CHEMICAL ENGINEERING TRANSACTIONS

VOL. 29, 2012

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Hon Loong Lam, Jiří Jaromír Klemeš

ISBN 978-88-95608-20-4; **ISSN** 1974-9791 DOI: 10.3303/CET1229192

Overview of Biofuels for Aviation

Judit Sandquist[a], Berta Matas Güell*[a]

[a] SINTEF Energy Research AS, Postboks 4761 Sluppen, NO 7465 Trondheim
Berta.Guell@sintef.no

Aviation is a significant contributor of the worlds economy, and especially in Norway, it is a major transportation method for people and goods. The role of aviation is expected to increase in the future and with it the fuel demand and the environmental impact. The increased CO_2 emissions are of major concern, thus being recommended to look into emission-reducing measures.
Today, the aviation sector uses petroleum derived liquid fuels. Therefore, environmental impacts, security of supply and oil depletion are issues of concern. A number of potential alternative fuels and fuel blendings may be considered for aviation. The most likely alternative fuels for aviation are those with similar characteristics to conventional jet fuel. These are by definition "drop-in" fuels, which meet the oil-derived kerosene specifications.
Today, there are two biofuel types certified for aviation, both in maximum 50 % blends with conventional Jet A/A-1. One of these is hydrotreated vegetable oil (HVO) derived from oil seed plants. This type of biofuel is commercially available and in small quantities is already in use. The other type, Fischer-Tropsch (F-T) kerosene derived from lignocellulosic materials is to be expected on the market within 5-10 years. The life-cycle benefits of a HVO fuel are very sensitive to biomass feedstock as it needs oil seed crops. However, the fuel itself is cheaper than the other alternatives, and is expected to be competitive with aviation kerosene when subsidized. The F-T fuel is more expensive, but its feedstock is cheaper and it has a better environmental profile.

1. Introduction

Among environmental impact factors of aviation, emissions to air, especially at high altitudes, emissions from ground operations (airport operations, fuel production, etc.) and noise, as well as sustainability of the overall sector are of major importance. Besides CO_2, it is the emission of NO_x, water vapor and particulates at altitude that account for the extra impacts of aviation emissions (Jardine, 2005). These effects are usually not accounted for in conventional GWP calculations (CIENS, 2011). Due to the fact that CO_2 has a long time effect, the emissions from road transport give the largest global warming impact on the long term.
This paper looks into possibilities for alternative jet fuels in the near and mid-term future, giving a background for further studies in this field. The already certified fuels are presented and the environmental impacts are discussed. Possible future fuels are introduced shortly and their potential for future use as aviation biofuels is discussed. The other environmental issues of aviation such as increased energy efficiency of jet engines and airplane fuselages, long-term drivetrain solutions, ground operations and detailed evaluation of the current environmental impact of aviation are beyond the scope.

Please cite this article as: Sandquist J. and Güell B. M., (2012), Overview of biofuels for aviation, Chemical Engineering Transactions, 29, 1147-1152

1.1 Kerosene
The current aviation fuel, kerosene (Jet A/A-1), is derived from oil and is a middle distillate between gasoline and diesel. Traditionally, aviation kerosene is around 10% of the crude oil cut globally, with a technical maximum of 15%, depending on the oil field (Blakey et al., 2010). Several requirements need to be satisfied for fuels to be suitable for commercial aviation. These requirements are to ensure safe air transportation. Aviation fuels need to deliver a large amount of energy content per unit of mass and volume in order to minimize fuel carried for a given range, the size of fuel reservoirs, and the drag related to the fuel storage. Aviation fuels also need to be thermally stable to avoid freezing or gelling at low temperatures, and to satisfy other requirements in terms of viscosity, surface tension, ignition properties and compatibility with the materials typically used in aviation. The aviation kerosene fuel is defined in the ASTM D1655 standard in the US and in the UK DefStan 91-91 in Europe.

1.2 The alternatives
A number of potential alternative fuels and fuel blending may be considered for aviation. These can be derived from coal, natural gas or biomass. Not all of them, however, would significantly reduce GHG emissions. The short and mid-term alternative fuels for aviation are the "drop-in" fuels, which meet the oil-derived kerosene specifications. Non-drop-in fuels and drivetrains (solar, hydrogen, FC, etc.), on the contrary, require new aircrafts and ground infrastructure, and considering (i) the slow rate of aircraft fleet renewal, (ii) investment costs and (iii) tailoring the technology to a specific drivetrain, these fuels can be considered as long-term solutions. These solutions should not be rejected but the balance between potential advantages and implementation costs should be carefully considered. A drop-in fuel needs to be certified in the same way that conventional kerosene and needs to undergo the same tests as kerosene does today, but once accepted it does not need to be recertified.

2. Aviation biofuels

The two recent biofuel alternatives, Hydrotreated Vegetable Oils (HVOs) and Fischer-Tropsch (FT) fuels have been through several engine and flight tests in civil and military aircrafts as well as supersonic flights. These tests are essential prior certification of these fuels. KLM performed the first passenger flight using a biofuel blend between Amsterdam and Paris on a special permission on 29 June 2011. The bio jet fuel used was derived from waste cooking oil (ATAG, 2011).

2.1 Hydrotreated Vegetable Oils
The American Society for Testing and Materials (ASTM) D7566-11 specification issued on 4 July 2011 allows a 50 % blending of fuels derived from hydroprocessed esters and fatty acids (HEFA) with conventional petroleum-based jet kerosene. This fuel is also referred as Hydrotreated Vegetable Oil (HVO), Hydrotreated Renewable Jet (HRJ) or Bio-derived Synthetic Paraffinic Kerosene (Bio-SPK), fuel derived from crops such as jatropha or camelina has been given a new name, Hydroprocessed Esters and Fatty Acids (HEFA), by the ASTM. However, the stakeholders are still using the term HVO and in this paper this fuel will be referred as HVO.
Vegetable oils and fats can be hydrotreated to produce a HVO fuel that consists almost totally of hydrocarbons, and compared to Fatty Acid Methyl Esters (FAME or 1. gen biodiesel, a fuel containing oxygen), HVO is much closer in properties to conventional jet fuel. Hydrotreating can be carried out in oil refineries. The chemical processing is similar to the conventional refinery technique (Kinder and Rahmes, 2009). First, the oils are cleaned to remove impurities using standard oil cleaning procedures. The oils are then converted to the shorter chain diesel-range paraffins, by removing oxygen molecules from the oil and converting any olefins to paraffins by reaction with hydrogen. The removal of the oxygen atoms raises the heat of combustion of the fuel and the removal of the olefins increases the thermal and oxidative stability of the fuel. A second reaction then isomerizes and cracks the diesel range paraffins, to paraffins with carbon numbers in the jet range. The end product is a fuel that contains the same types of molecules that are typically found in conventional petroleum-based jet fuel.

2.2 Fischer-Tropsch fuels
Since the early 1990s Sasol has developed a coal-derived (CtL – Coal to Liquid) fuel for aviation. This work pioneered the approval of any drop-in fuels. Coal-derived fuel from Sasol was first approved in South Africa (as 50% blend with Jet-A1 and then as neat product) and in September 2009, generic

Fischer-Tropsch fuels were approved for 50% blend with JetA/A-1 by the ASTM in its D7566 standard (Blakey et al., 2010). Synthetic Fischer-Tropsch fuels are high-quality fuels that can be derived from natural gas, coal or biomass *via* the Fischer-Tropsch process. The individual fuel production processes share some common features. Coal and biomass to liquid fuels are typically produced *via* a gasification step, through the formation of a synthesis gas (mainly CO and H_2) and its conversion to liquid hydrocarbon fuels *via* the Fischer-Tropsch (F-T) process. Natural gas, instead, is cleaned and reformed before entering the Fischer-Tropsch reactor.

Synthetic biodiesel, also called F-T biodiesel, is a result of gasification of biomass. The main advantage of biomass gasification is that all kinds of organic materials, even different wastes such as waste from agriculture, wood processing, paper production or municipality can be used. Even if the quality of the feedstock can be quite different, the contents of the synthetic gas are almost the same. In this reaction, biomass is heated with an oxygen deficit and a gas, called syngas, containing mainly CO and H_2, is formed. Besides these two components, syngas contains CO_2 and contaminations (tars, methane, particles, inorganics, etc.), which need to be removed. The tars represent significant energy and carbon content (depending on the gasification technology used) and have to be cracked or removed first. There are mainly three ways of tar removing/cracking: thermal cracking, catalytic cracking or scrubbing. Mainly, combinations of these are used (Knoef, 2005). Other impurities in the produced gas are the organic BTX (benzene, toluene, and xylenes), and inorganic impurities as volatile metals, NH_3, HCN, H2S, COS and HCl, which are often removed by scrubbers. There are also dust and soot, which are removed by filters and cyclones. After gas cleaning, the clean gas will be the raw material for the Fischer-Tropsch reaction in which the syngas is converted to hydrocarbons.

Mainly two setups are suggested to gasify biomass. The high temperature setup (~1200 °C) uses entrained flow reactors, which are practically the same as for coal gasification. This process has high efficiency and produces low-tar containing syngas. However, the biomass feeding is not fully resolved yet. Due to the feeding issue, many actors are looking into combined processes where the biomass is thermally pretreated either by torrefaction, flash pyrolysis (Bioliq) or an incomplete gasification (Choren). The low temperature (up to 900 °C) processes employ either bubbling (Andritz Carbona) or circulating (FosterWheeler) fluid bed reactors. These processes are simpler and easy to feed, but the syngas quality can be challenging for downstream F-T processes. The fluid bed processing technology is a commercial process for production of combined heat and power from biomass, where the gas is combusted in an internal combustion engine producing power.

2.3 Examples of biofuels with a potential to become aviation fuels

Sugars converted to hydrocarbons

From sugar it is possible to produce hydrocarbon fuel precursors/components *via* catalytic processing or specially designed microbes. Several companies are making hydrocarbon biofuels, which can be cheaper to produce than ethanol and have higher energy density. Startups such as LS9 and Amyris (Savage, 2007) are trying to genetically engineer the metabolic systems of microbes so that they ferment sugars into useful hydrocarbons.

Other researchers, such as an initiation at the University of Wisconsin-Madison (Patel, 2008), believe in chemical reactions instead of microbial fermentation. They use catalysts at high temperatures to convert glucose into hydrocarbon biofuels. In the first reactor, a sugar-water solution is passed over a platinum-rhenium catalyst at about 500 K. This strips five out of six oxygen atoms from the sugar, creating a mixture of various hydrocarbon compounds, such as alcohols and organic acids. The compounds form an oil-like layer that floats on top of the solution. The oil is transferred to the second reactor, where it is passed over various solid catalysts, resulting in a range of hydrocarbon molecules that make up gasoline, diesel, and jet fuel. The alcohols and organic acids in the oil from the first step could also be used to make plastics and industrial chemicals.

Alcohol-to-jet focuses mainly on chemical or biochemical conversion of alcohols to hydrocarbon fuels.

These processes are not commercial yet and the fuels are neither tested nor certified. However, the claimed cheap processes will have high potential in the future.

Pyrolysis oil derived fuels

Fast pyrolysis is a process where biomass is rapidly heated in the absence of oxygen. As a result biomass decomposes to generate gasses, vapors and aerosols and some charcoal. After cooling, a dark brown mobile liquid, named pyrolysis oil or bio-oil is formed with a complex chemical composition. The main components comprise mainly of water, carboxylic acids, carbohydrates and lignin derived substances (Huffman et al., 1993). The pyrolysis oil is not a drop-in fuel as it has a very high oxygen content (up to 50%), it is immiscible with petroleum, due to its acidity (corrosiveness) and due to its instability upon heating and coke formation. In order to convert it to a fuel that can be used in a jet engine, upgrading of the fuel and co-feeding of the upgraded fuel into refineries is the feasible way. Upgrading reduces the acidity as well as the water and oxygen contents and makes the pyrolysis oil more miscible with petroleum (Heeres, 2011). These processes are not commercial yet.

Liquid hydrogen

Hydrogen is a potential non-CO_2 emitting fuel for aircraft, but its use poses a number of significant technical challenges. According to estimations of an EU project called *"Cryoplane – Liquid Hydrogen Fuelled Aircraft System Analysis"* the earliest implementation of this technology could be expected in 15 to 20 years, under the condition that the research work will continue on a certain level. Furthermore, it is expected an increase of the operating costs by 4% to 5% associated only with fuel. Overall, LH_2 is not promising as an alternative fuel for aviation in the near of mid-term future. It could only be viable in the long term if there were significant technological developments, entirely new aircraft designs and substantial infrastructural changes.

3. Biomass and competition for the resource

The aviation industry has made it clear that it is only looking at sustainable biofuels and is determined not to repeat the mistakes made with first-generation sources in the road transportation, expecting any supply to be fully sustainable. However aviation biofuels are not produced in large amounts yet as for road biofuels.

Since HVO uses the same type of resources as the first generation biodiesel, it is important to mention the resource-related issues and the comprehensive research efforts attached. Oil seed crops (for example rape, soy as well as camelina, jatropha) and oil containing algae can be used to produce first generation biodiesel, named fatty acid methyl ester (FAME). FAME is used in road transportation but it is not suitable for aviation due to not satisfactory properties for jet engines. The same feedstock can be used to produce hydrotreated vegetable oils (HVO) which is a certified aviation fuel. The difference between the two fuels lays in the production process which results in different chemical composition. One of the main issues of oil seed crops is the fact that HVO/biodiesel production in sufficient amounts would require large amounts of land and/or cultivation of highly efficient tropical biomass. Studies by WWF (2008) and Greenpeace (2009), for example, have highlighted the environmentally and socially destructive nature of the palm oil industry in South East Asia, one of the leading suppliers of feedstock oils for the biodiesel industry. The Roundtable on Sustainable Palm Oil worked out guidelines for sustainable palm oil production (RSPO, 2006). Sustainably produced palm oil will probably be an interesting option for aviation industry when the demand increases far beyond production capacities. Palm oil derived fuel is currently "banned" from aviation due to the former issues aforementioned. There are crops that can be grown on poor or set-aside lands, providing jobs and living for people in poor countries. These biofuels are not only environmental friendly fuels, but also support the economics of these countries, and fight against poverty. These crops are used in aviation biofuel blends today. The drawback of these crops is that they have not been produced in significant quantities yet, and on the other hand, the crops yields will be marginal on marginal land and without irrigation and fertilizers, meaning that even more land is needed to produce biofuels.

Aquatic biomass present a number of advantages that makes their cultivation an interesting and needed option to meet the biofuels need. One of the main advantages is the fact that algae grow in aquatic environment and in that sense no land is needed and in some cases, the use of fresh water can be avoided. In addition, algae are very efficient photosynthetic creatures, resulting in a fast growth.

Microalgae produce storage lipids in the form of triacyglycerols (TAGs), which can be extracted and used to produce oil-based biofuels. Oil from microalgae has been used to produce aviation fuel in very small quantities. Microalgae production is not yet commercial and it has several challenges to overcome before scale-up. Cultivation of macroalgae, on the other hand, is simpler than that of microalgae, but the conversion technologies available are more challenging. One of these technologies with great potential is hydrothermal gasification, which allows converting wet biomass with a natural water content of more than 80 % (g/g) with no need for drying (Kruse, 2008). Syngas produced in these processes after a cleaning step can undergo the previously mentioned Fischer-Tropsch process and be converted to aviation biofuels.

The entire gasoline consumption in Norway in 2009 (2.7 billion L) could be replaced with pure biomethane if 2% of the Norway's sea area is devoted to macroalgae cultivation for biofuels production. If the same amount of biomethane is used to produce biokerosene described the same way as fuel produced from natural gas (assuming 60% energy efficiency in the GtL process and 32% kerosene yield from the F-T process) it will provide 2.45 billion liters of biokerosene which is approximately 3.4 times the jet fuels sold at Gardermoen airport (Norway's main airport).

4. Case studies and large ongoing projects

Probably the most relevant case study for Nordic conditions is the one that was prepared by the Swedish Värmeforsk in 2009. This study considers the possibility to produce sustainable jet fuel for Stockholm-Arlanda Airport. Two possible configurations are suggested. One of them is the Brista plant with 108 t/h (289 MW) biomass input producing jet fuel, power and heat. The second configuration is Igelsta with 229 t/h (611 MW) biomass input producing a F-T product (that needs to be upgraded at an external refinery), power and heat. Both plants use available Swedish biomass, wood chips and forest residues, and gasify the feedstock in pressurized O_2-blown fluidized bed reactors. The gas is extensively cleaned and conditioned, and fed to the Fischer-Tropsch synthesis. Power is generated in steam turbines.

The study shows promising results, high efficiency and cost competitiveness. The Brista plant is not cost competitive in 2009 conditions, but the authors account for a slightly bigger plant and future emission trading system. The Igelsta plant delivering a F-T product to a refinery is seen as cost competitive, but it has a very large scale. The authors anticipate that the same configuration would be cost competitive at a smaller (400 MWth) scale as well. However, it will be essential to locate the plant at a site where good biomass logistic as well as possibility to sell the heat is given. In Norway, there is an aim to double the biomass production and increase it from 14 TWh to 28 TWh by 2020. 14 TWh woody biomass used mainly for biokerosene production in a process described by Värmeforsk would give 360 million liters (290 000 tons) biokerosene to Norwegian airports and heat and power in addition.

CSIRO (2011) has prepared a roadmap document to investigate the possibilities to supply Australia and New Zealand with sustainable jet fuel. As both countries lie at hot climate zones, not only wood and wood residues can be used as feedstock for jet fuel production but locally grown oil seed plants as well. The report points out that it will be possible to support 46 % of the aviation fuel needed both in Australia and New Zealand by 2020 and 100 % by 2050. However, the authors point out that it will be challenging to scale up the sustainable and economically viable feedstock production.

After certification of the hydrotreated vegetable oils as jet fuel in 50% blending, aviation biofuels became a hot topic throughout the entire industry. The major stakeholders reported by the World Biofuel Markets (2010) within fuel production from vegetable oils are UOP Honeywell and Neste Oil at the processing side and Solazyme, Altair Fuels, Sustainable Oils, Sapphire Energy and Terasol on the oil supplying side. The oils are supplied from sustainable sources such as waste oil, canola, camelina, jatropha and algae. Waste oil and canola/camelina have the largest share.

For F-T fuels, two major stakeholders are standing out, Solena and Rentech. Solena has agreement with several airlines to set up commercial plants in northern California and in London, converting urban waste to aviation fuels by biomass plasma gasification technology. Rentech sells aviation fuel from its demonstration plant located in Colorado and has plans to start up a commercial scale plant within the Rialto project in California. Rentech has acquired a patented indirectly heated fluidized bed gasifier, named SilvaGas, but Rentech's main activity covers the Fischer-Tropsch process. Rentech will also assist with their F-T process in Solenas London plant.

5. Conclusions

In this paper, the different biofuels suitable for recent and future aviation purposes were investigated. Today, there are two biofuel types certified for aviation, both in maximum 50 % blends with conventional Jet A/A-1. The environmental performance of the HVO fuel is very sensitive to biomass feedstock as it needs oil seed crops. However, the fuel itself is cheaper than the alternatives, and is expected to be competitive with aviation kerosene when subsidized. The F-T fuel is more expensive, but its feedstock is cheaper and it has a better environmental profile.

In Norwegian climate and conditions it is not likely that oil seed production will appear for fuel purposes, due to limited cropland and cold climate. There is, however, better potential to produce aviation fuel from wood or woody residues. For domestic production, fuels from lignocellulosic feedstock have the only potential. The only certified fuel of this kind is the F-T kerosene today, but other fuels might appear in the future as the resulting hydrocarbon fuels from other technologies (such as via ethanol or upgraded and refined bio-oil) become available and certified.

6. Acknowledgement

The authors wish to acknowledge the financial support from the Research Council of Norway and a number of industrial partners through the project GasBio ("Gasification for Biofuels").

References

ATAG Global Briefing,2011, Issue One, (October) <www.atag.org> accessed 23.03.2012

Blakey S., Novelli P., Costes P., Bringtown S., Christensen D., Sakintuna B., Peineke C., Jongschaap R.E.E., Conijn J.G., Rutgers B., Valot L., Joubert E., Perelgritz J.F., Filogonio A., Roetger T., Prieur A., Starck L., Jeuland N., Bogers P., Midgley R., Bauldreay J., Rollin G., Rye L., Wilson C, State of the Art on Alternative Fuels in Aviation. 2010, SWAFEA. Sustainable Way for Alternative Fuels and Energy in Aviation, <www.swafea.eu> accessed 15.06.2011.

CIENS Luftfart og klima, 2011, <www.ciens.no> accessed 23.03.2012, (in Norwegian)

CRYOPLANE Liquid Hydrogen Fuelled Aircraft – System Analysis, 2003, <www.airneth.nl> accessed 26.10.2011

CSIRO, Flight path to sustainable aviation, 2011, <www.csiro.au> accessed 19.09.2011

Greenpeace, Illegal forest clearance and RSPO greenwash: Case studies of Sinar Mas (2009) <www.greenpeace.org.uk> accessed 23.03.2012

Heeres E., 2011, Catalytic hydrotreatment of fast pyrolysis oil using bimetallic Ni-Cu catalysts. Presentation at the TCBiomass conference, Chicago, USA

Huffman D. R., Vogiatzis A. J., Bridgwater A. V., 1993, The characterization of fast pyrolysis bio-oils Advances in thermochemical biomass conversion 2 p 1095.

Jardine C. N., 2005, Calculating the Environmental Impact of Aviation Emissions <www.jpmorganclimatecare.com> accessed 23.03.2012

Kinder J. D., Rahmes T., 2009, Evaluation of Bio-Derived Synthetic Paraffinic Kerosene (Bio-SPK) <www.boeing.com> accessed 23.03.2012

Knoef H.A.M., 2005, Handbook biomass gasification, issued by BTG Biomass Technology Group

Kruse A.,2008, Supercritical water gasification. Biofuels, Bioproducts and Biorefining, 2, 415-437.

Patel P., 2012, New Route to Hydrocarbon Biofuels <www.technologyreview.com> accessed 23.03.2012

RSPO Principles and Criteria for Sustainable Palm Oil Production, 2006, <www.rspo.org> accessed 23.03.2012

Savage N., Building Better Biofuels, 2007 <www.technologyreview.com> accessed 23.03.2012

Värmeforsk, Pilot study of Bio-jet A-1 fuel production for Stockholm-Arlanda Airport, 2009, <www.varmeforsk.se> accessed 22-09-2011

WWF, Biofuel Plantations on Forested Lands: Double Jeopardy for Biodiversity and Climate, 2008, <www.worldwildlife.org> accessed 23.03.2012

World Biofuel Markets, Aviation biofuels – the major developments, opportunities, players and issues, 2010 <worldbiofuelsmarkets.info> accessed 23.03.2012