Achates Power (API) Single Cylinder 1.6L Engine
Initial Hydrogen Test Results Report

Ref: Powertrain-24-07: Single-Cylinder Hydrogen Fuel Engine Prototype Development

This report outlines the test set up details and initial test results from API's Single Cyilnder Engine (SCE) tested at Argonne National Lab in Lemont, Illinois.

Test Setup

Achates Power's H2 1.6L OP2S single-cylinder engine (SCE) is installed at Argonne National Laboratory's (ANL) start-of-the-art testing facility. The ANL test cell features a hydrogen supply, metering, safety, and monitoring systems as well as further hydrogen-specific instrumentation. Bottled hydrogen fed to the engine is stored in high-pressure cylinders at 165 bar (2400 PSI). The hydrogen fuel flow is measured with a Coriolis meter with an accuracy of ±0.5% of the actual flow rate. An uncooled pressure transducer from AVL and a crank angle encoder with 0.5° resolution are being used to generate the in-cylinder pressure traces. Furthermore, an H-Sense mobile hydrogen analyzer from V & F with a repeatability greater than 99% related to the range was used for the measurement of unburnt H_2 emissions.

Figure 2 illustrates the hydrogen opposed-piston SCE currently undergoing testing at ANL. To address the broad flammability limits of hydrogen, an enclosure has been installed over the engine, featuring an H2 detection sensor positioned above the enclosure. Additionally, a sprinkler system has been implemented as a safety measure in the event of a fire.

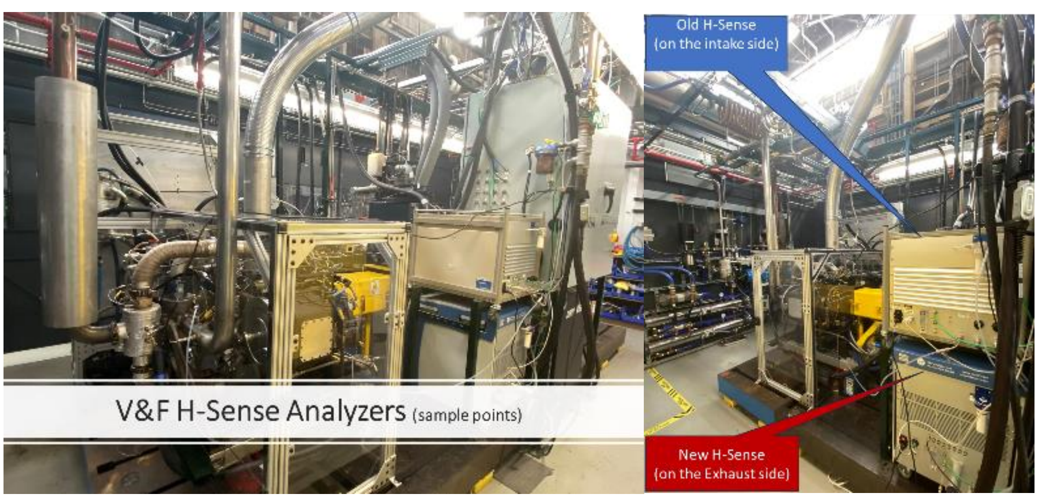


Figure 2 API H2 SCE OP engine currently being tested in ANL test cell

Test Results

The testing of the engine was conducted at ANL and this section will discuss findings from the initial stage of the tests. Figure 3 illustrates the in-cylinder pressure and AHRR at 1100 RPM, which corresponds to the peak torque speed of the engine. The engine was operated at approximately 10% load, both with and without the activation of the spark plug. Hydrogen was directly supplied from a pressurized bottle at a rail pressure of 80 bar. The start of injection (SOI) occurred at -100 crank angle degrees (CA), approximately 5 CA after the piston ring passed the ports, corresponding to full port closure. In both cases, the engine exhibited stable operation with a trapped lambda slightly above 2.0.

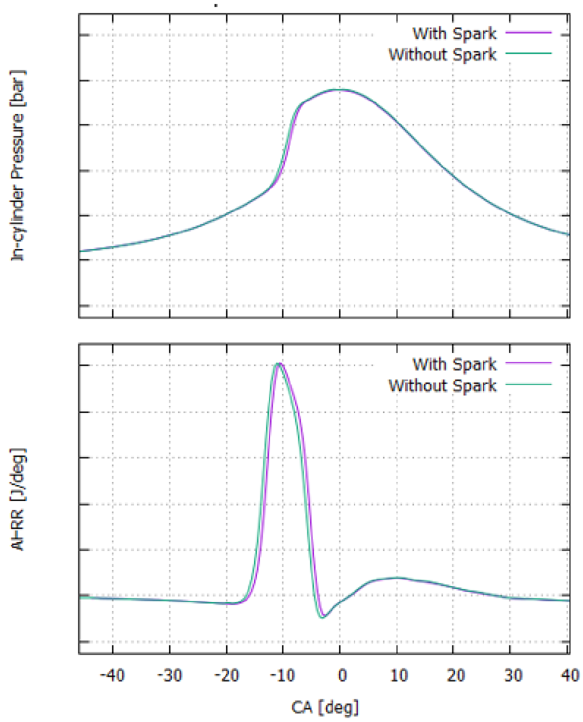


Figure 3 H2 SCE combustion at 1100 RPM, 1.7bar IMEP.

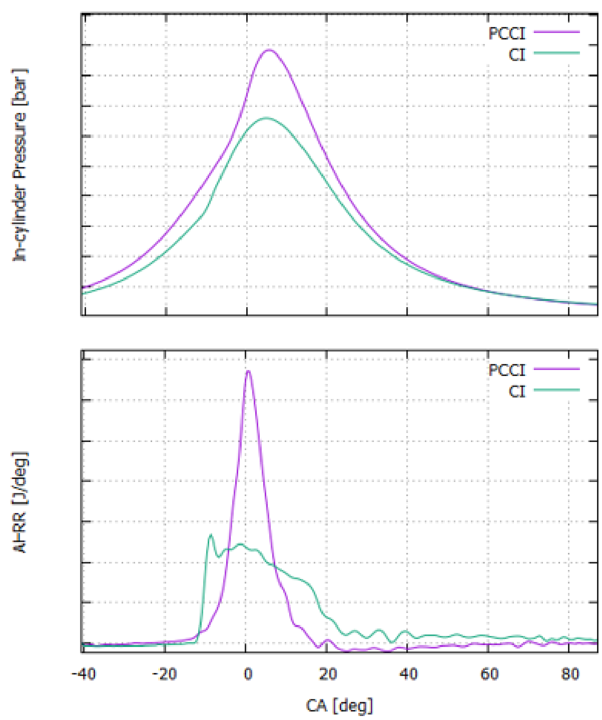


Figure 4 H2 SCE combustion at 1100 RPM, 2.8bar IMEP

Notably, it is intriguing to observe that the combustion process was minimally affected when the spark plug was deactivated. To confirm that ignition was not reliant on any hot surfaces near the spark plug, the two spark plugs were later replaced with two metal plugs. Subsequent testing confirmed that the engine continued to operate smoothly under the same conditions, thus affirming that ignition was solely attributed to PCCI.

The PCCI combustion exhibited distinctive characteristics, including a very short combustion duration and a high maximum pressure rise rate (MPRR), as evidenced in Figure 3. In both cases, the MPRR exceeds 10 bar/deg, which is much higher compared to that of diesel running at similar load conditions.

Figure 4 shows the in-cylinder pressure and AHRR at 1100RPM, 2.8bar IMEP, operated at two different combustion concepts. Again, hydrogen is directly supplied from a pressurized bottle with rail pressure of 120 bar for both cases. The trapped lambda and SOI are quite different though. In the case of non-premixed CI combustion, trapped lambda of 2.5 and SOI of -12CA has been targeted whereas trapped lambda of 3.5 and SOI of -100CA are set for PCCI.

Combustion characteristics are drastically different among the two combustion modes, as expected. The lean-burn PCCI mode, marked by extremely rapid combustion, delivered close-to-diesel thermal efficiency and low NO_x emissions. However, the high maximum pressure rise rate associated with PCCI could potentially pose challenges from both mechanical and noise, vibration, and harshness (NVH) perspectives.

Meanwhile, the non-premixed CI mode exhibited a notably prolonged combustion duration, primarily due to the low injection pressure currently deployed. While the thermal efficiency in this configuration has not yet reached the baseline established by conventional diesel engines, it is promising to observe the engine's smooth operation with non-premixed CI under low-speed, low-load conditions, with an injection pressure of only 120 bar. This feature carries important implications for enhanced transient control and smoother transitions between various combustion concepts, such as the shift from a cold-start mode to normal running conditions.

Despite operation constraints imposed by the rail pressure limit, the team explored load limits by incrementally increasing fuel amounts until the engine either became unstable or exhibited significant incomplete combustion, indicated by excessive hydrogen in the exhaust. The engine successfully operated at up to 5.4 bar IMEP, representing close to 40% load at 1600 RPM. Sweeps have been conducted over the injection SOI timing and trapped AFR, identified as two influential parameters affecting hydrogen OP engine CI combustion.

Figures 5 to 8, along with summarized values in Tables 1 and 2, showcase the calibration efforts as examples. Figure 5 illustrates the cylinder pressure and AHRR corresponding to approximately 25% load of the original engine. With the introduction of main injection, the test explores the impact of various parameters, including trapped lambda, pilot, and main ratio. The injection SOI for both pilot and main injections is maintained at the same timing, while the duration is varied to achieve different pilot-main ratios. All cases demonstrate stable CI combustion with pilot injection, with NOx levels comparable to the diesel version.

In Figure 6, the injection profile is superimposed over the AHRR highlighting the sequence of the injection events in relative to the combustion phasing. The initial spike observed in AHRR is predominantly contributed by the pilot injection, occurring immediately after the port closure. The introduction of main injection distinguishes this combustion mode from "pilot-only," as previously implemented in the 2-bar IMEP case. In previous low-load case of 2bar IMEP, a main SOI near the minimum volume would have resulted in excessive hydrogen in the exhaust and unstable running. The combination of pilot and main injection results in a combustion mode referred to as partial-premixed charge compression ignition (PCCI). In this mode, a higher pilot injection amount potentially introduces more combustion, as illustrated in Figure 6. During the test, Coefficient of Variation (COV) of IMEP and PCP are also calculated to examine the cycle variability, and misfire rate of the hydrogen combustion. The COV values are also closely monitored as the EGR is introduced. It is noteworthy that an increased pilot injection amount leads to faster combustion and improved efficiency. However, this comes at the expense of higher Maximum Pressure Rise Rate (MPRR) and higher COV suggesting a potential optimum point where the tradeoff is balanced.

As speed and load increased to 1600 RPM, 5.4 bar IMEP, the hydrogen OP engine demonstrated CI combustion even without pilot injection (Figures 7 and 8), representing “non-premixed” CI combustion. The AHRR profile exhibited a long tail, attributed to the limited injected flow rate, and prolonged injection duration. Trapped lambda appeared to be a significant factor impacting thermal efficiency and emissions, with leaner combustion leading to improved efficiency and lower NOx, CO, and HC emissions. However, lean combustion conditions also resulted in higher COV of IMEP.

Figure 9 provides a comparative analysis of the H2 OP2S engine with other diesel OP platforms, indicating that the H2 OP2S has achieved close to diesel-like efficiencies under similar trapped lambda conditions. Despite compromises on compression ratio and injection pressure, these results underscore the substantial potential of the OP engine to enhance hydrogen Internal Combustion Engine (H2ICE) efficiency compared to conventional H2ICE using spark ignition combustion. This positions the OP engine as a strong candidate for advancing hydrogen adoption in high load on and off-road applications.

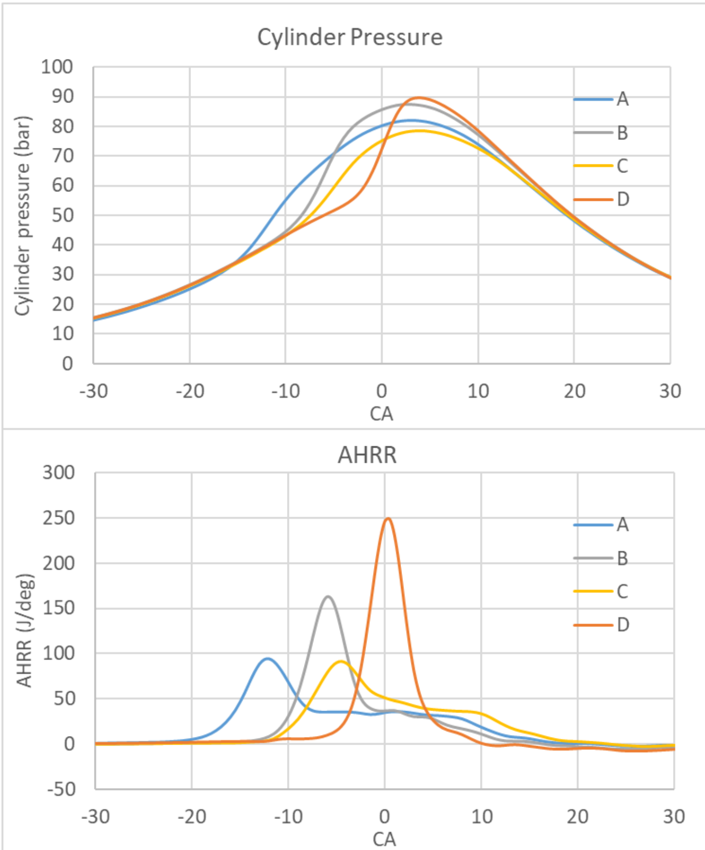


Figure 5 Cylinder Pressure and apparent heat release rate at 1400RPM, 4.3bar IMEP

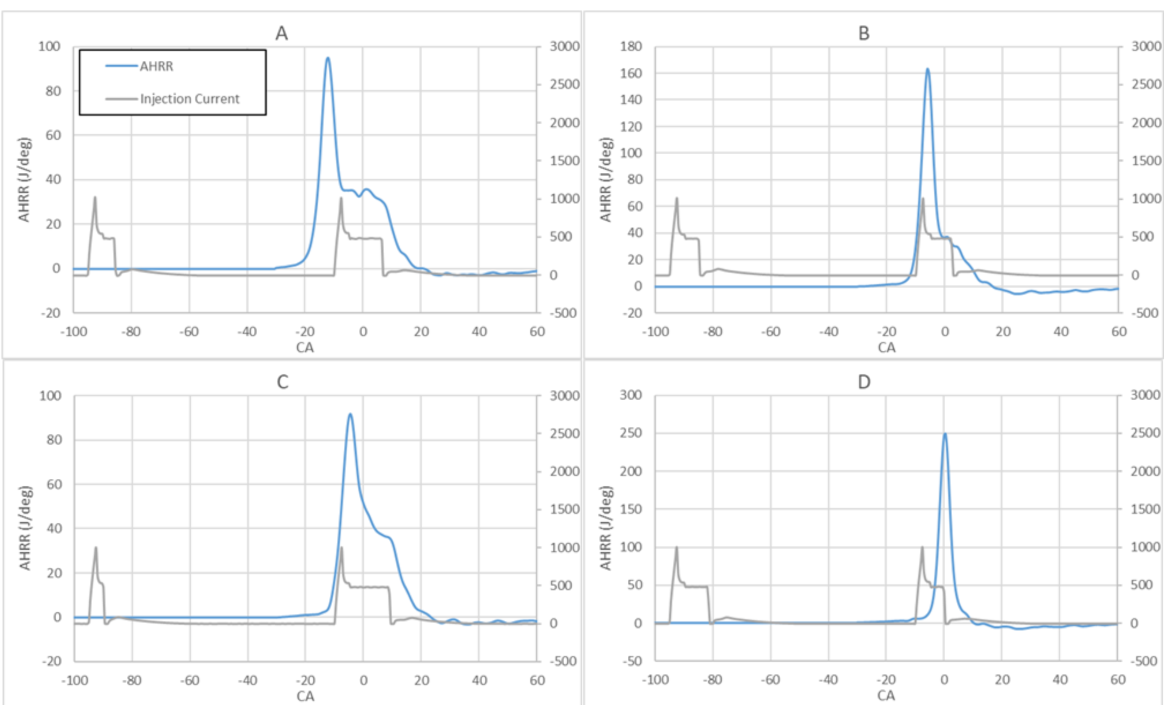
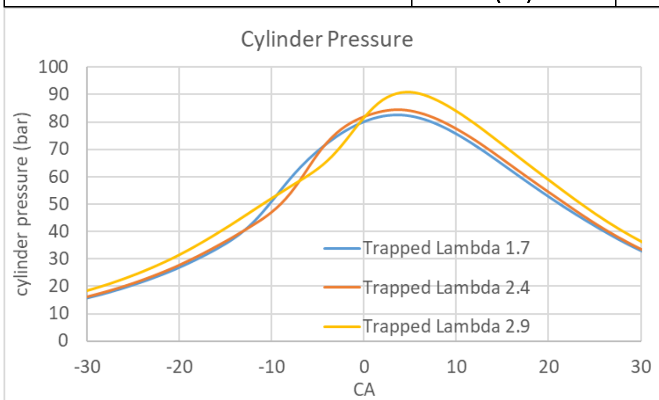


Figure 6 Apparent heat release rate overlayed with injection timing at 1400RPM, 4.3bar IMEP

Table 1 Combustion Summary at 1400RPM, 4.3 bar IMEP with different injection timing.

		A	B	C	D
Speed	(RPM)	1400	1400	1400	1400
IMEP	(bar)	4.3	4.2	4.3	4.3
Injection Pressure	(bar)	121.0	120.0	117.0	116.0
Pilot SOI	(deg aMV)	-95.0	-95.0	-95.0	-95.0
Pilot Duration	(deg)	10.0	12.0	6.0	15.0
Main SOI	(deg aMV)	-10.0	-10.0	-10.0	-10.0
Main Duration	(deg)	18.0	14.0	20.0	11.5
Trapped Lambda	(-)	2.4	3.3	3.2	3.0
EGR	(%)	0	0	0	0
Indicated Thermal Efficiency	(%)	40.6	43.9	44.4	46.1
Peak Pressure	(bar)	82.1	87.6	78.7	89.7
MPRR	(bar/deg)	4.6	6.9	4.3	8.3
CA10	(deg aMV)	-14.4	-8.5	-7.3	-2.9
CA50	(deg aMV)	-7.3	-4.7	-0.8	0.5
NOx	(g/kWh)	5.4	7.6	5.7	5.2
CO	(g/kWh)	0.039	0.018	0.024	0.017
THC	(g/kWh)	0.069	0.034	0.039	0.024
COV of IMEP	(%)	3.1	4.1	3.6	6.7
COV of PCP	(%)	1.0	1.3	1.4	1.8



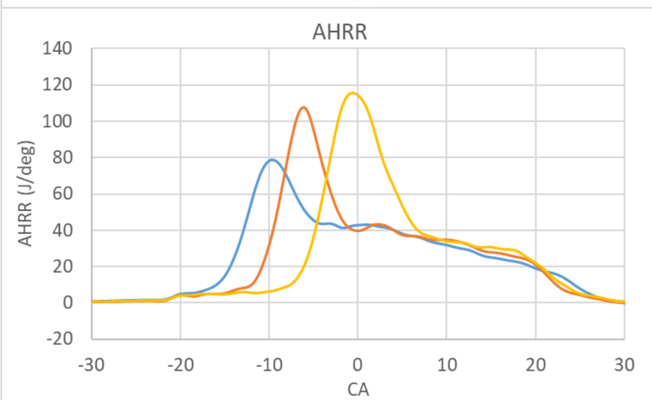


Figure 7 Cylinder Pressure and apparent heat release rate at 1600RPM, 5.4 bar IMEP

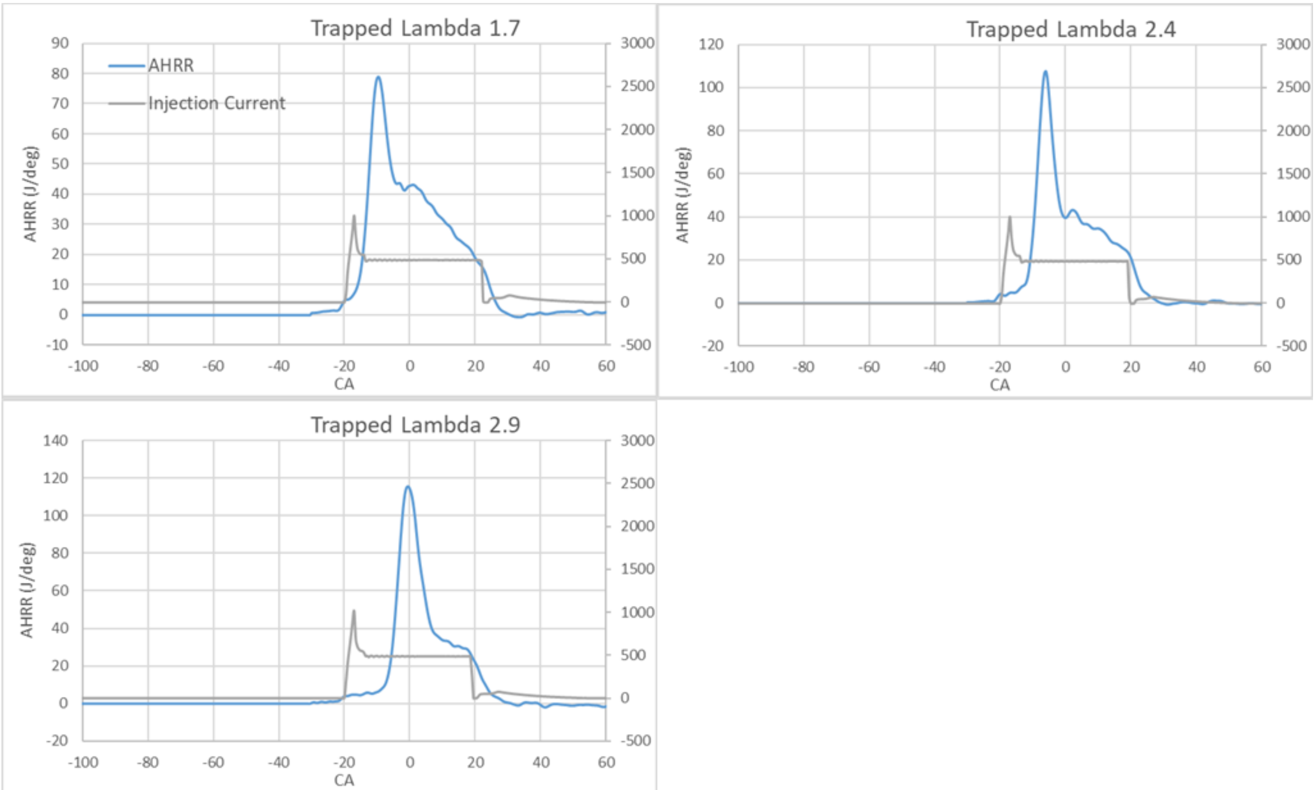


Figure 8 Apparent heat release rate overlayed with injection timing at 1600RPM, 5.4bar IMEP

Table 2 Combustion Summary at 1600RPM, 5.4 bar IMEP with trapped lambda

		λ = 1.7	λ = 2.4	λ = 2.9
Speed	(RPM)	1600	1600	1600
IMEP	(bar)	5.4	5.4	5.6
Injection Pressure	(bar)	127.0	127.0	127.0
Pilot SOI	(deg aMV)	-	-	
Pilot Duration	(deg)	-	-	
Main SOI	(deg aMV)	-20.0	-20.0	-20.0
Main Duration	(deg)	46.0	43.0	42.5
Trapped Lambda	(-)	1.7	2.4	2.9
EGR	(%)	18.7	17.5	16.2
Indicated Thermal Efficiency	(%)	41.3	45.0	47.2
Peak Pressure	(bar)	82.7	84.4	90.9
MPRR	(bar/deg)	4.2	5.0	4.3
CA10	(deg aMV)	-11.6	-8.4	-4.2
CA50	(deg aMV)	-0.4	-0.2	2.3
NOx	(g/kWh)	3.5	3.7	3.1
CO	(g/kWh)	0.16	0.06	0.05
THC	(g/kWh)	0.08	0.04	0.04
COV of IMEP	(%)	5.4	5.9	7.3
COV of PCP	(%)	1.1	0.9	2.4

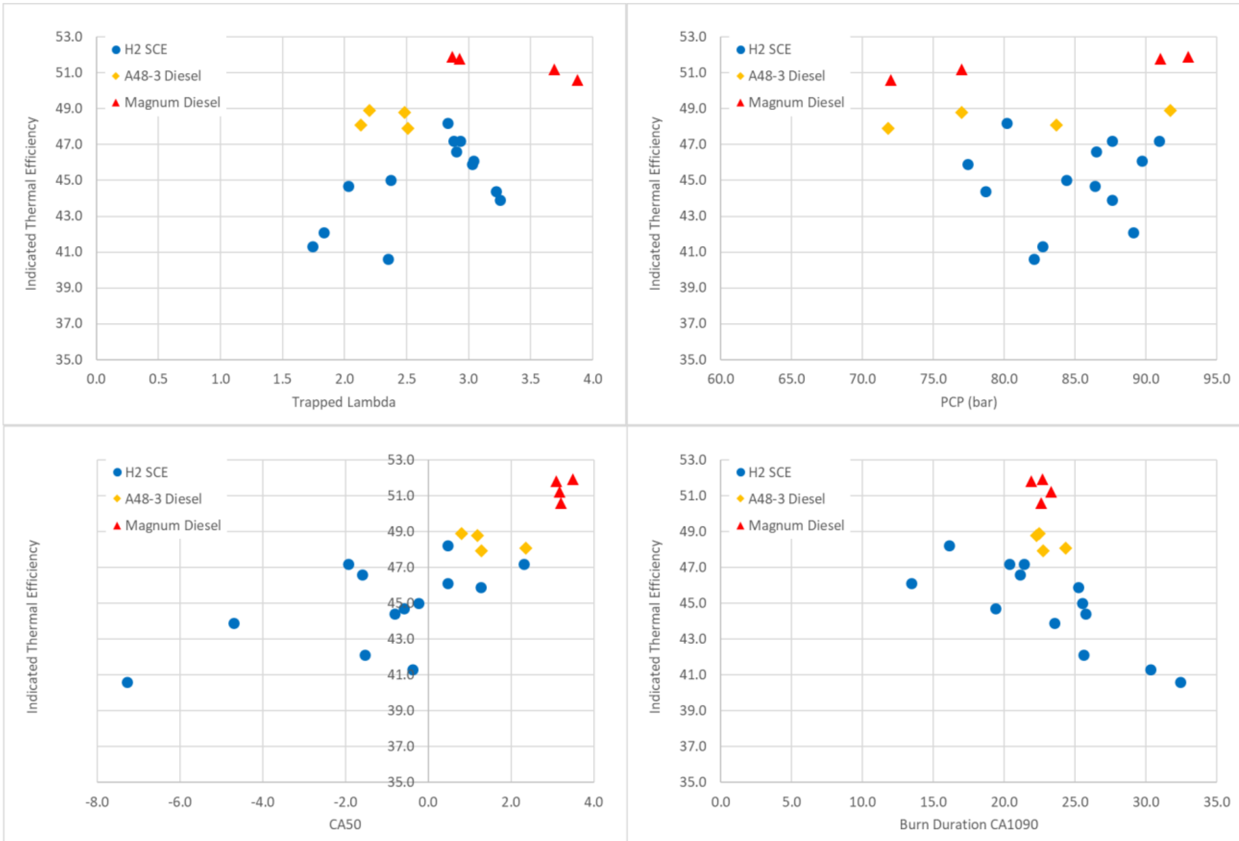


Figure 9 Comparison to diesel OP engines at similar speed/load range.

<u>Conclusion and Next Steps</u>

The operation of hydrogen internal combustion engines under both PCCI and non-premixed CI regime represents a significant stride toward fully unlocking the potential of H2ICE technology. This approach holds the promise of achieving thermal efficiency levels that are comparable to or surpassing those of conventional diesel engines, all while maintaining close-to-zero green-house gas (GHG) emissions. The potential of high thermal efficiency[1], particularly at high loads, renders H2ICE an attractive option for many heavy-duty applications in both the short and long term.

The initial testing has already showcased the remarkable capability of the H2 OP2S engine to operate in either PCCI or non-prmixed CI mode, without support from spark plugs or a diesel pilot, even under low-speed, low-load conditions. Such capability presents a unique potential to operate H2ICE under the CI concept, which has long been deemed as challenging in a four-stroke engine due to the high autoignition temperature of hydrogen, but which is necessary to optimize engine efficiency and power density. The next phase of the testing include further

[1] High efficiency is a critical factor for military vehicles to enable expanded range of operation and minimize supply chain logistics and risk.

optimize the combustion system include injectors and piston designs to fully unlock the hydrogen OP engine potential.