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The Use of Partial Fuel Stratification to Enable Stable Ultra-lean Deflagration-based SI Engine Operation with Controlled End-gas Autoignition of Gasoline and E85

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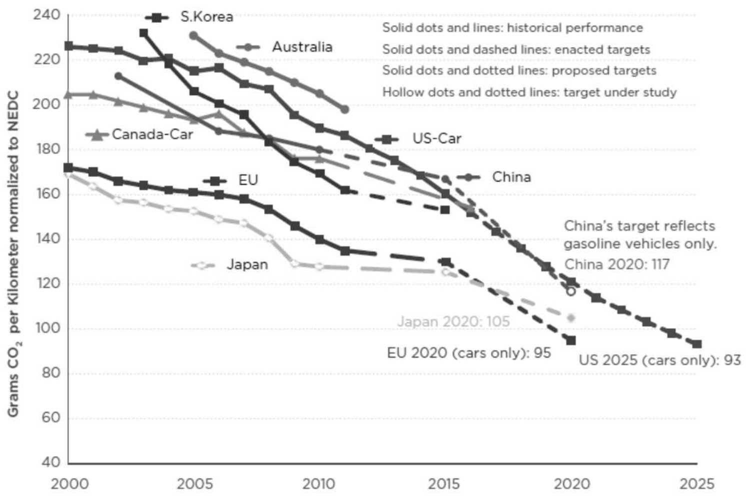
Introduction

- CO_2 emission reduction is worldwide urgent.
- IC engine thermal efficiency improvement is one key factor for vehicle section.
- Lean and/or dilute SI operation of DISI can improve fuel economy.
- Fuel type, like alternative fuel or E-fuel, plays a fundamental role in IC engine combustion mode.



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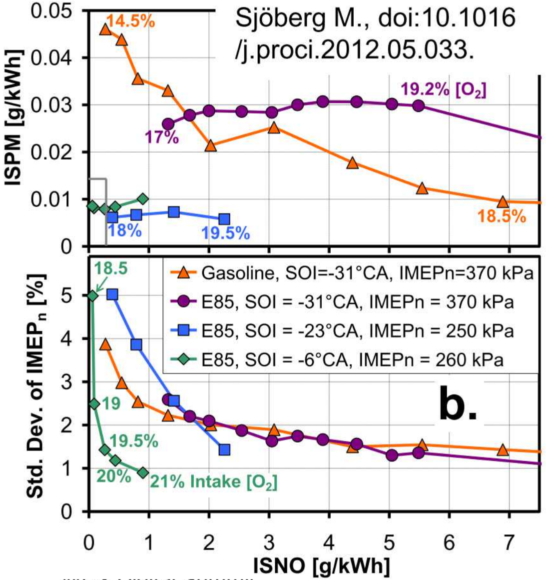
Introduction

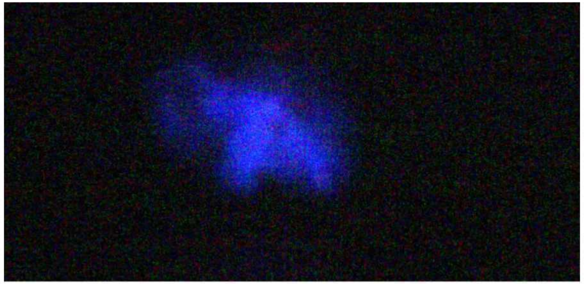
- Well-mixed stoichiometric DISI combustion is widely used without fully exploring potentials of DISI.
- Lean combustion offers higher efficiency, but it is challenging to achieve stable ignition for well-mixed operation.
- Stratified lean combustion can suffer from combustion instability & NO_x / soot trade-off.



Sjöberg M., doi:10.1016 /j.proci.2012.05.033.

- **Partial Fuel Stratification can stabilize lean combustion – focus of this study.**

ϕ = 0.55, 33°CA after ST



ϕ = 1.0, T_{in} = 30°C, ST = -13°CA

ϕ = 0.55, T_{in} = 100°C, ST = -57°CA

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Outline

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- PFS combustion
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- Conclusions
- Acknowledgments

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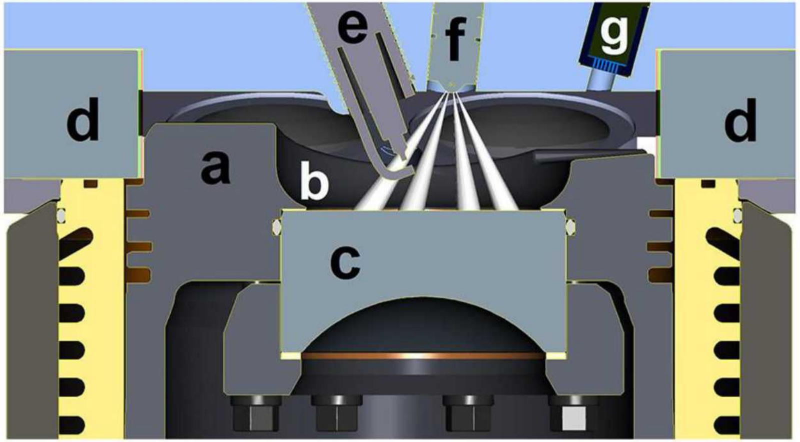
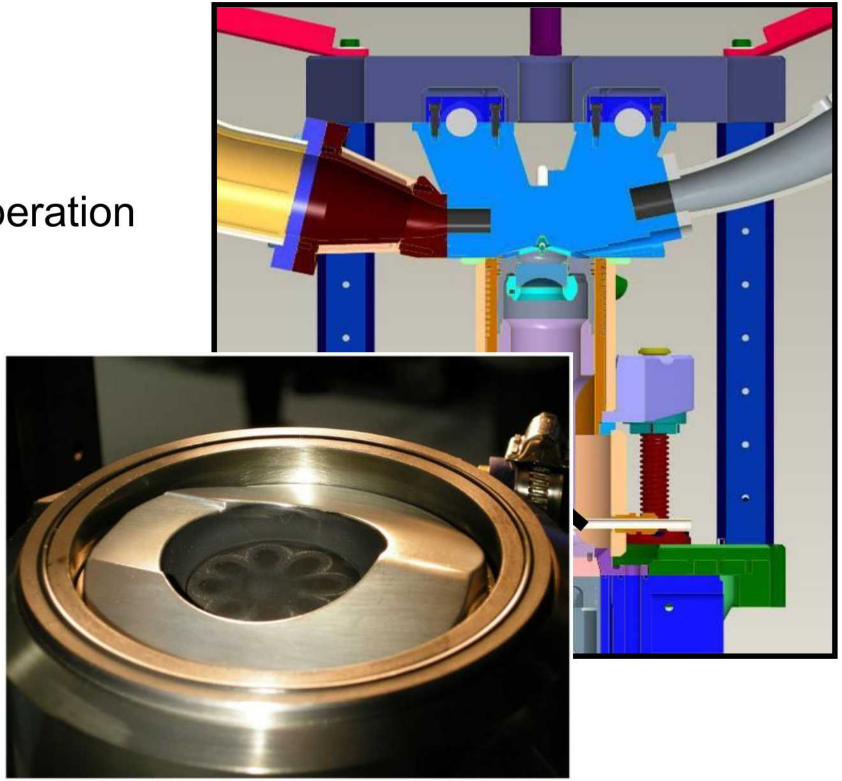
Research Engine

- Drop-down single-cylinder engine.
- Identical geometry for All-metal and Optical.
- Designed for spray-guided stratified-charge operation
  ⇒ Piston bowl.





All-metal piston and cylinder in its dropped-down position

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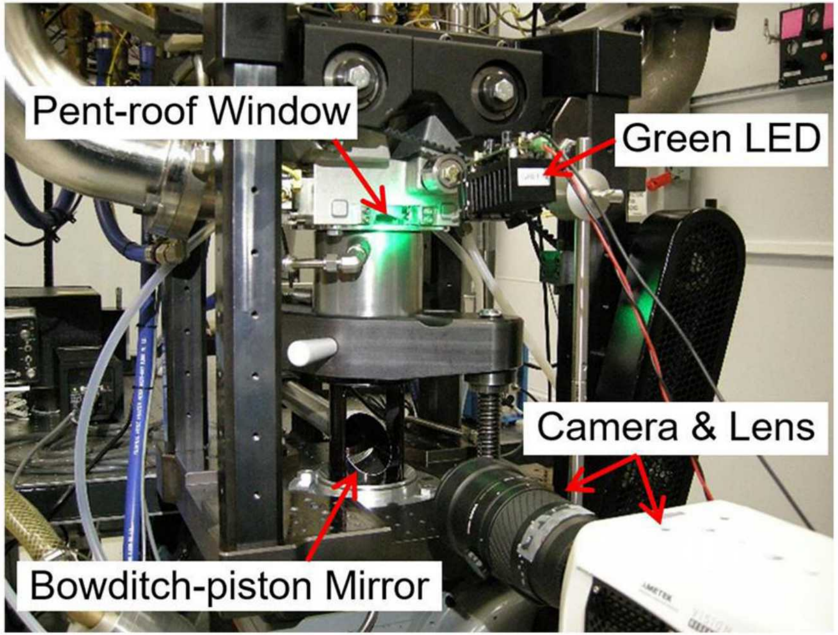
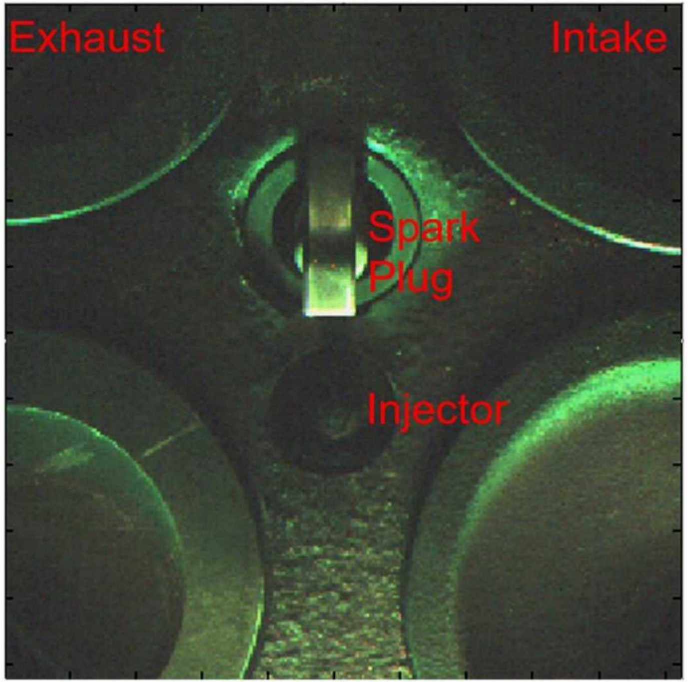
Research Engine



Optical experimental system



Camera field-of-view with piston at -30°CA

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Research Engine

Table 1. Engine specifications.

Displacement	0.552 L
Bore	86.0 mm
Stroke	95.1 mm
Connecting rod length	166.7 mm
Geometric compression ratio	12:1
Intake valve diameter	35.1 mm
Intake valve angle relative cylinder axis	18°
Exhaust valve diameter	30.1 mm
Exhaust valve angle relative cylinder axis	16°
Swirl/tumble index (one intake valve deactivated)	2.7/0.62
Fuel injector	Bosch eight-hole solenoid-type
Injector hole orientation	Symmetric with 60° included angle
Injector hole size	Stepped hole, minimum diameter = 0.125 mm

Table 2. Haltermann EPA Tier II Certification Gasoline.

Research Octane Number	96.6
Motor Octane Number	88.7
Anti-knock index	92.7
Density (kg/L)	0.743
Carbon (wt%)	86.7
Hydrogen (wt%)	13.3
Oxygen (wt%)	None detected
A/F stoichiometric	14.54

Table 3. Estimated properties of E85 fuel.

Research Octane Number	108
Motor Octane Number	91
Anti-knock index	100
Specific gravity	0.782
A/F stoichiometric	9.79
LHV, gas-phase fuel (MJ/kg)	29.2
LHV for stoichiometric charge (MJ/kg)	2.706
Hydrocarbon type (vol.%)	
Oxygenates	85
Aromatics	4.9
Branched alkanes	8.2
Linear alkanes	1.1
Cyclic alkanes	0.4
Alkenes	0.01
Not classified	0.3

LHV: lower heating value.

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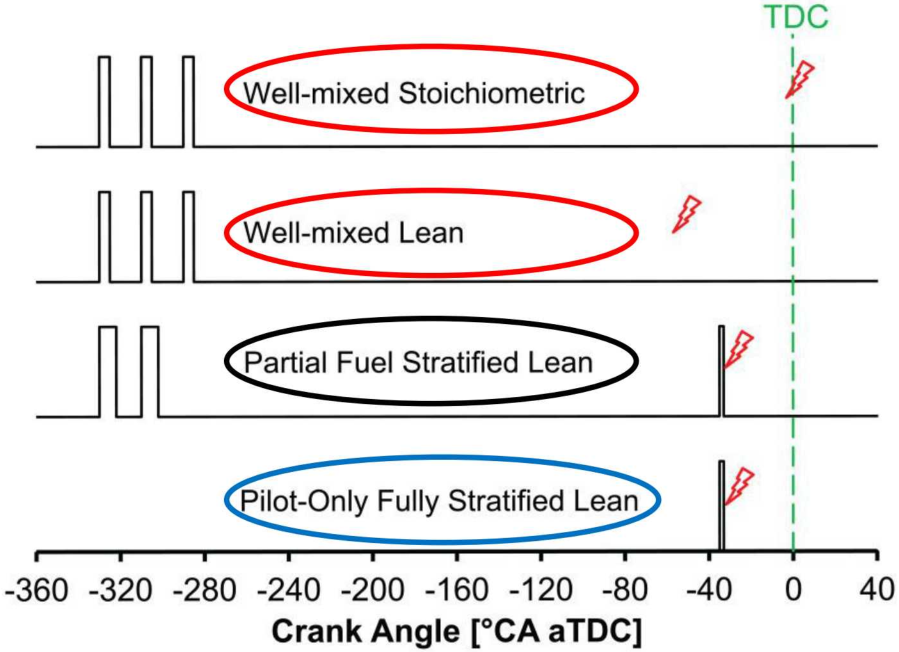
Methodology

Injection and Ignition Strategies



- Early injections during intake stroke ⇒ well-mixed charge, adjusting load.
- Late injection followed by ignition with 3° CA delay at 1000rpm, igniting spray tip ⇒ Partial Fuel Stratification (PFS)
- Only Late injection ⇒ Pilot-Only

Table 4. Operating conditions.

Fuel	E85, gasoline	
Engine speed	1000 r/min	
Injection pressure	170 bar	
Coolant temperature	75°C	
Intake temperature	30°C, 60°C, 100°C	
Intake-air flux	Lean modes	4.5 g/s
	Stoichiometric modes	1.6–3.5 g/s
Intake-tank pressure	Lean modes	95–110 kPa
	Stoichiometric modes	40–79 kPa

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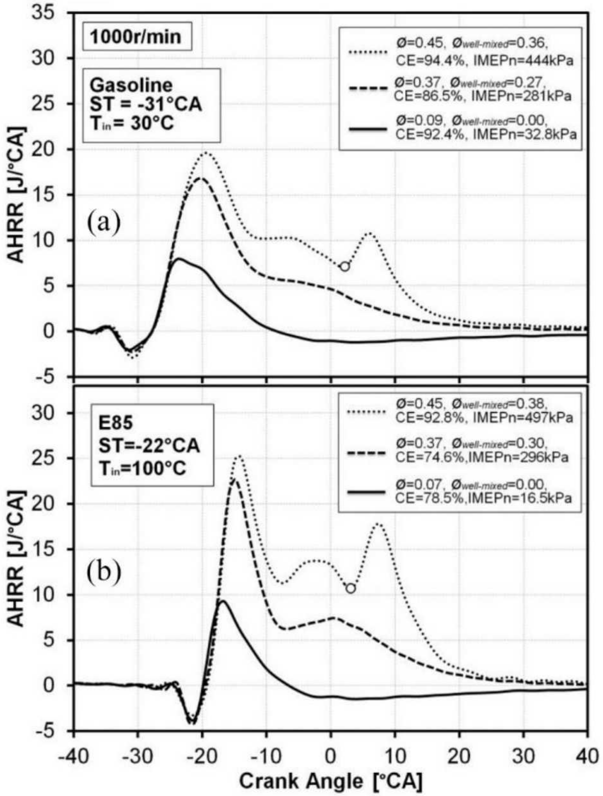
Heat-release comparison of Pilot-Only and PFS

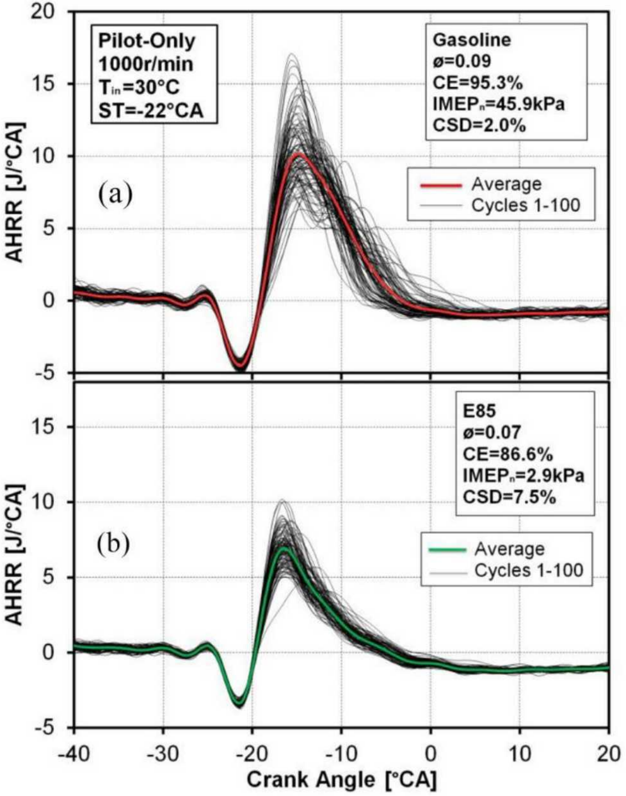
Only pilot-injection combustion with ultra-low overall equivalence ratio (ø)

- Spark stably ignites pilot-injected fuel with high combustion efficiency due to strong fuel stratification

Fuel addition in well-mixed lean background

- Stronger heating release at all stages
- 1→2→3 stage profile
- End-gas autoignition is triggered





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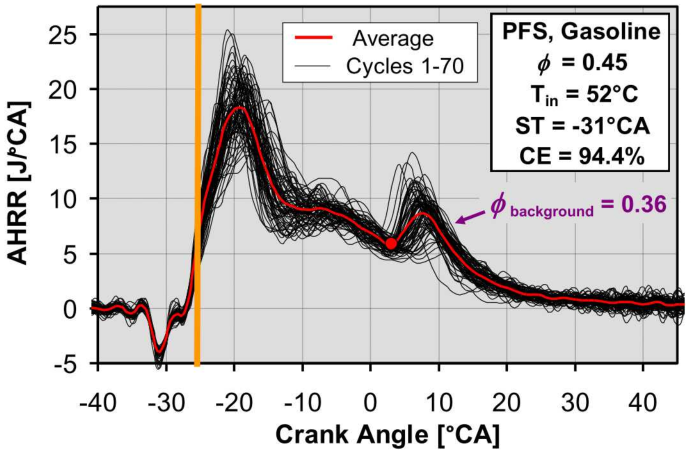
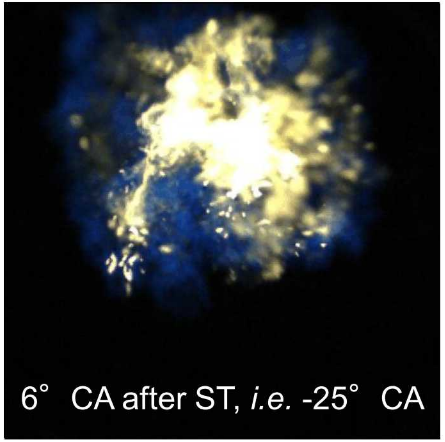
High-speed spray and flame imaging, flame variability of PFS with *ø=0.45*

- **Liquid fuel vaporizes quickly**
- **Flame spread is rapid throughout piston-bowl area**

- **Flames fronts propagate out of view by -20° CA**
- **End-gas autoignition cannot be visualized in this configuration**





- **Very repeatable inflammation**

Explains repeatable end-gas autoignition. Even for transient optical-engine operation.

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3-stage combustion mode of PFS

For reference, throttled well-mixed stoichiometric operation with similar IMEPn as PFS *ø=0.45*.

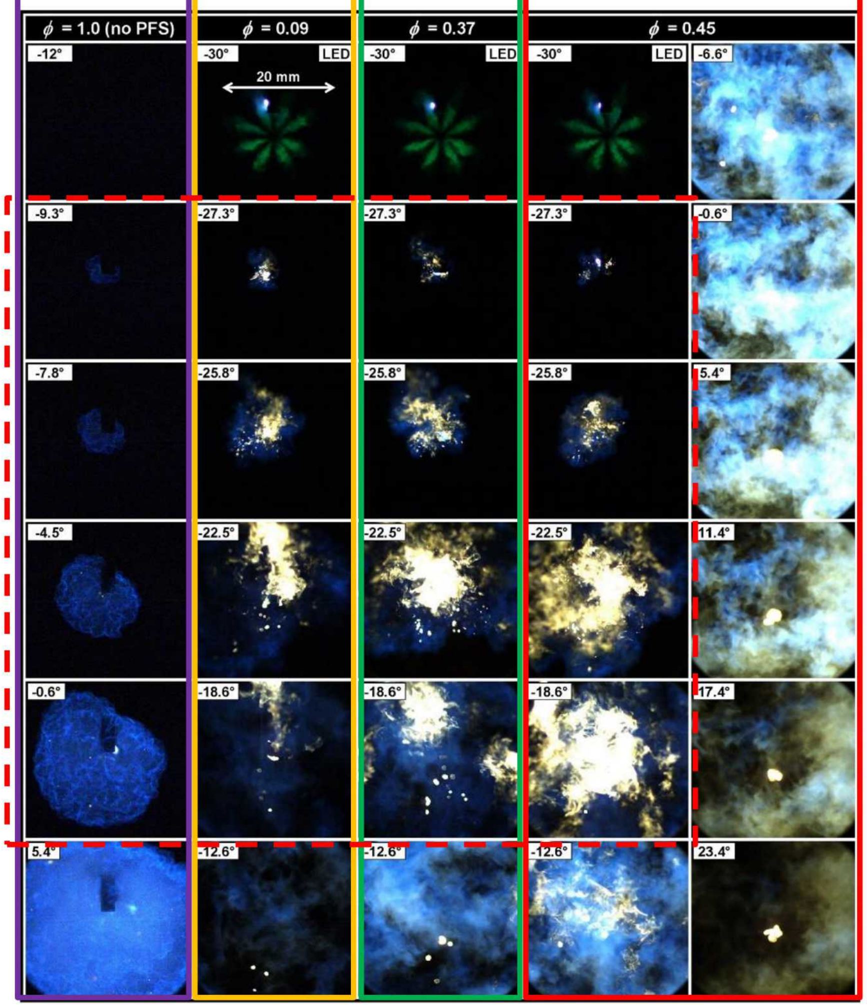
PFS: *ø=0.45* *ø=0.37* Pilot-only : *ø=0.09*

Flame spread rate is comparable for all lean cases in the -30 ~ -25.8CA, but slightly faster than the well-mixed stoichiometric case

'Pilot' in PFS creates vigorous combustion, showing its effectiveness in igniting a lean background.

LHV of pilot-injected fuel is > 90 J ≈ 1000*spark, acting as a "Flying Super Igniter" for ultra-lean background mixture, leading to "Fast Lean Combustion".

3-stage hypothesis when *ø=0.45* :
 Ignited diffusion flame in strong-stratified charge;
 Flame propagation in weak-stratified mixture;
 Autoignition in ultra-lean end-gas.



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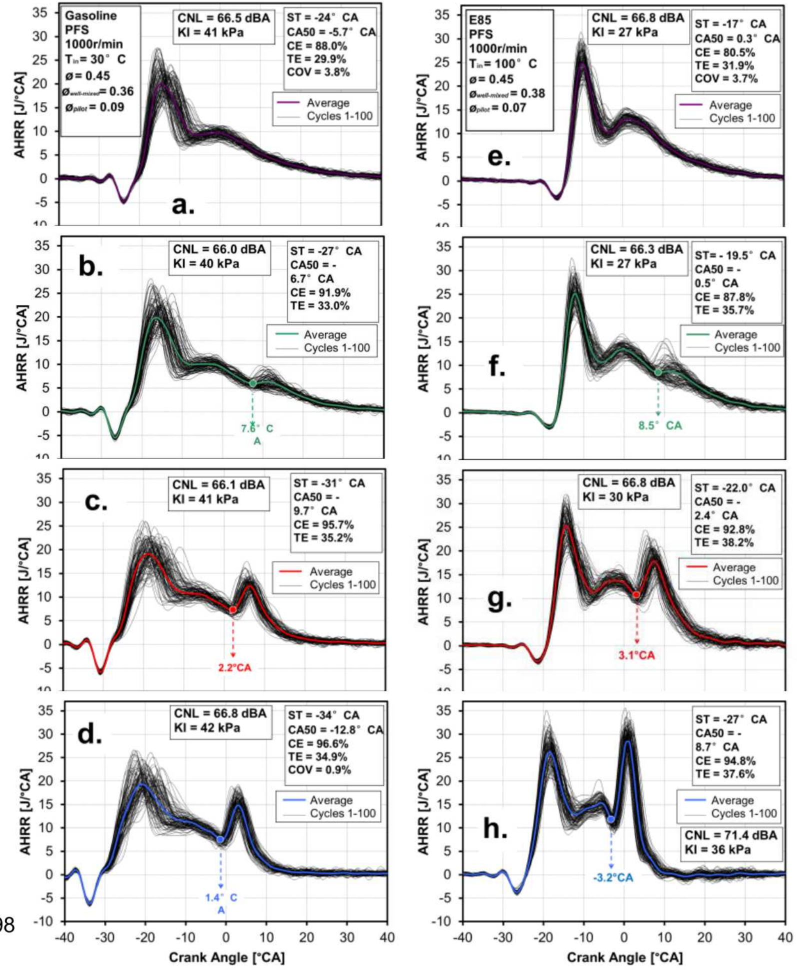
ST-controlled end-gas autoignition optimizing TE and CE for gasoline and E85

- When ST is late, there is a stable 2-stage combustion, but its CE and TE are low.
- As ST is advanced, part of heat releases become 3-stage occurring randomly and weakly with higher CE and TE but a slight increased COV.
- With further advancing ST, the 3rd peak emerges regularly and more strongly in each single cycle, leading to <u>highest CE and TE, with lowest COV</u>.
- If ST is further advanced, the 3rd stage heat release is too strong making engine knock intolerable, with TE starting drop, despite increasing CE and further reduction of COV.
- Fueled with E85, combustion mode transfers similar as gasoline.
- 1st and 2nd peaks shift with unchanged amplitudes, showing 3rd end-gas autoignition plays key roles.



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Fundamental factors for end-gas autoignition – FUEL

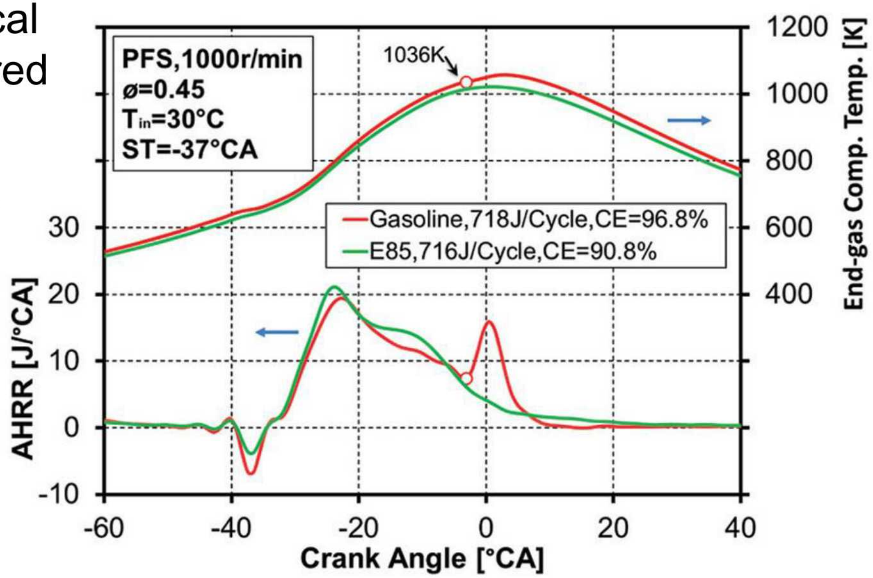
Fuel properties (like RON, MON) are critical factors affecting the fuel-air mixture autoignition.

- using same ø, ST, T_{in} and similar supplied chemical energy, E85 and Gasoline can be directly compared for PFS operation.
- There is no end-gas autoignition in the E85 case, but a strong autoignition in gasoline case, despite the end-gas is much leaner than the rich conditions of the RON and MON tests.

  a. E85 has lower reactivity.

  b. Strong vaporization cooling of E85 reduces compression temps.

  ⇒ End-gas autoignition is suppressed.



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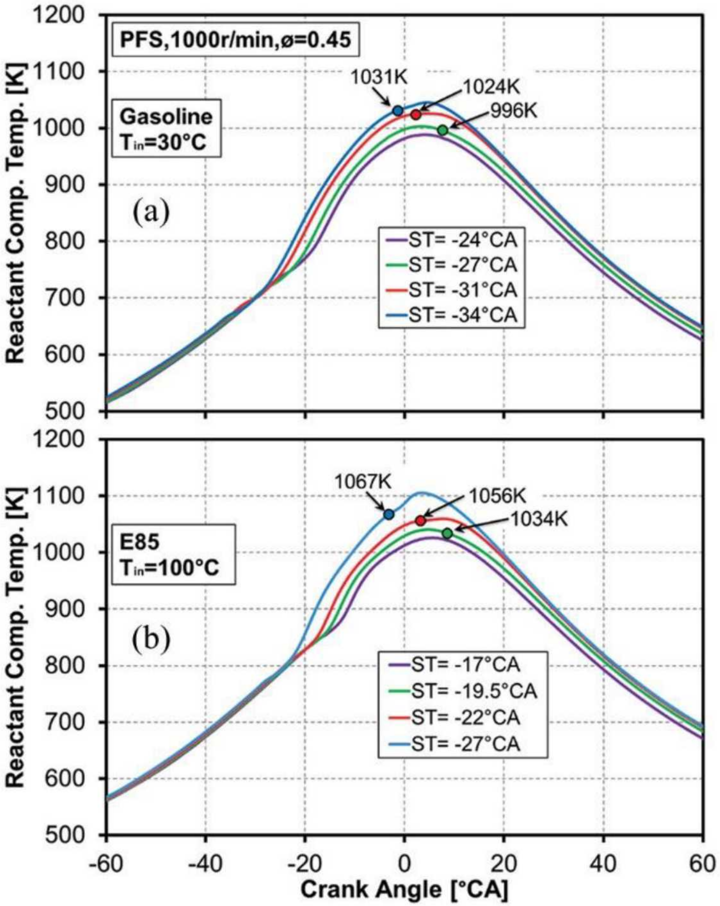
Fundamental factors for end-gas autoignition – End-gas TEMPERATURE

The markers indicate the starts of end-gas autoignition.

With an earlier ST and combustion, the end-gas is compressed faster, the reactant temperature rises earlier and reaches higher values, so less time is available for autoignition reactions, leading to a higher gas temperature before autoignition occurs.

The required compression temperature for gasoline autoignition is 996K at ø = 0.45 ($ø_{well\text{-}mixed}$=0.36).
E85 requires at least 1034K ($ø_{well\text{-}mixed}$=0.38).



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Fundamental factors for end-gas autoignition – Intake TEMPERATURE

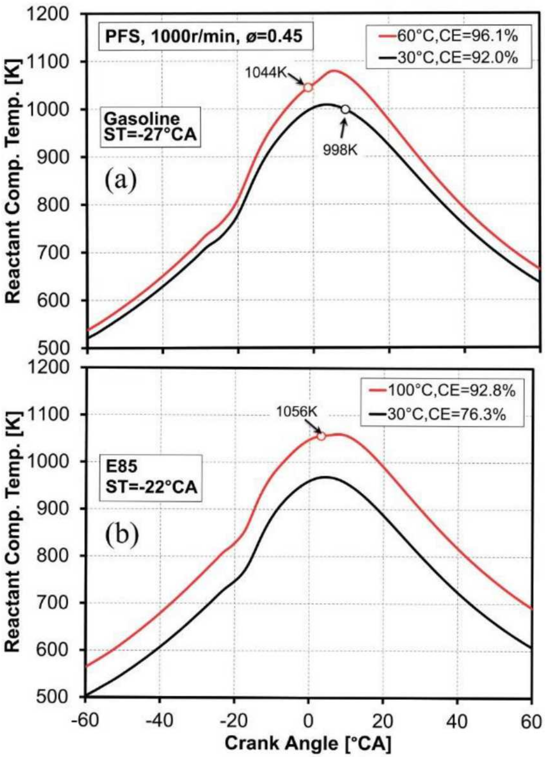
ST kept constant for two fuels.

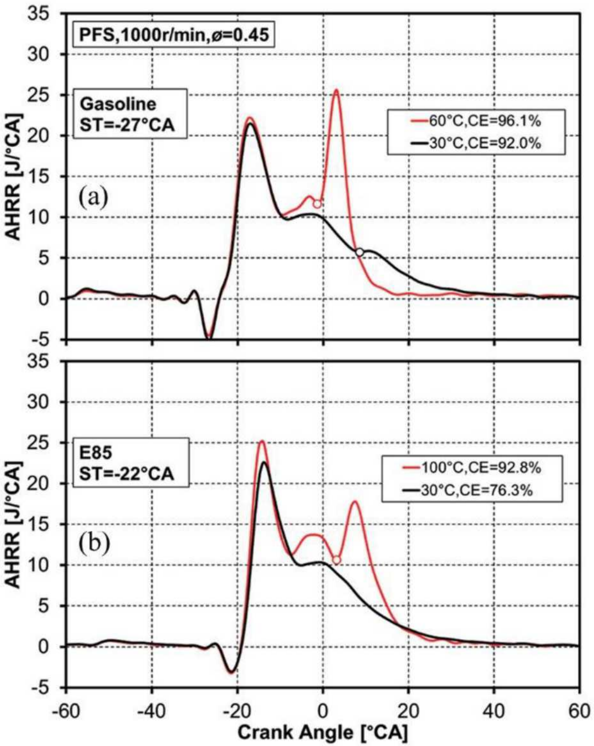
For gasoline, end-gas autoignition occurs when T_{in} = 30 ° C, becomes stronger with a modest heating up to 60 ° C.

For E85, end-gas autoignition does not occur when T_{in} = 30° C, becomes evident at 100° C.

The estimated end-gas compressed temperatures for two gasoline cases are higher than the threshold value 996K at ø = 0.45.

When T_{in} = 100° C, E85 case exceeds its threshold value 1034 K at ø = 0.45.





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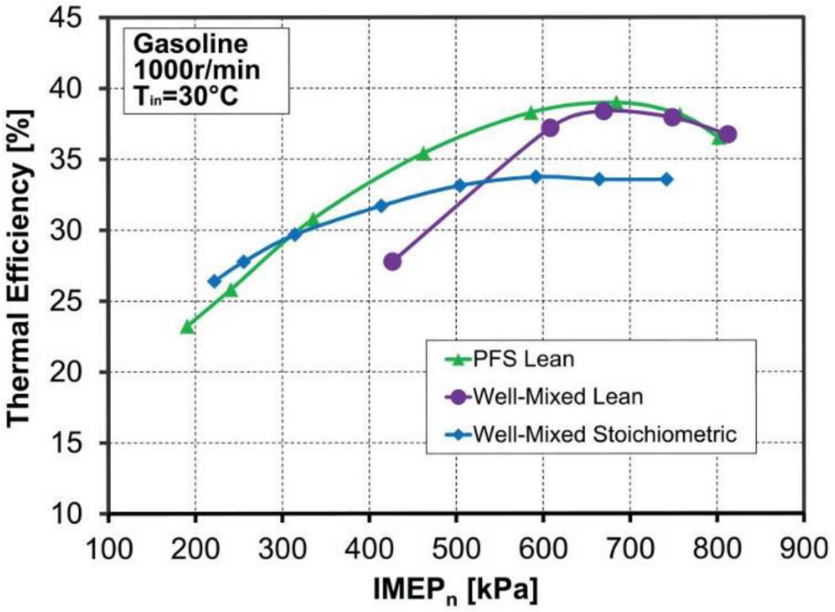
Engine performance of PFS mode – TE

Three combustion modes, PFS/well-mixed lean/well-mixed stoichiometric, are compared.
Gasoline; T_{in} 30° C; 1000r/min; ST @ max IMEPn; KI <78 kPa, CNL <70 dBA for PFS

$IMEP_n$ =350-800 kPa, PFS mode has a higher TE than well-mixed stoichiometric mode. The largest TE improvement is >5%-units around $IMEP_n$=700kPa

PFS and well-mixed lean mode have similar TE when $IMEP_n$ > 650 kPa.
TE of well-mixed lean mode drops faster than PFS for $IMEP_n$ < 600 kPa because of unstable combustion.



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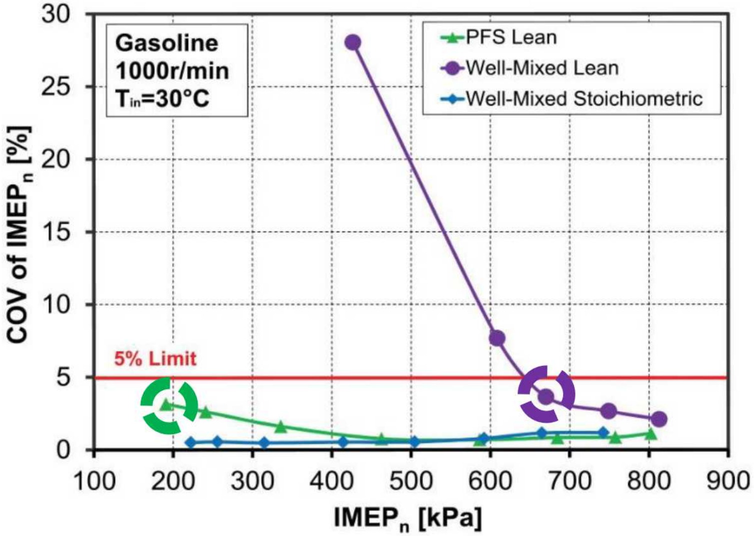
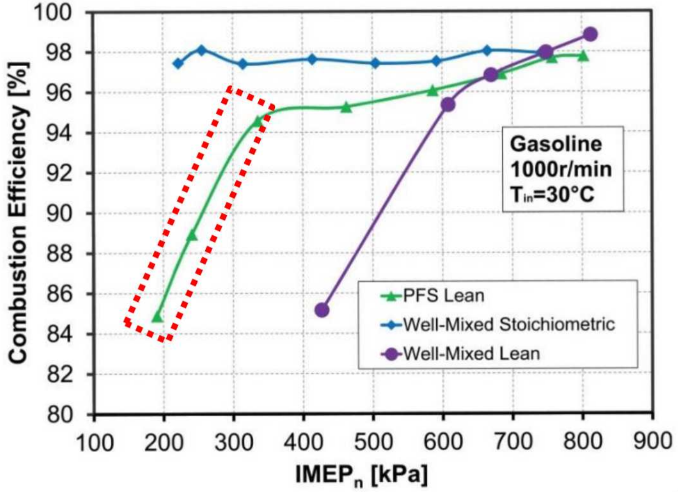
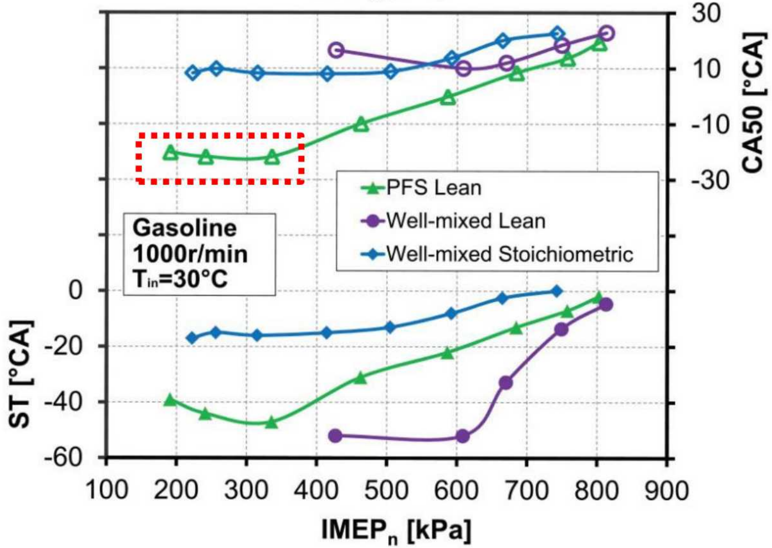
Engine performance of PFS mode – COV

If the stable limit is defined as COV = 5%, PFS wo
ø ≈ 0.60 for well-mixed lean mode.







PFS operations at low-load suffer due to excessively early CA50, reduced CE, finally leading to lower TE than well-mixed stoichiometric mode.

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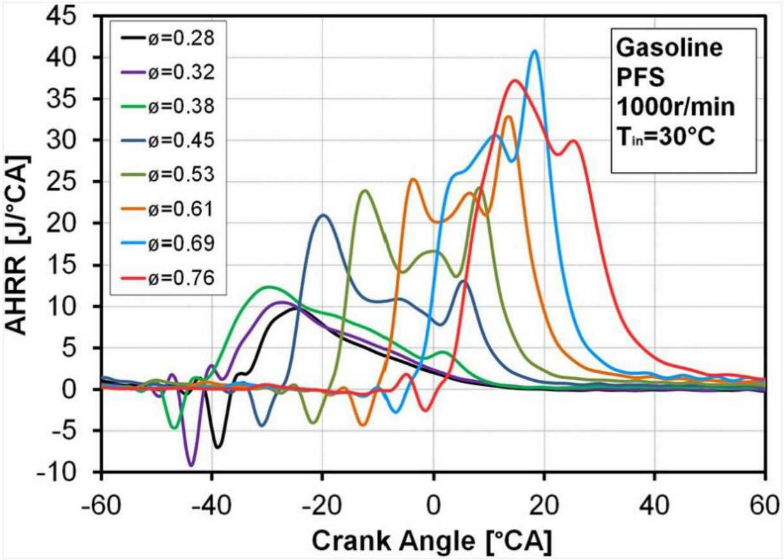
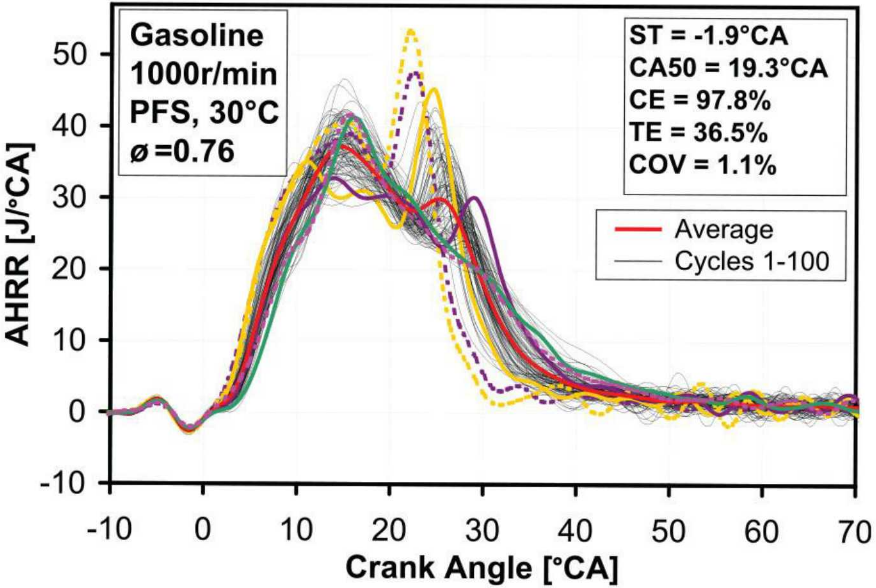
Engine performance of PFS mode – load level

The end-gas autoignition becomes very weak for ø = 0.38, and disappears at even lower loads, contributing to a drop of CE/TE/Stability… for ø < 0.40.





At the highest PFS load, ø = 0.76, some cycles have no end-gas autoignition, but it is not needed and CE is very high.

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Engine performance of PFS mode – NOx, Smoke

NO_x of PFS mode increases linearly with load reduction in middle load region, due to linearly advancing ST and CA50.

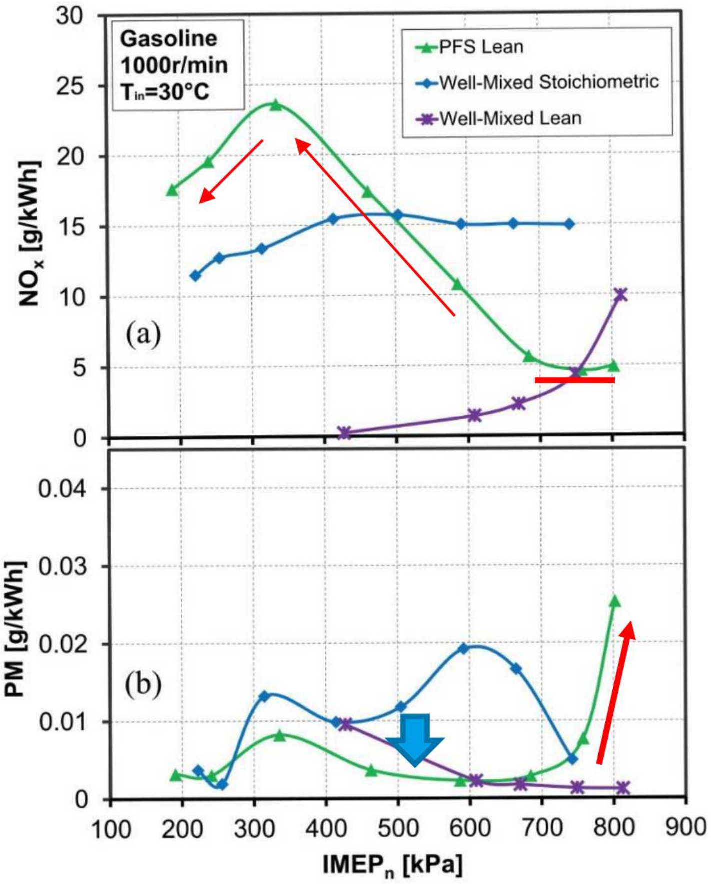
NO_x reduction of two lowest loads may result from low CE.

NO_x at three PFS highest loads remains similar level, but PM starts to increase in this range, possibly because the overall ø is high.

PM emissions of PFS are mostly lower than well-mixed stoichiometric operation.

NO_x emission is the main exhaust-emissions challenge for the current implementation of the lean PFS mode.

Future work could use a smaller amount of pilot-injected fuel, possibly in combination with EGR or trapped residuals.



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Conclusions

- Pilot-injected fuel, ignited by a normal spark, works as a super igniter with very high ignition energy and widely spreads flame initiation of the well-mixed ultra-lean charge, ensuring a very repeatable deflagration without misfires.
- Overall combustion often shows a 3-stage mode: 1st spark-ignited stratified charge combustion, 2nd blue flame propagation, 3rd compression autoignition stage in well-mixed ultra-lean end-gas.
- End-gas autoignition is critical for achieving high combustion efficiency, high thermal efficiency, and stable IMEP for ultra-lean operation.
- Appropriate and repeatable end-gas autoignition can be achieved by combustion-phasing control adjusting ST. Compared with gasoline, it is more difficult to induce end-gas autoignition for E85, consistent with the higher RON and MON of E85.
- The highest TE improvement is found near $IMEP_n$=700kPa ($\phi \approx 0.6$), corresponding to a relative >15% increase of fuel economy at 1000 r/min and T_{in}=30° C fueled with gasoline.
- The main challenge with the current gasoline PFS implementation is elevated NO_x emission at lower loads.

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