The Future of General Aviation is Electric, but what will be the Fuel Source?

In the quest for reduced emissions, General Aviation (GA) will need to migrate to sustainable fuels. The burning question is what will be the power source, hydrogen, hybrid-electrical or other fuels such as ammonia?

As we are all aware, there is an increasing demand for sustainable, zero emission transportation by the public and this includes General Aviation. Whilst the combustion of hydrogen in piston or gas turbine engines is perfectly feasible, the downside is that NOx is still produced, whereas the conversion of hydrogen into electricity emits only H2O.

If we look at other transport infrastructures such as automobiles, passenger busses and coaches and heavy goods vehicles, there is already significant progress in the development and availability of vehicles in each of these segments that use hydrogen as the main energy source. This technology will spill over into aviation, and percolate down to General Aviation, but the question is – what form will the hydrogen take?

Hydrogen can be considered an ideal gas for sustainable transport over a wide temperature range and even at high pressures. At standard temperature and pressure conditions, it is a colourless, odourless, tasteless, non-toxic, non-corrosive, non-metallic diatomic gas, which is in principle physiologically not dangerous. One of its most important characteristics is its low density, which makes it necessary for any practical applications to either compress the hydrogen or liquefy it. It is positively buoyant above a temperature of 22 °K, i.e., over (almost) the whole temperature range of its gaseous state.

Because of its small size, its small molecular weight and its low viscosity, hydrogen can cause a problem with respect to the propensity of the gas to leak at a larger molecular flow rate than other gases. Diffusion in small amount is even possible through intact materials, in particular organic materials, which may lead to gas accumulation in confined spaces. Leakage rates are by a factor of 50 higher than for water and by a factor of 10 compared to nitrogen. The addition of an odorant or colorant would ease the detection of small leaks; however, this is not practicable in most situations, and not feasible for Liquid Hydrogen (LH2).

LH2 has the advantage of extreme cleanliness and the more economic type of storage, however, on the expense of a significant energy consumption of about one third of its heat of combustion. Another drawback is the unavoidable loss by boiloff which allows to maintain the cold temperature in the tank. A comparison would be the visible mist bubbling off a liquid Nitrogen container that we have all witnessed in a science experiment at some time or other.

To summarise, hydrogen can be a fuel in many different states, each with a specific gravimetric density, all of which are lower than current fossil fuels or Sustainable Aviation Fuel (SAF) but at the same time hydrogen does has a higher calorific value. Any hydrogen fuel system will have leaks, after all we are dealing with the smallest atom in the periodic table, so systems will have to be designed to ensure that leaked hydrogen doesn't accumulate in pockets and become a potential flammability issue.

Carrying hydrogen aboard an aircraft will require a pressure vessel as opposed to a traditional vented to atmosphere fuel tank and being a pressure vessel, this will need reinforcement of the vessel walls and thus mass – the aviator's natural enemy.

Another change of ideology with hydrogen fuelling, is that there is relatively little weight penalty in the hydrogen fuel itself, and particularly in the case of LH2. Consequently there will be a shift to taking off with full tanks as opposed to just fuelling for the flight. Also jettisoning hydrogen fuel is not an option, so hydrogen pressure vessel equipped aircraft will have a higher Maximum Landing Weight (MLW) than a fossil fuelled equivalent.

Let's consider gaseous hydrogen, typically at pressures of 350bar or 700bar, has significant mass in the pressure vessel – just imagine carrying a number of 47kg /100lb propane cylinders aboard an aircraft. Therefore, aviation borne gaseous hydrogen will need re-enforced composite technologies to become cost effective and certifiable to facilitate a mass conscious use of Hydrogen in this state. On the upside, gaseous hydrogen doesn't have the boil off issue associated with LH2, so the dormancy intervals or fuel hold times can be quite long which would suit some General Aviation applications.

LH2 is also contained in a pressure vessel. This is because the pressure of the LH2 has to be maintained at the desired state, ordinarily 1.013bar (nominal atmospheric pressure at sea level) whilst the surrounding air pressure may decrease with increasing altitude during a flight. With LH2, as well as the pressure vessel mass issue, albeit it this being less severe compared to gaseous Hydrogen bottles, there is also the added contention of thermally insulating and isolating the LH2 vessel to maintain the nominated cryogenic state of the LH2.

There are a number of issues with LH2 that would tend to preclude hydrogen in this form being adopted for GA. The fuelling of the LH2 system from empty requires a basic three stage process.
Initially the system is filled with relatively cheap liquid nitrogen. This is done for two reasons, to reduce the temperature of the system from ambient to approximately 69 °K, and to also purge the atmospheric gases from the system. Generally, this takes quite a while.

Next the system is filled with rather expensive and limited liquid Helium to displace the liquid nitrogen, thus further reducing the system temperature towards the 20 °K target but also rather importantly ensuring that any remaining oxygen gases are removed from the system. This Helium, due to its finite supply (you cannot produce Helium and the earth's supply is limited) needs to be recovered for future uses.

Finally, the LH2 can be introduced and the aircraft is ready to fly. The aim is to keep the system suitably primed with LH2 that the first two stages are undertaken as an exception rather than as a rule.

There are however a number of drawbacks with LH2. Not all the LH2 can be used as fuel, a portion – anything between 17% and 25% depending upon the pressure vessel and insulation design and properties will need to remain in the system to ensure cryogenic stability. To little LH2 and the system will experience run away boil off necessitating the purging and refuelling of the system from scratch.

Having established that to achieve suitable densities that hydrogen needs to be stored in a pressure vessel, there are a number of other storage protocols available. One such storage protocol is that being explored by Daimler Benz within the German based Clean Energy Partnership (CEP). Daimler Benz and a number of other companies are working on a "subcooled" liquid hydrogen, (sLH2) fuel technology and protocol for long range heavy goods vehicles with a range of 1,000km being the target. sLH2 is pressurised cryogenic Hydrogen at 16bar and 26.5 °K. The advantages of sLH2 are the ease of fuelling the system, the lack of boil off due to hydrogen being in a supercrital phase coupled with very well insulated pressure vessels giving a hold time with minimal boil off that can be measured in hours rather than minutes.

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The suitability of sLH2 for GA is many folds. The pressure vessel weight increase over LH2 is negligible, the refuelling protocol is simplified and there is a significant improvement in the hold time without active cooling.

Having established that LH2 or sLH2 does have the potential to be used as the primary fuel source in future green aviation, the next question is how best to match this hydrogen fuel to the technologies available to use this energy?

The fuel cell is the obvious answer to this question, but this is also not without its own issues and hurdles to overcome. The current generation of fuel cells are primarily designed for land or marine based applications and consequently are not particularly mass or volume efficient from an aviation perspective.

Fuel cells are a complex system, reliant upon close control of a number of parameters including fuel and air flow as well temperature control. Fuel cells also tend to have a slow response time, so fuel cells are usually coupled with a suitably sized battery pack which acts twofold. Firstly the battery provides additional energy to supplement the fuel cell when required, but also acts as an energy sink when there is regenerative energy, such as coming into land with an idling propeller. There have been a number of unsuccessful and successful fuel cell powered experimental flights, the most recent of which being a modified Dornier Do 228 at Cotswold Airport. Consequently, a complex balance of plant control architecture is required to balance the everchanging flight requirements against the energy available from the fuel cell and battery system, whilst at the same time keeping the fuel cell in its optimum operating window and maintaining regenerative capacity. Having created a hydrogen fuel containment pressure vessel, balanced fuel cell system and mated this to an electric motor and suitable inverter, via reduction gearing to a propeller, the next hurdle will be certifying this against as yet unpublished standards and shifting airworthiness mindsets. ■

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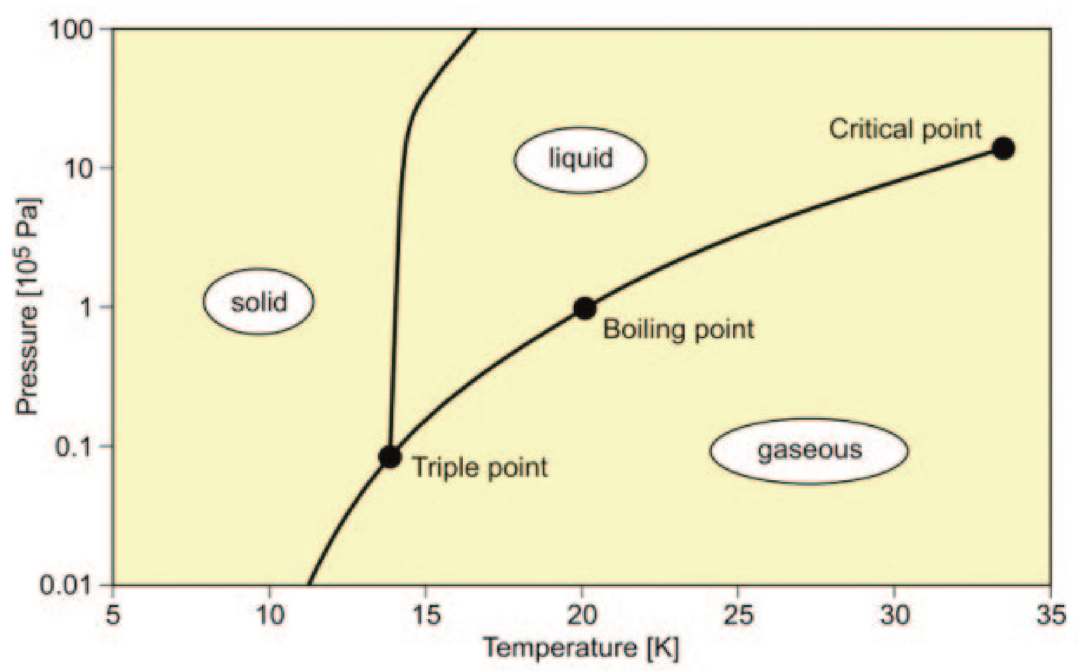
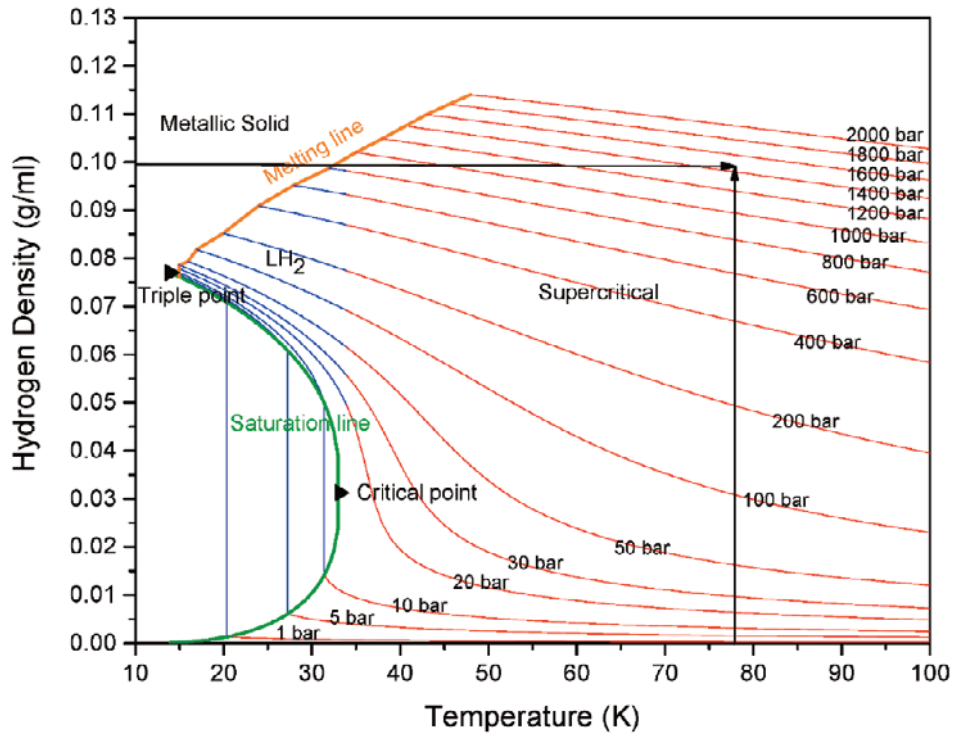
Phase diagram of hydrogen



Phase diagram showing the hydrogen density as a function of temperature at different pressures



Typical Hold Times, sLH2

sLH2 Unique Properties		
Operating Pressure		4 to 8 Bar
Hold Time vs. sLH2 volume	@100%	10 h
	@80%	130 h
	@50%	200 h
	@20%	130 h

Simplified Fuel cell Architecture