Vrije Universiteit Brussel

FACULTY OF ENGINEERING
Department of Electrical Engineering and Energy Technology

Analysis of the CO_2 and non-CO_2 Climate Impacts of Aviation: Recommendations and Tools for Mitigation

Thesis submitted in fulfilment of the requirements for the award of the degree of
Doctor in Engineering (Doctor in de ingenieurswetenschappen) by

Julien Matheys

June 2010

Promoter: Prof. dr. ir. Joeri Van Mierlo

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List of Acronyms

AIC	Aviation-Induced Cloudiness
AIRE	Atlantic Interoperability initiative to Reduce Emissions
APU	Auxiliary Power Unit
AOGCM	Atmosphere-Ocean General Circulation Model
ATM	Air Traffic Management
Aviactor	AVIation And Climate calculaTOR
BAU	Business As Usual
bpd	Barrels Per Day
BPR	ByPass Ratio
BtL	Biomass-to-Liquid
BWB	Blended wing-body
CCS	Carbon Capture and Storage
CDA	Continuous Descent Approach
CDM	Clean Development Mechanism
CER	Certified Emissions Reduction
CFD	Computational Fluid Dynamics
CNG	Compressed Natural Gas
CRL	Brussels South Charleroi Airport
CSV	Comma-Separated Values
Defra	UK Department of Environment, Food and Rural Affairs
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DWD	Deutscher Wetterdienst
ECAC	European Civil Aviation Conference
ECS	Environmental Conditioning System
EEA	European Environmental Agency
EMIC	Earth System Model of Intermediate Complexity
ERU	Emission Reduction Unit
EU	European Union
EU-ETS	European Emission Trading Scheme
FAA	Federal Aviation Administration
FBAA	Belgian Federation of Autocar and Autobus companies
FL	Flight Level (1 FL is equivalent to 1000 feet)
FLAP	Frankfurt, London, Amsterdam and Paris
FT	Fischer-Tropsch
GAARF	Globally and Annually Averaged Radiative Forcing
GCD	Great Circle Distance
GHG	Greenhouse Gas
GPU	Ground-based Power Unit
GTP	Global Temperature Change Potential
GTF	Geared Turbofan or Gearbox Turbofan
GWP	Global Warming Potential
HRJ fuels	Hydroprocessed Renewable Jet fuels
IATA	International Air Transport Association
IEA	International Energy Agency

IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
IRA	Intercooled Recuperated Aeroengine
ISS	Ice Supersaturated
JAL	Japan Airlines
JI	Joint Implementation
LDV	Light-duty Vehicles
LGG	Liège Airport
LFC	Laminar Flow Control
LLGHG	Long-Lived Greenhouse Gas
LULUCF	Land-use/land-use change/Forestry
MVC	Model-View-Controller
MTOW	Maximum Take-Off Weight
NEXTGEN	Next Generation Air Transport System
NMBS/SNCB	Nationale Maatschappij der Belgische Spoorwegen / Société Nationale des Chemins de fer belges – Belgian National Railways
pkm	passenger.kilometer
ppm	parts per million
PPP	Public-Private Partnership
PSC	Polar Stratospheric Clouds
RF	Radiative Forcing
RFI	Radiative Forcing Index
RH	Relative Humidity
RPK	Revenue Passenger Kilometer
RTK	Revenue Ton Kilometer
RVSM	Reduced Vertical Separation Minimum
SESAR	Single European Sky Air traffic Research Programme
SLGHG	Short-Lived Greenhouse Gas
SRES	Special Report on Emissions Scenarios
SMR	Steam-Methane Reforming
SSA	Supersaturated (air) Areas
TAR	Third Assessment Report
TH	Time Horizon
TIT	Turbine Inlet Temperature
TTW	Tank-to-Wing / Tank-to-Wake
UFO	Umweltgerechte Flugrouten Optimierung
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UTC	Coordinated Universal Time
UT/LS	Upper Troposphere/Lower Stratosphere
VHO	Very Heavy Oils
WTT	Well-to-Tank
WTW	Well-to-Wing / Well-to-Wake

List of Symbols

A	frontal/reference area (in m^2)
AF	aspect ratio of a blade or wing
°C	degrees Celsius
C_d	drag coefficient
C_p	specific heat capacity of air (1.004 $J.kg^{-1}.K^{-1}$)
CO_2-eq	CO_2-equivalents
EI_{H2O}	emission index of water vapour (about 1,25)
EJ	1 exajoule = 10^{18} joules
F_d	drag force (in N)
g	gravitational constant (9,81 m/s^2)
G	contrail parameter (final gradient of the mixing line)
Gt	1 gigaton = 10^9 tons
Hz	Hertz
J	narrow-body jet
K	Kelvin
kWh_e	1 kWh of electric energy
L	wingspan (or length of blade) (in m)
m_f	mass flow rate (in kg/s)
MJ	1 megajoule = 10^6 joules
mph	1 mile per hour = 1,609344 km per hour
msl	meters above sea level
Mt	1 megaton = 10^9 tons
mW	milliwatt = 10^{-3} watt
nm	1 nautical mile = 1,852 km
Nm^3	normal cubic metre
p	(ambient) pressure (in Pa)
P	propulsive power of an engine (in W)
P	turbopropeller aircraft
Q	combustion heat (of a fuel) (in MJ/kg)
R	regional jet
RF	radiative forcing (in W/m^2)
S	wing area (in m^2)
t	time
T	thrust (in N)
Tg	Teragram = 10^{12} gram
T_s	surface temperature (in °C)
v	(relative) speed of an object/aircraft (in m/s)
W	wide-body jet
W	air mass passing through the engine (lb/s or kg/s)
Δmsl	sea level rise
ΔT_s	mean surface temperature change (K),
ε	ratio of the molar masses of water and air (0,622)
η	efficiency
θ	helix angle
λ	climate sensitivity parameter or “efficacy” (in $K/(Wm^2)$)
ρ	density of the medium/air (in kg/m^3)
τ	atmospheric lifetime of a gas