approach

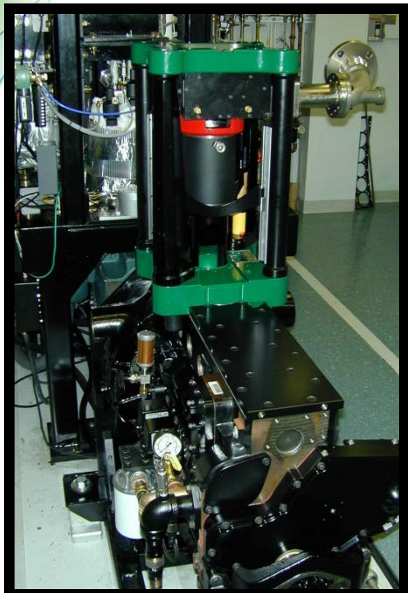
- Use a combination of metal- and optical-engine experiments, analysis and modeling to build a comprehensive understanding of LTGC processes.

- **Metal Engine** ⇒ high-quality performance data ⇒ well-controlled experiments
  - Energy-Loss Distribution: Acquire data for several parameter sweeps & analyze.
  - DI-PFS for increased TE: Systematically evaluate TE vs. load for multiple fueling strategies ⇒ 1) well-premixed, 2) single-injection DI at two T_{in}s to separate out effect of initial charge T, 3) double-injection DI for a range of late DI timings & fuel fractions.
- **Optical Engine** ⇒ detailed investigations of in-cylinder processes.
  - Fuel Distribution Imaging: 1) PLIF imaging calibrated in-situ; 2) Vertical laser sheet to see all elevations, 3) Obtain ϕ-map images for various fuel-injection strategies.
    ⇒ **Guide application of PFS in metal-engine for higher TE** ⇒ **Model validation**
- **Analytical Techniques** ⇒ Develop & apply 1) duplicate methods for computing energy lost to heat transfer and exhaust, 2) method to determine changes in TE attributable to changes in CA50 & γ ⇒ **Guide further TE improvements**
- **Computational Modeling**: **1)** Collaborate with UC-B and GM on CFD modeling for improved understanding of PFS. **2)** Work with LLNL on kinetic mech. for Cert-fuel.
- Combining techniques provides a better understanding & more-optimal solutions
- **Transfer results to industry:** 1) physical understanding, 2) improved models.

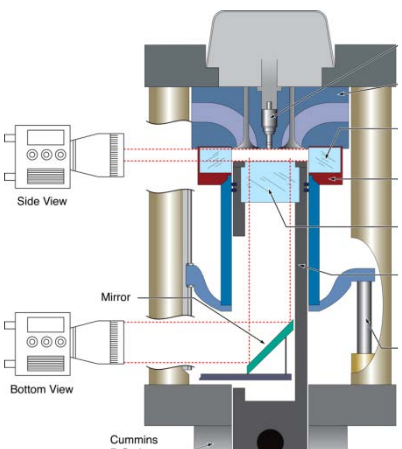
Approach – Milestones

- **September 2014**
  Complete installation and shakedown testing of new low-swirl cylinder head with spark-assist capability.
  ⇒ Postponed Milestone until September 2015: Needed to complete double-injection DI-PFS study with the same cylinder head used for previous work.
  ✓ ⇒ New head has now been installed and initial testing is underway.
- ✓ **December 2014**
  Prepare and submit a paper on recent results to the SAE International Congress.
- ✓ **March 2015**
  Determine the magnitude of the various energy losses for LTGC-engine operation (combustion inefficiency, heat transfer, and exhaust energy) and how they change with operating conditions.
- ✓ **June 2015**
  Present an overview of project accomplishments and directions at the DOE Annual Merit Review.
- ✓ **September 2015**
  Major Milestone - Determine the effectiveness of double-injection fueling strategies for reducing the heat-release rate in LTGC engines over a range of injection timings and fuel-fraction splits between the two injections.

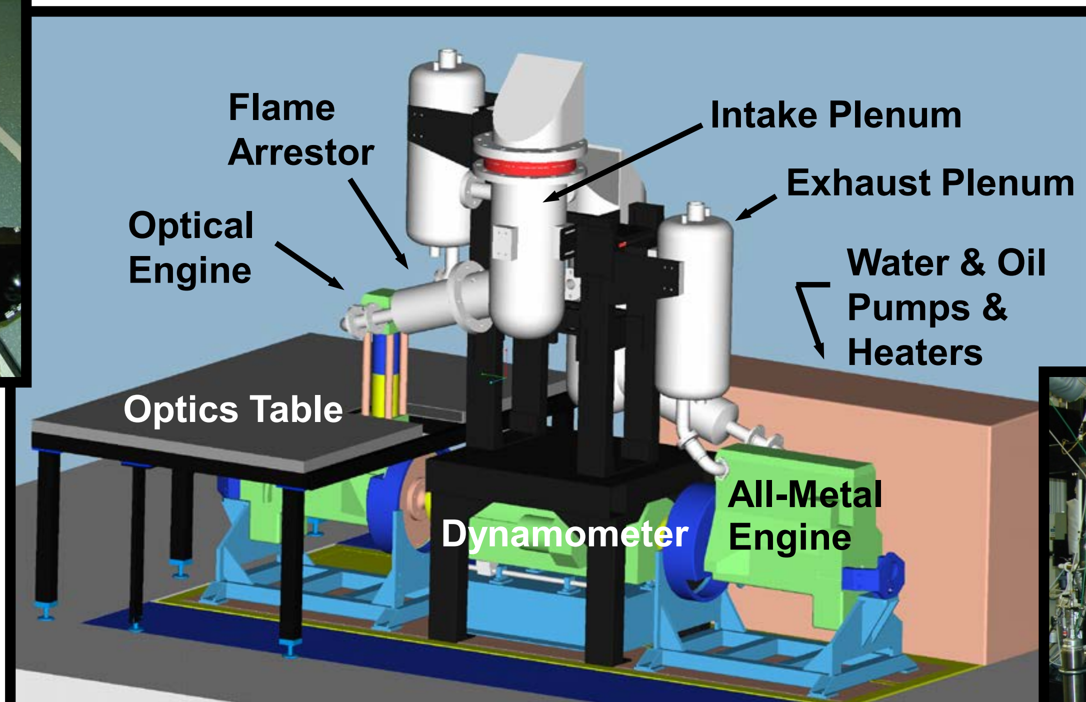
Sandia LTGC Engine Laboratory



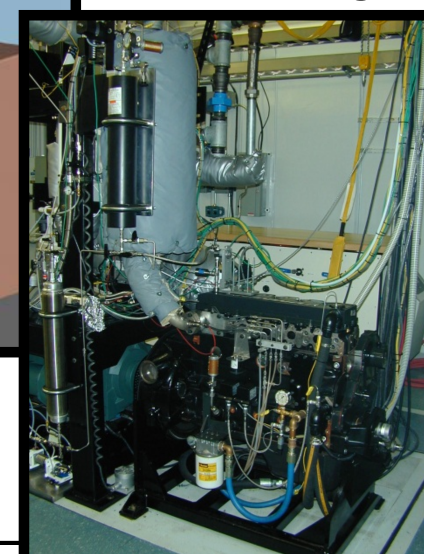
Optical Engine



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



All-Metal Engine



- Bore x Stroke = 102 x 120 mm
- 0.98 liters, **CR = 16:1**

Unless noted: Ringing ≤ 5 MW/m^2 & spd = 1200 rpm
NO_x & soot emiss. more than 10x below US-2010

Accomplishments – Overview

∗ Indicates additional accomplishment not in original objectives.

- **Determined magnitude of energy-loss terms** (heat transfer, combustion inefficiency, exhaust) **& evaluated changes for several parameter sweeps**
  - – Developed analysis techniques for heat-transfer loss and exhaust loss terms.
  - ∗ Developed analysis technique for change in TE attributed to changes in CA50 & γ.

∗ Extended heat-transfer analysis technique to developed a more objective & accurate **method for determining the onset of knock** in LTGC engines.

- Completed an **in-depth study of DI-PFS for increased TE** using both single and double direct injections.
  - – Various GDI timing and fuel-fraction strategies evaluated.
  - ∗ Analyze energy-loss terms to explain changes in TE for double-DI strategies.
- On track with PLIF imaging study to understand how changes in GDI injection strategy affect the in-cylinder fuel distribution.
  - – Resolved problem with optical engine.
- **Facility upgrade** ⇒ completed modifications to new cylinder head for low-swirl, 300-bar GDI injector and spark assist, and installed head on engine.
  - – On track to complete shakedown tests & performance comparison this FY.
- Collaborated with UC-B and GM on CFD modeling and LLNL on kinetics.

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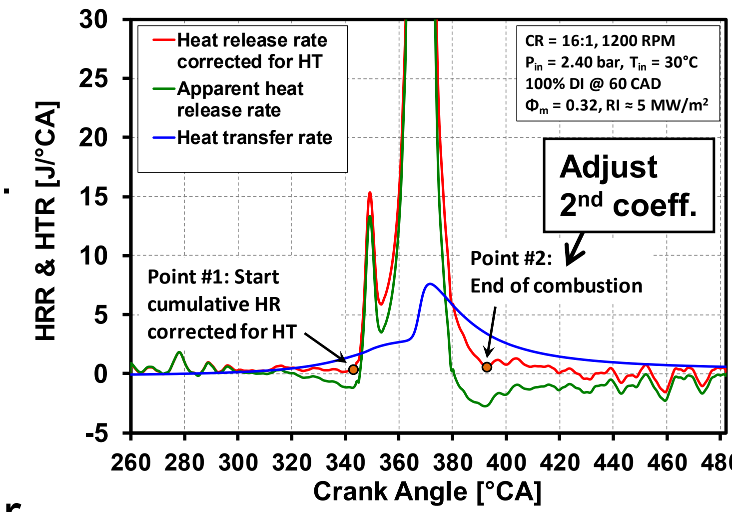
Energy-Distribution Analysis

- Understanding the reasons for changes in TE with operating conditions is critical for finding ways to improve efficiency.
- Analyze how Energy distribution varies with conditions.
  - Energy-loss terms: 1) combst. inefficiency, 2) heat transfer, 3) Exhaust Loss (EL)
  - Energy shift, Work ➡ EL: 1) Effective Expansion Ratio (ER), CA50, 2) $\gamma = c_p/c_v$
- Heat Transfer computed by two methods:
  1) Woschni HT correlation with coeffs. adjusted to make HRR flat before and after combustion. ⇒ Also total HR equals energy of burned fuel.
  2) Exhaust loss and energy closure ⇒ Exh Loss based on T_{EVO}, corrected for work after EVO.
  - HT similar for both ⇒ confidence in analysis



- Changes in CA50 and γ directly affect whether energy produces work or is lost to exhaust.
  - Compute changes in TE and EL using ideal Otto-cycle analysis using γ based on real-gas properties averaged over expansion stroke ⇒ with CR = Effective ER.

$$\text{TE} = 1 - \frac{1}{CR^{\gamma} - 1}$$

Changes in Energy Dist. for ϕ_m Sweep

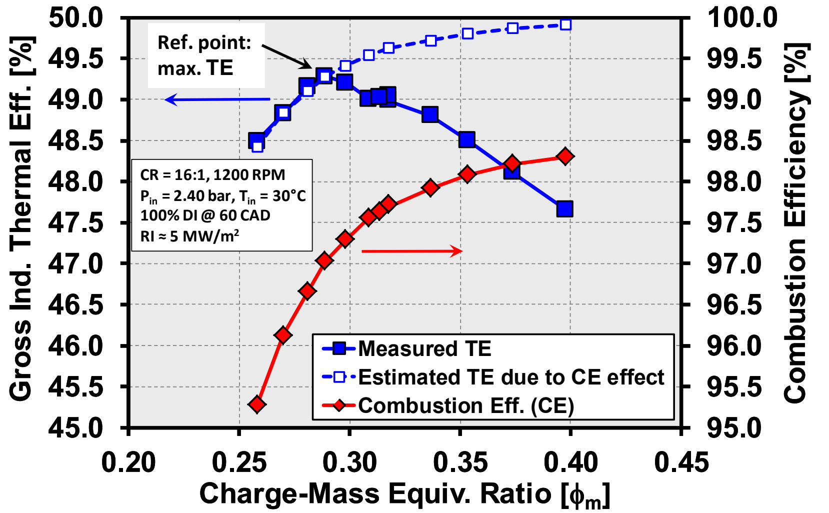
$\phi_m = (F/C) / (F/A)_{stoich}$

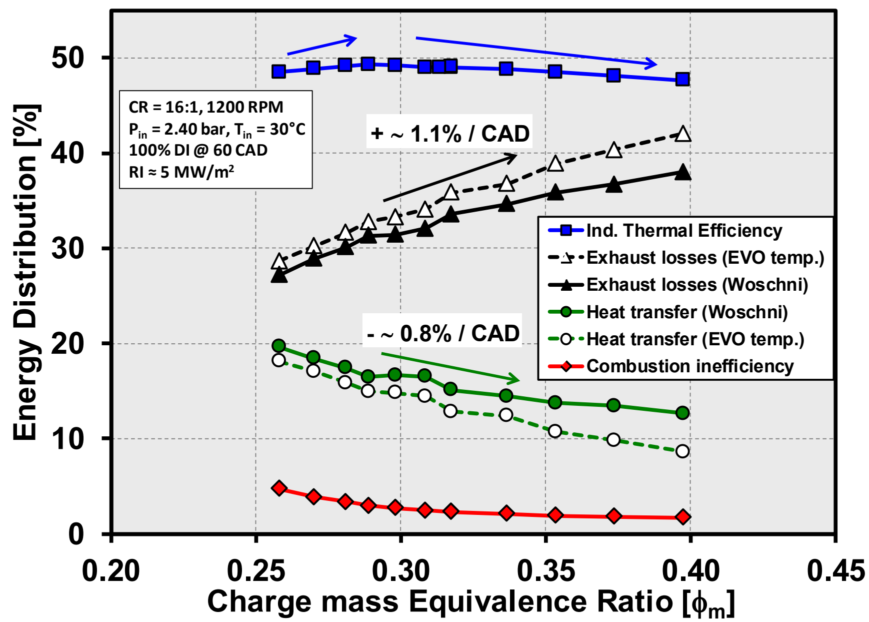
For each ϕ_m, advance CA50 until Ringing Intensity (RI) = 5 MW/m² for max TE w/o knock

- As ϕ_m increases, TE increases to a maximum of 49.3%, then decreases.
- Improved Combustion Eff. (CE) explains increase, but not decrease.
- Analysis of energy-loss terms with increasing ϕ_m shows:
  - Combustion inefficiency decreases
  - Heat transfer losses decrease
  - Exhaust losses increase significantly
    - > Woschni & T_{EVO} methods give similar trends ⇒ Woschni considered more accur.

- Decrease in TE is related to increase Exhaust Losses (EL).
  ⇒ What are the causes?

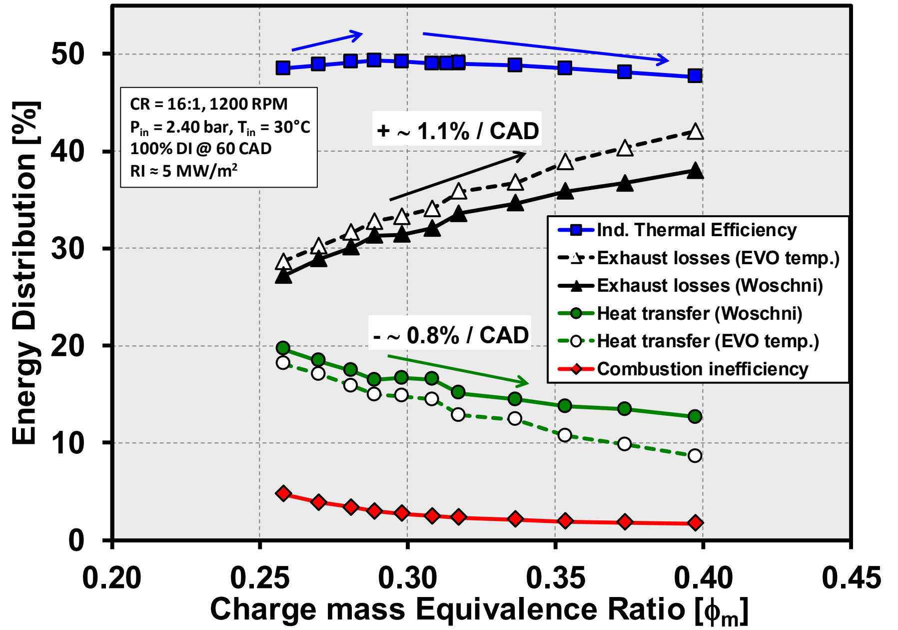
Early-DI, P_{in} = 2.4 bar, T_{in} = 30°C, CR = 16

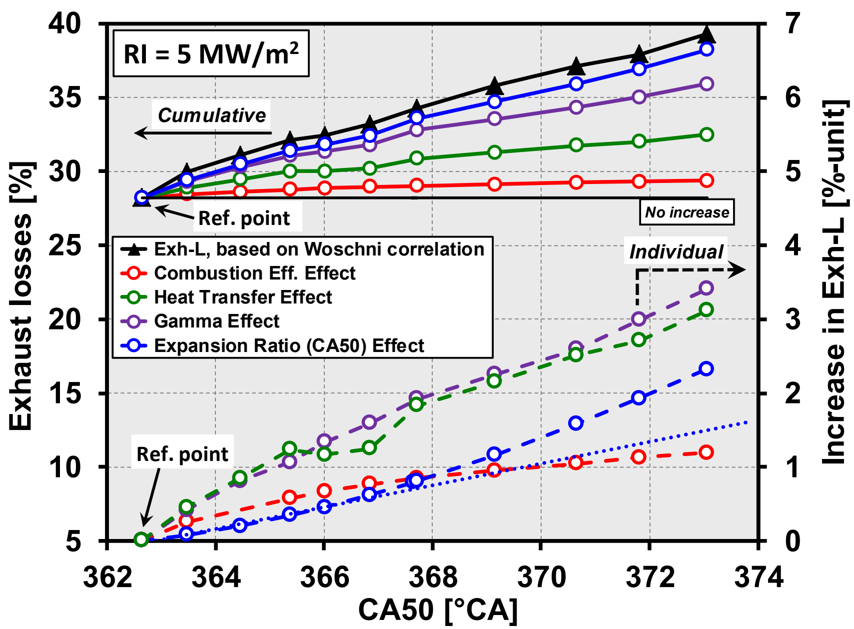


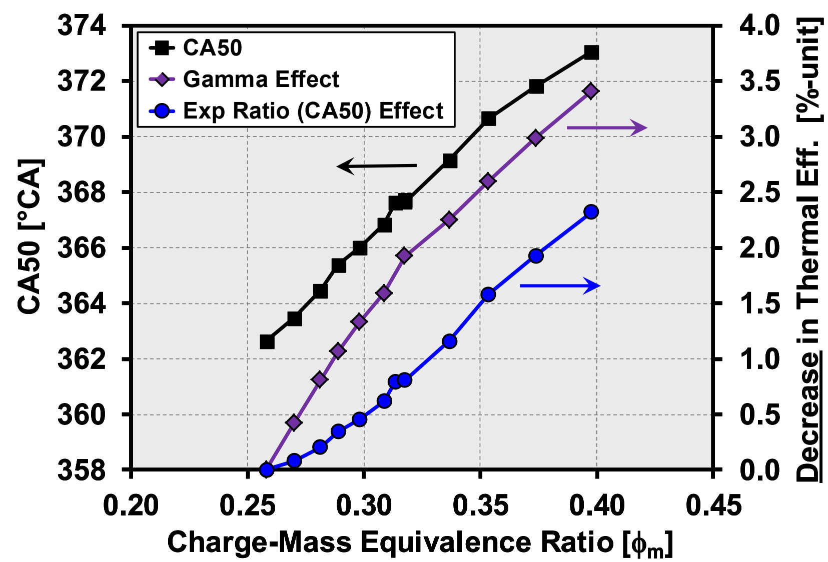


Contributions to Exhaust Loss for ϕ_m Sweep

- CA50 is retarded with increased ϕ_m to hold RI = 5 MW/m².
  ⇒ Eff. ER ➘, Decreases TE & incr. EL
- γ decreases with higher ϕ_m (T, EGR, TA)
  ⇒ Decreases TE and increases EL
- Lower HT & better CE increase TE & EL
- γ-effect **>** CA50-effect on the TE reduction.
- Sum of individually computed terms closely matches EL based on Woschni.



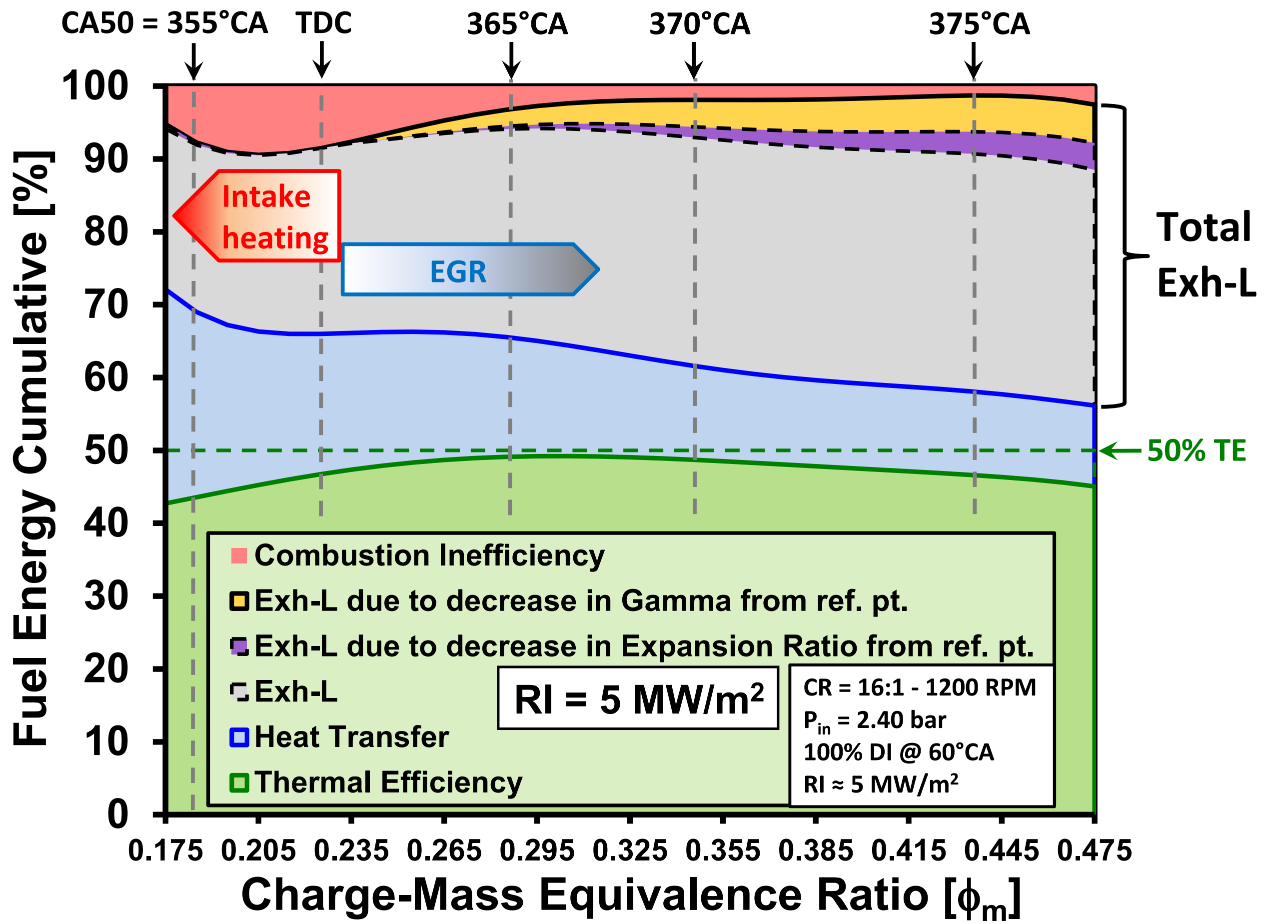




Shift of Energy Distribution over ϕ_m Sweep

- "Stacked" plot more clearly shows the shift and reasons for changes in TE.

- Decreased TE for $\phi_m < \phi_m$-Max-TE due to:
  - Reduced CE for CA50 after TDC.
  - Increased HT for CA50 before TDC.
- Decreased TE for $\phi_m > \phi_m$-Max-TE due to:
  - Lower gamma (γ) $\Rightarrow \phi_m$, $T_{combustio}$, and EGR all higher.
  - Lower Exp-Ratio $\Rightarrow$ more retarded CA50 to prevent knock.

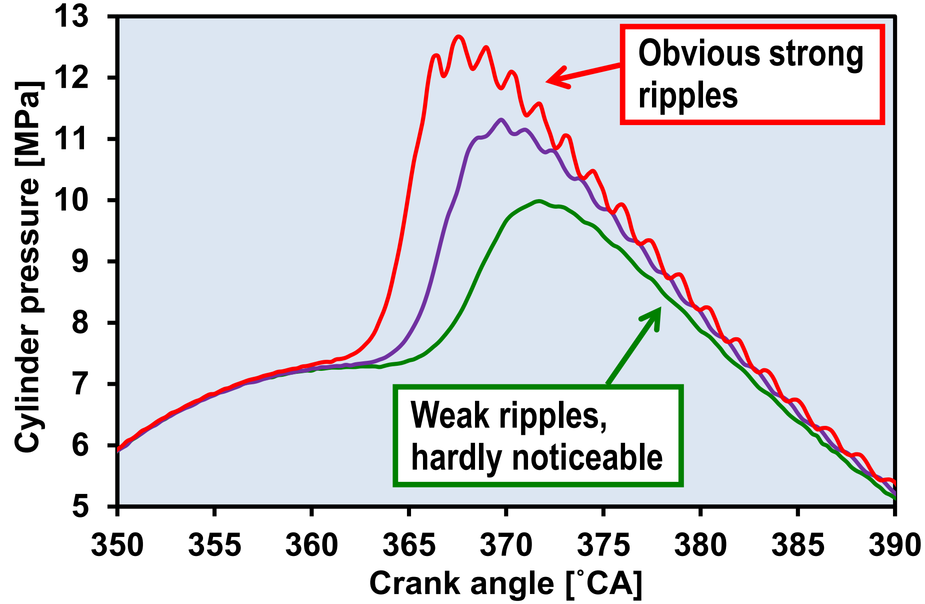


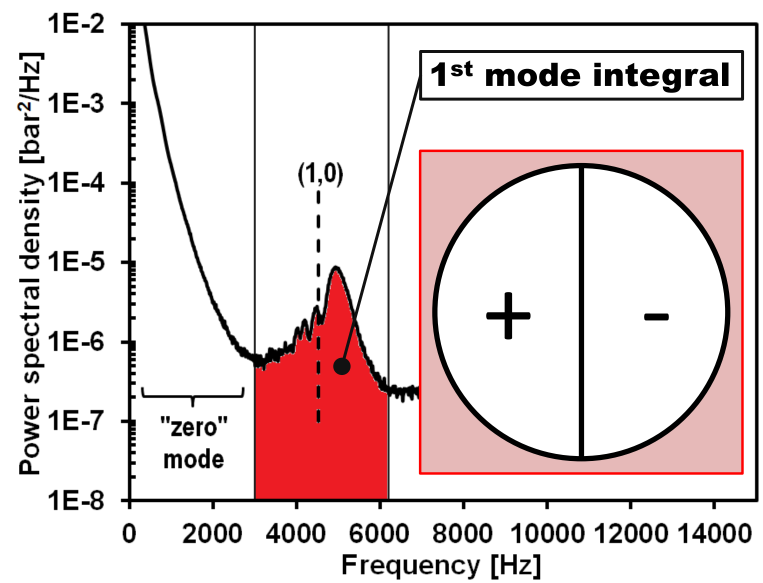
- Effect of γ dominates over CA50 retard.
- Improved CE and reduced HT mitigate γ and CA50 effects.

- Energy distribution analyses also conducted for:
  1) Two CA50 sweeps
  2) T_{in} sweep
  3) Speed sweep

Determining the Onset of Knock

- As load (ϕ_m) increases, or CA50 advanced, PPRR & RI increase
  $\Rightarrow$ RI ~ $PPRR^2/P_{max}$.
  - Excites acoustic modes of chamber.
  - Weak ripples even for low PPRR, but no detrimental consequences.
- If acoustic oscillations (Ringing) become too intense
  $\Rightarrow$ Distinctive irritating sound
  $\Rightarrow$ Commonly known as **engine knock**.
- Criterion required to define knock onset.
- Magnitude of ripples $\Rightarrow$ energy content of 1st acoustic mode, **Knock Integral (KI)**
- Not always consistent $\Rightarrow$ sensitive to location of pressure transducer relative to direction of acoustic wave.
- A better metric is needed.



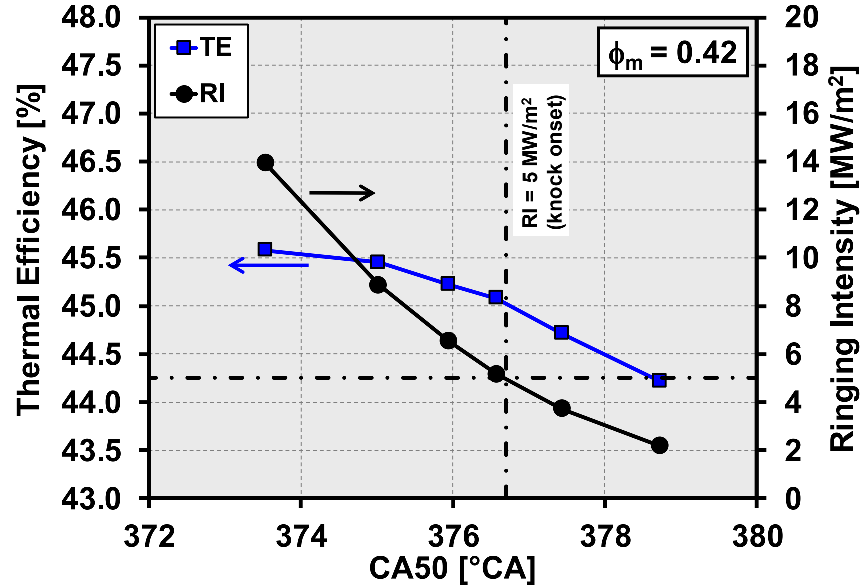


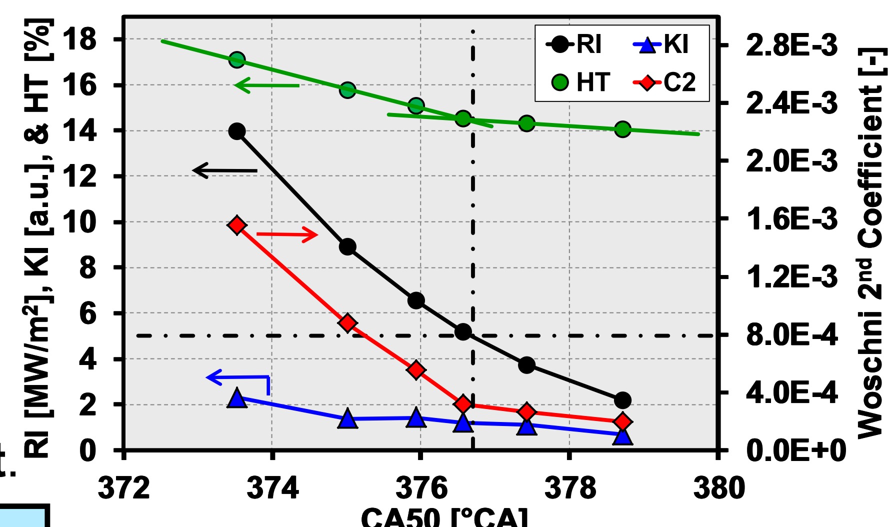
Improved Metric for the Onset of Knock

- Previously, selected RI = 5 MW/m^2 as the maximum RI w/o knock.
  - Based on knocking sound and strong ripples on P-trace ⇒ somewhat subject.

Example: CA50 sweep at constant ϕ_m

- As CA50 advanced, RI increases ⇒ TE↗ due to greater Exp Ratio.
- Also, RI↗ due to increased PPRR. ⇒ Strong knock at more adv. CA50s.
- **KI increases**, but no distinct indicator of knock ⇒ sensitive to direction of P-osc.
- **HT↗ at a greater rate for RI > 5**
  - P-osc. have associated Vel-osc., HT↗
  - **Woschni 2nd coeff.** indicates combust-induced velocities & **captures this effect.**



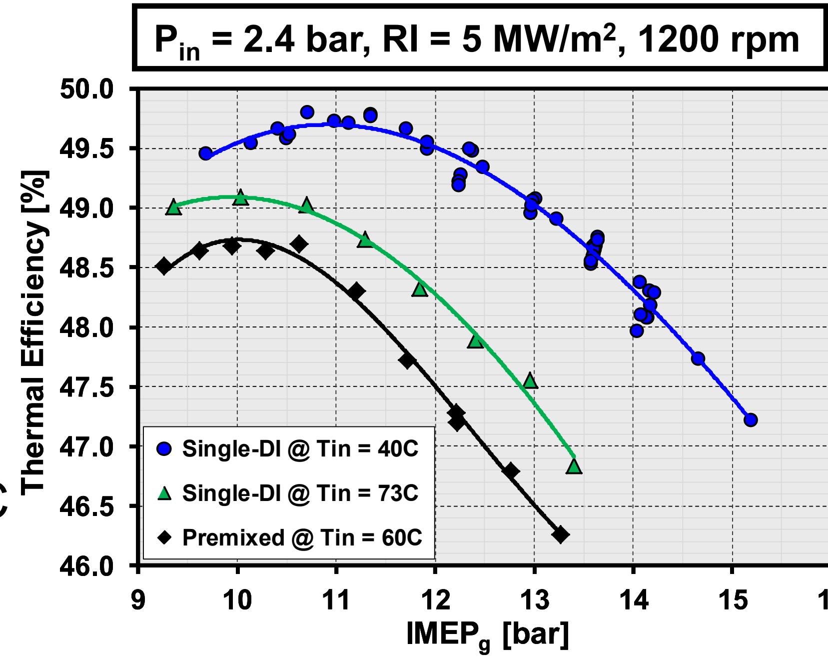


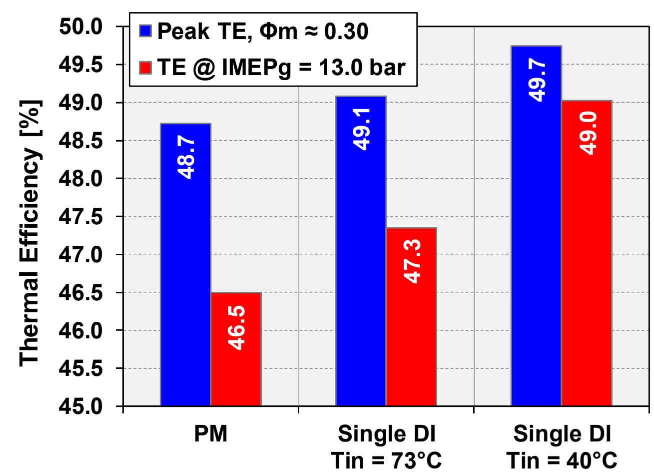
- **C_2 is a consistent, objective indicator of knock** ⇒ a spatially integrated measure

- Verified for several param. sweeps ⇒ most match RI = 5 MW/m^2.

DI-PFS with Single Injection

- PFS with DI fueling can significantly improve TE and/or max. load.
  - Single DI at 60° CA (DI-60) ⇒ mixing is incomplete ⇒ gives PFS.
  - PFS reduces HRR if fuel is ϕ-sensitive. ⇒ More adv. CA50 or incr. load w/o knock.
  - DI fueling allows lower T_{in} w/o fuel conden.
- Baseline: PreMixed(PM) fueling, T_{in} = 60°C
- Single DI-60, T_{in} = 73°C to match T_{BDC} of PM with T_{in} = 60°C (fuel-vap. cooling).
  - TE↗ ~0.5% ⇒ CA50 adv, but not sufficient. Perhaps HT↘ ⇒ further analysis required.
- Single DI-60, T_{in} = 40°C ⇒ **Lower T_{in} means:**
  - PFS more effective ⇒ greater CA50 adv.
  - $T_{combust}$↘, EGR↘, ϕ_m↘ (ρ↗) ⇒ higher γ
  - T_{in}↘ and $T_{combust}$↘ ⇒ less HT



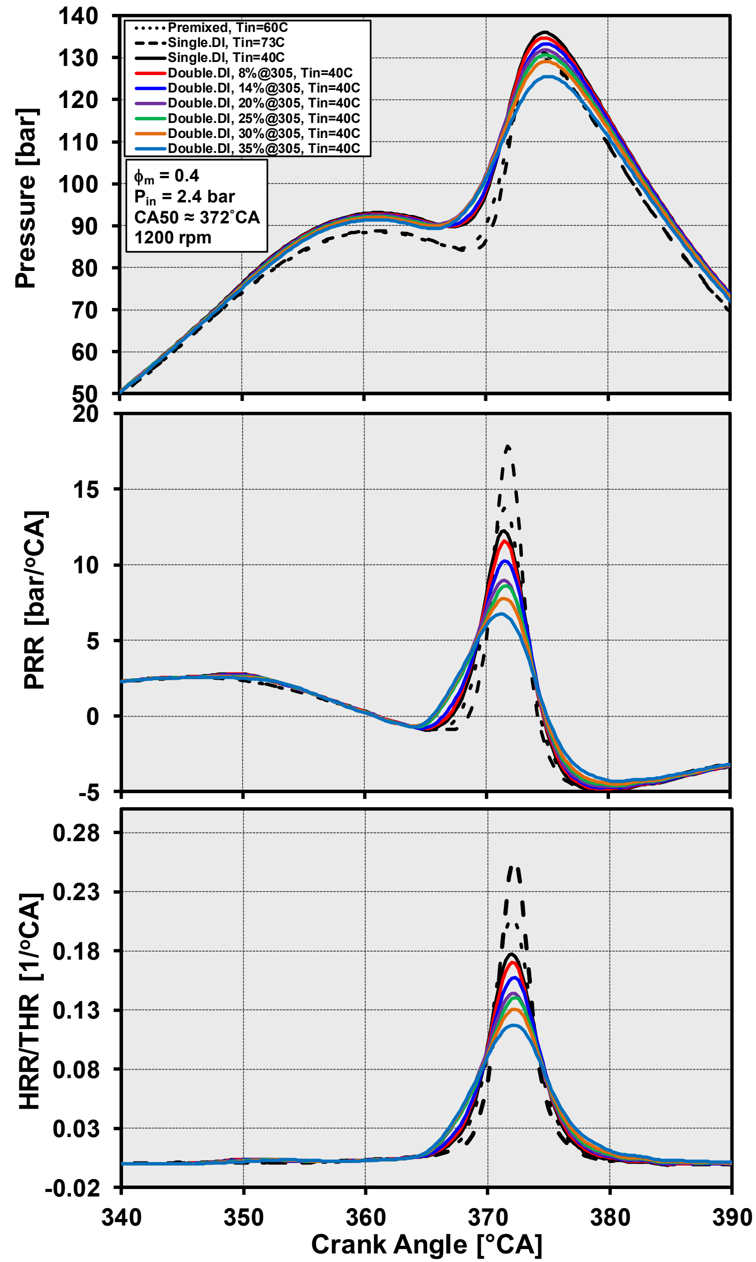


- Peak TE increases by 1.0 %-units ⇒ TE at 13 bar $IMEP_g$ increases 2.5 %-units.
- Substantial TE benefit to Single-DI-PFS w/ lower T_{in} ⇒ particularly at high loads.

Double-Injection DI-PFS at ϕ_m = 0.4

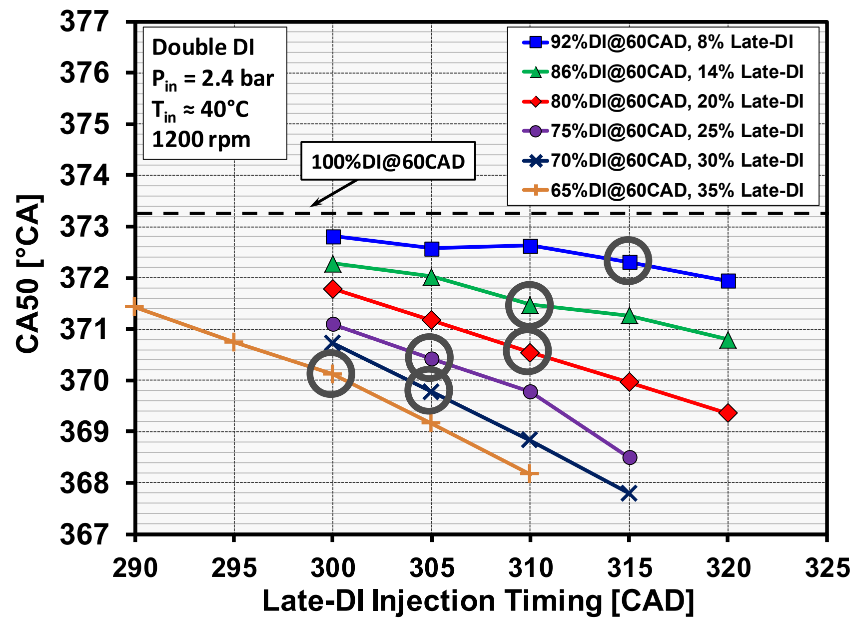
- Can further gains in TE be made by increasing the fuel stratification?
- Double-DI PFS = Early + Late DI injections (DDI-PFS)
  - Hold Early-DI timing constant at 60° CA.
  - Varying timing and fuel fraction of the late-DI injection.
- Although single-DI PFS already reduces Peak PRR & HRR significantly vs. PreMixed ⇒ DDI-PFS gives a much greater reduction.
  - Better optimizes stratification to further slow HR.
- Peak HRR ↘ and burn duration ↗ progressively with increasing late-DI fraction.
  - Late-DI fraction increased from 8% ⇨ 35% of total fuel ⇒ holding late-DI timing = 305° CA.

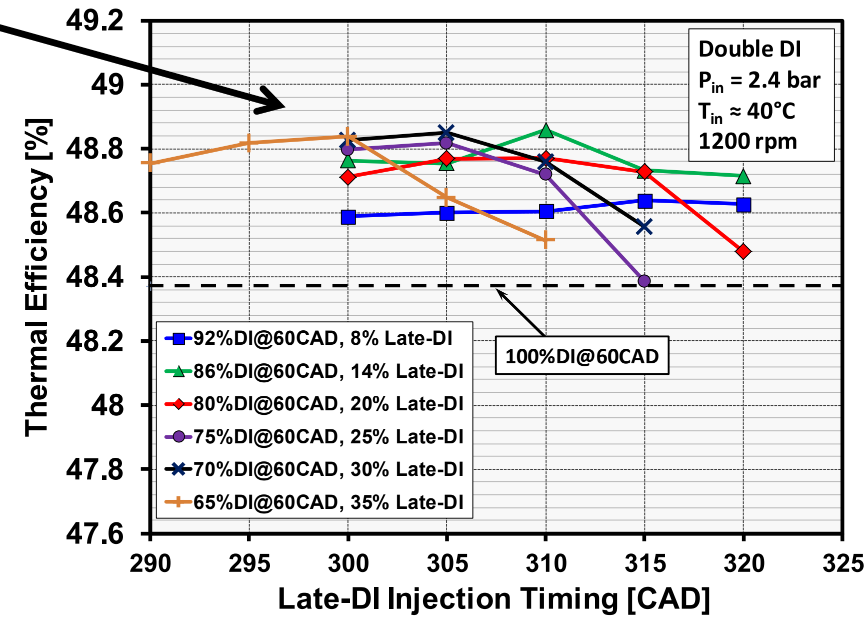
- DDI-PFS should allow significant CA50 advancement w/o knock (RI ≤ 5 MW/m^2).
  - CA50 advancement will act to improve TE.



CA50 and TE for Double-DI PFS at $\phi_m = 0.4$

- Systematically vary both DI timing and DI fraction.
- CA50 for RI = 5 MW/m^2 advances progressively as stratification is increased by both:
  - Later late-DI timing
  - Greater late-DI fraction
  - **Should increase TE.**
- However, max. TE is about the same for all late-DI fractions ≥ 14%.
  - Optimal late-DI timing for each DI%.
- CA50 continues to advance for later DI-timings, acting to improve TE.
- Therefore, other factors must act to reduce TE for these later late-DI timings down to the measured values.

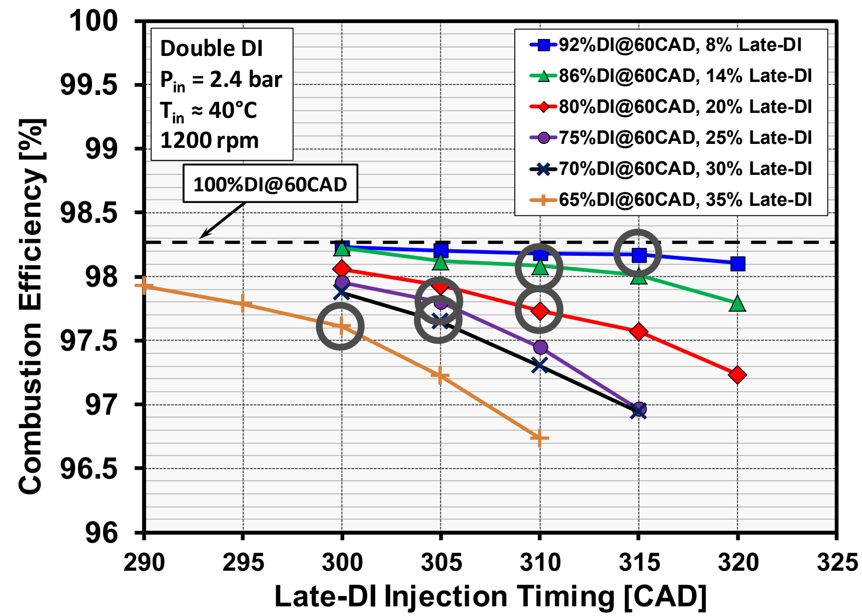


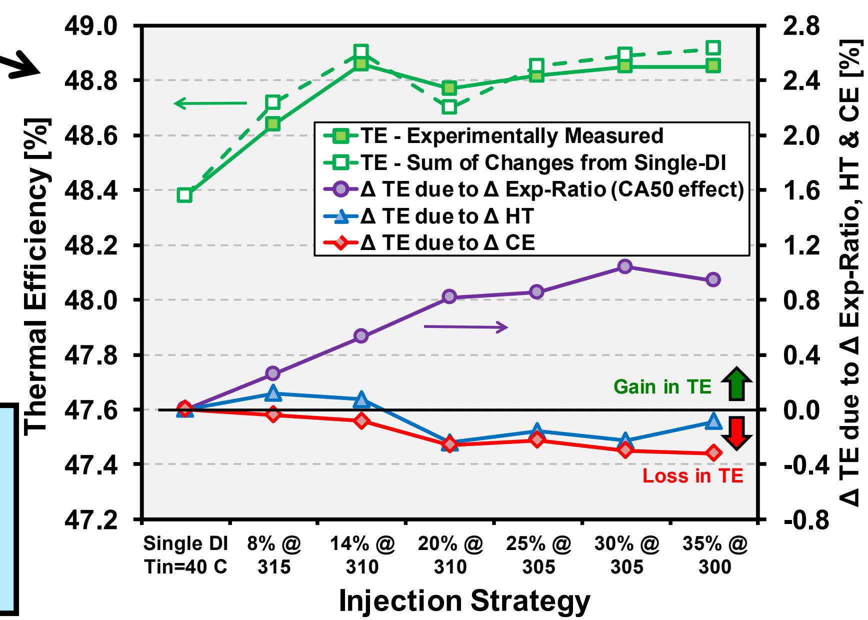


CE & HT Losses for Double-DI PFS at ϕ_m = 0.4

- Combustion Efficiency (CE) for DDI-PFS ⇒ Decreases with greater stratification.
  - Later Late-DI timing & greater Late-DI%
- Due to increased CO from overly rich regions. HC emissions are slightly lower.
  - Smoke is near zero at peak TE points, but rises rapidly for later late-DI timings.
  - NOx increases slightly, but remains more than a factor of 20 below US-2010 stds.
- CE acts opposite CA50 advancement
  - Accounts for about half of discrepancy.
- Apply HT analysis ⇒ found that HT loss increases with increased stratification.
  - Due to adv. CA50 or to injection velocities?
  - Additional studies needed to understand.

- Sum of expct'd TE gain for CA50 + losses from CE & HT closely match expr. TE.
- Explains the limit of the TE improvement.

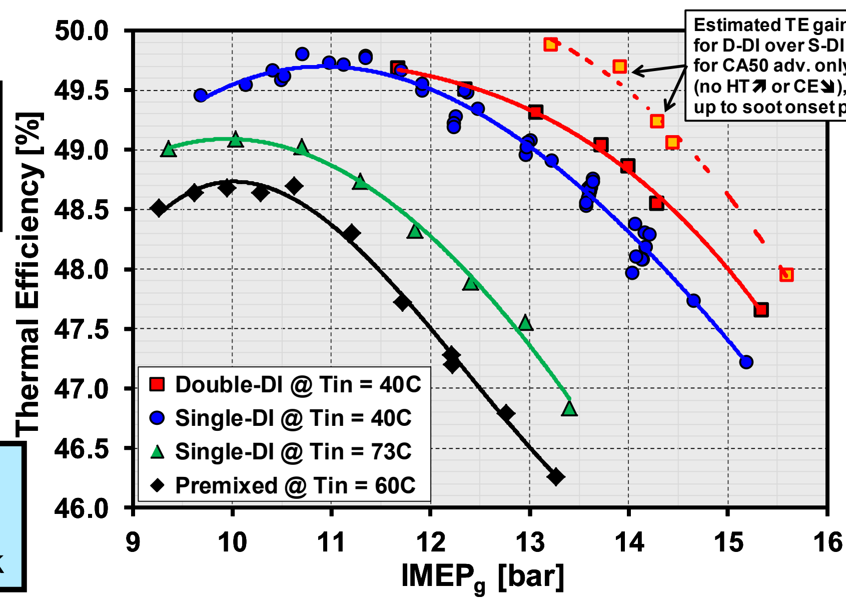


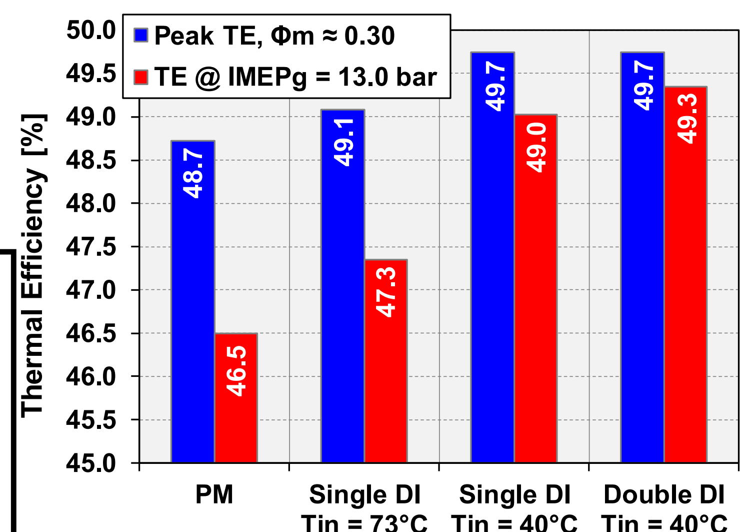


DI-PFS with Single and Double Injections

- Have shown that Single-DI PFS, T_{in} = 40°C substantially increases TE vs. PreMixed.
- D-DI PFS further incr's TE at higher loads.
  - Later CA50 ⇒ advance w/ PFS ⇒ TE↗.
- No TE gain with D-DI at lower loads where CA50 close to TDC (< ~368°CA).
  - Also, HT↗ mitigates TE gain w/ CA50 adv.
- D-DI PFS acts to further flatten TE vs. load curve ⇒TE at 13 bar $IMEP_g$ close to TE_{Peak}
- Noteworthy that CA50 advancement w/ D-DI PFS could give even greater TE gains if increase in HT & CE loss could be mitigated.
  - More-optimized strat. ⇒ likely reduce CE loss.
- D-DI PFS could also incr. max load if not O_2 ltd.
- Further gains likely at other oper. conditions and with regular gasoline, AKI 88 (RON 91).
  - Current data for E0-Cert fuel, AKI 93 (RON 97)

P_{in} = 2.4 bar, RI = 5 MW/m², 1200 rpm





Response to Reviewer Comments

1. **Reviewers made many positive comments.** ⇒ We thank the reviewers.
2. **Several comments supported the CFD modeling work, requested more details, mentioned model validation, and use of the models to guide PFS optimization.**
   - CFD modeling can provide an important complement to expr. work. However, the models currently show limited agreement w/ experiment ⇒ See Backup Slides for FY14 & FY15.
   - Does not seem valuable to provide more-detailed results until models are improved for better agreement. ⇒ Currently, kinetic submodels appear to be a key problem.
   - We plan to compare fuel-distribution images w/ model as become available. ⇒ Will help model validation. Unclear if models will be accurate enough to guide expr. as hoped.
   - A difficulty is that the modeling effort has limited resources and is not directly linked with our expr. program. ⇒ Progress could likely be improved with in-house modeling effort.
3. **Will future work investigate more than two injections?** - Yes
   - The best PFS performance requires a high level of stratification w/o overly rich regions that produce CO & reduce CE, as can occur with only two injections ⇒ see previous slides.
   - Three or more injections offer the potential to better tune the mixture distribution. We plan to investigate this in combination with PLIF imaging, and multi-zone kinetic modeling to help determine desired distribution. CFD may also be used to guide if results can be improved.
4. **Practical considerations – est. brake TE, required turbo eff, transient controls.**
   - Current work is on fundamentals of PFS mixture ⇒ As we move to new studies of high-load and TE limits with regular E10, we will apply turbo and friction models for est. brake TE.
   - Combst. ctrl. systems can require substantial resources ⇒ OEMs ? However, we do have plans to study potential of Spark Assist for ctrl. & use of small late fuel injection as a trigger.

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).
  - Twelve OEMs, Three energy companies, Six national labs, & Several universities.
- General Motors: Bimonthly internet meetings ⇒ in-depth discussions.
  - Provide data to GM on boosted LTGC and for modeling PFS-LTGC.
- Cummins, Inc.: Design & fabrication of low-swirl, spark-plug cylinder heads.
- LLNL: Support the development and validation of a chemical-kinetic mechanism for Certification Gasoline (CF-E0), Pitz *et al*.
- U. of California - Berkeley: Collaborate on CFD modeling of PFS-LTGC.
- U. of Melbourne, Australia: Collaborate on analysis methods. Patent application filed on new biofuels.
- Chevron: **Funds-In project** on advanced petroleum-based fuels for LTGC.

Future Work

Extend Operating Range of PFS-LTGC (multi-year task)

- Evaluate potential for extending the benefits of PFS over a wider load & speed range by using E10 regular gasoline and reducing the CR to 14:1.
  - Research-grade regular E10 reactivity > current Cert-Fuel (AKI = 88 vs. 93)
  - Analysis indicates that these changes will increase load range for PFS
  - Changes more in-line with OEM targets, but will reduce TE ~1.0 to 1.5 %-units.
- Investigate multiple-injection strategies to better optimize PFS for this config.
- Image fuel distributions in optical engine to guide fuel-injection strategies.
- Guidance from multi-zone kinetic models on desired fuel dist., & CFD if practical

Apply New Capabilities and Analysis Techniques

- Potential of 300 bar GDI injector to improve PFS, & late injection for control.
- Parameter sweeps to study range of conditions w/ potential for spark-assist ctrl.
- Heat-transfer analysis to understand cause of tradeoffs with fueling strategies.
- Apply turbo-charger and friction models from GM to evaluate these effects.

Support of LTGC/HCCI Modeling

- Continue to provide data, analysis, and discussions to support: 1) kinetic modeling at LLNL, and 2) CFD modeling at UC-Berkeley and GM.

Summary

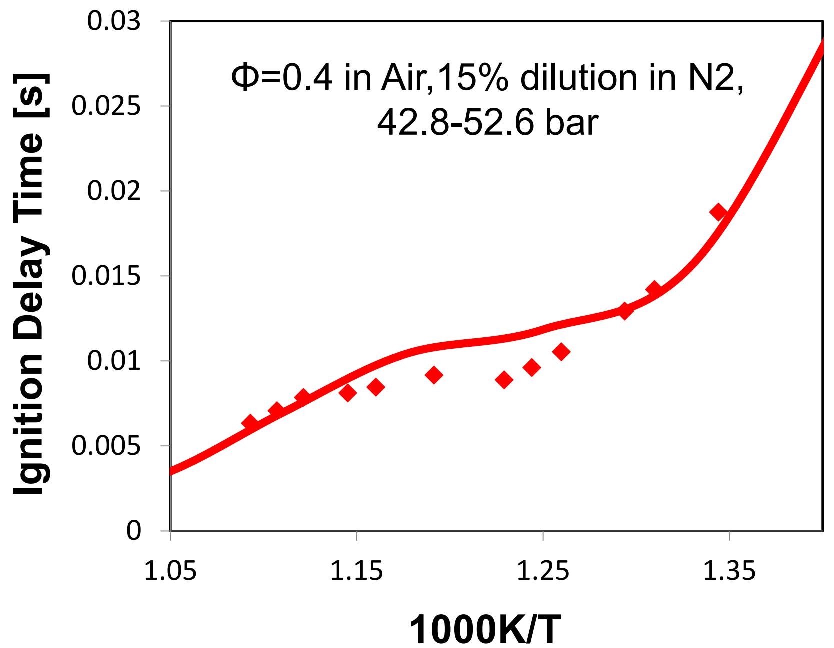
- Developed analysis techniques to compute the heat transfer and exhaust losses independently. ⇒ Used energy-closure to show they agreed well.
  - Also developed technique to compute the energy shift between TE & Exh-Loss for changes in CA50 and γ. ⇒ Showed that it gives a very good energy closure.
- Applied these techniques to determine the shift in energy distribution over a fueling rate (ϕ_m) sweep, and sweeps of CA50, T_{in}, & engine speed. ⇒ Understanding the tradeoffs helps guide further TE improvements.
- Discovered that changes in Woschni 2nd HT coefficient give a consistent, objective indicator of knock onset. ⇒ Verified for several parameter sweeps.
- Investigation of Single-DI PFS with injection early in intake stroke showed:
  - TE ~0.5 %-units above Premixed, even with higher T_{in} to match T_{BDC} of Premix
  - Much larger TE improvement w/ T_{in} = 40°C ⇒ higher γ, less HT, more adv CA50
- Conducted an in-depth study of Double-DI PFS ⇒ Early + Late DI inj.
  - Can greatly increase strat. for a large reduction in HRR and large CA50 adv.
  - Lower CE & increased HT can mitigate the large TE gain from CA50 advance ⇒ but Double-DI PFS still significantly improves TE at higher loads.
- Collaborated with CFD modelers at UC-B & GM on PFS, & chemical-kinetic modelers at LLNL on certification gasoline ⇒ see Technical B-up Slides

Technical Backup Slides

LLNL Collaboration – Kinetic Modeling

- Collaborators: Pitz and Mehl ⇒Worked on the development of a mechanism for zero-ethanol Certification Gasoline (CF-E0) from Haltermann (97 RON, 93 AKI).
  - CF-E0 is widely used by industry for certifying performance and emissions of gasoline spark-ignition automobiles.
- CF-E0 used for Sandia LTGC experiments, FY13 – FY15.
  ⇒ Data for model validation.
- LLNL developed a chemical-kinetic mechanism based on a 5-component surrogate.
  - Toluene + branched & straight-chain alkanes.
- Mechanism transferred to UC-Berkeley for CFD modeling of PFS with CF-E0.
  - UC-B reduced mechanism to 250 species for CFD.
- Provided experimental LTGC-PFS data using CF-E0 to UC-B for CFD modeling.
  ⇒ See next slide for UC-B collaboration.

LLNL CF-E0 mechanism & RCM data



RCM data from MIT (Wen Sang, Wai Cheng)

UC-Berkeley Collaboration – CFD Model of PFS

- Collaborators: Dr. Ben Wolk & Prof. J-Y Chen (funding DOE-NSF grant).
  - Supplied and explained expr. PFS data and engine geometry for grid development.
  - Guide interpretation of modeling results and give feedback for improvement.
- FY15 work focused on standard PFS (premixed + late DI): DI timing sweep w/ 13% DI fueling.
  - Model captures comb. timing, but not HRR shape. ⇒ too much early HR even for Premixed (PM).
  - Analysis shows this is from kinetic mech., not CFD.
- Kinetic mechanism does correctly capture sequential autoig. from richest to leanest zones.
- Efforts underway to determine if problem is in basic mech., or the result of reducing mech. for CFD.
- Also working on another dataset for PFS with CF-E0 (Cert. Fuel).