Hydrogen for aviation: High in the sky or pie in the sky?

By Stephen B. Harrison on Mar 29, 2024 FEATURE | MOBILITY

Aviation carbon dioxide (CO2) emissions are one billion tonnes per year – similar to the total annual CO2 emissions from Germany or Canada. And aviation CO2 emissions are rising faster than other transport sectors.

Green hydrogen can be produced from renewable electrical power. Blue, low-carbon hydrogen is produced from fossil fuels with permanent storage of the CO2 emissions.

Sustainable aviation is in its infancy. The breadth of solutions is broad. The winning solutions may be known to us today or could yet emerge. However, the benefits of pursuing defossilisation in this sector will be felt in our lifetime and will leave a legacy that we can be proud of for generations to come.

Jets and props

The first wave of hydrogen-fuelled aircraft were turboprop aircraft with powerful fuel cells to drive the propellors. Airbus, Zero Avia, Ruixiang, H2FLY, Sirius Jet, and Pipistrel have all experimented in this way. High-temperature PEM fuel cells are currently favoured for aviation, due to their high power density, which allows them to generate more than 1MW for the power train at minimum weight.

Type 4 composite compressed hydrogen storage on a drone

More recently, testing of hydrogen-fired jet engines has taken place with Rolls Royce and easyJet confirming the successful land-based firing of an AE 2100-A regional jet engine on a test bed in 2022.

Long-mission duration drones were the first major application of hydrogen for aviation. Compressed gaseous hydrogen stored in a lightweight Type 4 composite cylinder can flow through a fuel cell to achieve a significantly longer range than a battery-powered drone with a similar payload.

Tanks and gravity

For land-based fuel storage and use, the volume of the stored fuel is often more important than its mass. For example, at a crude oil storage terminal, the mass of the fuel is of little consequence since it is borne by the land on which the storage tanks sit.

In aviation, both the volumetric and gravimetric energy density are of critical importance. In a commercial aircraft, volumetric density plays a role since space must be left for fare-paying passengers.

Both liquid and gaseous hydrogen have a remarkably high gravimetric energy density. This alone puts them in the running as a prime aviation fuel candidate. However, the fuel alone is not the only consideration.

The total mass of the fuel and its container is critical when benchmarking across alternative fuels. On this basis, the efficiency of traditional hydrogen storage is very poor, with less than 1% of the weight of a steel cylinder filled to 200 bar pressure being hydrogen and the remainder being steel.

When using high-pressure Type 4 gas cylinders with pressures of 700 bar, as are now the standard on hydrogen fuelled cars, the gravimetric efficiency of storage is still only 5%. This may be acceptable for a very light drones with a short mission duration, but this is not a good starting point for storing fuel for commercial aviation.

Switching to liquid hydrogen means that under current technical limitations, a metal storage tank must be used. Even when maximising the use of cryogenically compatible aluminium alloys in place of the heavier steel, the gravimetric efficiency of liquid hydrogen storage is currently limited at around 30%.

The space race

For vertical take-off in a helicopter or drone the focus shifts to gravimetric energy density as the key parameter. For space rockets the issue is even more acute.

The first large-scale application of liquid hydrogen was as a rocket-fuel for NASA missions. Since it was built in the 1960s, the hydrogen storage sphere built by CB&I at Launch Complex 39B of Cape Canaveral's Kennedy Space Center remained the largest liquid hydrogen storage tank in the world for many years. It had a usable capacity of 2,800 m^3 of liquid hydrogen and was used for the Apollo and space shuttle launches.

In 2022, the crown for the world's largest liquid hydrogen storage tank was passed to a larger tank. Again, CB&I were awarded the contract to build a new tank of 4,700 m^3 capacity at the same location to support longer missions and improve the insulation to reduce boil off losses.

On board the rockets, ultra-lightweight composite tanks were used. The advantage of this construction was that the gravimetric efficiency was between 75 and 85% for various rocket types. On the other hand, the tank was built to be usable only once.

For commercial aviation, the idea of a single-use tank would not be realistic. However, multiple use composite tanks to store liquid hydrogen are under development. This technology may offer the prospect of achieving a gravimetric efficiency of more than 50% in a re-usable tank.

High efficiency, high density

Working on the materials of construction for the tank is one lever that can be used to improve the gravimetric efficiency of liquid hydrogen storage. Exploiting the thermodynamic and physical properties of hydrogen is an alternative.

As hydrogen is compressed, its density progressively increases. For example, at 350 bar a compressed gas cylinder with a volume of one litre contains 16 grams of hydrogen. At double the pressure, 700 bar, the same container holds 27 grams, almost twice as much.

When hydrogen is cooled to a cryogenic liquid, its density reaches 36 grams of hydrogen per litre of storage tank volume. Beyond the gaseous and liquid phases of matter, there is an additional phase known as a super-critical fluid. In this phase, when hydrogen is both cold and compressed, the density of hydrogen is greater than normal liquid hydrogen at atmospheric pressure. At 300 bar, a one-litre storage tank would contain 40 grams of cryo-compressed hydrogen.

In many applications, the gravimetric energy density advantage of cryo-compressed hydrogen may not justify the additional complexity of this medium. However, in aviation the gravimetric energy density is so critical that cryo-compressed hydrogen may find an application niche.

Zero Avia, based in the UK and the US startup VERNE announced their collaboration to explore the use VERNE's cryo-compressed hydrogen storage solution for aviation. Also of deep importance, is that in addition to having a higher gravimetric energy density, the power input requirement to densify VERNE's cryo-compressed hydrogen is approximately half the electrical power required to liquefy hydrogen. As hydrogen aviation scales up, this energy saving will escalate to become many MWh of avoided power usage.

Spend a little, save a lot

Achieving a high energy efficiency in the hydrogen supply chain is imperative. This message has clearly been understood by the US company GenH2. Their concept is to use power, to save power.

GenH2 technology relies on helium being cooled in a Brayton refrigeration cycle to temperature about 10°C colder than -253°C, the temperature at which hydrogen liquefies at atmospheric pressure. This helium is used to sub-cool liquid hydrogen to make sLH2. There is a power penalty involved in operating the helium compressor in the Brayton refrigeration cycle, however the boil-off losses of hydrogen in the supply chain are reduced.

When cryogenic liquid hydrogen sits in a storage container for more than a few hours, a tiny amount of ambient heat begins to 'leak' through the storage vessel and vaporise the hydrogen. The pressure in the tank builds up to the point where safety devices fitted on the tank release the pressure.

When hydrogen is vented, not only does this represent a loss of cold energy that was required to liquefy the hydrogen, it also represents a loss of the energy that was required to produce the hydrogen itself. So, avoiding boil off venting can justify some additional amount of power for sub-cooling liquid hydrogen.

Sub-cooled hydrogen has not yet been used in aviation, but for several years it has been the fuel of choice for hydrogen storage on board Daimler Trucks. Linde and Daimler Truck opened the first sLH2 refuelling station at Wörth am Rhein in Germany.

Airport infrastructure

The absence of liquid refuelling infrastructure at airports would be a bottleneck for cryogenic liquid hydrogen in aviation. Construction of multiple fuelling locations at a single airport with the installation of cryogenically insulated liquid hydrogen pipelines running underground would be an enormous engineering challenge, to be undertaken at great cost.

To kick-start access to liquid hydrogen for aviation, the startup Universal Hydrogen has conceived a removable, refillable liquid hydrogen storage tank and supply chain concept. The company is based both at Toulouse, where Airbus has one of its main manufacturing locations and Hawthorne in California.

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Universal Hydrogen proposes to use cryogenically insulated, metal containers with more than 1,000 litres of capacity to store liquid hydrogen. The containers can be rolled on and off the aircraft in the same way that luggage waggons are currently used to load and unload passengers' suitcases. The containers are moved by truck to a central filling location and redistributed to the aircraft.

The Universal Hydrogen concept avoids liquid hydrogen tankers moving around the airport to refuel fixed tanks on the aircraft. It also eliminates the need for static storage and refuelling equipment in multiple locations on the airport apron.