Hochschule für Angewandte Wissenschaften Hamburg

Hamburg University of Applied Sciences

AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Specific Fuel Consumption of Jet Engines – Implications in Aircraft Design and Performance Calculations

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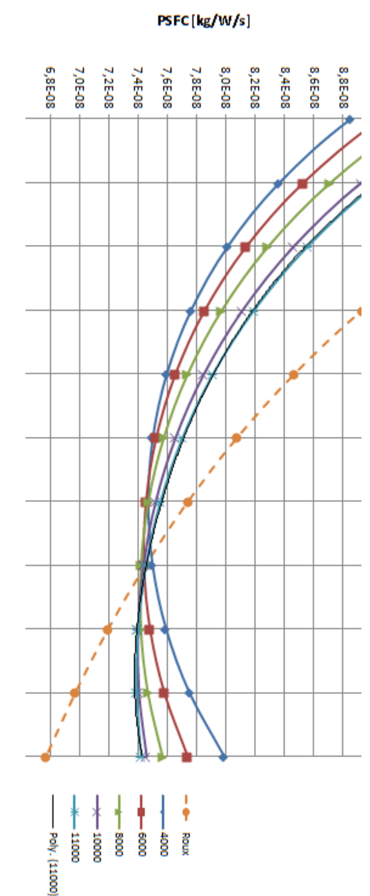


Abstract

Basic considerations about an overall efficiency of an aircraft lead to the conclusion that a power-specific fuel consumption (PSFC) has to be constant, whereas a thrust-specific fuel consumption (TSFC) has to be proportional to speed. This however, leads to a contradiction, because the fuel consumption at zero speed cannot be zero. Furthermore, specific fuel consumption is a function of thrust (or drag) which varies with speed. This links SFC not only to engine characteristics, but to the whole aircraft and its flight condition. We understand that (in contrast to tradition) the Breguet range equation for jets could be written with a (constant) power-specific fuel consumption (PSFC). Optimizing for maximum range now leads to a different optimum speed compared to a derivation based on a constant thrust-specific fuel consumption (TSFC). We also understand why flying low and slow (for reduced fuel consumption) does not work as well as expected – even for a newly designed aircraft for which the wing area is not yet fixed.

Keywords: specific fuel consumption, SFC, Breguet, range, fuel, saving, flight, low, slow

Contents

Introduction

- It is: $c = c_T =$ TSFC, the thrust-specific fuel consumption as used for jet aircraft

  Typical value: 16 mg/N/s
- It is: $c' = c_P =$ PSFC, the power-specific fuel consumption as used for propeller aircraft
- The fuel mass flow for jet aircraft is $\dot{m}_F = c\,T$
- The fuel mass flow for propeller aircraft is $\dot{m}_F = c'\,P$
- Power is $P = T\,V = D\,V$

  with

  T thrust

  D drag

  V speed
- H heating value. Kerosene: 42,5 MJ/kg
- E energy

The First TSFC-Paradox

We define a "mystical" **overall efficiency for an aircraft**, η

$$H = \frac{E}{m}$$

$$\dot{E} = P$$

$$\dot{m}_F \cdot H \cdot \eta = P = T \cdot V = D \cdot V$$

$$c_T \cdot \cancel{T} \cdot H \cdot \eta \overset{!}{=} \cancel{T} \cdot V$$

$$\boxed{c_T \cdot H \cdot \eta = V}$$

$$\boxed{\eta = \frac{V}{c_T \cdot H}}$$

With parameters as given

η = 1 :

$V = 680$ m/s

M **= 2.3**, $M = V / a$

for speed of sound

$a = 295$ m/s in $h > 11$ km

Consequences for η :

η = 0.35 at $M = 0.8$

η = 0.22 at $M = 0.5$

η = 0 at ***M*** **= 0**

The Second TSFC-Paradox

We learn from the first Paradox:

The trust-specific fuel consumption

$$c_T = \frac{V}{\eta \, H}$$

increases proportionally with speed, V

$$\boxed{c = c_a \, V}$$

E.g. during take-off **at $V = 0$ m/s**

$$c_T = 0$$

and hence also

$$\boldsymbol{\dot{m}_F = 0}$$

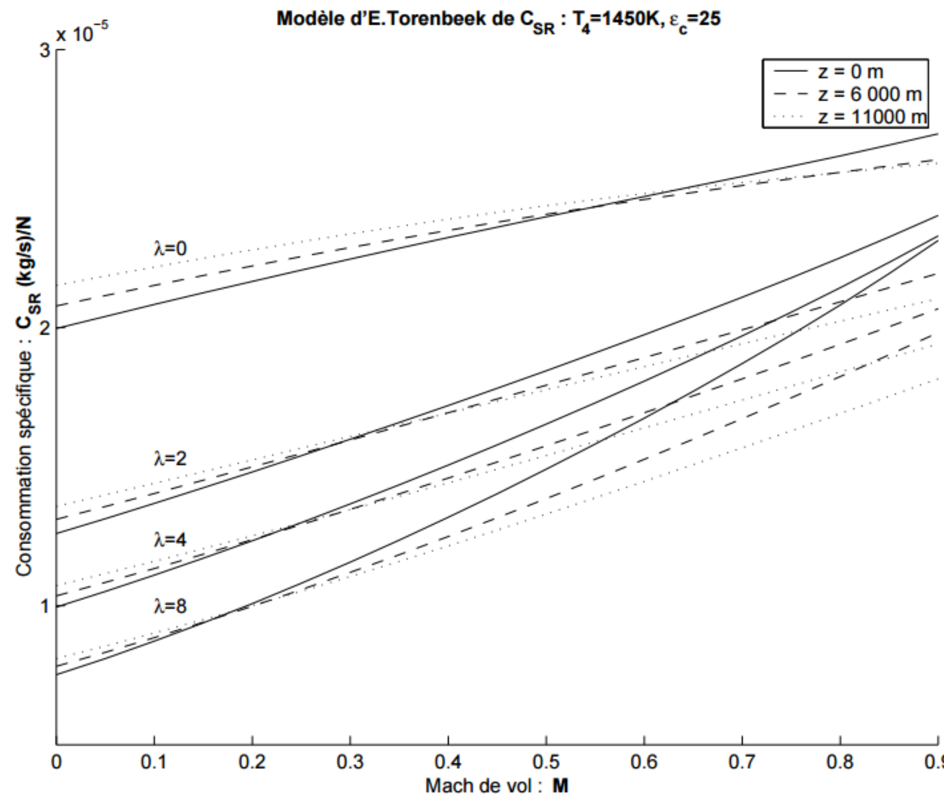
INSA ROUEN SUPAERO ONERA

MODÈLES MOTEUR ...
Réacteurs double flux civils
et réacteurs militaires à faible taux de dilution avec PC

FIG. 1 – *Réacteur d'un A320-211. Photo : Manfred Biel*

Thèse : Pour une approche analytique de la Dynamique du Vol.
Volume : 1
Directeur de thèse : Jean-Luc Boiffier.
Doctorante : Élodie Roux.
Date : 2002

TSFC from Literature (Torenbeek)



Paradox Eliminated with TSFC from Common Sense

$$\boxed{c = c_a V + c_b}$$

$$V = a\,M = a_0 \sqrt{\frac{T}{T_0}}\,M = a_0 \sqrt{\theta}\,M$$

$$c = c_a\,a_0 \sqrt{\theta}\,M + c_b$$

PSFC from First Principles

$$\dot{m}_F = c_P \cdot P$$

$$P = \dot{m}_F \cdot H \cdot \eta$$

$$\cancel{P} = c_P \cdot \cancel{P} \cdot H \cdot \eta$$

$$\boxed{\eta = \frac{1}{c_P \cdot H}}$$

The <u>power-specific</u> fuel consumption PSFC

$$c' = c_P = \frac{1}{\eta\, H}$$

is based on first principles **constant**.

Conversion:

$$c_P = \frac{c_T}{V}$$

TSFC from Literature (Mattingly)

Jack Mattingly

Puisque nous nous intéressons essentiellement aux réacteurs ayant un grand taux de dilution λ, nous retiendrons le modèle correspondant au "High-bypass-ratio turbofan" qui exprimé en unités du système international devient :

$$\boxed{C_{SR} = (1.13\ 10^{-5} + 1.25\ 10^{-5} M)\sqrt{\theta}}$$

C_{SR} :	Consommation Spécifique Réacteur	$(kg/s)/N$
M :	Mach de vol	
θ :	Rapport des températures en vol et au sol $\theta = \frac{T}{T_0}$	
T :	Température ambiante en vol	K
T_0 :	Température au sol $T_0 = 288.15K = 15^\circ C$	K

Considering technology improvements corrected with factor (Roux): 0.92 yields

$$c = (1{,}04 \cdot 10^{-5} + 1{,}15 \cdot 10^{-5} M)\sqrt{\frac{T(h)}{T_0}}\ \frac{\text{kg}}{\text{Ns}}$$

Note: This is different from "Common Sense Equation":

$$c = c_a\, a_0 \sqrt{\theta}\, M + c_b$$

TSFC from Literature (BADA, Juchmann)

EUROCONTROL: *User Manual for the Base of Aircraft Data (BADA)*.
EEC Technical/Scientific Report No. 14/04/24-44, Revision 3.12. – URL:
https://www.eurocontrol.int/sites/default/files/field_tabs/content/documents/sesar/user-manual-bada-3-12.pdf

"For jets the thrust specific fuel consumption, η [kg/(min·kN)], is specified as a function of the true airspeed, VTAS [kt]:"

jet: $$\eta = C_{f1} \times \left(1 + \frac{V_{TAS}}{C_{f2}}\right)$$

Evaluation of 100 jet aircraft from BADA to calculate average coefficients:

c_f1 = x kg/min/kN
c_f2 = y kt

Compare with:

$$c = c_a V + c_b$$

TSFC Calculation with Torenbeek / Herrmann

$$SFC = \frac{0.697\sqrt{\frac{T(h)}{T_0}}\left(\phi - \vartheta - \frac{\chi}{\eta_{comp}}\right)}{\sqrt{5\,\eta_{noz}\left(1+\eta_{fan}\,\eta_{turb}\,BPR\right)\cdot\left(G+0.2\,M^2\,BPR\frac{\eta_{comp}}{\eta_{fan}\cdot\eta_{turb}}\right)} - M\,(1+BPR)}$$

$$G = \left(\phi - \frac{\chi}{\eta_{comp}}\right)\cdot\left(1 - \frac{1.01}{\eta_{gasgen}^{\frac{\gamma-1}{\gamma}}\cdot(\chi+\vartheta)\cdot\left(1-\frac{\chi}{\phi\cdot\eta_{comp}\cdot\eta_{turb}}\right)}\right)$$

$$\vartheta = 1 + \frac{\gamma-1}{2}\cdot M^2 \;;\quad \phi = T_{TE}/T(h)\;;\quad \chi = \vartheta\cdot\left(OAPR^{\frac{\gamma-1}{\gamma}} - 1\right)\;;\quad \eta_{gasgen} = 1 - \frac{0.7M^2(1-\eta_{inlet})}{1+0.2M^2}$$

Turbine entry temperature in cruise: $T_{TE} = \frac{-8000\ \mathrm{K}\cdot\mathrm{kN}}{T_{TO}} + 1520\ \mathrm{K}$

TSFC Calculation with Torenbeek / Herrmann

$$OAPR = 2.668 \cdot 10^{-5}\ 1/\mathrm{kN} \cdot T_{TO} + 3.517 \cdot BPR + 0.05566$$

$$\eta_{comp} = \frac{-2\ \mathrm{kN}}{2\ \mathrm{kN} + T_{TO}} - \frac{0.1171}{0.1171 + BPR} - M \cdot 0.0541 + 0.9407$$

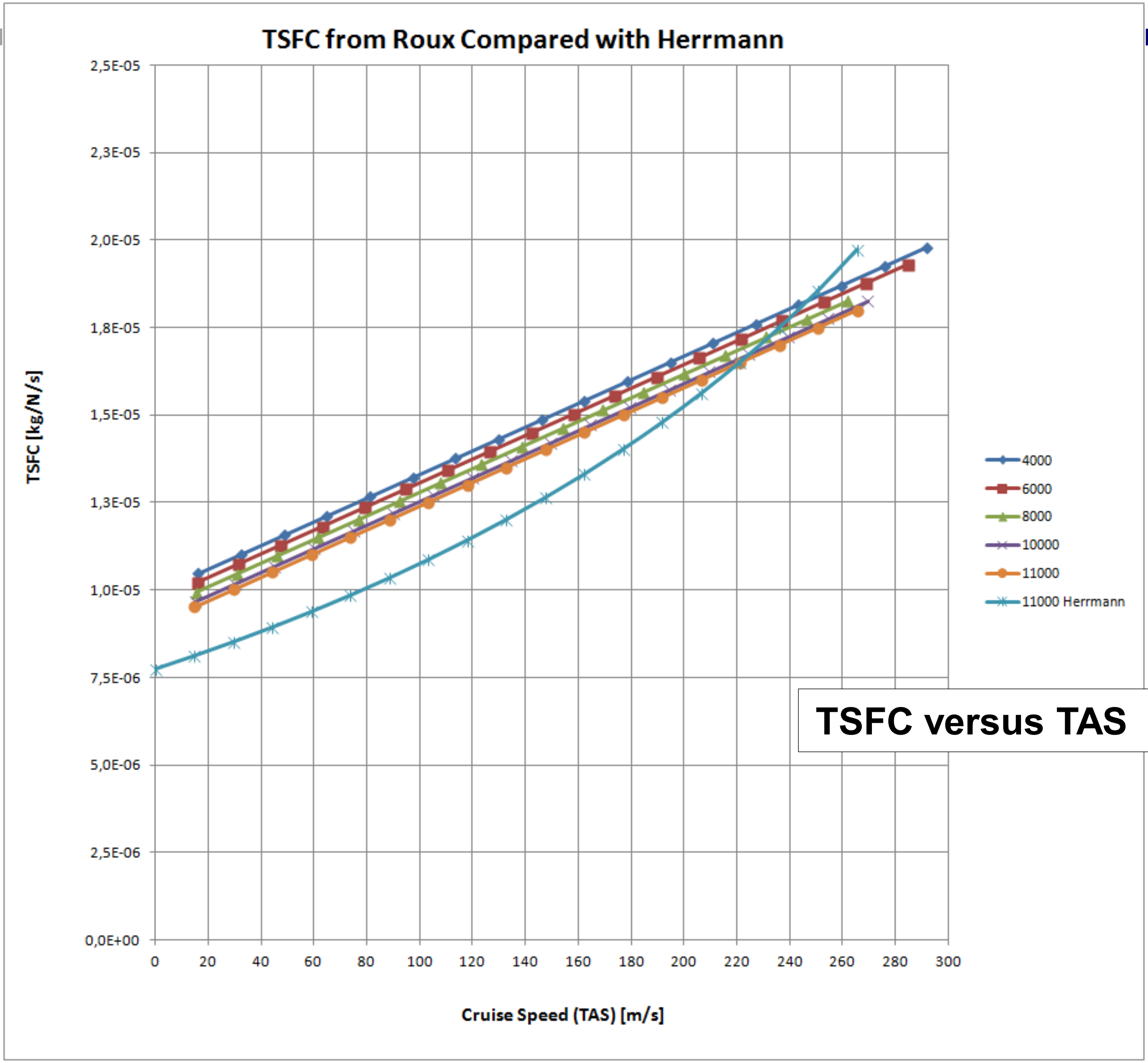
$$\eta_{turb} = \frac{-3.403\ \mathrm{kN}}{3.403\ \mathrm{kN} + T_{TO}} + 1.048 - M \cdot 0.1553$$

$$\eta_{inlet} = 1 - (1.3 + 0.25\ BPR) \cdot {}^{\Delta p}\!/_{p}$$

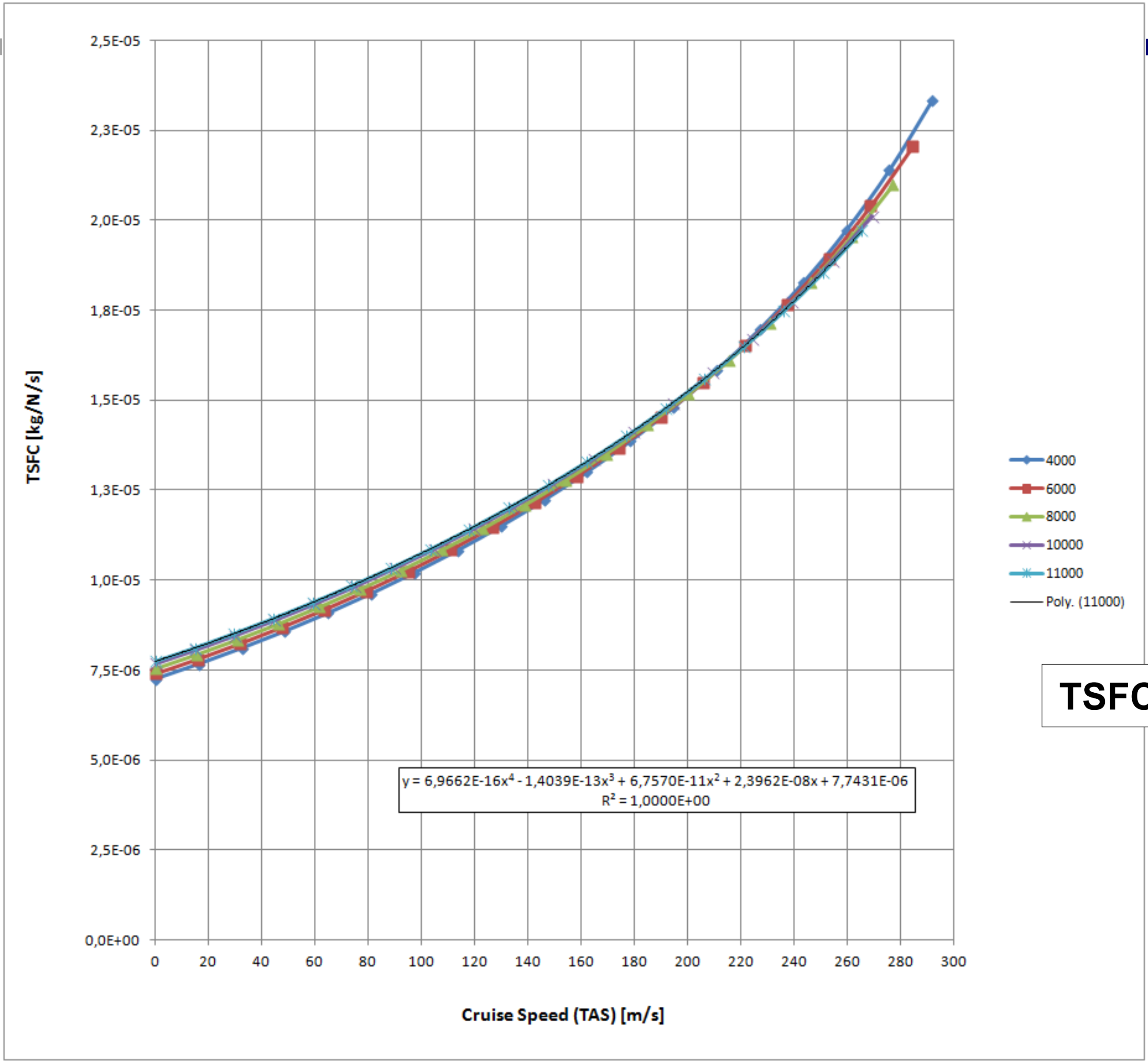
$$\eta_{fan} = \frac{-5.978\ \mathrm{kN}}{5.978\ \mathrm{kN} + T_{TO}} - M \cdot 0.1479 - \frac{0.1335}{0.1335 + BPR} + 1.055$$

$$\eta_{noz} = \frac{-2.032\ \mathrm{kN}}{2.032\ \mathrm{kN} + T_{TO}} + 1.008 - M \cdot 0.009868$$

$T(h)$ is the temperature at altitude, $T_0 = 288$ K, T_{TO} is the take-off thrust of one engine and $\Delta p/p \approx 0.02$ is the inlet pressure loss, the ratio of specific heats $\gamma = 1.4$. Efficiencies are only valid for $T_{TO} > 80$ kN.

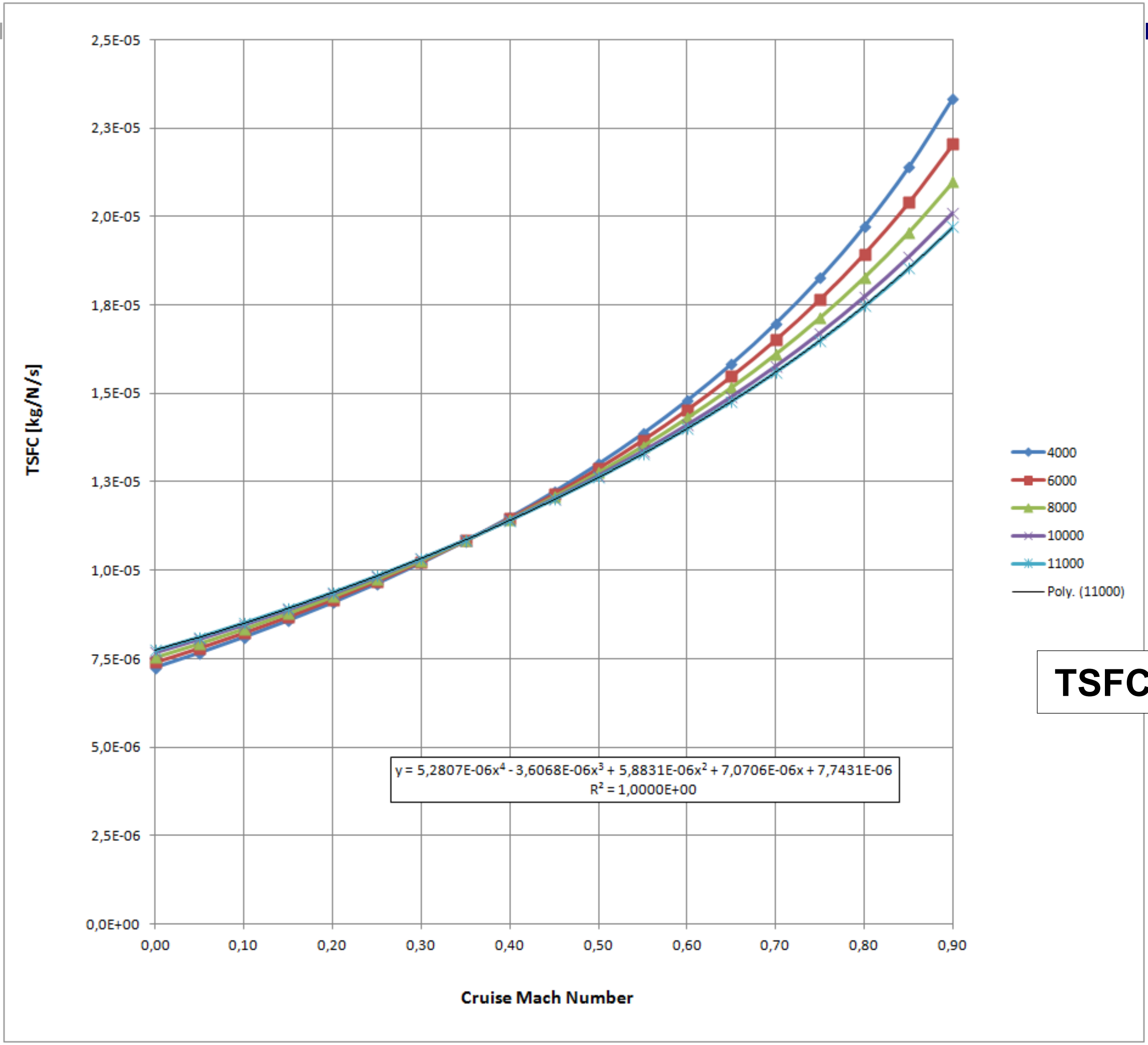


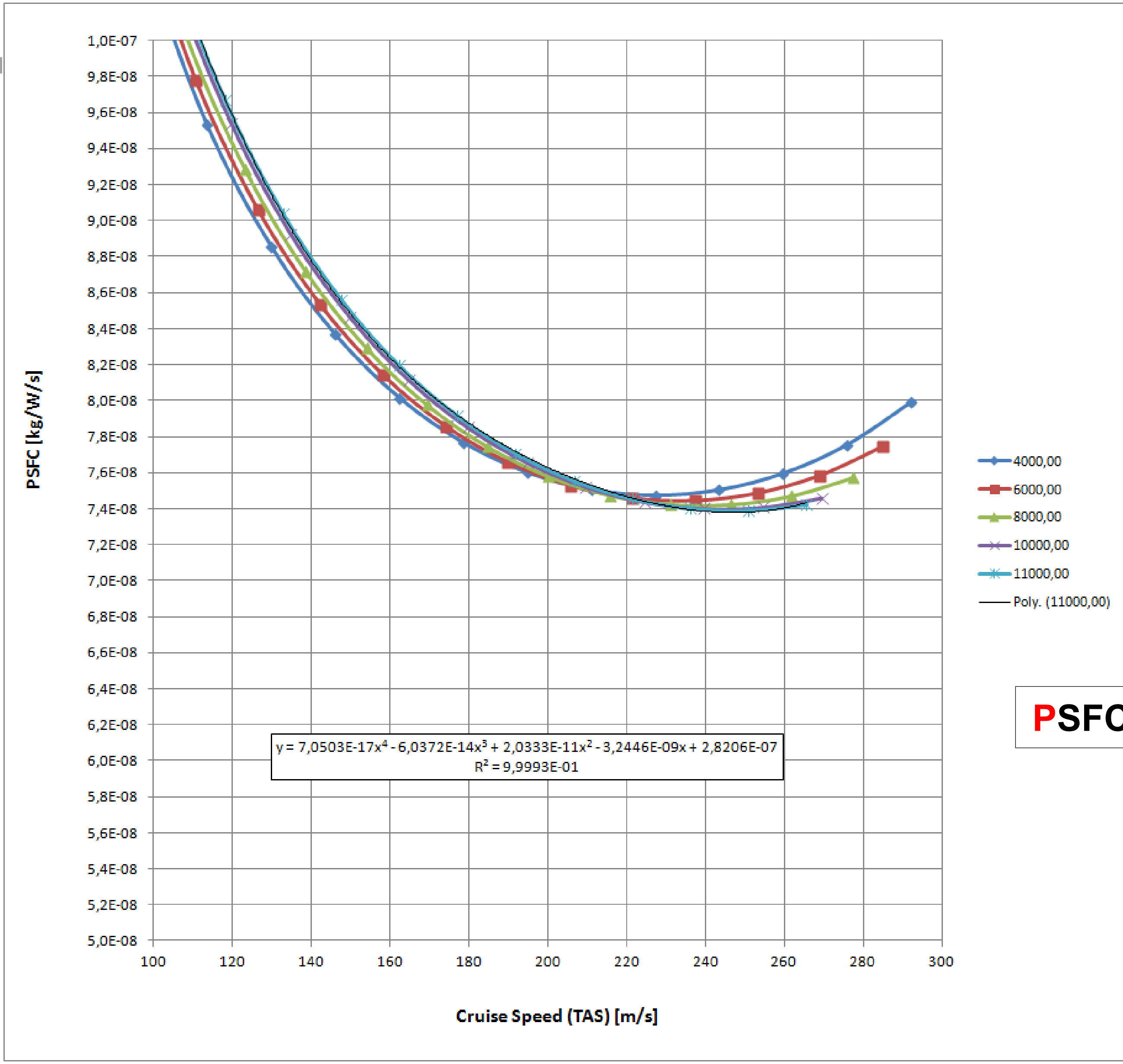
TSFC versus TAS (Equation & Model)



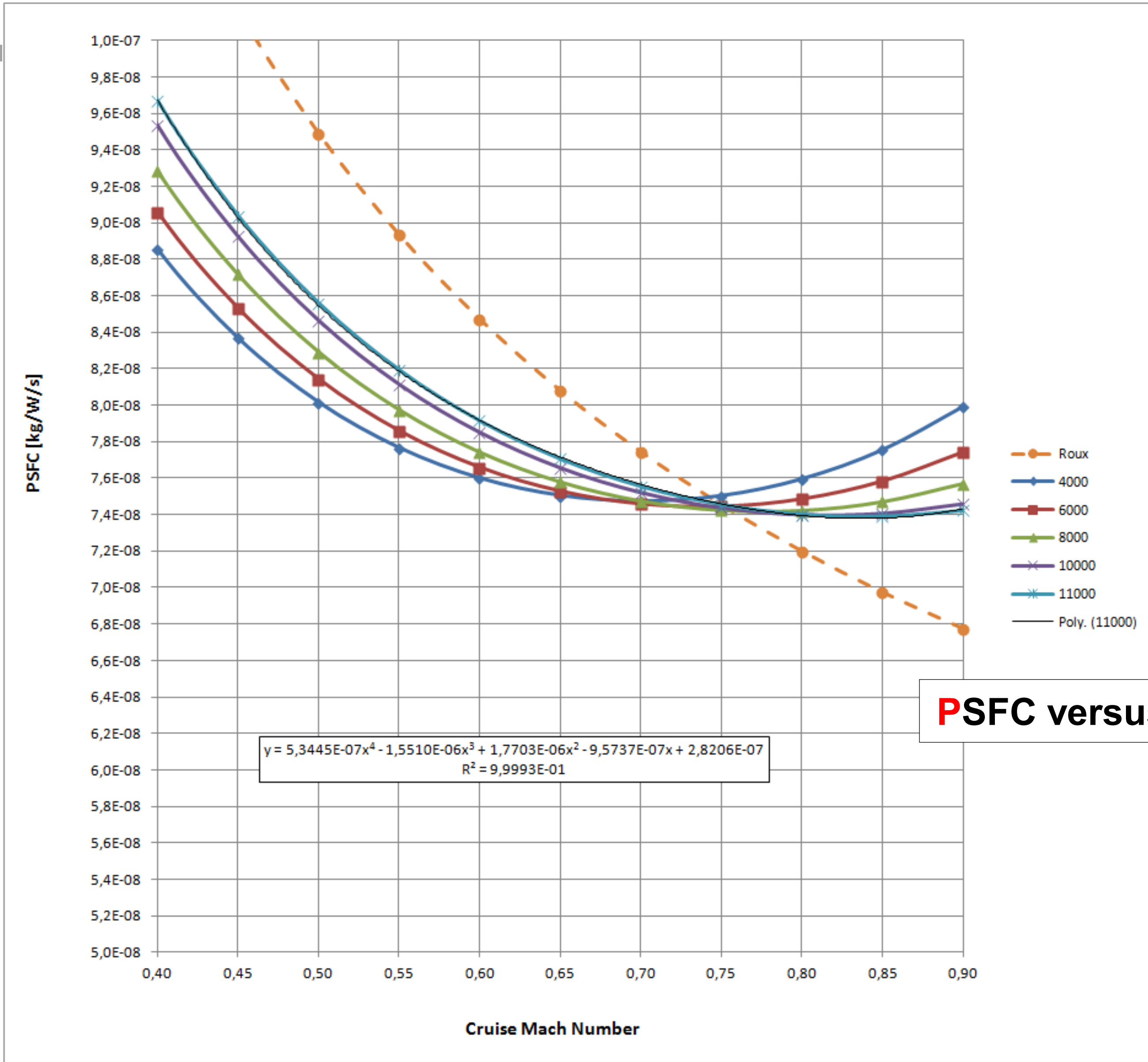
TSFC versus TAS (Model)

TSFC versus Mach (Model)





PSFC versus TAS (Model)

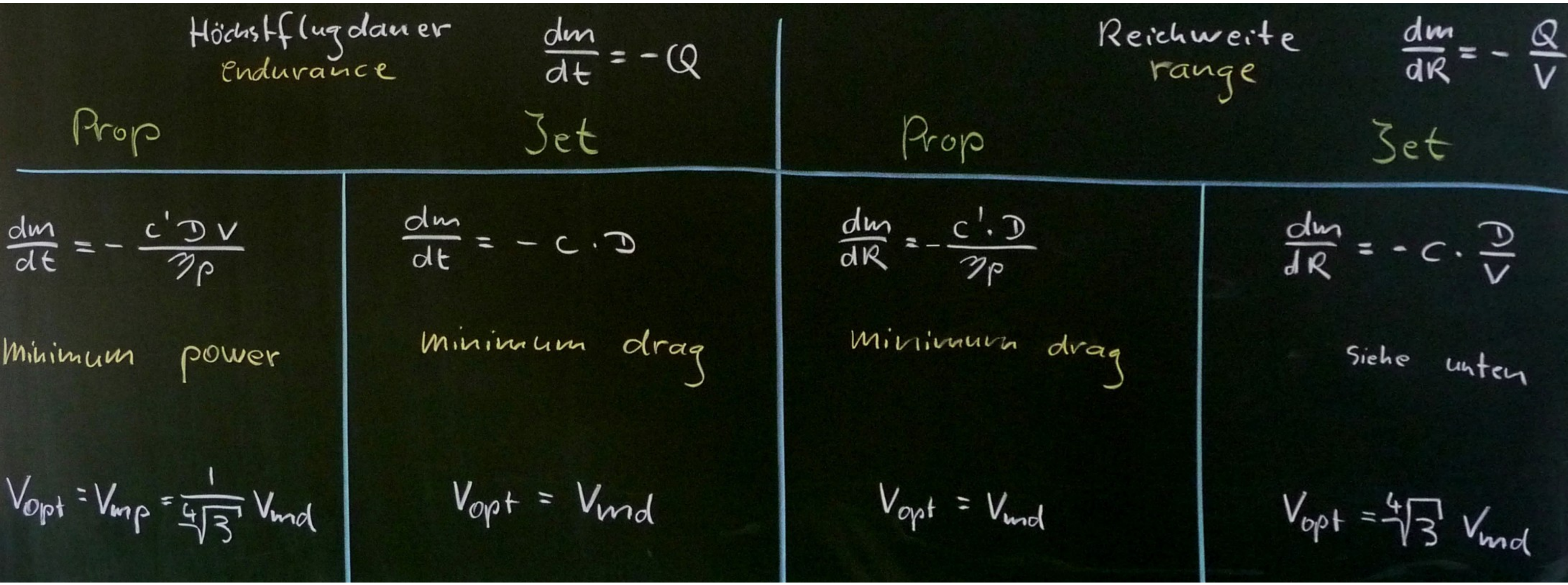


Conversion:

$$c_P = \frac{c_T}{V}$$

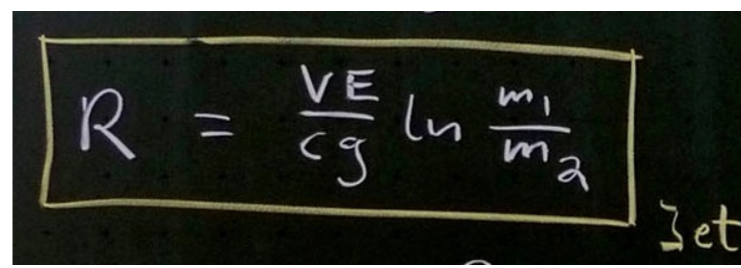
PSFC versus Mach (Equation & Model)

Consequences for the Optimum Range Speed of a Jet



Conversion:

$$c_P = \frac{c_T}{V}$$



Aero

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AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Flying Low and Slow

(and the Tools for its Calculation)

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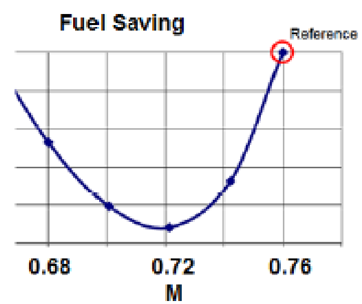

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Delft, 10. September 2015

Results

V	m/s	224	220	215	210	205	200	190
rho	kg/m³	0,364	0,378	0,396	0,415	0,435	0,458	0,507
h	m	10999	10698	10333	9955	9563	9158	8300
T	K	217	219	221	223	226	229	234
a	m/s	295	296	298	300	301	303	307
M		0,76	0,74	0,72	0,70	0,68	0,66	0,62
k_e_M		0,8450	0,8988	0,9399	0,9651	0,9802	0,9891	0,9970
CD0W		0,0011	0,0009	0,0007	0,0005	0,0004	0,0003	0,0001
E		17,9	18,6	19,1	19,4	19,7	19,8	20,0
c	kg/N/s	1,66E-05	1,65E-05	1,64E-05	1,63E-05	1,61E-05	1,60E-05	1,58E-05
Bs	m	2,47E+07	2,53E+07	2,56E+07	2,56E+07	2,55E+07	2,52E+07	2,45E+07
Mff		0,893	0,895	0,896	0,897	0,896	0,895	0,892
m_F/m_TO		0,1072	0,1048	0,1036	0,1034	0,1040	0,1049	0,1077
fuel saving		0,00%	-2,26%	-3,39%	-3,51%	-3,01%	-2,11%	0,48%

- E = ***L/D* increases** continuously with flying slower (down to M = 0.3).
- Thrust-specific fuel consumption c = **SFC decreases** with flying slower.
- The **Breguet factor B_s** is **proportion to speed** and decreases once E stops increasing with substancial rate.
- Fuel consumption decreases as long as the Breguet factor B_s increases.

Summary / Conclusions

- **TSFC is certainly not constant with speed.**
- PSFC is constant with speed following first principles (assuming constant overall efficiency), but is also not constant based on the (better) linear TSFC function.
- **PSFC can be approximated as constant within a usable band of Mach numbers in cruise** according to the Torenbeek / Herrmann model.
- In search of an optimum cruise speed (longest range, or minimum fuel for given range), the **"classical derivation"**, which considers TSFC = const. **is wrong**.
- **Working with a constant PSFC yields that the optimum range speed is the minimum drag speed.**
- A detailed calculation showed that TSFC (and hence also PSFC) is only moderately dependant on thrust. Looking for the best cruise speed means that thrust varies. Hence this needs to be included also in the TSFC & PSFC calculation. **Doing so increased the optimum range speed only very little above minimum drag speed.**
- **"Flying low an slow" (in contrast to aerodynamic considerations alone) does not work well due to engine fuel burn characteristics.**

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