2020:00651- Restricted

Report

Report title

Aircraft fuel savings by regular washing. Evaluation of MSG documentation.

Author(s)
John Christian Morud

SINTEF Industry
Flow Technology
2020-06-26

SINTEF Industri
SINTEF Industry
Address:
Postboks 4760 Torgarden
NO-7465 Trondheim
NORWAY
Switchboard: +47 40005100

info@sintef.no

Enterprise /VAT No:
NO 919 303 808 MVA

Report

Report title

Aircraft fuel savings by regular washing. Evaluation of MSG documentation.

KEYWORDS:

VERSION 1.0	**DATE** 2020-06-26
AUTHOR(S) John Christian Morud	
CLIENT(S) MSG AS	**CLIENT'S REF.** Per Ivan Januschas
PROJECT NO. 102022935	**NUMBER OF PAGES/APPENDICES:** 9 + Appendices

ABSTRACT

MSG Production AS offers products and solutions for washing, de-sanding, de-icing, engine flushing, and inspection for the aviation industry. One selling point is the importance of clean aircraft for the fuel economy of the aircraft, and the advantage of optimized cleaning schedules. MSG has asked SINTEF to verify their claim that fuel savings of the order of 1% or better is feasible by systematic cleaning policies.

Skin friction represents about 50% of the total drag of a commercial aircraft, such as the B737. This aircraft is hydraulically smooth when the surface equivalent sand roughness is smaller than about 10 µm. Increasing the roughness beyond this results in about 2% increase in total drag per 10 µm increase in roughness height. Thus, it is clear that dirty planes use more fuel than clean ones. SINTEF has no data from aviation operators regarding how quickly the planes become dirty.

We have checked calculations by MSG regarding savings of fuel and CO_2 emissions by regular cleaning ("CO2 besparelse kg pr pax pr vask 0.1.xlsx" per 22/6-2020). The calculations by MSG seem to be correct assuming the 1%/2% saving scenarios and that the input data from Wikipedia are correct. We have not gone through every aircraft in the spreadsheet, but have checked a few cases.

PREPARED BY John Morud		John Morud	**SIGNATURE**
CHECKED BY Are Simonsen		Are J. Simonsen	**SIGNATURE**
APPROVED BY Kristian Leonard Aas		Kristian L. Aas	**SIGNATURE**
REPORT NO. 2020:00651	**ISBN** ISBN	**CLASSIFICATION** Restricted	**CLASSIFICATION THIS PAGE** Restricted

Document history

VERSION	DATE	VERSION DESCRIPTION
1.0	2020-06-26	First version

Table of contents

APPENDICES

[List appendices here]

1 Background

MSG Production AS offers products and solutions for washing, de-sanding, de-icing, engine flushing, and inspection for the aviation industry. One selling point is the importance of clean aircraft for the fuel economy of the aircraft, and the advantage of optimized cleaning schedules.

MSG has asked SINTEF to verify their claim that fuel savings of the order of 1% or better is feasible by systematic cleaning policies. This document reports SINTEFs analysis on aircraft aerodynamics and fuel savings. To be concrete, a Boeing737 aircraft is used as a typical example.

2 Effect of dirt on aircraft fuel consumption

To understand the effect of dirty airplanes on fuel consumption, some basic theory is presented.

2.1 Still air range and fuel consumption

The fuel consumption of a cruising airplane per distance flown can be calculated from [1]

$$\frac{W_{fuel}}{R} = \frac{SFC \cdot W_{plane}}{V(L/D)}$$

where W_{fuel}[N] is the weight of fuel consumed, R[m] is the distance flown, W_{plane}[N] is the total weight of aircraft and fuel, V[m/s] is the cruising speed and L/D is the lift-drag ratio. The specific fuel consumption, SFC, is the rate of fuel consumption per unit thrust of the engine and is an engine parameter.

A commercial aircraft such as the B737 has its optimal speed at a Mach number of about 0.8. The lift, L, has to match the weight of the plane. Thus, it is seen that the fuel consumption per distance at given speed and total weight of the plane is directly proportional to the drag, D, of the plane. This means that e.g. an 1% reduction in the drag force will directly lead to 1% decrease in fuel consumption at cruising[1].

A B737 consumes about 3-4 kg fuel per km, depending on the model. Thus, a 1% reduction in fuel consumption corresponds to about 30-40 gram saved fuel per km, and a reduction of CO_2 emissions of about 90-120 gram per km.

2.2 Drag of airplanes

According to the Boeing bulletin AERO magazine [4], the drag of the B737 can typically be broken down as follows. We will take this as typical for commercial aircraft.

- Skin friction (53.2%). This is due to friction in the boundary layers around the aircraft.
- Induced drag (29.5%). As a plane needs to have an angle of attack to provide lift, the net pressure forces that produce lift also has a horizontal component, induced drag. As the lift has to match the weight of the plane, the induced drag will be a function of the plane weight.
- Pressure drag, trim, interference, wave and excrescence (17.3%).

It is reasonable to assume that a 2% reduction in the skin friction will result in about 1% reduction in the total drag. Induced drag is essentially an inviscid effect and should not be very much influenced by the

---

[1] Strictly speaking, the reduced drag by cleaning will slightly improve the optimum lift-drag ratio, and the optimum (max. range) cruising speed will slightly increase. However, assuming that the speed is already near optimum, this consideration only leads to a negligible, second-order effect on the fuel economy and can be ignored.

equivalent sand roughness of the surface. Pressure drag is sensitive to surface roughness for bluff bodies, since the location of separation points are affected by turbulence. However, since an airplane is a streamlined body, surface roughness is mainly expected to influence skin friction. This is consistent with the article by Longmuir et al. [5].

In this report, Nikuradse equivalent sand roughness is used throughout. The relation to other roughness measures is discussed in [7].

2.3 Effect of surface roughness on skin friction

It is customary to base skin friction estimates on flat plates and correct them using form factors for the aircraft. The boundary layer along a plate is shown in Figure 1.

- The boundary layer is defined as the region near the wall with a velocity less than 99% of the freestream velocity.
- The boundary layer is initially laminar near the leading edge, then transitions into turbulent a distance downstream. For a commercial airplane, the boundary layer can be considered as turbulent almost everywhere.
- Very close to the surface, about 0.5% of the boundary layer thickness, viscosity dominates (viscous sublayer). Surface roughness smaller than this does not influence skin friction.

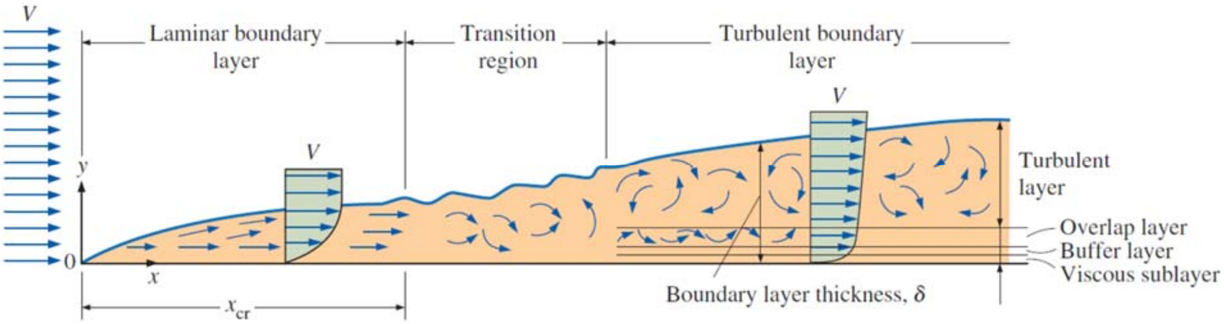

Figure 1. Boundary layer on flat plate. From Cengel [6]

Figure 2 shows the drag coefficient for the plate as function of Reynolds number and relative roughness. It can be seen that roughness reduction improves the drag up to a certain point where the surface becomes hydraulically smooth. Roughness reduction further than that does not improve skin friction.

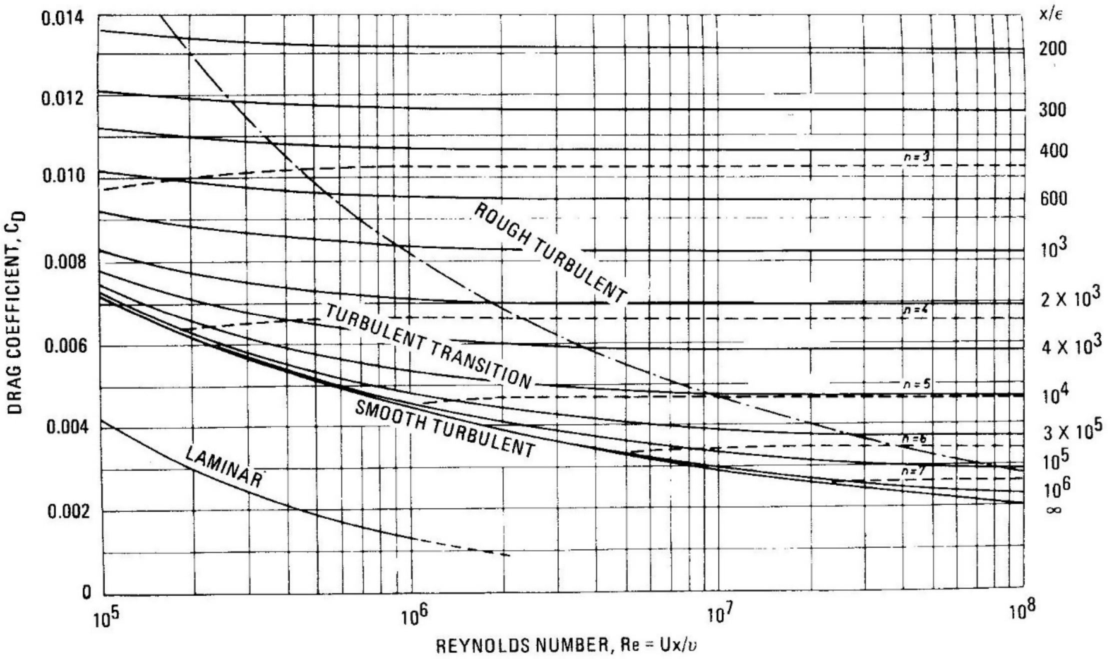

Figure 2. Drag coefficient for turbulent flow over a flat plate. x[m] is the distance from the leading edge and ε[m] is the roughness height. From Blevins [2]

For fully rough plates, the drag coefficient depends on the relative roughness as [2]

$$Cd = \frac{1}{[2.635 + 0.618\, ln(x/\epsilon)]^{2.57}}$$

where Cd=D/(qA) is the drag coefficient, x[m] is the distance from leading edge, ε[m] is the roughness height, A[m^2] is the plate area (one side), and q=1/2ρV^2 [Pa] is the freestream dynamic pressure.

Hoerner [3] presents the following criterion for whether a surface is hydraulically smooth

$$\frac{V\epsilon}{\nu} \lesssim 100$$

where V[m/s], ε[m] and ν[m^2/s] are the freestream velocity, roughness height and air kinematic viscosity. The roughness is the Nikuradse equivalent sand roughness. For a B737 cruising at speed 260 m/s in air with viscosity 1.5e-5 m^2/s, this results in a roughness height of about 6 μm.

Boeing [4] reports that roughness height less than about10 μm (400 μinch) does not affect skin friction and that the B373 is smoother than this. Figure 3 shows their data. It is seen that above 10 μm sand roughness, the friction drag increases by about 4% for every 10 μm increase in equivalent sand roughness. Since friction drag represent approximately 50% of the total drag, this corresponds to 2% increase of the total drag, and correspondingly 2% of the fuel consumption at cruising.

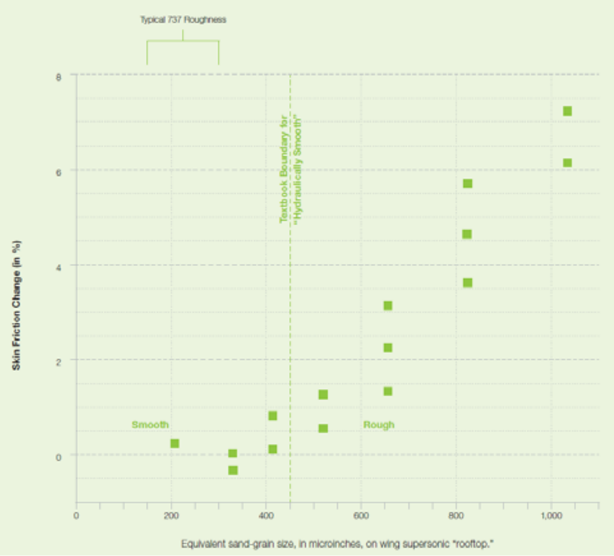

Figure 3. Increase in skin friction coefficient as function of roughness (micro-inch) for a B737 ([4])

2.4 Accumulation of dirt on aircraft

Airplanes become dirty during use. This can be due to e.g. insects and dust collection on surfaces that are contaminated by hydrocarbon fluids (hydraulic oil, fuel etc.). SINTEF does not have data from aviation operators regarding the rate of accumulation.

2.5 Fuel penalty due to weight of dirt

In addition to increase in surface roughness, the weight of the dirt will in principle increase fuel consumption, since the lift has to be increased to counter the extra weight.

To get a feel for the magnitude, consider a B737 with a wetted surface area of about 800 m^2. If we assume that the bulk density of the dirt is of the order of 2000 kg/m^3, each increase of, say 10 µm thickness of dirt, corresponds to $(2000 kg/m^3) \cdot (800 m^2) \cdot (10 \cdot 10^{-6} m) = 16 kg$.

The weight of the B737 varies with the amount of fuel and cargo. A very rough estimate is of the order of 50 ton weight. 16 kg dirt thus corresponds to about 0.32‰ of the total weight of the aircraft.

In practice, one can estimate that the fuel consumption is proportional to the aircraft weight [8]. Each increase of 10 µm dirt thickness thus corresponds to roughly 1 g extra fuel consumption per km (assuming that the B737 consumes about 3.5 kg fuel per km).

Thus, there is a small weight penalty of the dirt in principle. However, comparing with the effect of surface roughness discussed above, the effect is much smaller.

2.6 Optimal washing intervals

If we assume that the drag due to dirt increases linearly in time and that cleaning has a fixed cost per wash, the overall cost per time from increased drag and cleaning can be written as

$$Cost = Cost_{drag\ increase} + Cost_{washing} = A\,\tau + \frac{B}{\tau}$$

where A and B are coefficients determined from operational data and τ is the time between cleaning.

Differentiation yields the minimum cost

$$0 = \tau \frac{\partial Cost}{\partial \tau} = A\tau - \frac{B}{\tau} = Cost_{drag\ increase} - Cost_{washing}$$

or

$$Cost_{drag\ increase} = Cost_{washing}$$

According to this simplistic analysis, the optimal policy is thus to balance the cost increase due to drag and the cost due to washing. This analysis does not consider reduced corrosion on the aircraft by removing corrosive fluids.

Longmuir et. al. [5], using curve fitting of operator data, have found that dirt accumulation is accelerating with time (However, the fitted parameters in Table 6 in their paper appear dubious). If we instead of the linear assumption assume that the drag increases as a power law with time between washing, the cost function becomes:

$$Cost = Cost_{drag\ increase} + Cost_{washing} = A'\tau^{n} + \frac{B}{\tau}$$

where n is the power exponent of the drag increase. Repeating the analysis above, we get:

$$n \cdot Cost_{drag\ increase} = Cost_{washing}$$

For example, if n=2 we find that the cost of washing at the optimum occurs when washing costs are twice the cost due to drag increase, or equivalently two thirds of the total cost of drag increase and cleaning.

Thus, if the cost spent on cleaning an aircraft (including opportunity costs, and possibly wear) is smaller than the fuel costs of increased drag due to roughness, this would suggest that more frequent cleaning would be profitable. A possibility is to perform a randomized trial where parts of a fleet are cleaned more frequently than the rest, and compare the fuel consumption between the two groups.

3 Evaluation of MSG documentation

We have evaluated calculations by MSG regarding savings of fuel and CO_2 emissions by regular cleaning ("CO2 besparelse kg pr pax pr vask 0.1.xlsx" per 22/6-2020). The calculations are based on the following basis:

- Two scenarios are considered: 1% and 2% fuel savings
- Fuel consumption for various aircraft are taken from Wikipedia (https://en.wikipedia.org/wiki/Fuel_economy_in_aircraft)
- CO_2 emissions are taken as 3.15 kg CO_2/kg jet fuel. This is in accordance with IATA guidelines[2].

SINTEF did not check the entire spreadsheet, but only a few cases. The calculations by MSG seem to be correct assuming the 1%/2% saving scenarios and that the input data from Wikipedia are correct.

4 Summary/Conclusion

We have checked MSGs claim that fuel savings of 1% or better are possible by systematic cleaning of aircraft. It is clear from a fluid dynamics point of view that dirty aircraft have a larger drag and thus consume more fuel than clean ones.

---

[2] Basically, the fuel consists mainly of CH_2 groups in chains, with a molar weight of 12+2=14, whereas CO_2 has molar weight 44. The ratio becomes 44/14=3.14 kg CO_2/kg fuel, which is close to the IATA number…

Skin friction represents about 50% of the total drag of a commercial aircraft, such as the B737. This aircraft is hydraulically smooth when the surface roughness is smaller than about 10 µm. Increasing the roughness beyond this results in about 2% increase in total drag per 10 µm increase in roughness height. SINTEF has no data from aviation operators regarding how quickly the planes become dirty.

We have checked calculations by MSG regarding savings of fuel and CO_2 emissions by regular cleaning ("CO2 besparelse kg pr pax pr vask 0.1.xlsx" per 22/6-2020). The calculations by MSG seem to be correct assuming the 1%/2% saving scenarios and that the input data from Wikipedia are correct. We have not gone through every aircraft in the spreadsheet, but have checked a few cases.

5 References

1. Sadraey, M. H. (2017). *Aircraft performance: an engineering approach*. CRC Press.
2. Blevins, R. D. (1984). Applied fluid dynamics handbook Van Nostrand Reinhold Co. *New York, NY*.
3. Hoerner, S. F. (1965). Fluid-Dynamic Drag. Theoretical, experimental and statistical information. *Copyright by: SF Hoerner Fluid Dynamics, Vancouver, Printed in the USA, Card Number 64-19666*.
4. AERO Magazine, Quarter 1, 2013. Boeing Edge.
5. Longmuir, M., & Ahmed, N. A. (2009). Commercial aircraft exterior cleaning optimization. *Journal of Aircraft*, *46*(1), 284-290.
6. Y.A. Çengel , J.M. Cimbala, Fluid Mechanics Fundamentals and Applications, 3rd edition, McGraw-Hill, 2014
7. Afzal, N., 2007. Friction factor directly from transitional rough pipes. J. Fluid Engg. Trans. ASME 129 (10), 1255-1267
8. Torenbeek, E. (2013). *Advanced aircraft design: conceptual design, analysis and optimization of subsonic civil airplanes*. John Wiley & Sons.

SINTEF

Technology for a better society

www.sintef.no