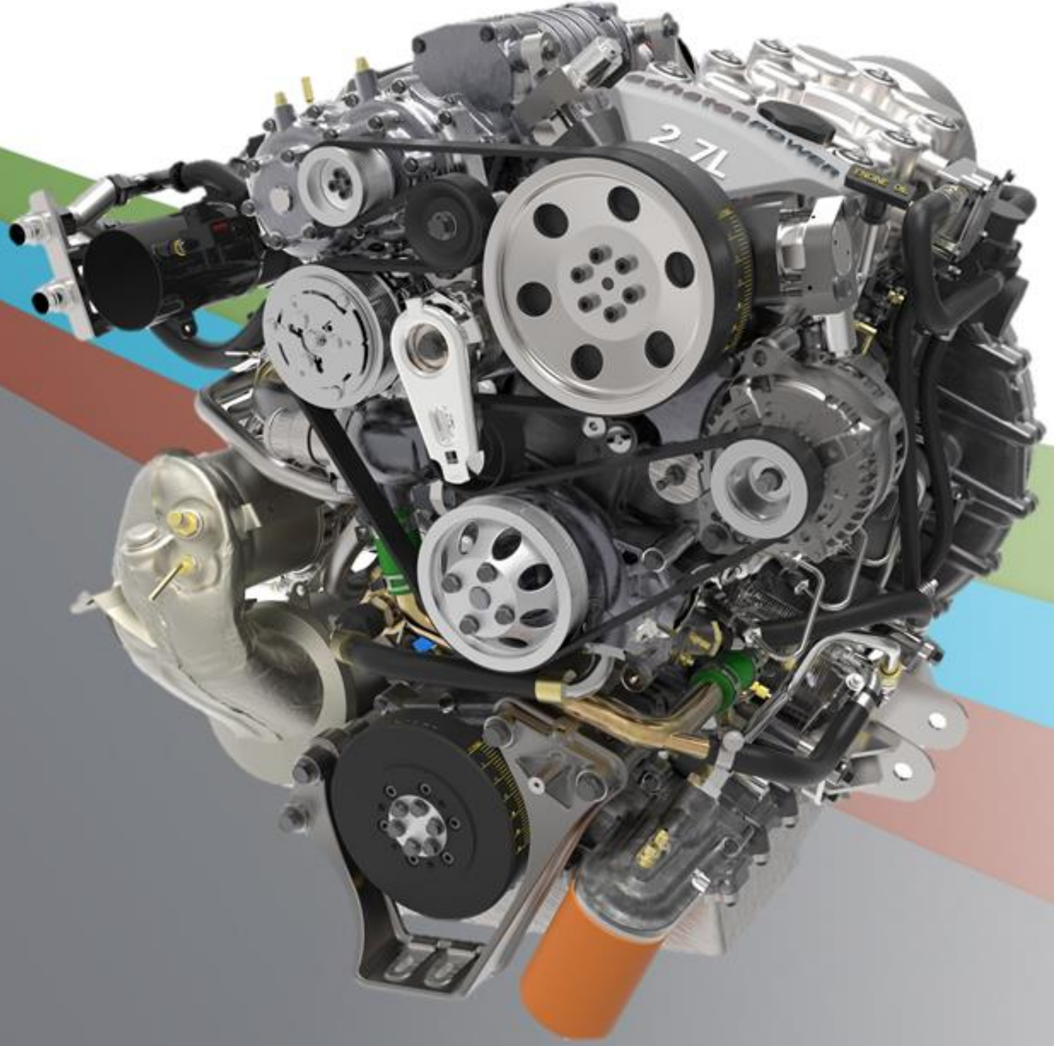


Hydrogen Opposed Piston Two Stroke (H2 OP2S) Engine

March 2023

Ming Huo

achatesPOWER™ Fundamentally Better Engines®

Outline

- Opposed piston two stroke (OP2S) engine
- H2 OP2S engine
- CFD modeling work on H2 OP2S

Opposed Piston Engine

Efficient and Clean

- Higher stroke to bore ratio for lower heat loss and higher efficiency
- External flexible charge control
- Lower heat loss with the elimination of the cylinder head
- Ability to shape two converging pistons enable greater control of gas dynamics
- Fuel flexibility, including hydrogen

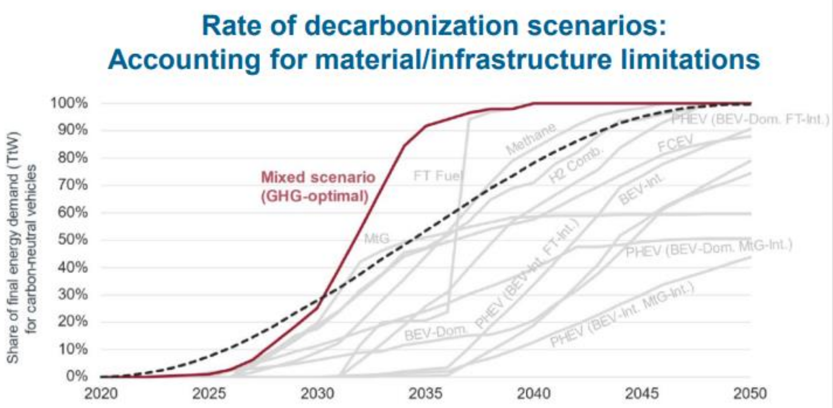
Cost Effective

- Reduced part count and lower manufacturing requirement. No cylinder head or valve train
- Side injection increases design flexibility
- Common 4-stroke failure modes eliminated – cylinder heads, head gaskets, exhaust valves
- Uses common materials, processes, tools, existing supply base
- Less expensive than conventional engines of the same power and torque

Hydrogen Internal Combustion Engine

- “H2ICE development and demonstration programs are gaining momentum”
- “H2ICEs have both short-term and long-term potential”
- “Single technology scenarios will delay decarbonization”
- “A technology-neutral mixed-scenario is likely the fastest, most cost-effective, and lowest risk path to carbon neutrality”

-- Ales Srna, H2IQ webinar



Rate of decarbonization scenarios: Accounting for material/infrastructure limitations

BEV	Battery-Electric Vehicle	PHEV	Plug-In Hybrid Electric Veh.
FCEV	Fuel-Cell Electric Vehicle	Dom.	EU domestic sourcing
FT	Fischer-Tropsch	Int.	International sourcing
MtG	Methane to Gasoline		

Source: FVV Future Fuel Study IVb, Project Nr. 1452, Final Report, 2022; https://www.fvv-net.de/fileadmin/Storys/Wie_schnell_geht_nachhaltig/FVV_H1313_1452_Future_Fuels_FVV_Fuel_Study_IVb_2022-12.pdf
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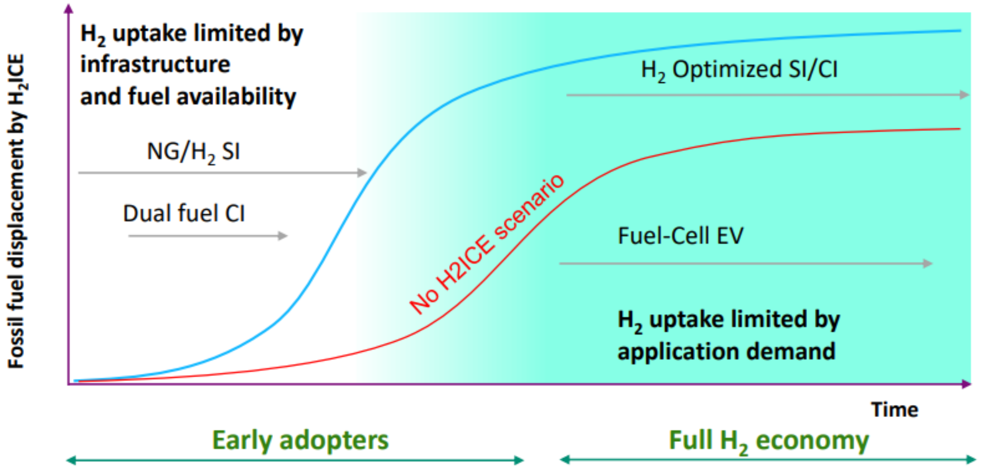


Fuel flexibility: (NG/H_2 blends, low-purity H_2, backup diesel operation

Retrofits: key to decarbonizing the existing fleet

Robustness/TCO:
H_2 penetration into applications challenging for H_2-FC

Key H2-ICE advantages in time

https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office-webinars

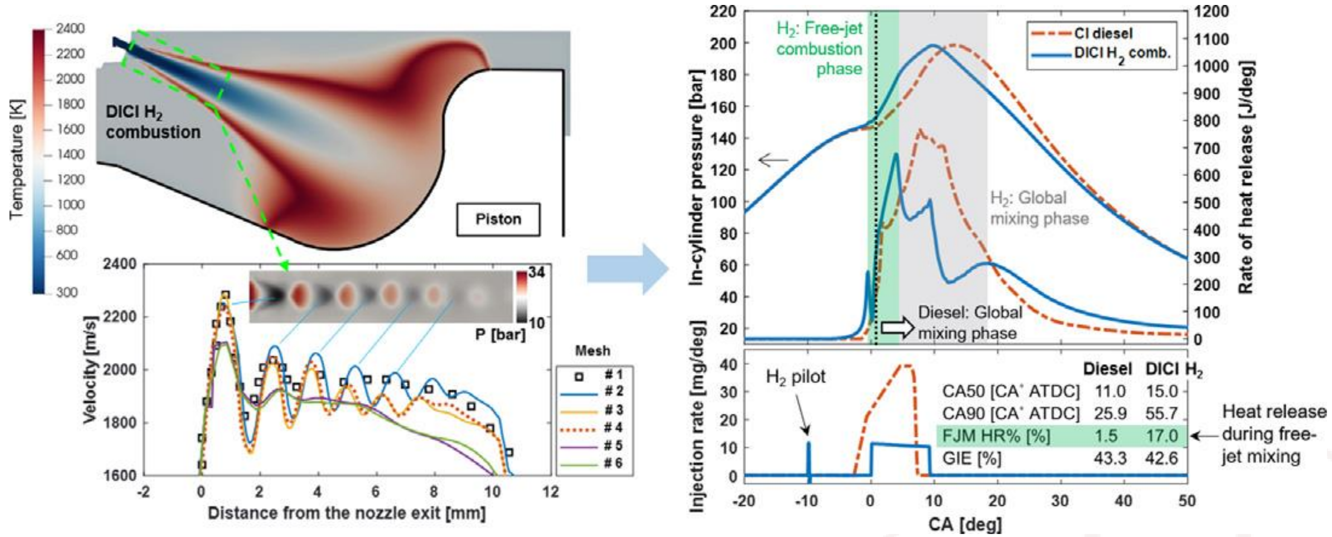
H2 Combustion Concepts

	Port fuel injection (PFI)	**Low-Mid Pressure DI**	**High Pressure DI**	**High Pressure DI**
H2 pressure [bar]	<20	20-100	200-300	200-300
Ignition source	Glow- or spark- plug	Glow- or spark- plug	Carbon based fuel	Direct CI w/wo pilot injection
Combustion	Lean homogeneous SI	Lean homogeneous SI	Diffusive CI	Diffusive CI
Main Benefits	• Low conversion effort • Low failure risk	• Robust against backfire • Better efficiency and power density compared with PFI	• Increased CR potential • Excellent efficiency • Higher power density without knocking • Better transient response	• Increased CR potential • Excellent efficiency • Higher power density without knocking • Better transient response
Main Challenges	• Low efficiency; • Low transient response; • Risk of backfire • Low power density	• Conversion effort • Mixture preparation • Knocking tendency at high load	• "Carbon emissions" • NOx emissions • Complex fuel system	• H2 CI ignition challenge • NOx emissions • High pressure fuel system integration

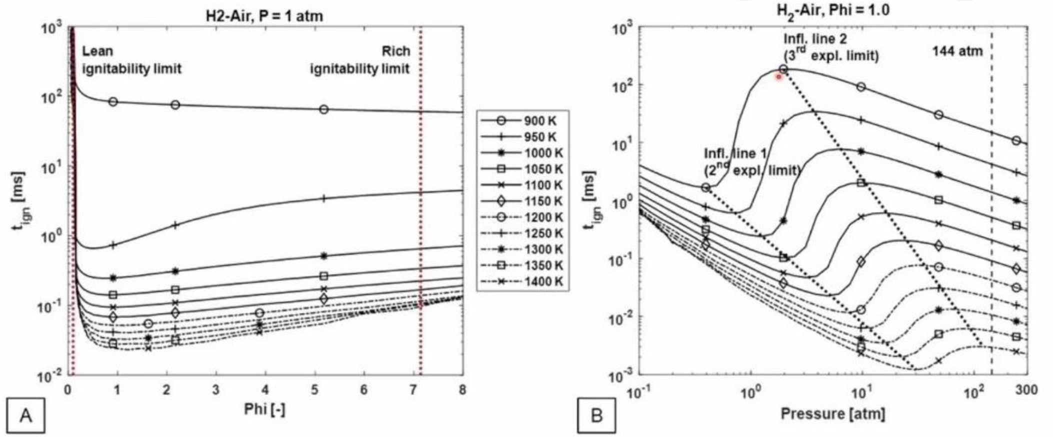
- Preliminary CFD studies conducted on the hydrogen-fueled OP2S engine with lean spark ignition have revealed knocking and preignition tendencies even at some low and mid-load points.
- This prompted consideration of using diffusive CI across the majority of the map
- The OP2S engine offers the advantage of flexible control over the trapped temperature through scavenging, which can overcome the challenge posed by the high autoignition temperature of H2 for CI combustion.
- Ultimately, the goal is to leverage the benefits of OP engine with lower heat loss and faster combustion to get the most efficient carbon free H2 Engine

H2 Compression Ignition (CI) Engine

- Most of the H2 CI studies involve dual fuel operation
- Recent study from Prof. Bengt Johansson's Group uses pilot-assisted H2 ignition in a double compression expansion engine (DCEE)
- High auto-ignition temperature of H2 is the main challenge for CI combustion



	Diesel	DICI H_2
CA50 [CA˚ ATDC]	11.0	15.0
CA90 [CA˚ ATDC]	25.9	55.7
FJM HR% [%]	1.5	17.0
GIE [%]	43.3	42.6



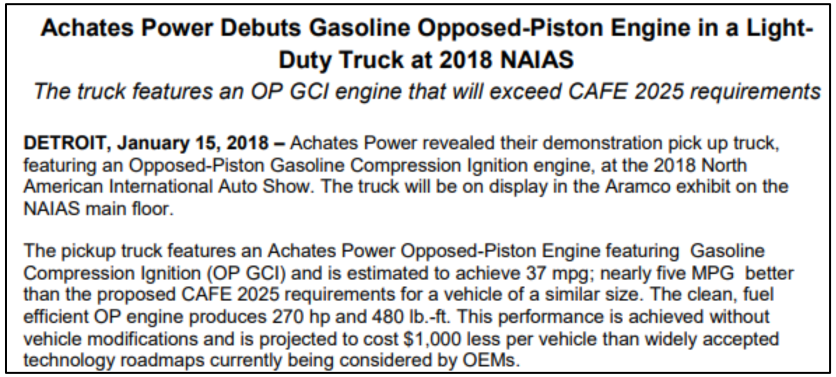
1000 K (727 ˚C) – ignition delay = 10-30 CA˚ at 50 % EGR

1130 K (857 ˚C) – ignition delay = 1-3 CA˚ at 50 % EGR

Babayev et al. 2022

OP2S GCI Engine & Alcohol Fuels CI Engine

- Opposed Piston Two Stroke (OP2S) has inherent advantage over scavenging control
- For high auto-ignition temperature fuels, OP2S Engine can overcome the challenge by elevating trapped temperature and using pilot injections
- OP2S engine has demonstrated such capabilities in previous and ongoing projects

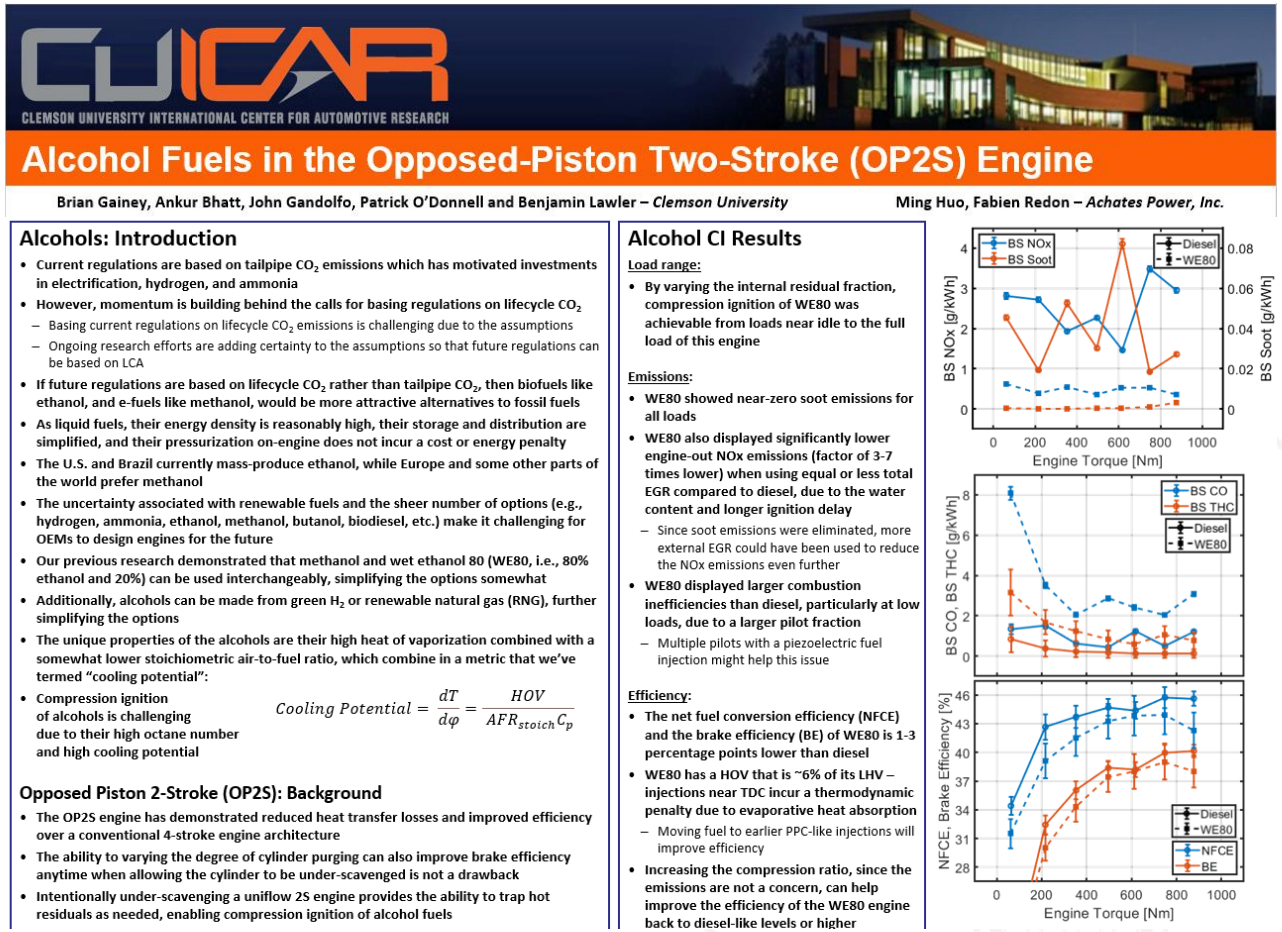


Achates Power Debuts Gasoline Opposed-Piston Engine in a Light-Duty Truck at 2018 NAIAS

The truck features an OP GCI engine that will exceed CAFE 2025 requirements

DETROIT, January 15, 2018 – Achates Power revealed their demonstration pick up truck, featuring an Opposed-Piston Gasoline Compression Ignition engine, at the 2018 North American International Auto Show. The truck will be on display in the Aramco exhibit on the NAIAS main floor.

The pickup truck features an Achates Power Opposed-Piston Engine featuring Gasoline Compression Ignition (OP GCI) and is estimated to achieve 37 mpg; nearly five MPG better than the proposed CAFE 2025 requirements for a vehicle of a similar size. The clean, fuel efficient OP engine produces 270 hp and 480 lb.-ft. This performance is achieved without vehicle modifications and is projected to cost $1,000 less per vehicle than widely accepted technology roadmaps currently being considered by OEMs.



CU-ICAR

CLEMSON UNIVERSITY INTERNATIONAL CENTER FOR AUTOMOTIVE RESEARCH

Alcohol Fuels in the Opposed-Piston Two-Stroke (OP2S) Engine

Brian Gainey, Ankur Bhatt, John Gandolfo, Patrick O'Donnell and Benjamin Lawler – ***Clemson University*** **Ming Huo, Fabien Redon –** ***Achates Power, Inc.***

Alcohols: Introduction

- Current regulations are based on tailpipe CO_2 emissions which has motivated investments in electrification, hydrogen, and ammonia
- However, momentum is building behind the calls for basing regulations on lifecycle CO_2
  - Basing current regulations on lifecycle CO_2 emissions is challenging due to the assumptions
  - Ongoing research efforts are adding certainty to the assumptions so that future regulations can be based on LCA
- If future regulations are based on lifecycle CO_2 rather than tailpipe CO_2, then biofuels like ethanol, and e-fuels like methanol, would be more attractive alternatives to fossil fuels
- As liquid fuels, their energy density is reasonably high, their storage and distribution are simplified, and their pressurization on-engine does not incur a cost or energy penalty
- The U.S. and Brazil currently mass-produce ethanol, while Europe and some other parts of the world prefer methanol
- The uncertainty associated with renewable fuels and the sheer number of options (e.g., hydrogen, ammonia, ethanol, methanol, butanol, biodiesel, etc.) make it challenging for OEMs to design engines for the future
- Our previous research demonstrated that methanol and wet ethanol 80 (WE80, i.e., 80% ethanol and 20%) can be used interchangeably, simplifying the options somewhat
- Additionally, alcohols can be made from green H_2 or renewable natural gas (RNG), further simplifying the options
- The unique properties of the alcohols are their high heat of vaporization combined with a somewhat lower stoichiometric air-to-fuel ratio, which combine in a metric that we've termed "cooling potential":
- Compression ignition of alcohols is challenging due to their high octane number and high cooling potential

$$Cooling\ Potential = \frac{dT}{d\varphi} = \frac{HOV}{AFR_{stoich} C_p}$$

Opposed Piston 2-Stroke (OP2S): Background

- The OP2S engine has demonstrated reduced heat transfer losses and improved efficiency over a conventional 4-stroke engine architecture
- The ability to varying the degree of cylinder purging can also improve brake efficiency anytime when allowing the cylinder to be under-scavenged is not a drawback
- Intentionally under-scavenging a uniflow 2S engine provides the ability to trap hot residuals as needed, enabling compression ignition of alcohol fuels

Alcohol CI Results

__Load range:__

- By varying the internal residual fraction, compression ignition of WE80 was achievable from loads near idle to the full load of this engine

__Emissions:__

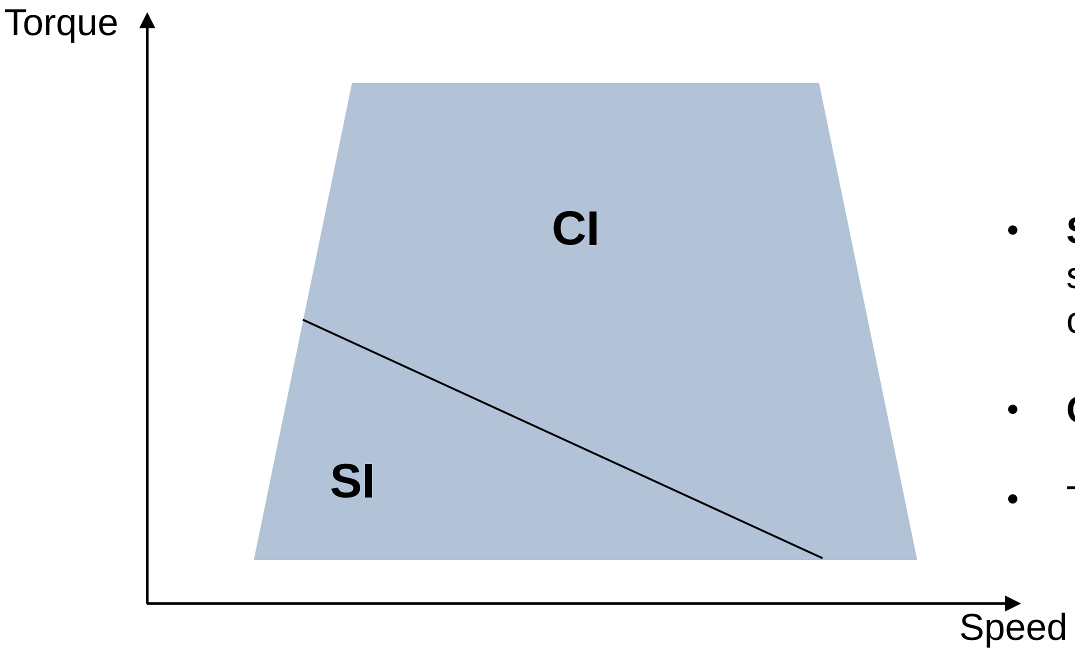
- WE80 showed near-zero soot emissions for all loads
- WE80 also displayed significantly lower engine-out NOx emissions (factor of 3-7 times lower) when using equal or less total EGR compared to diesel, due to the water content and longer ignition delay
  - Since soot emissions were eliminated, more external EGR could have been used to reduce the NOx emissions even further
- WE80 displayed larger combustion inefficiencies than diesel, particularly at low loads, due to a larger pilot fraction
  - Multiple pilots with a piezoelectric fuel injection might help this issue

__Efficiency:__

- The net fuel conversion efficiency (NFCE) and the brake efficiency (BE) of WE80 is 1-3 percentage points lower than diesel
- WE80 has a HOV that is ~6% of its LHV – injections near TDC incur a thermodynamic penalty due to evaporative heat absorption
  - Moving fuel to earlier PPC-like injections will improve efficiency
- Increasing the compression ratio, since the emissions are not a concern, can help improve the efficiency of the WE80 engine back to diesel-like levels or higher

Dual Ignition Mode Combustion

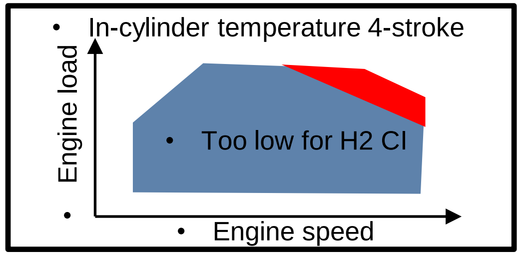
- The Innovative Dual Ignition Mode Combustion Strategy:
  - SI at cold start and low-load conditions
  - CI at medium and high-load conditions
- Such strategy offers the potential to meet diesel-like engine performance at medium and high load conditions, while engine can still start/run smoothly at cold/low-load conditions

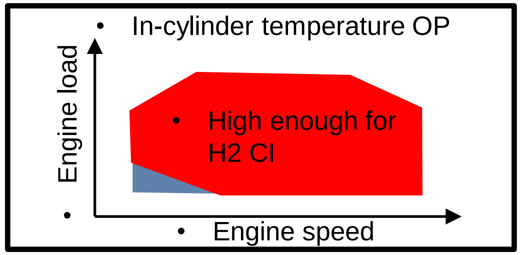


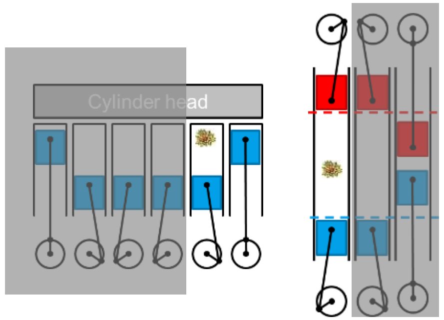
- **SI:** Early cycle direct injection (i.e., at port closure), spark source can be either spark plug, glow plug, or a pre-chamber for MJI
- **CI:** Late direct injection, w/wo H2 pilot
- The transition will be explored through calibrations

OP Engine Enablers for Hydrogen Combustion

Higher in-cylinder temperature from internal residuals enables compression ignition diffusion flame combustion **without dual fuel** injection system



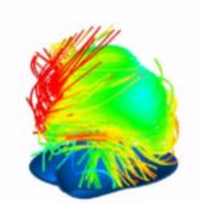




Lower BMEP enables lean combustion with optimized lambda for **NOx control** and leverages hydrogen high combustion speed without exceeding mechanical limits and **preserve power density**

Low surface area combustion volume minimizes heat losses associated with hydrogen high combustion temperatures to **maximize efficiency**.

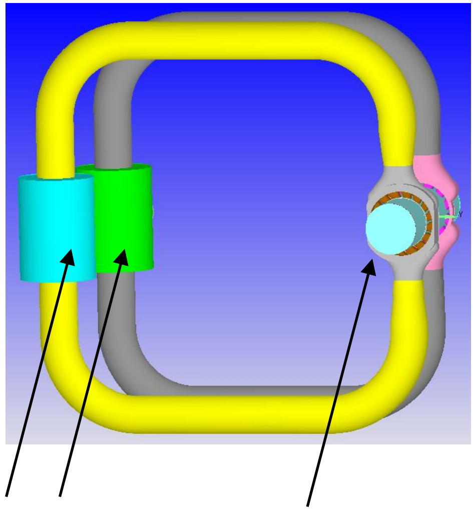
More **flexible integration** of injection and ignition devices around the cylinders



Enhanced ability to control air motion (swirl + tumble) uniquely enables air/fuel stratification and mixing for **stable combustion**.

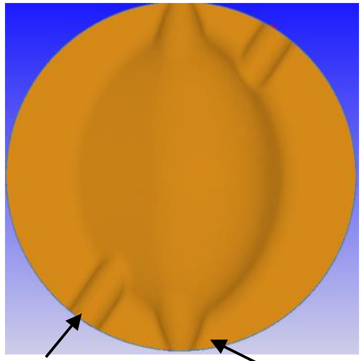
H2 OP2S Engine CFD Model

- CFD Simulation are conducted on the API single cylinder research engine
- Workflow
  - 1D GT Model
  - Open-cycle
  - Closed-cycle
- Combustion Simulation
  - Spark Ignition Combustion
  - Compression Ignition Combustion



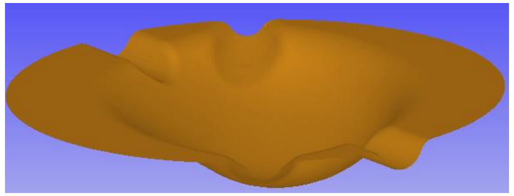
Intake & Exhaust Plenum

Single cylinder OP engine

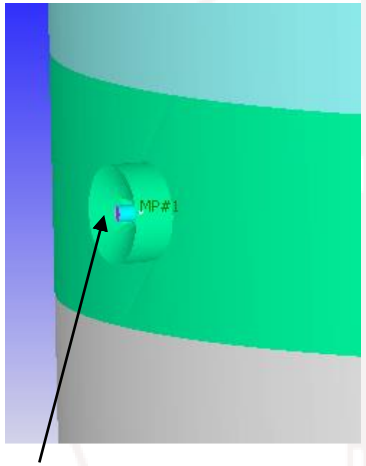


Spark plug trench

Injector trench



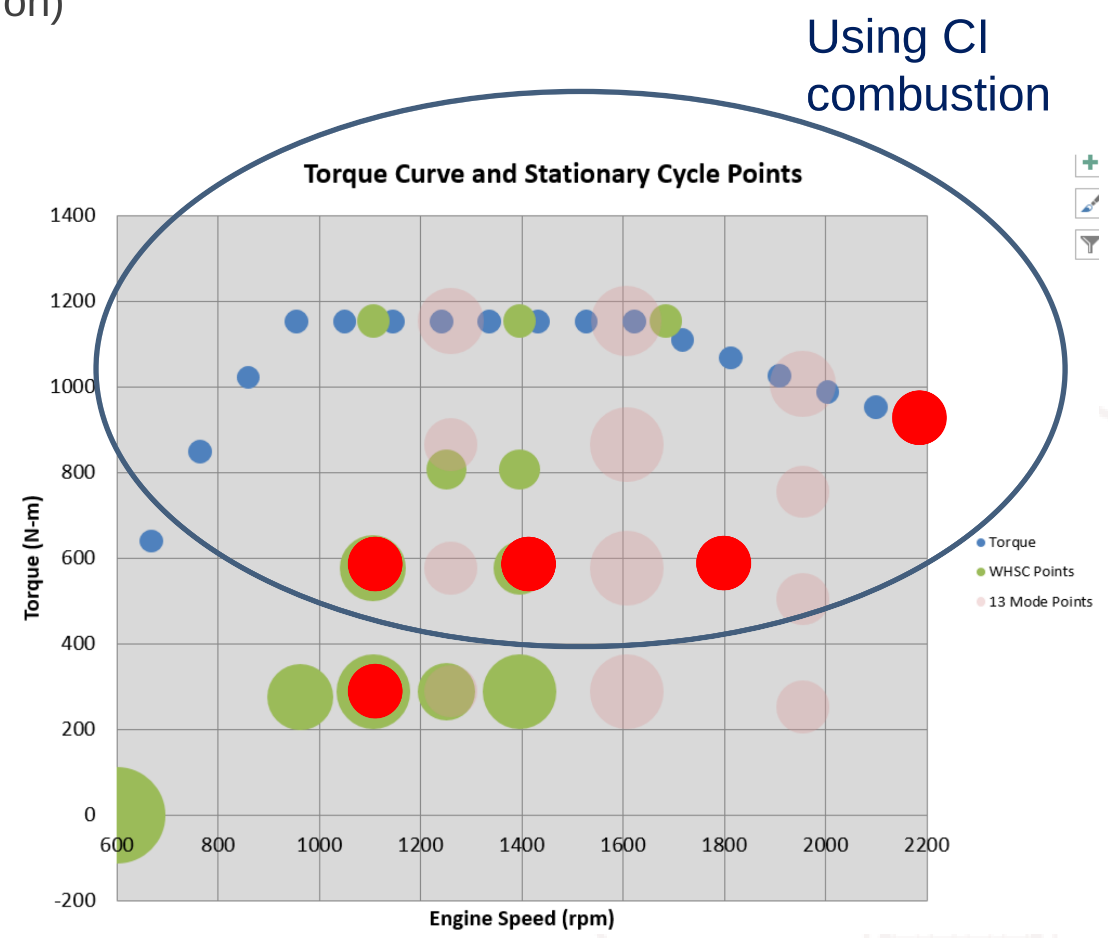
Piston with spark plug trench



Single hole injector
Injector nozzle volume modeled with embedding

Baseline OP Engine & Modeling Speed/Load Points

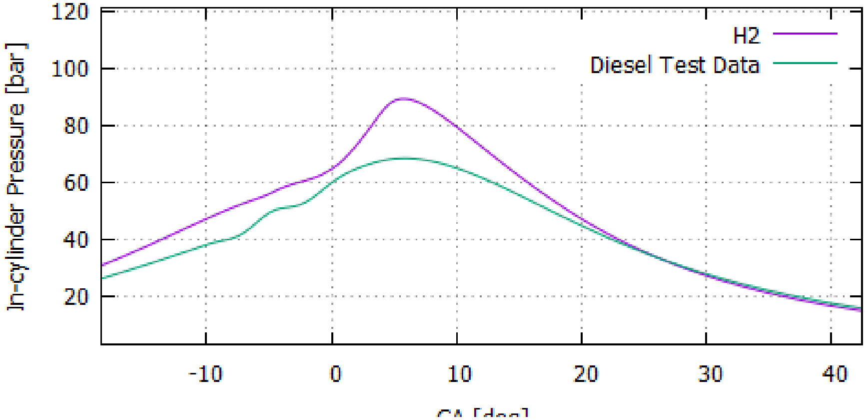
- 1.6L Single-Cylinder OP engine (modified from diesel version)
  - Bore: 98.4mm
  - Stroke 215.2mm
- Five points were picked for H2 CFD study
  - 2200 RPM, 100% load (rated power)
  - 1100 RPM, 50% load
  - 1400 RPM, 50% load
  - 1800 RPM, 50% load
  - 1100 RPM, 25% load
- Dual H2 combustion mode
  - Non-premixed CI for mid- and high-load points (pilot or SI assisted)
  - SI for low load

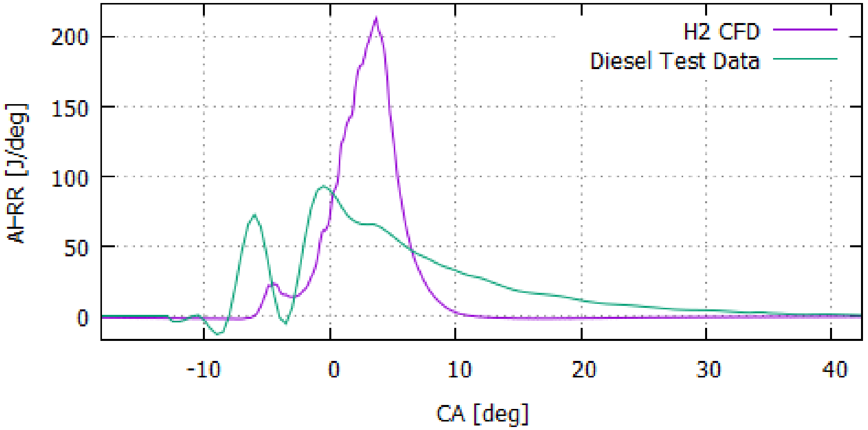


Low-Load SI Combustion

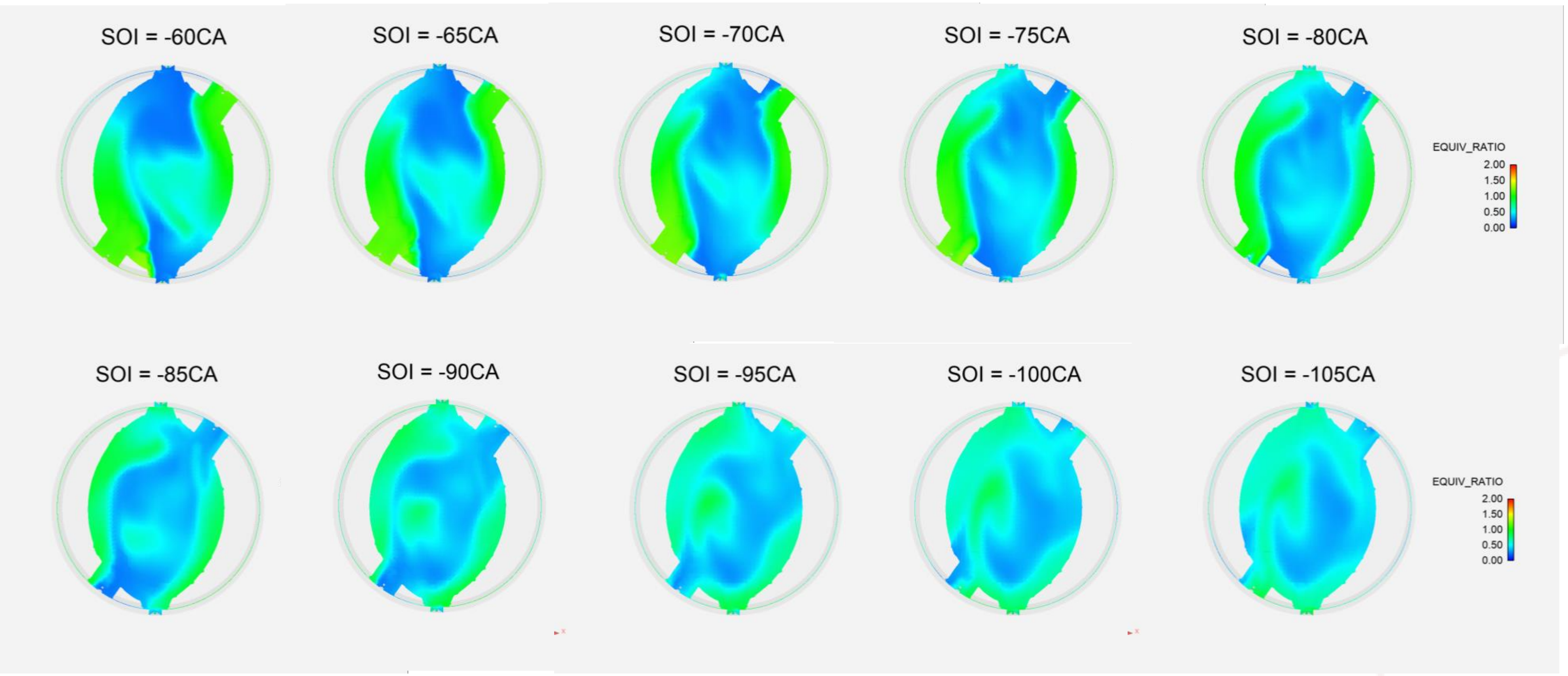
- H2 direct injection (DI) during compression stroke with external source used to ignite the mixture
- Combustion and NOx emissions are sensitive to the injection and spark timing
- With proper calibration, H2 SI yields even better ITE than diesel CI because of the much shorter burning duration

	H2	Diesel
Closed cycle ITE(%)	47.5	47.1
ahrr_ca_10(deg)	-1.0	-2.5
ahrr_ca_50(deg)	2.9	2.0
ahrr_ca_90(deg)	5.6	14.5
ahrr_ca_10_90(deg)	6.6	17.0
pcp(bar)	89.2	71.7
max_prr(bar/deg)	6.1	3.7
NOx (g/kg)	45.1	15.8
Soot(g/kg)	0.0	0.05
CO(g/kg)	0.0	4.3
HC(g/kg)	0.0	3.2



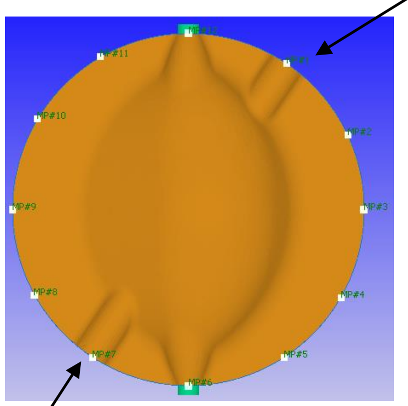


Low-Load SI Combustion



- Start-of-injection (SOI) is critical: 1) SOI too early may lead to misfire/pre-ignition 2) SOI too late can also lead to the stratified mixture miss the spark source causing misfire
- To achieve optimal SOI timing may require extensive calibration to account for the specific spark plug location and swirl level
- The target is to strike good balance of solid ignition and combustion performance, and transition out to CI mode asap

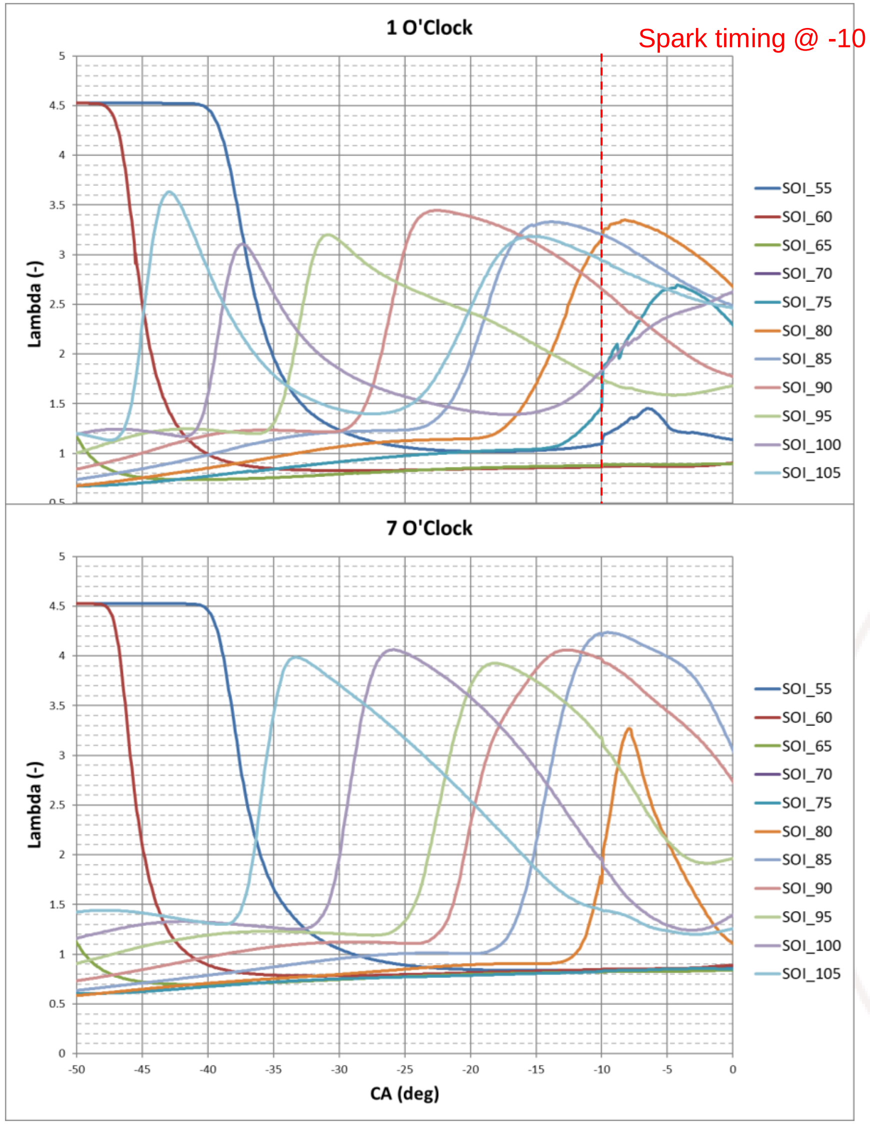
Monitor Local Mixture at External Spark Source



1 o'clock

7 o'clock

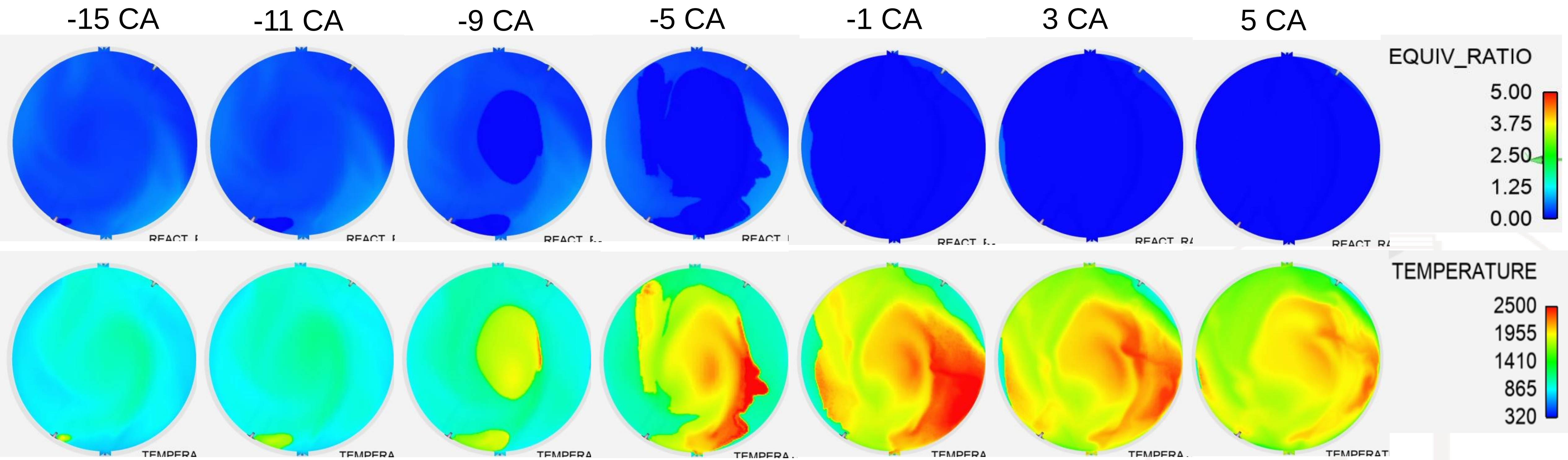
Monitor points are set to track the local mixture behavior along the periphery



Spark timing @ -10 CA

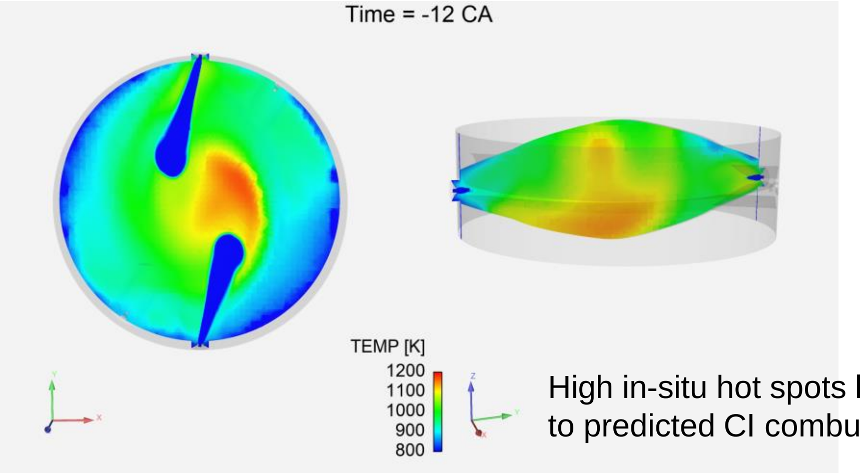
- The asymmetry between the local lambda behavior at the spark source using mapped flow field has been observed.
- With current model, CFD predicts misfire if the lambda values at both locations are above 3.0.

SI Combustion – Low Load

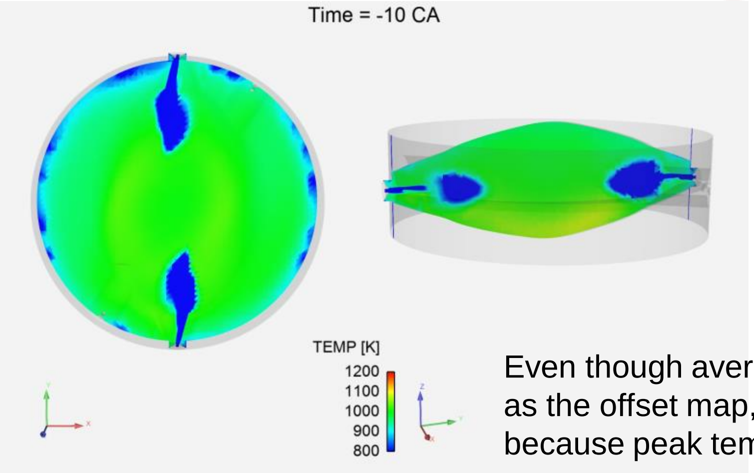


H2 CI Combustion

- Trapped temperature flow field is critical for examining the feasibility of different ignition & combustion concepts
- In diesel closed-cycle simulation, trapped temperature are often “offset” from an existing field to match the 1D trapped temperature, without necessarily running the open-cycle
- Iteration between 1D -> open-cycle -> closed-cycle is necessary to accurately predict the onset of ignition combustion



High in-situ hot spots lead to predicted CI combustion



Even though average temperature is similar as the offset map, misfire is predicted because peak temperature is lower

Injection Flow Rate Study

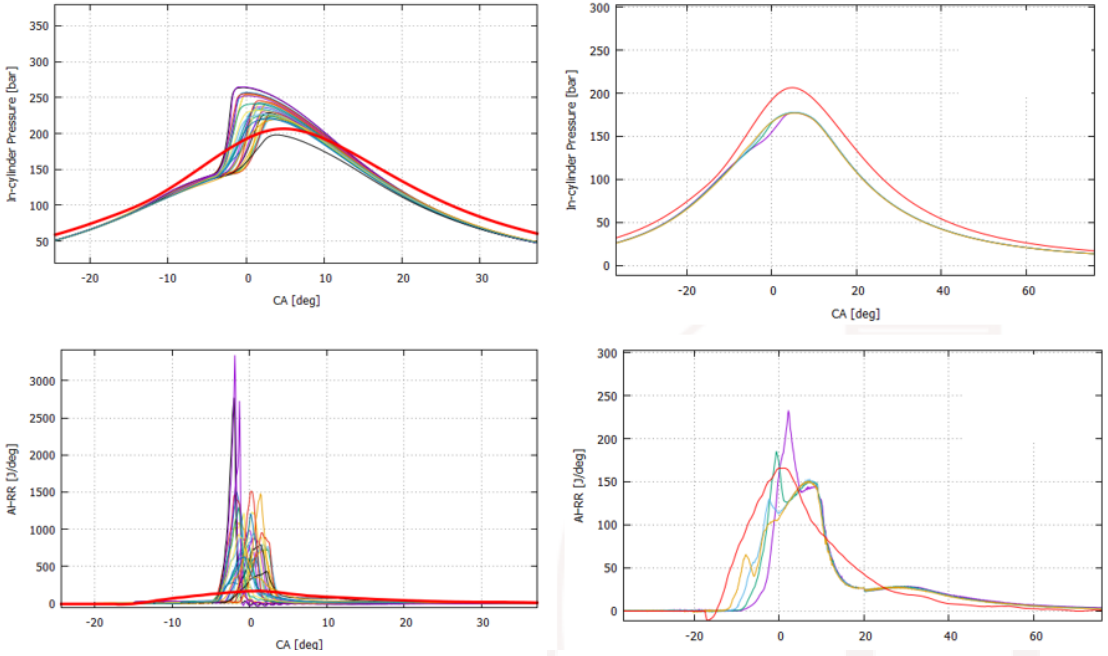
	H2				Diesel
Closed cycle ITE(%)	44.3	48.0	49.2	49.1	47.6
ahrr_ca_10(deg)	0.5	4.8	2.5	4.0	-7.3
ahrr_ca_50(deg)	4.3	7.0	4.4	5.9	2.2
ahrr_ca_90(deg)	43.5	8.5	5.4	7.1	20.8
ahrr_ca_10_90(deg)	43.0	3.7	2.9	3.1	28.1
pcp(bar)	198.9	207.4	236.5	222.1	217.4
max_prr(bar/deg)	14.5	30.1	44.8	36.3	7.5
NOx (g/kg)	48.6	52.7	86.0	69.1	20.8
Soot(g/kg)	0.0	0.0	0.0	0.0	0.154
CO(g/kg)	0.0	0.0	0.0	0.0	4.8
HC(g/kg)	0.0	0.0	0.0	0.0	0.02

→ Increasing H2 injection flow rate without pilot

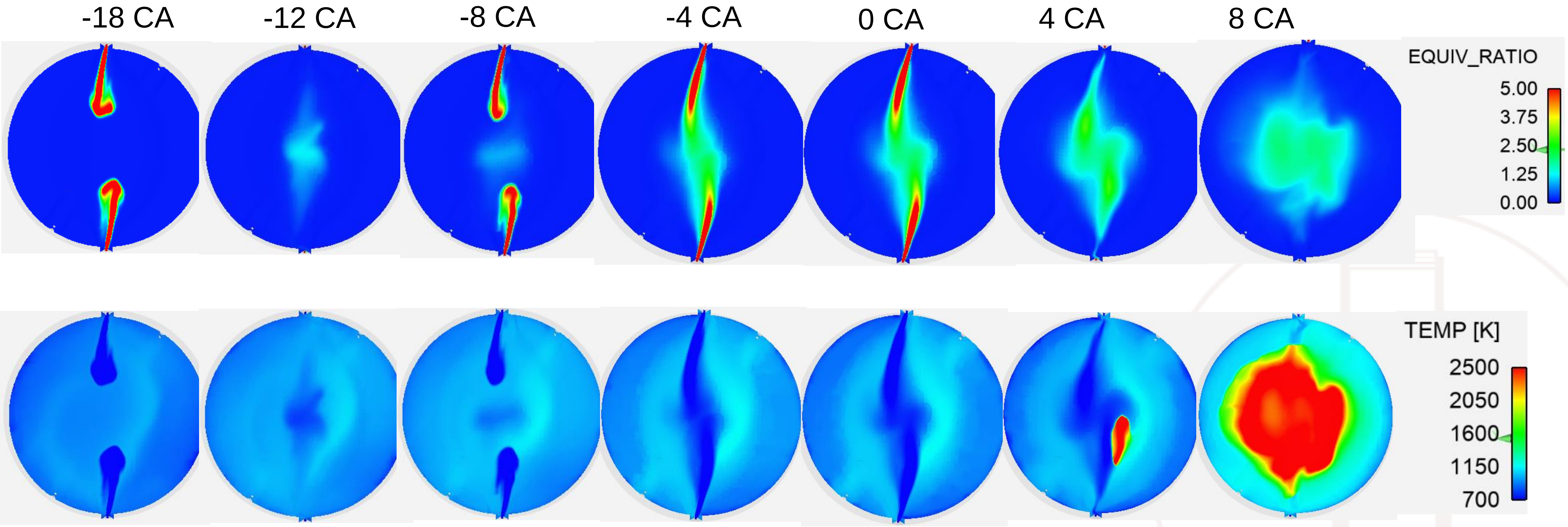
- Lack of commercially available H2 gas injectors that meet the requirements of modern IC engines is one of the major challenge for H2 CI combustion
- API has been working with supplier on the H2 injector; the study serves to provide an outlook of the performance with higher flow rate injector
- As H2 flow increase, results demonstrated that one could use more retard SOI timing to enable decent CI combustion even without pilot and surpass diesel ITE
- Maximum pressure rise rate and NOx control will be challenging without using pilot injections

DOE Study At High-Speed High Load Conditions

- Parameter examined included:
    - Pilot Injection Quantity
    - Pilot injection Timing
    - Main injection Timing
    - Trapped Temperature
    - Injection rate ramp-up (injection rise rate)
- The right combustion recipe will result in close-to-diesel engine maximum pressure rise while retaining good ITE



Pilot Assisted CI Combustion – Mid & High-Load



Summary

- Computational fluid dynamics (CFD) simulations have demonstrated the possibility of an innovative H2 dual mode combustion concept over OP2S engine, with spark-ignition (SI) employed during cold start and low-load conditions, and non-premixed compression-ignition (CI) combustion utilized at mid- and high-load conditions.
- At low-load conditions, the timing of the start of injection (SOI) is a critical factor in combustion, as early injection may cause misfire/pre-ignition while delayed injection may also result in misfires. The optimal timing and transition to CI mode need to be further explored during calibration.
- At mid- and high-load conditions, Opposed Piston Two Stroke (OP2S) Engine can overcome the high autoignition temperature of H2 by balancing the trapped temperature/trapped lambda tradeoff – elevate trapped temperature without repercussions on efficiency and emissions.
- Trapped temperature, injection rate shape ramp-up, pilot quantity and timing will all affect the efficiency as well as the maximum pressure rise rate

Ongoing Work over H2 OP2S Development

- Combustion system optimization with University of Wisconsin
  - Until now the engine is still using baseline diesel combustion system designs
  - UW Team has been developing Eulerian-Lagrangian approach for H2 injection simulation, which will make H2 combustion DOE study more streamlined
- Higher compression ratio study
  - Higher CR than diesel engine; Fully leverage the benefit of CI concept
  - Much less constraint with fuel impingement on piston walls
- Single-cylinder H2 engine testing in Argonne National Lab

“With the OP2S engine we can leverage the benefits of the OP engine with lower heat losses and with faster soot free combustion to get the most efficient carbon free H2 engine so in the end it will be an even more efficient engine that the diesel OP version”