# $H_2$-StarFire Engine with built-in Hydrogen-Oxygen electrolyzer: An Innovative technology set to transform the energy industry by using hydrogen on the fly

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## ABSTRACT

As climate change intensifies, the demand for carbon-neutral energy solutions in transportation and power generation has become critical. Hydrogen, known for its high energy density and clean combustion, is a promising alternative to fossil fuels. However, conventional hydrogen production methods like steam methane reforming contribute to greenhouse gas emissions, while water electrolysis, a cleaner method, faces challenges in efficiency and cost. This paper introduces the $H_2$-StarFire engine with an integrated electrolyzer from Astron Aerospace, a cutting-edge technology that generates hydrogen on demand from water using plasma electrolysis. Unlike traditional engines, this compact rotary engine enhances efficiency and performance while reducing environmental impact. By producing hydrogen on the fly, the $H_2$-StarFire engine dramatically reduces the need for external hydrogen supply, making it a sustainable solution for heavy-duty applications. With its unique design, high power-to-weight ratio, and minimal maintenance requirements, the $H_2$-StarFire engine has the potential to revolutionize the transportation and power generation sectors, paving the way for a sustainable future.

## Introduction:

As the global community faces the rising threats of climate change, the necessity for carbon-neutral combustion engines in transportation or power generation has never been more critical. Traditional fossil fuels, while inefficient and widely used, contribute significantly to greenhouse gas emissions, causing environmental degradation. To mitigate this, the need for alternative energy sources that produce zero carbon emissions is of the greatest importance. Among these alternatives, hydrogen stands out as a promising solution due to its high energy density and clean combustion properties. Hydrogen can be produced through various methods like steam methane reforming (SMR) being the most prevalent. SMR involves reacting methane with steam to produce hydrogen and carbon oxides at high temperatures by burning fossil fuels[1]. To achieve carbon-free hydrogen, production methods, such as water electrolysis, are essential. Electrolysis involves splitting water into hydrogen and oxygen using electricity, ideally sourced from renewable energy[2]. Despite its potential, green hydrogen production faces several challenges. The efficiency of electrolysis depends on expensive catalysts like platinum, which can degrade over time. Additionally, the significant electricity required must come from intermittent renewable sources like wind or solar power. Hence, we need a solution that can effectively resolve the issues related to hydrogen production and utilization.

## Problem Statement:

Historically, gasoline and diesel combustion engines have dominated the transportation sector. In the past decade, lithium-based battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs) have emerged as alternatives. However, these technologies present their own hurdles as lithium is a finite resource, and its extraction and processing are costly and environmentally damaging. Hydrogen fuel cells, while promising, have lower energy efficiency,

Aggregation within the fuel cell itself from cross-contamination of environment, higher costs, and face challenges in pure hydrogen production, storage, and transportation. Conventional internal combustion like gasoline and diesel engines emits harmful pollutants and deteriorates air quality. Additionally, the efficiency of gasoline engines is limited by factors such as narrow air-fuel ratio ranges, high ignition energy requirements, and slower flame propagation, leading to higher fuel consumption and lower overall performance[3].

**Proposed Solution:**

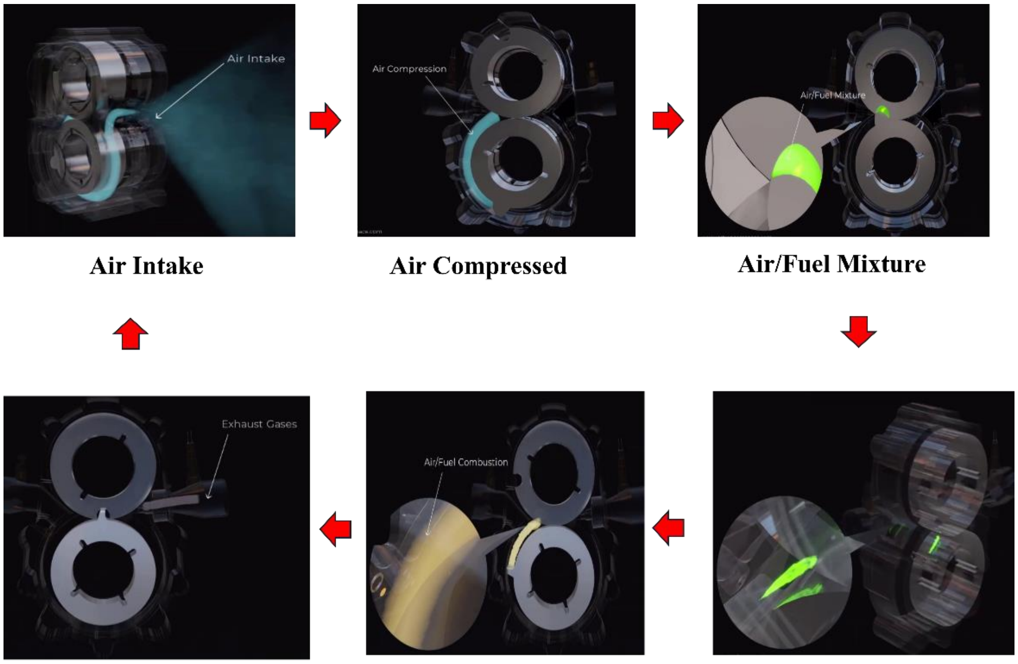
To address these issues, we need an alternative fuel source compatible with conventional combustion engines that produces no carbon footprint. Hence, hydrogen combustion engines present a viable solution to the environmental and efficiency challenges posed by traditional gasoline engines as the primary emission from hydrogen combustion is water ($H_2O$), making it a much cleaner alternative. They operate efficiently over a wide range of air-fuel ratios and have lower ignition energy requirements, faster flame propagation, and higher auto-ignition temperatures. Additionally, their high diffusivity and low quenching distance ensure more complete and efficient combustion, resulting in better fuel economy and higher performance[4]. Hence, there is a growing interest in integrating hydrogen into combustion engines, particularly for heavy-duty applications. Companies like Toyota and Volkswagen are exploring hydrogen combustion engines for trucks, marine vessels, and other large-scale power equipment.

Astron Aerospace took the initiative to transform the transportation and power generation industries with groundbreaking technology. $H_2$-Starfire engine marks a major advancement in engine design, as it combines the compactness of a traditional rotary engine with the better efficiency than a gas turbine engine. It features two pairs of rotors, blue for intake and compression, and red for combustion and exhaust. This new engine completely departs from the conventional piston engine design, incorporating neither pistons nor the Wankel engine's "triangle" configuration. It also eliminates the need for edge or Apex sealers, gaskets, and pads, thus preventing technical fluid leaks during assembly.

The $H_2$-StarFire engine is a groundbreaking advancement from the previous $H_2$-StarFire without electrolyzer model. Unlike $H_2$-StarFire without electrolyzer, which requires hydrogen fuel for each cycle, the $H_2$-StarFire Engine with electrolyzer incorporates innovative technology that generates hydrogen fuel on the fly using a static/plasma electrolyzer during operation. This cutting-edge approach not only enhances efficiency but also establishes the $H_2$-StarFire Engine as a sustainable and eco-friendly choice for the future.

**Working of the $H_2$-StarFire Engine without electrolyzer:**

In the **$H_2$-StarFire without electrolyzer**, during the first stage- Air is drawn in through intake plenum and compressed by the blue rotors then mixed with fuel in the pre-chamber assembly and ignition is initiated in the pre-chamber and combustion side rotor (red colored). This burning mixture proceeds towards/through the combustion chamber (red rotor), where the expanding flue gases drive the rotor to generate mechanical power to the output shaft, finally leaving the engine through the exhaust side as shown in Figure 1.



**Air Intake** **Air Compressed** **Air/Fuel Mixture**

**Exhaust Gases** **Air/Fuel Combustion** **Air/Fuel Ignition Starts**

**Figure 1:** Different Stages of operation in $H_2$-StarFire without electrolyzer.The image below showcasing the physical build of the $H_2$-StarFire powered by hydrogen. The through-hole indicated demonstrates how the engine manages its thermal signature without the need for separate liquid cooling, thereby enhancing overall efficiency.

**Figure 2:** A Live Demonstration of the $H_2$-StarFire Engine without electrolyzer (Check Astron Aerospace website for reference).

This groundbreaking engine technology is designed to usher in a greener and more sustainable future. Astron's innovative solutions are set to transform the way heavy-duty applications are powered, ranging from municipal generators to heavy-duty commercial vehicles, marine industry vessels, aerospace industry systems, and agricultural machinery.

Astron Aerospace team have devised a novel methodology to mitigate common anticipated challenges, including:

- Leakage throughout compression, power, and expansion strokes,
- Progressive component wear and frictional losses.

This innovative approach has significantly enhanced the overall efficiency of the engine.

Here are some key benefits of $H_2$-StarFire:

- Unprecedented Efficiency
- Pioneering HCCI Combustion Technology
- Versatile Multi-Fuel Compatibility
- Unmatched Power-to-Weight Ratio
- Adaptable Power Output for Various Heavy-Duty Applications
- Compact and Space-Efficient Design
- Minimal Mechanical Frictional Losses, reducing lubrication needs to only bearings and timing gears, unlike traditional internal combustion engines.
- Highly Effective Thermal Loss Management
- Streamlined Fuel Injection, leveraging pressure dynamics of incoming flow
- Outstanding Reliability
- Low Service and Maintenance Requirements (fewer than 100 components)
- Dramatically minimises the need for hydrogen transportation and storage

**How the new $H_2$-StarFire Engine with Electrolyzer Solves the Problems and Sets a New Standard:**

The $H_2$-StarFire without electrolyzer is designed to utilize Hydrogen as the fuel, but the new model of $H_2$-StarFire Engine with electrolyzer is projected to produce Hydrogen on the fly from Water by incorporating innovative technology like Static Plasma Electrolysis which utilizes Electrostatic discharge plasma to separate Hydrogen and Oxygen from steam generated from water.

**Working of the new $H_2$-StarFire Engine with electrolyzer:**

During the start-up of the **$H_2$-StarFire engine with electrolyzer**, the ambient air is taken into the multi-stage true split cycle rotary engine where it is compressed to high pressure resulting in a temperature rise due to the heat of compression but the temperature of the air after the final compression is not enough to attain the hydrogen auto-ignition. Hence, high-pressure hydrogen is fed initially during start-up and mixed with this compressed air in the pre-chamber and passed into the combustion section where with the help of a spark it is ignited where hydrogen and oxygen from air react to form water in the form of steam and a huge release of energy:

$$H_{2\,(g)} + \tfrac{1}{2}\, O_{2\,(g)} \Rightarrow H_2O_{(g)} + \text{Heat} \qquad \Delta H = 141.8\ \text{MJ/kg}$$

This exhaust gas is recirculated throughout the engine to heat all the parts getting the engine up and running while being brought in indirect contact with the air intake section where this very hot exhaust gas loses its heat to the air and takes it to the desired temperature to achieve hydrogen autoignition combustion conditions and or is forced into ignition through the static electrolyzer.

Once the entire engine and the compressed air are heated to standard operating temperatures and pressures, the Hydrogen flow is dramatically reduced and or switched with water flow as the main fuel for this engine. As the engine is already heated up to approximately 350℃, when the liquid water enters the engine, it is immediately vaporized into steam roughly at 300℃, and it proceeds at or above optimal, pressure and temperatures toward the plasma electrolyzer for rapid separation and Ignition.

In the hydrogen separation process, the catalyst plays a crucial role, alongside temperature and pressure, in optimizing efficiency. Specifically, hydrogen is introduced into the pre-chamber in a controlled manner, accounting for 5 to 20% of the stoichiometric hydrogen mixture. This hydrogen is supplied from an external source, such as a bottle. This externally supplied hydrogen complements the reaction dynamics within the system. After the warm-up phase, additional factors, including load variations and operating conditions, further influence the hydrogen separation process, ensuring optimal performance.

The plasma electrolyzer is maintained at a high AC voltage of 18 kV with a frequency of 10 kHz and low amperage of 6.67 mA producing a Dielectric-Barrier Discharge (DBD)[6] of plasma where one electrode is the annular region of the pipe, and the other is placed at the center like the one described in the Figure 3. Also, Ricci F., et al. have demonstrated similar Hydrogen Combustion in a Spark Ignition Engine where they utilized Barrier Discharge Igniter, it excels in accelerating the initial flame growth speed by the generation of non-equilibrium low-temperature plasma, a strong ignition promoter for the combined action of kinetic and thermal effects. Moreover, its volumetric discharge facilitates combustion initiation on a wide region, in contrast to the localized ignition of traditional spark systems[9] with less energy.

As high-temperature steam at 300℃ passes through the DBD between the electrodes, the water molecules are split into hydrogen and oxygen molecules and as they are operating at higher revolutions per minute, we essentially reduce the residence time of the steam inside the plasma electrolyzer reducing the conversion of steam hence are left with some amount of unreacted steam along with The oxygen that entered the engine on the intake plenum as well as the Production of $H_2$ and $O_2$ (2:1) In total become stoichiometric mixture!

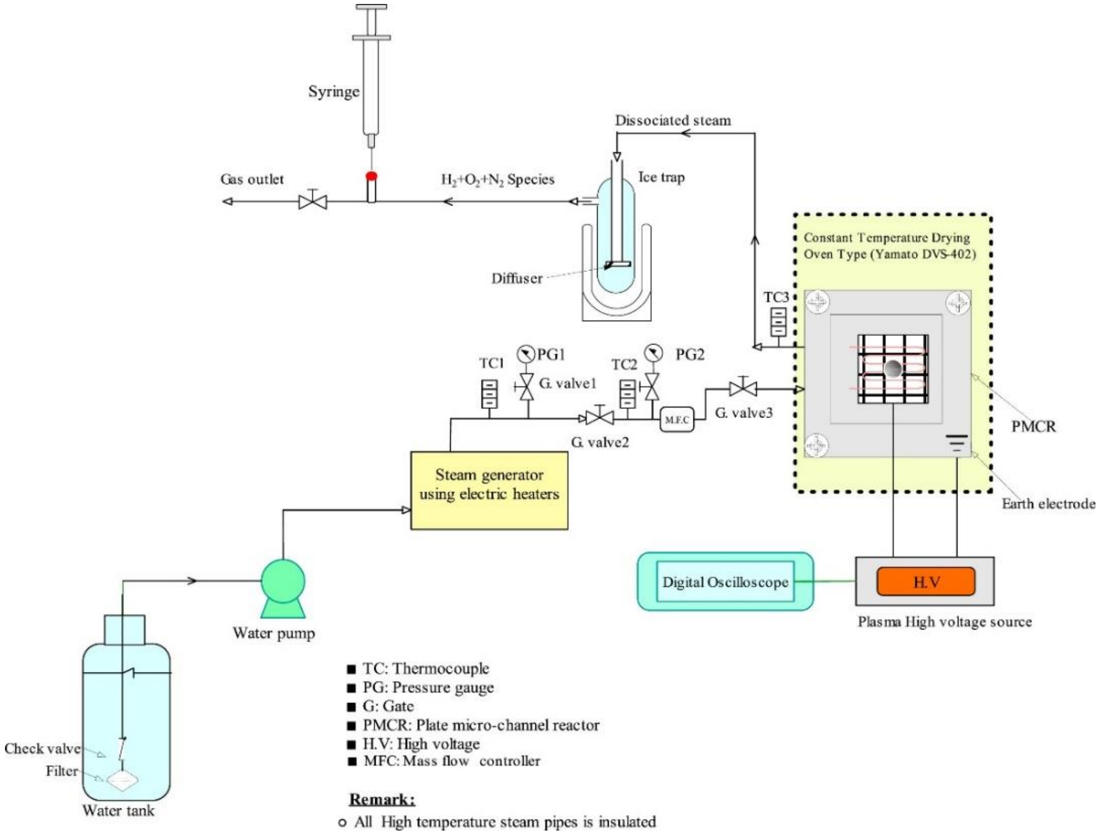
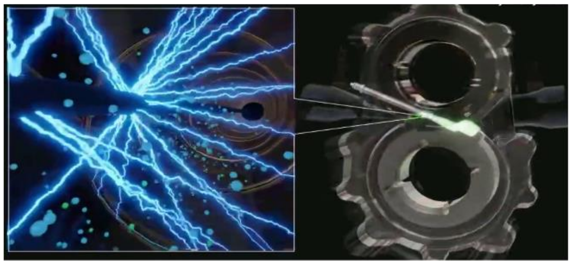


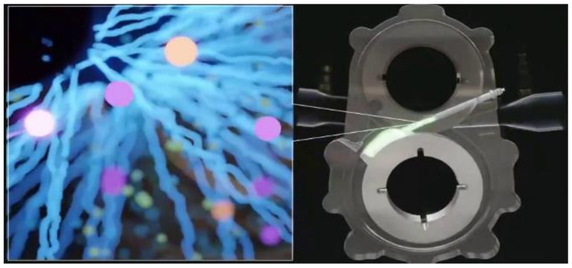
**Figure 3:** Experimental set-up for Hydrogen Production by Plasma Electrolysis of Steam generated from Water.[6] (one of the potential processes explained here)

Now, this mixture has an Air/Fuel ratio of 2.38:1 but the optimum value for efficient $H_2$ combustion should be between 32-36[8]. They take 34:1 as the ratio and to get to this value they make it up by mixing high-temperature compressed Air coming from the rotary engine intake plenum and mix it. With this it becomes a stoichiometric mixture in the pre-chamber. As this mixture passes through the prechamber zone, it self-ignites since it's already above the auto-ignition temperature of the $H_2$-Air Mixture which is 586℃ due to the low minimum ignition energy of 17 µJ for hydrogen-air mixture[7]. This combustion produces expanding gases which produce the thrust to rotate the rotary engine further. Afterward, the exhaust gases leave the engine from the exhaust manifold. As the velocity of this mixture is subsonic, it produces a whistling sound. This process continues further with a constant supply of water and continuous exhaust of steam and exhaust gas mixture.

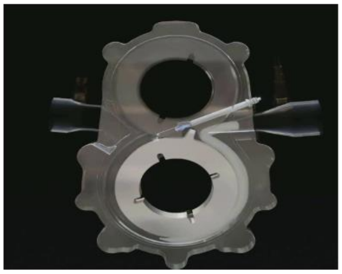
**Air Intake** **Air Compressed**



**Plasma electrolyzer splitting steam into $H_2$ and $O_2$, initiating the ignition process in the pre-chamber**



**Combustion-Cycle**



**Exhaust gases**

**Figure 4:** Different Stages of operation in $H_2$-StarFire engine with electrolyzer.

**Significance of achieving the optimum pressure and temperature:**

Referring the experimental reference, we understand that generally auto-ignition results from either the exothermic of chain branching character of the oxidation reactions that at certain conditions self-accelerate to reach high conversion and heat release rates. Auto-ignition limits can be established testing experimentally or theoretically a homogeneous mixture of volume V filling a vessel whose walls have a temperature $T_w$. Once the heat release rate in the volume due to reactions exceeds the heat lost to the walls or if the reaction rates in the vessel exceed the reaction quenching (termination) rates by the walls or in the gas a thermal or branched-chain (isothermal) auto-ignition occurs. Typically, as almost all combustion reactions are exothermic, chain auto-ignitions cause also self-heating and are accelerated by both factors. **Obviously auto-ignition limits are not only a feature of the mixture composition and parameters (pressure, temperature) but also of the vessel (**which is prechamber in $H_2$-StarFire engine case) **size, wall properties and internal flow conditions.**

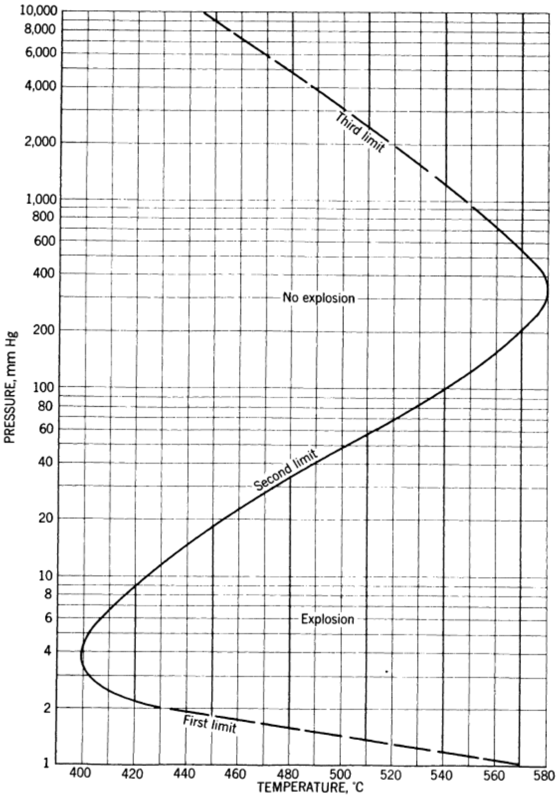


**Figure 5:** Explosion limits of a stoichiometric hydrogen-oxygen mixture[10]

This is illustrated in Fig 1-26 showing the auto-ignition limits often called also explosion limits for a stoichiometric mixture of hydrogen and oxygen (B. Lewis, 1987) providing the important parameters of the test vessel which is prechamber in $H_2$-StarFire case. We may note the logarithmic scale of pressure and linear scale of temperature showing that pressure effects on reaction rates are weaker than temperature effects as one would expect by the consideration of Arrhenius chemistry.

The initial reaction rate in auto-ignition is very small thus a certain time must pass before the reaction has reached a defined rate. This time interval is called ignition delay. Ignition delays are particularly important for operation of engines as they provide the engine speed limits where operation is possible due to auto-ignition (compression ignition engines) or where auto-ignition can be avoided when detrimental (knock in spark ignition engines)[10]

Most accurate ignition delay measurements can be performed in shock tubes in wall reflected shocks where the heating of the mixture is practically instantaneous. A research issue is then prediction of ignition delays using available kinetic data. The state of the art in this field is far from satisfactory as illustrated in Fig 1-27 - after Wang et al. (B. L. Wang, 2003) where a comparison of measured and calculated ignition delay times using different chemical reaction mechanism, available in the literature is provided[12].

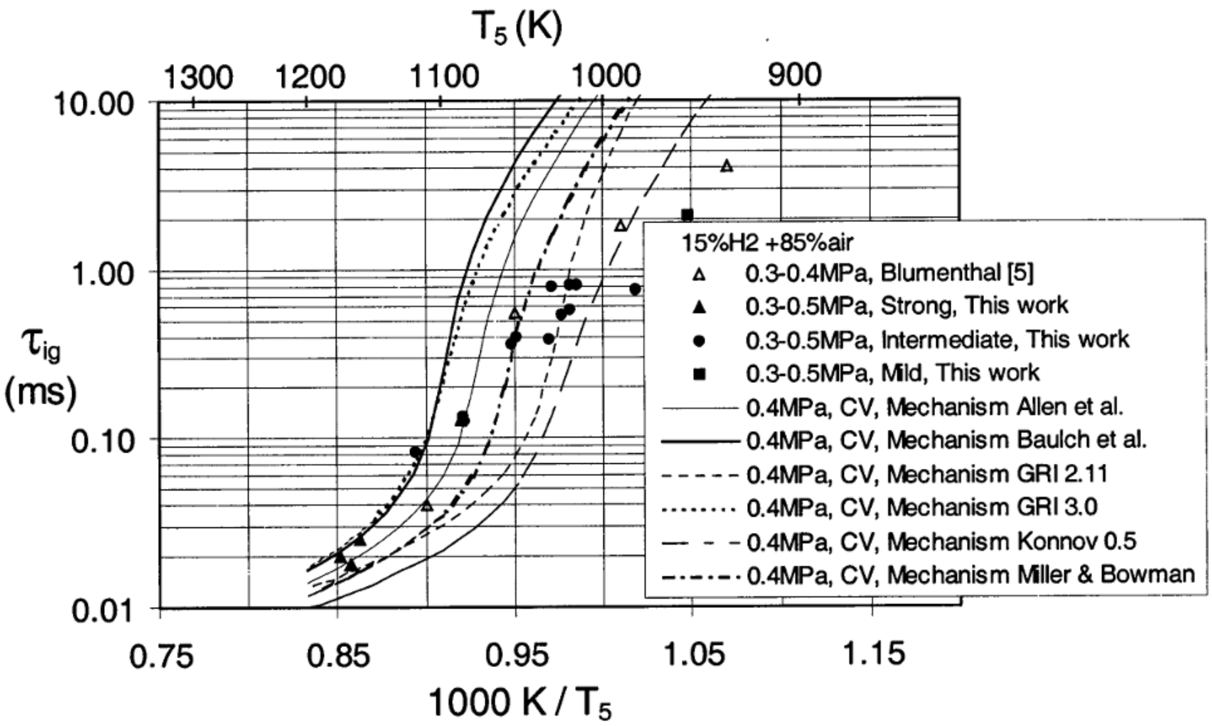


**Figure 6:** Measured and calculated ignition delay times in a $H_2$-air mixture[11]

**Significance of maintaining the engine pre-chamber wall temperature:**

Ignition by a hot surface occurs as a result of local heating of the hydrogen-oxidant mixture to the point where a sufficiently large volume reaches the autoignition temperature and the combustion reaction is initiated. For this to occur generally requires the surface to be at a temperature well above the autoignition temperature, see Powell (1984)[12], although the actual temperature depends on several factors in addition to the usual mixture concentration, ambient temperature etc. These additional factors determine the hot surface ignition behavior of flammable gases and not just hydrogen and include the size and shape of the hot surface, the degree of confinement around the surface, the strength of the convection currents across the surface, see Laurendau (1982)[13] and the material of the surface, Lewis and von Elbe (1987), page 380[10].

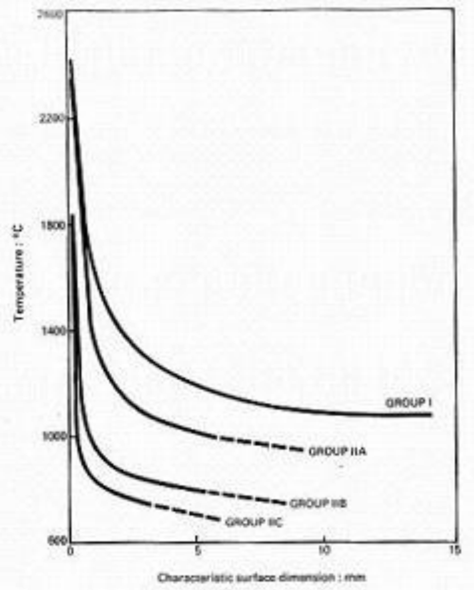


**Figure 7:** Summaries size dependence of hot surface ignition temperatures as a function of size (Hydrogen is represented by curve IIC)

For a particular hot surface, ignition is characterized by an ignition delay, which under ideal circumstances multiplied by the power for ignition gives a linear relationship between the product (energy) and ignition delay (Lewis and von Elbe, 1987, page 365 and Carleton *et al.* (2000)[14].The offset on the y-axis in this plot is the minimum power for ignition for that arrangement.

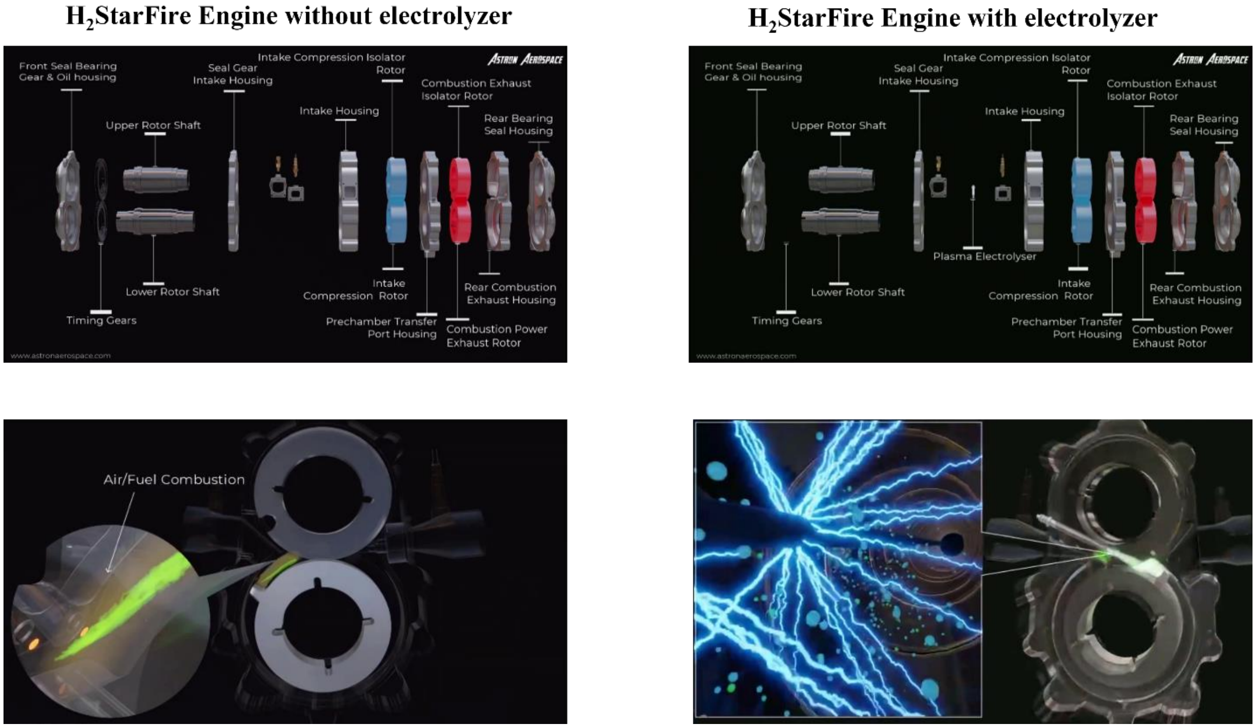
The temperatures required to cause ignition of mixtures of hydrogen with air and oxygen, see review in Buckle and Chandra (1996)[15], Carleton *et al.* (2000)[14] and Hawksworth *et al.* (2005), range from 640°C to 930°C, the spread of temperatures being explained the size, geometry effects etc. described in the first paragraph. While the temperatures quoted are above the auto ignition temperature, the increase is much less than seen for hydrocarbon-fuel air mixtures, as illustrated by the IIA curve in Fig 1-29. In terms of simple modelling of hot surface ignition, Laurendau (1982) presents a simple model in terms of a one-step reaction chemical kinetics model.

Interestingly, the most easily ignited mixture of hydrogen with air lies lean of stoichiometric, see Calcote and Gregory (1952)[17], while work using very small hot surfaces, Carleton *et al.* (2000) and Hawksworth *et al.* (2004), suggests that mixtures as low as 10 to 15% are the most easily ignited. For hydrogen-oxygen mixtures, the work of Buckle and Chandra (1996) indicates a flat $H_2$ concentration dependence (slight positive slope with increasing hydrogen concentration) between roughly 20 and 90% hydrogen in oxygen.

Catalytic surfaces have a dramatic effect on the ignition temperature required, Cho and Law (1986)[16], with ignitions reported at temperatures as low as 70°C.

**Concluding Remarks:**

Astron's $H_2$-StarFire engine without electrolyzer already sets a high standard by running on hydrogen fuel without an electronic fuel injection system, but their latest $H_2$-StarFire model with an integrated electrolyzer takes it to a whole new level. This advanced engine may generate hydrogen on-demand from water using cutting-edge Plasma Electrolysis technology. By employing electrostatic discharge plasma, it efficiently splits hydrogen and oxygen from steam, offering a superior, self-sustaining energy solution.



**$H_2$StarFire Engine without electrolyzer**

**$H_2$StarFire Engine with electrolyzer**

**Figure 5:** $H_2$-StarFire engine without electrolyzer(left two figures) *vs* $H_2$-StarFire engine with electrolyzer(right two figures)

Weighing just under 100 pounds, the $H_2$-StarFire engine with electrolyzer may produces an impressive 400 horsepower and 375 Nm of torque, while achieving a thermal efficiency of up to 60%,+ significantly higher than traditional internal combustion engines having an efficiency of 20-35% only. Additionally, the Star Fire engine is versatile and suitable for transportation, and Power Generation applications. One of the most exciting aspects of the $H_2$-Star Fire engine is its potential to produce hydrogen directly from water in the engine, reducing reliance on external hydrogen production and storage. This capability could drastically lower the costs and logistical challenges associated with all types of hydrogen, making it more accessible and practical for global widespread use. The $H_2$-StarFire engine is not just a step forward in engine technology; it represents a potential revolution in how we approach carbon-neutral energy and transportation. By addressing the major challenges of hydrogen production and utilization, Astron Aerospace is paving the way for a cleaner, more sustainable future.

Considering the energy balance across the $H_2$-StarFire engine and the intrinsic thermodynamics of the combustion, first we do need to feed hydrogen to get the engine heated up due to its heat of combustion to the standard operating temperature. Liquid water gets vaporized at the inlet and steam undergoes plasma electrolysis for which we need to supply electricity to maintain the plasma at desired voltage and form an arc of required amperage. Although the separated hydrogen and oxygen along with the supplied air gets ignited to produce heat and thrust, this engine cannot be thought of as a perpetual engine or over unity in anyway as we indeed need to supply energy to carry out the plasma electrolysis of steam. But the unique design and the fact that this engine is based on hydrogen combustion and hydrogen production on the fly from liquid water does constitute towards its superior energy efficiency and carbon neutrality when compared to traditional fossil fuel engines.

As we continue to seek solutions to the pressing environmental challenges of our time, embracing innovative technologies like the $H_2$-StarFire engine will be crucial. Industry stakeholders, policymakers, and consumers must support and invest in these advancements, driving the transition to a truly sustainable energy landscape. Reach out to Astron Aerospace and explore how their groundbreaking technology can be part of your carbon-neutral journey.

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