The Clean-Fuel Debate

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1. Introduction

Although I've written about this subject recently I've come across several new pieces of information that indicated my prior posts on this might need some clarification. My most recent post on this subject is summarized and linked below.

Participants in the Last Clean-Vehicle Segments Emerge: *I have written enough papers on hydrogen-fueled vehicles to know their potential advantages verses battery-electric vehicles (BEV):*

- *Fast refueling*
- *Very long run-time without refueling*

There are two segments of vehicles that appear to be unable to easily transition to designs with no greenhouse gas (GHG) emissions:

- *Construction vehicles (bulldozers, front loaders, dump trucks, backhoes, etc.)*
- *Long-range/duration road vehicles (interstate transports, heavy tow trucks, etc.)*

There seems to be a match between the above "advantages" and "vehicles" that might suggest the emergence of some hydrogen-fueled vehicles to meet the needs of the two vehicle segments.

https://energycentral.com/c/ec/participants-last-clean-vehicle-segments-emerge

Consider that the perfect should never be the enemy of the good.[1]

Or more specifically: For any transition to a cleaner method of operation, perfection is rarely achievable. However, correction of imperfections are relatively easy, so "good" is frequently good enough, and certainly better than current alternatives.

2. Hydrogen ICE & CF-ICE

You've probably guessed that ICE is for Internal Combustion Engines, and for the second acronym above, add "Continuous Flow" (mainly gas turbines, a.k.a. combustion turbines, including turbo-fans). This section will cover both of these technologies. The excerpts below are from two companies leading the charge to hydrogen-fueled vehicles.

Hydrogen ICE: *Regulations limiting greenhouse gas emissions (GHGs) from motor vehicles are tightening around the world. With this, both hydrogen engines and hydrogen fuel cells are receiving an increasing interest.*[2]

[1] This aphorism is an old Italian proverb first made popular by Voltaire who used it in his poem La Bégueule. The literal translation is, the best is the enemy of the good. https://donmcminn.com/2021/06/dont-let-perfect-be-an-enemy-of-the-good/#

[2] Jim Nebergall, Cummins, "Hydrogen Internal Combustion Engines and Hydrogen Fuel Cells," Jan 27, 2022, https://www.cummins.com/news/2022/01/27/hydrogen-internal-combustion-engines-and-hydrogen-fuel-cells#

Given medium and heavy-duty trucks are a major source of CO_2 emissions, the transportation sector's journey to destination zero features both technologies.

As more truck makers join the ranks of auto companies developing CO_2-free or CO_2-neutral alternative to gasoline and diesel vehicles, let's look at the similarities and differences between hydrogen engines and fuel cells.

Both hydrogen internal combustion engines and hydrogen fuel cells can power vehicles using hydrogen, a zero-carbon fuel.

Hydrogen engines burn hydrogen in an internal combustion engine, in just the same way gasoline is used in an engine. Hydrogen internal combustion engines (hydrogen ICE) are nearly identical to traditional spark-ignition engines…

Fuel cell hydrogen vehicles (FCEVs) generate electricity from hydrogen in a device known as a fuel cell, and use that electricity in an electric motor much like an electric vehicle.

Internal combustion engines tend to be most efficient under high load—which is to say, when they work harder. FCEVs, in contrast, are most efficient at lower loads…

So, for heavy trucks that tend to spend most of their time hauling the biggest load they can pull, internal combustion engines are usually the ideal and efficient choice. On the other hand, vehicles that frequently operate without any load—tow trucks or concrete mixer trucks, for example, may be more efficient with a fuel cell. Fuel cell electric vehicles can also capture energy through regenerative braking in very transient duty cycles, improving their overall efficiency.

Hydrogen engines can also operate as standalone powertrain solutions and handle transient response demand without the need for a battery pack. Fuel cells combined with battery packs can also accomplish the same.

Hydrogen engines and hydrogen fuel cells also have similar emissions profiles. FCEVs, actually, produce no emissions at all besides water vapor. This is a very attractive feature for vehicles operating in closed spaces or spaces with limited ventilation.

Hydrogen engines release near zero, trace amounts of CO_2 (from ambient air and lubrication oil), but can produce nitrogen oxides, or NOx. As a result, they are not ideal for indoor use and require exhaust after-treatments to reduce NOx emissions.

Author's comment: Hydrogen-ICE does emit a tiny amount of CO_2 and other pollution, but is has some advantages to offset these issues. First of all, vehicles using hydrogen-ICE require few modifications to convert from conventional ICE, and thus are a very good choice during the transition from greenhouse gas (GHG) -emitting vehicles to (almost) clean vehicles. Second, this is doubly-true for really large, expensive ground-vehicles with long lifetimes, like train locomotives and construction equipment. See "Participants in the Last Clean-Vehicle Segments Emerge," linked in the Intro for details on the last category.

Hydrogen CF-ICE: *Today's internal combustion engines in aircraft can be modified to run on alternative fuels for improved environmental performance. Now, hydrogen combustion—either via gas or liquid—is emerging as one of the most promising options in this respect. Airbus is exploring the technology's potential in preparation for its zero-emission aircraft program.*[3]

When the world's first internal combustion engine revved up, it was hydrogen gas—not gasoline or diesel—that burned as its fuel.

The year was 1804. After successfully designing several steam-powered carriages, Franco-Swiss inventor Isaac de Rivaz set his sights on using an explosive charge—instead of steam—inside a stationary engine to power a pump. His first experiments focused on creating an explosion within the engine's cylinder to drive the piston out. At the time, he used a mixture of hydrogen and oxygen gases to ignite this explosion—and it worked. By 1807, de Rivaz's experimental prototype engine was being used to propel a carriage a short distance—thereby garnering the distinction as the world's first vehicle driven by an internal combustion engine.

Throughout the 20th century, automobile companies, universities, inventors and hobbyists alike further tested the viability of internal combustion engines powered by hydrogen. In fact, in 1970, inventor Paul Dieges was the first to patent a modification to gas-powered internal combustion engines, which enabled them to run on hydrogen.

Today, hydrogen combustion engines have proven their ability to successfully power a variety of vehicles, from cars to buses. Tomorrow, hydrogen combustion may just power future commercial aircraft…

Hydrogen has many unique properties that make it suitable for combustion, including:

> ***Wide flammability range:*** *Hydrogen can be combusted via a wide range of fuel-air mixtures. Hydrogen can run on a "lean" mixture, which means the amount of fuel is less than the amount needed for combustion with a given amount of air. This results in greater fuel economy and a final combustion temperature that is generally lower, which reduces the amount of pollutants, such as NOx, emitted via the exhaust.*
>
> ***High auto-ignition temperature:*** *Hydrogen's high auto-ignition temperature enables higher compression ratios in a hydrogen engine compared to a hydrocarbon engine, which results in greater thermal efficiency...*

Hydrogen combustion has already been used to fuel aircraft. In fact, in 1988, the world's first experimental commercial aircraft operating on liquid hydrogen (and later, liquefied natural gas) took to the skies: the Tupolev Tu-155. It flew approximately 100 test flights and was then placed into storage.

[3] Matthieu Thomas, Airbus, "Hydrogen combustion, explained,"26 Nov, 2020, https://www.airbus.com/en/newsroom/stories/2020-11-hydrogen-combustion-explained

Now, more than 30 years later, the aviation industry is once again turning its attention to hydrogen combustion in commercial aircraft. Indeed, Airbus' ZEROe concept aircraft could run on hydrogen combustion. To explore the possibilities and limitations of this technology for commercial aircraft, Airbus will team up with a variety of partners...

"The only way to determine which hydrogen technology is best-placed to fuel our ZEROe concept aircraft is to test, test, test," says Matthieu Thomas, ZEROe Aircraft Lead Architect. "We look forward to sharing more details about an exciting cross-industry partnership on hydrogen combustion."

But for hydrogen combustion to work, liquid hydrogen must be stored safely and securely on board aircraft. Due to hydrogen's unique properties, this can be tricky. For example, tanks need to be insulated to avoid evaporation if heat is carried over into the stored content by factors such as conduction. This is why the Airbus Defense and Space's Engineering Division has stepped in to help. The team will provide support for the development and industrialization of cryogenic tanks for liquid hydrogen storage in a three-year project collaboration with the ZEROe program team.

"The space industry has been using pressure vessels for the storage of liquid propellant to fuel space exploration for decades," explains Renato Bellarosa, Head of Propulsion Products and Tanks at Airbus Defense and Space. "So we have a lot of expertise in damage tolerance, in advanced manufacturing technologies and in vessel pressure testing, all of which is key to supporting the development of liquid hydrogen storage tanks for future aircraft propulsion systems. It's cross-industry collaboration like this that will bring us closer to putting a hydrogen-powered aircraft into the skies over the next decade."

Author's comment: Liquid hydrogen is probably the best way to store hydrogen in commercial aircraft fuel tanks. However pressurized hydrogen to around 500 bar (7,250 psi) is generally the best way to store hydrogen in ground vehicle fuel tanks.

Note that: 1 kg of liquid hydrogen occupies 0.01 cubic meters of volume. At 500 bar pressure, 1 kg of hydrogen-gas occupies 0.023 cubic meters, or 2.3 times more space than liquid hydrogen. Also 500 bar requires very robust, heavy containers. For commercial applications these are typically cylinders (a.k.a. tubes) which are made from steel and weigh far more than the hydrogen they contain. Future ground vehicles will probably use layered composite pressurized hydrogen tanks. Although they are much lighter than steel they are still very heavy compared with space-industry liquid hydrogen containers.

Also, even with conventional jet-fuel, refueling a commercial aircraft is done by skilled technicians with specialized equipment. It would be reasonable to assume that these same individuals could be trained to also fuel aircraft with liquid hydrogen. Pressurized hydrogen refueling infrastructure suitable for normal consumer use already exists.

For more information on the Airbus ZEROe Hydrogen CF-ICE development, go through the link below.

https://www.airbus.com/en/innovation/zero-emission-journey/hydrogen/zeroe



Note that nm = nautical miles = about 1.15 U.S. miles