Elements of aircraft pollution

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Elements of aircraft pollution

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VSSD
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Preface to the first and second edition

Within the last few decades, concern about the environmental conditions on Earth has grown steadily as it has been recognized that the exhaust of pollutant emissions from burning fossil fuels into the atmosphere cannot be allowed to continue unlimitedly. The two environmental problems currently causing most concern are the global changes in the climate due to the enhanced greenhouse effect and the depletion of the stratospheric ozone layer.

This has also raised the question on the effects of emissions from aircraft upon the atmosphere. In addition to carbon dioxide, CO₂, and water vapor, H₂O, the emissions of carbon monoxide, CO, unburned hydrocarbons (UHC), nitrogen oxides, NOₓ, and smoke or soot are the essence of the problem of air pollution caused by aviation.

Although the total quantity of emissions from air traffic is very small compared to other man-made emissions, their impact on the environment may not be negligible. Important is the fact that aircraft emissions are the only significant anthropogenic source of pollutants in the upper troposphere and lower stratosphere. Also of importance is the fact that the demand for air travel is still growing.

Carbon dioxide and water vapor are important greenhouse gases. In addition, there is evidence that due to the exhaust of water vapor by aero-engines, the cloud cover of the Earth is increased to a certain extent by contrail-induced cirrus. Also the exhaust of nitrogen oxides is a matter of major concern because this compound may promote the enhanced greenhouse effect and as well as depletion of ozone in the stratosphere.

An enhanced greenhouse effect means that the world is becoming warmer, while a depletion of the stratospheric ozone layer will cause a harmful level of ultraviolet (UV) radiation at the surface of the Earth.

This book, especially, is concerned with the numerous sciences and technologies which make up the air pollution problem from flight operations, giving special attention to the performance and emissions of airplanes at their cruise altitudes. Obviously, a good knowledge of the different subjects involved is a prerequisite for obtaining an understanding of human influence on the environment. The contents of the book are a reflection of an annual course on propulsion, noise, and aircraft pollution, presented by the author to MSc Aerospace Engineering students at Delft University of Technology.
The author is grateful and happy to share the responsibility for the part performance in the book with his coauthor Mr. D.M. van Paassen, lecturer/pilot at Delft University of Technology.

The book is an attempt to place the question of aircraft pollution in the context of aerospace engineering by bringing together the most relevant topics covering the problem. To this end, many sources have been consulted because much of the material could only be obtained from textbooks, reports, and articles. The references to the literature are indicated in the text and listed at the end of the book. It should be mentioned, however, that the current state of knowledge of the effects of aviation upon the global atmosphere is described comprehensively in the Intergovernmental Panel on Climate Change Special Report (Ref.1). This IPCC report also makes clear that the effect of aviation on the environment is a complex problem, drawing upon several widely-different scientific disciplines.

In the book the International System of units (SI units) has been used throughout. A point to note is that in international civil aviation the use of certain non-SI units is prescribed, such as foot instead of meter for flight altitude, and so these units also have been cited in the text.

No claim to be comprehensive is made for the book, but it is hoped that no major part of the problem has been omitted from consideration. Above all, it is hoped that the contents of the book will somewhat clarify the various subjects and may urge the reader to further study in this field.

Delft, February 2005

G.J.J. Ruijgrok

D.M. van Paassen
Preface to the third edition

In this edition, apart from a few minor adjustments, all the material from the first two editions has been retained and errors found have been rectified.

At this place I would like to express my respect and appreciation to Mr Dick M. van Paassen, who, sadly, died in 2007. He was a colleague in much of the preparation of the book and without his cooperation this book could not have been written.

Delft, January 2012

G.J.J. Ruijgrok
Elements of aircraft pollution
Chapter 1

Introduction

1.1 Air pollution

When the natural composition of the atmosphere is changed, the air is considered to be polluted. Air pollution is recognized as one of the world’s most serious environmental problems, and includes both natural sources and anthropogenic sources (pollutants from human activities).

Sometimes it only manifests itself by an oppressive odor, however, often it concerns environmentally harmful substances for human beings, animals and vegetation.

In brief, air pollution may appear in the following forms:

- Unpleasant stench or odor nuisance.
- Small droplets, gases, and fumes.
- Particulate matter, PM (any airborne, finely divided, liquid or solid material).

As depicted in Figure 1.1, the order of magnitude of particulates varies from $10^{-9}$ to $10^{-2}$ m. The smallest particulates are called aerosols ($10^{-9}$ to $10^{-6}$ m), and are able to penetrate into our respiratory system. Aerosols involve extremely fine dust or droplets of microscopic size such as tobacco smoke and soot. By soot are meant the carbon-containing particles resulting from incomplete combustion of hydrocarbon fuels. Dust, having particulate sizes ranging from $10^{-6}$ to $10^{-2}$ m, refer to, for example, fly ash, coal dust, sand, and rain drops (Ref. 2).

This stuff, whether natural or man-made, stimulates the condensation of moist air a great deal. In the absence of condensation nuclei the air may remain supersaturated (see Chapter 4).

![Figure 1.1 Particulate sizes.](image)

Natural sources of air pollution are:

- Volcanic eruptions, emitting a variety of gases and particles into the atmosphere. These include water vapor $H_2O$, carbon monoxide $CO$, carbon dioxide $CO_2$, sulfur dioxide $SO_2$, nitrogen oxides $NO_x$ (NO and NO$_2$), mercury Hg, hydrogen sulfide $H_2S$, hydrochloric acid $HCl$, and dust particles.
- Saline droplets arising from the oceans.
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- Organic byproducts of biological activities and vegetable substances, such as pollen, ammonia NH₃, nitrous oxide N₂O, methane CH₄, and hydrogen sulfide H₂S.
- Dust storms.

Examples of anthropogenic forms of pollutants are combustion products of fossil fuels for power and heat generation. Other forms are residues from refineries and industrial processes. Note that petroleum and natural gas contain no fossils, because of the extreme conditions under which they have been formed. Identifiable fossils may only be found in coal and peat.

In residential areas the exhaust gas emissions near ground level from road traffic will considerably contribute to air pollution through the combustion of gasoline, diesel, and liquefied petroleum gas (LPG).

Figure 1.2a shows the world population increases since the year one (Ref. 9). The explosive growth of human population of the twentieth century is obvious. Figure 1.2b portrays the growth in world population and global number of motor vehicles since 1970 and projections to 2030, showing that the current number of vehicles may double in the next 20 years.

![Figure 1.2 World population and global number of motor vehicles.](image)

The number of cars per 1000 inhabitants varies substantially per country. In 1992 the number of vehicles per 1000 inhabitants was approximately 550 in the United States, in Western Europe 200 - 400, while in Africa it was only 9, in India 2, and in China 0.4 (Ref. 3). Certainly, the growth of the number of motor vehicles in China is enormous. As noticed earlier, the exhaust gases of motor vehicles are particularly harmful because the emissions take place in the environment in which we live. In urban environments, where dispersion barely takes place, high concentrations of pollutants may occur.

The air polluting substances from automobiles and trucks are, besides water vapor H₂O and carbon dioxide CO₂, carbon monoxide CO, nitrogen oxides NOₓ (NO and NO₂),
aerosols, sulfur oxides SO\textsubscript{x} (SO\textsubscript{2} and SO\textsubscript{3}), lead Pb, unburned hydrocarbons (UHC) and soot particles. Substances that evaporate at temperatures less than about 100 °C, are called volatiles, e.g., benzene C\textsubscript{6}H\textsubscript{6}. Also, the emission of sulfur, nitrogen oxides, and dust by shipping delivers a noticeable contribution to air pollution.

It should be noted that when considering the environmental effects of electrical systems of transportation, the environmental impact of power generation for their propulsion should also be taken into account, as it contributes likewise to air pollution.

Besides primary pollutants, those emitted directly from the source, secondary pollutant species may be formed. The latter arise from mutual chemical reactions involving originally dispollutants. This is called secondary air pollution.

1.2 Chemical composition of clean air

Air is a mixture of gases. The total mass of the atmosphere is approximately $5.30 \times 10^{18}$ kg. For comparison, the mass of the Earth is $5.98 \times 10^{24}$ kg and the total mass of the water on the Earth is $1.39 \times 10^{21}$ kg. More than 97% of the water is stored in seas and oceans. The atmosphere contains only about 0.035 percent of the water.

The bulk of the air mass is concentrated in the lower layers of the atmosphere as the air density becomes gradually lower with increasing height. For example, 50% of the atmosphere’s mass is contained within the first 6 km and 95% is concentrated below a height of 22 km. If the total air mass would be converted to mean sea-level pressure and temperature, a layer of just about 8 km would remain.

In Table 1.1 the chemical composition of clean air near the Earth’s surface is listed (Ref. 4). Evidently, the air we breathe at sea level consists for the greater part of the two diatomic gases nitrogen N\textsubscript{2} and oxygen O\textsubscript{2} (together about 99.03% by volume). Oxygen, O\textsubscript{2}, the second largest constituent, is one of the most reactive elements.

The remaining constituents, although present in relatively small quantities, may be nevertheless of great importance. For instance, the ample quantities of carbon dioxide CO\textsubscript{2} and water vapor H\textsubscript{2}O form a kind of shield, blocking the heat radiation from the Earth into outer space and heating up the Earth’s surface. This phenomenon is called the natural greenhouse effect, the condition that keeps an enclosure warm in the wintertime.

Ozone, O\textsubscript{3}, is present everywhere in the atmosphere. However, the amount of ozone varies significantly, geographically, with seasons, and, typically, depends strongly on the altitude.

Ozone is an unstable gas, formed by reaction of molecular oxygen O\textsubscript{2} and atomic oxygen O. Atomic oxygen arises from dissociation of molecular oxygen, caused by ultraviolet solar radiation.

Simultaneously, ozone depletion takes place, forming molecular and atomic oxygen, caused by infrared radiation. This continuous process of formation and depletion results in a constant overall equilibrium concentration of ozone in the atmosphere. Depending
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Table 1.1 Normal composition of clean atmospheric air near sea level.

<table>
<thead>
<tr>
<th>constituent gas</th>
<th>content, percent by volume</th>
<th>molecular mass kg/kmol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen N$_2$</td>
<td>78.084</td>
<td>28.0134</td>
</tr>
<tr>
<td>Oxygen O$_2$</td>
<td>20.9476</td>
<td>31.9988</td>
</tr>
<tr>
<td>Argon Ar</td>
<td>0.934</td>
<td>39.948</td>
</tr>
<tr>
<td>Carbon dioxide CO$_2$</td>
<td>0.0314</td>
<td>44.00995</td>
</tr>
<tr>
<td>Neon Ne</td>
<td>0.001818</td>
<td>20.183</td>
</tr>
<tr>
<td>Helium He</td>
<td>0.000524</td>
<td>4.0026</td>
</tr>
<tr>
<td>Methane CH$_4$</td>
<td>0.0002</td>
<td>16.04303</td>
</tr>
<tr>
<td>Krypton Kr</td>
<td>0.000114</td>
<td>83.80</td>
</tr>
<tr>
<td>Sulfur dioxide SO$_2$</td>
<td>0.00001</td>
<td>64.0628</td>
</tr>
<tr>
<td>Hydrogen H$_2$</td>
<td>0.00005</td>
<td>2.01594</td>
</tr>
<tr>
<td>Nitrous oxide N$_2$O</td>
<td>0.00005</td>
<td>44.0128</td>
</tr>
<tr>
<td>Xenon Xe</td>
<td>0.00000087</td>
<td>131.30</td>
</tr>
<tr>
<td>Ozone O$_3$</td>
<td>0-0.0000007</td>
<td>47.9982</td>
</tr>
<tr>
<td>Nitrogen dioxide NO$_2$</td>
<td>0-0.0000002</td>
<td>46.0055</td>
</tr>
<tr>
<td>Iodine I$_2$</td>
<td>0-0.0000001</td>
<td>253.8088</td>
</tr>
<tr>
<td>Water vapor H$_2$O</td>
<td>0-3.0</td>
<td>18.0</td>
</tr>
</tbody>
</table>

on the intensity of the solar radiation and the number of particles per unit volume, a maximum in the ozone concentration occurs at an altitude between 25 and 35 km. Important is that the ozone at these high altitudes acts as a filter against solar ultraviolet radiation, which otherwise has many harmful effects on Earth’s animal and plant life.

Water in the atmosphere can be present in the form of water vapor, an invisible gas, or as minute droplets and ice particles (clouds, precipitation). The amount of water vapor varies with geographical latitude, and decreases substantially with increasing altitude. Generally, the highest degree of humidity occurs near the Equator. At an altitude of 10 km virtually no water vapor is found.

The composition of the air remains more or less constant up to an altitude of about 90 km. Above this altitude the composition gradually changes, mainly because of molecular dissociation, i.e., the break up of the molecules of the various gases into their atoms, called radicals, due to the increased intensity of ultraviolet sunlight. In consequence, the molecular mass of the air decreases with increasing altitude.

1.3 Arrangement and nomenclature of the atmosphere

With respect to the chemical composition, the atmosphere may be classified into the homosphere and the heterosphere. The homosphere extends up to an altitude of 90 km, where the air is characterized by a nearly constant chemical composition (with the
exception of water vapor and ozone). The region above 90 km is indicated as the heterosphere. Here, the molecular mass decreases from about 29 kg/kmol at a height of 90 km, to 18 kg/kmol at a height of 500 km. The dividing plane between the homosphere and heterosphere is known as the homopause.

In Figure 1.3 the typical variation of the average temperature with altitude is sketched. Based on this temperature distribution, the atmosphere can be divided into the following four layers:

- **Troposphere.**
- **Stratosphere.**
- **Mesosphere.**
- **Thermosphere.**

The *troposphere* is characterized by a decrease in temperature with increasing altitude. In this layer occur the phenomena which we call *weather*, i.e., the local state of temperature, pressure, humidity, cloudiness, wind, and precipitation.

The troposphere can be subdivided into two parts (Figure 1.4). The first part, up to about 2 km above sea level, is called the *planetary* or *atmospheric boundary layer* and the remaining part is named the *free troposphere*. This distinction is of significance when considering the effects of air pollution, since the atmospheric boundary layer is most directly influenced by the underlying land or sea surface.

The dividing plane between the troposphere and the *stratosphere* is called the *tropopause*. For average latitudes, this plane is located at a height of about 11 km. Near the polar
Table 1.2 Number of particles per cubic meter for several altitudes.

<table>
<thead>
<tr>
<th>altitude [km]</th>
<th>number of particles, m⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>(2.5 \times 10^{25})</td>
</tr>
<tr>
<td>10</td>
<td>10^{25}</td>
</tr>
<tr>
<td>500</td>
<td>10^{14}</td>
</tr>
<tr>
<td>1000</td>
<td>10^{12}</td>
</tr>
<tr>
<td>1500</td>
<td>10^{11}</td>
</tr>
<tr>
<td>2000</td>
<td>10^{10}</td>
</tr>
</tbody>
</table>

regions it is located at about 8 km, while at the Equator it reaches up to approximately 17 km (Figure 1.5).

In the stratosphere, at first, there is a nearly constant temperature of about \(-50\) to \(-60^\circ\)C up to an altitude of 20 to 25 km. From thereon the temperature increases to a maximum value of \(0^\circ\) C at an altitude of about 50 km. The dividing plane between the stratosphere and the mesosphere is called the stratosphere.

This altitude sometimes is referred to as the ozonepause. In fact, the temperature increase above 20 km is related to the absorption of ultraviolet radiation, involving ozone formation.

Typical for the mesosphere is a decreasing temperature, reaching a minimum value of about \(-90^\circ\)C, at an altitude of 90 km. The latter altitude is called the mesopause.

The region between 90 and about 500 km is called the thermosphere. In the thermosphere, the temperature increases quickly with increasing altitude until at about 500 km the so-called exospheric temperature is reached. Depending on solar activity, the value of this temperature may vary between 200 and 1000 \(^\circ\)C. These temperatures are only an indication of the kinetic energy of the air particles. The temperature of an object at these very high altitudes is entirely determined by the heat balance between its absorbed heat radiation, its produced internal heat and its emitted heat radiation. Convective heat transfer is hardly possible due to the very low value of the air density.
From 90 km upwards, ionization processes occur, i.e., the generation of ions and the accompanying free electrons takes place. Therefore, in Figure 1.3 also is depicted the ionosphere, in which the highest concentrations of ions are found. Also the ionosphere extends roughly from a height of 90 to 500 km. Depending on electron density, the ionosphere is subdivided into four layers, designated D, E, F₁ and F₂. The curves in Figure 1.3 show that the extent of ionization increases with altitude up to approximately 300 km. Local maxima of the amount of ionized particles occur, corresponding to the four layers. At night, when no radiation is perceived, some of these sub-layers may be absent. The curves also vary with solar activity and time of the year.

As depicted in Figure 1.6, due to its ability to reflect electromagnetic radiation, the ionosphere is of paramount importance to long-distance radio communication using wavelengths greater than 10 m.

At altitudes above 500 km, where the air density decreases further, the number of particles per unit volume becomes extremely low. By way of illustration, Table 1.2 gives the number of particles per unit of volume for several altitudes. Consequently, the particles will show large mean free path lengths of several hundreds of kilometers or even more. Hence, particle collisions are unlikely to take place.

At a height of 500 km begins the region that is called the exosphere, where collisions between molecules are so rare that neutral particles move in trajectories which are subject to gravity only. Almost all the atmospheric gases are ionized, and the charged particle motions are strongly directed by the magnetic field surrounding them.

In the exosphere the distribution of the gases is controlled by diffusion, which process implies that a substance moves from a region where its concentration is high to one where its concentration is low. As a result, a transition from mainly atomic oxygen ions into primarily helium ions takes place at about 1000 km, and from helium ions to the lighter hydrogen ions at heights of the order of 3000 km.

Clearly, a knowledge of the Earth’s magnetic field is a prerequisite to an appreciation of exospheric motions. To this end, we have to consider the magnetosphere, which region refers to the magnetic properties of the Earth. Near the Earth’s surface, the magnetic field of the Earth may be represented by the dipole field of a bar magnet (Figure 1.7). The axis of the dipole is not aligned with the polar axis of the Earth, but is inclined to it at an angle of about 11.3°. Drawing a straight line through approximately the center of the Earth along the dipole axis yields the two geomagnetic poles at the points where this line breaks through the Earth’s surface. A compass needle will follow the magnetic
field lines, which run from one pole to the other.

Of course, the magnetic field of the Earth is three-dimensional and extends more or less spherically from the magnet, the lines of force converging at the two magnetic poles.

From rocket and satellite observations it is known that at very large heights the magnetic field is flattened on the side of the Earth turned toward the Sun and stretched out on the night side.

This transformation of the Earth’s magnetic field arises from its interaction with the solar wind, which is a stream of charged particles. The solar wind is emitted from the outermost layer of the Sun’s atmosphere, the solar corona, which consists of an extensive, very tenuous envelope of gases at high temperature (Figure 1.8).

Although the Sun has a strong gravitational field, its enormous high temperature contains enough kinetic energy that the particles can escape from the Sun into the interplanetary space.

The solar wind is composed almost of protons and electrons, which particles are electrically charged. Protons carry a positive charge and electrons a negative charge. Their

The apparent visible surface of the Sun, known as the photosphere, consists of a network of bright markings on a darker background. The effective temperature in the photosphere amounts to about 5800 K. The portion of the Sun’s atmosphere nearest the photosphere, called the chromosphere, is a layer of ionized gases extending to several thousand miles. The energy radiated by the Sun is the result of nuclear processes in the interior, where helium is formed by the fusion of hydrogen nuclei. In the Sun’s core, the temperature rises to about 20 million kelvin.
travel speeds vary between 300 and 1000 km/s, depending on solar activity. When the solar wind strikes the magnetic field of the Earth, a bow shock wave is generated, changing the shape of the Earth’s magnetic field. The resultant distortion is sketched in Figure 1.9, giving a two-dimensional representation of the magnetosphere, the three-dimensional magnetic field that surrounds the Earth. Figure 1.9 also shows that the Earth’s magnetic field is enclosed by the solar wind with the magnetopause as a quite definite boundary.

The electrically charged particles of the solar wind are trapped in the magnetosphere. The forces acting, cause them to follow spiral paths along lines of force. Charged particles are most abundant in a concentric series of belts, shaped like tires which surround the Earth, located over the Equator. These belts are known as the Van Allen radiation belts, named after the American physicist James A. Van Allen (1914-2006), who discovered their occurrence from information gathered by Explorer I, the first American satellite (1958).

The particles of the solar wind that carry no charges (neutrons) are also trapped by the magnetosphere, but at a lower level. They also penetrate the magnetosphere but, as they move toward the Earth, they collide with atoms of atmospheric gases, producing elementary particles.

The charged particles making up the Earth’s exosphere are not able to escape from the magnetosphere, so that the magnetopause can be regarded to be the outermost part of the Earth’s atmosphere. Recently, researchers discovered that a large collection of antimatter is trapped in the Van Allen belts. Antimatter is made up of elementary antiparticles, which differ from their normal particle counterparts in that they are oppositely charged. When antimatter is combined with an equal amount of matter, it results in the complete conversion of all substance to energy.

The electromagnetic radiation coming from the Sun is not affected by the presence of
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1.4 Harmful effects of engine emissions

The various pollutants from burning fossil fuels may contribute to the following five principal effects of air pollution:

1. Effects on the climate.
2. Acidification.
3. Ozone layer breakdown.
4. Photochemical air pollution.
5. Local effects at ground level.

Each of these effects is briefly discussed below.

1. Effects on the climate are commonly indicated as the enhanced greenhouse effect or global warming. Anticipating our discussion in Chapter 6, global warming is the term used to describe the phenomenon of the increasing global average temperature at the Earth’s surface. Analysis shows that this temperature has increased by about 0.6 °C in the last 100 years, taking full account of diurnal and seasonal temperature changes as well as for being averaged across the world in northern and southern hemispheres and over land and sea.

The atmosphere and the Earth receive energy through short-wave radiation by the Sun. At the same time, the Earth emits longer-wave, infrared radiation, of which the energy is partly absorbed by the molecules of atmospheric gases, such as water vapor H₂O, carbon dioxide CO₂, and ozone O₃. All the greenhouse gases are transparent to short-wave radiation, but partially opaque to long-wave radiation. Three or more atoms per molecule constitute the common property of greenhouse gases, with up to five atoms in the case of methane CH₄.

Like the action of the glass walls of a greenhouse (Figure 1.10), the heat absorbed by a shield of greenhouse gases is re-emitted both upwards to space and downwards to the Earth’s surface. Consequently, some of the heat that would

Figure 1.10 The greenhouse effect.

the magnetosphere. As will be discussed in Chapter 5, their fate is especially governed by their frequencies.
otherwise be radiated into space is ‘trapped’ by these gases. As mentioned earlier, this phenomenon is known as the natural greenhouse effect. As long as the annual global energy radiated into space equals the solar energy absorbed by the Earth, there is a global equilibrium temperature on the Earth.

Especially, the increasing man-made production of carbon dioxide by burning fossil fuels and cutting down tropical rain forests cause a continuous increasing CO₂ content in the atmosphere. Also enlarged concentrations of H₂O, NOₓ, CO, UHC, and soot from burning fossil fuels disturb the thermal equilibrium condition of the Earth, and may lead to an enhanced greenhouse effect and so to an increase of the Earth’s mean temperature. By NOₓ, CO, and UHC emissions the greenhouse gas ozone O₃ is introduced in the atmosphere via secondary air pollution. This is the so-called tropospheric or ‘bad’ ozone, formed by photochemical reaction of oxygen O₂ with nitrogen oxides, carbon monoxide, and unburned hydrocarbons.

The trapping of heat in the atmosphere may affect not only the Earth’s surface temperature, but also weather conditions such as heavier rainfall, more serious floods, and greater numbers of thunderstorms and tornadoes. For many coastal regions throughout the world the danger of storm surges may increase, especially in areas in which a rise in sea level and a greater risk of storms coincide.

2. A second issue of concern pertains to the occurrence of acid precipitation. Normal pure rainwater always has a slightly acid character because it takes up some of the atmospheric carbon dioxide and convert it into carbonic acid. Precipitation becomes an unnatural acidity by the presence of nitrogen oxides NOₓ and sulfur dioxide SO₂ as released into the air when burning fossil fuels. The oxides NOₓ and SO₂ readily combine with water vapor to form nitric and sulfuric acids. These acids then become condensation nuclei, thus producing acid precipitation. As soon as acid precipitation was detected, it was ascribed to anthropogenic pollution. It was found that, after evaporation, acid raindrops on plants and trees may leave behind high concentrations of acids, which may burn holes into the structure of the leaves. Evidently, acid precipitation may be harmful to forests and vegetation by accumulating acids in the soil. With high sulfur concentrations in the atmosphere, precipitation with sulfuric acid also can cause severe corrosion of mineral building materials. In recent years there has been an acceleration in damage of this type to old buildings and structures in city centers. Obviously, the only way to solve the problem is to stop or reduce the exhaust of harmful man-made products into the air.

3. Over the past twenty-five years, concern has grown over the effects of man-made chemicals on the ozone layer at very high altitudes in the stratosphere. Especially the introduction of chlorine and bromide compounds, and nitrous oxide N₂O into the atmosphere at ground level participates in the depletion of the ozone layer. Also due to a transport of nitrogen oxides to larger heights when emitted by aircraft in cruise, air traffic may participate in the catalytic destruction of ozone.
Elements of aircraft pollution

through which the risk is increased that harmful solar ultraviolet radiation penetrates to the Earth’s surface.

4. In addition, nitrogen oxides not only may cause the phenomenon of acidification, but also the formation of tropospheric ozone by a photochemical reaction with oxygen. In this way, NOx may promote an enhancement of the greenhouse effect. Also, ozone is the photochemical precursor of the OH radical, one of the most important oxidants in the global atmosphere. In chemistry, a radical is a group of atoms that is replaceable in a molecule by a single atom and is capable of remaining unchanged during a series of reactions. When in densely populated areas with high NOx concentrations photochemical smog is formed, irritation of the eyes and mucous membranes may occur. Increased concentrations of ozone near ground level not only may have harmful effects on human beings but also can damage vegetation and forests, for instance by faster aging and poorer assimilation of nutrients and water.

5. Unburned hydrocarbons (UHC) as a result of incomplete combustion or insufficient mixing of fuel and air, carbon monoxide CO, and smoke (vapor made visible by the presence of tiny particles) have direct local effects in addition to those of ground level ozone, especially in urban environments. Acids from nitrogen oxides and sulfur dioxide can precipitate locally and damage vegetation or cause corrosion to buildings. Unburned hydrocarbons and soot particles are also detrimental to the living conditions of both humans and plants. Partial oxidation of the fuel may lead, via the separation of hydrogen atoms, to the formation of aromatic (e.g., benzene C₆H₆ and polycyclic aromatic hydrocarbons (PAH). These substances can affect the body’s DNA (deoxyribonucleic acid) and can cause cancer.

Local air pollution occurs mainly in a stable atmosphere, with little or no convective motions. Dispersion of pollutants hardly takes place, possibly leading to photochemical smog formation. This type of smog is formed when high concentrations of pollutants (smoke) are combined with fog. Automobile emissions of UHC, NOx and VOC (volatile organic compounds), such as benzene and toluene may lead, under the influence of ultraviolet solar radiation, to the formation of ozone O₃ at ground level. Ozone is a strongly oxidative and poisonous gas.

A summary of the various harmful effects of combustion emissions is given in Table 1.3. Without doubt, the troposphere is of tremendous significance for the generation and dispersion of pollutant substances. In particular, the lowest 2000 meters of the atmosphere are of significance to accomplish the desired dispersion and dilution of air pollutants. Within this layer the horizontal and vertical motions of the air greatly affect the way in which pollutant substances disperse, and to what degree the atmosphere is self-cleaning.

A measure to reduce anthropogenic pollution near the ground from heavy industry is the use of high smoke stacks. In residential areas, the improvement of smoke disposal from
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### Table 1.3 Harmful effects caused by combustion emission.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Effects on environment</th>
<th>Effect on health</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>Tropospheric ozone production</td>
<td>Toxic</td>
</tr>
<tr>
<td>UHC</td>
<td>Global warming</td>
<td>Toxic</td>
</tr>
<tr>
<td>Smoke</td>
<td>Global warming</td>
<td>Respiratory problems</td>
</tr>
<tr>
<td>SO\textsubscript{x}</td>
<td>Global warming</td>
<td>Toxic</td>
</tr>
<tr>
<td>NO\textsubscript{x}</td>
<td>Global warming</td>
<td>Toxic</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>Global warming</td>
<td></td>
</tr>
<tr>
<td>H\textsubscript{2}O</td>
<td>Global warming</td>
<td></td>
</tr>
</tbody>
</table>

domestic chimneys is an effective measure. The replacement of coal by natural gas for heating and power generation purposes, and equipping motor vehicles with catalytic converters have also proven to be effective. Flue gases from installations using natural gas as a fuel contain relatively low amounts of sulfur dioxide SO\textsubscript{2} compared to the use of sulfurous coal.

#### 1.5 Motor vehicle emissions

Worldwide, the transport sector accounts for about 30 percent of the global energy consumption, almost all of which comes from oil-derived products. Ground transport (road and rail) is responsible for about 85 percent of the total energy use in the transport sector. Therefore, the transport sector is a major contributor to greenhouse gases as it produces about 18 percent of all carbon dioxide released from fossil fuels (Ref.3).

In addition, ground transport generates a large percentage of anthropogenic carbon monoxide (CO) emissions, unburned hydrocarbons (UHC), soot (particulate matter), nitrogen oxides (NO\textsubscript{x}), and sulfur oxides (SO\textsubscript{x}). Accordingly, road traffic contributes also to the acidification of the environment, and the formation of photochemical smog. Therefore, in confined places and congested streets, emission pollutants from ground transport may rise to levels that are hazardous to health.

At stoichiometric (ideal) combustion conditions, the combustion process consumes approximately 15 kg of air per kg of fuel, to form the combustion products carbon dioxide CO\textsubscript{2} and water H\textsubscript{2}O. If the sulfur contained in the fuel is burned completely, sulfur dioxide is produced.
The propulsion of motor vehicles generally involves combustion processes with less favorable fuel to air ratios, and insufficient mixing of fuel and air. Furthermore, the process often takes place too fast at a relative (too) low temperature. Consequently, pollutants will be formed.

Carbon monoxide CO is the intermediate product in the combustion process of carbon to carbon dioxide CO₂. If there is a lack of air or the combustion temperature and residence time in the flame are insufficient, part of the CO can escape along with the exhaust gases. If the hydrocarbons are not fully oxidized during combustion, in the combustor a decomposition process takes place, leading to the formation of new hydrocarbons via the separation of hydrogen atoms. In this way substances like aromatic and polycyclic aromatic hydrocarbons (PAH’s) are formed, which also are emitted along with the exhaust plumes.

The formation of soot (carbon-containing particles) results from the application of high flame temperatures and from incomplete combustion due to lack of oxygen O₂. Also nitrogen oxides NOₓ are formed during combustion processes with high flame temperatures through oxidation of the nitrogen N₂ in the air and through the combustion of the fuel-bound nitrogen. Primarily, nitrogen monoxide NO is produced, whereas nitrogen dioxide NO₂ is formed only after the combustion when there is a sufficient oxygen content in the exhaust gases and finally in the atmosphere.

A feasible measure to reduce pollutant emissions from motorized vehicles is the use of a three-way catalytic converter (Figure 1.11). The term "three-way" indicates that the three pollutants UHC, CO, and NOₓ are transformed, via the following gross reactions (Ref. 5):

1. Transformation of hydrocarbon:

   \[
   \begin{align*}
   C_xH_y + (x+y/4)O_2 & \rightarrow xCO_2 + y/2H_2O, \\
   CH_y + 2H_2O & \rightarrow CO_2 + (2 + y/2)H_2
   \end{align*}
   \]

2. Transformation of carbon monoxide:

   \[
   \begin{align*}
   CO + 1/2 O_2 & \rightarrow CO_2, \\
   CO + H_2O & \rightarrow CO_2 + H_2.
   \end{align*}
   \]
3. Transformation of nitrogen oxides and unburned hydrocarbons:

\[ \text{NO} + \text{CO} \rightarrow \frac{1}{2} \text{N}_2 + \text{CO}_2. \]
\[ 2(x+y/4)\text{NO} + C_xH_y \rightarrow (x+y/4)\text{N}_2 + (y/2)\text{H}_2\text{O} + x\text{CO}_2, \]
\[ \text{NO} + \text{H}_2 \rightarrow \frac{1}{2} \text{N}_2 + \text{H}_2\text{O}. \]

The body of the catalytic converter is placed in the engine exhaust pipe before the muffler. It should be noted that after disposal, the catalytic converter will have to be processed as well.

With the state of the art technology, the catalytic converter is only applicable to gasoline-powered and diesel-powered piston engines. Although diesel-powered vehicles emit lower amounts of carbon monoxide and unburned hydrocarbons than gasoline-powered vehicles, their emission of carbon particulates is considerably higher.

Table 1.4 Heating value of various fuels. (for remarks regarding the determination of the heating value, the reader is referred to Section 10.3.)

<table>
<thead>
<tr>
<th>fuel</th>
<th>heating value, J/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydrogen</td>
<td>$11.85 \times 10^7$</td>
</tr>
<tr>
<td>methane</td>
<td>$4.89 \times 10^7$</td>
</tr>
<tr>
<td>kerosene</td>
<td>$4.34 \times 10^7$</td>
</tr>
<tr>
<td>coal</td>
<td>$3.30 \times 10^7$</td>
</tr>
<tr>
<td>natural gas</td>
<td>$3.16 \times 10^7$</td>
</tr>
<tr>
<td>brown coal (lignite)</td>
<td>$2.70 \times 10^7$</td>
</tr>
<tr>
<td>fire wood</td>
<td>$9.83 \times 10^6$</td>
</tr>
</tbody>
</table>

Other measures to reduce air pollution from road traffic are:

1. The utilization of unleaded petrol. However, to accomplish a better knock-resistance, aromatic compounds such as benzene are to be used as a fuel additive.
2. Speed reduction, i.e., a reduction of the combustion temperature.
3. The development of clean fuels and economic engines. Economic engines involve adequate combustion and a high thermal efficiency $\eta_{th}$, which is defined by:

\[ \eta_{th} = \frac{P_{br}}{m_f H} \]  

(1.1)

where $P_{br}$ is the power delivered to the shaft, $m_f$ the fuel mass flow rate and $H$ the heating value or heat of combustion of the fuel. For gasoline, $H \approx 4.3 \times 10^7$ J/kg (Table 1.4). The thermal efficiency of current piston engines, approximately, amounts to 30%.
1.6 Aero-engine emissions

As shown in Figure 1.12, in an ideal (stoichiometric) combustion process, carbon dioxide CO\(_2\) and water H\(_2\)O are formed as combustion products. Unfortunately, ideal combustion processes do not exist and also undesirable compounds are formed, mainly consisting of nitrogen oxides NO\(_x\), carbon monoxide CO, unburned hydrocarbons (UHC), sulfur oxides SO\(_x\), and soot particles.

![Figure 1.12 The combustion process in a turbofan engine.](image)

At present there is only a limited knowledge about the formation and behavior of minor, trace species and aerosols found in the exhaust gases of turbo-engines. Even less is known about how they are influenced by engine features and characteristics (Ref. 1). Emissions of NO\(_x\), CO, and UHC can be reduced by improved combustion techniques, while reduction of CO\(_2\) and water H\(_2\)O requires reduced fuel consumption. A favorable feature of the kerosene fuel used for jet airplane propulsion is that it contains almost no sulfur. Therefore, the emission of sulfur dioxide SO\(_2\) by airplanes is very low and usually negligible.

Although air transport uses just 5 percent of the global oil consumption per year and about 13 percent of the yearly consumption of fossil fuels taken by all forms of transport, control of pollutant emissions from the combustion of kerosene is of increasing importance in the design and operation of airplanes and airplane propulsion systems. This is reflected by the fact that already for many years, standards for the pollutants produced by aviation engines, namely carbon monoxide CO, unburned hydrocarbons (UHC), nitrogen oxides NO\(_x\), and smoke, are set by the International Civil Aviation Organization (ICAO) in Ref. 6. According to its definition by ICAO, smoke is formed by the carbonaceous materials in exhaust emissions which obscure the transmission of light.

In the past, man was merely concerned with the effects of pollutant emissions at ground level near the airports. In this respect, with success, attention has been given to the reduction of CO and UHC, which appear to be dominating at low thrust settings of the engine (Figure 1.13). Smoke emissions, which used to dominate at high thrust settings,
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Figure 1.13 Emission level versus thrust setting.

have also been greatly reduced. Presently, much effort is devoted to the effects of emissions from aircraft upon the upper region of the troposphere and the lower region of the stratosphere, since at these heights the airplane is the only anthropogenic source of pollutants. Especially, the emissions of NOx, the result of burning kerosine at high temperatures, have been increased during the past decades. For long-range flights, naturally, the largest amount of NOx will be emitted during the cruise part of the flight, where is flown at altitudes near the tropopause.

Today, therefore, considerable effort is being made to lower the NOx emissions by improving the combustion process. Also, reducing the fuel consumption per flight will remain an effective way of decreasing the impact of aviation on the environment.

1.7 The hydrological cycle

A great influence on the removal of pollutants from the atmosphere has the hydrological cycle by which water evaporates from oceans and land, is transported by air motions, forming clouds and precipitations, and returns from oceans and land to the atmosphere (Figure 1.14).

Wind blowing across the oceans and wave action produce a fine spray of water droplets containing salt. Upon these solid particles the water vapor in the atmosphere may condense. Figure 1.15 illustrates the general, global pressure and surface wind distributions. Surface winds are defined as winds occurring at very low heights. Close to the Equator the surface water, and so the air in contact with it, is heated intensively by its direct exposure to solar radiation. The warming of air produces a region of low atmospheric pressure into which air is drawn. The low pressures near the Equator are the source of the well-known trade winds. Mariners exploited these winds, but dreaded the equatorial belt of light variable winds
lying between them, which they called the doldrums. In the mid-latitudes the familiar westerly winds (westerlies) prevail, while in both polar regions easterly winds (easterlies) occur.

Note that the direction of the wind is that direction from which it is blowing. If the wind is coming from the southwest, its direction is said to be southwest (S.W.). Usually wind directions are reported by directions on a 32 points compass or in degree (Figure 1.16). Thus, at the northern hemisphere the direction of the trade wind is N.E. (northeast) and at the southern hemisphere S.E. (southeast).

Like wind, also oceans and seas are important to the dispersion of heat energy over the Earth. Oceans and seas cover more than 70 percent of the total surface of the Earth. The average depth is 3.73 km and together they contain 1370 million km³ of water. If the Earth would be covered by one vast ocean, the ocean would be 2.7 km deep.

The trade winds drive the surface currents toward the Equator, through which cold water is heated and returns to warm the higher latitudes from which it came. Clearly, the transport of cool water to the Equator prevents the tropical regions from being as hot as they would be otherwise.

The atmosphere is warmed from underneath through which convection may ensue, with vertical ascents and descents of air, leading to a thorough mixing of the air. This situation is opposite to that at the surfaces of the oceans, where the water is heated from above by the Sun. This implies that there are layers of relatively warm water floating above cooler and denser water masses. As little vertical mixing occurs, the oceans can be divided into approximately horizontal layers with different water temperatures.
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At the same time, the water in the oceans is in constant horizontal motion. Friction between the water and the moving air keeps the water flowing in the direction of the wind. The interaction between wind and water has created the major global currents, which brings warm tropical water to the higher latitudes.

Figure 1.15 Global surface pressures and air currents. Figure 1.16 Wind direction scales.

Figure 1.17 Major ocean currents.

Figure 1.17 shows great surface motions of the oceans and seas, as caused by the prevailing surface winds. Due to the Coriolis force, which bends winds because of the
rotation of the Earth about its own axis, also the flow of water is deflected toward the right north of the Equator and toward the left south of it (see also Section 2.6). Summarizing, it may be said that by carrying warm water to cool latitudes, and cool water to warm latitudes, the ocean currents have a major effect on the local weather and the climates of the world’s regions.

In addition to the surface winds, the influence of tidal currents, as caused by the combined effect of the gravitational pull of the Earth, Moon and Sun upon the water mass on the Earth, is of importance to the transfer of heat over the Earth. The essentials of ebb and flow of the tides are discussed separately in the next section.

Besides the movement of surface water, there are the deepwater currents (Figure 1.18). These are flowing from the polar regions, mainly by the formation of sea ice, which removes fresh (saltless) water from the sea surface. Immediately below the sea ice, the water is therefore more saline. Moreover, the water has a temperature at which it has approximately its greatest density (Figure 1.19). These factors make the surface water more dense than the water below it. Accordingly, the water sinks below the less denser water and, at the same time, moves away from the sea ice. In this way a flow is established of very cold, saline water moving away from the Poles along the bottom of the ocean toward the Equator. Its place is taken by water flowing polewards beneath the surface water, and then is forced to rise as it encounters the denser water that is sinking. The above mechanisms are believed to drive the oceanic system of heat transport by ocean currents.

To conclude, it is important to emphasize that pollution not only implies the release of undesired substances into the atmosphere and soil, but also their introduction into the water. In this respect it should be noted that the oceans also are of great importance to the environment and the climate in the sense that they provide yearly the storage of an enormous amount of carbon dioxide from the atmosphere. The CO$_2$ leaving the atmosphere dissolves in the upper layers of the oceans and seas and, finally, becomes mixed into the deeper layers. Concerning this storage, it is worthy of mention that, as with oxygen, the solubility of water decreases as its temperature rises. In plain words,