Mitigating the Climate Impact of Aviation – What does Hydrogen Hold in Prospect?

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Abstract

This article discusses the impacts of aviation on global climate change, and shows attempts of the aviation industry to mitigate those impacts by means of the usage of alternative fuels. Special respect of this paper is given to the use of hydrogen as aviation fuel. Examples of practical and theoretical research projects on the application of hydrogen are presented and the current outlook towards an introduction of hydrogen into practice is presented. From a technological point of view hydrogen as aircraft fuel is feasible. However, in the current attempts of aviation industry to improve environmental friendliness hydrogen is not included as a measure within the foreseeable timeframe due to large financial and technical efforts.

INTRODUCTION

"Gliders use the energy of up-currents, while solar powered vehicles use the energy from the sun. Human-powered flight has also been demonstrated. Propulsive power for any other "down to earth" flying depends on fuel. This fuel is used in the aircraft main engines." (Scholz, 2003)

The meaning of aviation for economy and society

International air traffic and logistics are key factors for today's global community, economy and trade relations. The fast and safe transport of people and cargo allows for business and leisure flights and enables the intercontinental transport of perishable goods and express freight. Furthermore, aviation creates millions of jobs in aviation directly but also in related industries and service sectors. In detail, the Air Transport Action Group (ATAG), a coalition of several organizations and companies throughout the global air transport industry, states that 32 million jobs are globally generated by the air transport industry, of which:

- 17 % are directly linked (airports, airlines, manufacturing industry),
- 20 % are indirect jobs through purchases of goods and services (supply chain),
- 9 % are induced jobs through spending of industry employees, and
- remarkable 54 %, i.e. 17 million jobs are created through air transport's catalytic impact on tourism (ATAG, 2009).

With special respect to developing countries, "Tourism is one of the main export earners for 83% of developing countries and it is the principal export earner for one third of them. It is also a significant generator of employment: in twelve countries, employing one in five, and, in two instances (Maldives and Anguilla), employing over one half of the country's population…" (RGS-IBG, 2006). Consequently, these countries are especially dependant on air traffic as well. In total (direct, indirect, induced and catalytic), aviation's global economic impact is estimated as 7.5 % of the world Gross Domestic Product (GDP) (ATAG, 2009). Moreover, worldwide air traffic of passengers and cargo is still expected to continue expanding even in the light of the actual world economic crisis (Embraer, 2009). Annual growth rates over the next two decades are estimated as 4.9 % for passenger transport and even 5.8 % for cargo transport (Airbus, 2007; Boeing, 2008). This means that air traffic doubles roughly every 14 years.

The environmental effects and efforts of aviation

The global climate is warming, and there is very high confidence that human activities have been contributing to that (Penner et al., 1999). The carbon dioxide and other emissions of aircraft also add to this – especially because these emissions are produced in high altitudes. In its special report "Aviation and the Global Atmosphere" the International Panel on Climate Change (IPCC) stated in 1999 that it is estimated that 3.5 % of all anthropogenic contribution to climate change, expressed as 'radiative forcing', is due to air traffic (Penner et al., 1999). Figure 1 shows the estimated contribution of air traffic to the climate change, under different future scenarios. These scenarios reach from the low-growth scenario Fc1 (2.2 % annual traffic growth and broad technology improvements) to the high-growth scenario Edh with 4.7 % average annual traffic growth and technology improvements mostly concentrated on nitrogen oxides emissions. All scenarios predict rising radiative forcing, however, none of those scenarios include the use of hydrogen or other alternative fuels.

From an industry perspective, the International Air Transport Association (IATA), which is the international industry trade group of airlines, states in its leaflet "Debunking Some Persistent Myths about Air Transport and the Environment" (IATA, 2009a) that air transport is responsible for only 2 % of all global man-made CO2 emissions but supports 8 % of the global economic activity. On its website IATA writes that “The best estimate of aviation's climate change impact is about 3% of the total contribution by human activities. This may grow to 5% by 2050.” (IATA, 2009b). With a full passenger load, a modern jet consumes about 3.5 l/100 km per passengers. This is only 1/3 the consumption of a jet in the 1950s.

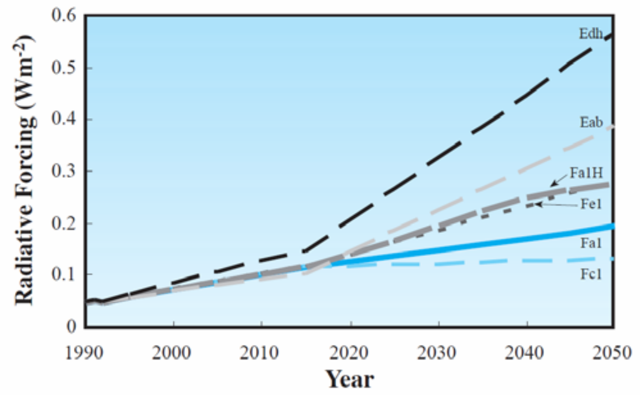

FIG 1. Estimates of the globally and annually averaged total radiative forcing (without cirrus clouds) associated with aviation emissions under different scenarios to 2050 (Penner et al., 1999), with Fa1 as the reference scenario that assumes improvement in fuel efficiency and mid-range economic growth

However, a return trip from Frankfurt to Sydney for a family of four amounts to 10 times their annual electrical energy consumption. A compact car consumes with about 1.5 l/100 km per passenger still considerably less than a modern jet. On a social level, aviation is facing increasing challenges: In recent years, an increase in public awareness of the climate change has been noticeable. Also, the general environmental consciousness has increased, and the public perception of aviation is becoming more critical. On a political level, the European Parliament decided in 2008 to include aviation into the emissions trading scheme of the European Union for carbon dioxide from 2012 on (European Parliament, 2009). Further environmental effects, besides global warming, that are linked to air traffic are noise, local air quality and land use due to an increase in the number of airports and airport growth. Regarding noise, numerous airports have introduced noise surcharges through individual sets of measures according to their specific needs (Krammer, 2009). Consequently, much effort is also spent on noise abatement procedures and the reduction of noise at the source, especially at the engine. Especially logistic companies are affected by night time operational restrictions, as their aircraft are most often operated during the night in order to deliver express freight during the office hours.

In the light of these enormous challenges, the Advisory Council for Aeronautics Research in Europe (ACARE) in 2001 set up the “Agenda for the European Aeronautics’ Ambition” referred to as “Vision 2020”. In this agenda, the two European top-level goals of “meeting society’s needs” and “winning global leadership“ are addressed through a series of goals, such as

- Reduction of the number of accidents in air transport by 80 %,
- Reduction of noise emissions by 50 %,
- Reduction of carbon dioxide emissions by 50 % and
- Reduction of nitrogen oxides emissions by 80 % in reference to year 2000 standards (ACARE, 2001).

These challenging goals put very high demands on future aircraft designs. Moreover, improvements in parameters like fuel burn and noise as well as fuel burn and nitrogen oxides emissions are conflicting. Thus, the outcome can only be a compromise. However, current developments in technology do not show the potential to achieve the ACARE percentages. Furthermore, the total amount of emissions is expected to increase as the rapid growth of air traffic outpaces the achievements of new technologies to safe fuel. In order to meet future fuel demands and lower the environmental impact of transport, the consequences have to be a combination of three aspects:

- higher fuel efficiency of current and future aircraft,
- alternatives to kerosene that are sustainable and cause a smaller carbon footprint (IATA, 2009b), and
- reducing the need to fly, e.g. by means of internet communication.

FUEL: KEROSENE AND ITS ALTERNATIVES

The world’s crude oil resources are limited. In the foreseeable future, crude oil will no longer be able to accommodate demand, as the worldwide energy consumption is permanently rising due to a growing world economy. The consequences are increasing fuel and energy prices in general and depleting resources. Thus, the time has already come to search for alternatives that can replace crude oil (BGR, 2007).

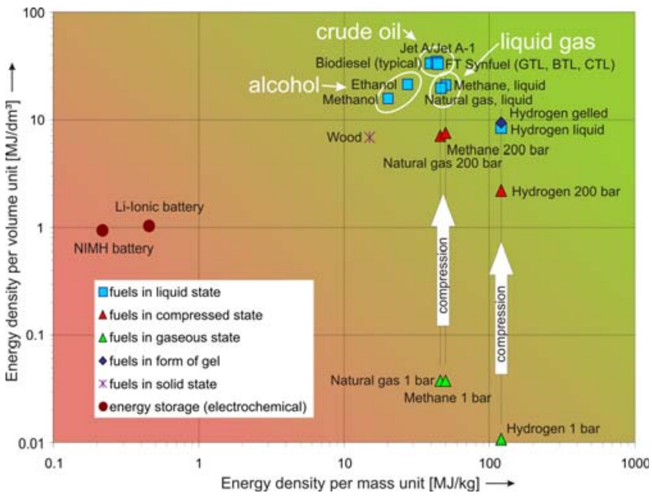

FIG 2. Volumetric and gravimetric energy contents of different fuels and batteries on a double logarithmic scale (based on Sieber, 2009)

Figure 2 shows a comparison of the energy densities of different fuels and batteries with respect to their energy-specific volume and mass on a double logarithmic scale. It becomes apparent how high the energy contents of crude oil-based fuels are. Their volumetric energy density, for example, is more than thirty times higher than the ones of batteries, which in return means that for the storage of the same energy content batteries need more than thirty times the volume that e.g. kerosene (Jet A/Jet A-1) needs. Also, between kerosene and liquid hydrogen there is still a factor of about four – again in favour of kerosene. With respect to mass, the factor between kerosene and liquid hydrogen is three; this time to the advantage of the liquid hydrogen. This means that same energy content has one third the mass of kerosene when stored in the form of liquid hydrogen. These numbers illustrate the very high demands posed to the alternatives that compete with current crude-oil based fuels. Energy storages in these forms become very voluminous and/or very heavy.

Hydrocarbons

Today's aviation fuel kerosene (Jet A/Jet A-1) has an energy content of 42.8 MJ/kg, and the combustion of 1 kg of kerosene requires 3.4 kg of air oxygen. Combustion products are 3.15 kg of carbon dioxide (CO2), 1.25 kg of water vapour (H2O) as well as further reaction by-products like nitrogen oxides, sulphur oxides and soot. The exact amounts of these by-products are highly subject to engine technology.

Synthetic fuels are very often produced by means of a chemical process named after its inventors Fischer and Tropsch. Thus, they are also referred to as FT-fuels. They mark an interesting alternative to conventional kerosene, as their volumetric and gravimetric energy densities lie in the same region as those of conventional kerosene. Their handling qualities are also widely the same as those of the actual fuel. The most important synthetic fuels today are called GTL (gas-to-liquid), CTL (coal-to-liquid) and BTL (bio-to-liquid) depending on their raw material. However, only the latter one has the chance to be judged 'climate-neutral', since GTL and CTL still rely on fossil fuels.

The challenge today is to develop a fuel that is sustainable and exhibits low pollutant emissions over its whole life-cycle from production to combustion (well-to-wing). Beside different feedstocks, there are also different production processes under investigation in several laboratories or relatively small production facilities especially in the United States (Decker, 2008). However, it will still take some time to ramp up production rates from laboratory size to industrial application. According to IATA's Report on Alternative Fuels (IATA, 2008), it does not appear possible at this time that a 100 % sustainable fuel source will be available for the aviation industry.

Hydrogen

The production of hydrogen is significantly different to that of conventional kerosene or other crude oil-based fuels. In nature, hydrogen does not exist in a pure form. Consequently, hydrogen has to be separated from a feedstock first, and only parts of the invested energy for this purpose can be recovered during its use afterwards. Hence, hydrogen must not be regarded as an energy source like e.g. crude oil or wood, but must be considered an energy carrier like a battery.

Hydrogen has an energy content of 122.8 MJ/kg. The combustion of 1 kg of hydrogen produces 9 kg of water vapour and up to about 90 % less nitrogen oxides compared to the combustion of fossil fuels (NOx, dependant on engine technology) (Funke, 2009). So, the combustion of hydrogen generates a multiple of water vapour but significantly less NOx than the combustion of an energy-equivalent amount kerosene. The development of nitrogen oxides cannot be avoided completely, since the surrounding air with 78 % of nitrogen, which is a reactive gas, is involved in the combustion process. In total, the use of hydrogen as future fuel for aviation offers the advantage to be an unlimited resource that, on top, contributes to a much more environmentally friendly operation of aircraft. However, today, more than 90 % of hydrogen is produced by reforming natural gas. The end products of the reforming process are hydrogen and carbon dioxide. Thus, although the combustion of hydrogen generates no carbon dioxide the reforming process itself produces a lot of this greenhouse gas. A more promising method to obtain pure hydrogen is called electrolysis. In this process, water is split up into hydrogen and oxygen by means of electricity. Thus, if the electricity is generated from renewable energy the production of hydrogen shows very low emissions.

With respect to safety, "Safe handling of hydrogen is no longer a problem in the industrial and commercial area" (LTH, 2008). It has been used for decades in various applications such as space flight or chemical industry. Nevertheless, it is important to stress out the cryogenic character of liquid hydrogen. Contact with liquid hydrogen, e. g. caused by a leakage, causes severe damages of the skin. Hydrogen has to be stored at below 22 K (-251 °C) to be available in liquid state (Brewer, 1991).

Batteries

Figure 2 illustrates that batteries do not have sufficient energy densities to lend themselves as energy storages for airborne applications, although there has been significant progress in recent years. Current and foreseeable energy densities are too low to compete with kerosene. Moreover, there are still a number of unanswered questions concerning aspects such as pollutants and non-recyclable materials in their production process and disposal as well as life-time and charging time.

Comparison of environmental impacts

For an overall environmental assessment of alternative fuels the resulting effects of an industrial production have also to be taken into account. Feared effects of otherwise very promising biofuels are e.g. the conversion of cropland for food production or rainforest into cropland for the production of energy crops. This could cause deforestation and biodiversity loss as well as a competition between these plants for fresh water. Concerning algae the implications of mass production on sea flora and fauna are not known yet (Kuhlmann, 2009).

Figure 3 compares the carbon dioxide emissions of different fuels over their whole life-cycle in relation to conventional kerosene. It becomes apparent that especially coal as raw material for the production of different fuels leads to significantly larger carbon dioxide emissions than today's kerosene when regarding the whole life-cycle. Biofuel and liquid hydrogen produced from water and nuclear power, hence, by means of electrolysis, show significantly less CO2 emissions. The emission level of the liquid hydrogen from water and nuclear power is even close to CO2-neutral. However, the use of nuclear power is highly controversial. Alternatives for the generation of the required electrical energy would be e.g. solar energy and wind energy.

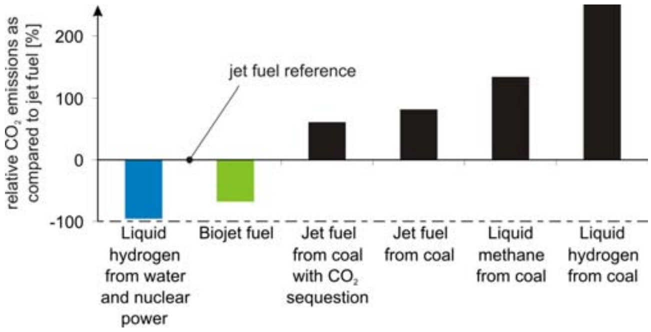

FIG 3. Relative carbon dioxide emissions of different alternative fuels over their whole life-cycle compared to conventional kerosene (based on IATA, 2008)

The climate impact of condensation trails, in short contrails, which form behind aircraft under certain atmospheric conditions in altitudes greater than 8 km is not so well understood yet. The already mentioned IPCC special report stated in 1999 that “Contrails tend to warm the Earth’s surface, similar to thin high clouds.” (Penner et al., 1999). More recent investigations support this tendency (Schumann, 2008). Due to their significantly larger emissions of water vapour, this is especially important for hydrogen-powered aircraft as it has effects on their climate impact and/or operational conditions if such aircraft have to stay out of the critical atmospheric conditions.

HYDROGEN-DRIVEN AIRCRAFT

The grown environmental awareness of the society has also reached the aircraft manufacturers. While in the last century the aircraft design process was mainly driven by purely economic factors, which focused on low operational and ground handling costs, now priority also comes to the environmental impacts of an aircraft. Ideally, the task is to provide society in the future with the same standards of mobility as today, but to achieve the environmental objectives in parallel. From the present technical perspective hydrogen-powered aircraft appear to have the potential of fulfilling both requirements.

The integration of a hydrogen propulsion system into an aircraft is not trivial. The large storage volume for the low-density fuel can be placed on the outside of the aircraft e.g. on top of the fuselage (see Figure 4) with a significant increase in drag and fuel consumption. Alternatively, the storage volume can be placed inside the aircraft’s fuselage (see Figure 5), which decreases the available space for passengers or cargo.

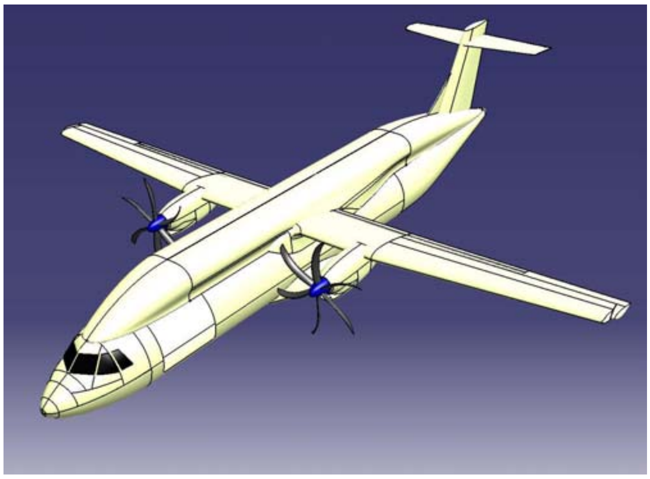

FIG 4. Regional cargo aircraft with fuel stores mounted on top of the fuselage

Flying aircraft

One approach towards hydrogen-powered demonstrator aircraft was the Russian Tupolev TU-155 (see Figure 5). It first flew in 1988 as a test and demonstrator vehicle, and one of the three engines could be run on liquid hydrogen or alternatively on liquefied natural gas. In the 1990s, the idea was continued theoretically by a Russian-German research collaboration.

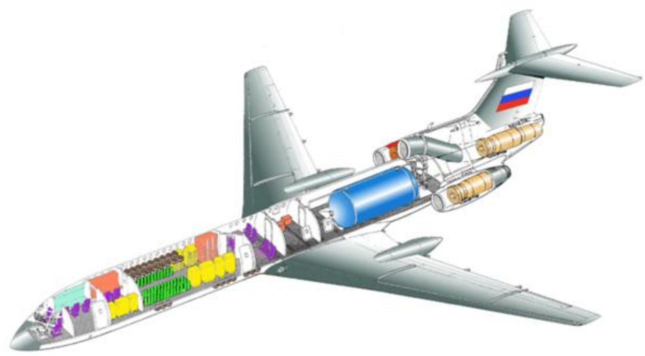

FIG 5. Russian Tupolev TU-155 (Tupolev, 2009)

Theoretical aircraft studies

Cryoplane

From 2000 to 2002 36 universities, research agencies and industrial partners of different nations all over Europe participated in the so-called “Cryoplane” project (see Figure 6) under Airbus leadership. Its objective was the theoretical investigation and re-design of several hydrogen aircraft types of different size (Westenberger, 2003). A real aircraft or mock up has not been built.

FIG 6. Hydrogen-powered medium-range aircraft (Forschungszentrum Jülich, 2006)

Green Freighter

The Green Freighter project is a joint research project with focus on the design and investigation of hydrogen-powered freighter aircraft. The project partners are the Hamburg University of Applied Sciences (HAW), the Institute of Aircraft Design and Lightweight Structures (IFL) of the Technical University of Braunschweig, Airbus and the engineering office Bishop GmbH. As the air cargo chain includes different types and sizes of freighter aircraft, the investigations include freighter aircraft from small regional, so-called feeders, to large long-range freighters. The ATR 72 full freighter version was chosen as the regional and the Boeing B777F as the large reference aircraft (Seeckt et al., 2008; Scholz, 2009a).

Figure 7 shows an example of a short-range aircraft that has been converted from kerosene to hydrogen as fuel. Investigations indicate that, based on current kerosene and an energy equivalent hydrogen price, such aircraft are not economically favourable (Seeckt et al., 2009).

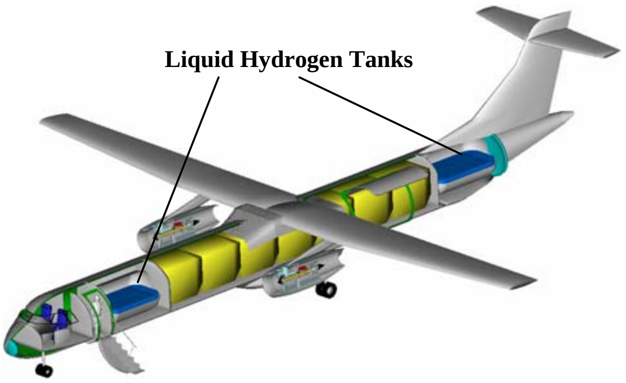

FIG 7. Hydrogen-powered regional cargo aircraft with fuel tanks inside the fuselage

Besides the investigation of hydrogen only on conventionally shaped aircraft, the Green Freighter project also comprises unconventional aircraft configurations, namely the Blended Wing Body (BWB) configuration (see Figure 8). In combination with the new aircraft layout the airplanes will then be even more fuel-efficient and environmentally-friendly.

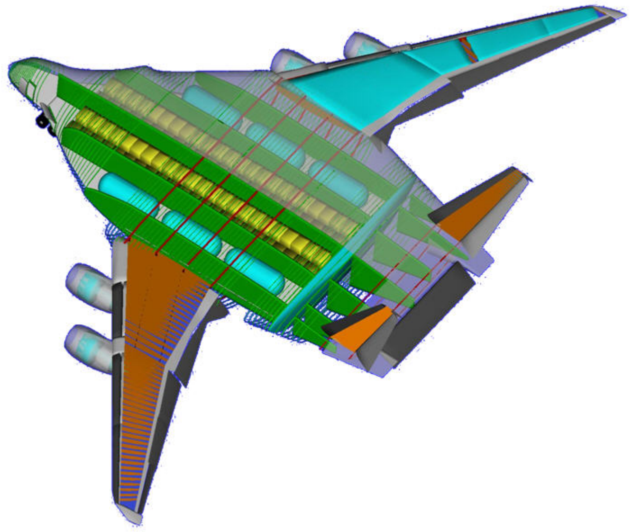

FIG 8. Blended Wing Body with (hybrid) hydrogen-propulsion technology

Hybrid-powered experimental freighter

The overall concept of a demonstrator aircraft has to be technically effective and at the same time simple in order to avoid extra spending on time and money. This leads to a hybrid propulsion concept which means that the right engine is powered by liquid hydrogen while the left engine remains unchanged and is operated on conventional kerosene. This special architecture decreases the emission during cruise by 50 %.

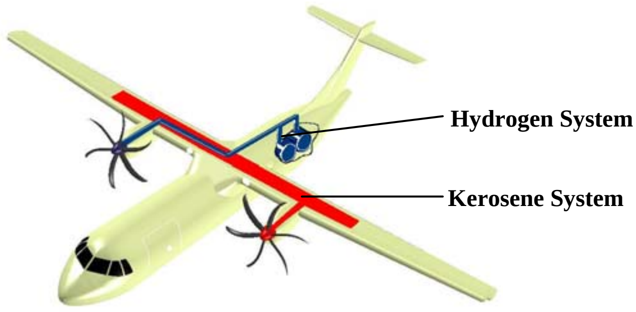

FIG 9. Hybrid-powered demonstrator aircraft

As with normal aircraft, during taxi, only one engine is operated. In this architecture, the active engine is the hydrogen-powered one. The hydrogen engine is also used for the power supply of the aircraft on the parking position. The propeller is decoupled from the engine in this mode and does not rotate. Thus, ground operation without CO2 emissions becomes possible and local air quality within the vicinity of airports is being improved.

The demonstrator aircraft is set up on the basis of the regional cargo aircraft ATR 72. The turboprop concept in combination with a moderate cruise speed is well known to be generally very fuel-efficient (Snijders & Slingerland, 2007), which further decreases the fuel that is needed to fly a certain reference mission.

This aircraft operates at cruising altitudes below 8 km, where the formation of contrails is very unlikely. The hydrogen engine is fed from two identical liquid hydrogen tanks, mounted in the rear of the aircraft. These tanks as well as the supply ducts have to be specially insulated due to the fuel's low storage temperature. In general, cargo aircraft offer a good possibility of demonstrating experience in the application of hydrogen, because psychological concerns of passengers do not need to be taken into account.

After the demonstration of reliability and safety by a liquid hydrogen-powered demonstrator aircraft, the next step could be to establish this technology in the commercial air cargo operation.

AIRCRAFT SYSTEMS

Tasks and impact of aircraft systems

Broadly speaking, an aircraft can be subdivided into three categories:

1. the airframe (the aircraft structure)
2. the power plant (the engines)
3. the aircraft systems (the equipment).

Aircraft systems comprise all the many mechanical, electrical, and electronic items, devices and components, which are installed in an aircraft for the various purposes.

Aircraft systems are needed to steer the aircraft (flight controls) and to handle it on the ground (landing gear). A fuel system is necessary for powered flight. Aircraft flying longer distances need navigation and communication systems; aircraft flying higher and taking passengers on board need cabin systems like air conditioning and oxygen systems. All these systems consume energy during their operation (Scholz, 2003).

The engines on an aircraft produce thrust in order to overcome aerodynamic drag and to accelerate the aircraft to the desired speed. The power required to achieve this is referred to as propulsive power. Power that does not contribute to the propulsion of the aircraft but is nevertheless needed during flight to operate the various aircraft systems is referred to as secondary power.

The consumption of secondary power is about 5 % of the total fuel consumed during the flight (Scholz, 2009b). 5 % is not much, but if we consider the absolute amount of fuel being burned on aircraft it definitely makes sense to consider also the impact of aircraft systems.

Energy types of secondary power systems are:

- electric,
- hydraulic (special hydraulic fluid under pressure),
- pneumatic (air under pressure).

Aircraft engines normally (e. i. during taxiing and in flight) provide all secondary power requirements onboard through electricity comes from generators attached to the aircraft engines, hydraulic power comes from engine driven hydraulic pumps and pressurized air is taken directly from the engine compressor ("bleed air").

On the ground with engines shut off or in certain failure cases in flight, secondary power comes from an auxiliary power unit (APU). Traditionally the APU is a gas turbine providing electric and pneumatic power. Hydraulic power is produced from electric motor driven pumps. Major airports provide secondary power to the aircraft so that there is mostly no need to run the APU once the aircraft is taken care of by the airport.

Greening of aircraft systems

As for the aircraft as a whole, the approach to greening of aircraft systems was and is to improve the efficiency. Measures of improving the efficiency of aircraft systems are: better efficiency of consumers, fewer steps of energy conversions, better efficiency in power generation, improved / less / no bleed air usage, reduced system mass, reduced ram air, reduced amount of added drag. Aircraft technology is today already quite mature. For this reason, it has become difficult to achieve further savings. A recent EU research program "Power Optimised Aircraft" (EU, 2004) claims that fuel savings in aircraft systems of 5 % would be achievable (Faleiro, 2006) i.e. 4,75 % instead of 5 %, hence saving (only) 0,25 % of total aircraft fuel burn. This saving potential is not much but will have to be considered because every effort helps.

Since most of the time (during cruise) secondary power for aircraft systems comes from the engines, an important statement is: "Aircraft systems are green if the engines are green". That means, if e.g. engines run on environmentally compatible hydrogen or bio fuels than automatically, all power on board is also produced from these green fuels. It would be possible to achieve in this way sustainable aircraft systems operation without the need for a change of aircraft systems technologies. Even old aircraft running on bio fuel would have the benefit of green systems.

Another vision (Heinrich, 2007) is to decouple secondary power production from the engines. In all phases of flight, secondary power would come from a fuel cell. The fuel cell directly converts fuel into electricity without burning the fuel. This totally different conversion principle from fuel into electrical energy has an efficiency that could safe up to 20 % to 30 % of fuel (Heinrich, 2007) in aircraft systems, hence saving about 1 % of total aircraft fuel burn. The fuel cell runs on hydrogen. This means that a fuel cell could be integrated nicely into a hydrogen powered aircraft that already stores hydrogen in large quantities for engine operation. If no hydrogen is available on board, kerosene could be converted into hydrogen (reforming) for fuel cell operation.

If the new fuel cell technology would be combined with using environmentally compatible hydrogen or bio fuels, than aircraft systems would be sustainable saving in addition considerable amounts of energy compared with aircraft systems of today's technology.

The fuel cell has some "by products" that make it especially interesting to integrate such a multifunctional fuel cell.

Multifunctional fuel cell

The application of the fuel cell in aviation is often referred to as multifunctional fuel cell because of additional advantages that are indirectly linked to fuel efficiency.

A continuously running fuel cell produces:

- oxygen-depleted exhaust gas that can be used for fuel-tank inerting (Doyle, 2008), decreasing the explosion risk, and
- water that can be used for
  - flushing toilets or for tap water (after a thorough purification and enrichment with minerals) (EADS Innovation, 2009) and hence reducing aircraft weight of otherwise carried water in tanks,
  - passenger amenities such as water for showers,
  - cabin humidification, or
  - water injection into the engines with the aim of increasing engine life and reducing costs and NOX emissions (Snyder, 2009)
- rejected heat could be used in heat exchangers to e.g.
  - heat up the fuel to required temperature or
  - to heat the wing leading edge for wing anti-icing.

With electricity from a fuel cell the aircraft could taxi on ground by an electric motor operated nose gear (autonomous taxiing) without engines running. This would improve overall fuel efficiency and would reduce emissions and noise in the airport vicinity.

In all cases where the hydrogen must be extracted from kerosene or other fuels, a reforming process is needed. Much research effort still has to be spent on fuel reforming. Today the mass to power ratio of fuel cells is still too high. Fuel cells have to show a considerable weight reduction (Turner, 2006) and reduction of purchase costs before it will be feasible to integrate them into aircraft in a way as discussed here. Furthermore, the introduction of the fuel cell technology on board aircraft will only be successful, if maintenance costs are low. Modern health monitoring techniques will have to be applied to achieve low maintenance costs of fuel cells (Scholz, 2009c).

Fuel cell demonstrator

For commercial wide-body aircraft a fuel cell demonstrator has been successfully demonstrated at the Berlin International Aerospace Exposition in 2008. The German Aerospace Centre (DLR) presented an Airbus A320 with an experimental 20 kW fuel cell in the rear cargo hold that replaces the Ram Air Turbine (RAT). The RAT is a little turbine that drops out if the aircraft encounters a loss of electrical power. The turbine is driven by ram air that drives an electrical generator to produce electricity for the cockpit and the primary flight controls. While the weight of fuel cell is comparable to that of RAT, the fuel cell may still supply sufficient power to extend the aircraft's flaps during a glide-approach at lower altitudes. Additionally, the fuel cell is easier to test, though it can be tested without really powering up the system (Doyle, 2008).

FUTURE TRENDS

Figure 10 shows the road map towards a more environmentally friendly air traffic as prospected by IATA. Its timeline consists of four major steps from retrofits today or in the very near future to new aircraft designs after 2020. It becomes apparent that the measures mentioned in this road map concentrate on improvements of details of current aircraft such as aerodynamics, materials and especially engines. Hydrogen is not yet listed in this outlook. This shows that from a nowadays airline perspective, hydrogen as fuel is not seen as a measure to improve the environmental friendliness of future air traffic.

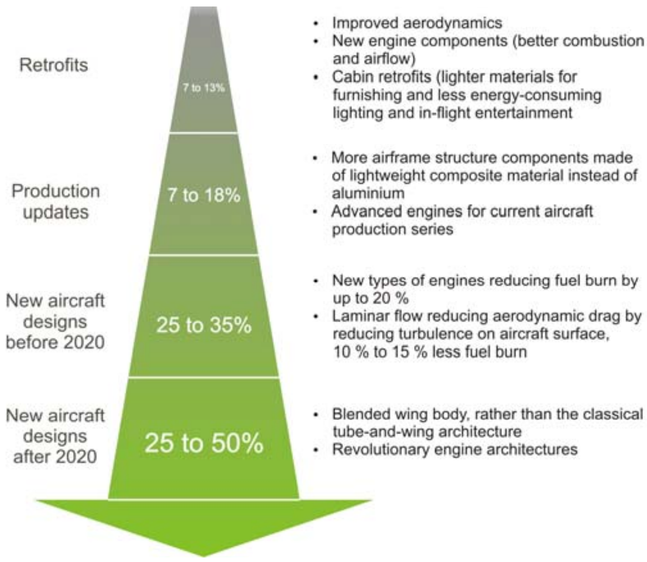

FIG 10. Road map for environmental improvement (based on IATA 2009b)

The reason for that are not technological issues concerning the use of hydrogen. "Technologies for production, storage, and transport are available, technologically mature, and scalable." (Albrecht, 2009). The main reasons are the high financial risk and technical effort of its introduction, since production and handling of hydrogen require a new airport infrastructure. Such large changes to the current airport and aircraft technology take time and are tried to be avoided. The effort to develop and introduce sustainable drop-in fuel replacements is much lower, cheaper and, therefore, more favourable for industry. Aircraft design takes decades from the preliminary studies via design, development and manufacturing until flight testing and delivery. That is why "IATA recognises that aircraft are long-lived assets and will be using kerosene or kerosene type fuels for many years to come." (IATA, 2009b).

In order to justify the large efforts required to build up a hydrogen infrastructure, the exact environmental benefits of a use of hydrogen must be numeralized, first.

SUMMARY

Worldwide air traffic of passengers and cargo is expected to grow, and it is estimated that air traffic doubles every 14 years. The global impact of aviation amounts to 7.5 % of the world Gross Domestic Product (GDP). Globally, 32 million jobs are generated by air traffic, of which remarkable 54 % are related to air transport's catalytic impact on tourism. These jobs are also found in developing countries. In summary, air traffic is very important to global business and society, and totally banning all air travel today would have disastrous consequences on the global economy.

However, as a consumer of fossil fuel, air traffic contributes to the global climate change. The emissions of aviation produced in high altitudes cause concern. Estimations of the fraction of air traffic in the total anthropogenic 'radiative forcing' range from 2.2 % to 4.7 %. Because these numbers may still appear as low in comparison to the contributions of other industries and in order to get a better idea of the influences related to flying, they have to be set in the right spotlight of energy consumption. A return trip from Frankfurt to Sydney for a family of four, for example, amounts to 10 times their annual electric energy consumption. Furthermore, in the future, the total quantity of emissions is expected to increase due to the rapid growth of air traffic.

Future fuel demands will have to be met even though the world's crude oil and, thus, aviation's kerosene resources are limited. So, in order to lower the environmental impact of aviation and to ensure the availability of future air traffic, a combination of (1) higher fuel efficiency, (2) alternatives to kerosene such as hydrogen, and (3) a reduction of the needs to fly has to be found.

The examples of aircraft studies, first and foremost the built and flown Tupolev Tu-155, show the technical feasibility of hydrogen driven aircraft. However, the financial and technical effort to introduce hydrogen as aviation fuel would be enormous. Consequently, the current efforts of aviation industry to develop sustainable air traffic favour alternative drop-in replacements of conventional kerosene due to the lower financial and technical effort and risk. Moreover, the current search for alternatives to crude oil-based kerosene also includes fuels that are based on other fossil feedstocks such as coal or natural gas. Consequently, the timeline for an introduction into practice of hydrogen as aviation fuel is still unclear.

German universities have contributed to the question of introducing hydrogen as fuel in aviation. This paper has given the examples of: hydrogen-driven regional cargo aircraft, Blended Wing Body (BWB) aircraft and hybrid-powered demonstrator aircraft. All three projects are considering freighter aircraft because the introduction of hydrogen technology into cargo aircraft seems to be reasonably free from obstacles. Furthermore, the Hamburg University of Applied Sciences works on the aspect of greening aircraft systems. It was recognised that the simplest way of greening aircraft systems is by using hydrogen or biofuels for the engines. In addition, the integration of the fuel cell to continuously supply power to the aircraft system during all phases off flight could result in considerable fuel savings.

CONCLUSION

Hydrogen as fuel for aviation is feasible. It offers the possibility to eliminate carbon dioxide emissions and to largely reduce other emissions such as nitrogen oxides that form during combustion of hydrocarbon fuels. In order to achieve these overall environmental benefits, hydrogen has to be produced environmentally friendly from renewable energy. The storage of hydrogen, even in liquid form at below -251 °C, requires very large tanks and additional mass of tank and insulation.

Today, the circumstances do not justify taking the large efforts and risks of an introduction of hydrogen into practice. Before hydrogen becomes a real fuel alternative, its benefits must be pointed out clearly: its environmental friendliness and the possibility to have a sustainable energy carrier produced from renewable energies.

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