McGill | Centre for Research in Air and Space Law
Centre de recherche en droit aérien et spatial

Occasional Paper Series

No. XII

July 2016

Technology Developments and Renewable Fuels for Sustainable Aviation

by

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Occasional Paper Series:
Sustainable International Civil Aviation

The attached Occasional Papers have been prepared by a group of scholars associated with the Institute of Air and Space Law (IASL) at McGill University. They are the result of a collaborative effort between the IASL and the Centre for International Sustainable Development Law and are designed to be part of a book prepared by authors from both groups which will eventually be published by the Cambridge University Press under the title *Sustainable International Civil Aviation*.

As the title of the book suggests, bringing together these various scholars and papers is the central theme of the sustainable development of international aviation. In particular, the work of the International Civil Aviation Organization (ICAO), the primary United Nations body tasked with regulating the environmental aspects of international aviation, and the provisions of the Chicago Convention which lays down powers of the Organization and the fundamental rules of international air law, form the primary focus of this collection. At the next ICAO Assembly in September-October of 2016, ICAO has the ambitious mandate to finalise a global scheme to limit CO2 emissions from international aviation. As many of the articles contained in the book are of immediate relevance to the discussions due to take place at ICAO, publishing and disseminating these draft chapters will contribute to the growing interest and debates on the issue of the environmental impact of aviation. It is hoped that these papers will contribute to the work of the Assembly and that informed readers and delegates participating at the ICAO Assembly will have constructive comments to share with the authors.

Readers are invited to send their comments to the authors whose e-mail addresses are set out on the title page of each paper as well as a copy to the following address: edannals.law@mcgill.ca

The authors and the Editors of this collection of papers thank all readers for their attention and their comments.

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SUMMARY

Technological Improvements in Aviation: How promising are the developments in technology in promoting a sustainable and environmentally conscious aviation industry?

The issue:

- Whether and to what extent are developments in Technology progressing towards the reduction of the environmental impact of aviation?

Its importance:

- Carbon dioxide (CO_2) emissions from aircraft engines directly affect climate change and have a lifetime of 50 to 200 years.
- Nitrogen oxide (NO_X) emissions from aircraft engines indirectly affect climate change by causing changes in ozone and methane concentrations through chemical reactions in the atmosphere.
- Contrails and aviation-induced cirrus clouds can cause a net warming effect.
- It is estimated that the number of commercial aircraft in the world will double in the next two decades, reaching 40,000.
- Economic measures that limit the environmental impact of aviation merely decreases the amount of air travel and do not address the growing demand for it.

The treaty law:
Nothing expressly provided for in the *Chicago Convention* with respect to technology improvement. However, Annex 16, Volume II, concerns emissions from aviation. Volume II regulates smoke and the following three gases: unburned hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NO_X). Volume III will provide for CO_2 emissions standard for new aircraft engines.

The analysis:

- Improvements in flight operations offer a limited scope in reducing aviation's impact on climate change but are readily available for implementation at present.
- Development of airframe technologies can improve the fuel efficiency of future aircraft. However, the regulatory environment and economic measures must

direct this technology to address environmental considerations rather than conventional objectives.

- Progress in engine technology can increase the efficiency of aircraft.
- The use of biofuels in aviation requires more research and development efforts in order to be viable.
- The trend in aviation technology dictates that nitrogen oxide will be dramatically reduced in the future. The effect of aviation induced cirrus/contrails has yet to be understood. This leaves carbon dioxide as the dominant problem in aviation that affects climate change.

Options for decision-makers:

1) Enact measures that will stimulate more research to reduce the environmental impact of aviation.
2) Rely entirely on economic measures which will not affect the growing demand for air travel.
3) Do nothing, which might lead technological improvements in aviation to pursue conventional objectives and without any regard or understanding on the environmental impact of aviation.

Technology Developments and Renewable Fuels for Sustainable Aviation

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1 Impact of Aviation on the Environment

The sources of the environmental impact of aviation can be divided into three categories: 1) in-flight operations, 2) airport operations, and 3) manufacturing and disposal. In-flight operation impact includes noise, emissions affecting local air quality at ground level, and emissions at altitude contributing to climate change. Airport operations impact is related to power consumption associated with the operation of the airport itself, emissions during taxiing, byproducts of aircraft and engine maintenance, and contamination resulting from the use of deicing fluid. Finally, the impact of manufacturing and disposal is associated with materials of concern, contaminants, and energy use.

Concentrating on in-flight impact, noise concerns are predominantly associated with take-off and landing operations, which primarily affect those living or working near airports. There are many studies indicating that exposure to increased noise levels can cause adverse effects on human health [19]. Noise is generated both by the engines and the airframe, with the landing gear and high-lift devices being the primary contributors from the latter. Aircraft noise is tightly regulated such that aircraft and engine manufacturers must meet increasingly stringent requirements in order to certify an aircraft. These regulations typically represent a balance between what is technologically feasible and the health impacts on people living in the vicinity of an airport. As a result, current aircraft are much quieter than in the past. Initially great strides were made in reducing engine noise to the point where during approach airframe noise is now comparable to engine noise. Consequently, increased attention is now paid to reducing airframe noise in addition to engine noise.

Local air quality at and near airports is similarly a health concern associated with pollutants emitted by aircraft at ground level during taxiing, take-off, and landing, including ozone, carbon monoxide, sulphate aerosols, and soot aerosols (particulate matter). A promising approach toward alleviating local air quality concerns is electric taxiing either by powering the aircraft's wheels with an electric motor or through an electric tractor that tows the aircraft to and from the gate.

Turning to the impact of aviation on climate change, this is associated with aircraft emissions in the upper troposphere and lower stratosphere [13]. This includes the direct effect of carbon dioxide emissions, which have a lifetime of 50-200 years. In addition, emissions of nitrogen oxides cause an indirect effect on climate change by causing changes in ozone and methane concentrations through chemical reactions. Ozone concentration is increased and methane decreased, with a net warming effect. This effect has complex dependencies on altitude, season, and latitude. Oxides of nitrogen have a lifetime of weeks in the atmosphere. A further impact of aviation emissions at altitude on climate change arises as a result of water vapour and particulate matter emissions, which under particular meteorological conditions can persist for hours and can spread into cirrus clouds. Contrails and aviation-induced cirrus clouds are believed to cause a net warming effect [13]. However, both their formation and their climate impact are presently not well understood in several respects, and the level of scientific understanding of this phenomenon is still evolving [22]. Finally smaller effects on climate change are associated with particulate and water vapour emissions.

The focus of this chapter is on the reduction of the in-flight impact of aviation with emphasis on climate change impact, which is the most important impact in the long term [7]. We will briefly review some opportunities offered by changes in flight operations followed by a discussion of airframe technologies, engine technologies, and biofuels.

2 Flight Operations

Operational improvements offer limited scope for reducing aviation's impact on climate change, but have the advantage that many of them can be implemented with today's technology. Optimized profile descents can be utilized to reduce fuel burn and hence carbon dioxide and nitrogen oxide emissions during approach, with potential reductions in noise as well [4]. Reducing the vertical separation minimum can enable more optimal trajectories with associated reductions in fuel burn and thus emissions [15]. Another possibility to reduce fuel burn is provided by multi-stage long distance travel, which enables the aircraft to begin the first stage with less fuel (and thus a reduced take-off weight) in comparison to flying the entire distance in one stage [8]. Moreover, contrail avoidance based on diverting around regions where the meteorological conditions are such that contrails are likely to form can reduce contrail and cirrus formation. This leads to a trade-off, since it will increase fuel burn, but given the possibly large warming impact of contrails and aviation-induced cirrus this may be worthwhile. An improved understanding of the impact of contrails and aviation-induced cirrus is needed before a quantitative assessment can be made.

One of the more promising operational opportunities is afforded by formation flight, which has long been exploited by Canada Geese. With formations of as little as two or three aircraft, substantial drag reductions are possible that translate directly into reductions in fuel burn and emissions [21]. Further efforts are needed to identify and address the remaining challenges associated with this concept. There is also considerable discussion in the aircraft design literature of flying at lower altitudes, although this generally involves a redesign of the aircraft for reduced speeds. Contrail formation and the effects of nitrogen oxides are greatly reduced at altitudes between twenty and thirty thousand feet. This is typically accompanied by an increase in carbon dioxide emissions; hence it is unlikely that such an approach will be adopted unless the confidence in our scientific understanding of the effects of both contrails and oxides of nitrogen is significantly increased [7]. Finally, designing large aircraft for short ranges, known as the LASR approach, has the potential to reduce climate change impact for short routes with high passenger volume [10].

3 Airframe Technologies

During the cruise segment, the fuel efficiency of an aircraft is determined by several factors, including speed, altitude, the engines' thrust specific fuel consumption, weight, and aerodynamic drag. Drag is the aerodynamic force acting in the direction opposite to the motion of the aircraft; lift is the aerodynamic force acting in the direction perpendicular to the motion of the aircraft. During straight and level flight at constant speed, the lift force is equal to the weight of the aircraft, and the thrust from the engines is equal to the drag force.

The drag force acting on an aircraft has three primary components. One is lift-induced (or simply induced) drag that is associated with the vortices shed most notably from the wing tips as a result of the production of lift. Another is viscous drag resulting from the viscosity of the air. The third is wave drag, which is caused by shock waves that can arise if the local fluid velocity in the frame of reference of the aircraft exceeds the local speed of sound. At the cruise speeds of modern aircraft shock waves are weak as a result of carefully designed supercritical wing section shapes and swept wings; thus wave drag is small. Hence the primary contributors to drag are induced drag and viscous drag.

In order to improve fuel efficiency, therefore, the aircraft designer seeks to reduce induced drag, viscous drag, and weight. The thrust specific fuel consumption of the engines is discussed in the next section. It is important to recognize that drag and weight are often interconnected such that a measure that reduces one increases the other, and vice versa. For example, induced drag can potentially be reduced by increasing the wing span, but this generally leads to an increase in wing weight. If the increase in weight (and the corresponding increase in lift) is too large, then the net effect may be an increase in induced drag. Similarly, an active flow control technology to reduce viscous drag will add weight and consume power. These trade-offs must be carefully considered such that an optimal configuration is designed.

The current dominant aircraft configuration, often referred to as the *tube and wing*, is typified by the Boeing 707 and Douglas DC8, which came into service over 50 years ago. Over the past 50 years, this configuration has been continually refined and optimized to incorporate new technologies, such as supercritical airfoil sections and composite materials. Together with improvements in engine technologies this has produced reductions in fuel burn per passenger-kilometer on the order of 70% [7]. Improvements in fuel efficiency have come from more efficient aircraft and more efficient engines in roughly equal measure. The tube and wing configuration is now well understood and highly optimized. Further large improvements in efficiency are unlikely to come through additional optimization of this configuration. Either new technologies or new configurations (or both) that lead to reduced weight and drag are required [7].

Induced drag is strongly dependent on the wing span, reducing as the span is increased. However, an increase in span typically results in an increased wing weight due to the additional structure needed to withstand the increased bending moments. Therefore, the optimal span balances this trade-off. Similarly, the induced drag is impacted by the spanwise load distribution, which also affects the wing weight. Therefore, the spanwise load distribution must be carefully chosen to provide the optimal balance between weight and drag such that fuel efficiency is maximized. Induced drag is associated with the vortices that arise when the higher pressure air beneath the wing interacts at the wing tip with the lower pressure air above the wing. Therefore, a further means of reducing induced drag is to reduce this interaction or displace the shed vortex through a nonplanar wing geometry. The classic example is a winglet, variations of which can be seen on many modern aircraft. However, this concept can be taken further to C wings, split wing tips, box wings, and general closed wing systems. These have the potential to reduce induced drag by as much as 30% [11]; however their impact on weight and viscous drag must be taken into account in order to determine the net improvement in fuel efficiency.

Viscous drag is associated with boundary layers, which are thin layers of air near the aircraft surface in which the effect of viscosity is significant. Boundary layers can be classified as laminar or turbulent. Laminar boundary layers are characterized by smooth, orderly flow, while turbulent boundary layers are characterized by apparently chaotic, random motion of the air. On an aircraft wing in flight, the boundary layers typically begin with laminar flow near the leading edge of the wing and at some point on the wing transition to turbulent flow. Since a turbulent boundary layer produces more surface friction than a laminar one, it is advantageous to design the wing such that the transition from laminar to turbulent flow occurs as far aft as possible, and the extent of turbulent flow on the wing is minimized.

A wing can be carefully shaped to move the laminar-turbulent transition point quite far aft; this is known as *natural laminar flow* and can lead to significant reductions in drag. However, this approach is limited in its applicability, becoming increasingly difficult at high speeds and on highly swept wings. This has motivated the development of *active flow control* techniques. With active flow control some form of actuation is introduced that delays the onset of laminar-turbulent transition. A classical approach involves removing some of the air in the laminar boundary layer near the wing surface by drawing it into the wing through small orifices. This inhibits the amplification of small disturbances that is central to the transition process and hence moves the location of transition downstream, thereby reducing drag. It is important to recognize that, in contrast to natural laminar flow (or passive flow control), active flow control consumes power, which must then be counted against the reduction in drag achieved in order to determine the net benefit. This has motivated the development of modern flow control techniques which attempt to minimize the power requirements by selectively targeting unstable disturbances that are responsible for the transition to turbulence through actuators that require little power, possibly through closed-loop feedback based on sensors placed on the wing [12]. Other drawbacks of active flow control include added weight and complexity. However, the primary issues to be addressed in order to bring active flow control into practice in civil aviation are reliability and safety. Therefore, it is most likely that active flow control will first be applied to vertical tails and engine nacelles.

Our ability to reduce the weight of aircraft is primarily dependent on the continued development of new materials with advantageous strength and stiffness to weight properties while retaining other characteristics essential for use on aircraft, such as fatigue life, thermal properties, and manufacturability. The latest generation of aircraft utilizes significantly more composite materials than previous aircraft. Further reductions in weight are possible by continuing to replace metallic materials with composites and plastics. Moreover, weight reductions can be achieved by improving our capacity to manufacture composite materials such that fully three-dimensional components can be designed, reducing our dependence on laminated plates. It is important to stress the interdependence of weight and drag. As a result, use of a new material with improved strength to weight properties can reduce the weight of an aircraft, but it can also reduce the drag by enabling a higher span or a thinner wing section. The ability to determine optimal designs is enhanced by recent advances in numerical multidisciplinary optimization.

It is also possible that a significant improvement in fuel efficiency will come through the use of an unconventional aircraft configuration other than the dominant tube and wing design. Among the most promising is the blended (or hybrid) wing-body configuration, which has no distinct fuselage and wing [14]. Instead the body of the aircraft holding the passenger compartment blends smoothly into the wing. Moreover, the body is shaped such that it produces lift, thereby reducing the lift that needs to be generated by the wings. The aerodynamic lift is thus better aligned with the loads, leading to reduced bending moments in the wing and hence lower structural weight. This configuration is believed to be most efficient for very large aircraft [20]. The blended wing-body configuration has numerous other advantages that can be exploited, such as opportunities for boundary-layer ingestion or distributed propulsion, leading to improved propulsive efficiency, and natural noise shielding obtained by locating the engines on the top of the aircraft. There are challenges with this configuration as well, most notably dealing with the non-cylindrical passenger compartment, which has the potential to add weight. This has spurred research into promising options to address this problem, such as pultruded rod stitched efficient unitized structure (PRSEUS), a new approach to composite design [24].

The D8 or double-bubble twin-aisle configuration has also been proposed based on having a fuselage that generates lift [5]. Although the fuselage is distinct from the wing as in the traditional tube and wing design, the fuselage is a wide lifting body which enables the weight of the wings to be reduced. The aircraft is also designed to fly at a somewhat lower speed than current transport aircraft. Therefore the wing has reduced sweep, further reducing the weight and facilitating natural laminar flow. A key aspect of this design is the use of a boundary-layer ingesting engine, potentially leading to reduced fuel burn in comparison to conventional engine placement.

Other promising novel aircraft configurations are based on nonplanar wing concepts with the potential to reduce weight and induced drag. These include the strut-braced wing [18] and various closed wing systems. For example, Lockheed-Martin has proposed a configuration that is a basic tube and wing design but an additional lifting surface joins the top of the winglet to the vertical tail, creating a closed wing system, and the engines are hung from that surface [16]. This configuration enables low induced drag with modest span, thereby reducing weight, and facilitates the use of ultra-high-bypass engines with reduced fuel burn, noise, and emissions. The strut-braced wing (also known as the truss-braced wing) is another promising approach where the wing is supported by one or more struts that also serve as lifting surfaces. This creates structural advantages, reducing weight, and improved aerodynamic efficiency by reducing induced drag.

One of the challenges facing the designer of a new aircraft and the developer of a new aircraft configuration is the need for a suitable metric enabling consideration of environmental impact [23, 7]. For example, how should environmental impact be weighed against conventional objectives, such as minimizing direct operating cost? This may well be driven by economic measures, such as emissions trading systems and carbon taxes. Even within environmental impact, there are measures that increase noise while reducing carbon dioxide emissions, while other measures have the opposite effect. These design decisions will be greatly influenced by the regulatory environment as well as economic measures. Hence it is critical that these be carefully and objectively considered based on a global perspective and the latest scientific understanding in order to avoid unintended consequences. For example, excessive tightening of noise regulations will hamper efforts to reduce climate change impact. In order to design aircraft with reduced climate change impact, a significantly improved understanding is needed of the relative impact of carbon dioxide, nitrogen oxides, and aviation-induced cirrus. The next generation of aircraft will typically be operational for thirty years, so there is great incentive to minimize their climate change impact, and it would be a serious mistake to design them based on an inadequate understanding of the relative impact of these three primary sources. Finally, aviation-induced cirrus and oxides of nitrogen have a more immediate shorter-term impact, while the impact of carbon dioxide is much longer lasting. It is not clear how these impacts should be weighted in the design of future aircraft.

To sum up this section, there are promising technological opportunities to develop aircraft with significantly reduced environmental impact. Active flow control and unconventional aircraft configurations are among the most promising technologies. Examples of unconventional aircraft configurations include: 1) the double-bubble concept combined with a reduction in speed and low-sweep wings; 2) the blended wing-body; 3) strut-braced wings. These configurations can potentially be even more efficient when combined with active flow control.

In order to derive the maximum benefit from new technology, it is crucial that the regulatory environment be driven by the best possible scientific understanding of the various sources of the environmental impact of aviation. This will require continued investment in the science needed. Furthermore, despite the high potential of the new technologies described here, a considerable amount of further research is needed to develop and de-risk new ideas and to mature existing ideas. This will require substantial financial investment.

4 Engine Technologies

Introduction of the gas turbine engine and the turbojet principle into aircraft propulsion more than 70 years ago led to a revolutionary change in transport technology. As a result of this transformation supersonic flight became possible, the cost of air travel and cargo

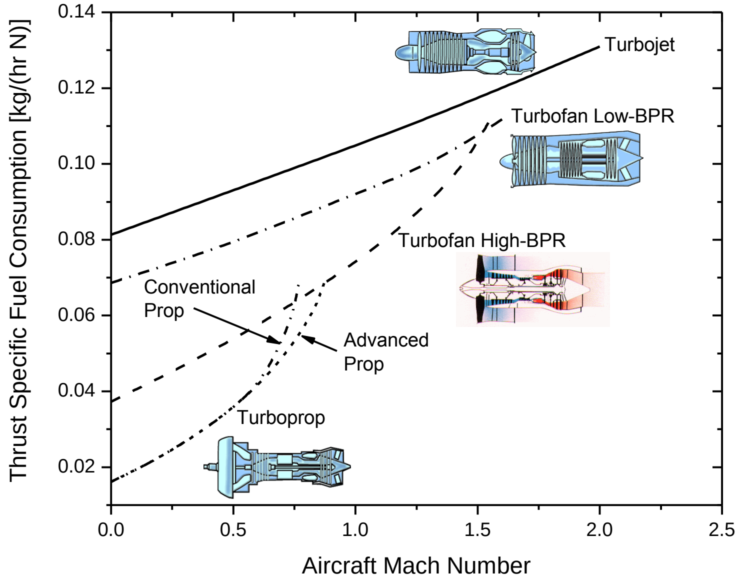

Figure 1: Thrust specific fuel consumption characteristics of typical aircraft engines. Adapted from [17]. BPR stands for bypass ratio referring to the ratio of air mass flow around the engine pushed by the fan to the air mass flow that goes through the engine for combustion.

transport was greatly reduced, and significant improvements in aircraft safety were achieved. The cost reductions were realized as a result of a combination of increasing flight speed and the ability to build much larger aircraft [9]. Prior to introducing gas turbine engines into aircraft propulsion, aircraft had piston engines to drive the propeller. As the performance and efficiency of turbine engines began to exceed those of piston engines, gas turbines became the dominant engines in aircraft. The adaptations of turbine engines in the form of turbojet, turbofan, and turboprop engines came with the different needs for thrust at various speeds.

A simple way to compare the performance of the three main engine types is to look at their thrust specific fuel consumption. This parameter gives the amount of fuel by weight required to provide a specific amount of jet thrust over a certain period of time. Thrust specific fuel consumption characteristics of typical aircraft engines as a function of aircraft Mach number are given in Figure 1.

It is clear that turboprops have superior fuel efficiency over turbofans and turbojets, but they are disadvantaged by the limitation of the flight speed. This limitation is induced by the tip speed of the propeller which should be below the sonic speed, hence limiting the engine shaft speed. The solution to this problem seems to be a geared-propeller, that is a geared transmission between the propeller and engine shafts. The gearbox is typically massive and requires extensive development effort to ensure reliability and durability; most of the time substantial speed reduction is necessary. The massiveness of the required gearbox becomes the limiting factor for relatively larger turboprop engines. However, for long range subsonic aircraft high bypass ratio turbofan engines are still the only choice. The latest design of this type of engine incorporates a geared turbofan which provides significant efficiency improvements. Another concept is the open rotor engine design that has the potential to provide appreciable fuel burn savings for single aisle aircraft as compared to that of an equivalent high bypass ratio turbofan engine. This concept is a follow up on known designs of unducted fans or fanprops which have not been commercially produced. Open rotor engines are likely to be noisier than turbofan engines as there is no nacelle to absorb and attenuate the noise generated by the engine. Other approaches that could improve the efficiency of jet engines are to find solutions to increase the compression ratio and the turbine inlet temperature. Both parameters directly influence the fuel efficiency. Today, the turbine inlet temperatures are limited by the blade materials available and the blade cooling technologies. Advances in these areas will further improve the fuel efficiency of aviation gas turbine engines.

The issue of high compression ratios and higher turbine inlet temperatures also has some negative implications since nitrogen oxide (NO_x) emissions increase with increasing pressure and temperature. NO_x control in current aviation gas turbine engines is achieved mostly by staged combustion schemes such as *rich burn / quick quench / lean burn.* The most promising technology now seems to be to operate aviation gas turbines in a premixed combustion mode instead of the current non-premixed mode. Premixed combustion technology permits better control over NO_x emissions and completely eliminates particulate matter (soot aerosol) production and emissions. Known as *lean premixed combustion*, this technology has long been used in stationary gas turbines. It should be noted that applying this technology to aviation gas turbines engines is not straightforward, and there are concentrated research efforts at both universities and industrial laboratories to find innovative solutions.

5 Biofuels

It is estimated that the number of commercial aircraft in the world will double in the next two decades, reaching 40,000 aircraft. Currently all commercial jet aircraft operate on a single fuel product obtained from fossil fuel sources [25]. Since the first turbine engine, aviation fuel has evolved into a tightly regulated commodity, and its specifications have narrowed as engine technology and refining methods have advanced. As a result, aviation gas turbine engine fuels today are the most highly regulated transportation fuels with the most extensive set of specifications [6]. Fuel specifications have material and manufacture requirements limiting the fuel feed stocks to petroleum crude oil, natural gas condensates, heavy crude oil, shale oil, and oil sands (i.e. hydrocarbons). The American Society for Testing and Materials (ASTM) is the governing body for establishing the requirements for aviation fuels, and the ASTM D1655 is the standard that lists the required specifications for turbine fuels [1].

Two major biofuels are present in the global fuel market: bioethanol, which is largely produced by the fermentation of sugars or starches, and biodiesel, which is produced from the transesterification of vegetable oils such as rapeseed, soybean or palm, as well as from animal fats. Ethanol and biodiesel are blended into gasoline and diesel fuels, respectively, in smaller percentages for ground transportation. However, unlike the use of biofuels in ground transportation, aviation gas turbine engines present more stringent restrictions on any candidate fuel due to several factors [6]. First, only a limited range of potential liquid fuels can satisfy the requirements for reliable and safe combustion taking place under the extreme conditions of a gas turbine combustion chamber. Second, any product proposed must be fully interchangeable with the current jet fuel product to avoid the logistic problems of airports handling multiple fuels of varying qualities and the commercial limitations this would impose. Finally, the long life of a commercial jet means any candidate fuel needs to be *backwards compatible* and suitable for use in existing engine technology [6]. For these reasons, bioethanol and biodiesel are not fit for aviation gas turbines. The overarching criterion in developing biofuels for aviation has been the development of *drop-in* fuels which can be used in the existing fleet without any modifications.

Currently synthetic paraffinic kerosene (SPK) produced by the Fischer-Tropsch (FT) process either from biomass sources or coal is allowed to be blended with conventional jet fuel up to 50% by volume [2]. It should be emphasized that both SPKs are mixtures of pure hydrocarbons of almost all paraffinic nature. Fatty acid methyl esters (FAME), which are the major components in biodiesel, are considered as contaminants in jet fuel because of their degrading effect on jet fuel thermal stability. In light of the above concerns, it is clear that any biomass based fuel should be first converted to pure hydrocarbon mixtures in order to be accepted as a jet fuel blending product. This limits, at least with the current technology, the potential biofuels for aviation to SPK obtained by the FT process from biomass and hydroprocessed esters and fatty acids (HEFA). HEFA is derived from animal and vegetable oils, but its composition is similar to SPK, that is, a mixture of pure paraffinic hydrocarbons. HEFA has also been approved to be blended with conventional jet fuel up to 50% by volume [3].

The technical path that should be taken in developing and adopting any new alternative jet fuel that would satisfy the drop-in fuel requirements should go through the following three stages:

1. Testing to ensure that the following properties are within the current jet fuel specification range: physical and chemical properties, fundamental combustion properties, and emissions measured in benchmark lab tests.

2. Testing to ensure that the candidate fuel meets the following: thermal stability and handling requirements, specifications dictated by standards, and the *fit-for-purpose* requirements.

3. Finally the following steps should be completed before certification: full engine tests including simulated altitude, and flight tests.

Of course drop-in fuel requirements do not include any environmental credentials. The analysis of an alternative fuel's environmental credentials – which is expected to become a key requirement of an alternative fuel either due to political pressures or environmental legislations – can only be achieved by assessing emissions at all stages [25]. At the moment, development of biofuels for aviation is being driven by ensuring supply (energy security) and the sector's environmental footprint. The cost of reducing aviation carbon dioxide emissions about 30% by powering the world's fleet by 50% biomass derived product seems unacceptably high at the moment. Despite current biomass feedstock being impractical, the search for and development of alternative high yield per tonne feed stocks are the focus of current major research and development initiatives.

The influence of blending up to 50% of SPK with conventional jet fuel on engine-out emissions are not well-documented except a few studies which demonstrated NO_x, CO, and unburned hydrocarbon emissions similar to those of jet fuel and a measurable reduction in particulate matter emissions. This is one of the areas that requires concentrated research and development efforts.

6 Discussion and Conclusions

There are numerous avenues available to reduce the environmental impact of aviation. As technology progresses, climate change impact is likely to emerge as the most important concern. It seems likely that nitrogen oxide emissions will be dramatically reduced in future generations of engines, leaving carbon dioxide and aviation induced cirrus/contrails as the dominant problems. Much remains to be understood about the effect of aviation induced cirrus and contrails, and it is relatively straightforward to reduce this impact if this turns out to be justified; hence the focus is on reducing carbon dioxide emissions. Some of the promising avenues include new aircraft configurations, new materials and advanced composite manufacturing techniques, new engine configurations, such as open rotors, active flow control for drag reduction, advanced materials and cooling technologies for engines, and biofuels. None of these provides the solution by itself, but many are complementary and can be combined. All will require considerable further research in order to have the desired impact while meeting the need for aviation safety, which of course cannot be compromised.

The ultimate goal is to meet the growing global demand for air travel while achieving the desired reduction in overall environmental impact, particularly climate change impact. Economic measures that succeed in reducing environmental impact simply by decreasing the amount of air travel cannot be said to achieve this goal, unless an alternative means of meeting the demand is provided. However, it is critical that the environmental impact of the alternative means of travel be properly measured. For example, in comparing the climate change impact of high-speed trains with that of aviation for routes where both are an option, it is important to consider the degree to which seats are filled on a regular basis, the nature of the energy source used, and the climate change impact of the construction of the necessary infrastructure in each case.

It is clear that the efficiency improvements historically achieved in aviation to date, which typically average between one and two percent per year, will not be adequate to enable both growth in air travel and a substantial reduction in total emissions. The preferred approach will involve measures that stimulate the research needed to achieve the above goal and, directly or indirectly, provide the funding required to support the required research and development.

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