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PERFORMANCE EFFECTS FROM ALTERNATIVE JET FUELS

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Abstract

In this paper an analysis has been made of the performance effects of several alternative aircraft fuels. Using numerical integration of flight mechanics equations combined with a gas turbine model, payload-range diagrams have been constructed for three categories of aircraft. It is shown that synthetic fuels performs quite comparable to currently used Jet A-1 whereas the more exotic FAME-type fuels show a reduced range at some points. Furthermore, a look has been taken into some typical flights for an Airbus A320 using different fuels. Non-linear changes of flight fuel consumption as a function of fuel heating value were observed.

1. INTRODUCTION

Fluctuating oil prices and environmental concerns are increasingly pushing aviation industry to consider alternative jet fuels for the near future. Some fuels considered have properties close to those of current kerosene; an important example is synthetic or Fischer-Tropsch kerosene. Other, more exotic options include Fatty Acid Methyl Esters (FAMEs) and other fuels containing components different than pure hydrocarbons. The use of these alternative fuels will have an effect on the operation and performance of civil jet aircraft. This paper will focus on the performance effects. The most obvious effects can be found in aircraft payload-range performance. These effects are primarily caused by the fuel heating value and density in combination with fuel mass and volume limitations of the aircraft. Fuel composition, viscosity, specific heat and other properties will have an effect on aircraft operations as well. These secondary effects are largely dependent on aircraft and especially engine design and may be considered small when compared with the primary effects.

This paper will address the effects of fuel type on aircraft range performance in general. Therefore, the secondary effects are omitted and fuel heating value and density are considered the only significant differences between fuel types. Aircraft performance is analysed using an engine and an aircraft model combined. In the first section, a short description is given of these models and the fuels analysed. The types of aircraft in this research will be discussed as well. Next, calculation results are given and presented in the form of payload-range diagrams for different aircraft groups. Furthermore, some typical flights are analysed for one of the aircraft. Finally some conclusions are drawn from these results.

2. CALCULATIONS

The calculation of payload-range performance for different fuels has been performed using a numerical integration of flight mechanics equations. Input parameters for this integration are the thrust and specific fuel consumption, derived from engine models.

2.1. Engine model

Engine data to be used in the performance calculations is gathered using the NLR Gasturbine Simulation Program (GSP) [1]. This program is based on a component stacking principle and calculates engine parameters at the engine stations based on the input given for each component. In steady state calculations, which are used in this model, the equations following from the set of components are solved using the multivariate Newton-Raphson method.

The data resulting from the engine models has been structured into look-up tables. These three-dimensional tables sort thrust and thrust specific fuel consumption (TSFC) against airspeed, altitude and engine setting. For the determination of thrust and TSFC between data points, linear interpolation is used. Furthermore, for each engine, two sets of look-up tables have been created, each for a different type of fuel. Under the assumption that no secondary effects of fuel type on fuel consumption and thrust are significant, a linear interpolation and extrapolation using these two sets of look-up tables proves to be accurate enough for fuel heating values up to 20% difference from the value of Jet A1. This has been verified using separate engine simulations.

2.2. Flight mechanics model

Payload-range performance is calculated using a numerical integration in Matlab of the flight mechanics equations of different flight phases. The flight phases combined form a complete flight including the necessary reserve flight phases according to the ATA ’67 reserve fuel policy [2]. Thus, a flight profile is established from take-off up to and including landing, with a reserve fuel calculation starting just before landing and finishing with another landing at an alternate airport. When determining the points on the payload-range diagram, the aircraft take-off mass and the zero-fuel mass are known, whereas the calculation of the fuel consumption on a typical flight uses a set zero-fuel mass and range. These input values determine the order in which the flight phases are calculated.

2.3. Aircraft

Three groups of civil jet aircraft are considered in this study. The first group is formed by business jets; in the calculations these are represented by data from a Cessna Citation II. The reason for using this specific aircraft is that fact that TU Delft together with the Dutch National Aerospace Laboratory (NLR) owns an aircraft of this type and use it as a laboratory aircraft. It is the intention to verify some of the calculated results with experiments in a later stage using this specific aircraft. The engines used on this aircraft are Pratt & Whitney Canada JT15D-4 turbofans.

A second group are medium range airliners, represented by the Airbus A320 equipped with CFM56 engines. An indication of the performance effects on long range airliners is found using the Airbus A330-300 with CF6-80 engines. The data for this last group are estimated and because of that, the absolute values of performance will show an unknown error. The comparison between fuels however, will still yield reasonable differences.

As there are usually different versions of an aircraft type, the empty mass and take-off mass of the three aircraft are presented in table 1 for clarity.

Aircraft	Empty mass [kg]	Max. take-off mass [kg]
Cessna Citation II	3,651	6,033
Airbus A320-200	42,400	77,000
Airbus A330-300	122,200	230,000

Table 1: Aircraft properties

2.4. Fuels

Several fuels have been considered and compared to currently used kerosene. Two sets of fuel properties have been used for Jet A-1. First an average fuel has been selected as can be seen in table 2. Furthermore, the 'worst case' fuel within the fuel specifications [3] with the lowest fuel density and minimum heating value has been selected.

Two alternative fuels have been selected that are most promising. The first one being synthetic or Fischer-Tropsch fuel is kerosene with properties close to regular Jet A-1. The name synthetic kerosene means it is being made artificially, it can not be mined. This fuel is made from syngas, a mixture of carbon-monoxide and hydrogen, which in turn can be produced from a variety of feedstock ranging from coal to biomass, as long as the feedstock contains a sufficient amount of carbon atoms. The data used are average values for Shell Gas-to-Liquid fuel.

A second alternative fuel is represented by an average density and heating value for biodiesel or FAME. This is a fuel with a higher density and it has a lower heating value; both values are located outside of the current aviation Jet A-1 fuel specifications.

Fuel nr	Fuel type	Density [kg/m^3]	Lower heating value [MJ/kg]
1	Avg Jet A-1	805	43.1
2	Lowest Jet A-1	775	42.8
3	Synth. fuel	742	44.2
4	FAME	880	38.5

Table 2: Fuel properties

3. RESULTS

Using all of the previously mentioned fuels, a payload-range diagram is constructed for each aircraft. These will be discussed first. After that, some typical flights for one of the aircraft and the effect of fuel type on fuel consumption will be discussed.

3.1. Payload-range diagrams

Figure 1 depicts the payload-range diagram for the Cessna Citation II business aircraft. The dotted line represents the use of regular Jet A-1; the solid line shows the lower bound of the Jet A-1 specifications. A small difference is observed at the point of maximum range at maximum payload, this is the result of the lower heating value. At the lower right hand corner of the graph a larger difference is seen, here the fuel tank volume becomes limiting. The effect of fuel density leads to a large difference in range. Thus, because of the fuel specifications, aircraft manuals show a very conservative range at this point when comparing to the average fuel.

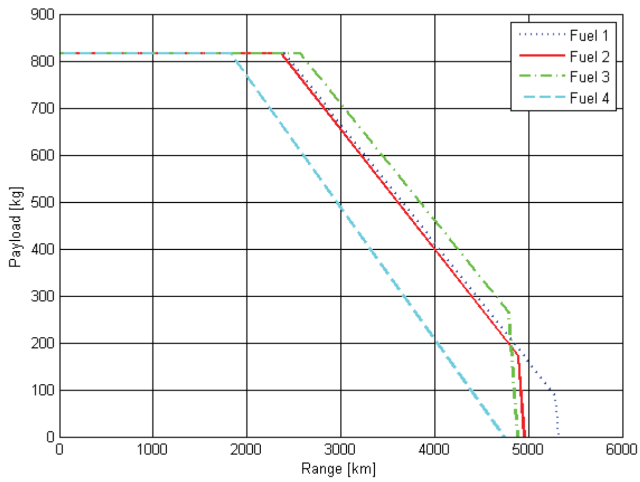

Figure 1: Payload-range diagram Cessna Citation II

Fuel 3, the synthetic fuel, has a higher heating value which results in an increased range at the maximum payload point, where the fuel mass that can be carried is limited. The higher range continues when exchanging payload for fuel up to the point that the fuel tanks are all completely filled up. At this point, the lower density of the fuel leads to a lower fuel mass with full tanks. At the same time, a somewhat larger payload can be carried, filling the aircraft to maximum take-off mass. Finally, the ferry range is lower than that of the 'worst case' Jet A-1 as a result of the decreased density

When considering the FAME or biodiesel type fuels (fuel 4), the dashed line in figure 1, the effect of the lower heating value is clearly visible. A significant decrease in range is found at maximum payload. Furthermore, for every kilogram of payload that is replaced by fuel, the amount of energy added is less than in the case of the other three fuels. Therefore, the line from maximum payload follows a steeper path downward. The lowest point on the payload-range diagram for this fuel happens to be a point where the fuel tanks are not full yet. Fully filled fuel tanks would, as a result of the high fuel density, lead to an aircraft mass above the maximum take-off mass, even though no payload is present. The resulting ferry range ends up being quite close that of the other fuels.

Figure 2 shows the payload-range diagram for the Airbus A320. It can be seen that the differences between the average Jet A-1 and the specification limited fuel, fuels 1 and 2 respectively, lead to the same differences as for the business jet. The synthetic fuel again shows a somewhat larger range at maximum payload whereas the fuel volume limited points again show a reduced range.

Fuel 4 however does result in a different diagram. At maximum payload the range is still reduced. But with the A320 it is possible to fill up the fuel tanks with this fuel completely while still carrying a reasonable payload. Surprisingly, using fuel 4 the aircraft can fly further than when using the synthetic fuel or the specification limited Jet A-1. This can be explained by the higher volumetric heating value of fuel 4 compared to fuels 2 and 3. Multiplication of the fuel density and lower heating values of table 2 gives the volumetric heating value which for fuel 4 is indeed higher.

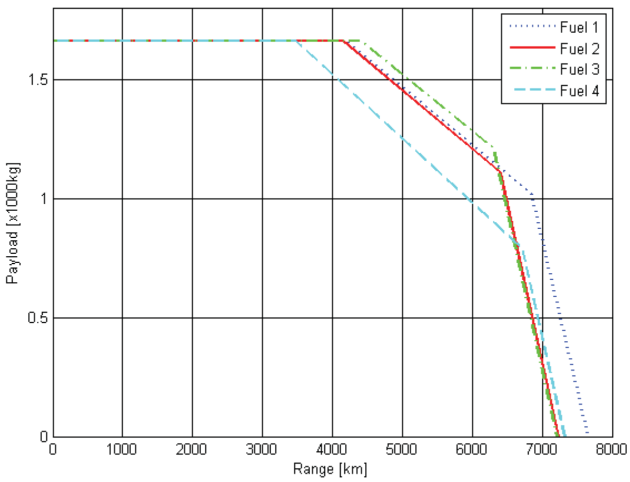

Figure 2: Payload-range diagram Airbus A320-200

The payload range diagram for the A330-300 is given in figure 3. It shows a comparable result to that of the A320. The only difference that can be seen is the slightly larger difference between the FAME-type fuel compared to fuels 2 and 3 at the maximum fuel volume points. This is the result of the longer range of the aircraft, which increases the effect of fuel type on range performance.

3.2. Typical flight performance

For the Airbus A320 some typical flights have been chosen that represent the normal use of the aircraft by an airline. The first flight is set at a high payload of 15,000kg, approximately 90% of the maximum payload. A range of 2,500km is used, so that a typical European holiday flight is established. Table 3 shows the fuel that is consumed during such a flight, reserve fuel has been taken into account but is not shown as it is not actually used in the flight. The fuel used for each type of fuel is given and the relative difference when compared to the average Jet A-1 is calculated.

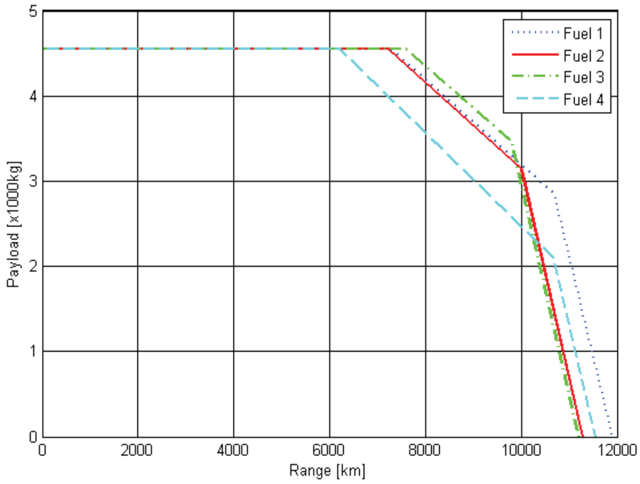

Figure 3: Payload-range diagram Airbus A330-300

Since at these points neither fuel mass nor fuel volume is limiting, the fuel heating value will be the only fuel property influencing the fuel used. There will however be cumulative effects of using more or less fuel; if less fuel is needed for normal and reserve flight, less fuel needs to be carried and a lighter aircraft will be the result. This in turn will lead to less fuel consumption and thus a loop exists. This loop converges rapidly to a final value. These effects can be observed in table 3. In the table it is seen that the synthetic fuel leads to a fuel consumption that is 3.2% less than when using regular Jet A-1 while only a 2.6% difference exists in heating value (table 2). The FAME-type fuel shows an even larger difference; fuel consumption is increased 13.5% whereas the fuel heating value is only 10.7% lower.

	Fuel 1	Fuel 2	Fuel 3	Fuel 4
Flight fuel [kg]	8,271	8,343	8,007	9,387
Difference to fuel 1	0%	0.9%	-3.2%	13.5%

Table 3 Fuel consumption Airbus A320 (R=2,500km, payload=15,000kg)

Another typical flight is set at a lower payload of 8,000kg but twice the range of the previous flight. The results of this flight are given in table 4, which quickly shows that at another point near to the edges of the payload-range diagram the effects of the changed fuel type are the same as for the previous flight.

	Fuel 1	Fuel 2	Fuel 3	Fuel 4
Flight fuel [kg]	14,399	14,523	13,935	16,336
Difference to fuel 1	0%	0.9%	-3.2%	13.5%

Table 4: Fuel consumption Airbus A320 (R=5,000km, payload=8,000kg)

The next flight investigated is a flight in which the range is only 1,500 km and only half of the seats are occupied (payload 5,000 kg). It can be seen that the cumulative effects mentioned above are increased somewhat. The mass of the reserve fuel becomes a larger part of the total aircraft mass and thus, a reduction in reserve fuel mass has a larger effect on flight fuel.

	Fuel 1	Fuel 2	Fuel 3	Fuel 4
Flight fuel [kg]	5,155	5,200	4,978	5,873
Difference to fuel 1	0%	0.9%	-3.4%	13.9%

Table 5 Fuel consumption Airbus A320 (R=1,500km, payload=5,000kg)

However, it must be noted that in the above it is assumed that the exact fuel properties are known before a flight. It is therefore assumed that the exact amount of fuel to be carried is known. In reality however, it might not be possible to known what type of fuel or blend of fuels is used for fuelling the aircraft. The amount of fuel taken aboard has to be based on a ‘worst case’ fuel and as a result it is possible that too much fuel is carried. In the case of synthetic fuel less fuel (mass) will be burned for the same amount of energy. At the same time the flight would start with a fuel mass that is already too high. This would result in a significantly higher fuel mass at the end of the flight, and thereby actually inverting the cumulative effect mentioned earlier.

In the case of a normal flight using FAME-type fuel the lower heating value must be taken into account since it is completely outside of the specifications. Here it is even more important to know the heating value simply to avoid running out of fuel during the flight. In practice it will be impossible to adapt the lower bound of the fuel specifications to include this fuel since that would mean that an aircraft will generally carry far too much fuel. Thus, the heating value of this fuel type will have to be increased or it can only be used under strictly controlled circumstances.

4. CONCLUSIONS

The payload-range diagrams constructed using numerical integration of flight mechanics equations clearly show that the type of jet fuel used has a significant influence on aircraft performance. In cases where fuel volume is limiting, different types of Jet A-1 within the fuel specifications already show large differences (5% to 7%). The use of fully synthetic fuel, fuel number 3 in the diagrams, leads to a slightly increased range (up to 6.8 %) when fuel mass is the limiting factor. At other points, the range is only marginally lower than the range resulting from fuel specifications. Blending of this fuel with Jet A-1 or a small change in the aircraft specifications can lead to full acceptance of this fuel when considering aircraft performance.

The properties of FAME-type fuels are quite different from current fuels and as a result, a much lower range is found in cases where fuel mass is limiting. The use of this type of fuel must therefore only be allowed under strict regulations in order to avoid aircraft accidentally running out of fuel. The high density of FAME-type fuels results in range performance at the lower part of the diagram (long range performance) that is comparable to that of current fuels.

The calculation of the fuel consumption on some specific flights for an A320 shows that the effects of fuel heating value will be considerable. Variation in the properties of Jet A-1 can already lead to an increase in fuel consumption of up to 1%. When using alternative fuels with properties further away from Jet A-1, the effects of the changed properties are increased. An increase or decrease in reserve fuel mass and flight fuel consumption is shown to lead to a cumulative change in flight fuel consumption. As a result, a 2.6% higher heating value of synthetic fuel leads to a decreased flight fuel consumption of over 3% on an A320. This fuel can therefore be an economically beneficial alternative even when fuel price is somewhat higher than current Jet A1 fuel prices.

The fuel consumption when using FAME-type fuel is a victim of the same effect. A 10% lower heating value leads to an increase in fuel consumption of over 13%. However, since this type of fuel is made from biomass, increased fuel consumption might not be a problem in environmental terms. When considering economics, the fuel will have to be affordable enough to compensate for the increased fuel consumption. The fact that it is made from biomass can possibly be used to compensate for higher fuel cost.

It is seen that the implementation of alternative jet fuels will have an impact on payload-range performance and fuel consumption. Special care must be taken to avoid safety risks because of reduced range performance. In terms of economics, the fuel consumption effects will have to be taken into account when introducing a new fuel into the market.

5. REFERENCES

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