

Advanced Hydrogen-Fueled Propulsion Systems: A Comprehensive Review of the G-Cycle Engine

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Abstract -

This paper offers an in-depth review of the G-Cycle Engine, an innovative advancement in hydrogen-fueled propulsion technology, pivotal for achieving sustainable transportation. With a focus on reducing greenhouse gas emissions, the G-Cycle Engine aligns with global sustainability goals and addresses the limitations inherent in fossil fuels and battery electric vehicles (BEVs).

Central to the G-Cycle Engine's design is its complex combustion process, marked by enhanced efficiency and reduced emissions. Key features include a sodium vapor chamber (SVC) for effective thermal management, variable water injection compression ratios, and hydrogen sealing mechanisms. These innovations lead to higher mean effective pressure (MEP), lower NO_x emissions, and superior engine performance. The engine's ability to operate at elevated temperatures using heat-resistant alloys significantly cuts coolant losses and boosts thermodynamic efficiency. Its rotary design ensures balanced power distribution, accommodating multiple chambers for compact and powerful output with minimal vibration.

The review also examines how G-Cycle technologies can be applied to traditional Internal Combustion Engines (ICEs) to enhance efficiency and sustainability. It highlights the engine's potential in shaping future propulsion systems, considering a mix of hydrogen ICEs, alternative fuel ICEs, hydrogen fuel cells, and electric vehicles. The G-Cycle Engine stands as a testament to the potential of hydrogen in revolutionizing sustainable transportation, offering insights for ongoing development in the field.

1. INTRODUCTION

The pursuit of sustainable transport, driven by goals like Europe's zero greenhouse tailpipe emissions[1], demands innovative powertrain and propulsion systems. The diminishing role of fossil fuels, due to their carbon emissions, is prompting a shift towards alternatives. Battery electric vehicles (BEVs), despite being a viable option, face challenges in charging infrastructure, resource demands, and recycling limitations[2,3]. In this landscape,

hydrogen emerges as a key player for sustainable Internal Combustion Engine (ICE) development[4]. Its clean combustion, producing zero greenhouse gases, marks a stark contrast to traditional fuels. This paper explores a novel, high-efficiency hydrogen-fueled engine and future technologies poised to revolutionize sustainable propulsion.

2. G-CYCLE COMBUSTION PROCESS

The G-Cycle engine's primary combustion process involves a series of intricate steps to enhance efficiency and reduce emissions [5]:

2.1 Intake

The rotor chamber, rotating past the intake port, draws in a full charge of fresh air, either naturally aspirated or turbo-boosted for optimal performance.

2.2 Compression with Heated water injection

As the rotor chamber moves beyond the intake, the housing geometry will compress the intake air. Concurrently, heated water (250-350°C) from the active cooling system is injected, stratifying along the chamber's sides and back half. This stratification alters the chamber's compression ratio, with the water volume adjustable to fine-tune this ratio. The chamber maintains a front-half air and back-half water stratification

2.3 Hydrogen Injection and Mixing

Heated hydrogen gas is directly injected into the rotor chamber during late-stage compression, avoiding pre-ignition issues. The hydrogen, lighter than air and water[7], stratifies near the chamber's front, mixing homogeneously with the air for efficient ignition.

2.4 Ignition

Hydrogen is ignited either by a spark plug or through controlled auto-ignition, depending on the effective compression ratio and operating temperature.

2.5 Combustion and Heat Transfer

As the rotor passes TDC, combustion heat (over 600°C) transfers through a perovskite thermal barrier coating (TBC) on the stator housing's inner surface into a Sodium Vapor Chamber (SVC). Where the sodium changes from liquid to a gas and flows along an expansion path.

The surface temperature of the of the peroskvite TBC matches the peak gas temperature of 1,800 K. This high temperature surface area is well above the hydrogen autoignition temperature of 585 C or 858 K and will improve the complete combustion reaction.

2.6 Second Water Injection

Early in the combustion/expansion phase, a second heated water injection (250-350°C or 523-623 K) cools the reaction, maintaining a peak temperature around 1,800 K. This cooling phase transforms water into superheated steam, expanding and increasing the chamber's mean effective pressure (MEP) for work.

2.7 Heat transfer & MEP maintenance

The SVC continuously transfers heat back into the rotating chambers, maintaining approximately 600°C (873 K). Centrifugal forces drive cooler, heavier water droplets against the outer housing, facilitating heat absorption from the SVC, thereby maintaining high vapor pressure and MEP.

2.8 Third Water Injection

Cooler water (30°C) from the cooling system is injected late in the combustion/expansion phase, cooling the exhaust gas, combustion chamber and surrounding components for the next cool intake charge and aiding in vapor condensation for easier recovery.

2.9 Exhaust and Turbocharging

High pressure, velocity, low temperature, and water dense exhaust gas, drives a variable geometry turbocharger turbine, powering an intake compressor.

2.10 Water Recovery

Finally, water from the exhaust is condensed, filtered, and recirculated into the active cooling system, completing the cycle.

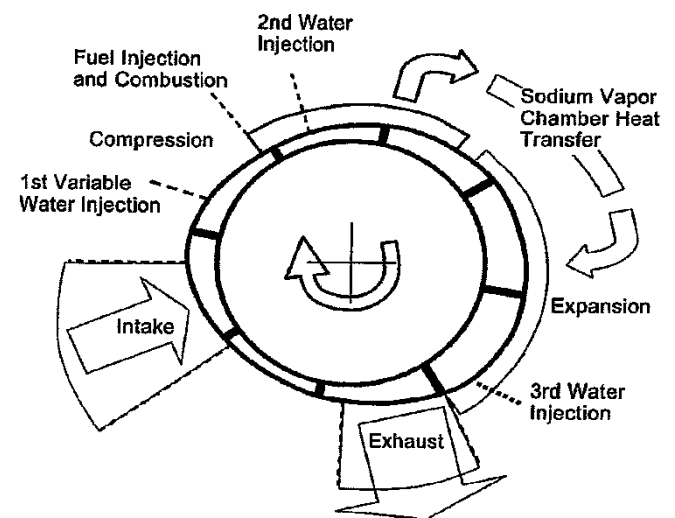


Figure 1: Simple G-Cycle rotary Vane Engine process representation. [5]

3. MAIN TECHNICAL FEATURES

The G-Cycle engine offers a range of technological advancements, on which its high efficiency and environmental performance are reliant. The following part will discuss some of the main points [5].

3.1 Active Cooling system

This engine integrates a thermal management system with a sodium vapor chamber (SVC), active cooling, and water injection. Operating in a closed-loop, it recycles heat to the engine chambers from both the SVC and the cooling system, enhancing thermal efficiency and contributing to positive exergy work. Controlled water injection regulates combustion gas temperature and balances engine workload, and maximises enthalpy. This synergy achieves brake thermodynamic efficiency, potentially up to 65-80%, while stabilising component temperatures to minimise thermal deformations and wear. Together, these elements of the G-Cycle engine's design coalesce to create an efficient, powerful, and durable engine system.

3.2 Sodium Vapor Chamber

The SVC, functioning like a two-phase heat pipe [6], absorbs heat from combustion and redistributes it during the expansion stroke, increasing housing temperature, stratification of water, and MEP. Robust housing and protective measures counteract sodium's reactivity with water.

3.3 Higher housing Operation Temperatures

With 20-27% of thermodynamic heat being lost to cooling components to 180-230°C, in conventional engines [5,7]. The G-Cycle efficiently operates at around 600°C using high-temperature-resistant alloys, reducing coolant losses.

3.4 High Balanced Power Density

Its rotary design allows for continuous, unidirectional power distribution, housing multiple chambers (6,8,9,12) for compact, high-displacement power. This design ensures smoother operation with less vibration and stress. Less cyclic loading increases reliability. Multiple rotors can be attached to each other for higher power like in a multiple cylinder style.

3.5 Variable Water Injection Compression Ratio

Adjusting water injection amount during compression alters the effective compression ratio. Allowing for compression ratio tuning depending on load, rpm,... Injecting water in the back of the combustion chamber ensures combustion at the front, increasing propulsion force on the rotor.

3.6 Ignition

Adjusting the compression ratio to approach the auto-ignition temperature of the hydrogen/air/water premix (585°C) [8] optimises combustion. Spark Ignition is used during startup, at operating temperature, the heat from the SVC is used through the inner housing surface for ignition. The high surface-to-volume ratio creates substantial gas turbulence during combustion, and, with centrifugal forces, pushing water against the housing, increasing water vapor pressures and MEP work throughout the complete expansion/work zone..

3.7 Combustion Chamber sealing

A dual-seal system in each vane, aided by centrifugal forces and gas pressure, reduces blow-by losses. An internal moving belt system manages centrifugal forces. Any blow-by losses are efficiently repurposed, as the escaped gas is utilized in the subsequent combustion chamber.

3.8 Hydrogen Sealing

The aim is to minimize hydrogen gas ignition within inner rotor components or its escape through the engine. Cooling water from the active system, running through zigzag channels under rotor seals, improves sealing and minimizes hydrogen leakage.

Should any hydrogen bypass these seals, it gets diluted by the cooling water, captured by the active cooling system, and then removed from the engine casing. Any collected hydrogen gas is used again when injected back into the combustion chambers during water injection.

3.9 Distorted Oval Inner Housing Stator Geometry

This design maximizes combustion/expansion by 61% compared to existing rotary expansion duration while minimizing intake/compression zones, thereby enhancing thermodynamic efficiency and reducing stress on engine components by smoothly changing the chamber volume. Figure 2 shows the shape.

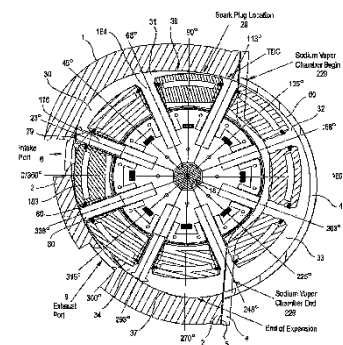


Figure 2: G-Cycle housing, rotary vanes [5]

3.10 Improved Hydrogen Fuel Delivery

The engine's design prevents icing due to the high-pressure change in hydrogen delivery systems and ensures efficient combustion by pre-mixing hydrogen with heated water, supplying heat needed in the gas expansion.

3.11 Lower NoX Emissions

By controlling peak combustion temperatures to 1800K, compared to conventional 2500K, NoX emissions are significantly reduced. [9]

3.12 Light Weight Materials, Lubrication

With the reduction in engine volume and mass, Advanced alloys like Haynes 230 and specialized steels are used for different temperature zones, enhancing strength and durability while minimizing mass and thermal deformations

These alloys are also resistant to hydrogen permeation and embrittlement.

Oxide lubricants and coatings are used can handle millions of slides with virtually no wear. The seals are designed so that they allow for lubricant wear and dynamically adjust to maintain the sealing performance.

3.13 Alkali Metal Thermal Electrical Converter

The G-Cycle includes AMTEC for efficient heat-to-electricity conversion, utilizing sodium as a working fluid in a process where heated, pressurized sodium transforms from liquid to gas, generating electricity through a beta alumina electrode. [10]

4 G-CYCLE TECHNOLOGY FOR TRADITIONAL ICE EFFICIENCY ENHANCEMENT

This section discusses how G-cycle engine technologies can be applied to improve the efficiency of traditional Internal Combustion Engines (ICEs) and their potential future impact.

The primary enhancement in efficiency is attributed to advanced thermal management, which could be adapted in traditional ICE design.

High-grade materials and coatings enable higher operating temperatures, reducing excessive cooling needs and energy losses. A two-phase heat pipe, akin to the G-cycle's Sodium Vapor Chamber (SVC), effectively redistributes combustion heat, enhancing Mean Effective Pressure (MEP) a particularly beneficial approach for engines with longer strokes. This not only improves efficiency but also generates higher torque.

In engines with larger strokes, the increased surface area and piston travel offer opportunities for strategic injection at various stages of the expansion stroke, whether it's fuel or water. Water injection at different cylinder points can raise compression, aid combustion vaporization, lower combustion temperatures, and cool down components and exhaust gases, thereby reducing NOx emissions. An active cooling system for water recirculation negates the need for an additional water tank.

Atkinson cycle engines also demonstrate increased efficiency, suggesting that even simple modifications like water injection could significantly improve the expansion/compression ratio in conventional ICEs. Replacing crankcase oil with oxide lubricants and hard coatings can solve oil dilution and oil burn issues. Water cycling through crankcases aids in cooling, sealing, and hydrogen management.

Direct injection, timed precisely at the point of combustion, is a viable solution to prevent pre-ignition knock[12]. Altering the injector's position closer to the piston can maximize the mechanical work by leveraging the resistance offered by water and the piston's movement.

These adaptations, along with water injection, SVC, and active cooling, derived from the G-cycle engine, could enhance existing rotary engines, requiring sealing and lubrication modifications. While hydrogen combustion inherently produces low NOx emissions, these can be further reduced with exhaust after-treatment and EGR methods[11]

Hydrogen combustion naturally produces low NOx emissions, but further reductions are achievable with exhaust after-treatment and EGR methods. These innovations offer potential across ICEs, including hydrogen, fossil, and alternative fuels, to improve thermal efficiency and lower emissions. Their integration into traditional ICEs reduces the need for extensive manufacturing changes and recycling challenges.

In a broader perspective, engines could be designed for high efficiency at constant load and RPM, serving as range extenders. The G-cycle, despite its complexity and potential production challenges, offers innovative thermodynamic concepts for future development. A blend of propulsion methods, including Hydrogen ICE, alternative fuel ICEs, hydrogen fuel cells, and electric vehicles, seems pragmatic, given the current limitations and developmental needs of each. Future advancements will provide further insights,

ultimately determining the most effective and sustainable transportation methods.

5. CONCLUSIONS

The G-Cycle engine embodies a breakthrough in sustainable transport, aligning with global emission reduction goals. Its unique combustion process and features, such as advanced thermal management and efficient hydrogen utilization, significantly enhance efficiency and reduce emissions. This innovation not only underscores hydrogen's potential in revolutionizing Internal Combustion Engines but also sets a precedent for modernizing traditional ICEs with similar technologies. The continuous development of different propulsion methods paves the way towards more efficient and environmentally stable mobility solutions.

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