Number 2, Volume VII, July 2012

AVIATION EMISSIONS AND THEIR IMPACT ON ATMOSPHERIC CHEMISTRY

Sandra Krollová[1]

Summary: The emissions from the aircraft are split between CO_2, non-CO_2 gases and aerosols. CO_2 is a well-known long-lived greenhouse gas. The other emissions consist mainly of NO_x, water vapour, unburned hydrocarbons, sulphates and black carbon. The cruise altitude of present jet aircraft is approximately 9-13 km. Globally the largest proportion of emissions are released in this altitude range containing the upper troposphere and lower stratosphere. The geographical pattern of aircraft emissions reflects the structure of global scheduled air traffic. Emission maxima are found over North America, Europe, the North Atlantic flight corridor, Southeast Asia and the Far East. The largest amounts of emissions are released in the northern hemisphere. The impact of emissions of chemical compounds by aircraft engines can be seen in context of the chemical processes occurring in the natural troposphere and stratosphere. The changes in atmospheric chemistry due to aircraft emissions are investigated by usage of numerical models, for example atmospheric chemistry transport models and chemistry – climate models.

Key words: water vapour, carbon dioxide, oxides of nitrogen, aerosols, upper troposphere, lower stratosphere, local and regional air quality, climate change, atmospheric modelling.

INTRODUCTION

In the natural atmosphere a large number of chemical processes take place. Mostly they involve reactions between atmospheric trace gases, nitrogen and oxygen. The part of the atmosphere extending from the surface to approximately 10 km altitude (troposphere) and its chemistry forms an important part of the global chemical processes. The troposphere is strongly influenced by exchange processes of energy and matter with the Earth´s surface, for example hydrological cycle resulting in cloud and precipitation formation. Troposphere is characterised by efficient mixing and rapid overturning of air. This caused the uplift of emitted chemical compounds from the boundary layer into the free troposphere and their transport by the global atmospheric circulation. Atmospheric composition is controlled to large extent by emissions from the biosphere and by human influence. Substances that are not destroyed are gradually transported into the stratosphere. The stratosphere is characterized by formation of ozone (O_3) and lack of water vapour.

As a result of human activities (emitting pollutants, transforming the land surface), the composition of the atmosphere is altered to an increasing extent. The combustion of fossil fuel in aircraft engines produces a wide range of pollutants. Some of them interfere with the

[1] Ing. Sandra Krollová, PhD., University of Žilina Faculty of Transport and Communication, Air transport department,Univerzitna 1, 010 26 Žilina, Slovakia, Tel.: +420 41 513 3457, E-mail: krollova@fpedas.uniza.sk

natural chemical processes in the atmosphere. This causes chemical changes, which can be grouped into three categories:

1. *Chemistry of plume processes* – describes chemical interactions and transformation of substances in the wake of an aircraft, that occur few minutes after emission;
2. *Local air quality* – deals with pollution near the ground due to air traffic activities,
3. *Global atmospheric chemistry* – deals with impact of aircraft emissions on chemical processes over large spatial scales and time periods.

Aircraft emissions consist mainly of *water vapour* (H_2O) and *carbon dioxide* (CO_2). They further contain *oxides of nitrogen* (NO_x), *carbon monoxide* (CO), *oxides of sulfur* (SO_x), *unburned hydrocarbons* (HC) and *particulates*.

Water vapour and CO_2 are efficient greenhouse gases. Their changes in the atmosphere affect the radiative balance the Earth-atmosphere system. Emissions of water vapour into the troposphere are not of great significance. Water vapour emissions released inside the drier stratosphere result in HO_x increase and therefore contribute to O_3 destruction. Emissions of CO_2 are chemically inert in the atmosphere. CO_2 emissions from aviation accumulate in the atmosphere and are distributed globally; the CO_2 concentration eventually becomes indistinguishable in comparison with other sources. CO_2 has multiple lifetimes in the atmosphere and 20 – 35% of CO_2 will remain in the Earth´s atmosphere for many years. The annual emission rate of CO_2 from aviation was 733 Tg in 2005 according to International Energy Agency statistics of fuel sales. This represents approximately 2 – 2,5% of total anthropogenic CO_2 emissions.

Emissions of NO_x interfere in chemical processes of the troposphere and stratosphere, influencing the greenhouse gases, ozone and methane concentration up to an altitude 25 km. On a short time scale the NO_x emissions increase the ozone production in the troposphere. NO_x from aviation are emitted at cruise altitudes near the tropopause and is easily converted into other compounds (N_2O_5, HNO_3); other sources are convective activity, chemical production from lightning etc. NO_x are emitted by aircraft engines through all phases of operation. The local air quality impact is generally concerned with emissions of NO_x during the landing and take-off phase. The formation of MOx can occur via the thermal route (in combustion air at high temperatures N_2 and O_2 dissociate into atomic states), the prompt route (prompt NO_x is produced by the intermediate formation of HCN), the nitrous oxide route (N_2O) and the fuel NO_x.

Emissions of sulfur compounds play a significant role in the formation of aerosol by formation of H_2SO_4. Sulphate and black carbon particles (soot) with water vapour are involved in the formation of contrails. Sulfur is present in aviation kerosene in low concentrations. Black carbon is formed as a result of incomplete combustion of kerosene. The effects of aerosols are less known and seem of less importance on climate in case of aviation emissions.

1. IMPACT OF AVIATION EMISSIONS

Aviation emissions can have local and regional air quality effects and global effect in terms of climate change. The impact of aviation on atmospheric composition was investigated first in the early 1970s concerning the stratospheric ozone depletion due to large fleet of supersonic aircraft. While this has not become reality, it was acknowledged that the quantification of aircraft emission impact on atmospheric chemistry was limited by the large uncertainties associated with the knowledge of the global distribution of chemical compound.

In 1999 an assessment of the impact of aviation was undertaken within the Intergovernmental Pannel on Climat Change (IPCC) in a special report „Aviation and the Global Atmosphere“ (IPCC, 1999). Since then, a new assessment was recently conducted within the European Project ATTICA (Blockley and Shyy, 2010).

Tab. 1 – Global annual total emissions from civil and military aircraft from AERO2k inventory for the year 2002 in Tg (teragrams).

	Distance flown (10^9 nm)	Fuel used	CO_2	H_2O	CO	NO_x	HC	SO_x	Soot
Civil aviation	17,9	156	492	193	0,507	2,06	0,063	0,183	0,0039
Military aviation	-	19,5	61	24,1	0,647	0,178	0,066	0,023	-
Total	-	176	553	217	1,15	2,24	0,129	0,206	-

Source: Eyers et al. (2005)

More recent inventories of contemporary emissions from global aviation are available, form example EU-funded projects TRADEOFF (2006), SCENIC (2007), AERO2k (2005), QUANTIFY (2009) and SAGE from US Federal Aviation Administration (2007). Table 1 gives an overview of annual total emitted species within the AERO2k inventory for the year 2002.

In present day civil aviation use predominantly kerosene for fuel. An aircraft exhaust plume therefore contains species produced during the combustion of the kerosene and from atmospheric constituents passing through the combustion chamber. Combustion of hydrocarbon produces CO_2 and H_2O. The other emitted species are:

- NO_x from the oxidation of atmospheric nitrogen within the combustion chamber,
- SO_x from the oxidation of sulfur contained in the fuel,
- *CO*,
- *hydrocarbons*, and
- *soot particles* from incomplete combustion.

In the plume, sulfuric acid aerosol can be formed from the further oxidation of SO_2. Several of these emissions have a direct impact on the climate (such as the greenhouse gas CO_2 and aerosols). Other species, for example NO_x, which are not direct greenhouse gases, are chemically active in the atmosphere and modify the concentration of greenhouse gases such as ozone and methane.

Emissions or the quantity of species emitted by a certain amount of fuel burned, differ between the different stages of flight (taxing, takeoff, climb, cruise, descent). Aircraft at cruise altitude may also produce, under certain atmospheric conditions, contrails. Contrails may be persistent and evolve into cirrus clouds. The probability of contrails formation is dependent on the state of the atmosphere and exhaust gas temperature.

At ground level aviation emissions will affect the air quality of airports and surrounding areas. The sources of local pollutants include:

- *aircraft movements* (taxiing, holding, taking-off, landing),
- *road traffic* (construction traffic, airport access traffic, airside vehicles, car parking),
- *airport combustion plants*,
- *fuel handling*, and
- *railway operations* (Blockley and Shyy, 2010).

The most significant pollutants considered to local air quality are:

- *NOx* - are irritant gases that can affect the airways,
- *ozone* – arises from chemical reactions in the atmosphere between nitrogen oxides and hydrocarbons and can cause irritant effect in the airways,
- unburned *polycyclic aromatic hydrocarbons* (PAHs) – can cause damage to the genetic material in cells and may contribute to cancer,
- very *fine airborne particulate* – can worsen existing heart and lung diseases,
- *sulfur dioxide* – can act as a respiratory irritant.

The impact of airports as complete system on local community are monitored and modelled by air quality experts.

During climb, descent and at cruise altitude emissions impact the atmosphere on a global scale. They modify the atmospheric chemistry and the climate. The current knowledge of the aviation impact on the climate can be summarized in terms of radiative forcing (RF):

- *emission of* CO_2 result in positive RF,
- *emissions of* NO_x result in the formation of ozone and in positive RF,
- *emissions of* NO_x result in the destruction of methane and in negative RF,
- *emissions of sulfur* results in negative RF,
- *emissions of particulates* results in positive RF,
- *production of permanent contrails* results in positive RF,
- *production of cirrus clouds* results in positive RF.

A *positive RF* will produce warming and *negative RF* will contribute to cooling in the atmosphere. The total RF from aviation has been recently reassessed to be 55 $mW.m^{-2}$. Including aviation induced cirrus clouds the total RF from aviation is predicted to be 85

$mW.m^{-2}$, which represents approximately 3,5% of the total human RF change in 2005 (Blockley and Shyy, 2010).

Aviation activities can alter the radiative balance of climate system and contribute to the abundance of greenhouse gases in the atmosphere:

- directly by emission of greenhouse gases (principally CO_2),
- indirectly by emission of substances (principally NO_x) affecting the amount of radiatively active gases.

Air traffic can also perturb the radiative balance of the climate system by changing the properties of earth-atmosphere system and cloud coverage. The most visible effect is the formation of contrails and aircraft induced cirrus.

The study of impact of aviation on the global atmosphere depends significantly on results from atmospheric models. Global measurements using aircraft equipped with monitoring instruments or satellites have been used to validate model results.

2. MITIGATION OPTIONS

The calculation of future emission scenarios was undertaken by ICAO´s Committee for Aviation and Environmental Protection (CAEP). More than 2050 emission scenarios have been calculated up to the year 2020, for example, emissions of CO_2 are projected to grow by factors ranging between 2,0 and 3,6; emisiions of NOx are projected to grow by factors between 1,2 and 2,7.

The development of air transport has been strong during the last two decades and is forecast to continue to grow. The civil aviation sector has grown strongly. In 2006, there where approximately 20 500 civil aircraft in service globally. By 2026, Airbus forecast the fleet to nearly double in approximately 40 500 aircraft (Airbus, 2007). New models of aircraft entering the fleet tend to have better fuel performance, but there are only produced irregularly (costs and long lifetime). There has also been an increase in efficiency in term of load factor.

Taking into account possible improvements in aircraft and air traffic efficiency the aviation CO_2 emissions are estimated to grow by 3,1% per year over the next 40 years. After 2050 potential developments in aviation include:

- blended-wings-body aircraft, which may offer a 25% improvement in traffic efficiency,
- biofuels, which reduce fuel cycle carbon emissions,
- hydrogen fuel, which would eliminate all carbon emissions.

Mitigation of aviation emissions is increasingly discussed but there complex technological and atmospheric tradeoffs to be considered. The core problém is how to balance the long-term effects from CO_2 against the short-term effect from O_3, contrails, aviation-induced cirrus etc.

3. CONCLUSION

Aircraft contribute to changes in atmospheric composition, generally in the upper troposphere and lower stratosphere, where most civil aviation occurs. The direct effect of in-flight aircraft engine emissions is characterized by an increase of atmospheric species concentration, such as nitrogen oxides and carbon dioxide. Indirect effects cause the changes of concentration of other species like ozone and methane that can be significantly modified by aviation. Aviation-related emissions can have significant implications for air quality on local and regional scale. Primarily, the issue that generates most complaints is aircraft noise. The impact of aircraft atmospheric emissions on air quality at airports is of secondary concern to nearby residents. In respect of environmental impact of aviation, we could say that the most serious issues are those associated with global climate change. In implementation of new technologies it is important to quantify the possible reductions in emissions and the climate impact they may produce.

This paper is published as one of the scientific outputs of the project: “Centre of Excellence for Air Transport” ITMS 26220120065. We support research activities in Slovakia/Project is co-financed by EU.

REFERENCES

(1) IPCC. *Aviation and the global atmosphere.* In: Intergovernmental panel on Climate Change, Cambridge University Press, 1999, Cambridge, UK.

(2) BLOCKLEY, R., SHYY, W. *Encyclopedia of Aerospace Engineering.* John Wiley Sons Ltd. Publishing, Chichester, UK, 2010. ISBN 978-0-470-75440.

(3) Airbus. Global Market Forecast 2006 – 2026, Airbus, 2007, France.

(4) ARYA, P. S. *Air pollution meteorology and dispersion*, 1999, Oxford University Press, UK. ISBN 0-19-507398-3.

(5) BRIDGEMAN, H. A., OLIVER, E. J. *The Global Climate System*. Cambridge University Press, 2006. ISBN-10 0-521-82642-X.

(6) NOVÁK, A.: *The research project of the Centre of Excellence for Air Transport*, Perner´s Contacts - ISSN 1801-674X. - 2011. - Vol. 6, No. 5 (2011), s. 224-228.

(7) NOVAK SEDLACKOVA, A.: *Projects supported by structural funds of EU realized at University of Žilina in cooperation with Air Transport Department and Flight Training Organization - Air School of the University of Žilina*, Perner´s Contacts - ISSN 1801-674X. - 2011. - Vol. 6, No. 5 (2011), s. 265-270.