**TREND ANALYSIS OF THE EFFECTS OF FUEL SAVING** **IMPROVED PROPULSION SYSTEMS.**

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by Kay Runne,

Independent Aerospace Researcher and Consultant.

[www.ramwave.eu](http://www.ramwave.eu)

[KayRunne@msn.com](mailto:KayRunne@msn.com)

Summary.

A dimensionless aircraft fuel consumption calculation model has been developed, based on the well-known Breguet range equation using dimensionless mass ratio numbers, leading to a parametric assessment of the effect of improved propulsion efficiency on the Fuel Mass to Zero Fuel Mass ratio versus Range, independent of the seize of the aircraft and its propulsion system, but with having a similar configuration arrangement.

Without having any data on new advanced energy and emissions saving propulsion systems this has been done parametrically for different values of the propulsion efficiency with a general crude mass assumption of constant Operating Empty Mass, only acceptable in a first preliminary design approach as a basis to start an iterative design process.

Also and on the same basis a dimensionless Payload Transport Efficiency as a quality number has been defined and determined in order to assess the relation of the transport of a payload over a distance to the energy produced by the burned fuel and consequently to the emissions associated with it.

The main conclusion is that with the introduction of new fuel saving propulsion systems a significant reduction of fuel consumption and emissions and a greater range flexibility, enhanced by the effect of a noticeable aircraft weight reduction due to the reduction of transported fuel quantity, can be achieved.

1. Introduction.

In order to respond to the necessity of saving fuel because of its scarcity and the necessary reduction of its emissions, improved propulsion systems and aircraft, in which they should be fitted in, are to be developed.

Since no reliable performance data are yet available of these systems and a comparison of those systems on a basis of the bare propulsion system only doesn’t make sense, an aircraft fuel consumption calculation model is developed, based on the well-known Breguet range equation using dimensionless mass ratio numbers, leading to a parametric assessment of the effect of improved efficiency of these new propulsion systems on the Fuel Mass to Zero Fuel Mass ratio versus Range, independent of the seize of the aircraft and its propulsion system, but limited to a similar aircraft configuration.

With an extension of our theoretical model we will conceive the aircraft as a vehicle transporting a payload over a distance with a calculated amount of fuel according to the propulsion efficiency and define a transportation efficiency being the ratio of this net transport work to the energy of the required fuel quantity.

For optimal cruise flight, during which the aircraft is increasing its altitude according to the decrease of its weight, the relation between the range of an aircraft and the required fuel is given by the well-known Breguet equation, mentioned above. But in reality these condition can almost never be realized due to Air Traffic Management and operation economics, ref.[1].

For our purpose here of the assessment and comparison of tendencies rather than exact numbers however, we will stick to the use of the Breguet equation in a way as it has been described in the next chapter. Additionally general crude assumptions for the design changes of the aircraft are made in order to form a starting base for the cyclic iterative design process of such aircraft and their new propulsion systems.

2. Fuel Consumption versus Range.

The required fuel for a given still-air distance (range) depends on the factors including the characteristics of the airplane and its propulsion system, the climb, cruise and descent and the prescribed flight planning allowances for taxiing, route reserve, fuel for diversion to an alternate airport and final reserve fuel. In international jet operations typically 5% of the trip fuel (JAR-OPS 1) or 10% of trip time (FAR 125) is applied as route reserve and 30 min. holding at 1500 ft as final reserve fuel, ref.[1].

Let us define for our calculation model an Equivalent Breguet Range EBR with appropriate simplifying assumptions for this trend analysis. This EBR would be the range performed, when all the fuel including allowances and reserves would be consumed on optimum cruise flight conditions. The fuel consumption according to the EBR covers that of all flight phases within the aircraft Design Range Rd and includes all the prescribed allowances and reserve fuel as mentioned before. We can then write according to the well-known Breguet equation for the EBR:

 eq.[1], in which:

TAS = True Air Speed [],

CT = Thrust Specific Fuel Consumption [],

L/D = Lift-to-Drag Ratio, ZFM = Zero Fuel Mass [kg],

FM = Fuel Mass [kg].

g = gravity acceleration []

With  [2], in which: P = Propulsion Efficiency,

hl = Fuel Lower Heating Value [],

we obtain:  [km] eq.[3]

In this equation we find the influence of the propulsion performance parameters P and hl on the EBR, together with L/D and FM/ZFM. Except for hypersonic aircraft, where Lift is also generated by centrifugal force, this range equation is valid for all types of aircraft propulsion, as well as kind of fuels.

We see that the EBR is proportional to a factor r, which we define as Range Factor, with

 [km] eq.[4]

This Range Factor r combines the proportionality factors determining the EBR and is therefore treated here as a single parameter, so that we can simplify then eq.[3] to:

 [km] eq.[5]

For the Fuel Mass ratio parameter FM/ZFM we can write then:

 eq.[6]

This equation forms the basis of our parametric investigation.

3. Aircraft Design Range Rd, Design Payload PLd and the EBR.

The Design Range Rd and the Design Payload PLd are the principal requirements for the design of a transport aircraft. They represent a single point of the Payload – Range Diagram, which displays also other ranges that can be flown by the same aircraft with other payloads.

Now we must investigate the relation between the EBR and the Design Range Rd in order to determinate the Fuel Mass Ratio FM/ZFM for different aircraft with respectively different Design Ranges Rd by making an appropriate generalizing assumption. The verification of such an assumption must be left to an implementation within the design iteration process in a next phase of more detailed project studies.

Let us make for this first global investigation the following crude assumption for the EBR, which should cover all the fuel allowances including reserve fuel cited above:

 [km] eq.[7]

With this assumption of eq.[7] we obtain for FM/ZFM :

 eq.[8], with r and Rd in [km].

We have with eq.[8] a direct relation between the Fuel Mass Ratio FM/ZFM and the Design Range Rd with the range factor r as a parameter.

4. Mass Relations and Assumptions for Mass and Wing Area.

Now we must consider the influence of the required Fuel Mass FM to cover a given Design Range Rd on the Zero Fuel Mass ZFM itself, since the Take-Off Mass TOM depends directly from the Fuel Mass FM, as is explained by eq.[9]:

 eq.[9], or  eq.[10]

If we further split up the ZFM into the Operating Empty Mass OEM and the Pay Load mass PL, we can write:

 eq.[11]

With the reduction of the TOM resulting from the lower fuel mass of an aircraft with a new generation more fuel efficient propulsion system than that of the reference aircraft, we can reduce the wing area AW and its structural mass WSM as well as that of the landing gear LGM.

If we assume that all the fuel of the aircraft is carried in the wing we obtain for the reduction ratio of the wing area AW -AW/AW according to the square-cube law:

 eq.[12]

This means also a reduction of the wing loading at maximum take-off mass TOMm/AW, which will be beneficial for take-off characteristics in connection to flight safety conditions and community noise subjection.

Now we make another assumption, which is also crude and can only be permitted for early preliminary investigations, but which allows us to find a direct correlation between the required Fuel Mass FM, the Design Pay Load PLd and the Design Range Rd. We assume therefore that the increase of the mass of the propulsion system is balanced by the decrease of the structural masses of the wing, landing gear and in some extend the tail plane, briefly that:

 eq.[13].

This assumption is not valid for a possible use of cryogenic fuels like LH2 or LCH4, since these fuels must be stored in pressure vessels.

With eq.[8] we can write then:

, with Rd and r in [km] eq.[14].

For a required Design Payload PLd and a required Design Range Rd according to the overall design requirement of the aircraft we can calculate then the required Fuel Mass FM.

5. Aircraft Design Requireement.

The overall design requirement for a transport aircraft is the delivery of the Design payload PLd at the distance of the Design Range Rd. So we take this requirement as the basis of comparison of aircraft with the same required PLd and Rd, but with different kind of propulsion systems, with a reference aircraft with a state-of-the-art turbofan propulsion system.

The payload range diagram displays for the same aircraft for every other payload the range within the stress limited ZFM or load volume limit and fuel capacity. We can thus compare the payload versus range diagrams of an aircraft with actual turbofans and of aircraft with different, less fuel consuming propulsion system, but with the same design requirement, i.e. the same PLd and Rd. This principle is shown on a exemplary and not to scale qualitative basis and schematically in fig.1.

Fig.1: Payload versus Range for aircraft with the same design requirement

Payload

Range

Design requirement Rd

Actual Turbofan A/C

Adv. Propulsion System 1

Adv. Propulsion System 2

PLd

for different kind of propulsion systems with different efficiencies.

We see from fig.1 that with the introduction of propulsion systems with lower fuel consumption the penetration of the payload-range diagram to bigger ranges is larger. It means that a greater flexibility in transport capability due to the lower fuel consumption with consequently a lower take-off mass would be attained. This is an important additional advantage to obtain with new fuel saving propulsion systems with consequently less emissions.

6. Numerical Evaluation of the ratio FM/ZFM.

In fig. 2 the ratio FM/ZFM depending on the Design Range Rd is displayed for state-of-the-art turbofans and for advanced propulsion systems differing in propulsion efficiencyp, assuming in cruise flight an L/D = 25, ref.[4], taking into account that g = 9,81 [m/s2], for kerosene hl = 43,2 [MJ/kg], ref.[2], and the values of p of the different types of propulsion systems indicated in table 1:

|  |  |
| --- | --- |
| Propulsion System | Propulsion Efficiency p |
| Actual High Pressure Turbofan | 0,35 |
| Advanced Propulsion System 1 | 0,40 |
| Advanced Propulsion System 2 | 0,45 |

Every combination of Rd, PLd and Propulsion System represents an aircraft design. Advanced Propulsion System 1 could represent the application of a Geared Turbofan and Advanced Propulsion System 2 the application of a High Speed Propeller, ducted or open.



Fig.2: FM/ZFM ratio depending on Design Range Rd and Propulsion

Efficiency p.

We see a substantial reduction of the increase of the FM/ZFM ratio with the Design Range Rd and according to it a substantial reduction of the Take-off Mass TOM determined primarily by a reduction of the wing size leading to a reduction of the Zero Fuel Mass ZFM. Thus the thrust requirements for those new fuel saving propulsion systems and their mass can be reduced and with it again the required Fuel Mass determined by the FN/ZFM ratio. We will end up then for the same design requirement with a smaller aircraft consuming substantial less fuel generating substantial less emissions and a greater range flexibility.

Alternatively we could increase the Design Pay Load PLd and keeping the same Design Range Rd by stretching the fuselage of an already existing aircraft, but then our assumption of compensating the increase of propulsion system mass with a reduction of the Wing Structure Mass WSM and the Landing Gear Mass LGM isn’t anymore valid and we must make a more elaborated mass estimation. However that would be the way to assess the benefit of installing an advanced propulsion system as a retrofit on an existing aircraft or a change in the design of a new aircraft project.

7. Payload Transport Efficiency.

In Chapter 6 of the SBAC Aviation and Environment Briefing Papers, ref.[3], the parameter Payload Fuel Efficiency = Payload  Range / Fuel Mass is introduced, which is not an efficiency according to its usual definition, but merely a quality number for the Range factored with the Payload Fuel Mass Ratio, which is commonly used in aircraft performance evaluations. However this parameter doesn’t take into account the energy produced by burning the fuel in the propulsion system, differing for different fuels.

Let us define here for a transport aircraft a dimensionless Payload Transport Efficiency PTE as a quality number by extending the above defined parameter for the Payload PL and the Range R with the Lower Heating Value hl and the gravity acceleration g as written in eq.[15], assuming that in accordance with JAR – OPS 1 95% of the stored Fuel Mass FM is used, ref.[1].

 eq.[15].

However the product PL • g • R doesn’t represent the energy needed to transport the payload PL over the range R, since the payload weight is merely perpendicular to the flight path and for that reason values of the PTE may well exceed unity, what cannot be possible with a thermodynamic efficiency. The energy output to the aircraft is represented by the product of the total thrust Ftot of the propulsion system over the range and the ratio of it to the produced energy by burning the fuel represents the Propulsion Efficiencyp as expressed by eq.[16]:

 eq.[16], with Ftot = Total Thrust [N].

We can easily recognize that:  eq.[17]

According to eq.[3] the Total Thrust of the Propulsion System Ftot decreases during the cruise flight with the increment of the altitude, so for Ftot we can write:

 eq.[18]

For p/PTE we obtain then:

 eq.[19]

With  and with eqs.[3], [8], [13] and [14] we obtain for thethe Aircraft Design Requirements:

 eq.[20]

In fig. 3 the decrease of the PTE according to eq.[20] is showed for the different values of the Propulsion Efficiency p of the different types of propulsion systems, assuming OEM/PLd = 2,4, ref.[4], in agreement with eq.[13]. With the decrease of the PTE with Rd the difference in the PTE for increasing p is also decreasing, but very slightly.



Fig.3: Payload Transport Efficiency PTE depending of Design Range Rd and Propulsion Efficiency p.

We see that the PTE at a given Design Range Rd is clearly improved by increasingp. The decrease of the PTE with Rd is caused by the well known necessity to carry more fuel with increasing range. For a significant improvement of the PTE at bigger ranges a refueling stop would have effect, as well as in-flight refueling could possibly have. Another way, but farther in the future would be suborbital hypersonic flight with a large part of the required lift to be compensated by the centrifugal force. An even farther away possibility would be in-flight energy transfer into the aircraft by a high power laser.

1. Conclusions and Discussion.

The development of advanced propulsion systems with higher efficiency for transport aircraft will lead to a significant reduction of fuel consumption and emissions enhanced by the effect of a noticeable aircraft weight reduction and to a greater range flexibility.

Also the required fuel quantity to transport a payload over a distance and with it the emissions quantity can be markedly reduced.

With the dimensionless calculation model developed here new propulsion systems can be compared in an early development stage on the basis of their expected or also in a later stage of measured propulsion efficiency and with it of their emissions quality. The incorrect direct comparison of only the characteristics of the bare propulsion systems can be avoided.

A comparison is also possible on the basis of the here defined payload transportation efficiency and by consequence the transportation emissions quality, which both are reduced with increasing range due to fuel transportation, but increased with increasing propulsion efficiency.

The dimensionless calculation model can be used as the basis for the propulsion system and aircraft design iteration process.

1. References.

[1]Joop Wagemakers,

Aircraft Performance Engineering,

Prentice Hall International (UK), 1991,

New York, London, Toronto, Sydney, Tokio, Singapore.

[2] SBAC Aviation and Environment Briefing Papers,

Chapter 4: Air Traffic Management and Operations, July 2008.

[3] SBAC Aviation and Environment Briefing Papers,

Chapter 6: Aircraft Technology and Emissions, May 2008.

[4] Brochure Airbus A340 – 300, Rev.6,

Airbus Industrie, April 1990.