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Combined Effect of Intake Flow and Spark-Plug Location on Flame Development, Combustion Stability and End-gas Autoignition for Lean SI Engine Operation using E30 Fuel

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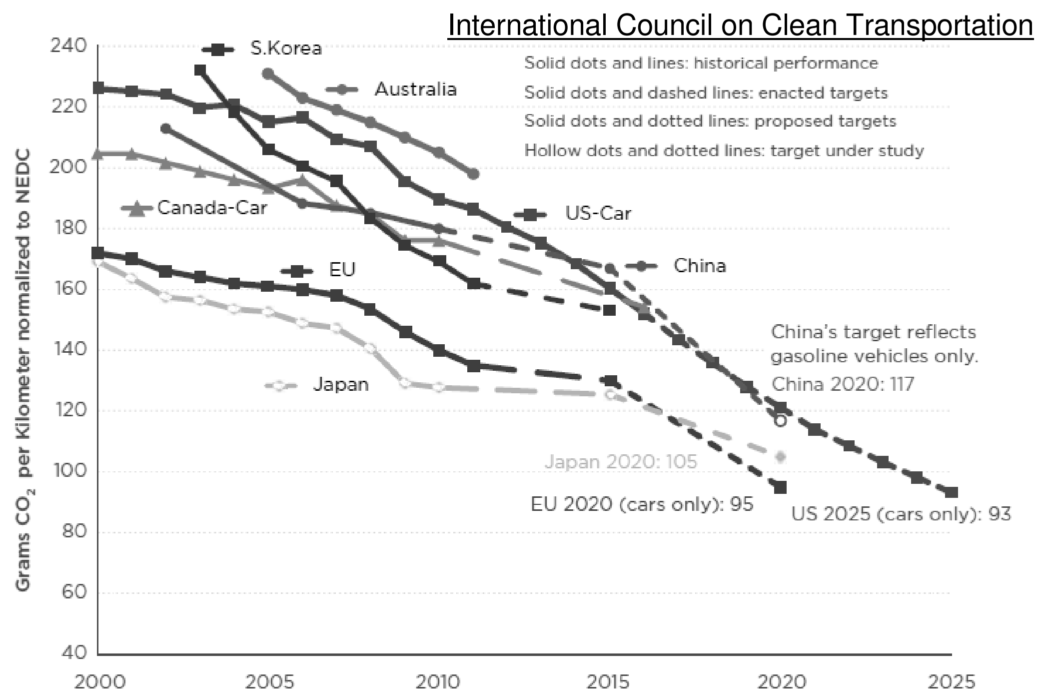
Abstract

Lean or dilute SI engine operation can provide efficiency improvements relative to that of traditional well-mixed stoichiometric SI operation. However, the realized gains depend on the ability to ensure both stable and complete combustion. In addition, the 10-90% burn duration needs to remain shorter than 30°CA. For the current DISI engine hardware, mixed-mode combustion is required to ensure sufficiently short burn duration for ultra-lean operation. Such mixed-mode combustion uses a combination of deflagration and end-gas autoignition whereby the pressure rise of the deflagration-based combustion compresses the end-gas reactants to the point of autoignition. For better understanding of the transition from deflagration to autoignition, it is desirable to apply optical diagnostics. However, with the use a single centrally located spark plug, the end-gas is found at the periphery of the combustion chamber, where it is difficult to diagnose. To overcome this, two additional spark plugs were mounted in modified pent-roof window blanks (called East & West). Initial high-speed flame imaging confirms that a portion of the end-gas exists within view of the piston-bowl window. In addition, the flame imaging shows that the flame development and end-gas location are affected by the intake-flow configuration (swirl vs. no swirl). To guide the selection of operating points for diagnosing end-gas autoignition, performance testing was performed for five different spark scenarios: Central Only, East-West, All Three, East Only & West Only. The five spark scenarios are combined with swirl or no-swirl operation, for a total of ten ϕ-sweeps. A high-octane E30 fuel is used here, and intake heating is used to promote both lean combustion stability and end-gas autoignition. The results reveal that operation with the East Only spark creates a particularly strong end-gas autoignition combustion event, consistent with the large geometric volume available on the west side of the combustion chamber. Unfortunately, operation with the East Only spark does not allow stable ultra-lean operation due to a very slow inflammation. Best lean combustion stability is found for the All Three spark scenario, followed by the East-West and Central spark scenarios, enabling stable mixed-mode SI combustion for ϕ down to 0.50 and 0.55, respectively. Here, operation without swirl provides the most stable operation. High-speed imaging of ultra-lean operation at $\phi = 0.55$ with All Three and East-West spark scenarios reveals that the transition from deflagration to end-gas autoignition frequently occur within the view offered by the piston-bowl window. These results encourage further optical investigations of fuel effects on this transition process.

Introduction

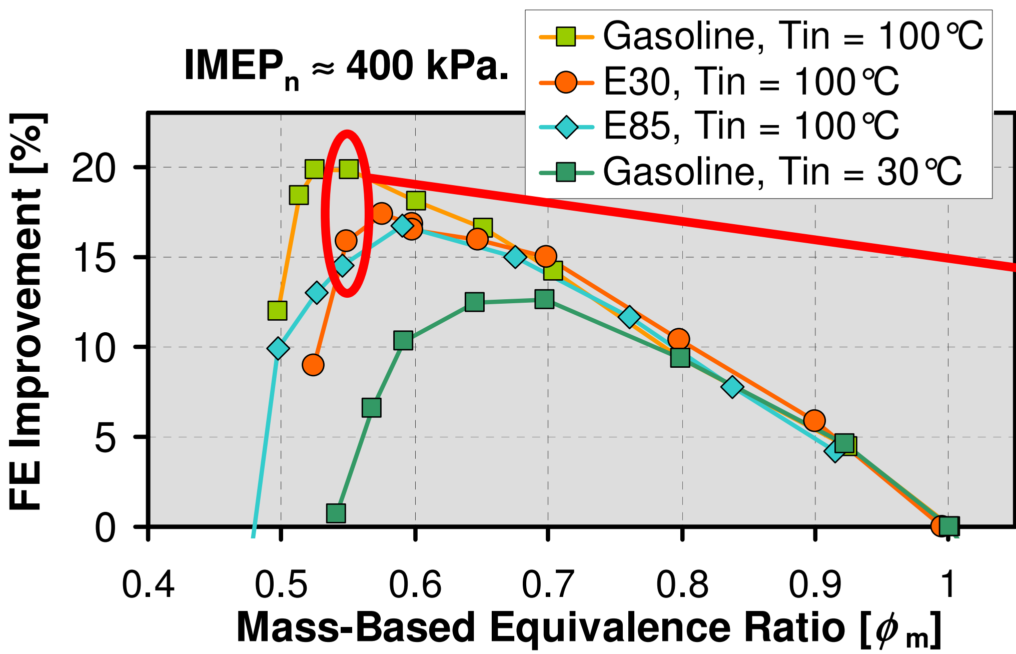
- Strong pressure to reduce CO_2 emissions.
- Improved engine efficiency is one key factor.
- Stoichiometric SI operation is standard for gasoline-type engines.



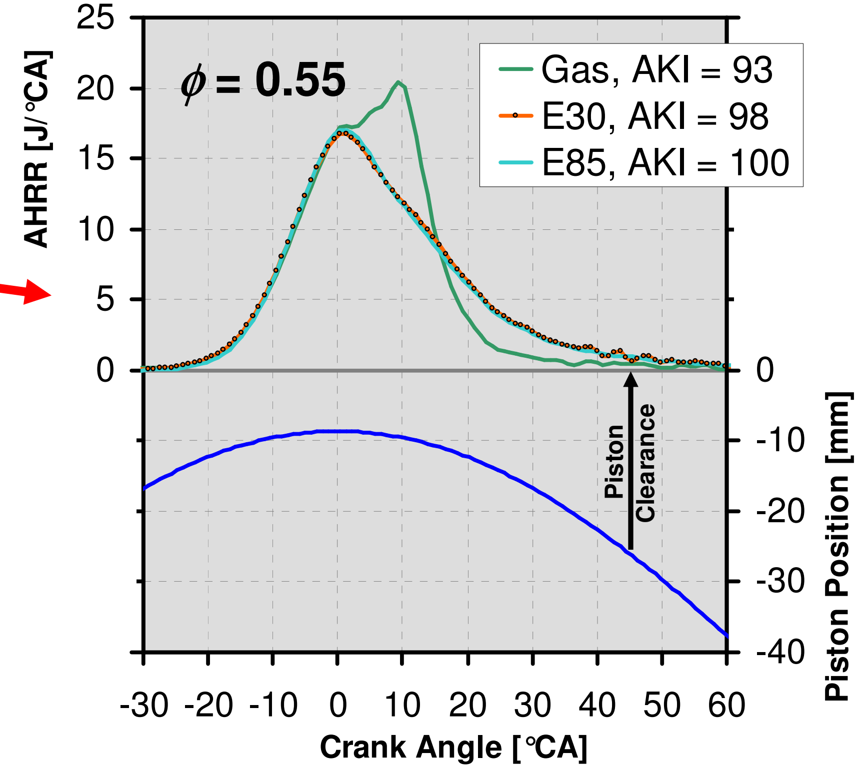
- Lean and/or dilute SI operation can improve fuel economy.
- What fuel properties promote such operation?
- Previous studies: gasoline, E30 and E85.

Review Lean Operation with E85, E30 and Gasoline

- Intake air heating improves lean operation for all fuels.
  - Higher temperature stabilizes early flame development.
  - FE gain is less for E30 and E85. High octane number suppresses beneficial end-gas autoignition.
  - With current hardware, mixed-mode combustion is required for sufficiently short burn duration at ultra-low ϕ.
  - 10-90% < 30°CA



Gasoline: 10-90% = 23°CA.
E30, E85: 10-90% = 32°CA.



Current Fuels and Studies

- **Current E30** was blended from anhydrous ethanol and certification gasoline.
  - 30% / 70% blend ratio ⇒ E30. It has a very high RON.

	Certification Gasoline	⇒ E30	RD-587	Alkylate	New E30	High Aromatic
S	7.9	14	7.5	1.2	10.7	10.7
RON	96.6	105	92.0	97.9	98.3	98.0
MON	88.7	91	84.5	96.7	87.6	87.3
Ethanol [vol.%]	0	30	10	0	30	0
Aromatics [vol.%]	32.7	22.9	20.7	0	8.1	30.8
T90 [℃]	158	?	156	106	155	166

- Thrust 1 relevant Co-Optima research will address several fuel aspects with respect to knock-limited $\phi = 1$ SI operation.

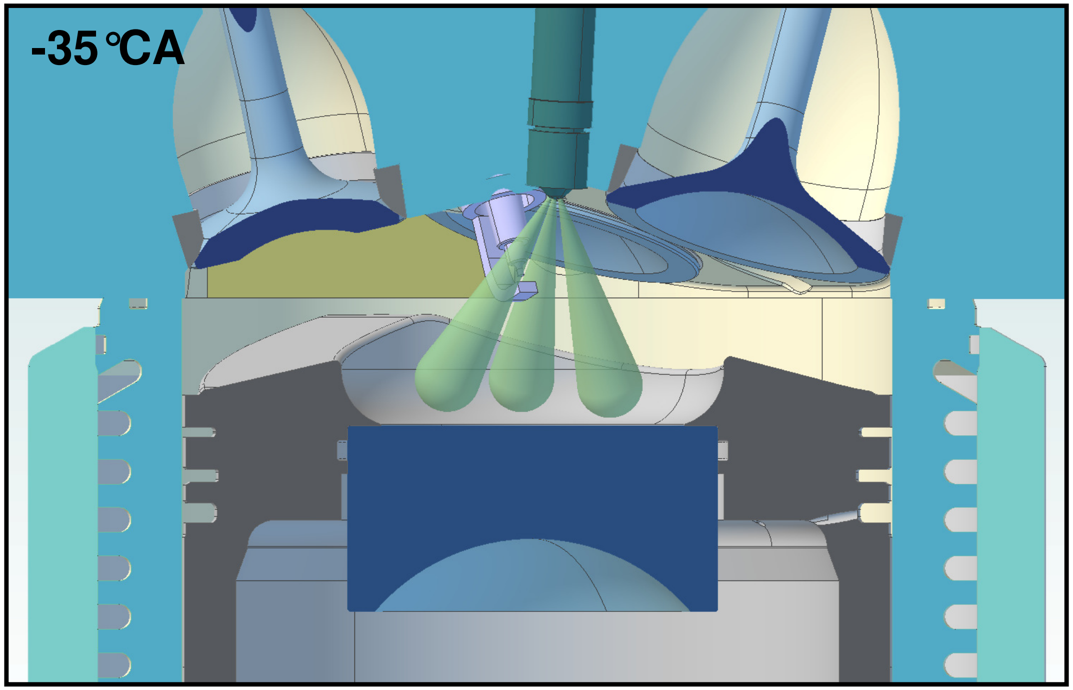
1. Efficiency gains due to increase of octane from AKI = 88 to RON = 98.
2. Combined effects of composition and (RON-MON) sensitivity for RON98 fuels.

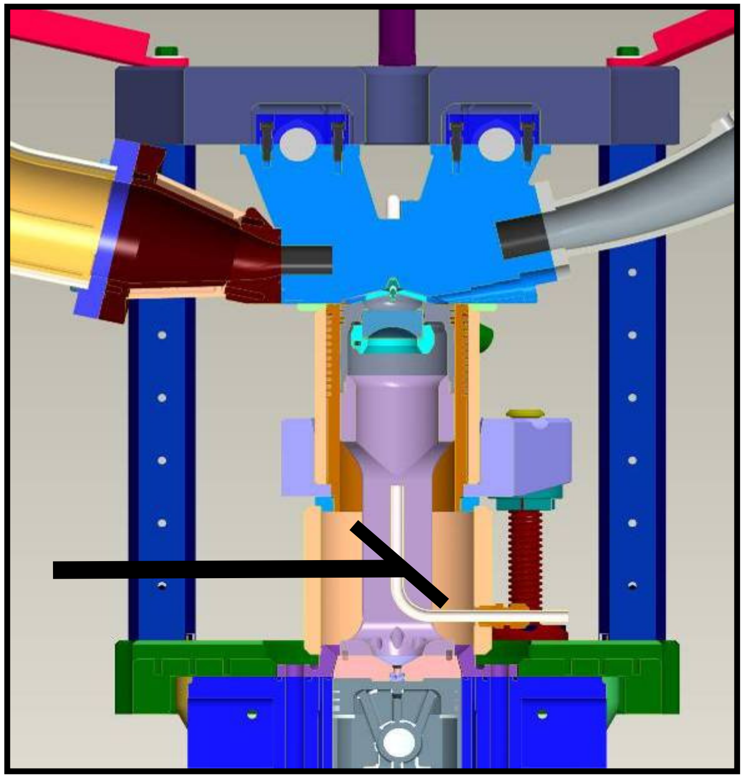
In addition, advanced combustion modes will be assessed.

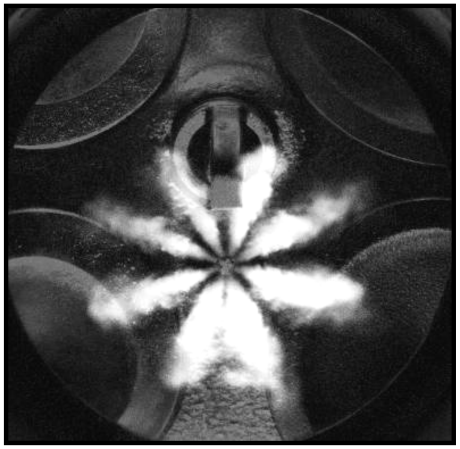
3. Relevance of RON and MON for ultra-lean or dilute mixed-mode operation.
4. Effects of new bio-components on soot pathways for stratified-charge operation.

Research Engine

- Drop-down single-cylinder engine.
- Automotive size. 0.55 liter swept volume.
- Identical geometry for **All-metal** and **Optical.**
- Designed for spray-guided stratified-charge operation ⇒ Piston bowl.
- Injections during intake stroke ⇒ well-mixed charge (relatively).

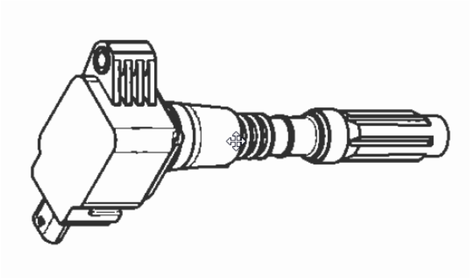




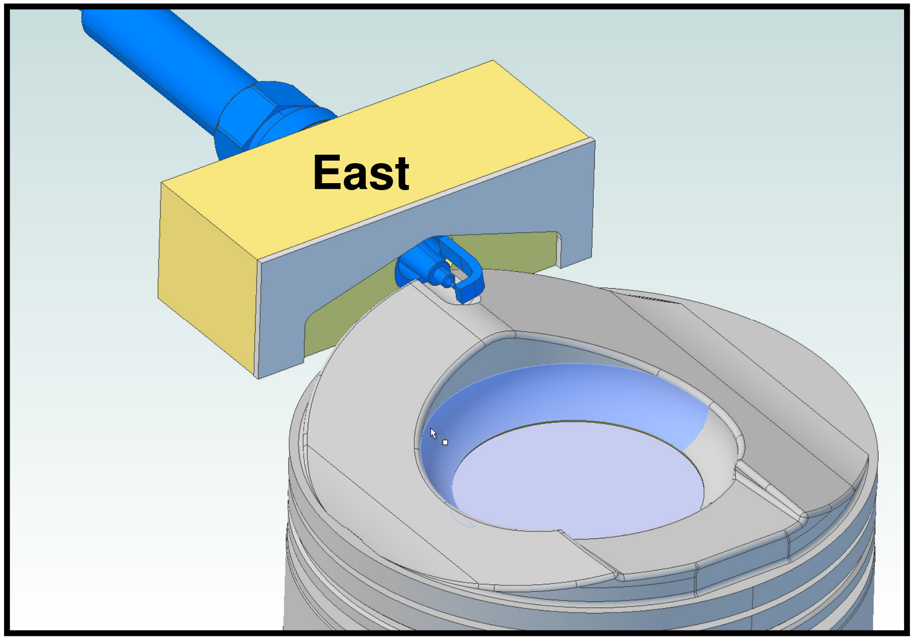


Dual-Spark Plug Installation

- For better understanding of mixed-mode SI combustion, study transition from deflagration to autoignition.
- With current optical access, need to ensure that the end-gas exists in the center of the combustion chamber ⇒ 2 side-mounted spark plugs.
- Modify existing piston to avoid interference with spark plug.
- Use Diamond Electric FK0425-KAI
  - 85 mJ secondary energy.

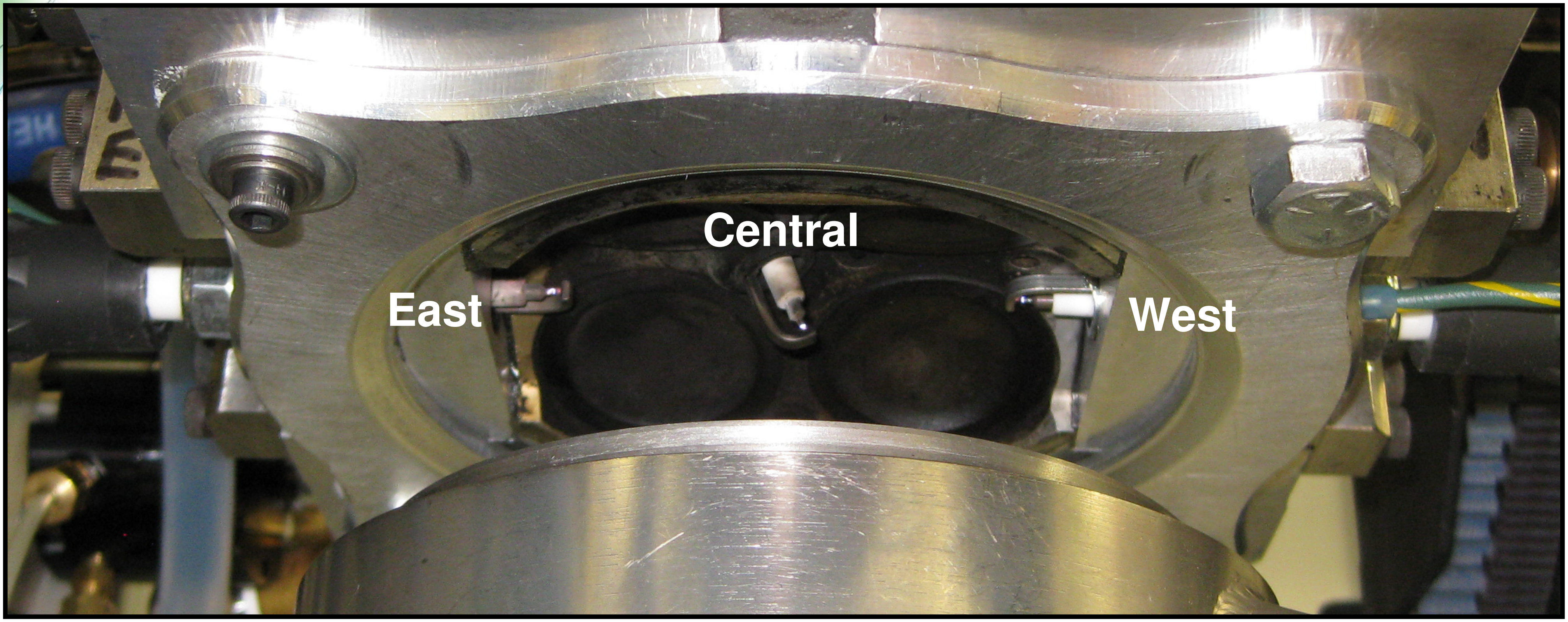


- Keep existing centrally located long-reach spark plug.
- Bosch ZS-L 1x1E
  - Most new data also use 85 mJ.



West

Hardware Setup

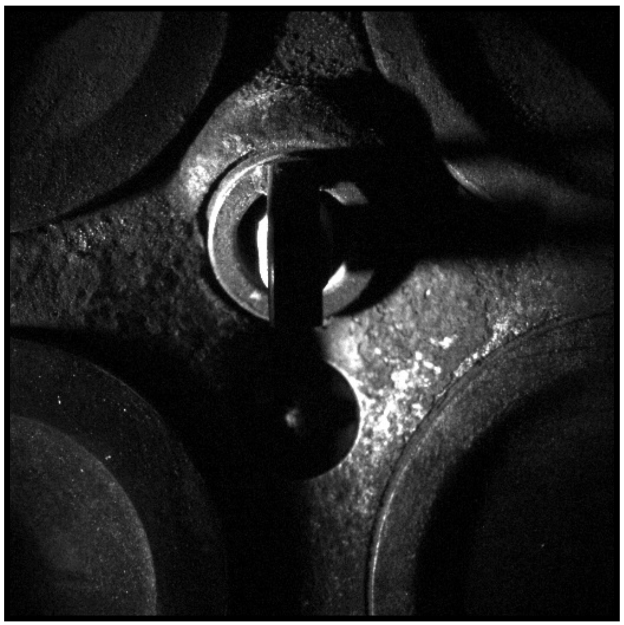


- Three spark plugs allow multiple ignition scenarios.
- Here, study lean operation for five such scenarios:
  - A: Central Only
  - B: East-West
  - C: All three
  - D: East Only
  - E: West Only

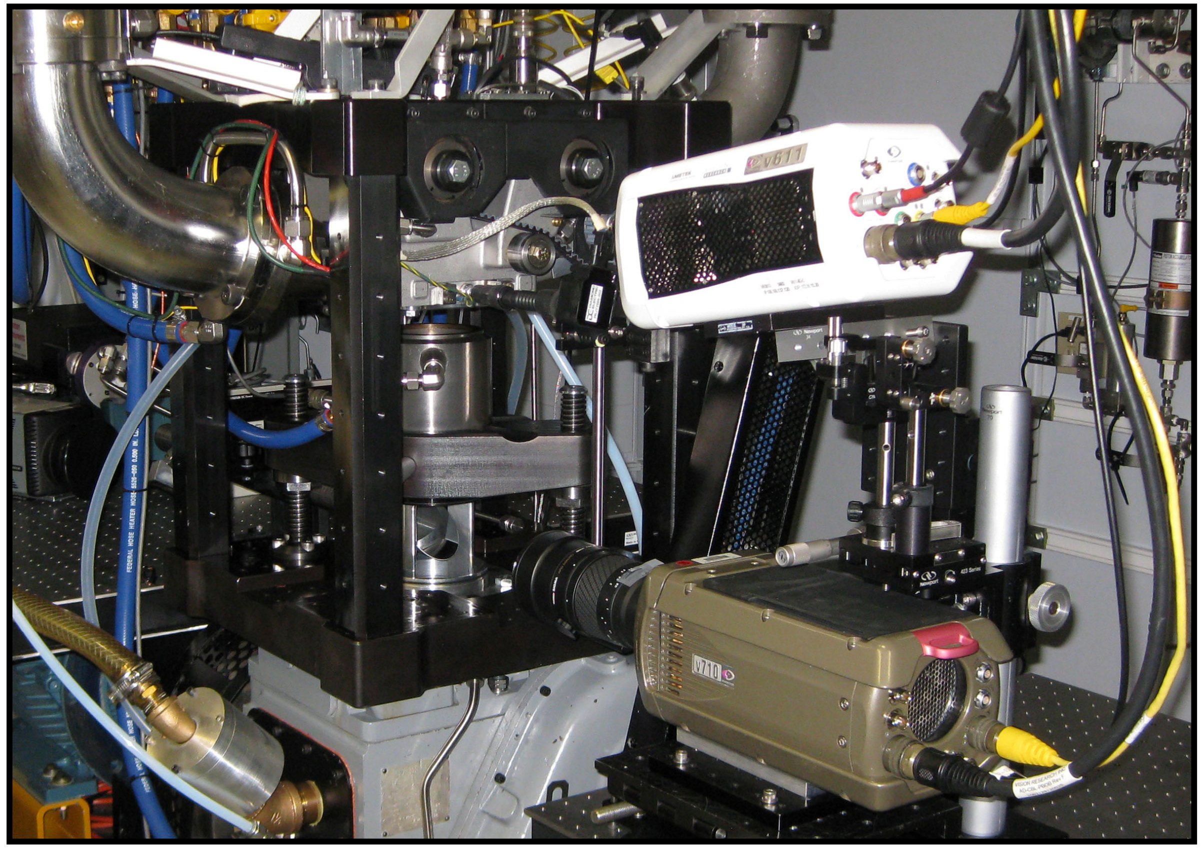
Optical Setup

- Use only Phantom v710, operated at 20 kHz = 0.3 °CA with 512 x 512 pixels.
- 48 μs exposure. f-stop = 2.8.
- Reference image at -25 °CA.
  - Illumination from north.

East

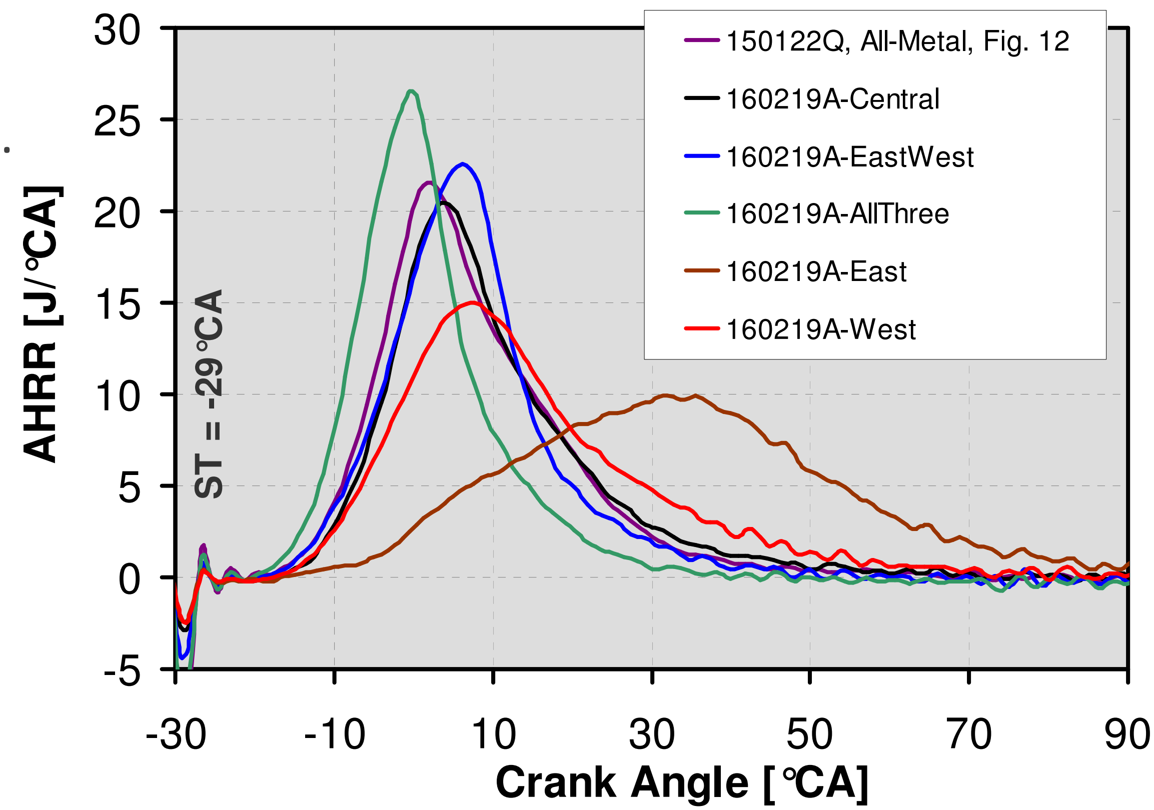


West



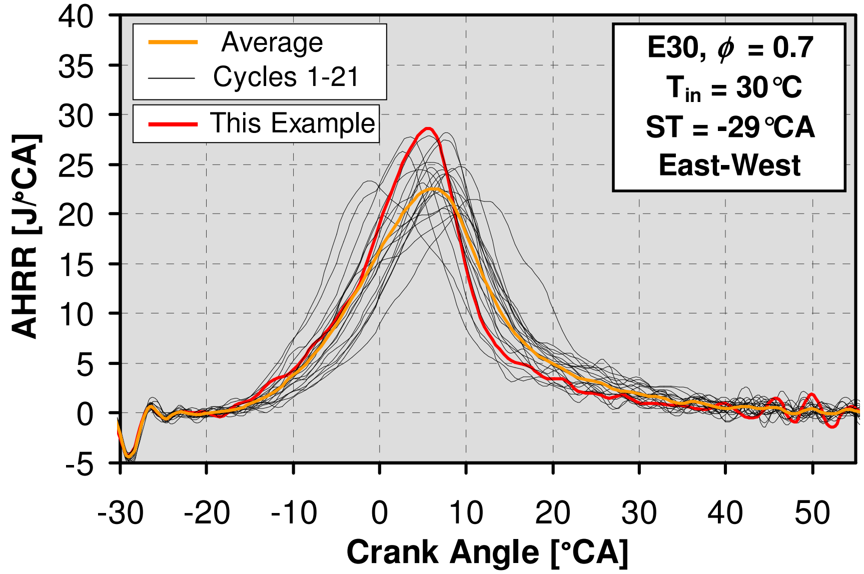
Effect on AHRR, Swirl

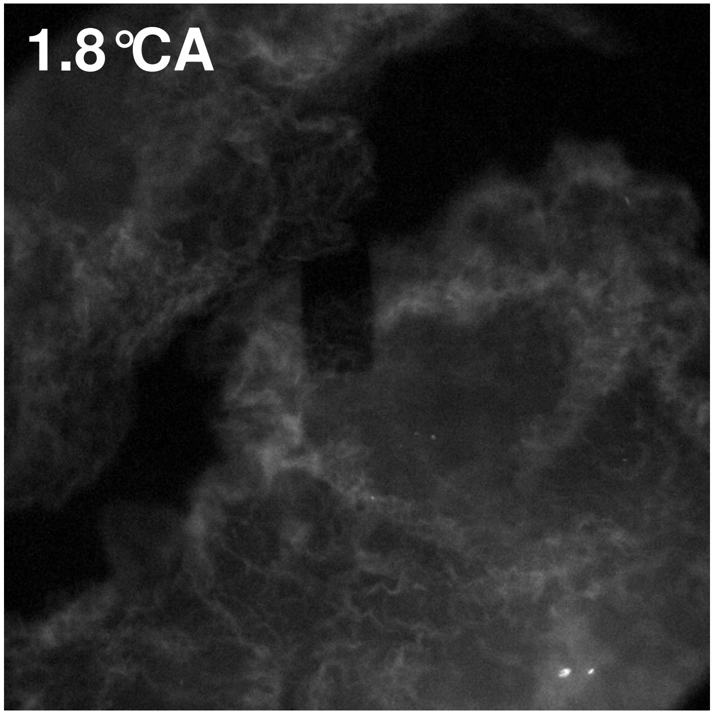
- Start with existing well-established moderately lean operating point.
- See Fig. 12 in SAE 2016-01-0689. E30 fuel, 1000 rpm, $\phi = 0.70$, $T_{in} = 30$ °C.
- Fire3-Skip9 for 25% duty cycle. Acquire 21 cycles per ignition scenario.
- A: Central Only matches fairly well ensemble-averaged AHRR of all-metal, continuously fired operating point of Fig. 12.
- B: East-West matches fairly well too.
- C: All Three shows higher peak AHRR.
- D: East Only has slow inflammation, leading to late combustion.
  - Early flame develops slowly due to limited volume near ignition site.
- E: West Only has reasonably fast inflammation, but reduced peak AHRR.

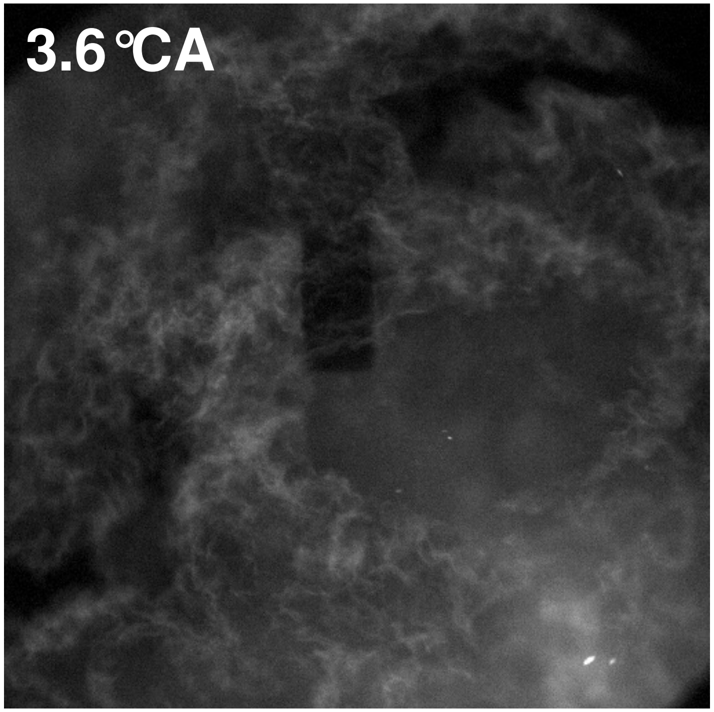


East-West Movie Example with Swirl

- East-West ignition shows that end-gas can be well imaged via piston-bowl window.
- Flame fronts start to meet near peak AHRR.
  - Tilted flame fronts due to effect of swirl.
- Larger window view should facilitate viewing of end-gas autoignition.







Scope of Study

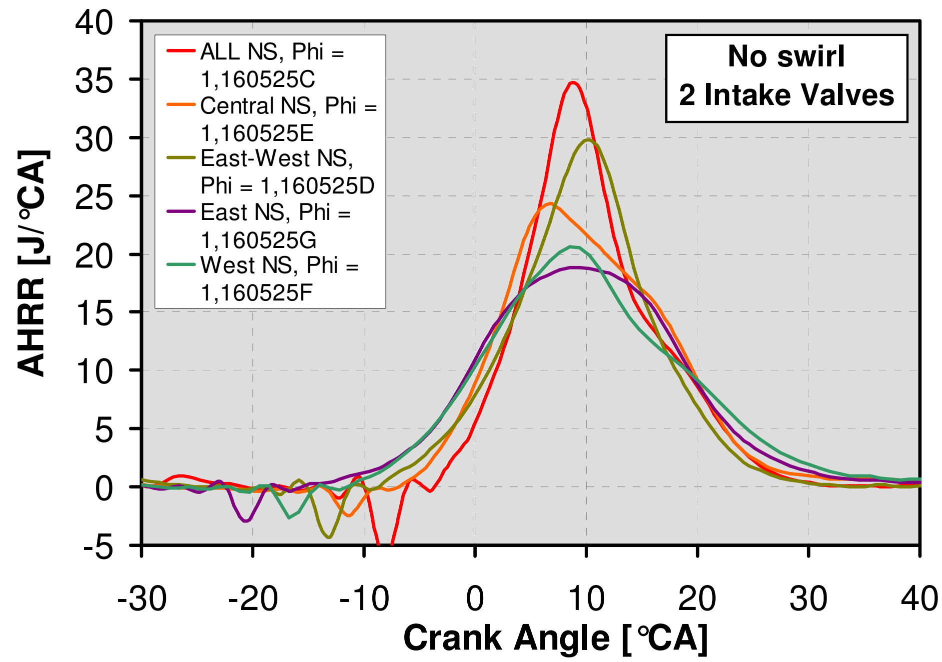
- Study combined effects of spark-plug location and intake-generated flow on:
  - Flame-spread patterns and ability to probe optically end-gas autoignition.
  - Lean limits
  - Mixed-mode combustion (deflagration to autoignition)
  - Thermal efficiency gain.
- T_{in} = 100 ℃. 1000 rpm. Constant E30 fueling rate: 17.8 mg/cycle.
  $IMEP_n \approx$ 350 kPa for $\phi = 1.0$.
- 10 ϕ – sweeps:

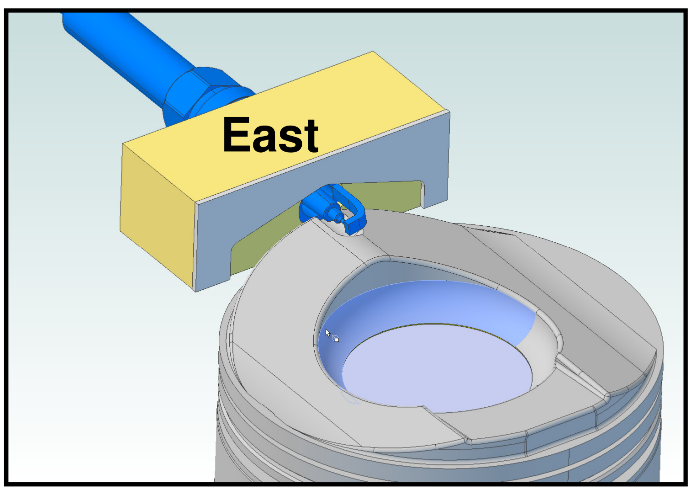
	Swirl (one intake valve)	No swirl - NS (two intake valves)
ALL Three	✓	✓
East-West	✓	✓
Central	✓	✓
East	✓	✓
West	✓	✓

+ Flame imaging at selected operating points

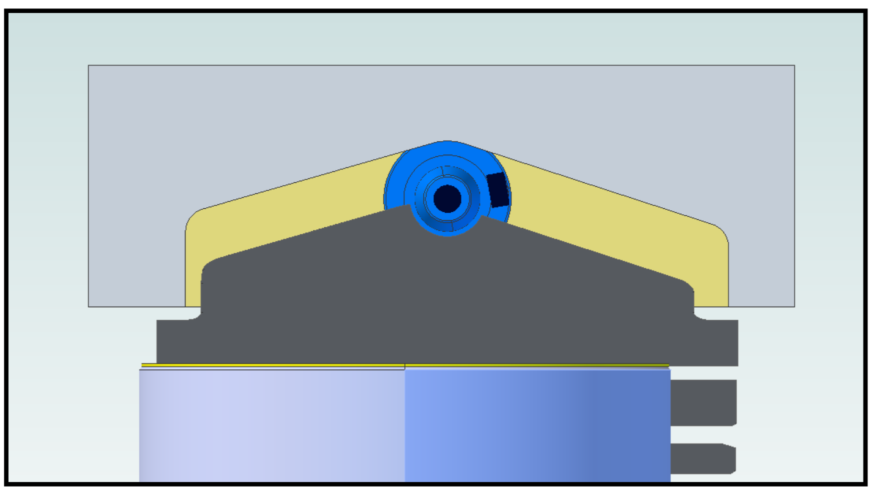
Effect on AHRR, Stoichiometric

- Start with $\phi = 1.0$. CA50 ≈ 10°CA.
  - Negative bump on AHRR traces indicate start of spark discharge.
- Inflammation is slowest with East.
  - Very tight space near TDC.
- West spark has access to more gas volume because of bowl-rim cut-out.
- Also means that end-gas volume can be large for East spark.

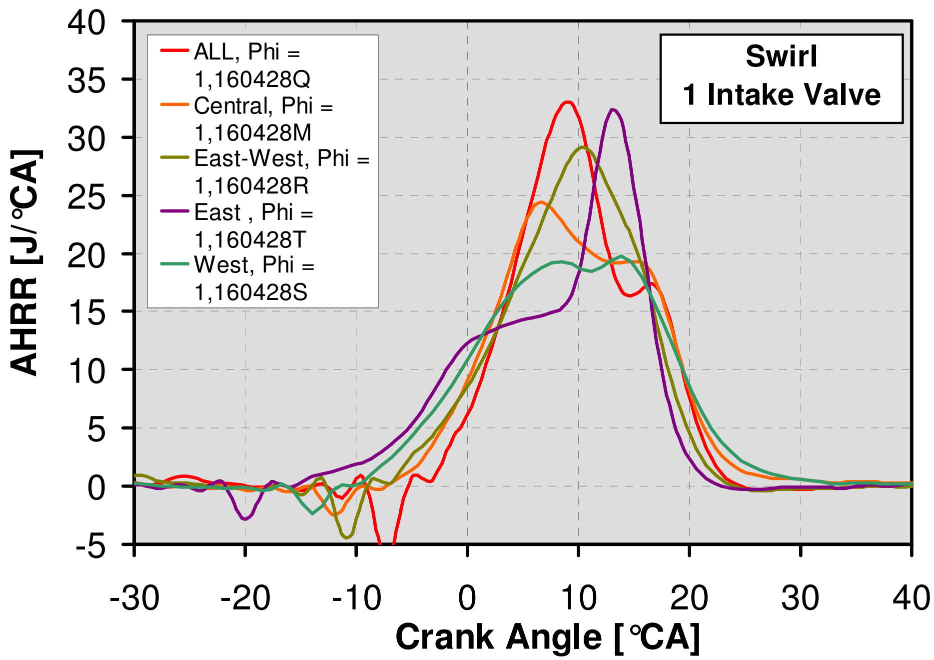


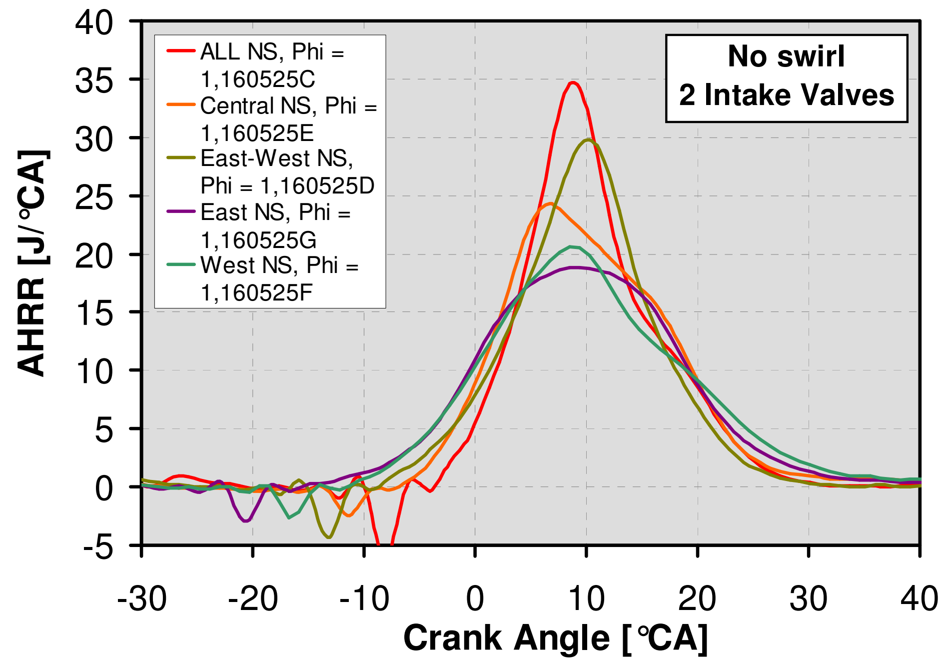


West

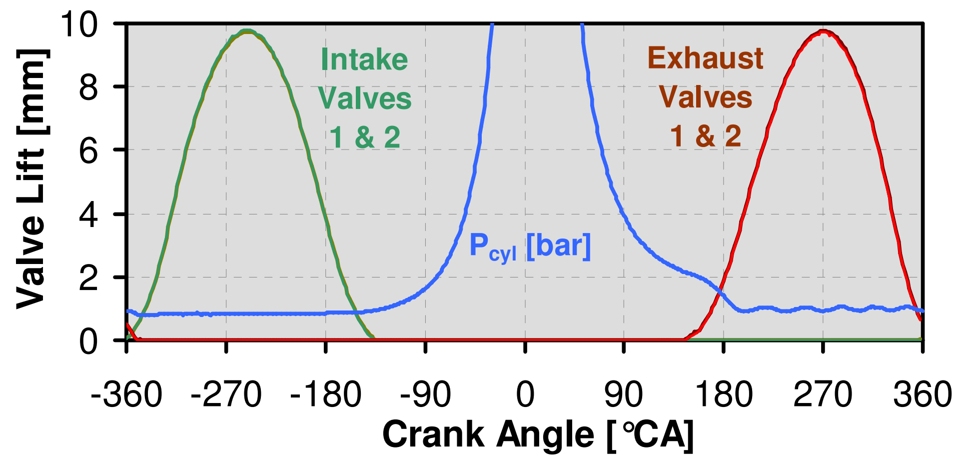


Effect on AHRR, Stoichiometric



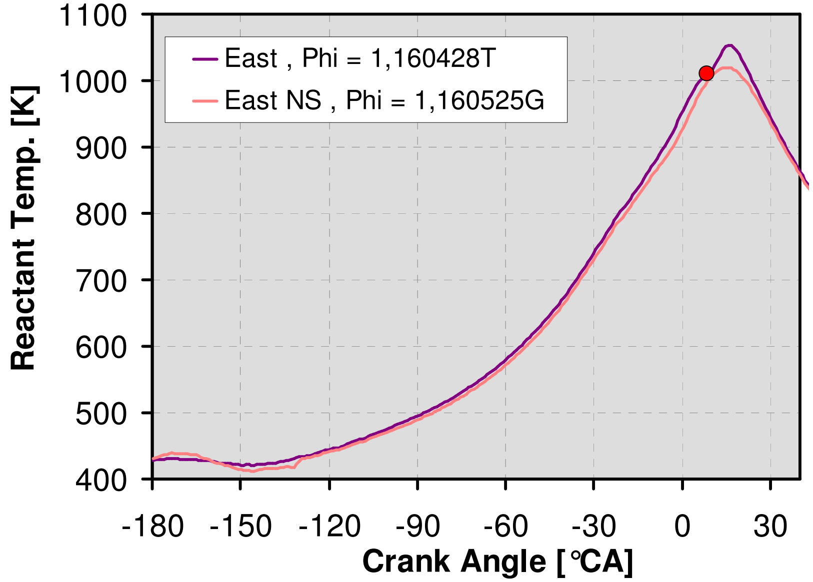


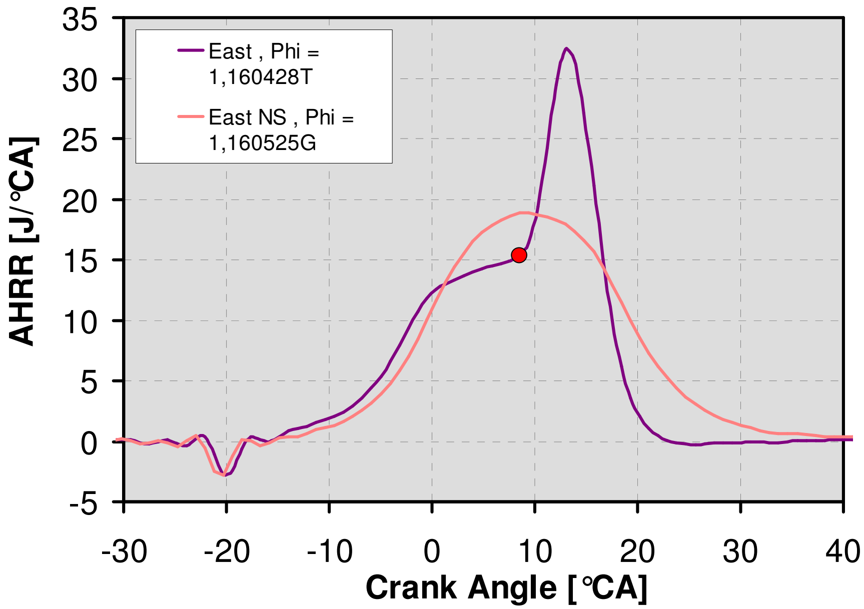
- Operation with swirl causes knocking operation for several spark scenarios.
  - Single-valve operation effectively advances start of compression.

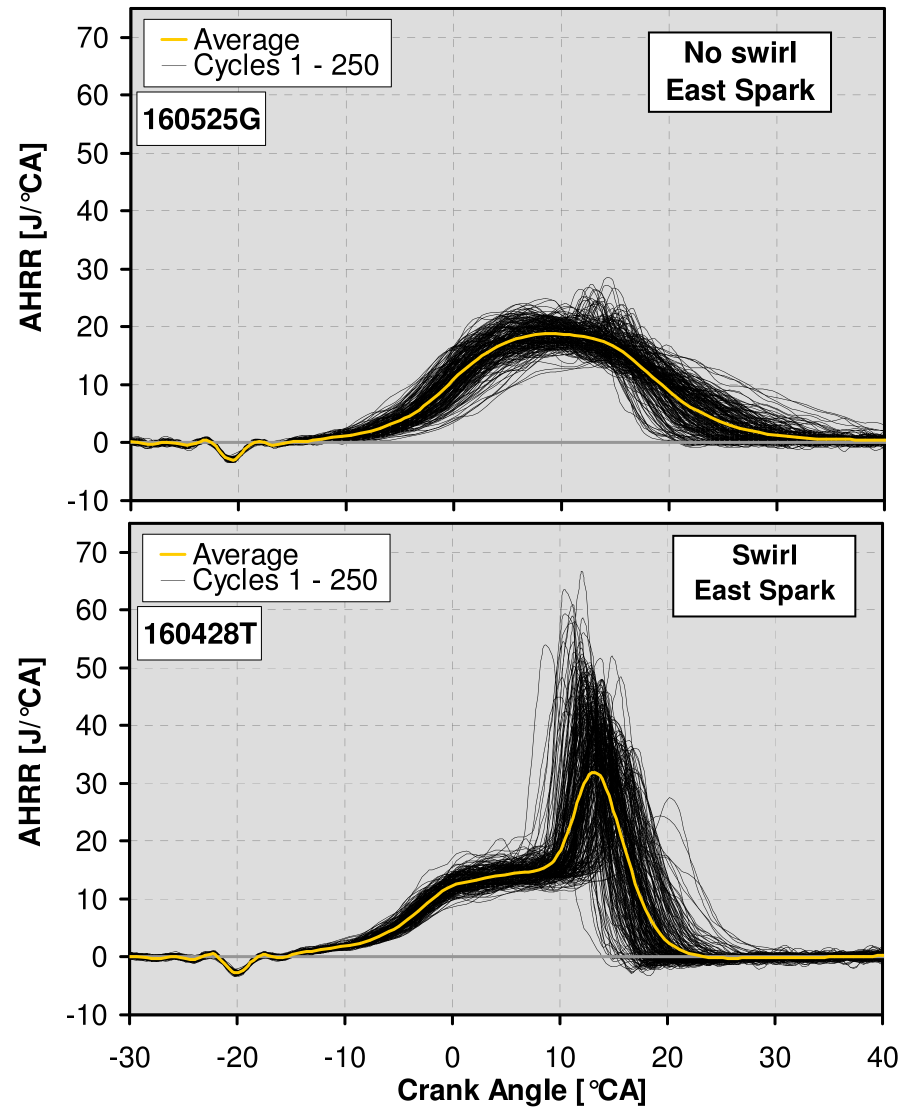


East Spark Induces Knock

- In particular, East spark with swirl leads to strong knocking.
  - Large end-gas volume due to rim cut-out.

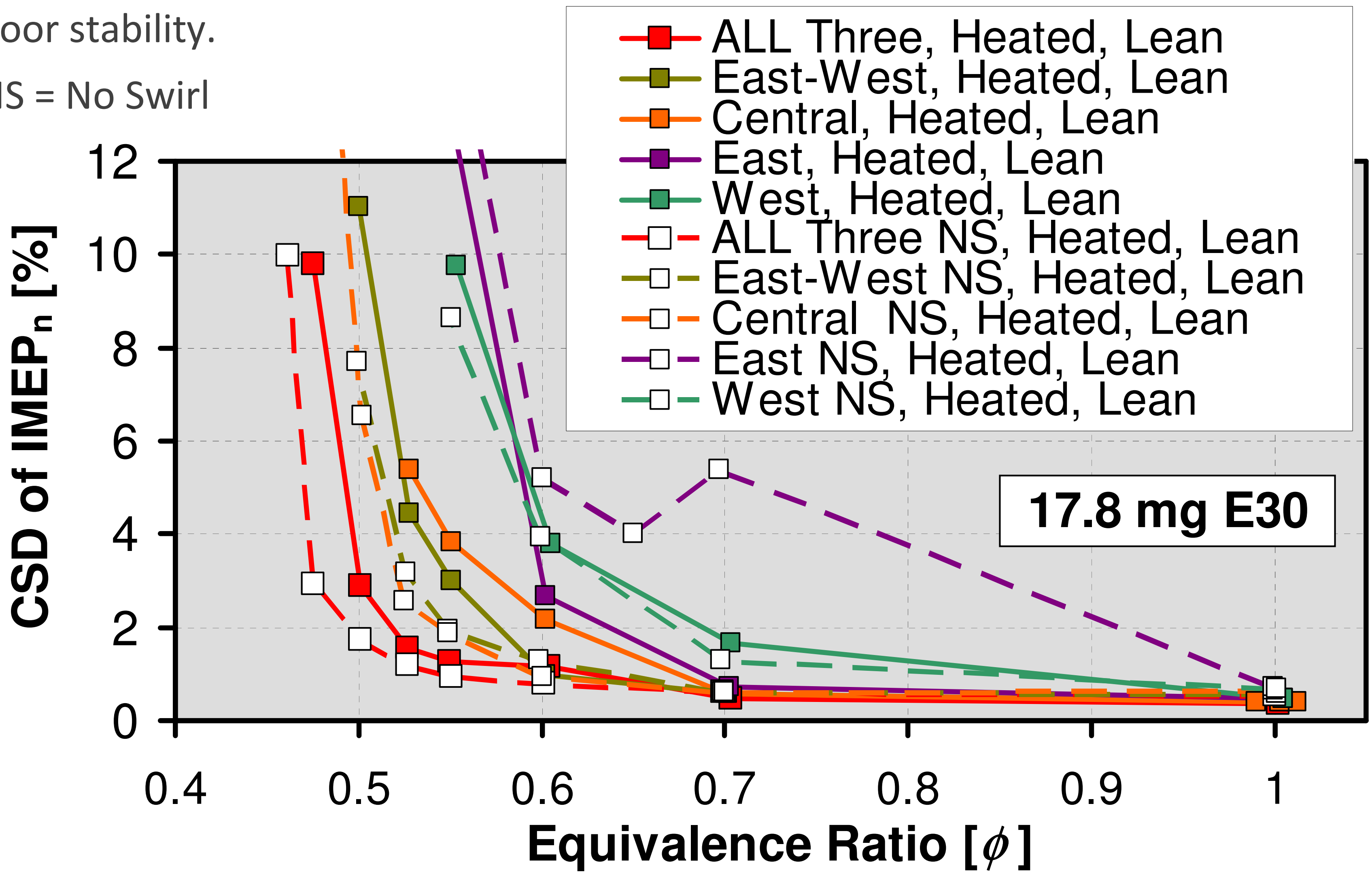






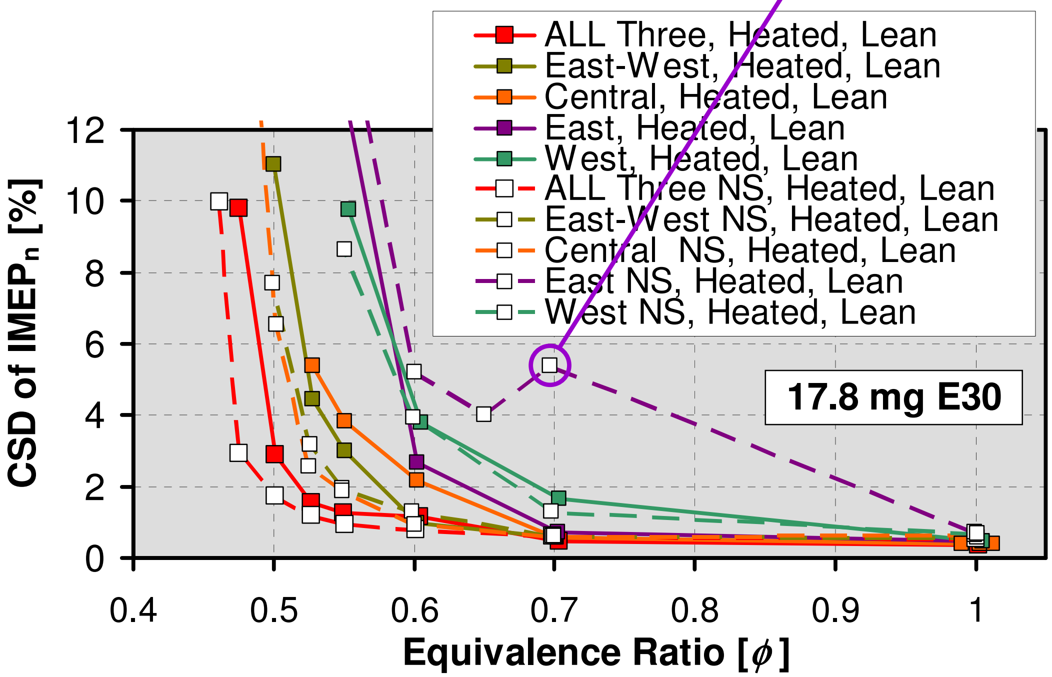
IMEP Instability

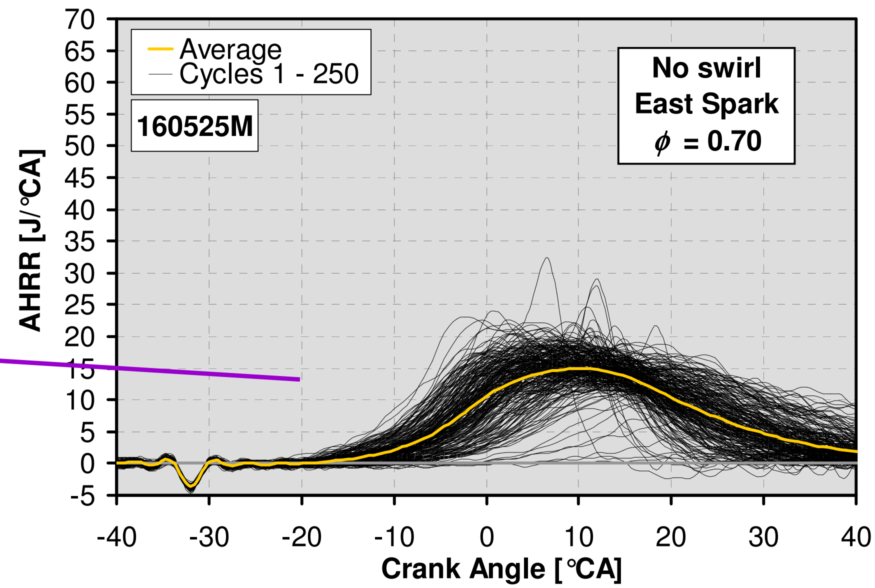
- Despite strong end-gas autoignition, East spark is not suitable for studying ultra-lean mixed-mode combustion.
  - Poor stability.
  - NS = No Swirl

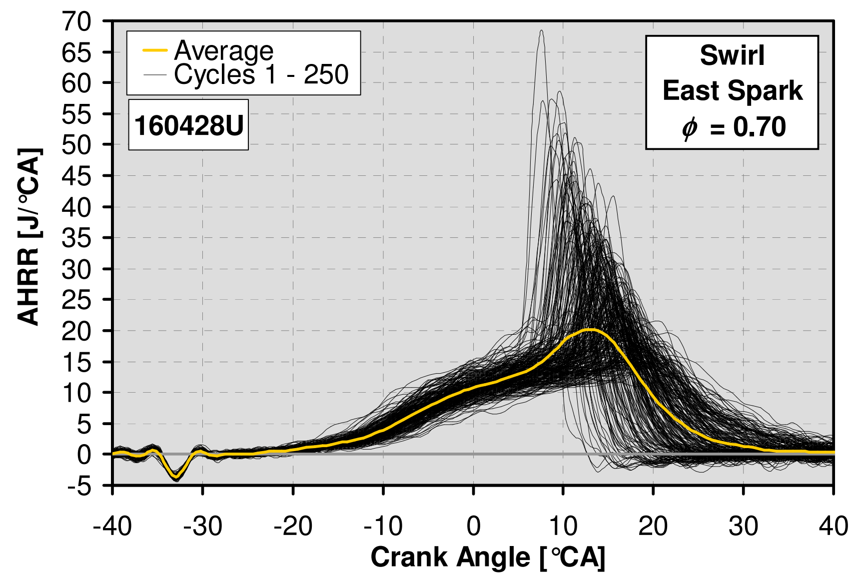


IMEP Instability for East

- Both East and West have very poor IMEP stability at ϕ where mixed-mode combustion is feasible from a noise standpoint, *i.e.* $\phi \leq 0.55$.
- Fuel-distribution issues at spark gap for East spark plug without swirl?

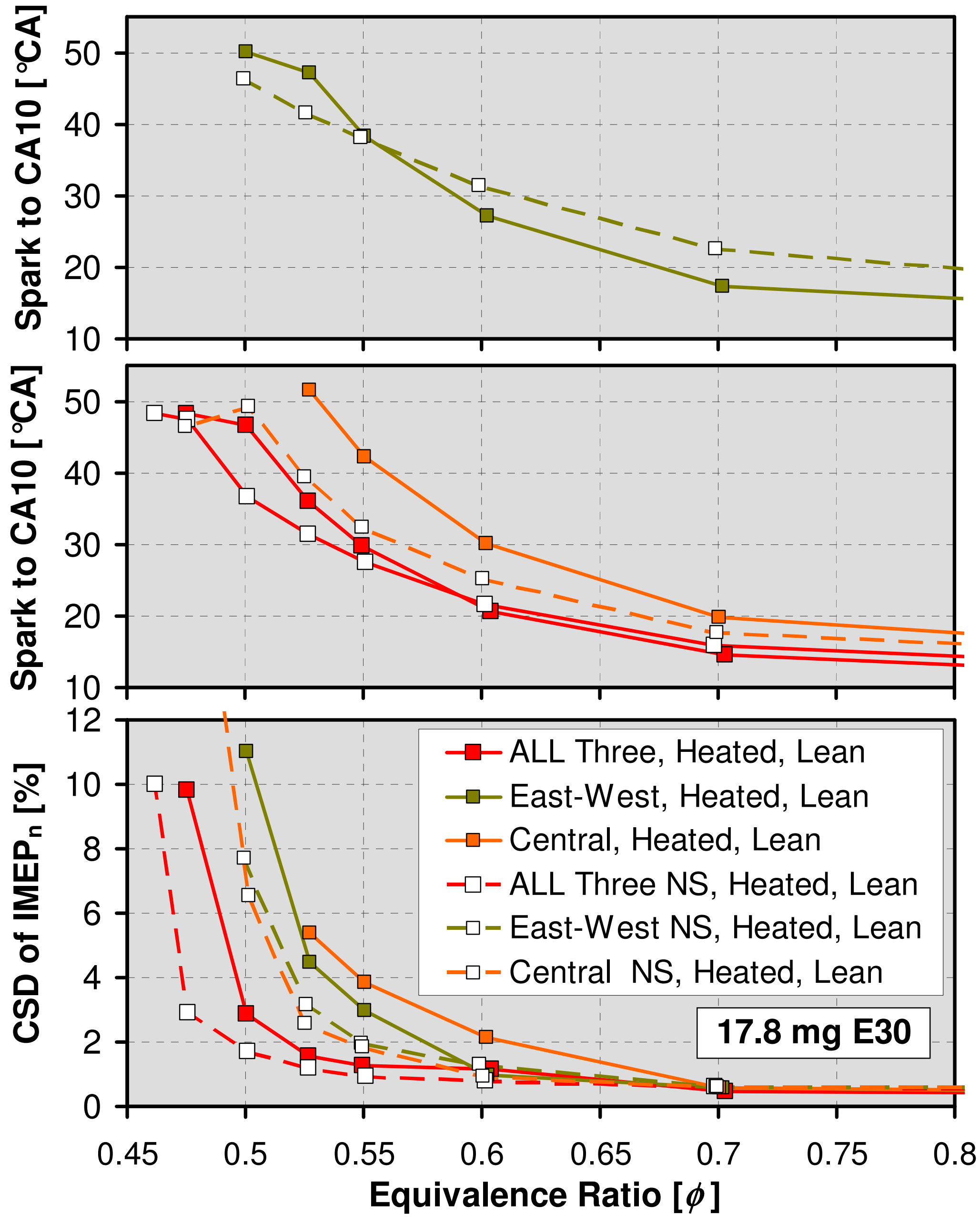






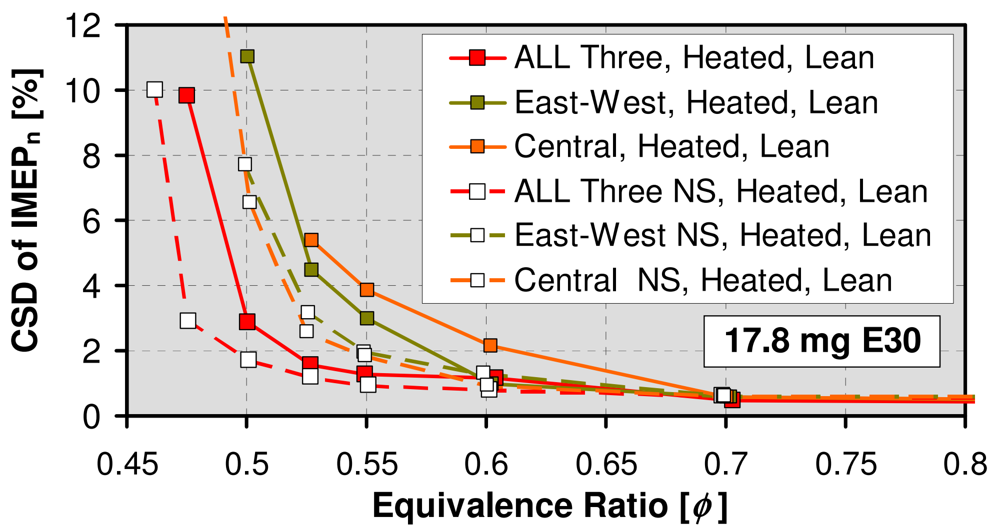
IMEP Stability vs. Inflammation

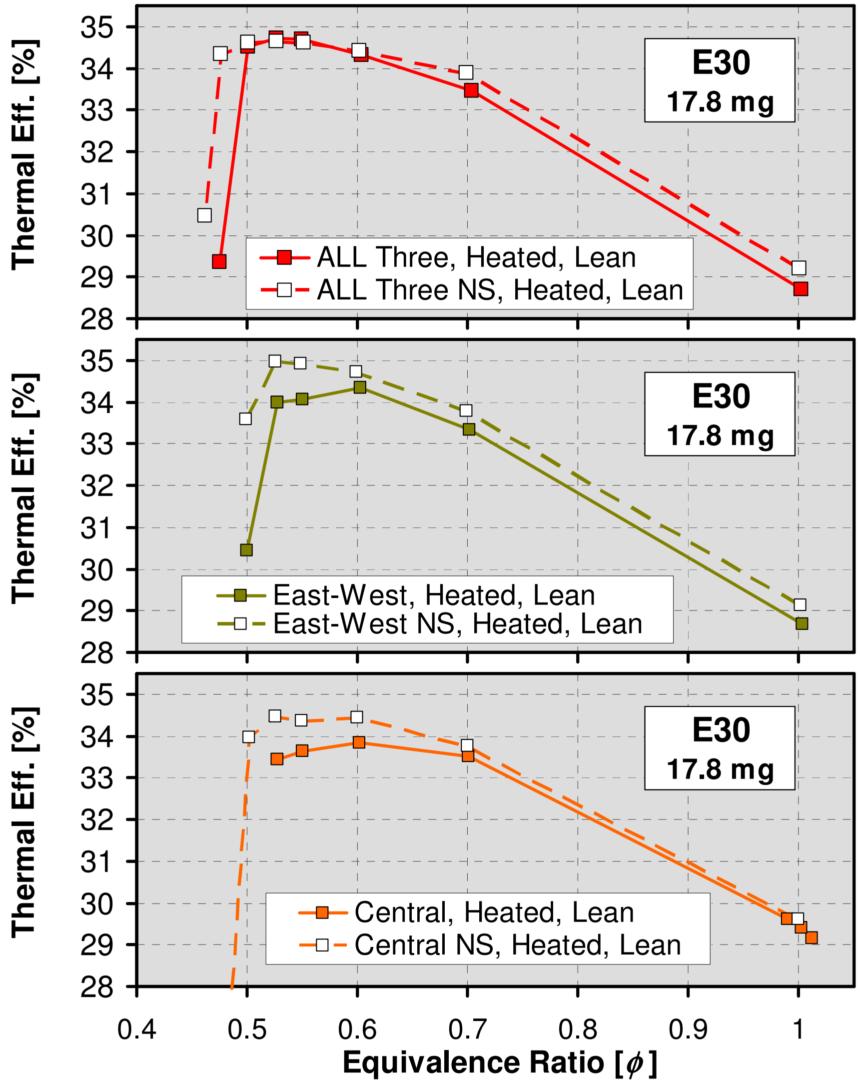
- ALL, East-West and Central enable ultra-lean SI operation.
- Focus on these three scenarios.
- No-swirl operation improves stability.
- For ALL and Central, no-swirl operation speeds up inflammation.
- Inflammation speed of East-West has more complex response to swirl.



TE Improvement

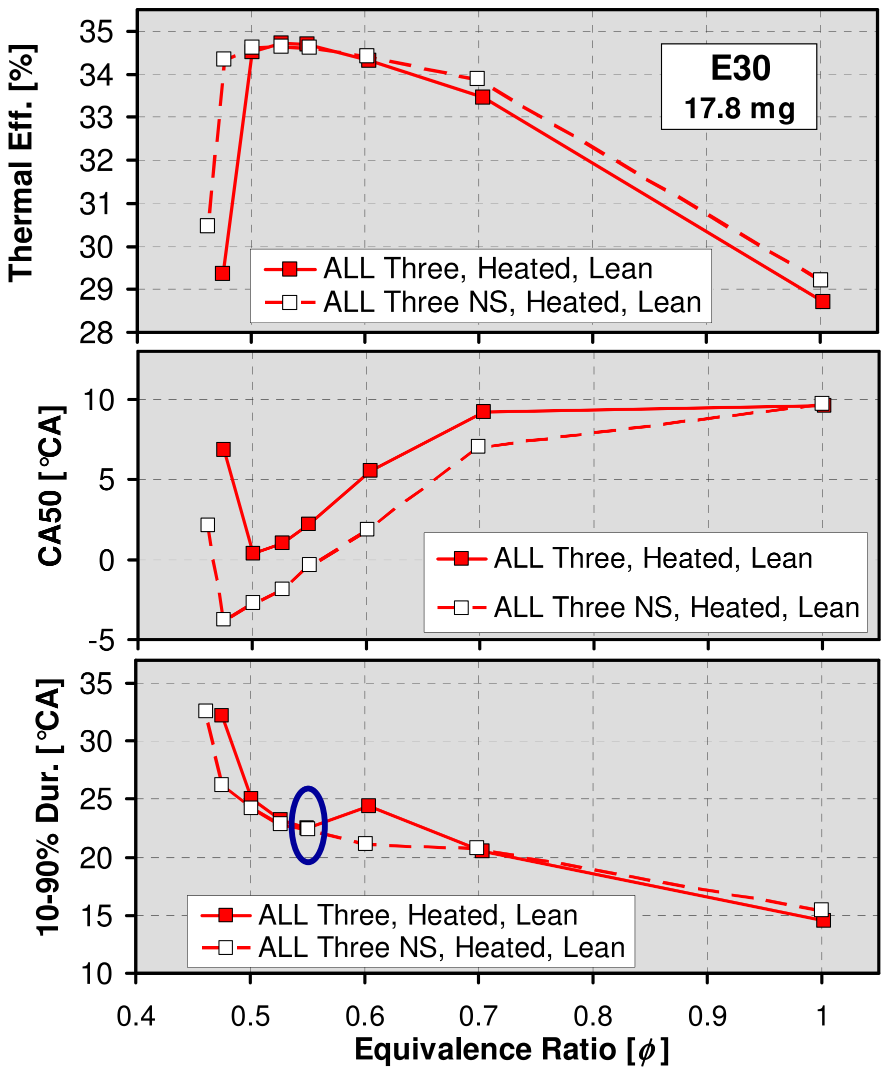
- Swirl comes with an efficiency penalty, even for stoichiometric operation.
  - Increased heat-transfer losses.
- Two extra spark plugs and piston cut-out also increase heat-transfer losses.

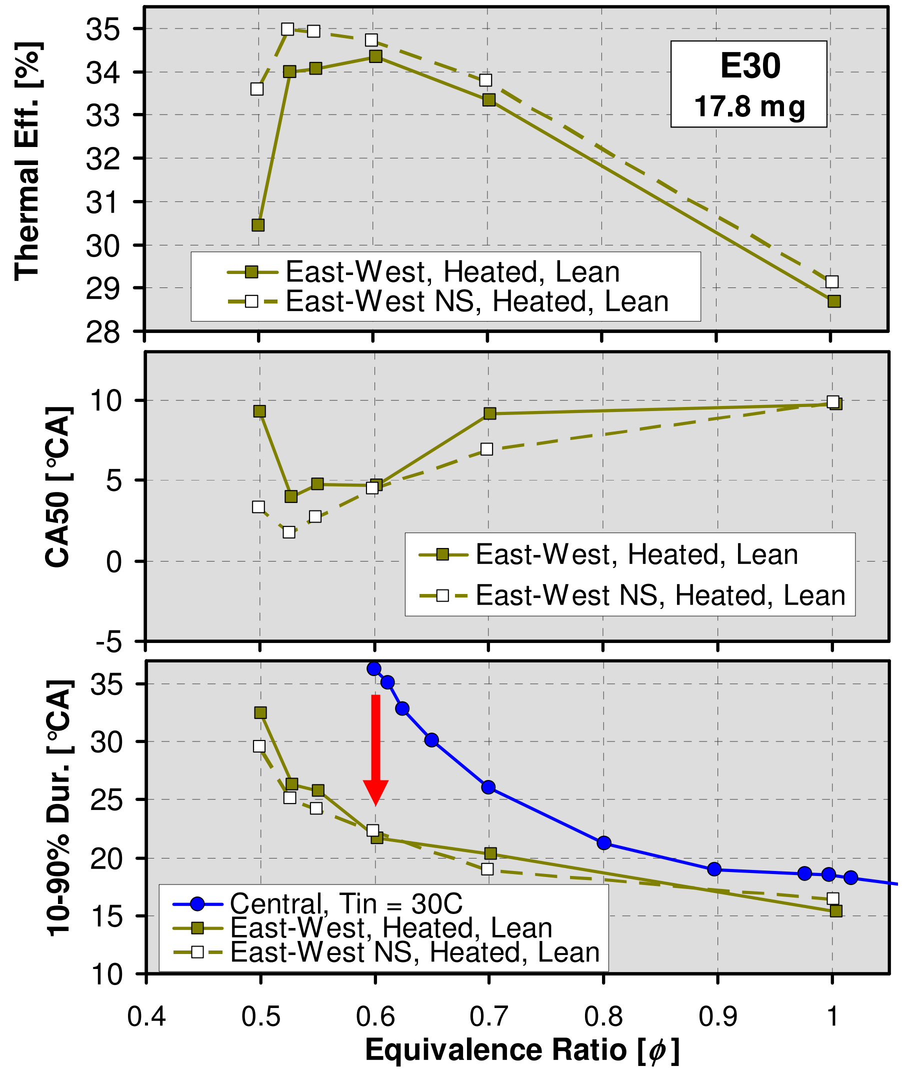




CA50 Needed for Mixed-Mode Comb.

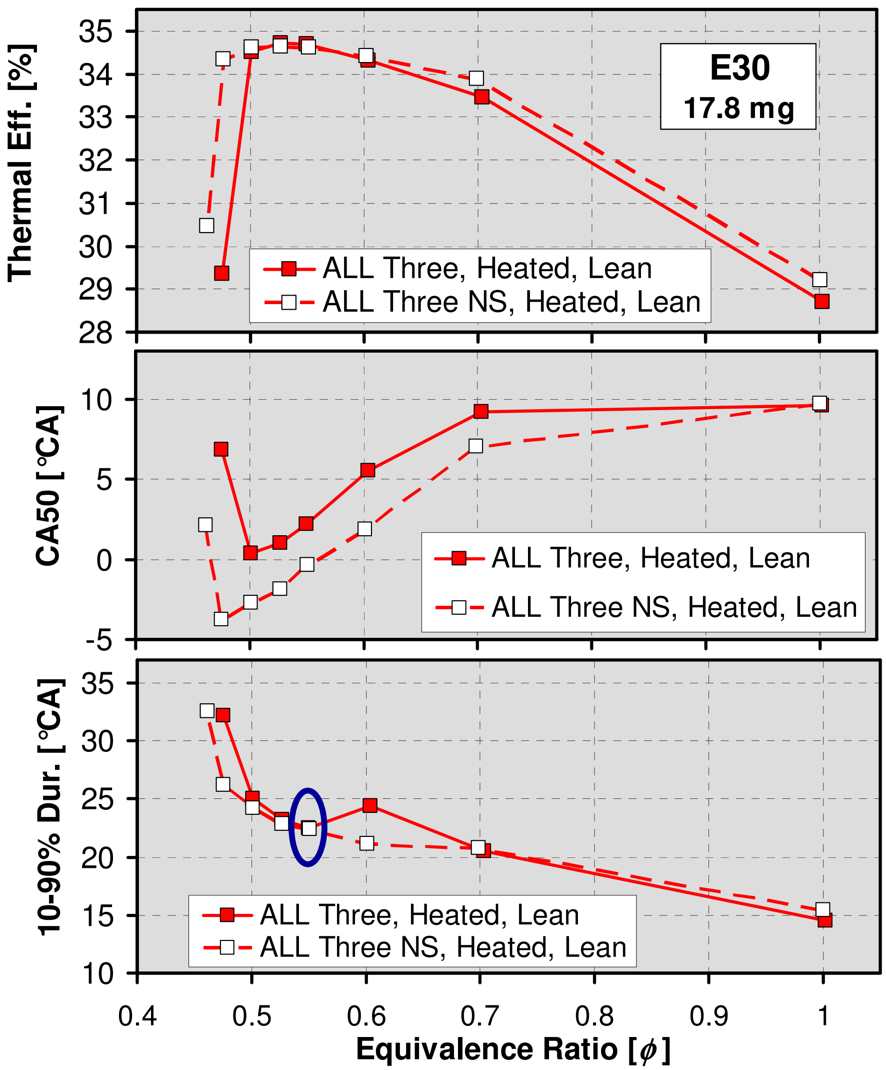
- Focus on ALL and East-West. (End-gas autoignition never visible for Central.)
- ALL without swirl requires very early CA50 to induce end-gas autoignition. Why?
- Mixed-mode combustion maintains CA10-90 burn duration below 30°CA.
  – Essential for efficient ultra-lean operation.

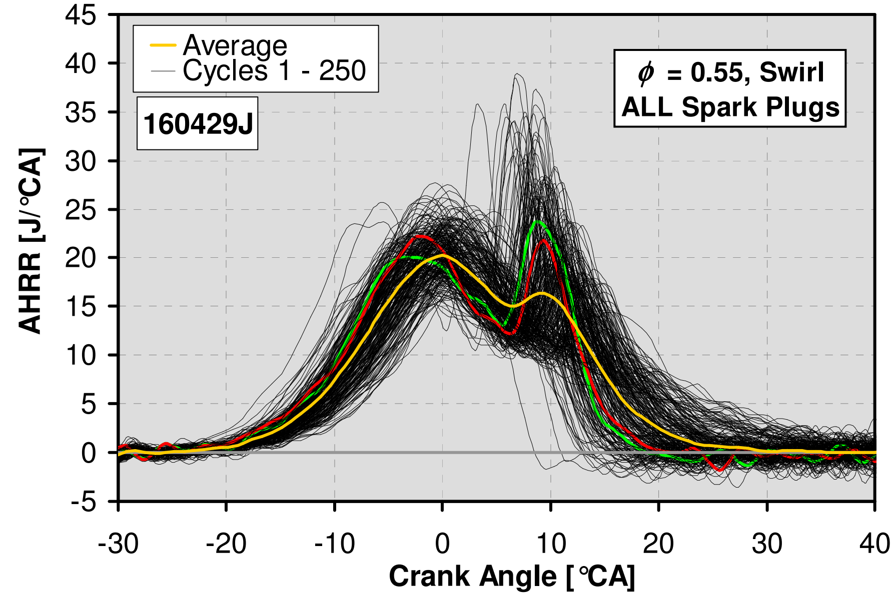


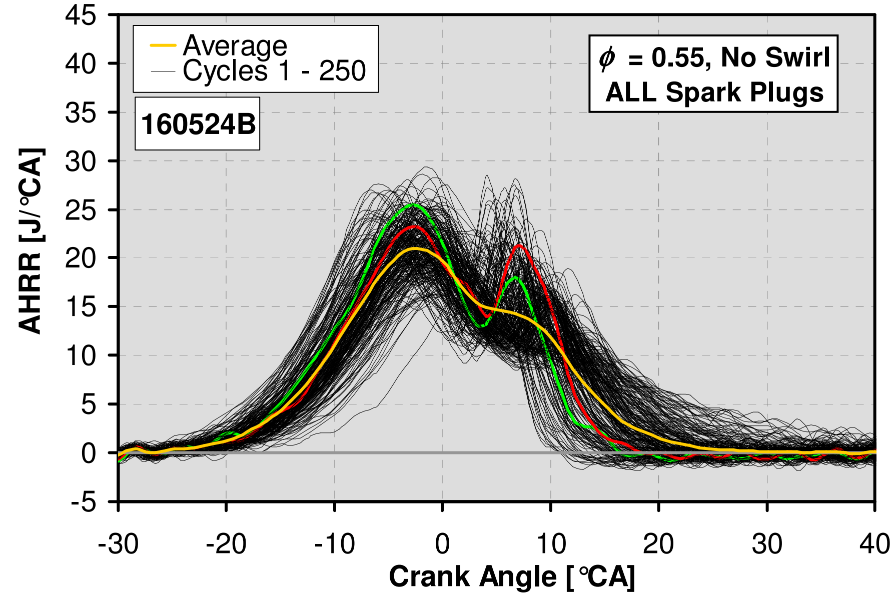


AHRR Patterns for ALL Sparks

- Similar heat-release patterns for operation with and without swirl.

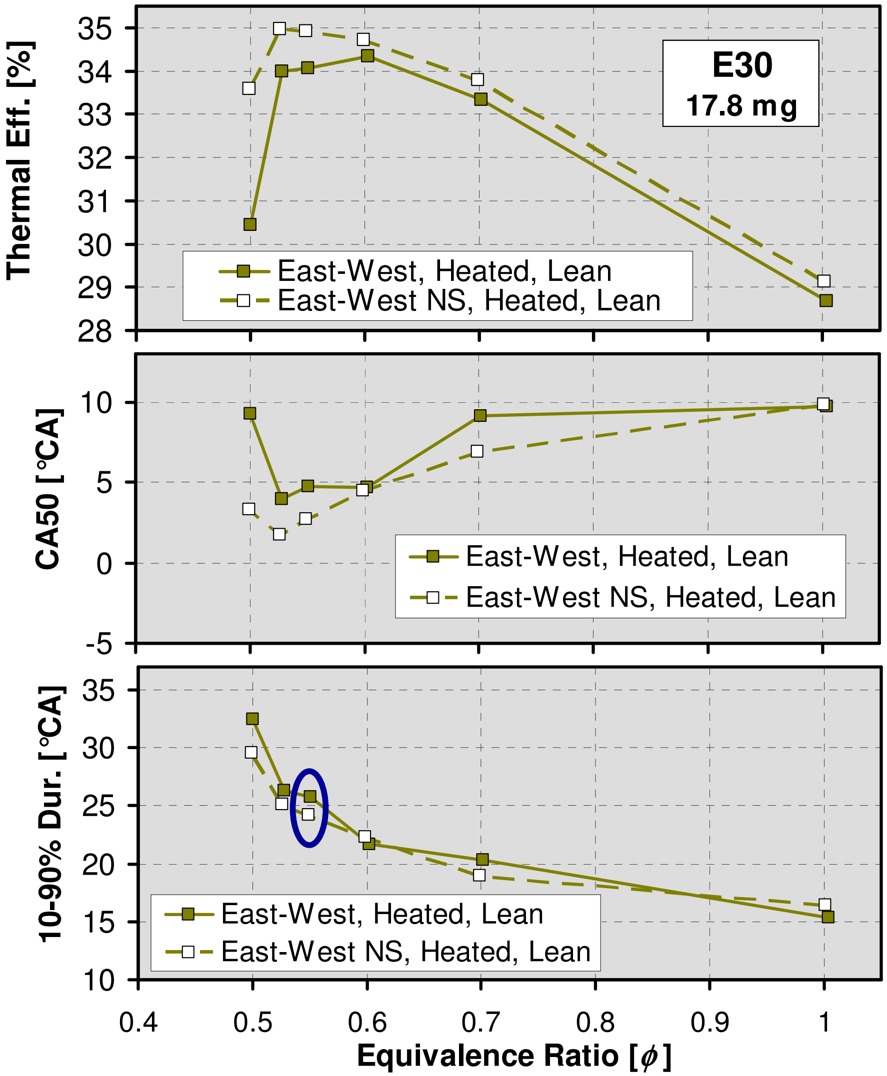


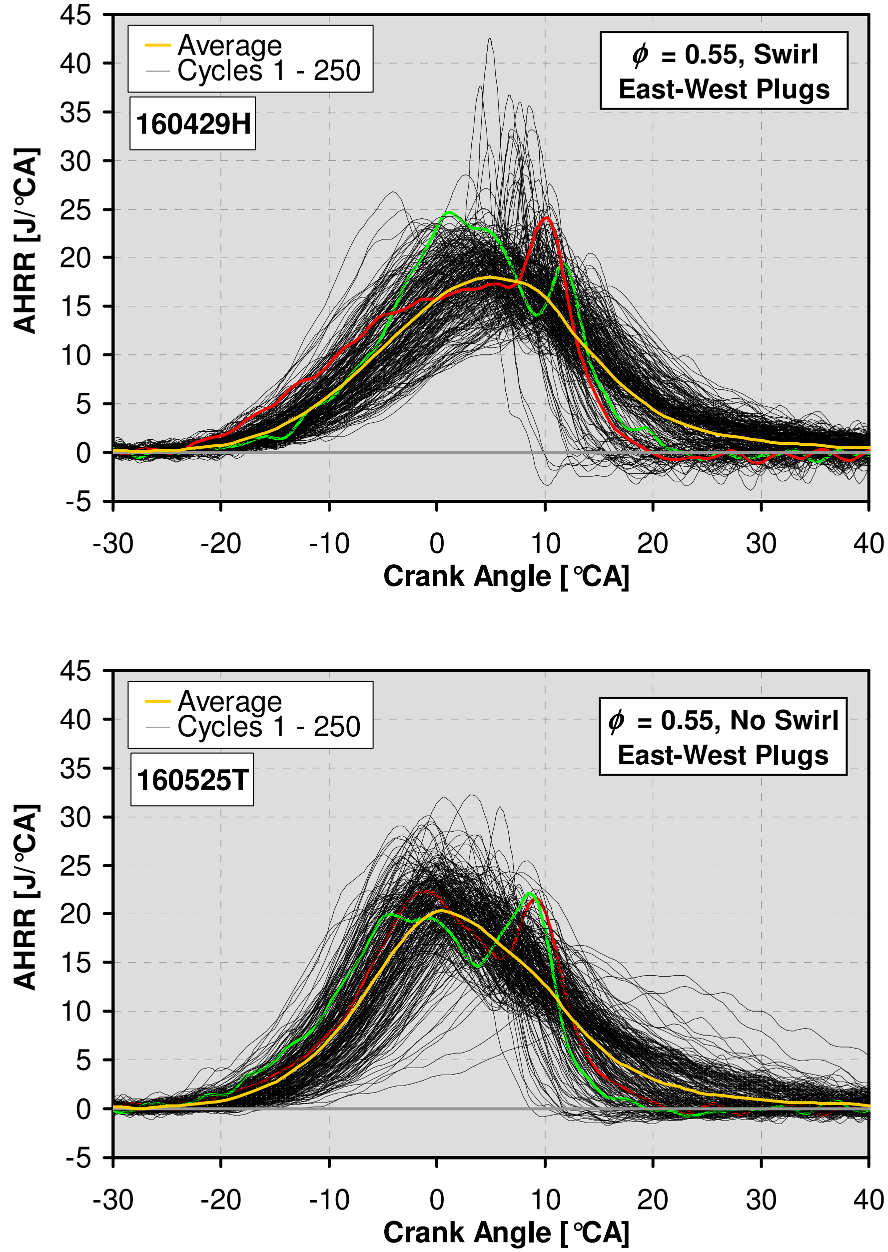




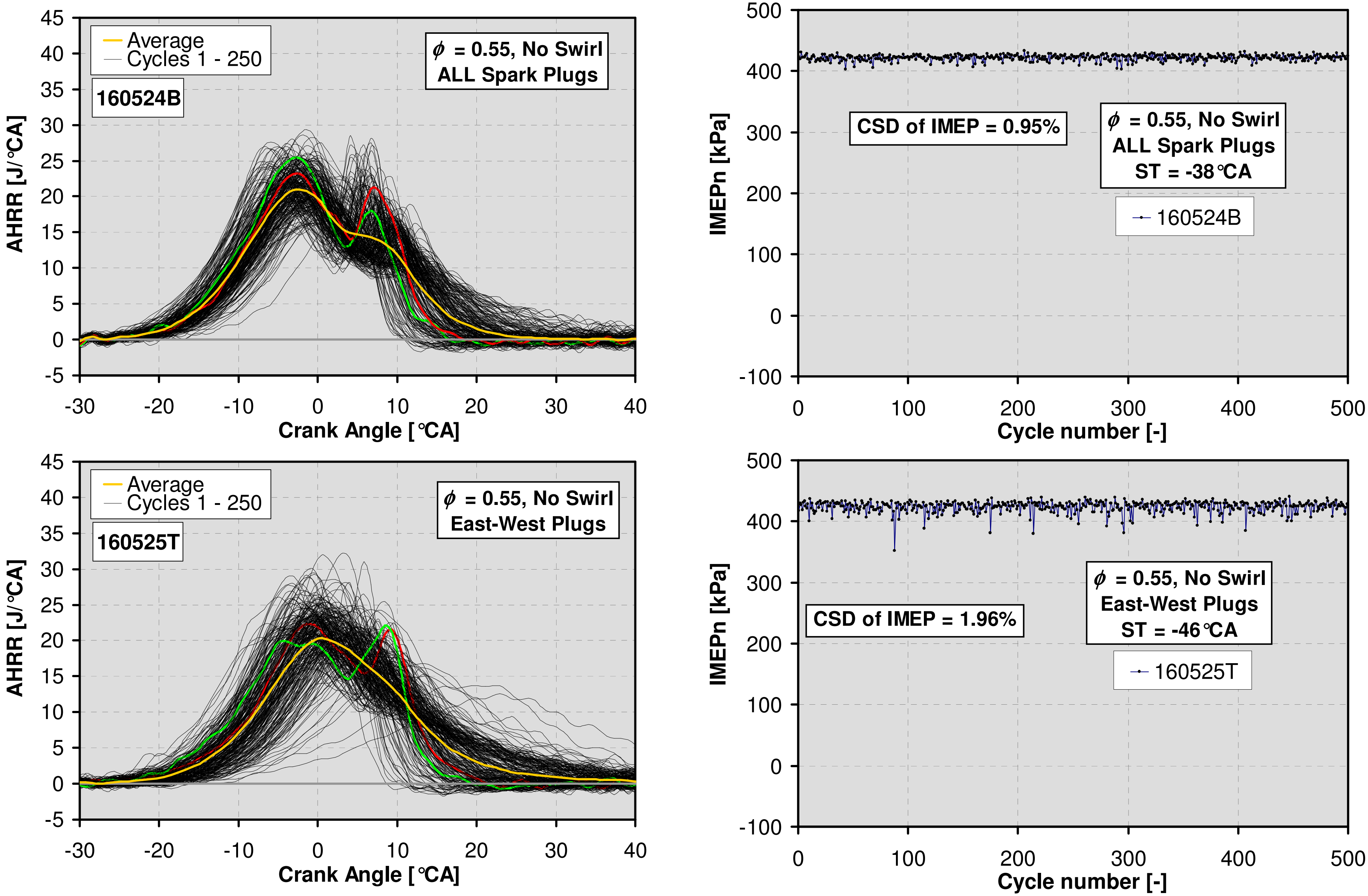
AHRR Patterns for East-West

- Similar heat-release patterns for operation with and without swirl.



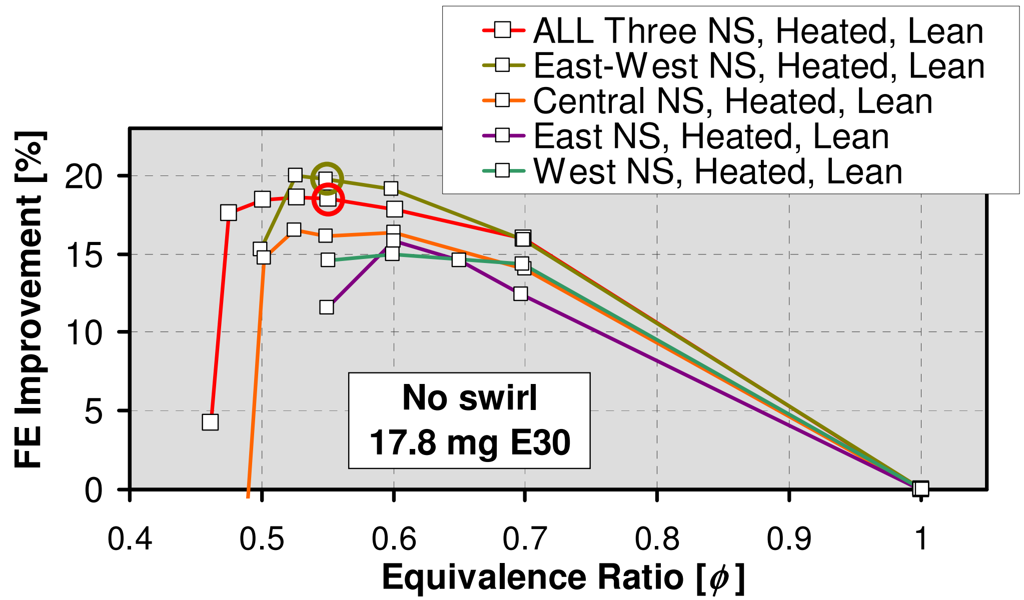


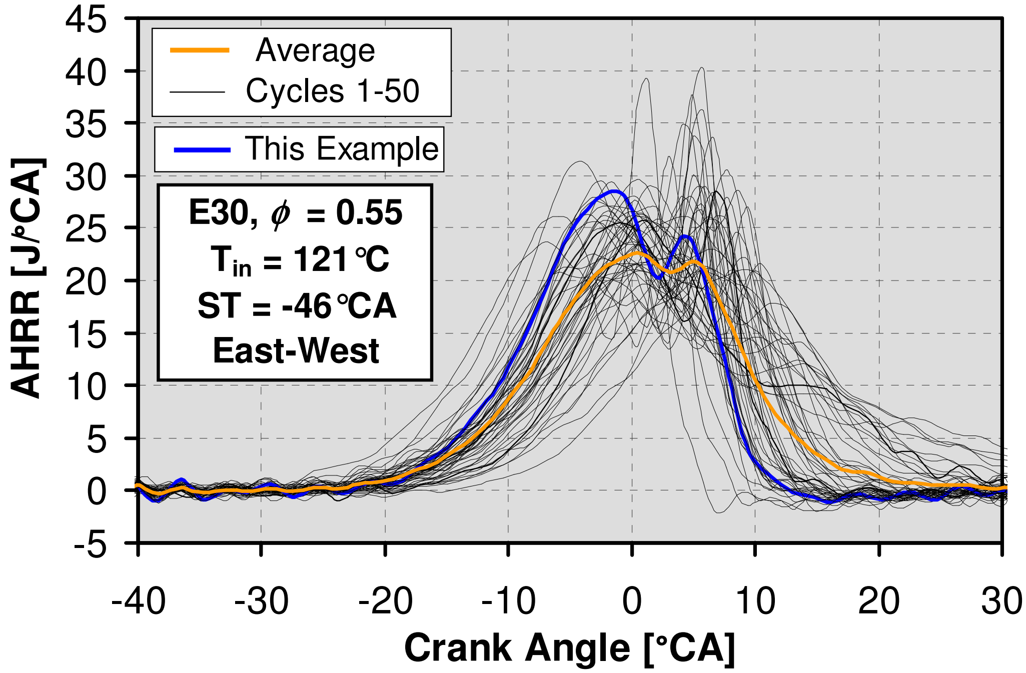
IMEP Instability, No Swirl



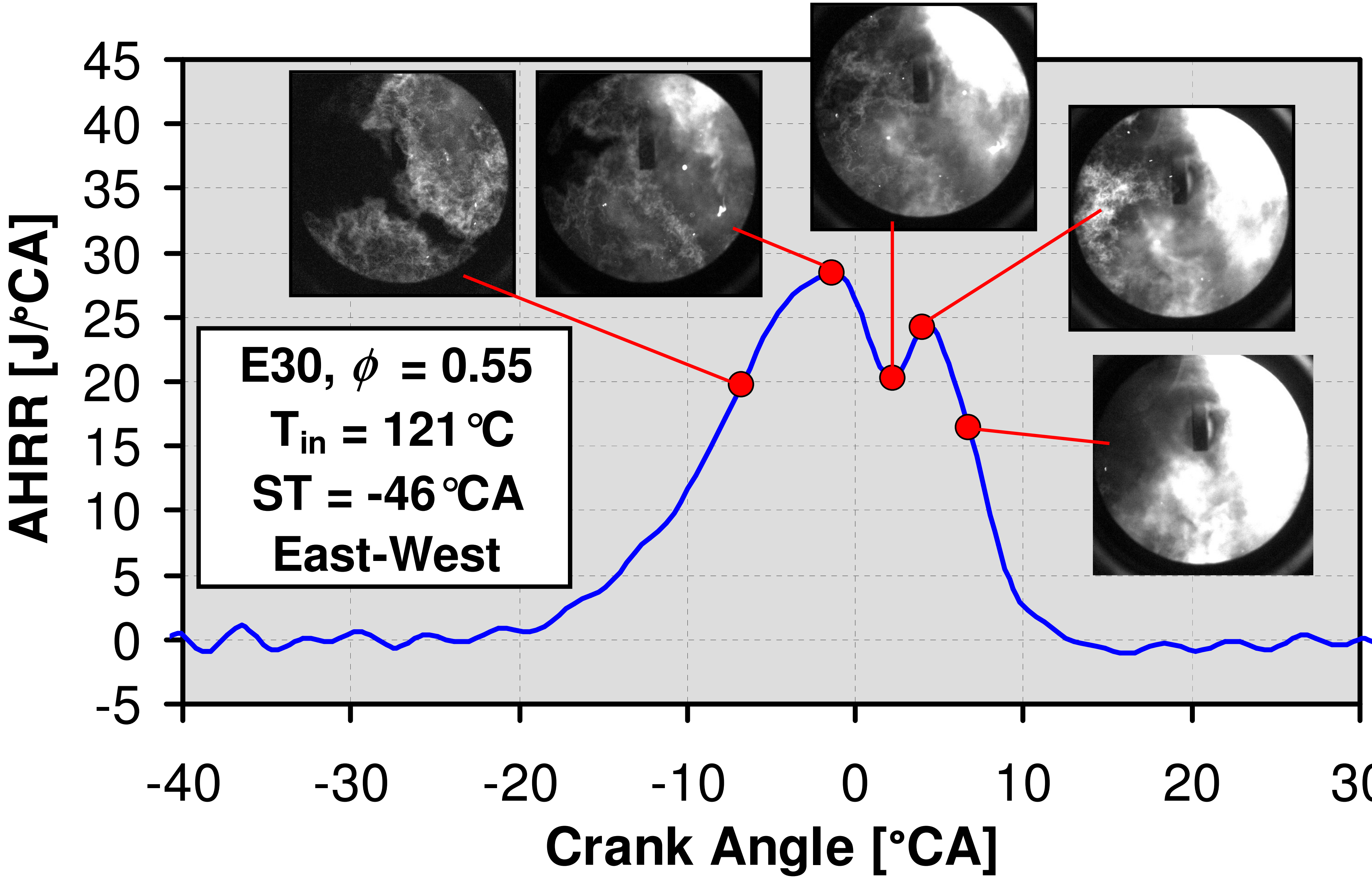
Imaging of End-gas Autoignition

- East-West and ALL scenarios have best TE improvement
- Performed imaging of:
- ϕ = 0.55, T_{in} = <u>121 °C</u>, no swirl.
- Here, only examine East-West.
  – Multiple cycles with mixed-mode combustion.
- Presented movie is for “blue” cycle.



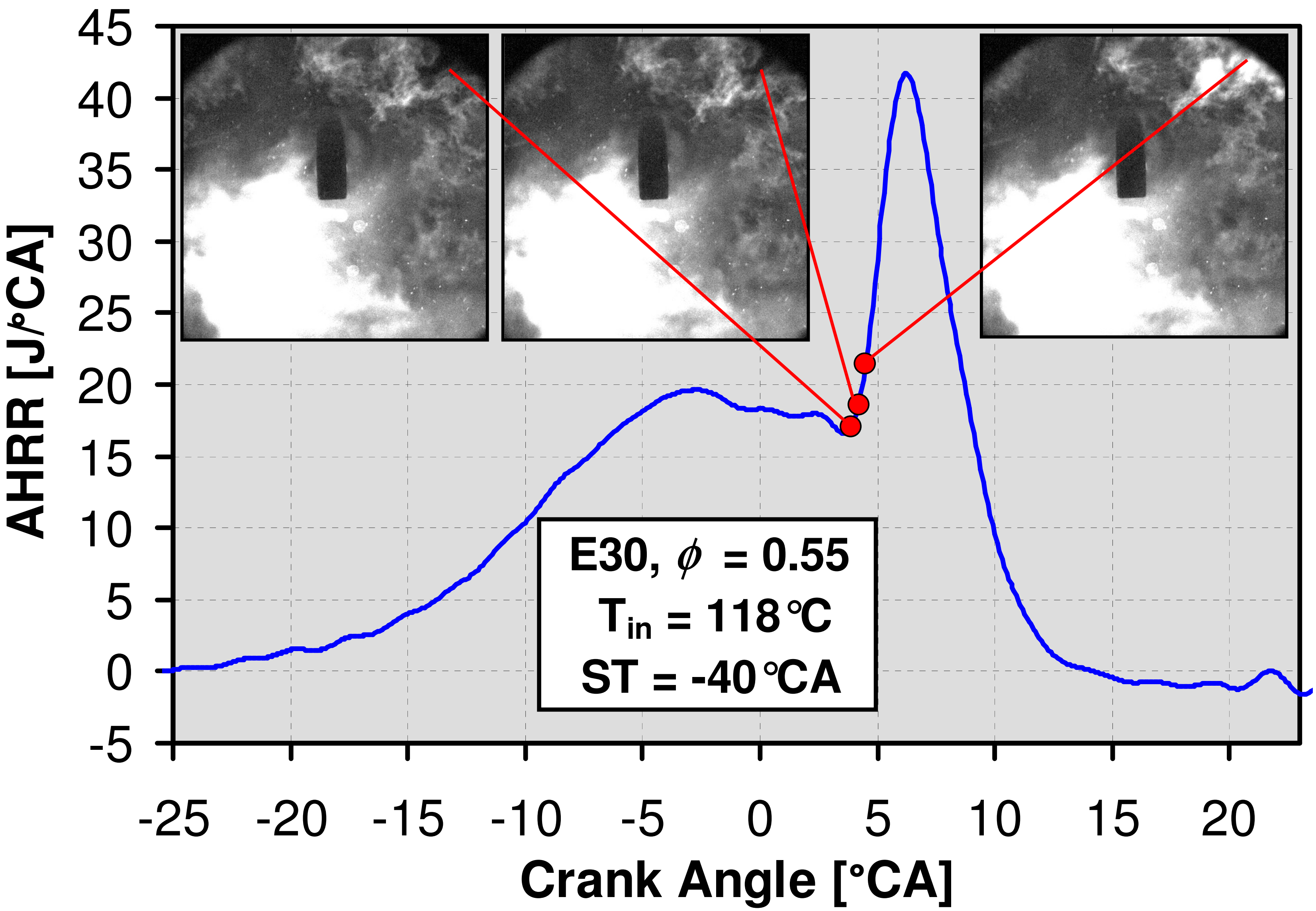


Imaging of End-gas Autoignition, NS



All Three with Swirl

- Rapid increase of chemiluminescence coincident with onset of autoignition AHRR.



Conclusions

- Both spark location and intake-generated flow are important for the stability of lean operation.
- Mixed-mode combustion (deflagration to end-gas autoignition) can ensure sufficiently short burn duration for ultra-lean SI operation so that efficiency benefits are realized.
- Mixed-mode operation is possible, even with a high-RON E30 fuel. Probing end-gas autoignition is important for complete understanding.
- The use of the East spark location creates large end-gas volume, but flame development is too unstable for meaningful ultra-lean studies.
- Operation with East-West and ALL spark plugs appears most promising for probing end-gas autoignition in central locations of the combustion chamber.
- Swirl reduces thermal efficiency slightly. Increased heat transfer?
- No-swirl operation provides more stable ultra-lean operation, and higher thermal efficiency.
  - Except for ALL sparks, which requires overly advanced CA50 for mixed-mode combustion without swirl.
- Removal of swirl benefits Central spark in particular with shorter inflammation.

Acknowledgements

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Co-Optimization of Fuels & Engines

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