Aerospace Propulsion AERO2356

The viability of hydrogen and methanol fuel as an alternative to Jet A1

Research Project
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Link to Presentation Video
https://www.youtube.com/watch?v=Q0FL-cMGs1w

Consideration of the existing literature and the state of carbon neutral alternative fuels.

Significance

During 2019, around 4.5 billion passengers traveled through the air. The aviation industry is also responsible for about 5% of all human caused global warming (Lee et al., 2021). The aviation industry is a difficult sector to reduce carbon emissions, due to the nature of jet fuel being extremely high in energy content, both per unit mass and per unit volume. With these two important qualities, regular A1 jet fuel is very difficult to replace, without significant costs and aircraft performance ramifications (Mukhopadhaya and Rutherford, 2022).

There is growing interest in liquid hydrogen as an aviation fuel, due to its zero CO2 emission, especially if created using renewable energy. The two significant caveats are, the low energy density of liquid hydrogen and the cryogen requirements. Both these factors will significantly increase the weight of the aircraft leading to performance penalties. Although, the latter factor may be solved through the implementation of cryo-compressed hydrogen gas that may be available at future airports.

The US Department of Energy report shows that commercial propeller and air transports could reduce turboprop aircraft energy usage by 40-60%, and emissions by 90% through the use of methanol (Alternative Fuels Data Center: Methanol, 2022). Although significantly less energy density than jet A1 or liquid hydrogen, methanol is cheap to produce, readily available and technology to utilize it is already in existence.

Literature Review

Even though total energy consumption in aviation has increased, the aviation industry has significantly improved efficiency through technological and operational improvements (Rao, Yin and Werij, 2020). System wide fuel consumption has been reduced by more than 50% in the last 50 years.

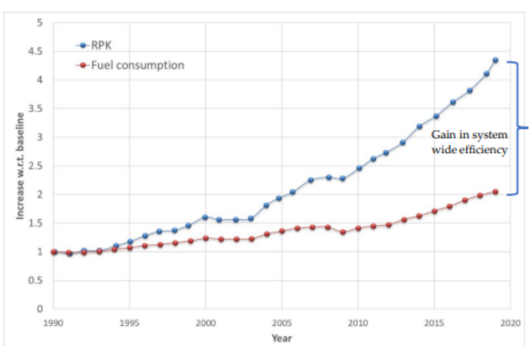

Figure 1: (Rao, Yin and Werij, 2020)

There are several factors that will determine the fuel selection of aircraft, which includes fuel price, availability and emissions. There is currently a sole dependence on kerosene, the equivalent to A1 jet fuel.

For aircraft, the most important criteria is the energy density, this is due to the fact that weight and volume are key factors in aircraft efficiency. Specific energy density and volumetric density are both excellent for Jet A1 fuel or kerosene. Biofuels such as methanol have very similar energy density to Jet A1, however, their availability and costs make them significantly less attractive. In terms of cryogenic hydrogen, LH2 has very high specific energy density but very poor volumetric energy density. This means that we would require a much larger volume (about four times the volume of kerosene) to carry an amount of LH2 necessary for air travel (Rao, Yin and Werij, 2020).

Infrastructure required for production, storage and distribution of cryogenic hydrogen, and biofuels means that until we have reached a certain technical maturity, it will be very difficult to motivate airlines to adopt cryogenic hydrogen or biofuel technologies.

In conclusion, the requirements for cryogenic fuels means significant storage capacity as well as new carrier models to account for the huge volumetric requirements. Bio-fuels such as methanol have already been adopted into certain blends, but the net carbon costs from production, storage and transportation are still lacking for current airline adoption.

Evaluating PSFC values for engines running on hydrogen or methanol.

Three types of fuel were assessed and assumptions were made regarding engine efficiencies, these values are within a reasonable range as they are comparable for other turboprop engines.

Table 1: Engine properties and efficiencies

Engine Properties	Value	Units
Turbine entry temperature (T04 /K)	1500	K
Turbine adiabatic efficiency	0.9	%
Compressor adiabatic efficiency	0.85	%
Combustion (burner) efficiency	0.95	%
Diffuser adiabatic efficiency	0.9	%
Nozzle adiabatic efficiency	1	%
Compressor pressure ratio (P03/P02)	6	Ratio
Turbine pressure ratio (P04/P05)	6	Ratio

When assessing engine performance, an altitude of 10,000m was taken as the cruise altitude of the aircraft. A Mach number of 0.6 was chosen due to the efficiency losses associated with higher Mach numbers and turboprops. The values for the gas constants and ratios for jetA1 was taken from the AERO2360 course program. As for the hydrogen and methanol related values, they were referenced from the engineering toolbox.

Table 2: PSFC values, engine considerations and air conditions.

Properties	Units	Jet A1	Hydrogen	Methanol
Heating value of fuel / (J/kg)	J/kg	42800000	120000000	23000000
Cruise Mach number		0.6	0.6	0.6
Cruise altitude	m	10,000	10,000	10,000
Ambient temperature at cruise altitude	K	288	288	288
Ambient pressure at cruise altitude	Pa	101325	101325	101325
Gas constant	J/(kg K)	287.14	4124	259.5
Ambient density	kg/m3	1.225	0.085	1.356
Ratio of specific heats of air		1.4	1.41	1.23
Speed of sound	m/s	340.3	1294.1	303.2

Flight speed	m/s	204.2	776.5	181.9
Specific heat of air, cp	J/(kg K)	1005	14304	3620
Freestream specific enthalpy, ha	J/kg	289440	4119552	1042560
Freestream specific stagnation enthalpy, h0a	J/kg	310279.5	4420993.3	1059106.6
Post diffuser specific stagnation enthalpy, h02	J/kg	310279.5	4420993.3	1059106.6
Post diffuser stagnation pressure, P02	Pa	126227.5	126174.8	109309.2
Post compressor stagnation pressure P03	Pa	757364.8	757048.6	655855.4
Post compressor specific stagnation enthalpy, h03	J/kg	554309	7977157.7	1555020.8
Specific work of the compressor	J/kg	244029.5	3556164.4	495914.2
Post combustor specific enthalpy, h04	J/kg	1507500	21456000	5430000
Actual specific work of the turbine	J/kg	543599.6	7841537.7	1391298.2
Specific heat release in the combustor	J/kg	953191	13478842.3	3874979.2
Fuel-to-air ratio		0.02435	0.14565	0.23599
Post turbine pressure, P05	Pa	126227.5	126174.8	109309.2
Nozzle pressure ratio, P06/P7 assuming P7 =Pa		1.24577	1.24525	1.0788
Post turbine specific stagnation enthalpy, h05 = h06	J/kg	963900.4	13614462.3	4038701.8
Nozzle exit specific enthalpy, h7	J/kg	905241.4	12773266.2	3981825.6
Nozzle exit velocity	m/s	342.5	1297.1	337.3
Specific thrust of core flow	Ns/kg	146.7	709.5	235
Specific power output of shaft	J/kg	299570.1	4285373.3	895384
PSFC	g/kw s	0.0813	0.034	0.2636

After predicting the PSFC values a variety of graphs were plotted in order to better assess performance variance and consider how fuel type affects the final performance. Mach number, Compressor ratio, and turbine entry temperature were selected to be analyzed over the PSFC(g/N.s) and PSFC(g/Kw.s) in order to find the best performance.

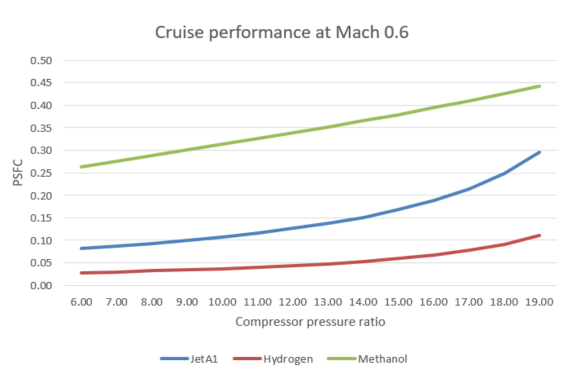

Figure 2: Cruise performance on Mach number

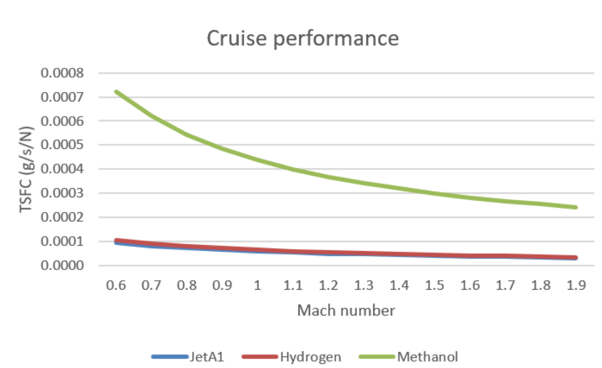

Figure 3: Cruise performance on compressor pressure ratio

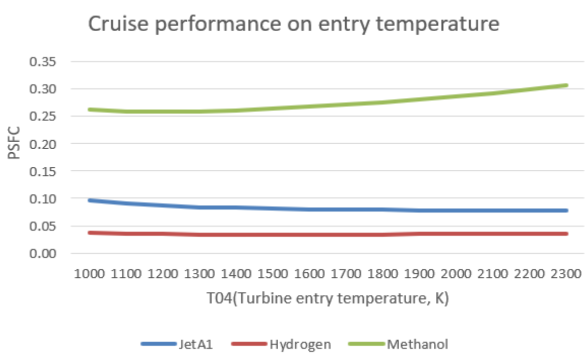

Figure 4: Cruise performance on entry temperature

As can be seen in these graphs - hydrogen shows a better performance when compared with the other fuels types, and it should also be noted that even though hydrogen is better in the three aspects mentioned above, it has a low density, and so requires a larger fuel tank for long range flights. This impacts the aircraft design and makes some analysis inaccurate. Another interesting point is that turboprops tend to have poor performance at supersonic speeds so the values over mach 1.0 are not reliable.

Assessing fuel burn and minimum tank size.

In this section we calculate the required fuel weight and tank size for each fuel type over a range of 500km. Taking the values for PSFC in **Figure 2** above for the 3 Fuel types we can use the Breuget Range Equation to approximate the mass of each fuel required for a given range. We can then take the resulting fuel mass and along with the relevant densities calculated at the fuel storage temperature and pressure combine these values to acquire the required volume. To account for fuel expansion we include a ullage, this was calculated at an additional 10% of the fuel volume.

Table 3: Outlining the necessary tank volume required based on a 500km range, for A1, Hydrogen and Methanol.

Value/Assumption	**Hydrogen**	**Methanol**	**A1**	**Units**
Flight Velocity	204.2	204.2	204.2	m/s
Effective PSFC	2.09E-03	4.98E-05	2.22E-03	
Aircraft Weight without Fuel (ATR 72 2020)	17000	17000	17000	kg
Fuel burn for Breguet range of 500 km	13771	214	15017	kg
Actual fuel load carried take-off	13771	214	15017	kg
Internal fuel tank storage temperature	333.15*	77†	333.15*	K
Internal fuel tank pressure	0.101325*	35†	0.101325*	MPa
Fuel density (aircraft storage)	765&	65	792	kg/m^3
Fuel volume at take-off	18.00	3.29	18.96	m^3
Necessary tank volume (including ullage)	19.80	3.62	20.85	m^3

* (*Fuel and oil safety ADVISORY CIRCULAR AC 91-25 v1.0 For Flight Operations Regulations commencing on 2 December 2021* 2021)

† (Kunze & Kircher n.d.)

& (*Fuel Density* n.d.)

Technical Modifications

Necessary technical modifications to the aircraft in order to convert it from Jet A1 to cryo-compressed gaseous hydrogen and/methanol usage.

There are several reports that evaluate the use of hydrogen in turbine engines. Riple (1992) suggests that a complete redesign of the combustor using newer technologies is needed in order to make use of hydrogens properties, making use of a combustor that is smaller and has a greater pattern factor. Riple (1992) also suggests that a redesign of the turbine cooling system is needed as the lower temperatures of the hydrogen cooled air could cause problems. These lower air temperatures could cause higher thermal gradients that would result in low cycle fatigue damage Riple (1992). Riple (1992) suggests development of a new cooling system with coinciding development of new turbine blades with a higher cyclic fatigue strength.

Another problem to overcome is the issue of the current fuel pumps not being able to be adapted to the properties of hydrogen. While there are many hydrogen fuel pumps, many of them are developed for rockets, this gives them low cycle times Riple (1992). Due to hydrogens density being around 1/11th of kerosene based fuels a pump needs to be developed will need to have greater Head, flow range and suction) Riple (1992).

The fuel system would need a complete overhaul. As cryo compressed hydrogen is stored at much higher pressures than jet a1, the tanks would need to be replaced with heavy pressure vessels(Mukhopadhaya and Rutherford). The fuel system would also need to account for any phase change between the hydrogen itself having to deal with both liquid hydrogen and vapor Riple (1992).

Conclusion

Based on these findings we find both Methanol and Hydrogen to be viable fuel types. Although it is notable that Methanol can more readily replace Jet A1 as the infrastructure and engine configurations for management, storage and combustion are interchangeable (with minor modifications) regardless of fuel type. The largest issue with Methanol is in the production as it needs to be done in an environmentally considerate way, this would likely require large amounts of arable farm land or advances in indoor growing tech to be viable. Hydrogen in contrast is a highly abundant fuel but its low density introduces the need for a complicated fuel storage, transport and combustion system. This means although hydrogen fuel is a viable option work needs to be done regarding the conversion or creation of infrastructure capable of managing hydrogen. The issue is therefore not an issue of hydrogen performance in this regard we have shown it is a good alternative, the issue is the funding needed to convert billions of dollars worth of infrastructure on the chance that hydrogen fuel is the future of aviation. This is a big ask when there has been no real need to consider and invest in alternatives until the somewhat recent climate change backlash and awareness which seems to have motivated the aviation industry to look more seriously into alternatives. For the near future our belief is that Jet A1 will still remain dominant with carbon neutral methanol starting to become common and hydrogen solutions taking up the rear and/or being used in other more viable industries first.

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