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# Hydrogen Opposed-Piston Engine with Direct Injection, Compression Ignition Combustion

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## Summary

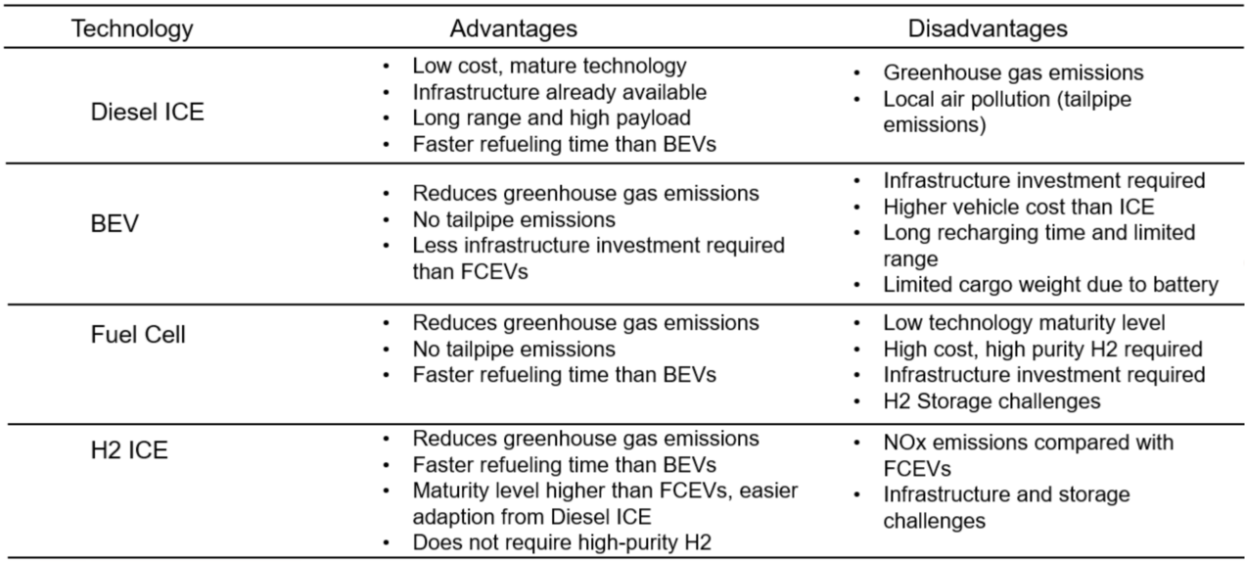
- Unique characteristics of the opposed-piston engine architecture enable efficient compression ignition across most of the operating range of the engine.
- Achates Power and Argonne National Laboratory are collaborating to develop direct injection, compression ignition on a Achates Power opposed-piston engine.
- Notably, the combustion process is nearly identical with and without operation of a spark plug, confirming that the engine is capable of efficient compression ignition.
- Two different combustion concepts were evaluated, partial-premixed compression ignition (PCCI) and non-premixed compression ignition. Thermal efficiency, NOx formation, and maximum rate of pressure rise vary between the concepts.
- The initial results show that the thermal efficiency of hydrogen combustion may match or exceed that of diesel fuel in an opposed-piston engine.
- Further research is warranted to develop and refine the hydrogen compression ignition opposed-piston engine.

## Powertrain Technology Overview

Because greenhouse gas emissions (GHGs) are considered the main cause of global climate change, governments across the globe are enacting regulations curtailing GHG. Heavy-duty commercial vehicles are one focal point of these efforts, but it is a challenging sector to decarbonize. Corporations, academia, and research labs are actively exploring and championing alternative powertrain technologies to replace the diesel internal combustion engine (ICE) in heavy-duty applications.

Table1. outlines the advantages and disadvantages associated with four distinct powertrain technologies. The diesel engine, considered as the baseline technology here, boasts a range of significant merits such as 1) It is a well-established technology with existing infrastructure and wide fuel availability. Having served as a cornerstone in transportation for decades, diesel engines have garnered a reputation for their reliability and familiarity. 2) It features high energy density, allowing for long driving ranges and heavy loads rendering them resistant to substitution in various use cases, 3) It offers a cost-effective solution, both in terms of initial acquisition cost and total ownership expense when compared to alternative technologies. This long-standing technology has afforded humanity its benefits for well over a century. Nevertheless, while the challenges of replacing diesel ICEs in many applications loom large, the imperative to address GHG emissions will lead to a gradual reduction in their market share over the long term. Apart from GHG emissions, diesel ICE also produces nitrogen oxides (NOx) and particulate matter (PM), though extensive research has yielded advanced emissions control technologies capable of mitigating these emissions.

Table 1 Advantages and Disadvantages of different technologies



| Technology | Advantages | Disadvantages |
|---|---|---|
| Diesel ICE | • Low cost, mature technology<br>• Infrastructure already available<br>• Long range and high payload<br>• Faster refueling time than BEVs | • Greenhouse gas emissions<br>• Local air pollution (tailpipe emissions) |
| BEV | • Reduces greenhouse gas emissions<br>• No tailpipe emissions<br>• Less infrastructure investment required than FCEVs | • Infrastructure investment required<br>• Higher vehicle cost than ICE<br>• Long recharging time and limited range<br>• Limited cargo weight due to battery |
| Fuel Cell | • Reduces greenhouse gas emissions<br>• No tailpipe emissions<br>• Faster refueling time than BEVs | • Low technology maturity level<br>• High cost, high purity H2 required<br>• Infrastructure investment required<br>• H2 Storage challenges |
| H2 ICE | • Reduces greenhouse gas emissions<br>• Faster refueling time than BEVs<br>• Maturity level higher than FCEVs, easier adaption from Diesel ICE<br>• Does not require high-purity H2 | • NOx emissions compared with FCEVs<br>• Infrastructure and storage challenges |

Meanwhile, battery electric vehicles produce no tailpipe emissions, offering a significant reduction in local air pollution. Electric motors, complemented by regenerative braking technology, are usually highly efficient and have quiet operation. Although BEVs lag behind diesel in terms of infrastructure availability, it has lower storage and logistics issues than hydrogen fuel, used in either a fuel cell or hydrogen ICE. Nonetheless, BEVs contend with several inherent disadvantages at the moment including limited range, long charging time, lack of charging infrastructure, reduced payload capacity due to large battery packs, etc.

The fuel cell vehicle emerges as another technology that produces zero tailpipe emissions, surpassing BEVs in terms of range and refueling time, rendering it relatively well-suited for heavy-duty applications. However, the hydrogen infrastructure for fuel cell vehicles lags behind even that of electric charging, with the challenge of high-density hydrogen storage remaining a prominent obstacle. Furthermore, the high costs and complexity of fuel cell systems have been identified as limiting factors for widespread adoption.

The hydrogen ICE shares similarities with fuel cell technology in using hydrogen as an energy source, thus eliminating GHG emissions. (albeit hydrogen ICE still releases a minute amount of $CO_2$ from lubrication oil). Both technologies face similar challenges in terms of hydrogen storage, logistics, and infrastructure. Nevertheless, certain distinctions are noteworthy. Hydrogen combustion still generates nitrogen oxides that necessitate mitigation efforts. Meanwhile, hydrogen ICE does not require high-grade hydrogen, its robustness to impurities makes it an attractive solution for the transportation industry. Furthermore, the efficiency profiles are quite different, with fuel cells exhibiting superior efficiency at part load while H2 ICEs operate most efficiently at their designed speed and under high load. Importantly, the prime difference arises from the technological maturity level as ICEs have been in operation for decades, supported by extensive service networks. The transition to hydrogen engine drivetrains involves familiar components and technologies, making it a more comfortable solution from the perspective of vehicle manufacturers and fleet operators.

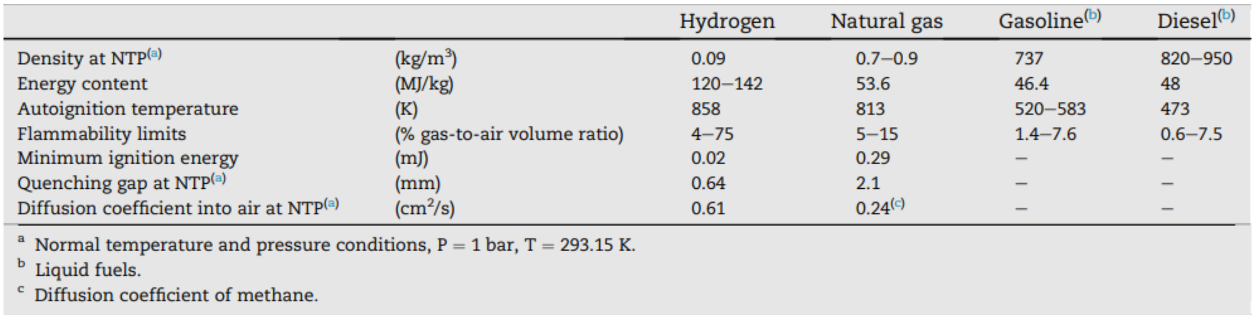
**Hydrogen Combustion Concept**

Hydrogen exhibits distinct characteristics in comparison to conventional fuels such as gasoline. It possesses a lower calorific value of 120 MJ/kg and a stoichiometric air-fuel ratio of 34.3. Notably, hydrogen boasts a broader flammability range, a reduced ignition energy requirement, and significantly faster laminar flame speed. These properties have long been associated with knocking and pre-ignition issues experienced in hydrogen ICEs. On the other hand, hydrogen's autoignition temperature is markedly higher in contrast to diesel fuel (585°C as opposed to 225°C), rendering compression-ignition combustion a challenging task.

Various hydrogen engine combustion concepts have been explored for commercial applications, as summarized in Table. 2. Among these concepts, the multi-point injection (MPI) or port fuel injection (PFI) involves the least conversion effort from existing hardware, leading to a series of recent industry demonstration projects. In this approach, achieving ultra-low $NO_x$ is feasible with proper mixture formation and lean combustion. However, the risk of backfire and preignition tendencies pose a limit on break mean effective pressure and therefore efficiency, making it unsuitable for heavy-duty applications.

Low-pressure direct injection addresses the risk of backfire yet brings the challenges to air-fuel mixing. The pre-ignition issues may still persist depending on the compression ratio and specific hardware design. In both cases, the thermal efficiency remains suboptimal due to the limited compression ratio.

Table 2 Fuel properties (Dimitrious et al. 2017)



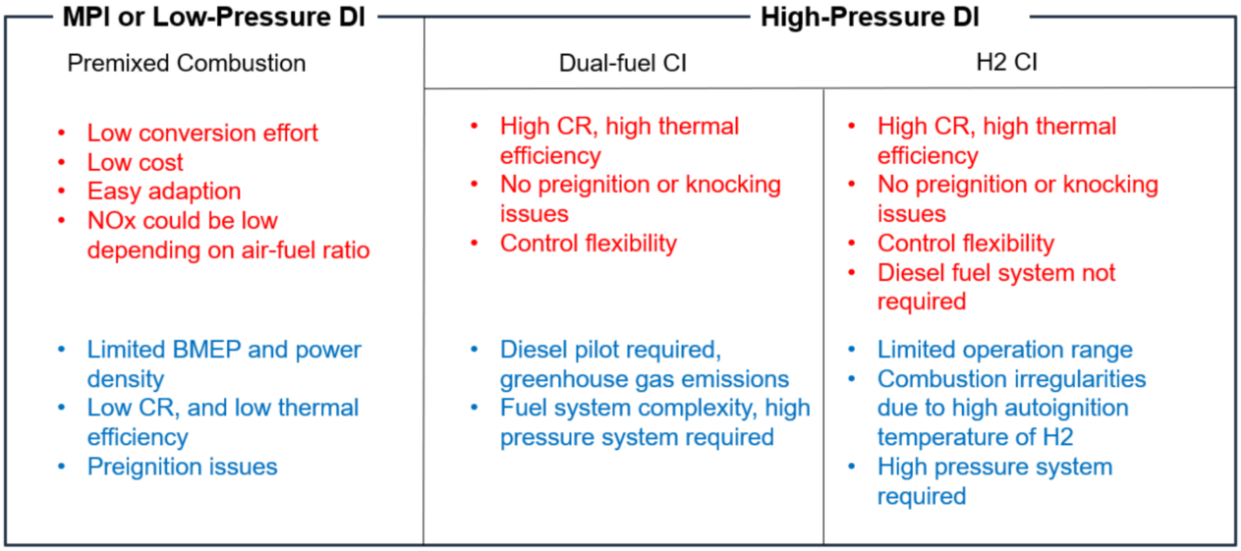
| | | Hydrogen | Natural gas | Gasoline[(b)] | Diesel[(b)] |
|---|---|---|---|---|---|
| Density at NTP[(a)] | ($kg/m^3$) | 0.09 | 0.7–0.9 | 737 | 820–950 |
| Energy content | (MJ/kg) | 120–142 | 53.6 | 46.4 | 48 |
| Autoignition temperature | (K) | 858 | 813 | 520–583 | 473 |
| Flammability limits | (% gas-to-air volume ratio) | 4–75 | 5–15 | 1.4–7.6 | 0.6–7.5 |
| Minimum ignition energy | (mJ) | 0.02 | 0.29 | – | – |
| Quenching gap at NTP[(a)] | (mm) | 0.64 | 2.1 | – | – |
| Diffusion coefficient into air at NTP[(a)] | ($cm^2/s$) | 0.61 | 0.24[(c)] | – | – |

[a] Normal temperature and pressure conditions, P = 1 bar, T = 293.15 K.
[b] Liquid fuels.
[c] Diffusion coefficient of methane.

The idea of using hydrogen in a high-efficiency, compression ignition (CI) engine has been pursued for a long time. The efforts encompass various combustion concepts such as spark-assisted H2 CI combustion, glow plug-assisted CI combustion, dual-fuel CI combustion, and H2 CI combustion in a double compression expansion engine. Non-premixed hydrogen compression ignition offers several advantages over premixed combustion, including the mitigation of knocking and preignition risks, higher (diesel-like) thermal efficiency, and increased power density compared to PFI concepts. Late injection of hydrogen also eliminates backfire issues and reduces the risk of hydrogen leakage into crankcases. However, the main challenge of hydrogen compression ignition is its limited operating range due to hydrogen's resistance to autoignition as described previously. Another hurdle is the requirement of high-pressure injection systems, including dedicated high-pressure, hydrogen-compatible gaseous injectors, which are still in the early stages of development in the industry.

Among the mentioned hydrogen compression ignition concepts, the dual-fuel approach using diesel as a pilot fuel to assist ignition has been considered a pragmatic way to transition existing diesel engines to future hydrogen compression ignition engines. This concept is particularly appealing for large engines, many of which have already been converted to run on dual fuels, such as natural gas and diesel. Competitive thermal efficiency figures have been posted in a few recent studies using hydrogen high-pressure direct injection (HPDI) injectors, indicating the potential of this technology. However, the drawback is that diesel usage, typically ranging from approximately 3% to 10% of the energy ratio depending on load, results in non-negligible greenhouse gas emissions. Additionally, the cost and complexity associated with managing two fuel systems present challenges for the widespread adoption of this technology.

Table3 Different H2 Combustion Concepts



| **MPI or Low-Pressure DI** | **High-Pressure DI** | |
|---|---|---|
| Premixed Combustion | Dual-fuel CI | H2 CI |
| • Low conversion effort<br>• Low cost<br>• Easy adaption<br>• NOx could be low depending on air-fuel ratio | • High CR, high thermal efficiency<br>• No preignition or knocking issues<br>• Control flexibility | • High CR, high thermal efficiency<br>• No preignition or knocking issues<br>• Control flexibility<br>• Diesel fuel system not required |
| • Limited BMEP and power density<br>• Low CR, and low thermal efficiency<br>• Preignition issues | • Diesel pilot required, greenhouse gas emissions<br>• Fuel system complexity, high pressure system required | • Limited operation range<br>• Combustion irregularities due to high autoignition temperature of H2<br>• High pressure system required |

**Achates Power H2 Direct Injection, Compression Ignition Opposed-Piston Two-Stroke (OP2S) Engine**

Achates Power Inc., driven by the challenges faced in the realm of hydrogen CI engines, has committed to the development of a hydrogen OP2S engine with testing support from Argonne National Laboratory. This innovative engine aims to achieve diesel-like thermal efficiency and power density while operating exclusively on hydrogen. The uni-flow scavenging design inherent to the opposed-piston engine presents a unique advantage over its four-stroke counterparts, primarily in its ability to control trapping conditions upon port closure (equivalent to valve closure in a four-stroke engine).

A pivotal limitation faced by conventional engines adopting hydrogen CI combustion pertains to their operational range. Specifically, it is very difficult to maintain adequate trapped temperatures at partial loads (since nearly all the hot residual gas is exhausted as a free charge of air is inducted), resulting in insufficient cylinder temperatures for hydrogen autoignition. In contrast, the OP engine governs scavenging by leveraging the delta pressure between intake and exhaust, affording it a unique capability to dynamically manage the scavenging ratio. This feature empowers the H2 OP2S with great flexibility to control the portion of retained residual gas and therefore the trapped temperature. This feature enables efficient non-premixed compression ignition to operate stably across a significantly wider range, resolving one of the core challenges faced by hydrogen CI combustion.

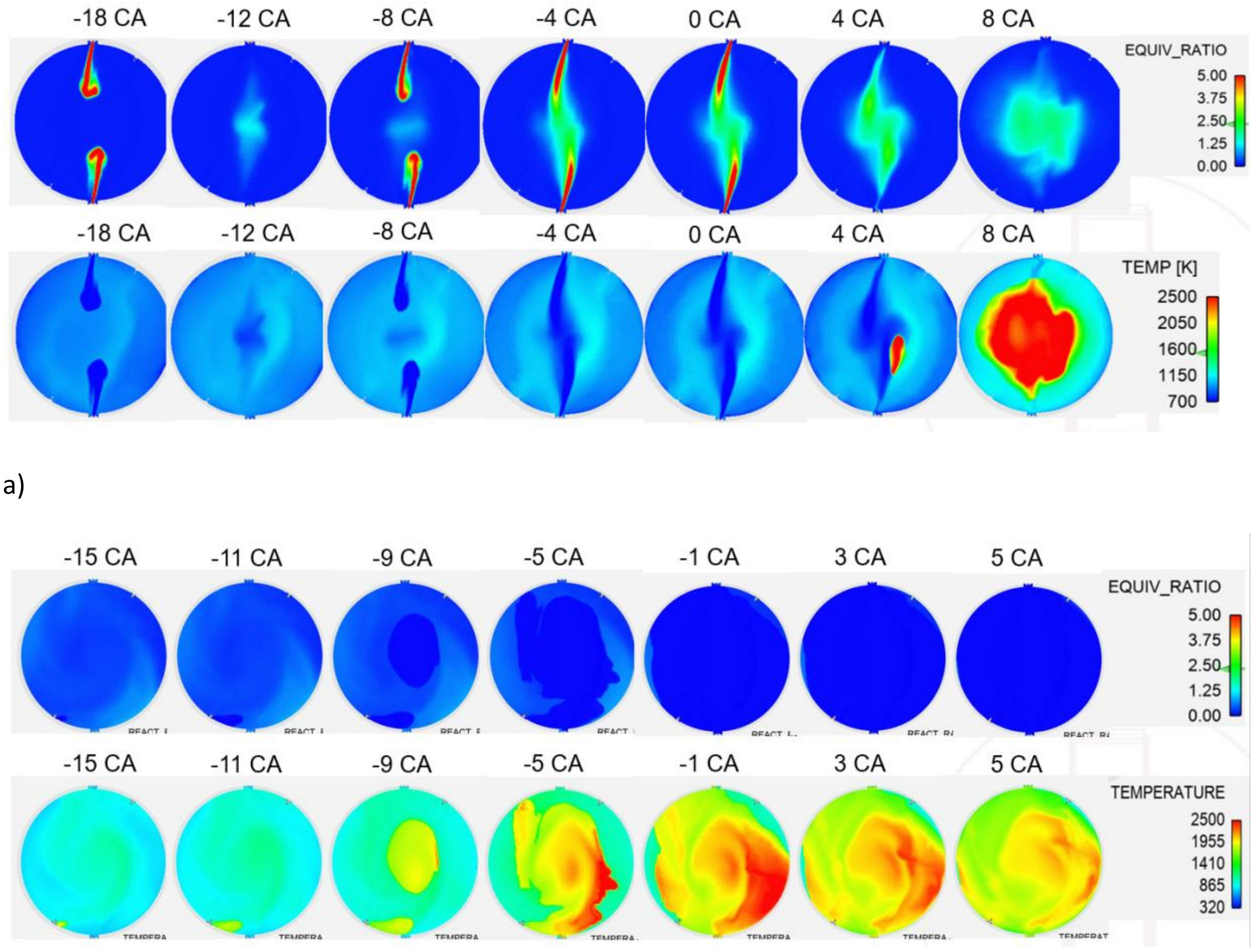


Figure 1. H2 OP2S Combustion Concept. a) Non-Premixed CI, b) Partial-Premixed CI

Figure 1 provides a visual representation of two combustion concepts that were initially formulated for the H2 OP2S, based on CFD predictions. These combustion concepts are tailored for different operating conditions across the speed/load map.

In the compression ignition concepts, which cover the majority of the engine's speed and load range, the start of injection (SOI) occurs late in the compression stroke, similar to conventional diesel engines. Gaseous fuel plumes are induced to swirl within the combustion chamber by the in-cylinder charge motion. The leading edge of the flame auto-ignites following a specific ignition delay, subsequently initiating combustion throughout the entire jet plume. Importantly, both the ignition delays and the combustion characteristics are strongly dependent on the in-situ temperature within the chamber.

Conversely, partial-premixed charge compression ignition (PCCI) concepts are devised for idle and low-load operating conditions, resembling the successful Gasoline Compression Ignition (GCI) concept demonstrated previously on the opposed-piston engine. In the context of PCCI, early injection, typically occurring around the time of port closure (~-100 crank angle degrees), is employed. This early injection strategy results in the formulation of a stratified fuel-air mixture toward the end of the compression stroke. The fuel mixture ignites as a result of temperature rise, with the flame propagating outward from ignition nuclei within the mixture.

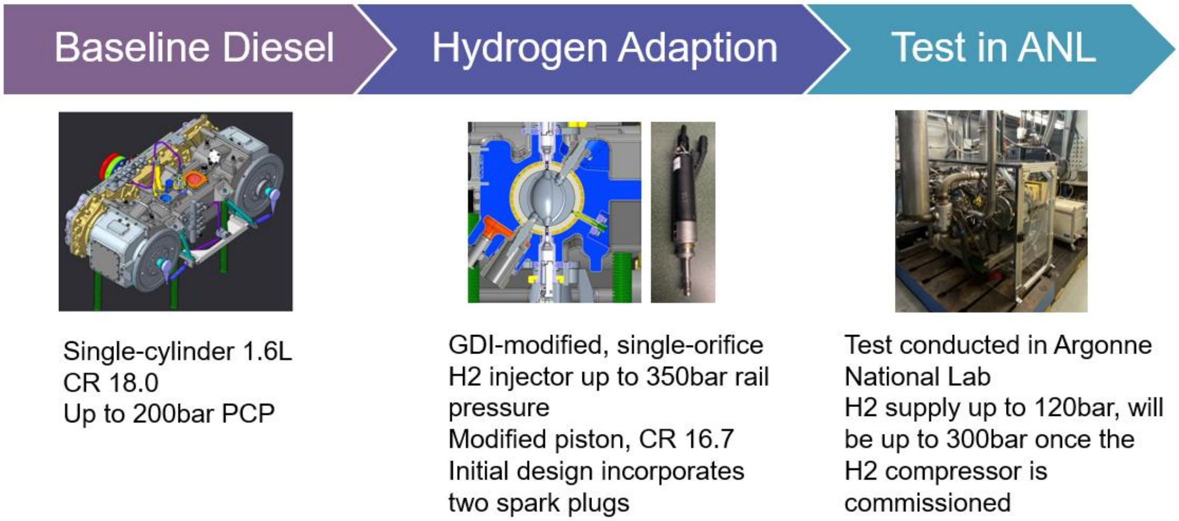
Figure 2 elucidates Achates Power's approach in the development of the H2 OP2S engine. The prototype research engine employed for this endeavor is adapted from an existing 1.6-liter single-cylinder diesel engine which features a compression ratio of 18.0 and a peak cylinder pressure (PCP) limit of up to 200 bar.

The key modifications include the replacement of the two conventional side-wall-mounted diesel injectors with two single-orifice H2 injectors modified from gasoline direct injection (GDI) injectors, capable of delivering rail pressures up to 350 bar. The pistons have been modified as well, involving the accommodation of GDI injector installation, alongside the integration of two spark plugs. This piston modification results in a trapped compression ratio of 16.7. The spark plugs are employed primarily to address cold start conditions and assist partial-premixed compression ignition (PCCI) combustion if needed.

Additionally, the engine incorporates two air plenums, serving air delivery into the combustion chamber and regulating pressure differentials within the system. An EGR system is also implemented in the test cell. These meticulous modifications collectively form the foundation for the development of the H2 OP2S engine.

## Experiment Setup

The H2 OP2S single-cylinder engine is installed inside Argonne National Laboratory’s start-of-the-art facility. The facility 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 was 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 were 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.



Single-cylinder 1.6L
CR 18.0
Up to 200bar PCP

GDI-modified, single-orifice H2 injector up to 350bar rail pressure
Modified piston, CR 16.7
Initial design incorporates two spark plugs

Test conducted in Argonne National Lab
H2 supply up to 120bar, will be up to 300bar once the H2 compressor is commissioned

Figure 2 Achates Power H2 SCE Development

**Initial Testing Results**

The testing of the engine was conducted at the Argonne National Laboratory, 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.

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.

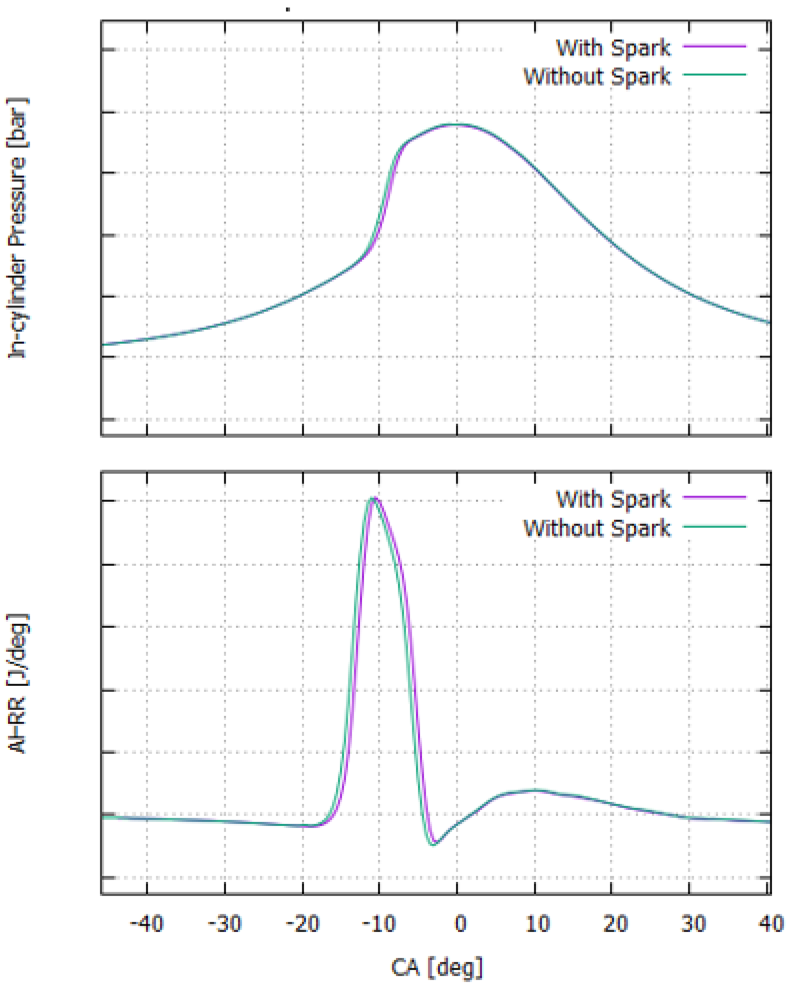


Figure 3 H2 SCE combustion at 1100 RPM, 10% load. Rail Pressure 80bar, SOI: -100CA

Figure 4 shows the in-cylinder pressure and AHRR at 1100RPM, 25% load, 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 concepts, as expected. The lean-burn PCCI concept, 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.

Conversely, the non-premixed CI concept 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.

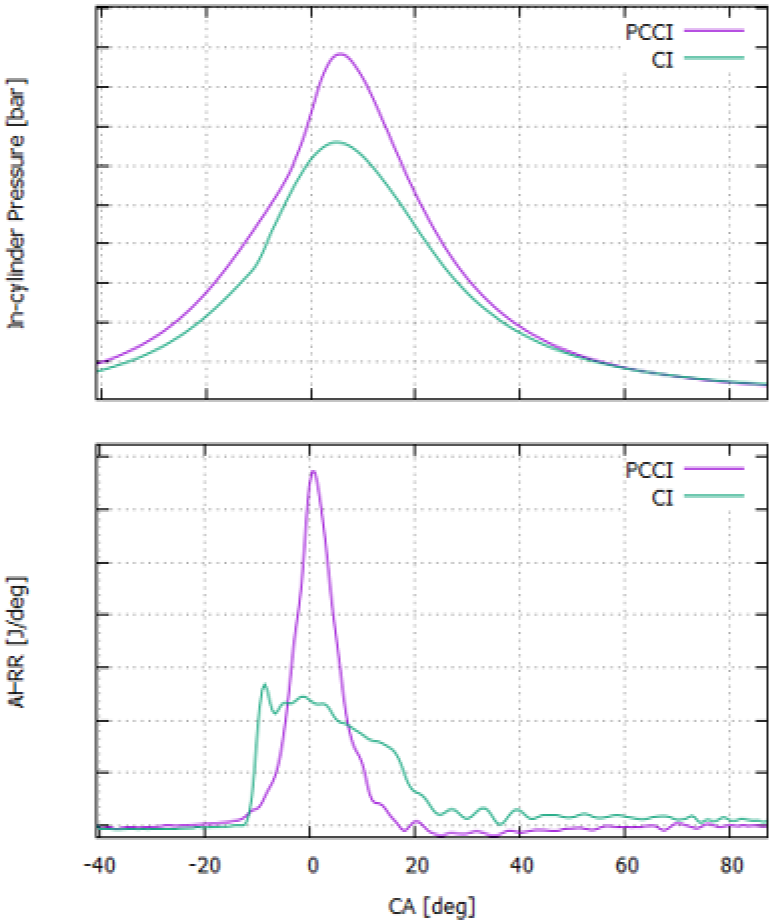


Figure 4 H2 SCE combustion at 1100 RPM, 25% load. Rail pressure 120bar

**Conclusion and Next Steps**

The operation of hydrogen internal combustion engines under the 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 greenhouse 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 a non-premixed compression ignition (CI) or partial-premixed compression ignition (PCCI) 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.

As the next step in the development process, the team will explore the combustion performance of the engine by implementing higher injection pressures, with the introduction of a hydrogen compressor in the test cell. This endeavor will be particularly intriguing as it seeks to uncover the operational boundaries of the engine, including:

- Identifying the lowest injection pressure that can still deliver efficiency levels comparable to diesel engines.
- Determining the conditions under which non-premixed CI is no longer feasible.
- Assessing the engine's cold-start capability in the absence of spark-plug assistance.

These investigations represent crucial steps in advancing the understanding and potential of hydrogen combustion technology, paving the way for more sustainable and efficient powertrain solutions powered by hydrogen.

*For more information about Achates Power contact*
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[1] High efficiency is a critical factor for heavy-duty commercial vehicles. It is even more critical when using more expensive fuels. A highly efficient hydrogen internal combustion engine may be an essential step in the transition to a hydrogen economy as it enables cost-effective, zero carbon transportation.