Factors Affecting HCCI Combustion Phasing for Fuels with Single- and Dual-Stage Chemistry

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Introduction

- HCCI engines can provide diesel-like efficiencies and ultra-low NO\textsubscript{x} and PM emissions – However there are several technical barriers.

- Control of combustion phasing with changes in fueling rate is particularly important.
  - Various control techniques are available: intake heating, VCR, VVT.
  - Ultimately adjust the compressed-gas temperature (T\textsubscript{CG}) at “ignition.”

- Often considered that combustion phasing can be affected by F/A mixture ⇒ Ignition is faster with richer mixtures created by higher fueling rates or charge-mixture inhomogeneities.

- However, as the fuel load is varied, several factors are affected, each of which can affect combustion phasing.
  - Most factors directly or indirectly cause changes in the T\textsubscript{CG}.
  - Additionally, these factors can sometimes mask changes – or lack of changes – due directly to F/A-mixture effects.
Objectives

- Identify the factors that cause changes in combustion phasing with changes in fueling rate (fuel-air equivalence ratio, \( \phi \)).

- Systematically remove the changes due to each factor.
  - Understand the relative magnitude of these factors.

- Isolate the effect of changes in fuel chemistry with equivalence ratio to understand the importance of this factor.
  - Compare behavior of various fuel-types: iso-octane, gasoline, & PRF80.

- Investigate the potential of fuel stratification for controlling combustion phasing.
HCCI Engine and Subsystems

Fuel flow meter

Exhaust-Gas Analyzers
- CO
- CO₂
- O₂
- HC
- NOₓ
- Smoke/Soot

125 hp Dynamometer

Exhaust Plenum

Air Flow Meter

GDI Fuel Injector

On-Off Valves for Optional Premixed Fueling

Fuel Vaporizer

Auxiliary Heater

Sonic Nozzle for Metering Intake Air

Main Air Heater

Throttling Valve

Dehumidifier

Air Compressor

Port for PFI Injector

Over-Sized Flywheel

Centrally Mounted GDI Fuel Injector

Cylinder 6 Active HCCI Cylinder

Dual Butterfly Valve for Swirl Control

Cylinders 1-5 Deactivated

Cummins B
0.98 liter / cyl.

Piston design:
- CR: 17.6
- Swirl ratio: 0.9
- Speed: 1200 rpm
- \( P_{\text{in}} \): 100 kPa

Fueling: Premixed GDI

Base Condition
Observed Changes with Variation in Fueling

As fueling ($\phi$) is varied, $T_{CG}$ must be adjusted to maintain combustion phasing.

- 50%-burn phasing at TDC (indication of performance).
- Adjust $T_{CG}$ by varying Intake temperature ($T_{in}$).

All fuels show a trend of a lower required $T_{in}$ with increased $\phi$.

- Do richer mixtures autoignite more easily for all fuels?
- What role do other factors play?

For example, wall heating and residuals will change with $\phi$.

- Figure shows fuel-on transients for $\phi = 0.2$ and 0.3, iso-octane (avg. of 10 events).

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Factors Causing Changes in $T_{in}$ with Fueling

1. Combustion duration increases at lower $\phi$. This requires that the start of combustion occur earlier to maintain 50% burn at TDC.

2. Wall temperatures increase with increased $\phi$, causing higher $T_{CG}$ for a given $T_{in}$.

3. Temperature of residuals increases with $\phi$, reducing required $T_{in}$.

4. Heating/cooling during induction changes with $\phi$ as the $\Delta T$ between $T_{in}$ and $T_{wall}$ varies, amount of fuel vaporization, & “dynamic heating.”

5. Fuel-chemistry effects.
   – Differences in $\phi$ can affect the chemical-kinetic rates of autoignition.
   – Thermodynamic properties of mixture – particularly specific heat ($\gamma=c_p/c_v$).

- Systematically remove factors 1-4 leaving only fuel-chemistry effects.
1. Changes in Combustion Duration

- Burn duration increases as $\phi$ reduced.
  - Phasing remains very stable – Std. Dev < 0.3°CA for 10 & 50% burn over range of interest.
  - 0.1<$\phi$<0.3 (idle to moderate load).

- Fuel-chemistry effects should correlate with ignition point.

- Select 10% burn as “ignition” pt.
  - Use Woschni correlation to account for heat transfer.

- Retake data with const. 10% burn at 357.4°CA, match $\phi$=0.2.
  - Change in $T_{in}$ with $\phi$ is greatly reduced, from 24°C to 8.5°C.

Base Fuel: Iso-Octane

- Changes in Combustion Duration

- Fuel-chemistry effects should correlate with ignition point.

- Select 10% burn as “ignition” pt.
  - Use Woschni correlation to account for heat transfer.

- Retake data with const. 10% burn at 357.4°CA, match $\phi$=0.2.
  - Change in $T_{in}$ with $\phi$ is greatly reduced, from 24°C to 8.5°C.
2 & 3. Remove Changes in $T_{\text{wall}}$ and Residuals

- Remove changes in $T_{\text{wall}}$ & residuals using alternate-firing technique.
  - Hold 10% burn phasing at 357.4°.

- Reverses trend – higher $T_{\text{in}}$ with higher $\phi$.

- Change in slope between the curves gives relative magnitude of factors.
  - $\phi < 0.2$, burn duration dominates.
    - Comb. eff. low: long burn, low heating.
  - $\phi > 0.2$, opposite is true.

- Separate $T_{\text{wall}}$ & residual effects estimated from transient data and fire18/2 data.

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4. Heating/Cooling During Induction

- $T_{in} \neq T_{BDC}$ due to heating/cooling during induction.
- Developed technique to estimate $T_{BDC} \Rightarrow$ Details in SAE 2004-01-1900.
- Compute changes in $T_{BDC}$ from measured changes in mass flow relative to a base condition.

$$T_{in,\text{effective}} = T_{in,\text{effective,base}} \cdot \frac{m_{air,base}}{m_{air+fuel}} \cdot \frac{M_{air+fuel}}{M_{air}} \cdot \frac{P_{in}}{P_{in,base}}$$

- Base condition: motored $T_{in} = T_{\text{coolant}} = 100^\circ\text{C}$, minimizes heat transfer.
  - Dynamic heating $\Rightarrow T_{BDC,\text{base}} = 110^\circ\text{C}$ (from WAVE code, Ricardo).

- Estimate $T_{\text{residuals}} \approx \text{average of } T_{\text{exhaust}} \text{ and } T_{\text{blowdown}}$.

- Combine to get:
  $$T_{bdc} = \frac{T_{in,\text{effective}} \cdot m_{air+fuel} + T_{\text{residuals}} \cdot m_{\text{residuals}}}{m_{air+fuel} + m_{\text{residuals}}}$$

- A straightforward procedure. Technique is very sensitive.
4 & 5. Use $T_{BDC}$ to Isolate Effects of Fuel Chemistry

- For fire19/1, residuals are constant; use effective $T_{in}$ rather than $T_{BDC}$.

- Effective $T_{in}$ curve shows only changes due to fuel-chemistry.
  - Autoignition kinetics & $\gamma = c_p/c_v$.

- Does a higher $\phi$ enhance autoignition for iso-octane?
  - Higher $\phi \Rightarrow$ smaller $\gamma \Rightarrow$ higher $T_{in}$ required for same $T_{CG}$.

- Lesser slope of Effective $T_{in}$ curve indicates an enhancement with $\phi$.
  - Effect fairly small for iso-octane.
    - Much less than sum of other four factors.
  - Single-stage ignition fuel.
5. Fuel-Chemistry Effects – Various Fuels

- Alternatively, hold $T_{in}$ constant and observe changes in phasing.  
  - Trends similar to effective $T_{in}$.

- The 10%-phasing curves show isolated fuel-chemistry effects.

- Iso-octane: enhancement of ignition kinetics $<$ effect of $\gamma$.

- Gasoline: a little more enhancement of ignition kinetics with increased $\phi$ than iso-octane.

- PRF80: autoignition kinetics greatly enhanced with $\phi$.
  - Correlates with increasing cool-flame chemistry with $\phi$ (infers diesel fuel).
  - At low $\phi$ cool-flame activity is minimal, and trend is similar to iso-octane.
50% Burn Phasing for Constant $T_{in}$ and $T_{wall}$

- 50% burn is a better indicator of engine performance.

- Fire 19/1 data simulates behavior during a rapid load change before $T_{in}$ and $T_{wall}$ can respond.
  - Iso-octane & gasoline: small variation, little compensation required. ⇒ single-stage ignition
  - PRF80: large variation, significant compensation required. ⇒ dual-stage ignition (cool-flame chem.)

- Data can also be interpreted as indicating the potential for changing combustion phasing with mixture stratification ($T_{wall}$ & residuals constant).
  - PRF80: mixture stratification has a strong potential to control phasing.
  - Iso-octane and gasoline: stratification offers little benefit for phasing control.
Stratification Advances Combustion for PRF-80

- **PRF80**: simulate load change from $\phi = 0.24 \Rightarrow 0.18$.
  - $\phi = 0.24$, $T_{in} = 59^\circ$C for 50% burn at TDC.
  - $\phi = 0.18$, $T_{in} = 102^\circ$C for 50% burn at TDC.

- Stratification can rapidly adjust phasing for PRF80.
  - Injection at 270°CA, in phase.
  - Also, improves combustion eff., as shown in SAE 2003-01-0752.

- **Iso-octane**: stratification does not advance phasing.
  - Weak enhancement of autoignition kinetics with $\phi$.
  - Does not overcome charge cooling due to vaporization.

SAE 2004-01-0557
Summary and Conclusions

- In addition to fuel-chemistry, several factors affect the change in intake-temperature required to maintain constant 50%-burn phasing when the fueling rate is varied.

- The relative magnitude of these factors depends on the load range.
  - At low loads, ($\phi < 0.2$), changes in burn duration have the largest effect.
  - For higher loads ($\phi > 0.25$), changes in $T_{\text{wall}}$ are dominant.

- The effect of residuals is relatively small in this engine.
  - They could be the dominant factor in a high-residual engine.

- The effect of F/A mixture ($\phi$) on ig. timing depends strongly on fuel type.
  - Single-stage ignition fuels: iso-octane & gasoline $\Rightarrow$ effect is small.
  - Dual-stage ignition fuels: PRF80 $\Rightarrow$ effect is substantial due to cool-flame chemistry. (Similar effect expected for diesel fuel.)

- Mixture stratification can significantly and rapidly advance combustion phasing for PRF80 (or by inference diesel fuel), but not for iso-octane.