Boosted HCCI for High Power without Engine Knock, and with Ultra-Low NO_X Emissions using a Conventional Fuel

John Dec and Yi Yang

Sandia National Laboratories

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Program Manager: Gurpreet Singh

Introduction

- Advanced engines using HCCI or HCCI-like combustion can provide both high efficiencies and very low emissions of NO_X and PM.

- Limited max. power is a significant limitation to implementation of HCCI.

- Intake boosting is well-known as a method for increasing power.
  - Application to HCCI challenging because increased P_{in} enhances autoignition ⇒ combustion becomes overly advanced ⇒ knock.
  - Reduced CR and/or special fuels (natural gas, ethanol) often required.

- Previous work on boosted HCCI.
  1. Christensen & Johansson ⇒ 16 bar IMEP using natural gas.
  2. Olsson *et al.* ⇒ 16 bar BMEP using ethanol and *n*-heptane.
  3. Bessonette *et al.* ⇒ 16 bar BMEP using low ON gasoline & low CN diesel, CR = 12.
  4. Kalghatgi *et al.* ⇒ 16 bar IMEP using gasoline in a DI diesel, but NO_X = 0.58 g/kWh, well above US 2010 limits.

- IMEP or BMEP ~ 16 bar, but used special fuels or other changes.

Objective and Approach

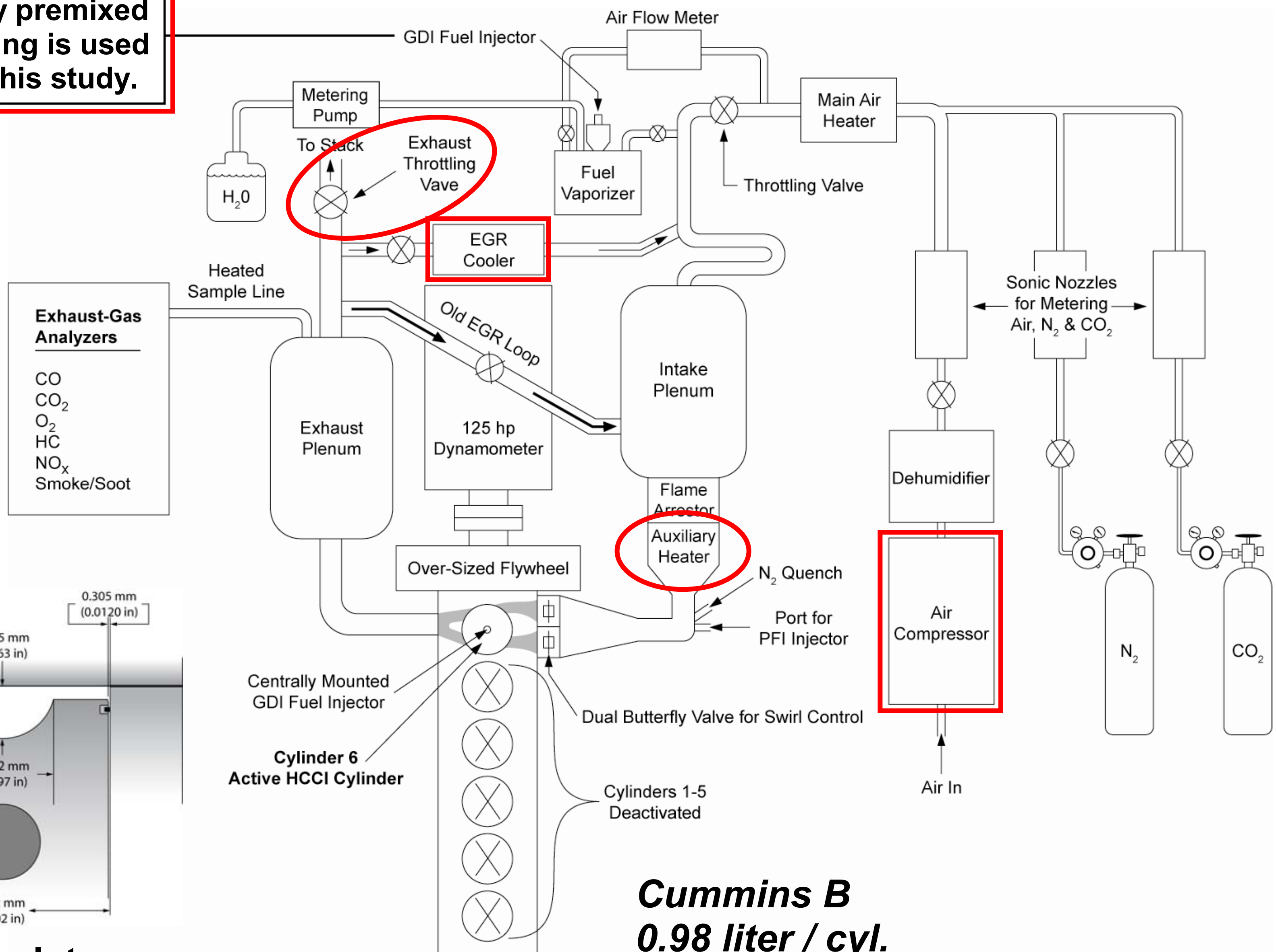
- Desirable to use a conventional fuel and to keep NO_X below US 2010 limits without aftertreatment.
  - Maintain a relatively high CR for high efficiency/low fuel consumption.

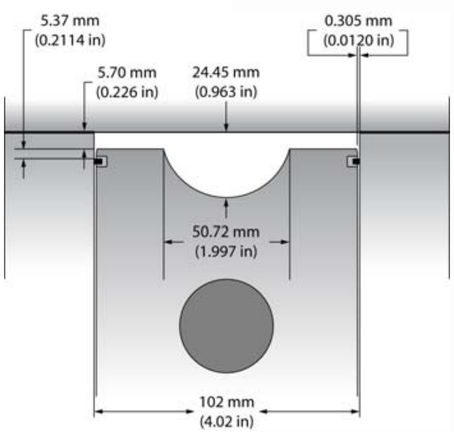
- **Objective**: Determine the potential boosted HCCI using conventional gasoline ⇒ with no engine knock and NO_X < US2010.

- **Approach:**
  1. Conventional Gasoline: (R+M)/2 = 87, RON = 90.8, MON = 83.2.
     Aromatics 23%, Olefins 4.2%, Alkanes 73%
  2. Piston: CR =14, open combustion chamber.
  3. Current data at 1200 rpm.
  4. Control pressure-induced enhancement of autoignition with a combination of:
     ⇒ Intake temperature control
     ⇒ Cooled EGR
  5. Maintain $P_{exhaust} \approx P_{in}$ + 2 kPa. (P_{in} = intake pressure)

HCCI Engine and Subsystems

Only premixed fueling is used for this study.





CR = 14 piston

Cummins B
0.98 liter / cyl.

Test Procedure

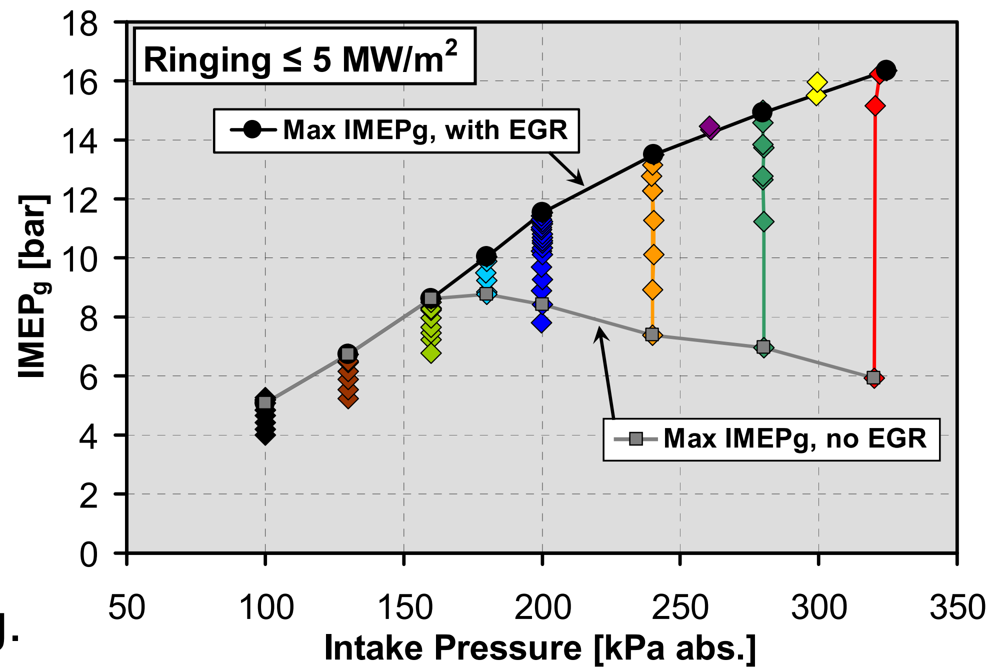
- Systematically increase P_{in} and determine maximum attainable $IMEP_g$.
  - Overly advanced combustion can cause knock and reduced efficiency.
  - Control pressure-induced enhancement of autoignition using a combination of T_{in} adjustment and cooled EGR.
- Retard combustion to prevent knock $\Rightarrow$ eventually reach stability limit.
- For each P_{in}, load is limited by knock/stability limit.
- Knock-limit criterion: **Ringing ≤ 5 MW/m²** $= \frac{1}{2\gamma} \cdot \frac{\left(0.05 \cdot \frac{dP}{dt, \max}\right)^2}{P_{\max}} \cdot \sqrt{\gamma R T_{\max}}$

Jim Eng, SAE 2002-01-2859

  - Corresponds to 8 bar/°CA at 1200 rpm, P_{in} = 100kPa absolute.
  - Increase in P_{max} helps $\Rightarrow$ $dP/d\theta > 8$ bar/°CA is OK with boost.

High-Load Limits with Boost

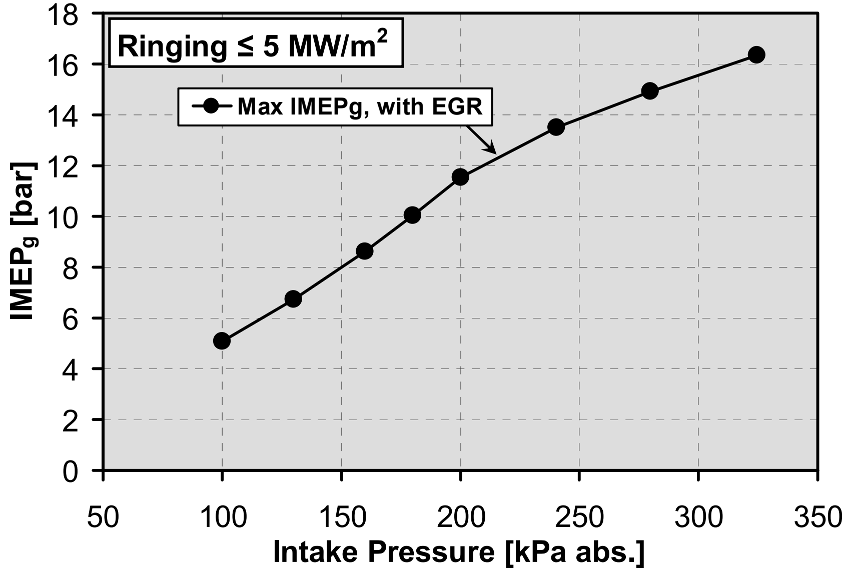
- Naturally aspirated, requires $T_{in} \approx 130°C$ (or hot residuals).
- Reduce T_{in} with boost to maintain sufficient combustion retard.
  - For P_{in} > 160 kPa, $T_{in} \rightarrow T_{amb}$ $\Rightarrow$ limits allowable fueling.
  - Max. $IMEP_g$ = 8.8 bar at P_{in} = 180 kPa.
- Cooled EGR to further slow autoig.

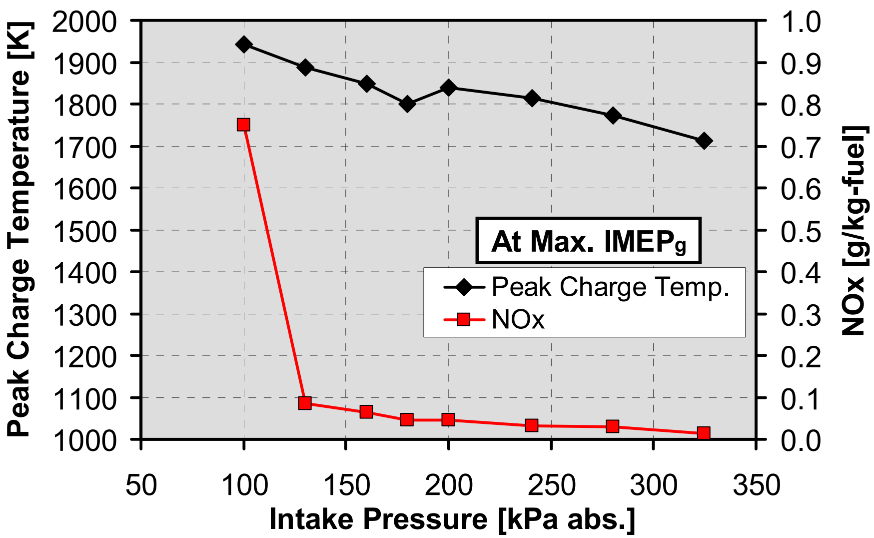


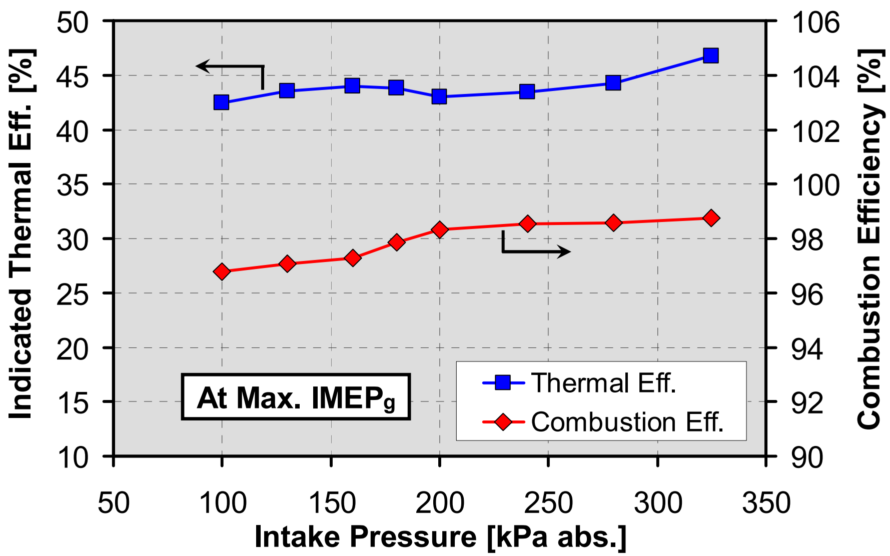
- Maintain T_{in} = 60°C $\Rightarrow$ allows substantial timing retard w/o significant LTHR.
  - Allows a large increase in fueling $\Rightarrow$ Max. $IMEP_g$ increased to 16.3 bar at 324 kPa.
- For P_{in} ≥ 260 kPa, EGR levels are so high that the mixture is stoichiometric.
  - Mass-fraction of reactants must be reduced as P_{in} is increased above 260 kPa.
- Therefore, higher loads require proportionally more boost.
  - Currently limited by max. allowable cylinder press.~170 bar.
  - 100-cycle avg. peak pressure at max.-load point is 150 bar.

Performance at Maximum $IMEP_g$ Points

- Indicated thermal efficiency ~45%.
  - Increases slightly with boost → 47%.
- Combustion eff. increases, 97 → 99%.
  - Higher wall temps. ⇒ improve combst.
  - Increased EGR reduces HC & CO emiss.
- NOx emissions extremely low for all boosted cases, < 0.1 g/kg-fuel.
- Correlates with low peak charge temp.
  - NOx higher for P_{in} = 100, T_{peak} > 1900K.

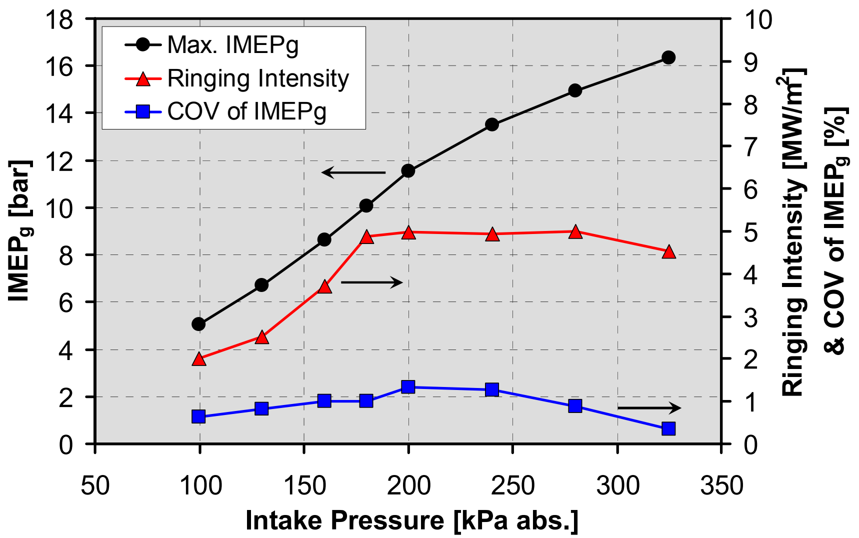




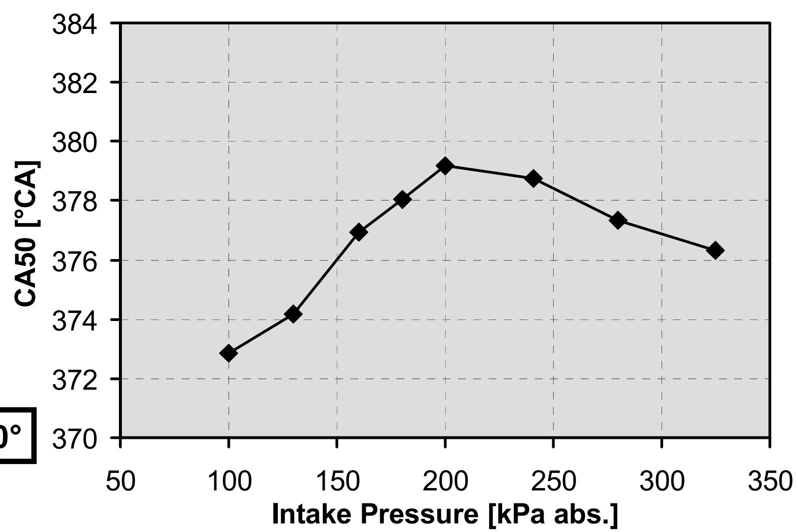


Maximum $IMEP_g$ Point – Stability and Knock

- Achieved **$IMEP_g$ = 16.3 bar**, P_{in}=324.
  - Stoichiometric C/F = 38.5, EGR = 60%, $T_{exhaust}$ = 407°C.
- COV of $IMEP_g$ ≤ 1%, VG stability.
- Ringing ≤ 5 MW/m², No Knocking.
  - Ringing increases P_{in} = 100 – 180 kPa.
  - P_{in} ≥ 180 kPa, Ringing held at 5 by substantially retarding combustion timing.
- Allowable combustion retard (CA50) increases greatly with increased P_{in}.
  - Less retard required, P_{in} > 200 kPa.



TDC = 360°

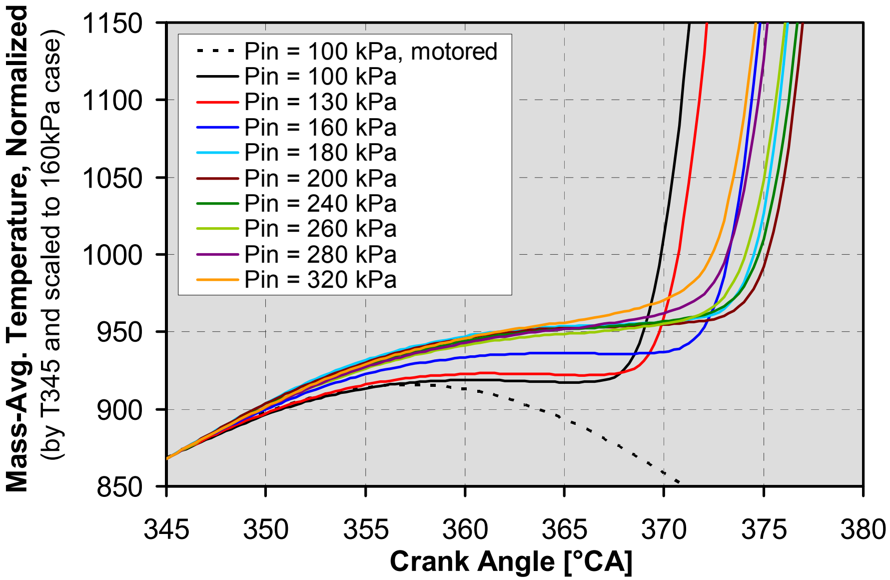


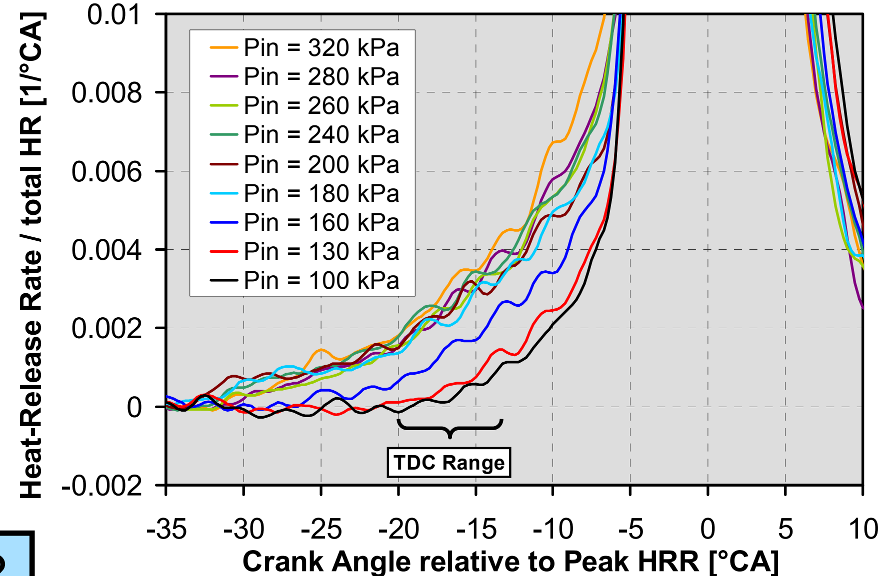
- Substantial timing retard with good stability is the key to controlling knock.

Retarding Combustion for Boosted Operation

- Retard combst. to reduce max. PRR.
  - Sjöberg *et al.*, *SAE 2005-01-0113*.
- Stability depends on dT/dθ prior to onset of main combustion.
  - Sjöberg & Dec, *P. Comb. Inst. 2006*.
- dT/dθ increases with intake boost.
  - Allows more retard with good stability.
- Compare HRR curves ⇒ align by peak HRR & normalize by total HR.
- Shows that the cause is increased ITHR (intermediate-temperature heat release) at higher boost.
  - Increases greatly P_{in} = 100 - 180 kPa,
    - > T_{in} is reduced from 130 → 60°C.
  - Little change for P_{in} > 180, T_{in} = 60°C.

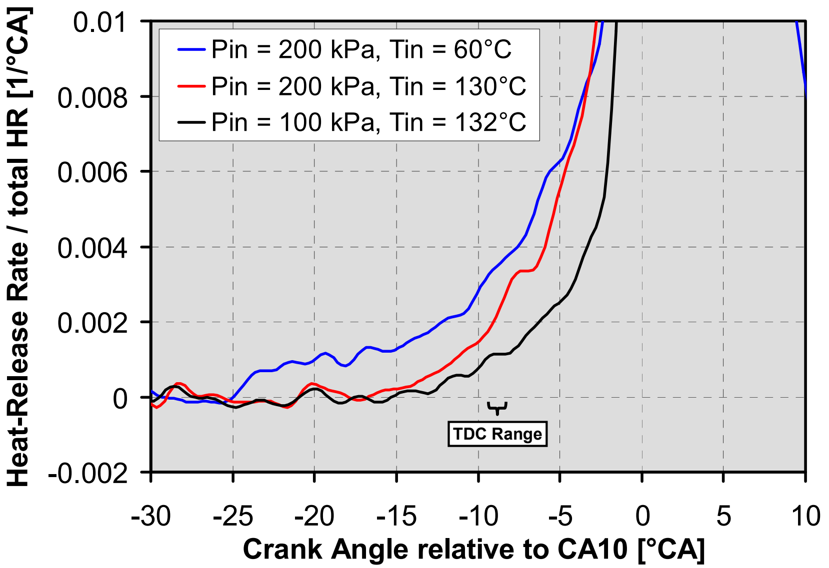
- Is increased ITHR due to ↑P_{in} or ↓ T_{in}?



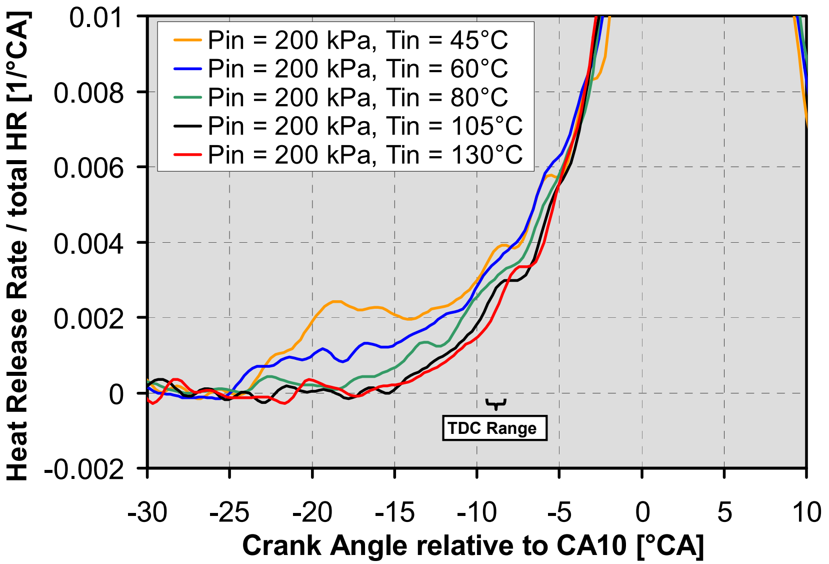


P_{in} and T_{in} Effects on ITHR with Boost

- T_{in} fixed at 130°C ⇒ Increase P_{in} from 100 → 200 kPa, ITHR ↑ significantly.
  - Mainly late ITHR ⇒ most important.
- Reduce T_{in} 130 → 60°C ⇒ more ITHR.
  - Mainly early ITHR; and onset of LTHR.
  - Further decr. T_{in} to 45°C, more LTHR.
  - Less important for stability.



- Temp. reduction contributes to the increase in ITHR.
- Pressure-induced increase in the ITHR is the more important effect.



Concluding Remarks

- Intake boosting allowed high $IMEP_g$ = 16.3 bar with 87-ON gasoline fuel.
  - No ringing, very good stability, high efficiency, and ultra-low NO_X.
  - Higher $IMEP_g$ should be possible with greater boost $\Rightarrow$ max. cyl. press?
- The key to this success was the ability to substantially retard combustion. $\Rightarrow$ CA50 to 379°CA (19°aTDC) with good stability.
  - This is possible because the ITHR increases significantly with boost $\Rightarrow$ keeps bulk-gas temperatures rising despite late CA50.
  - Detailed investigation showed that enhancement of ITHR by increased P_{in} is most important, but the enhancement by the reduction of T_{in} also contributes.
- For all data, $P_{exhaust} \approx P_{in}$ + 2 kPa
  - Also tested $P_{exhaust}$ = 250 for P_{in} = 200 kPa $\Rightarrow$ little effect on performance.
  - For max. $IMEP_g$ points, $T_{exhaust}$ = 407 – 470 K $\Rightarrow$ OK for turbo-charger.
- Study suggests that boosting has good potential as a viable approach for extending the load of gasoline-fueled HCCI.
- Future studies are planned to investigate boosted HCCI over a wider range of operating conditions.