Emissions testing on Gas-to-Liquid kerosene blends

Tim A. Snijders[1] and Joris A. Melkert[2]
Delft University of Technology, Delft, 2629 HS, The Netherlands

The search for alternative fuels has lead to a number of possibilities. The most promising alternative fuels for the short term are drop-in fuels such as synthetic fuel and hydrotreated renewable jet. These fuels are similar to Jet A-1 but some differences are present. Synthetic fuels are produced using a process that results in a fuel without trace elements and almost no aromatics. Furthermore, synthetic fuels have a higher energetic content and lower gravimetric density than Jet A-1. These differences cause several effects when considering the use of synthetic fuel in aircraft. A performance model is used to show that the payload-range performance is changed and that an efficiency gain is achieved on the fuel consumption for a regular flight. Measurement of the soot emissions for several blends of synthetic fuel with Jet A-1 show that increasing the amount of synthetic fuel leads to significant reductions in soot emissions. Reductions of 50 to 70% in particle mass emitted can be reached by using 50% synthetic fuel. This might reduce the amount of contrails and aircraft induced cirrus clouds and seriously increase local air quality around airports.

I. Introduction

THERE are several reasons why alternative fuels for jet aircraft are being developed and researched. Energy security is a very important reason for governments to put an effort in the search for and development of non-petroleum based energy sources. Large areas in the world currently depend on oil from countries in the Middle East and other, possibly politically unstable countries. Alternative fuels made from often abundantly available coal, natural gas or other fossil sources as well as from biomass could replace foreign oil based products to a large extent. A second important reason for alternative fuel research is the global climate change due to greenhouse gas emissions. Petroleum based kerosene as well as any other fossil energy source based jet fuel results in the emission of carbon dioxide and other greenhouse gasses both at ground level as well as at cruise level. Biofuels could be a solution to reduce the amount of greenhouse gasses emitted and, partially, solve this problem.

Several alternative, i.e. non-petroleum based, fuels are considered for jet aircraft. Some very exotic solutions require a complete change in aircraft design. For example the use of liquid natural gas (LNG) or liquid hydrogen (LH2) results in the need for large fuel tanks that are insulated and pressurized. Electrical propulsion would mean the replacement of gas turbines by electric engines and the development of appropriate batteries. These types of energy sources still need significant technological development and thereby are not a solution in the short run. Therefore, currently fuels are considered that can replace or be blended into normal petroleum-based kerosene. These so-called 'drop-in' fuels can be used in aircraft that are currently in operation without requiring any modifications to the aircraft or requiring major changes in the fuel supply infrastructure. This narrows down the possibilities for alternative fuels considerably. Many types of fuel can be used in a gas turbine, but have disadvantages like a too high freezing point or corrosive effect on aircraft and engine parts. Only fuels that are fully compatible with the aircraft engines, operating conditions and all parts that are exposed to the fuel can be used. The most promising options for use as a drop-in

[1] Ph.D. Student, ASSET, T.A.Snijders@TUDelft.nl
[2] Assistant Professor, ASSET, J.A.Melkert@TUDelft.nl.

fuel are synthetic fuels and hydrotreated renewable jet (HRJ). Synthetic fuels are already included in the fuel specifications and can be used as a neat fuel (Sasol fully synthetic jet which contains aromatics) or as blends with Jet A-1 up to 50% for synthetic paraffinic kerosene. The specifications for synthetic fuels can be found in ASTM D7566[1].

The safe use of synthetic fuels is a significant step towards the use of biofuel. Synthetic fuels are the first really new type of fuel allowed for use in jet aircraft since the start of the jet age in the 1950s. The certification process and introduction in the fuel specifications of synthetic fuel provided a good insight in what is needed to introduce new fuels, the procedure for fuel certification can be found in ASTM D4054. Using the experienced gained during this process, other alternative fuels can be implemented quicker and HRJ is currently undergoing the certification process. In recent and coming years the production of synthetic fuels shows a large rise. Currently large scale production is starting up in Qatar, where the Sasol, Shell and other companies have facilities that will produce large amounts of synthetic fuel every day, a total of 783.000 barrels oil-equivalent per day is planned[2].

The research presented in this paper forms part of an investigation of alternative jet fuels performed at the Delft University of Technology. This investigation strongly focuses on the use of synthetic fuels; however, other alternative fuels are included. This research consists of different parts, both theoretical and practical. Calculations of the expected aircraft performance changes and fuel consumption are combined with actual fuel tests in an aircraft engine to prove safe operation with the fuel. Furthermore, the effects of alternative fuels on the environment are measured and analysed.

As part of the investigation, an emission measurement campaign was performed on the use of synthetic fuels. The main topic of this paper is the emission measurement campaign, while results from the performance and fuel consumption analysis are presented in short.

II. Synthetic fuels

Synthetic fuels can be made from different types of feedstock. Any feedstock that can be converted into a synthesis gas consisting of carbon monoxide (CO) and hydrogen (H_2) is a possible source for synthetic fuel. In fact, every material containing carbon and hydrogen atoms is a possible feedstock, although the efficiency of the production and the emissions during the production strongly depend on the hydrogen/carbon ratio of the feedstock. For example, coal as a feedstock will result in more carbon dioxide emissions than when natural gas is used as feedstock. The use of biomass would strongly decrease the net carbon dioxide emissions to (almost) zero. The exact process of transforming the feedstock into synthesis gas is different for every type of feedstock and its properties. However, when the synthesis gas is obtained, the following process that converts the gas into synthetic crude oil is independent of the feedstock type as the synthesis gas is generic. The production process of the synthetic oil from the synthesis gas, called the Fischer-Tropsch[3] process, uses a catalyst that, under the right conditions, enables the formation of hydrocarbons. The carbon chain lengths of the hydrocarbons created this way are generally too large for direct practical use as a jet fuel. Some cracking and refining is therefore necessary to produce the required fuels.

As a result of the production process of synthetic fuels from synthesis gas, the contents of the fuel are very clean. Regular jet fuel contains many different types of molecules and different carbon numbers. The molecules include paraffins, naphthenes and aromatics[4]. Furthermore, trace elements like oxygen, nitrogen and sulphur are present in petroleum-based kerosene. Synthetic fuel, on the other hand, mostly consists of n- and iso-paraffins while other molecules are only present in minor numbers. Trace elements are not found in synthetic fuel in any significant amount. Of course, when Jet A-1 and synthetic fuel are blended, their contents are mixed equivalently.

The properties of synthetic fuels are very comparable to the bulk properties of Jet A-1. This made the certification process much easier. However, some differences are present and these can have a significant influence on the use of the fuels. First of all, an increased lower heating value and decreased gravimetric density of the fuel (see Table 1) will have an effect on range performance and fuel consumption as will be discussed in the next section. Differences in the fuel composition, as mentioned above, may influence materials compatibility. This is not due to the presence of certain molecules but actually the absence of them. Aromatics are not present in synthetic fuels while these are needed for the swell of specific polymer seals. This swell is required for keeping the seals tight over time. In preparation of the emission measurements material compatibility tests have been performed and it was found that at for synthetic fuel blends up to 90% no problems are to be expected. This is supported by the low reduction in seal swell found in literature for neat synthetic fuel[5]. Finally, the lower viscosity of synthetic fuel compared to Jet A-1 can change the properties of the spray in the combustion chamber. This may result in an altered flame and temperature distribution in the combustion chamber and the efficiency and emissions can change consequently. To avoid safety issues due to these differences in fuel properties, the certification process of the fuel ensures that all fuel properties are within a range that is safe during operations.

Table 1 Fuel properties

	Jet A-1	100% synthetic fuel
Lower heating value [MJ/kg]	42.8	44.2
Density [kg/m^3]	800	742
Volumetric heating value [GJ/m^3]	34.2	32.8

III. Performance effects

An aircraft performance model was created in Matlab to assess the influence of fuel properties on payload-range performance and flight fuel consumption. The model allows for the analysis of alternative fuel use in different aircraft. Typical aerodynamic and mass values for an aircraft need to be known. Furthermore, engine data is needed in the form of look-up tables. These look-up tables relate the engine thrust and thrust specific fuel consumption to the Mach number, flight altitude and engine setting throughout the flight envelope. These tables can be created using an engine simulation program like GSP[6]. Different fuels that need to be analysed can be represented by engine data for their respective lower heating value. It was found that within the range of lower heating values of currently considered alternative fuels, interpolation between two sets of engine data created for different fuels is possible without introducing a significant error. Thus, as long as two sets of engine data for sufficiently different lower heating values are available, interpolation allows for the analysis of a complete range of fuels.

In the performance model, the aircraft and engine data have been combined. A numerical integration of the aircraft equations of motion during the different phases of a flight then calculates the range or fuel consumption. These flight phases are depicted in Figure 1; the ATA '67[7] policy is used for reserve fuel calculation. The phases are connected by basic aircraft state parameters, being altitude, airspeed and momentary aircraft mass including remaining fuel. The exact aircraft flight attitude is considered not important in most flight phase connections. The connections only form a very minor part of the overall flight duration. Starting conditions for a flight are the aircraft total mass and fuel mass at engine start. The final conditions are the aircraft empty mass, payload mass and remaining unusable fuel after reserve flight. Fuel mass at the start of the flight is determined by the fuel density, which depends on the fuel type, and fuel volume. Using this model, the possible range of an aircraft with a given take-off mass or the fuel needed for a given range can be determined. Thereby, a payload-range diagram can be constructed or the flight fuel for a typical flight can be calculated.

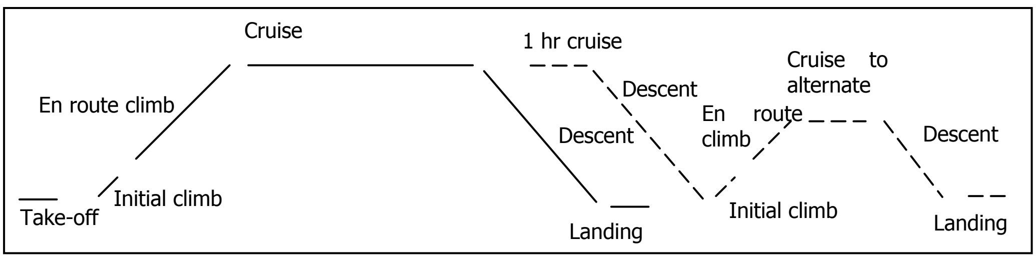


Figure 1 Flight phases (reserve flight is dashed)

The effects of fuel properties on payload-range performance are best shown in a diagram. In Figure 2 a payload-range diagram is given for the Cessna Citation II using neat Jet A-1 as well as a

50% synthetic fuel blend. The figure shows a distinct difference between the two fuels at the three main points in the diagram. At maximum payload the range using the 50% synthetic fuel blend is higher than when using Jet A-1. At this point, the fuel mass is limited by the maximum take-off mass of the aircraft. Thus, with a fixed fuel mass, the higher heating value of the synthetic fuel leads to a larger range. The calculations show an increased range of 4.5%. However, at the two points at the lower right of the payload-range diagram, the range is limited by the fuel volume that can be taken on board. At both these points, the fuel tanks are filled completely. Looking at the points where the diagrams intersect the horizontal axis it is clear that the synthetic fuel blend leads to a lower range than Jet A-1. This is opposite to what was found at the maximum payload point. The reason for this is that the fuel is volume limited instead of the aircraft mass. The volumetric heating value of synthetic fuel is lower than that of Jet A-1 and consequently, less energy is carried in the tanks. As a result, the range is 2.9% smaller. Finally, the corner point in the payload-range diagram with long range and a small payload shows the same effect of the fuel volume limit and the resulting smaller range. However, the smaller density of synthetic fuel allows for more payload in the aircraft before maximum take-off mass is reached. The increase in payload together with the smaller amount of energy carried in the fuel tanks gives a range reduction of 3.8%.

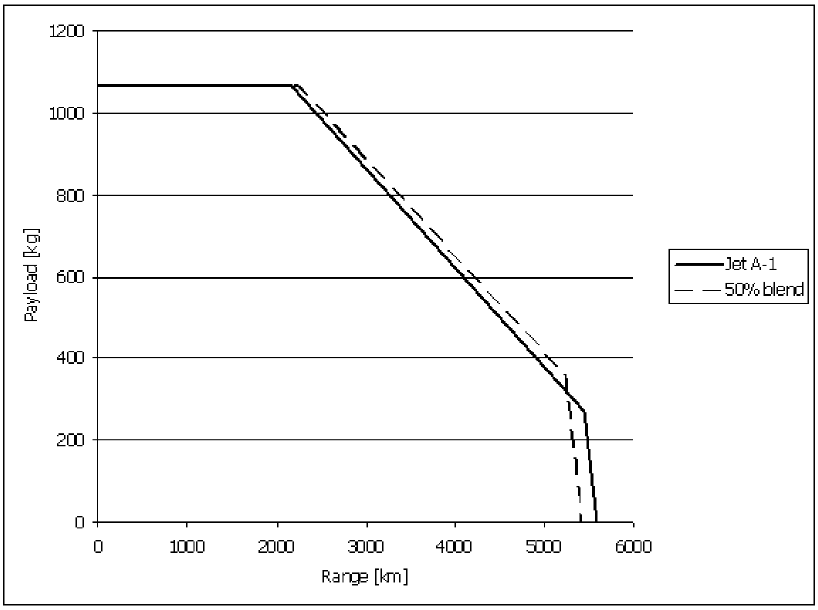


Figure 2 Payload-range diagram for the Cessna Citation II

Two typical flights within the flight envelope of the Cessna Citation II have been used to analyse the effect of fuel type on fuel consumption. The fuel used during each flight is calculated for the case of neat Jet A-1 fuel and for a 50% synthetic fuel blend. The lower heating value of the blend is 1.61% higher than that of Jet A-1 and it is expected that thereby the fuel needed for the total flight is reduced by at least that same amount. This is concluded from the direct reduction in fuel consumption by the engine at any point in the flight. In the model it is assumed that the amount of fuel taken onboard for a flight is the amount needed for that flight considering the fuel type. An increased heating value would then mean that less fuel has to be taken onboard for the flight. Under that assumption, it is expected that the fuel needed for a flight with 50% synthetic fuel is even lower than the 1.61% decrease deduced from the lower heating value directly.

The results of the fuel consumption calculation are presented in Table 2. The first flight represents a relatively short flight with almost maximum payload. On this flight, a reduction in used fuel of 1.70% is achieved, which indeed is larger than the fuel heating value dictates directly. The fuel reduction is 5.3% larger than what can be derived from the heating value. This reduction can be considered an efficiency gain. The second flight is a somewhat longer flight with less payload on board. Because of the longer range, the effect of the reduced amount of fuel on board is now stronger. This leads to an extra reduction of 6.4% for the fuel used for that specific flight. Similar results can be found for other aircraft[8].

Table 2 Typical flight fuel consumption

	Payload	Range	Fuel used 0% synth	Fuel used 50% synth	Difference	Fuel difference	Efficiency gain
	kg	km	kg	kg	%	%	%
Flight 1	800	2000	882	867	-1.70	1.61	5.3
Flight 2	400	4000	1392	1368	-1.72	1.61	6.4

IV. Emission measurements

An emission measurement campaign was performed to find the effects of blending synthetic fuels with Jet A-1. The measurements were done at the KLM engine test run area at Amsterdam Airport Schiphol, using the TU Delft/NLR Cessna Citation II laboratory aircraft (see Figure 3), a small business jet aircraft. The right hand engine, a Pratt & Whitney Canada JT15D-4 turbofan engine, was fuelled with different test fuels provided by Shell Aviation. Some data of this engine is provided in

Table 3. A probe is placed in the core flow of the engine at a distance of 0.2 m behind the engine. This probe consists of a stainless steel tube placed vertically with a series of 2 mm holes facing the jet to sample the jet flow. The sampled jet flow is transported through a heated tube to a van with measurement equipment. In the measurement equipment, the air is diluted by a factor of 70 with pure nitrogen gas to avoid overloading of the measurement equipment. Next, part of the air is led to equipment that analyses the particle concentration and spectrum to find the composition of the particle emissions of the jet flow. The equipment used for this is a TSI Engine Exhaust Particle Sizer. The smoke number (SN) was not determined. The rest of the sampled exhaust air goes to a gaseous emissions analyser for determination of the content of the air. This includes the measurement of emissions of carbon dioxide, carbon monoxide, nitrogen monoxide and nitrogen dioxide. For the gaseous emissions an MKS MultiGas Purity Analyzer is used.

Figure 3 The Cessna Citation II laboratory aircraft during emission measurements

Table 3 Engine data of the P&WC JT15D-4[9]

Parameter	Unit	Value
Type	-	2-spool turbofan
Take-off thrust	kN	11.12
Bypass ratio	-	2.68
Pressure ratio	-	10.1
Fuel flow at take-off	kg/s	0.1697

Two base fuels, Jet A-1 kerosene from two different refineries, were blended with different amounts of synthetic fuel and used for testing. Since Jet A-1 has a variable composition, the use of two base fuels is needed to find the general effect of blending synthetic fuel with regular kerosene. Each fuel is blended with synthetic kerosene to form five test fuels per base fuel. The neat base fuel is tested as a reference. Next to that, blends with 10, 20, 30 and 50% synthetic fuel are used. An emphasis is placed on the lower blending percentages as these are included in current fuel specifications and production of synthetic fuel is not high enough to provide for higher percentages.

Table 4 Engine settings for the LTO cycle

Setting	N1 [%]
Idle	26
Approach	60
Intermediate	86
Climb	93
Take-off	Max N1 of the day

A test program was devised to find the emissions of the fuel blends at different operating points of the engine. The test program includes the LTO (landing and take-off) cycle used in the ICAO engine exhaust emissions databank[9]. The LTO cycle makes use of a fixed thrust setting for take-off, climb, approach and idle. However, the thrust is not measured in the cockpit of an aircraft. Therefore, GSP was used to transform these into core speed (N1) settings that can be controlled by the pilot during tests. An extra test point was added between the approach and climb setting in order to create a more complete variety of engine settings. The engine settings were used for static engine running during which the emissions were measured. The settings are presented in Table 4. It is noted that the weather on some days during the test period required a rather low take-off engine setting which was very close to the climb setting. Therefore, this setting was omitted whenever it was within 1% N1 of the climb setting.

Figure 4 shows the particle emissions results with varying engine setting for the two base fuels. The diagrams in this figure are used to show that the results follow logical trends of particle emissions. The diagram in figure 4a shows the mean diameter of the particles in the exhaust flow. As can be seen, the particle diameter steadily increases with increasing engine power. No difference is found between the two base fuels. The diagrams in figure 4b and c show the particle number concentration and particle mass concentration in the exhaust flow. Both these numbers have been normalised by dividing the results by the idle result of base fuel 1. The particle number concentration in figure 4b again shows an increase with higher engine power. Some difference is found between the base fuels at higher engine power. This difference between the base fuels, however, does not repeat itself for the synthetic fuel blends with these base fuels. The particle mass concentration is constructed by a multiplication of particle number density and mean particle diameter, assuming a constant soot particle density. This leads to an apparently quadratic increase of the soot emissions with engine power setting as can be seen in figure 4c. This is normal behaviour for soot emissions and thus the results seem reasonable. The results for the different synthetic fuel blends show behaviour similar to the results of the neat base fuels.

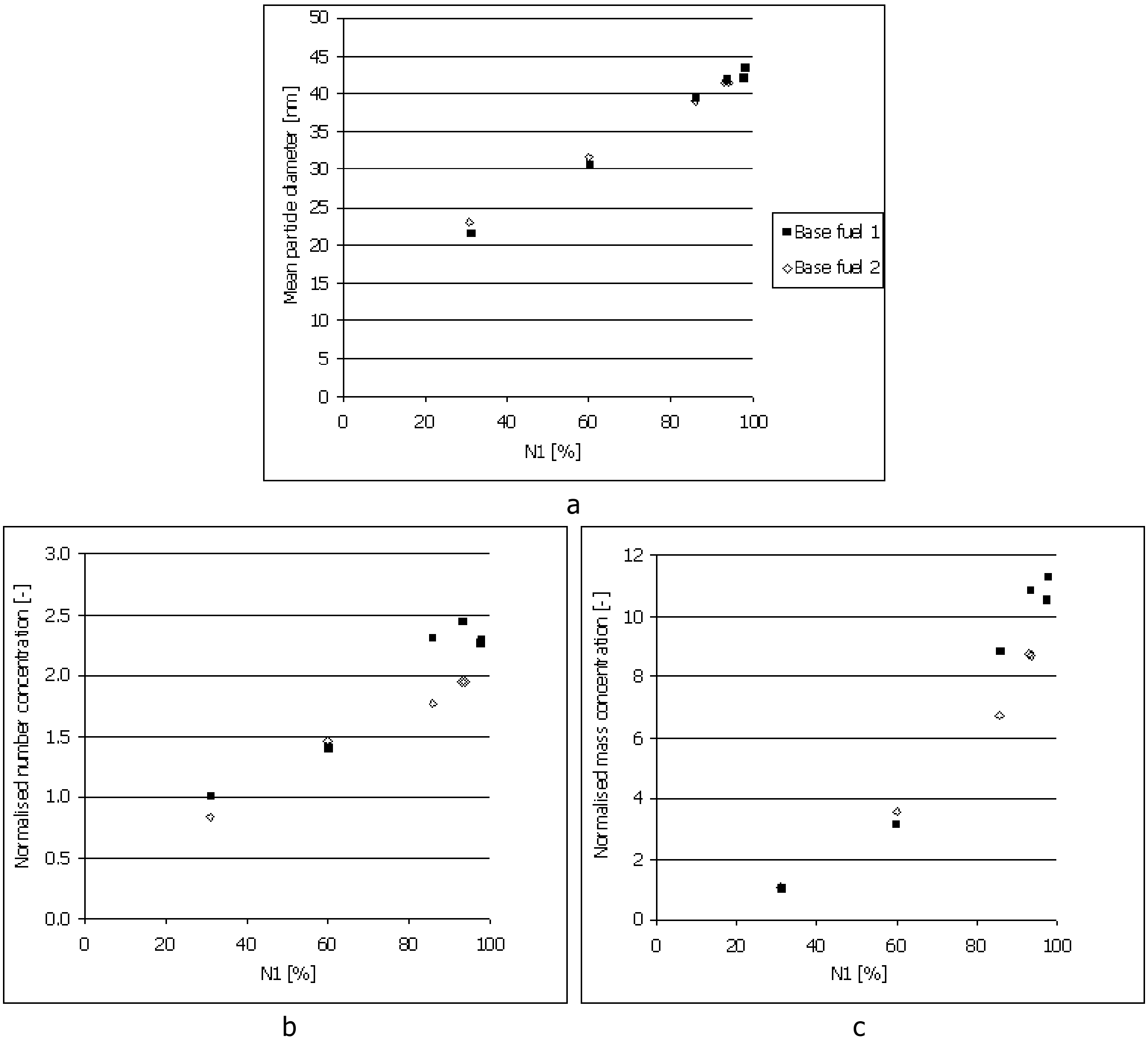
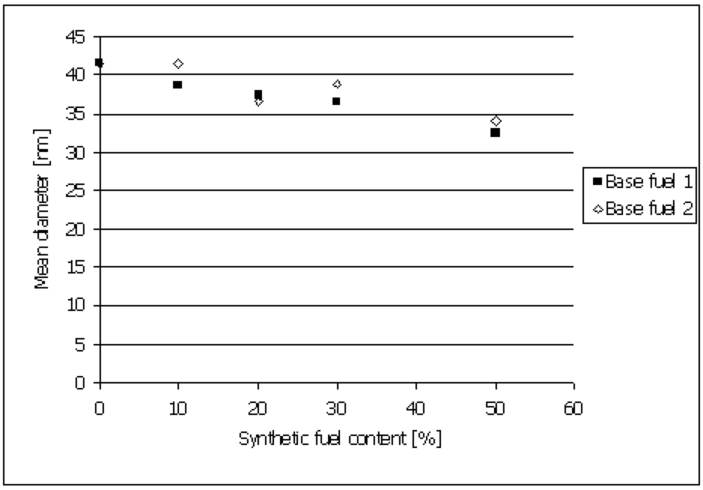
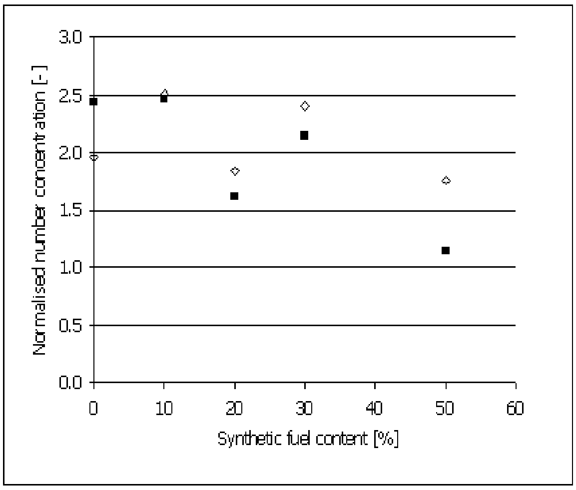


Figure 4 Particle emissions vs. engine setting

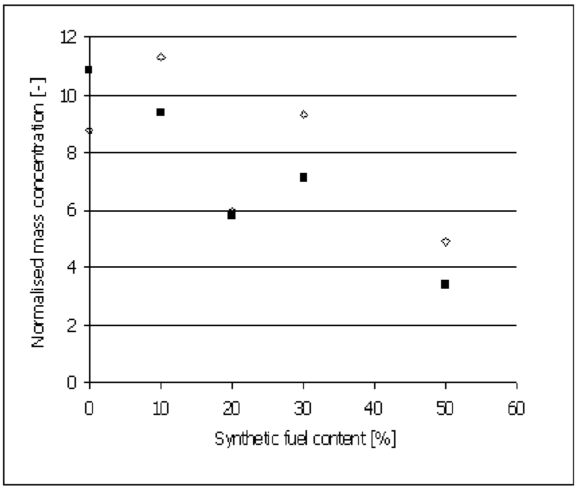
Next the particle emissions for the different synthetic fuel blends are analysed. The results for the climb engine setting are presented in Figure 5, results for other engine settings show similar behaviour. The first diagram of the figure shows that the particle diameter is reduced by the synthetic fuel content. The diameter drops from around 42 nm for the neat base fuels to about 34 nm for the 50% synthetic fuel blends, a reduction of almost 20%. The diagram suggests an approximately linear trend. The particle number concentration does not show a very clear pattern although it suggests a decreasing number of particles with increasing synthetic fuel content. Looking at the mass concentration, the downward trend of particle diameter is combined with the slight decrease of the particle number concentration. This results in a significant reduction of the particle mass. At 10% synthetic fuel, no difference is shown, but for higher percentages of synthetic fuel, a reduction of over 50% in soot emissions is found. This very large reduction is found at other engine settings as well. At idle and approach setting this reduction is even larger. This is supported by measurements on other engines[5,10]. It can thus be concluded that the introduction of synthetic fuel as blending component with Jet A-1 can result in a significant reduction in soot emissions.



a



b



c

Figure 5 Particle emissions vs. synthetic fuel content at climb setting

Currently, the data of the gaseous emissions is being analysed. However, preliminary results indicate reductions in the emissions of unburned hydrocarbons, carbon monoxide and nitrogen oxides. This is in line with emission measurements found in literature[10].

V. Conclusion

In this paper, the effects of using synthetic kerosene blends were presented. Using an aircraft performance calculation combined with fuel consumption data it was shown that the range of a small jet aircraft at maximum payload increases by 4.5% with the use of 50% synthetic kerosene. The ferry range however, decreases with 2.9% when increasing synthetic fuel content. Emission measurements were performed on a Cessna Citation II aircraft using different blends of Jet A-1 and synthetic kerosene. The measured soot emissions followed expected trends with varying engine setting for all tested blends. When plotted against the synthetic fuel content, it was found that both the mean particle diameter and the particle number concentration in the exhaust flow are reduced by increasing the synthetic fuel content. Adding 50% synthetic fuel to Jet A-1 leads to a 20% reduction in particle size and a 34% lower particle number concentration at high engine power. As a result, the particle mass concentration in the exhaust flow decreases dramatically and reductions of up to 70% are reached by using a 50% synthetic fuel blend. The use of these blends promises to lead to a significant local air quality increase around airports and might lead to a reduction in contrail and aircraft induced cirrus cloud formation.

References

[1]ASTM, "Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons," ASTM D7566-10a, ASTM International, 2010.

[2]Butcher, P., "Sasol Chevron – Future GTL Pathway", [online document], URL: http://www.sasol.com/sasol_internet/downloads/7_PatB_SasolChevron_1109333362778.pdf [cited 15 March 2011]

[3]Speight, J. G., *Synthetic Fuels Handbook*, 1st ed., McGraw-Hill, New York, 2008, Chap. 1.

[4]Hemighaus, G., et al., "Aviation Fuels Technical Review," Chevron FTR-3, 2006.

[5]Rahmes, T. F., et al., "Sustainable Bio-Derived Synthetic Paraffinic Kerosene (Bio-SPK) Jet Fuel Flights and Engine Test Program Results," AIAA paper 2009-7002, 2009.

[6]GSP, Gas Turbine Simulation Program, Software Package, Ver. 10.0.1.6, National Aerospace Laboratory, Netherlands, 2005.

[7]ATA, "Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Airplanes", Air Transport Association of America, 1967

[8]Hileman, J. I., Stratton, R. W., and Donohoo, P. E., "Energy Content and Alternative Jet Fuel Viability," *Journal of Propulsion and Power,* Vol. 26, No. 6, 2010, pp. 1184-1195.

[9]ICAO, "JT15D-4 series," *ICAO Engine Exhaust Emissions Data Bank* [online database], URL: http://www.caa.co.uk/default.aspx?catid=702&pagetype=90 [cited 15 March 2011].

[10]DeWitt, M. J., Klingshim, C. D., Striebich, R. and Cheng, M.-D., "Emissions Characteristics of Military Helicopter Engines with JP-8 and Fischer-Tropsch Fuels", *Journal of Propulsion and Power,* Vol. 26, No. 2, 2010, pp. 317-324