DE GRUYTER Physical Sciences Reviews. 2017; 20160122

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Air pollution engineering

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Abstract:
Air pollution is an environmental and a social problem which leads to a multitude of adverse effects on human health and standard of human life, state of the ecosystems and global change of climate. Air pollutants are emitted from natural, but mostly from anthropogenic sources and may be transported over long distances. Some air pollutants are extremely stable in the atmosphere and may accumulate in the environment and in the food chain, affecting human beings, animals and natural biodiversity. Obviously, air pollution is a complex problem that poses multiple challenges in terms of management and abatements of the pollutants emission. Effective approach to the problems of air pollution requires a good understanding of the sources that cause it, knowledge of air quality status and future trends as well as its impact on humans and ecosystems. This chapter deals with the complexities of the air pollution and presents an overview of different technical processes and equipment for air pollution control, as well as basic principles of their work. The problems of air protection as well as protection of other ecosystems can be solved only by the coordinated endeavors of various scientific and engineering disciplines, such as chemistry, physics, biology, medicine, chemical engineering and social sciences. The most important engineering contribution is mostly focused on development, design and operation of equipment for the abatement of harmful emissions into environment.

Keywords: Air pollution, Pollutants, Air pollution sources, Particulate matter, Gaseous air contaminants, Air pollution control techniques

DOI: 10.1515/psr-2016-0122

> Who does not learn from the past will not succeed in the future.
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> Paul Crutzen, Nobel Prize Winner in Chemistry (1995)

1 Introduction

1.1 The complexities of the air pollution protection

Economic, industrial and population growth in the world have had a significant impact on urban and rural air quality. Today, air pollution presents a substantial environmental risk, especially in some areas that are frequently exposed to elevated concentrations of toxic air pollutants. Emissions from power generation, industrial sources, traffic and transport vehicles, as well as from other industrial and anthropogenic activities are significant contributors to the air quality. In addition to human activities, air pollution can also be caused by natural disasters (e. g. volcanic eruptions, forests fires), by sea-salt emissions, natural processes and biological processes. According to some estimates, there are about 1,500 active volcanoes around the world, 50 of which erupt every year and 2012 was declared as *The Year in Volcanic Activity*. However, it is generally accepted that the major contributors to the increasing emissions into atmosphere are mostly the man-made or anthropogenic activities [1].

The US National Oceanic and Atmospheric Administration (NOAA) recorded 2015 as the hottest year since records began in 1880 and the 16 warmest years recorded are in the 1998–2015 period [2]. In 2015, the five largest emitting countries (including the European Union), which together account for two thirds of total global emissions, were: China (with a 29 % share in the global total), the United States (14 %), the European Union (EU-28) (10 %), India (7 %), the Russian Federation (5 %) and Japan (3.5 %) [2]. Climate model projections indicated that during the twenty-first century the global surface temperature is likely to rise a further 0.3 to 1.7 °C for their lowest emissions scenario and 2.6 to 4.8 °C for the highest emissions scenario [3]. Increased temperature, especially in the Arctic, melts ice caps and glaciers and affects the oceans, resulting in habitat changes for many species of plants and animals. Extreme weather, such as increased rainfall in some areas, droughts and heat waves in others, affects the growth of food crops and other plants. Climate change – a result of global

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warming, which have been observed and scientifically proved in the last few decades, depend significantly on the specific problems related to the air pollution. There is no doubt that human activities are the critical cause of the climate change that Earth is experiencing since the Industrial Revolution in the mid-eighteenth century. It is well known that Industrial Revolution marked the beginning of a dramatic increase in the use of fossil fuels. Fuel combustion is also directly related to the number of people and their standard of living and energy consumption. According to the UN calculations, today there are more than 7 billion living humans on the Earth [4]. Between 1900 and 2000 the increase in world population was three times greater than the entire previous history of humanity with an increase from 1.5 to 6.1 billion in just 100 years. Coal is still the biggest source of energy for electricity production and the biggest contributor to carbon dioxide (CO_2) emissions and CO_2 is the most important representative of the greenhouse gases (GHGs) responsible for the warming effect [5].

Developed countries are in particular faced with the problems of air pollution in big cities and industrialized areas and sometimes they try to solve this problem by the relocation of theirs industrial plants in less developed countries. Apparently, this is a bad example of temporary problem solving and transferring the problem to another location. Currently, some politicians and special interest groups in the more developed parts of the world still refuse to act in order to reduce environmental pollution on the global level, mainly due to significant economic impacts of particular industries or some segments of the economy. On the other hand, in the developing countries and countries in transition, development is usually based on “dirty” industry and unsustainable technologies. The consequence is pollution on a global scale, due to the fact that air pollutants can be transported over long distances from their source. The amount of time that an air pollutant, like ozone, greenhouse gases and others, will stay in the atmosphere is determined by its reactivity and removal rate by natural mechanism (dry or wet deposition, natural reservoirs or sinks). Some air pollutants remain in the atmosphere from a few hours, days to several thousands of years. Therefore, protecting human health and the environment from the impacts of air pollution and climate changes become the critical challenges of the twenty-first century. These challenges are additionally complicated by the interrelation between the air quality, climate changes as well as existing and advanced energy options [6].

Although there is significant progress in the last half-century because of numerous efforts to reduce air pollution and greatly improve air quality, many people are still living in counties that do not meet current air quality standards for the air pollutants regulated by the environmental agencies, such as European Environment Agency (EEA) and many national environmental agencies worldwide. Thus, continued improvements and understanding of emissions, atmospheric processes, exposure and effects are still critical tasks to ensuring continued improvement of the air quality. Reducing emissions of critical pollutants into the atmosphere is technically difficulty and very expensive. Although there are some natural air self-cleaning mechanisms, efficiency of such natural mechanisms is insufficient to meet the regulatory requirements.

Air quality management is definitely one of the most demanding and complex activities that involve a high degree of organization of all parts of human society and require effective implementation of institutional system of air protection and the whole society. The overall air protection strategy is based on the basic principles of the environmental protection, the principles of international politics as well as environmental laws, regulations, decisions and directives with respect to the latest scientific knowledge and the world’s best practices. The most important factors influencing air pollution control system are: policy or political commitment at international, regional, national and local level, legislation, resources (human and financial) and available equipment or technical devices. An effective air quality management system is based on environmental policy that, besides other, includes the continuous improvement of the installation by the efficient management, adoption and implementation of adequate legislation and regulations to limit emissions of air pollutants from all kind of sources and recommended emission limit values, monitoring and measurement of emissions to air, processing the collected data and presentation of obtained results to the wider professional community, development and application of appropriate educational and promotional activities aimed at raising public awareness of environmental protection, application of economic incentives and privileges, checking performance and taking corrective action with respect to the emission levels, product quality standards and in accordance with the conditions and mode of legal entities responsible to perform professional activities in the field of the environmental protection. Regulations are very important, but they are effective only after implementation. Since 1972 many countries published a lot of acts and rules to protect air and environment, but the effectiveness of the implementation of legislations is still questionable. The regional and global environmental problems related to atmospheric pollution cannot be solved only by the local regulations used for some types of air pollutants. In some cases the only solution is worldwide action and application of different approaches. Environmental policy in the European Union (EU) has a long history and in line with other international instruments and conventions. During the 1970s and 1980s, a series of problems and scandals, involving waste treatment, gave the necessary impetus for the creation of the common environmental policy and appropriate strategies. Since then several policy strategies have been adopted, but probably the most famous are *The Lisbon Strategy* (2001) and *The Europe 2020 Strategy* (2010). The Lisbon Strategy established a strategic goal for the EU with aim to transform EU into a competitive knowledge-based economy, with particular emphasis on environmental protection and sustainability. Term *sustainable development* was defined in 1987 in a report of the United Nations as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs". Although according to some opinions, *The Lisbon Strategy* was not entirely successful, one of the most important goals of this strategy was consideration of an economy with low CO_2 emissions. In 2010 the European Commission inaugurated *The Europe 2020 Strategy*. The well-known objectives of this new strategy for viable development, the so-called 20-20-20 include the following: reducing the greenhouse gas emissions by 20 % against the 1990 baseline before the year 2020, raising the share of renewable energy sources to 20 % measured in terms of actual final consumption and increasing energy efficiency by 20 %. This strategy is based on the new technologies with low carbon emissions. Although scientists and politicians do not always agree on the best course of action and cooperation at global, European, national and local levels, most of them agree that some changes need to be made to slow global climate changes associated with air pollution. The current European policy includes implementation of the legal limits for ambient concentrations of air pollutants and the emission mitigation controls to national and specific sources or sectors. Over the last three decades these policies have resulted in significantly decreased emissions of some air pollutants (such as SO_2, CO, NO_x, lead and some particulates) and noticeable improvements in air quality, but there is still huge room for improvement of existing technical processes, particularly those for reducing greenhouse gas emissions and persistent organic compounds.

1.2 Basic definitions and classifications

Air is a mixture of gases forming the Earth's atmosphere, which cannot be seen, but which exists all around us. This layer of gases surrounding our planet is retained the Earth's gravity. The atmosphere is a very complex system in which physical and chemical reactions are constantly taking place, but dynamic of these processes can be disrupt due to the presence of some unwanted and harmful compounds.

The term **air pollution** can be defined in different ways (Figure 1). Generally, air pollution is the release or emission of different chemicals, particulates, biological materials or other harmful materials into the Earth's atmosphere, both from natural and from anthropogenic sources. Generally speaking, an emission refers to the discharge of pollutants into the atmosphere, including not only gaseous, vaporous and solid substances, but also heat, noise and radiation. In the context of air pollution extremely important are all stationary sources, such as smokestacks, vents, surface areas of domestic, commercial or industrial facilities as well as numerous mobile sources. Generally, the air pollution refers to any kind of the air contamination, regardless of the atmosphere, which can be indoors or outdoors atmosphere. Thus, general classification of air pollution involves both *indoor and outdoor air pollution*.

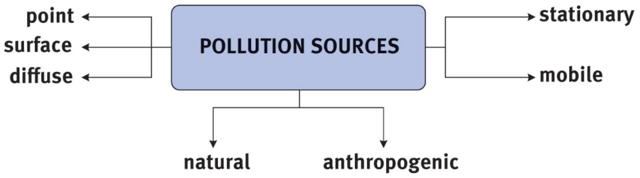

Figure 1: Classification of air pollution sources.

When a building is not properly ventilated, pollutants can accumulate and reach concentrations greater than those typically found outside. This problem has received media attention as the so-called *Sick Building Syndrome* (SBS). Tobacco smoke is one of the main contributors to indoor pollution as well as carbon monoxide, nitrogen monoxide and sulfur dioxide, which can be emitted from furnaces and stoves. Cleaning or remodeling a house contributes to elevated concentrations of harmful chemicals such as volatile organic compounds (VOCs) emitted from household cleaners, paint and varnishes. On the other hand, when bacteria die, they release endotoxins into the air, which can cause adverse health effects, too. More information on indoor air pollution can be found in the literature [7]. Indoor air pollution and urban air quality are often considered as two of the world's worst environmental pollution problems. According to data of the World Health Organization (WHO) due to air pollution each year die more than 3 million people, which represent about 3 % of deaths annually [8]. Surprisingly, the higher mortality rate refers to the indoor air pollution. Indoor air pollution is a very dangerous problem, because indoor air is far more concentrated with pollutants than outdoor one. According to some estimation, the level of pollutants indoors can reach values that are 2–5 times, sometimes even up to 100 times larger in comparison to those outside the buildings [5]. In addition to the different industrial emission sources and other sources connected with various human activities, mostly related to the heat and electricity production, the air pollution from mobile sources and transportation is becoming increasingly dominant in recent years, due to the high level of motorization in economically developing countries. According to some estimates, the air pollution from the mobile sources is growing faster than from industrial sources. Copper and Alley [5] have pointed out that motor vehicles account for 10–60 % of total air pollution emissions.

Air pollution sources can be classified as *natural (biogenic)* and *man-made (anthropogenic)* as a function of the origin of emissions or precursors. There are many *natural sources of air pollutant emissions* such as: volcanic activities (which produce sulfur, chlorine, ash, particulates), anaerobic microbial degradation in soil (which produce oxides of nitrogen), atmospheric electrical discharges (source of ozone), methane emitted by the digestion of food by animals, forest fires (which produce smoke and carbon monoxide), evaporation of droplets of sea water resulting in sea salt crystals being suspended in the air, some VOCs emitted from vegetation, natural radioactivity (which increases with altitudes and also depends on type of soil, e. g. marl soil and often is connected with intensive use of fertilizers), new buildings connected with the presence of radioactive elements (such as radon in concrete and building materials). Some air pollutant such as CO_2, CH_4 and N_2O can occur in significant amounts from the natural sources, but there are also some natural mechanisms of their removal from the atmosphere (or sinks).

Most air pollutants originate from *human-made sources or anthropogenic activities*, including: (a) *stationary sources* (all activities connected with the combustion of fossil fuels in the production of heat, electricity or other forms of energy, i.e. production processes and power plants, households and waste incinerators, furnaces and other types of fuel-burning heating devices, traditional biomass burning): different industrial plants (the so-called non-energy source like refining and petrochemical processing of oil, ceramic and glass industry, production of cement, fertilizers, steel industries); production and use of organic chemicals and solvents (including paints, adhesives, aerosols, metal cleaning, printing); activities such as mining operations, extraction and distribution of fossil fuels (dust, minerals and some chemicals); agricultural activities and farming (including crop growing, silage manufacture, sludge spreading, fertilizer application); waste treatment and disposal; produced or artificial radioactivity (nuclear reactors and accelerators, nuclear medicine, radiotherapy and (b) *mobile sources and all kind of transport vehicles* (motor vehicles, marine vessels, aircraft).

Another possible way of characterizing air pollutants emission sources according defined locality of emission and type of emission involve: point, line, surface (or area) and volume sources. *Point sources* of emission (like chimneys, stacks, vents and other functional openings) belong to the independent single sources, which typically emitted contaminants on a continuous basis. Because of the small exit area, the emission from such source will always be very large. *Line sources*, like vehicle emission from roadways, surface or area sources (e. g. volatile emissions from lagoons, forest fires) and *volume sources* (e. g. diffuse air pollutant emissions from oil refineries) are considered as *diffuse or fugitive sources*. Contrary to emissions from point sources, fugitive emissions are emissions that cannot reasonably be collected and pass through a stack, vent or similar opening. This difference also determines the technical devices adopted for the abatement of such emissions.

What is an air pollutant? **Air pollutant** is any kind of solid, liquid or gaseous substance present in the air in such concentration that can have adverse effects on human beings or other living organisms, natural biodiversity, construction, building and other types of common materials and the whole ecosystem. The atmosphere contains a number of air pollutants generated or emitted from different either natural or anthropogenic sources. The *common air pollutants*, their sources and some effects on human heath are summarized in Table 1.

Table 1: Common air pollutants, sources and theirs effects on human health.

Common air pollutants	Source of emission	Effects
Carbon monoxide (CO)	Fuel combustion from vehicles and engines (transportation, residential heating, industrial processes).	Reduces the amount of oxygen reaching the body's organs and tissues; aggravates heart disease, resulting in chest pain and other symptoms.
Volatile organic compounds (VOCs): non-methane hydrocarbons (NMHC) and oxygenated NMHC (e. g., alcohols, aldehydes, organic acids)	Photosynthesis, vegetation and oceans, biomass burning, agriculture; the use of paints, coatings, printing; surface cleaning; fuel production, distribution and combustion.	The outdoor air pollutant that contribute to the emergence of the Sick Building Syndrome (SBS); the aromatic NMVOCs (e. g. benzene, toluene and xylene) are suspected carcinogens and may lead to leukemia with prolonged exposure.
Nitrogen oxides (NO_x, x = 1,2)	Any kind of fuel combustion in air including mobile sources and stationary combustion sources (vehicles, electric utilities, big industrial boilers, wood burning, etc.).	Impacts on respiratory conditions causing inflammation of the airways at high levels; long term exposure can decrease lung function, increase the risk of respiratory conditions and increases the response to allergens.

Sulfur dioxide (SO_2)	Fossil fuel combustion for electric power generation, industrial processes (petroleum refining, nonferrous metal smelting, etc.).	Irritates the skin and mucous membranes of the eyes, nose, throat and lungs; inflammation and irritation of the respiratory system; people with asthma or chronic lung or heart disease are the most sensitive to SO_2.
Ground-level ozone (O_3)	Secondary pollutant formed by chemical reaction of VOCs and NO_x in the presence of sunlight.	Decreases lung function and causes respiratory symptoms (coughing and shortness of breath); makes asthma and other lung diseases get worse.
Lead (Pb) and other heavy metals such as arsenic (As), cadmium (Cd), chromium (Cr), nickel (Ni), mercury (Hg)	Mining and smelting operation, industrial production and use, combustion, metal corrosion and leaching of heavy metals, waste incinerators, agriculture	Pb attacks the brain and central nervous system to cause coma, convulsions and even death. Arsenic exposure affects virtually all organ systems (including the cardiovascular, dermatologic, nervous, hepatobilliary, renal, gastro-intestinal and respiratory systems). A short-term exposure to a high level of Ni showed damage to the lungs and kidneys, gastrointestinal distress, neurological effects. Cd, Pb and Hg are recognized as being toxic to biota.
Particulate matter (PM) or particulates	Materials handling processes (crushing or grinding ores, loading dry materials in bulk), combustion processes, industrial processes, farming (ploughing, field burning), unpaved roads and road constructions, etc.	Increased levels of fine particles in the air are linked to health hazards, such as heart disease, respiratory problems and lung cancer.

According to the last report of the EEA from 2016 [9] emissions of many air pollutants have decreased substantially over the past decades, resulting in improved air quality across the European region. However, a large proportion of European populations and ecosystems are still exposed to air pollution in exceedance of European standards and WHO Air Quality Guidelines (AQGs). Europe's most problematic pollutants in terms of harm to human health are PM, ground-level O_3 and NO_2. In addition, benzo(a)pyrene (BaP), an carcinogenic pollutant and indicator for polycyclic aromatic hydrocarbons (PAHs), is still of increasing concern, particularly in Central and Eastern Europe.

There are several classifications of air pollutants. The United States Environmental Protection Agency (US EPA) and most countries in the world recognized the *criteria air pollutants* including: ozone (O_3), atmospheric particulate matter (PM_{10}, $PM_{2.5}$), lead (Pb), carbon monoxide (CO), sulfur oxide (SO_2) and nitrogen oxides (NO_x). *Heavy metals* adhered on atmospheric particles are very dangerous for human health and impose a long-term burden on environmental quality. Among all the heavy metals, lead (Pb), arsenic (As), mercury (Hg), cadmium (Cd) and chromium (Cr) are of the greatest concern for public health because of their high toxicity. Heavy metals in atmospheric particles originate from some natural sources (volcanic eruptions, forest fire, etc.), but most environmental pollution and human exposures are caused by anthropogenic activities such as mining, smelting, industrial production and use, traffic, fossil fuel combustion, domestic and agricultural use of metals and metal-containing compounds. Other important groups of air pollutants are: greenhouse gases, minor air pollutants, persistent organic pollutants (POPs) and radioactive pollutants.

Among all air pollutants that are commonly associated with global environmental problems the most important are GHGs, most frequently CO_2, CH_4 and N_2O. These gases contribute directly to the climate change owing to their positive radiative forcing effect. Many countries that have signed and ratified the Kyoto Protocol are obligatory to reduce their GHGs by an agreed amount. The GHG inventory covers the seven direct greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3). Compounds such as HFCs, PFCs, SF_6 and NF_3 are known as the synthetic gases. In addition, NO_x, CO, NMVOC and SO_2 are also sometimes considered as the indirect greenhouse gases.

Minor air pollutants include hazardous air pollutants (HAPS) and POPs. HAPS, also known as toxic air pollutants or air toxics, are pollutants that are known or suspected to cause cancer or other serious health problems (such as reproductive effects or birth defects and other adverse environmental effects). Almost 200 pollutants are recognized as toxic air pollutants and most representative examples include: benzene, perchloroethylene, methylene chloride, dioxin, asbestos, toluene as well as some metals (e. g. cadmium, mercury, chromium and lead). The US EPA is required to control 188 HAPS. POPs are halogenated organic compounds that are resistant to chemical, biological and photolytic degradation processes and also exhibit high lipid solubility. Thus, they bioaccumulate in fatty tissues and have negative impacts on human health as well as on the environment. Those compounds are also classified as PBTs compounds (**p**ersistent, **b**ioaccumulative and **t**oxic). Many POPs are currently used or were used in the past as pesticides, solvents, pharmaceutical and industrial chemicals. Some POPs arise naturally (volcanoes, various biosynthetic pathways, etc.), but mostly they are man-made. At the beginning, the so-called *Stockholm Convention list* (2001) recognized only 12 POPs, such as: aldrin, chlordane, dieldrin, endrin, heptachlor, hexachlorobenzene (HCB), mirex, toxaphene, polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloro ethane (DDT), dioxins and polychlorinated dibenzofurans). Recently, new compounds such as PAHs, brominated flame retardants and others are added on this list. PAHs are composed of two or more condensed aromatic rings and contain only carbon or hydrogen (naphthalene, anthracene, pyrene, BaP). Heteroatoms such as nitrogen, oxygen and sulfur can be also substituted into PAHs (carbazole, dibenzofuran, dibenzo-*p*-dioxin, etc.).

Radioactive pollutants in the air are generated from geogenic and anthropogenic sources. Geogenic radioactivity results from the presence of radionuclides, which originate either from radioactive minerals in the Earth's crust or from the interaction of cosmic radiation with atmospheric gases. Anthropogenic radioactive emissions originate from nuclear reactors, the atomic energy industry (mining and processing of reactor fuel), nuclear weapon explosions and plants that reprocess spent reactor fuel. Since coal contains small quantities of uranium and thorium, these radioactive elements can be emitted into the atmosphere from the coal-fired power plants and other sources.

Waste heat and light pollution also belong to specific forms of atmospheric pollution, but they are not considered in details in this chapter. Briefly, *waste heat* contained in the flue gases or vapor streams is usually generated in process of the fuel combustion or by chemical reaction. A part of the waste heat can recovered and losses of the heat/energy minimized using the waste heat recovery devices, such as recuperators, regenerators, heat wheels, heat pipe exchanger, heat pumps and similar technical devices [10]. The strategy of the waste heat recovery mostly depends on temperature of waste heat gases and economics involved. *Light pollution (or photo pollution)* is a side effect of industrial civilization. This term refers to multiple problems, all of which are caused by inefficient or unnecessary using of the artificial light. Some categories of light pollution include over-illumination, glare and light clutter. Medical research shows that various harmful health effects, such as headache, worker fatigue, medically defined stress and increase in anxiety, may be caused by light pollution or excessive light exposure.

According to the aggregate state the air pollutants are classified into two phases:

- *gaseous air contaminants and vapors of volatile liquid substances (including odors)* and
- *PM or particulates (aerosols)* (Table 2).

Table 2: Anthropogenic pollution sources and their harmful influence [11].

Pollutant and the source	**Influence***			
	A	**B**	**C**	**D**
Organic gases and vapors (hydrocarbons, HC)				
Paraffins: processing and transport of oil products; solvents usage; motor vehicles, etc.		+	+	
Olefins: processing and transport of gasoline; motor vehicles etc.	+	+	+	
Aromatics: processing and transport of oil products; solvents usage; motor vehicles etc.	+	+	+	Odor
Other:				
oxidized HC (e. g. aldehydes, ketones, alcohols)		+	+	Odor
halogenated HC (e. g. CCl_4)		+	+	Odor
Inorganic gasses				
Nitrogen oxides: fuel combustion; motor vehicles; electrical discharges, etc.	+	+	+	+
Sulfur oxides: fuel combustion; chemical industry, etc.	+	+	+	+
Carbon monoxide: motor vehicles; petroleum and metal industry, etc.				+
Particles and aerosols				
Solid particles (carbon, ash or soot); fuel combustion; motor vehicles, etc.			+	+
Metal oxides and salts: catalyst particles; fuel combustion; motor vehicles, etc.			+	
Silicates, minerals, metal foams and other: metal industry, etc.			+	

*Influence: A-plant detriment, B-eye irritation, C-reduced visibility, D-other.

The odors are sometimes distinguished as a separate category of air pollutants, although basically they belong to a group of easily VOCs [10].

Organic and inorganic gaseous and vaporous air pollutants include compounds such as SO_2, CO, NO_x, NH_3, different hydrocarbons, VOCs, PAHs, halogen derivatives and odorous substances. In order to understand the basic principles of air pollution control it is important to distinguish the terms gas and vapor. Sometimes confusion arises from the fact that under various conditions of temperature and pressure the differences between gas and vapor are very small. A gas is a single well-defined thermodynamic phase and one of the four fundamental states of matter (along with solid, liquid and plasma). Generally, a substance in the *gaseous state* is considered as a gas if the temperature of this substance is above its critical points (the highest temperature at which this substance can be condensed), while *vapor* refers to a gas phase at a temperature where the same substance can exist in the liquid or solid state, which is below the critical temperature of the substance. For example, water vapor can coexists with liquid water and with ice.

Gases can be organic or inorganic and typical examples of gases are: O_2, CO_2, SO_2, O_3, NO_x, CH_4 and similar gases. Vapor can be also organic and inorganic according to their chemical composition and typical examples include H_2O, Hg, but mostly different VOCs compounds. There are several definitions of VOCs. The European Union defines a VOC as any organic compound having an initial boiling point less than or equal to 250 °C measured at a standard atmospheric pressure of 101.3 kPa. This includes most of the organic compound with less than 12 carbon atoms and compounds which contain organic carbon, i.e. carbon bonded to the carbon, hydrogen, nitrogen or sulfur (excluded are CO, CO_2, hydrocarbon acid, metallic carbides or carbonates and ammonium carbonate). VOCs are numerous and include both human-made and naturally occurring chemical compounds (e. g. isoprene, terpenes, green leaf volatiles, molds). Most *odors* are also VOCs. The VOC Solvents Emissions Directive is the main policy instrument for the reduction of industrial emissions of VOCs in the European Union. It covers a wide range of solvent using activities (e. g. printing, surface cleaning, vehicle coating, dry cleaning and manufacture of footwear and pharmaceutical products) [12].

The terms *particulates* (or particles) and *aerosols* can be regarded as synonyms, i.e. they include heterogeneous mixture or suspension of solid particles or liquid droplets in the air, with particle sizes ranging from 0.001 to over 100 µm (including dust, fumes, smoke, soot, spray and mists). According to chemical composition particles can be classified as: organic carbon compounds (carbon soot, condensable organic compounds, PAHs, etc.), inorganic compounds (metal oxides, salts in the form of nitrates, sulfates, carbonates, chlorides, etc.) and others (silicates, minerals, etc.). Emission of particulates can be generated from different sources including: mechanical (powdering, crushing, traffic), chemical or thermal (particles formed by the chemical reactions or high-temperature evaporation followed by condensation) and biological sources (pollen, fungi, bacteria). Some particles are large and can be seen as soot or smoke and some are very small. Solid particles are at least of the order of about 0.002 µm (i.e. 2 nm). For the comparison a typical gas molecules dimensions are from 0.0001 to 0.001 µm, a typical strand of human hair is 70 µm in diameter and a grain of salt is about 100 µm. Solid particles with typical dimensions between 1 and 100 µm in diameter are called dust particles, while solid particles less than 1 µm in diameter are called fumes or smoke.

Dusts are solid airborne particles, often formed by operations such as grinding, crushing, milling and sanding. The size of the dust particles is important as there is a difference between inhalable and respirable dusts and the nature of the hazards they present. The EPA defines *inhalable dust* as a fraction of airborne dust entering the body, but lags behind in the nose, throat and upper respiratory tracts (size about 10 µm). *Respirable dust* containing dust particles small enough (all below 10 µm in size and 50 % below 3.5 µm) to penetrate deep into the lungs through the nose and upper respiratory system and as a rule, they can not “be cleaned” by natural mechanisms of mucous membrane cleaning and will be kept in the respiratory system. *Fumes* are solid particles formed by condensation from the gaseous state (e. g. lead fume). *Smoke* is a substance made up of small particles of carbonaceous matter in the air, resulting mainly from the burning of organic material, such as wood or coal. The largest suspended particles are of the order of about 100 µm (i.e. 0.1 mm). Individual suspended particles can be classified according their size on:

- *coarse particles* (2.5–10 µm),
- *fine particles* (<2.5 µm) and
- *ultrafine particles* (<0.1 µm)

and commonly are referred to as PM_{10}, $PM_{2.5}$ and $PM_{0.1}$, respectively. For regulatory purposes PM_{10} fraction is usually collected. PM_{10} fraction includes all particles smaller than 10 µm, including $PM_{2.5}$ fraction. The EPA currently has standard that measure $PM_{2.5}$ and PM_{10}. The WHO air quality standards for PM_{10} is 50 $\mu g/m^3$ (24 h average) and 20 $\mu g/m^3$ (annual average) and for $PM_{2.5}$ 25 $\mu g/m^3$ (24 h average) and 10 $\mu g/m^3$ (annual average).

2 Transport and transformation of air pollutants in the atmosphere

Possibly one of the most important properties of air pollutants is their transboundary nature, because they can easily travel and affect the areas far away from the point of theirs origins. During movement or transport in the atmosphere air pollutants pass through various changes in location and chemical forms, due to chemical, biochemical and photochemical processes. The physico-chemical properties determine how a specific compound will interact in the environment. These properties also affect how those compounds move in the environment and how efficiently they can be removed from the environment.

Air pollutants released into atmosphere are transported by the wind and dispersed as a function of many variables, including (**Figure 2**):

- properties of pollutant source (type of source, the concentration or quantity of pollutants, source location and intensity),
- climatology and meteorological parameters (e. g. wind speed and direction, atmospheric turbulence, ambient air temperature, relative humidity, solar radiation, atmospheric stability), local and regional geographic features (topography) and
- the receptor type and location [13].

Air quality is often modeled by air dispersion or diffusion models (e. g. the Gaussian plume models, the multiple cell models), represented by a set of mathematical equations describing physical and chemical processes in the air and solved by various numerical methods. They can be also used for air quality forecasting, which is important for emergency planning and operation of accidental chemical releases.

2.1 Primary and secondary air pollutants

Air pollutants may be additionally categorized as either primary or secondary. A **primary pollutant** is one that is emitted into the atmosphere directly from the source of the pollutant and retains the same chemical form, i.e. CO_2 or the ash produced by the burning of solid waste. The effect of primary pollutants is most pronounced in the immediate vicinity of their source. A **secondary pollutant** is formed by atmospheric reactions of precursor or primary emissions. Examples of the secondary air pollutants are ozone (O_3), secondary nitrogen dioxide (NO_2), peroxyacetyl nitrates (PANs), secondary PM

2.1.1 Formation of secondary air pollutants in the atmosphere

The emission of pollutants into the air as a result of various human activities may change the natural dynamics of processes in the atmosphere. On the dry volume base air consists almost entirely of the four gases: molecular nitrogen (N_2, 78 %), oxygen (O_2, 20.94 %), argon (Ar, 0.93 %) and carbon dioxide (CO_2, 0.04 %), while other gases like neon (Ne), helium (He), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), hydroxyl radicals and some other constituents come in traces. Even though some gases such as O_3, N_2O, CH_4 are at trace concentration, they exert profound effects on the environment. Air also contains a variable amount of water vapor (H_2O), with value that varies from 0–4 %, depending on the geographic position, part of the day, weather conditions and other parameters. The Earth's atmosphere extends to a height of several thousand kilometers and can be divided into several layers: troposphere (0–12 km), stratosphere (12–50 km), mesosphere (50–85 km), thermosphere (85–500 km) and exosphere (>500 km). The most important parts of the atmosphere with respect to air pollution are **troposphere** and **stratosphere** (Figure 3).

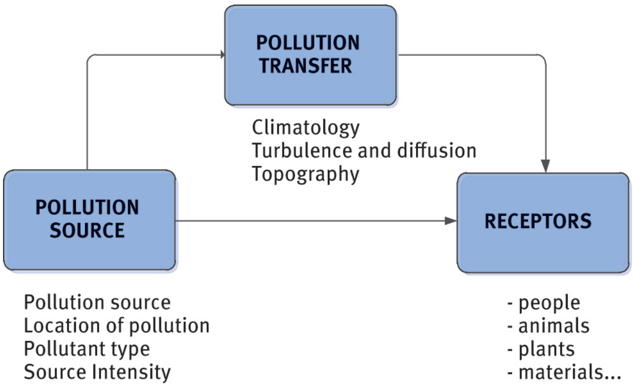

Figure 2: Air pollution transport and dispersion [13].

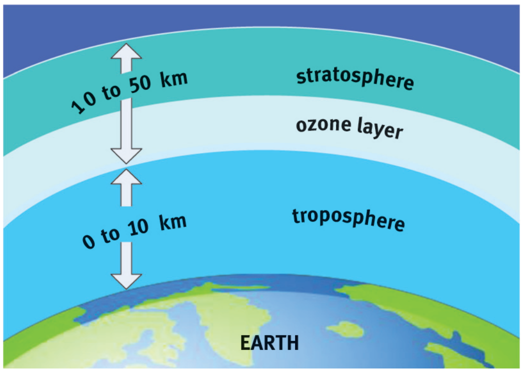

Figure 3: The most important layers of the atmosphere for the human life [14].

2.1.2 Tropospheric vs stratospheric ozone

Emissions of air pollutants contribute to local, regional (or transboundary) and global air pollution (see Figure 4.).

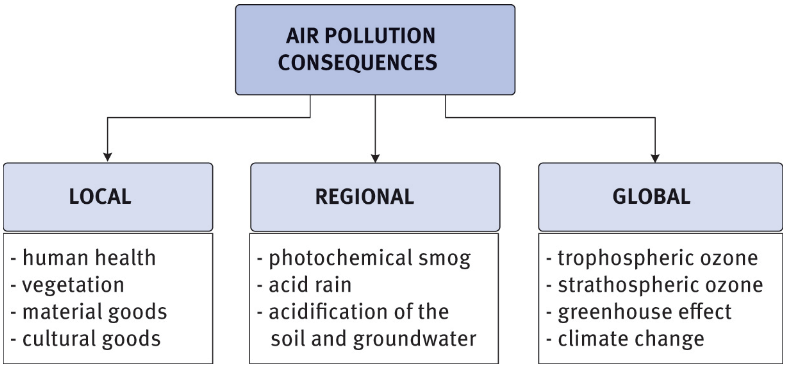

Figure 4: Consequences of air pollution – the influence of air pollution on different scales.

When we talk about the local and urban air pollution, the emphasis is mostly on the protection of the human health and preservation of natural biodiversity, protection of the materials and buildings, historical and cultural heritage materials. *Transboundary air pollution* refers to pollution transported in the atmosphere from one country or region to another and often undergoing chemical transformation in the process. Acidification, eutrophication and ground-level ozone are types of transboundary air pollution, arising from the emissions of the air pollutants such as: NO_x, SO_2, NMVOC, NH_3.

Ozone (O_3) is a secondary air pollutant which is found in two different layers of the atmosphere: troposphere and stratosphere. In the troposphere, the ground-level, **tropospheric or "bad" ozone** is a secondary air pollutant that damages human health, vegetation and many common materials. It is also a key ingredient of the urban photochemical smog and the third-most important greenhouse gas, after carbon dioxide and methane. The primary sources of the pollutants responsible for formation of photochemical smog are fossil fuel-burning power plants and all types of the internal combustion engines. Formation of tropospheric ozone by chemical reactions between nitrogen oxides (NO_x), carbon monoxide (CO) and hydrocarbons (HCs) in the presence of sunlight is summarized in eq. (1):

$$NO + HC + O_2 + \text{sunlight} \rightarrow NO_2 + O_3 \tag{1}$$

NO_x and O_3 interact in the atmosphere by the following reactions:

$$NO_2 + h\nu \rightarrow O + NO \quad (\lambda < 420nm) \tag{2}$$

$$O + O_2 + M \rightarrow O_3 + M \tag{3}$$

$$NO + O_3 \rightarrow NO_2 + O_2 \tag{4}$$

where $h\nu$ represents a photon of light of proper wavelength and M denotes any other molecule which must carry away some of the energy released in the reaction (usually N_2 or O_2). Instead of HCs the other terms like non-methane hydrocarbons (NMHC), VOCs and reactive organic gases (ROG) are often used in this context. The major anthropogenic sources of these chemicals are motor vehicle exhaust, industrial emissions and chemical solvents. Nitric oxide (NO) is also an important component of aircraft exhaust, which is formed by oxidation of atmospheric N_2 at the high operating temperatures of the aircraft engine. NO easily react with oxygen in the air to form nitrogen dioxide (NO_2), a foul-smelling brown gas – secondary air pollutant. Some of the NO_x reacts with hydroxyl radicals ($OH^{\cdot}$) and produce HNO_3 which fall to the Earth in wet or dry forms, including acid rain, fog or dust that is acidic. Although O_3 is the main cause of the photochemical smog formation, some aldehydes (RCHO), peroxy and hydroperoxy radicals and peroxyacyl nitrates (PANs or $RC(O)OONO_2$) also contribute to this process through the similar mechanism [15]. PANs are powerful respiratory and eye irritants present in photochemical smog. As secondary air pollutants they are formed from other pollutants by chemical reactions in the atmosphere. For example, formation of the peroxyacetyl nitrate ($CH_3COOONO_2$) can be described by:

$$HC + O_2 + NO_2 + h\nu \rightarrow CH_3COOONO_2 \tag{5}$$

Since PANs dissociate quite slowly in the atmosphere into radicals and NO_2, they are able to transport these unstable compounds far away from the urban and industrial origin.

From a global point of view, the environmental problems which have to be solved or at least minimized involve the **stratospheric ozone depletion** (the so-called ozone holes), the greenhouse effect as well as the global climate changes and similar emerging environmental problems. In the stratosphere, we find **the stratospheric or “good” ozone** that protects life on the Earth from the harmful effects of the Sun’s ultraviolet (UV) radiation. About 90 % of the ozone in the Earth’s atmosphere lies in the stratosphere (between 16 and 48 km above the surface of the Earth), where it is a kind of layer (ozone layer) in the stratosphere. Although O_3 is concentrated in the ozone layer more than anywhere else, its concentrations are extremely small, typically only 1 to 10 parts of ozone per 1 million parts of air, compared with about 210,000 parts of oxygen per 1 million parts of air. The concentration of the stratospheric ozone is result of dynamic equilibrium between the chemical processes of its formation and processes of its destruction [16]. The first photochemical mechanism of the stratospheric ozone formation was proposed in 1930 by the famous British scientist Sydney Chapman, who assumed that ozone formation occurs by continuously cyclical processes that begin by photolysis of oxygen in the upper stratosphere. However, it was soon found out that Chapman mechanism predict much higher ozone concentrations than actually measured and it was assumed that ozone is consumed by additional chemical reactions. A large contribution to the understanding of the stratospheric chemistry was given by Paul Crutzen, who won the Nobel Prize for chemistry (in 1995 with Mario José Molina and Frank Sherwood). Paul Crutzen linked nitrogen oxides with the chemistry of stratospheric ozone depletion. He pointed out that emissions of nitrous oxide (N_2O), a stable, long-lived gas produced by soil bacteria or formed as result of the increasing use of fertilizers, could affect the amount of nitric oxide (NO) in the stratosphere. Mario José Molina and Frank Sherwood Rowland predicted the influence of chlorine released from chlorofluorocarbons degradation to stratospheric ozone depletion. It is worth mentioning that the ozone hole over Antarctica was discovered even in 1985, thanks to a British geophysicist Joe Farman.

According to the Chapman mechanism the ozone is produced by the photolysis of oxygen molecules into oxygen atoms, shown in eq. (6), followed by the reaction of one oxygen atom with an oxygen molecule, eq. (7):

$$O_2 + h\nu \rightarrow O + O (\lambda < 242 nm) \tag{6}$$

$$O + O_2 + M \rightarrow O_3 + M \tag{7}$$

$$2O_2 + h\nu \rightarrow O_3 + O \tag{8}$$

The third molecule, M is needed to remove the excess energy and can be any other molecule in the atmosphere (usually N_2 or O_2). The overall reaction eq. (8) indicates that ozone and oxygen atoms are produced from oxygen molecules and light (hν). Ozone can be also destroyed by photodissociation of ozone in the presence of ultraviolet radiation (UV), eq. (9) or by reaction with an oxygen atom, eq. (10):

$$O_3 + h\nu \rightarrow O_2 + O \ (\lambda < 320 nm) \tag{9}$$

However, reaction given by eq. (9) produces an oxygen atom and oxygen molecule, which can participate in the regeneration of oxygen molecule and the recombination of ozone as in eq. (7). The above reaction is the predominant mechanism by which ozone performs the function of shielding the Earth from harmful UV light. The formation of O_3 is balanced by its dissociation through several reactions and one of them is:

$$O + O_3 \rightarrow 2\,O_2 \tag{10}$$

There are many other ways in which ozone can be destroyed besides by the reaction given by eq. (10). Paul Crutzen assumed in the early 1970s that ozone can be catalytically destroyed in a cycle involving NO_x (x = 1, 2). He proposed the following catalytic cycle:

$$NO + O_3 \rightarrow NO_2 + O_2 \tag{11}$$

$$O + NO_2 \rightarrow NO + O_2 \tag{12}$$

The overall reaction is also given by the eq. (10), indicating that cycle of ozone destruction is only catalyzed by NO_x, because the NO consumed in reaction (11) is regenerated in reaction (12) and the NO_2 produced by reaction (11) is consumed in reaction (12). Obviously, this cycle can be repeat as long as NO_x is available for the reaction. NO_x in the stratosphere originate from natural and anthropogenic sources. A natural source of NO_x is the oxidation of N_2O released by bacteria in soil and oceanic microorganisms. An anthropogenic source of N_2O is fertilization. N_2O reacts with highly energized oxygen atoms which results in formation of NO molecules. Some other molecules can also participate in the chemistry of the stratospheric ozone destruction, such as chlorine or bromine molecule, eqs (13)–(15)

$$CCl_3F + h\nu \rightarrow CCl_2F + Cl \ (\lambda < 230 nm) \tag{13}$$

$$Cl + O_3 \rightarrow ClO + O_2 \tag{14}$$

$$ClO + O \rightarrow Cl + O_2 \tag{15}$$

with the same overall reaction given by eq. (10). According to some estimation one chlorine atom can participate in the degradation of 10^4–10^6 ozone molecules. The main source of chlorine molecules is CFCs, known by the DuPont brand name *freons*. Many CFCs, like CF_2Cl_2 (Freon-12, CFC-12) and $CFCl_3$ (Freon 11, CFC-11), are chemically stable molecules in the troposphere, but they drift into the upper atmosphere where their chlorine components destroy ozone. In the past, CFCs were used as inert, non-toxic and easily liquefied chemicals in refrigeration, air-conditioning, as solvents, as well as aerosol propellants. Because of their recognized contribution to the depletion of stratospheric ozone, after the signing of the Montreal protocol in 1987, they are replaced with other compounds such as HFCs. HFCs are "safer" than CFCs for the ozone layer, because they react in the troposphere. Bromine species are 50–100 times more destructive for ozone than chlorine species [17]. The main source of bromine in the stratosphere is methyl bromide. It is emitted naturally by oceanic biological activity and from anthropogenic activities, such as soil fumigation and biomass burning. The well-known anthropogenic bromine sources are halons used in fire extinguishing systems, agriculture, dry cleaning and other applications. Fortunately, production of halons is currently being regulated for the same reasons like CFCs. Hydroxyl radicals ($OH^{\cdot}$) can also catalyze the dissociation of ozone in the stratosphere; however, this kind of reaction is estimated to account for the degradation of only ca. 15 % of the stratospheric ozone. Many of the molecules released on Earth do not reach the stratosphere because they are soluble in water and return to the surface in precipitation or are broken down by chemical reactions in the troposphere.

2.1.3 Secondary particulate maters

PM can be directly emitted to the atmosphere (primary PMs) and formed in the atmosphere (secondary PMs). Primary PM originates from both natural and anthropogenic sources. Natural sources of PMs include sea salt, naturally suspended dust, pollen, volcanic ash. Anthropogenic sources of PMs, such as dust or soot (black carbon), include fuel combustion in thermal power generation, waste incineration, domestic heating for households and fuel combustion for vehicles, as well as vehicle (tyre and brake), road wear and other types of anthropogenic dust. The main precursor gases for secondary PMs are SO_2, NO_X, NH_3 and VOCs. The largest sources of NH_3 emissions are agricultural activities and NH_3-based fertilizer applications. Other sources of NH_3 emissions include some industrial processes, biomass burning (including forest fires) and to a lesser extent fossil fuel combustion and volatilization from soils and oceans. The result of the atmospheric reactions in which participate NH_3, SO_2 and NO_X is formation of ammonium (NH_4^+), sulfate (SO_4^{-2}) and nitrate (NO_3^-) compounds, which form new particles or condense onto existing ones and form *secondary inorganic aerosols*. Some VOCs also contribute to formation of the *secondary organic aerosols*.

2.2 Acid rain

Acid rain or acid deposition is considered as washout of air pollutants by precipitation. Any precipitation with a pH level less than 5.6 is considered to be acid rainfall. The dominant precursors of acid deposition are sulfur dioxide (SO_2) and nitrogen oxides (NO_x). The acidity of acid precipitation depends on emission level as well as on the chemical mixtures in which SO_2 and NO_x interact in the atmosphere through several chemical reactions (photo oxidation by means of ultraviolet light, reaction with moisture found in the atmosphere, reaction with ozone). A prerequisite for acid deposition is oxidation of the emitted SO_2 and NO_x either in the gas phase, after absorption into water droplets (sulfuric, nitric or nitrous acid) or after dry deposition on the ground (suspended sulfates and nitrates). These materials can be deposited on the ground unchanged (as primary pollutants) or in a transformed state (as secondary pollutants). Transformed pollutants can be deposited in wet form (rain, fog, snow) or in dry form (sulfates, nitrates).

2.3 Greenhouse effect

Many GHGs, such as water vapor, CO_2, CH_4 and N_2O occur naturally in the atmosphere. It is important to distinguish *the natural greenhouse effect* and *the enhanced or anthropogenic greenhouse effect*. The natural greenhouse effect is a phenomenon caused by gases naturally present in the atmosphere that affect the behavior of the heat energy radiated by the sun. Without this natural process the average temperature on Earth would be about −18 °C, instead of the current about 15 °C. On the other hand, the disruption to Earth's climate equilibrium caused by the increased concentrations of greenhouse gases has led to an increase in the global average surface temperatures and this process is called *the enhanced greenhouse effect*. It should be taken in mind that prior to the Industrial Revolution, the components of the greenhouse effect were in balance, but today's increasing amounts of greenhouse gas emissions are created mostly by the human activities, such as the burning of fossil fuels, new industrial processes, deforestation and extensive agriculture.

Concentrations of GHGs in the air vary daily, seasonally and annually. They have specific physical and chemical properties, which make them to interact with solar radiation and infrared light (heat) given off from the Earth. In such a way they affect the energy balance of the globe. As already mentioned, H_2O is also a greenhouse gas, since it traps heat in the atmosphere. However, the most abundant and the most problematic GHGs is CO_2. It is convenient to use carbon dioxide equivalent as a measure to compare the emissions from various greenhouse gases based upon their global warming potential. For example, the global warming potential for methane over 100 years is 21, which means that emissions of one million metric tons of CH_4 is equivalent to emissions of 21 million metric tons of CO_2. CH_4 is even more potent GHG than CO_2, but its atmospheric residence time (9 years) is far less than that of CO_2 (between 5 and 100 years). Since 1970, CO_2 emissions have increased by about 90 %, with emissions from fossil fuel combustion and industrial processes contributing about 78 % of the total greenhouse gas emissions increase from 1970 to 2011 [18]. On the global level, there are some signs of decreased global CO_2 emissions because of structural changes in the global economy, such as improvements in energy efficiency and the energy mix of the key global players (China, United States, India). However, small positive trends in this sense are probably coupled to a recent global economic recession [18].

2.4 Global climate change *vs* global warming

Sometimes is hard to recognize the difference between *global climate change* and *global warming*, because a term climate change is frequently used in reference to greenhouse gas emissions from human activities. The term global warming is used to describe the current increase in the Earth's average temperature. An indicator of global warming is the Earth's average global temperatures (AGT). The AGT for the Earth in the twentieth century was about 15 °C, but it increased significantly during the last three decades [5].

On the other hand, *climate change* refers not only to global changes in temperature but also to changes in wind, rising sea levels, changing precipitation, the expansion of deserts in the subtropics, the length of seasons as well as the strength and frequency of extreme weather events, including heat waves, tornados, droughts, heavy rainfall with floods and heavy snowfall.

3 Air pollution control

3.1 Selection of the air pollution control approach and control technique

From the engineering point of view, the good air quality can be achieved by using different approaches. Some of the possible approaches to the air pollution control include:

- *the primary or preventative approach* – all control measures applied to prevent pollutants formation directly on the potential source of emission,
- *the secondary approach* – technical devices applied to remove pollutants from the gas stream before releasing to the environment *and*
- *the integral approach (or process-integrated techniques)* – combination of different engineering approaches and methods of control, identification and application of specific measures for simultaneous removal of different air pollutants across various process plants in order to achieve the environmental targets at least costs.

Depending on simplicity or complexity of air pollution problem, the single or complex technical devices and even combination of different process equipment can be used for the purpose of reducing/eliminating emission of pollutants into the atmosphere. The economy (i.e. investment, operating and maintenance costs), regulation, space constraints and availability of control equipment in the market are some of the possible limitations which define choice and installation of the appropriate technical equipment (BREF). In the framework of the implementation of the *Industrial Emissions Directive* (2010/75/EU) [19] and as the result of the exchange of information between EU Member States, the European Commission's Joint Research Centre prepared *The best available techniques (BAT) reference document (BREF) for Common Waste Water and Waste Gas Treatment/Management Systems in the Chemical Sector (BREF)* [10]. This document provides general information on waste water and waste gases and describes techniques to prevent or to reduce their environmental impact. An overview of the available control techniques for common waste gas treatment in chemical sector is given in Figure 5.

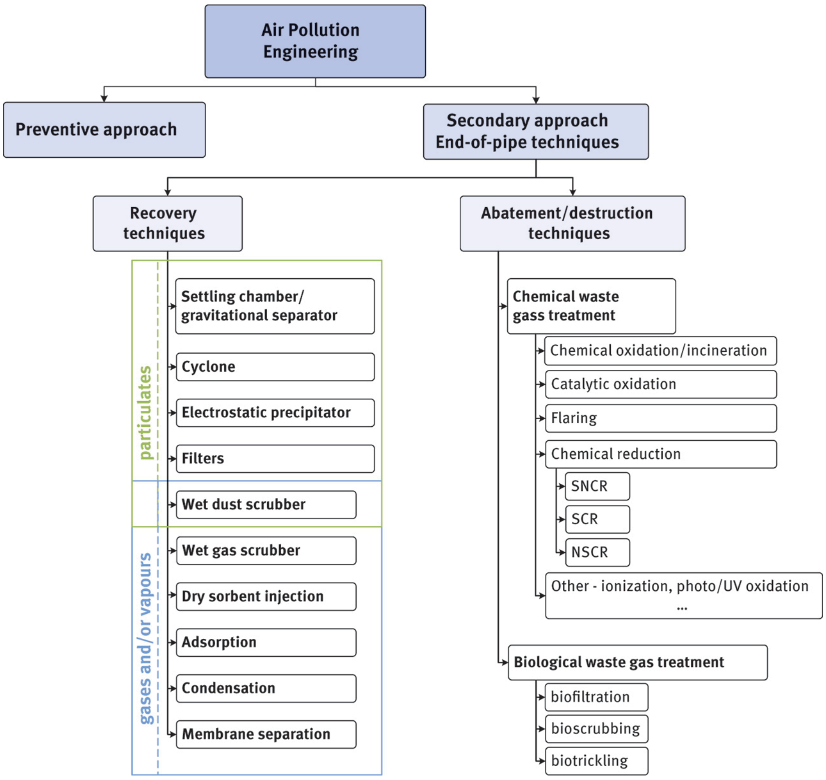

Figure 5: Air pollution control techniques for removing harmful gases, vapors and particulates from industrial process emissions (inspired by [10]).
*SNCR, selective non-catalytic reduction of NO_x; SCR, selective catalytic reduction of NO_x; NSCR, non-selective catalytic reduction of NO_x.

3.1.1 The primary or preventative approach to the air pollution control

An efficient air pollution control requires a complete knowledge of the air contaminants and the source of their emission. It is desirable to prevent the formation of pollutants whenever is possible. Changing or elimination of process steps that are basic sources of pollution is often one of the possible primary or preventative methods available for control of emissions of air pollutants discharged by the industries. Examples of such control measures to meet the emission standards are based on consideration of the source reduction opportunities, careful planning and process optimization to minimalize pollutants and carrier fluid generation at the source and include: operational changes, minimizing the volumetric flow rate of the stream to be treated, substitution of raw materials or fuels, use of efficient engines and more efficient burners design, delocalization of the plant, process equipment modification or replacement of old process equipment and other types of the process-oriented specific measures and control strategies. A modern nuclear power plants appears to be relatively pollution free solutions, compared to the more familiar fossil fuel-fired plants, which emit a lot of pollutants (carbon oxides, nitrogen oxides, sulfur dioxide, hydrocarbons and fly ash). However, waste and spent-fuel disposal problems may limit the apparent advantages[20, 21]. The biggest improvement in the air quality in most cities of the United States and European Union was achieved by replacement of coal with natural gas, by switching vehicles from gasoline to unleaded gasoline, compressed natural gas and other more environmentally friendly fuels, by addition of oxygenated compounds to motor fuels, by using of low-sulfur fuels, etc. [15]. There are also additional preventative ways to reduce air pollution including proper planning and location of the industrial areas, development of new technologies and legal regulations as well as using of administrative controls. The government plays a very important role in prevention of all kind of environmental pollution through government regulations that forced industries to reduce pollutant discharge and to promote new developments in technology.

3.1.2 The secondary approach to the air pollution control

The secondary air pollution control approach is relied on recovery or abatement of contaminants from the waste gas streams and application of the end-of-pipe treatment devices. This implies installation of control device (or equipment) between the source of pollutant generation and its release to the atmosphere. In that case control may consist of either removal/degradation of the pollutant or conversion to a less polluting form or recovery of economically valuable waste products. These solutions are focused on the specific air quality objectives or emission limits and primarily directed on the well-defined (or controllable) sources of emissions. *The end-of-pipe treatment devices* can be applied only for ducted emissions, which means that collection hoods and a ventilation system are required upstream of the end-of-pipe abatement system. *Abatement* is the term used for all technical and mechanical engineering devices, methods and technologies which may help in reducing quantity of pollutants emitted into atmosphere. Such devices are divided into two categories: devices (or equipment) for reducing particulates and devices for reducing emissions of gaseous and vaporous pollutants, although some of devices can be also used for simultaneous removal of the both groups of pollutants. In many cases, heating or cooling of the gaseous effluent is required before it enters the appropriate control device.

The environmental engineers must be aware of the gas laws, thermodynamic properties and all reactions ensuring a satisfactory design of the control device. The key design issues for air pollution control equipment are usually based on consideration: the process conditions, the physico-chemical and other important properties of pollutants and the added value of the emitted compound. *The process conditions* include: the total gas flow rate (or velocity) and volume of the waste gas to be treated, temperature limitations, allowable pressure drop, degree of variability depending on the operating and process conditions (i.e. variation in the pollutant concentration, gas flow rate, temperature), power/energy requirements, removal efficiency requirements, etc. Besides nature of the air pollutant and its concentration (including minimum and maximum values) *typical properties of pollutants* usually considered during design of air pollution control system are: solubility, corrosivity, flammability, toxicity or reactivity (if pollutants are gaseous) and size range and distribution, particle shape, agglomeration tendencies, corrosivity, abrasivity, hygroscopic tendencies, stickiness, flammability, toxicity, conductivity, electrical resistivity or reactivity (if pollutants are in the form of particulates). *The added value of emitted product* is also very important and can affect the selection of adequate air pollution control equipment or the chose between: *the recovery techniques* (e. g. fabric filter, cyclone, adsorption, condensation) and *the abatement or destruction techniques* (e. g. thermal or catalytic oxidation, chemical reduction, biofiltration). Typical air pollutants for which recovery technique is economically feasible are those which concentrations in the waste stream are high enough, e. g. VOCs from solvent vapors and vapors of low-boiling compounds, NH_3 (to recycle in the production process), SO_2 (converted into H_2SO_4, sulfur or gypsum), dust which contains higher amounts of solid raw products or end products [10]. Some of the mentioned recovery techniques can be used to minimize emissions of odors which also belong to the highly volatile compounds.

3.1.3 The integral approach (or process-integrated techniques)

In order to achieve all the stringent criteria of the air protection it is often necessary to combine different engineering approaches and methods of control, i.e. an integrated approach and comprehensive solution of the environmental pollution related to certain human activity. Some waste gas techniques (like scrubbing, adsorption, electrostatic precipitation) require further downstream treatment of the waste water or solid waste generated during the process of air purification. Unfortunately, the cost of the waste disposal can be a significant part of the total cost of the air pollution control.

Engineers working in air pollution control have many responsibilities and one of them is the design of air pollution equipment in order to achieve emission standards and the requirements of legal regulations. The key challenges in using appropriate equipment for air pollution control are [10]:

- quantity and concentrations of pollutants in air streams (including physical and chemical properties of the effluent from the emission source),
- available space and equipment location,
- contribution of air pollution control system to wastewater and land pollution as well as disposal of waste recovered,
- economy (costs of investment and installation of the process equipment, costs of maintenance) and
- safety.

3.2 Appropriate use of units and some basics of air pollution control

To understand air pollution control, one first must understand some fundamental concepts and properties of the common air pollutants. Typical mass concentration units for ambient measurements of air pollutants are mass (µg) per unit volume (m^3). Concentration of air pollutant can be also expressed in parts per million (ppm), which is almost always ppm *by volume or by mole* if it is concentration in a gas and ppm *by mass or weight* when applied to liquids or solids. For example, concentration of 1 ppm can be visualized as 1 cubic centimeter (cm^3) of gas per cubic meter of air (or 1 molecule of the gas in question per 1,000,000 molecules of all gases present). For gaseous pollutants these concentration units are related to each other through the ideal gas law, taking into account that a gas may occupy different volumes depending on operating temperature and pressure. The ideal gas law is commonly written as

$$pV = nRT \tag{16}$$

where p is the gas pressure (Pa), V is gas volume (m^3), n is number of moles (mol), R is universal gas law constant (8314 $J\,mol^{-1}\,K^{-1}$) and T is absolute temperature of the gas (K).

Particulates come in a variety of shapes and sizes and can be in the form of liquid droplets or dry dusts. Particles of concern to air pollution are typically measured in microns or micrometers (µm) or 1×10^{-6} m. Particles are frequently described by their diameter and size distributions. Many technical devices used for separation of particulates from the dirty gas streams exploit the difference in the physical size and/or mass (expressed by diameter and particles density) of particles and gas molecules. There are several diameters that are commonly used to define particle size, such as physical diameter, aerodynamic diameter, equivalent diameter, cut diameter and others. *The physical diameter* is the real diameter of a spherical or nearly spherical particle. To express the size of a non-spherical (irregular) particle as a diameter, several relationships are used, but most frequently aerodynamic and equivalent diameter. *The aerodynamic diameter,* d_a is the diameter of a spherical particle with the density of one gram per cubic centimeter that behaves aerodynamically in the same manner as the particle or aerosol of interest. That means that the actual particle and the spherical particle with density of 1 $g\,cm^{-3}$ will have the same momentum and drag characteristics as well as the same terminal settling velocity, which is also an aerodynamic property. As known, the terminal settling velocity is result of the simple force balance between the force of gravity and resisting drag force. *The equivalent diameter,* d_e is the diameter of a sphere that has the same value of a physical property as that of the non-spherical particle and is given by

$$d_e = \left(\frac{6V}{\pi}\right)^{1/3} \tag{17}$$

where V is volume of the particle. Sometimes is also used term *cut diameter,* d_c, which represents the diameter of particles collected with 50 % efficiency. The non-spherical shape of a particle can be quantified by a single quantity such as the sphericity, ψ, using a perfect sphere as a reference.

Particle size distribution can greatly affect the efficiency of any collection device. The separation or collection efficiency of the control equipment is normally specified before the equipment is purchased depending on emission standards and regulations. *The overall separation or collection efficiency,* η for the control device depends on the operating conditions as well as on the particle-size distribution. It may be calculated as

$$\eta\,(\%) = \frac{amount\ collected}{amount\ input} = \frac{input - output}{input} \tag{18}$$

In the case of particulates removal it is important to distinguish fractional separation efficiency, η_j from the overall separation efficiency, due to different size fractions of particulates in the waste gases. Information on particle size distribution can be obtained based on total number of collected particles or, more often, based on total mass of collected pollutant or a volume-based distribution which is closely related to a mass distribution. Alternatively, a surface-based distribution can be also used, depending on the measurement technique that is applied. It is common practice to represent particle size distribution in the form of either a frequency distribution curve or a cumulative distribution curve. Generally, particle size distribution is represented by a list of values or a mathematical function that defines the relative amount, typically by mass, of particles present according to their size. If the particulate size distribution is known it is possible to calculate the overall separation efficiency based on *the fractional separation efficiency,* η_j as follows:

$$\eta = \sum \eta_j m_j \tag{19}$$

where η_j is fractional separation efficiency (e. g. separation efficiency for the j-th size range of particles) and m_j is mass fraction of particles in the j-th size range.

The control of PM is an important aspect of industrial air pollution engineering. In all air pollution control devices, particles are separated from the surrounding fluid by the application of one or more external forces. These external forces acting on a particle include gravitational, centrifugal, electrostatic and other forces (e. g. drag force, buoyant force, magnetic force) and separation mechanisms (e. g. inertial impaction, direct interception, diffusion). The consequence of acting forces on a particle is *the settling (or terminal) velocity*. The settling velocity is a constant value of velocity reached when all forces (gravity, drag, buoyancy, etc.) acting on a particle are balanced. In order to determine an unknown particle settling velocity in the appropriate control device, it is important to understand the movement of a particle in the fluid (gas) stream and to know the flow regime. The flow regime is characterized by the Reynolds number. The Reynolds number (Re) for a particle is defined by the following equation:

$$\mathrm{Re} = \frac{d_p v_r \rho_f}{\mu} \tag{20}$$

where d_p is particle diameter (m), v_r is the relative velocity of the particle (m s^{-1}), ρ_f is density of fluid (kg m^{-3}) and μ is fluid viscosity (kg m^{-1} s^{-1}).

Depending on the values of Reynolds number, it is possible to distinguish three flow regimes with corresponding equations to calculate the settling velocity [22]:

- laminar regime or Stokes' low range (Re<1):

$$v_t = \frac{g\,{d_p}^2\,(\rho_p - \rho_f)}{18\mu} \tag{21}$$

- transitional regime or intermediate low range (2 < Re < 500):

$$v_t = 0.153\frac{g^{0.71}\,d_p^{1.14}\,(\rho_p - \rho_f)^{0.71}}{\mu^{0.43}\,{\rho_f}^{0.29}} \tag{22}$$

- turbulent regime or Newton's low regime (500 < Re < 200,000):

$$v_t = 1.74\left(\frac{g d_p(\rho_p - \rho_f)}{\rho_f}\right)^{0.5} \tag{23}$$

In the Stokes range (Re≤1) the particle diameter, d_p must be smaller than

$$d_p \leqslant \frac{0.304}{\sqrt[3]{\rho_p}}\,[mm] \tag{24}$$

which means smaller than 0.03 mm (or 30 μm) in order to remain within Stokes range, which is often the case in technical processes [23]. In the previous equations, e. g. eqs (21)–(24), ρ_p refers to the particle density. However, if the particle diameter is smaller than a lower limit, the particle is able to "slip" between the gas molecules and this slippage can affects the values of the settling velocity predicted by Stokes law. In this case the Cunningham correction factor, C has to be used to correct the settling velocity for this effect [22]:

$$v_t = \frac{g\,{d_p}^2\,(\rho_p - \rho_f)}{18\mu}C \tag{25}$$

The correction factor C can be calculated as [24]:

$$C = 1 + 2.0\frac{\lambda}{d_p}\left[1.257 + 0.40\exp(-0.55 d_p/\lambda)\right] \tag{26}$$

$$\lambda = \frac{\mu}{0.499P\sqrt{8M/\pi RT}} \tag{27}$$

where λ is the mean free path of the gas (m), P is absolute pressure (Pa), R is universal gas constant, M is molecular weight (g mol^{-1}), T is absolute temperature (K) and μ is absolute viscosity (kg m^{-1} s^{-1}).

3.3 Control of particulate air pollution

They are several *preventive measures* which are applicable specifically to PM emissions such as decreasing or elimination of PM production. This can be accomplished in several ways: by change to process that does not require operations such as crushing, grinding, milling, polishing, pulverizing, spraying, by change from solid to liquid or gaseous material, by change from dry to wet solid material, by change particle size of solid material or by change to process that does not require particulate material [10, 21]. *The secondary particulate control devices* may be divided into two large groups: dry dust removal equipment and wet dust removal equipment [23].

Dry dust removal equipment include: gravity settling chamber (or gravity settlers), centrifugal settlers (cyclones), electrostatic precipitators (ESP) and bag houses (fabric filters), while different kind of scrubbers (like packed column scrubber, vortex scrubber, Venturi scrubber) and some configurations of the so-called wet ESPs belong to the *wet dust removal equipment*. Selection of the most suitable device for control of particulate air pollution is always related to a specific particulates removal problem and depends on two groups of criteria: *a gas-stream specific criteria* (particles concentration, particles size distribution, gas temperature, tendency for agglomeration, chemical reactivity, flammability and explosiveness, toxicity, wettability, odors and foaming properties, etc.) and *equipment specific criteria* (fractional collection efficiency, security, availability, adaptability to various operating conditions, pressure drop, maintenance, sensitivity to erosion, corrosion and foam formation, water requirement, power requirement, operational and investment costs) [10].

It is important to emphasize that different separation devices operate in different particle size ranges. According to the additional classification these control devices can be divided in: process when an external force is applied to the particle (mechanical collectors and ESP) and processes where the gas stream is forced to go through a barrier that cannot be passed by the dispersed particles, in the form of holes smaller than the particles or a droplet cloud (different kind of filters and scrubbers). For larger particulates (>10 µm) gravity and centrifugal forces can be very effective means of the particles removal. For the fine particles (<2 µm) it is useful to apply an electrostatic force in combination with particle charging (ESP) or Venturi scrubbers. Venturi scrubbers are very efficient even for the separation of particles with size down to a few micrometers. Filters show very high efficiencies over wide size ranges and in that sense they are very flexible in comparison with other separation techniques, although they also have some disadvantages as will be explained later. Cost and energy requirement are very important in the selection of equipment as well as costs of the produced waste water and waste solid treatment.

3.3.1 Mechanical collectors

In the following text three types of control devices will be considered, including gravity settlers and cyclone separators, which belong to the mechanical collectors and electrostatic precipitators (ESPs). All these devices are function of driving the particles to a solid wall, where they adhere to each other to form agglomerates that can be removed from the collection device and disposed of. Therefore, these devices are sometimes called *the wall collection devices*. Instead of driving the particles to a wall, filters and scrubbers divide the flow into smaller parts in order to collect the particles. For this reason they are called *the dividing collection devices* [15].

3.3.1.1 Gravity settler

An gravity settler is a long chamber through which the polluted gases pass very slowly (less than about $0.5\,\mathrm{ms}^{-1}$ for good results), allowing particles enough time to settle out at the bottom of the chamber (in the hopper or collector) under the action of gravity (Figure 6). The chamber is cleaned manually to dispose the waste. Gravity settlers are more efficient in the laminar flow conditions. Under intense turbulent flow conditions deposition of particles is difficult and therefore the efficiency is lower. The separation effect is more pronounced by reducing the gas stream velocity by means of baffles and similar design elements (e. g. horizontal trays or shelves). Gravity settler is the simplest control device which is efficient only for large particles (>50 µm) and therefore it is useful for processing of very “dirty” gases (from cement industry, metallurgical processes, etc.). Even with horizontal trays the minimum particle size which can be removed is about 10 µm. The pressure drop through the gravity settler is very small and consists mostly of entrance and exit losses. Separated particles might be contaminated with toxic or hazardous contents which need to be considered for further treatment or disposal. Gravity settler is usually used as pre-cleaner, e. g. as preliminary step in various filter systems and scrubbers [10].

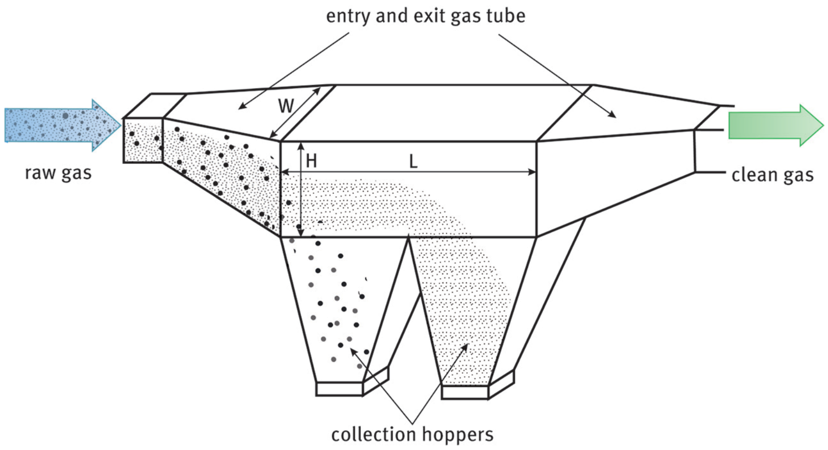

Figure 6: Schematic of gravity settler (inspired by [25]).

The mathematical analysis of the gravity settlers is very easy and with some exceptions it appears in similar form for cyclones and electrostatic precipitators. The separation efficiencies for laminar and turbulent settling chambers are given by the following equations [23]:

$$\eta_{la\min ar} = \frac{v_t L}{uH} = \frac{g{d_p}^2\rho_p}{18\mu}\frac{L}{uH} \tag{28}$$

$$\eta_{turbulent} = 1 - \exp\left(-\eta_{laminar}\right) \tag{29}$$

where v_t is the particle settling velocity (m s^{-1}) (Stokes low), L is chamber length (m), H is chamber height (m) and u is the average horizontal gas velocity in the chamber:

$$u = \frac{Q}{WH} \tag{30}$$

In the eq. (30) Q is the volumetric air flow rate (m^3s^{-1}).

3.3.1.2 Cyclone

Cyclones are the most common centrifugal or inertial separators. Their efficiency is much better compared to gravity settlers and yields about 90–99 % for particles with diameter between 5 and 10 µm [10, 22]. At modest velocities and common diameters the centrifugal forces acting on particles can be two orders of magnitude larger than the gravity forces [15]. The cyclone consists of a vertically placed cylinder which has an inverted cone attached to its base. The gas stream containing particulates enters tangentially at the inlet point to the cylinder. The velocity of this inlet gas stream is then transformed into a confined vortex (called “external vortex”), from which centrifugal forces tend to drive the larger suspended particles to the walls of the cyclone. Due to the reduction of the flow cross section, the increase in pressure and the higher concentration of solid particles in cone part, a part of “external” vortex turn into “inner” directed upward at the bottom of the cone part. The clean gas (also with the smallest particles) is removed from a central cylindrical opening at the top (called “apex”), while the dust particles are collected at the bottom in a storage hopper by gravity. Schematic of a cyclone separator and the flow field inside a cyclone is given in Figure 7.

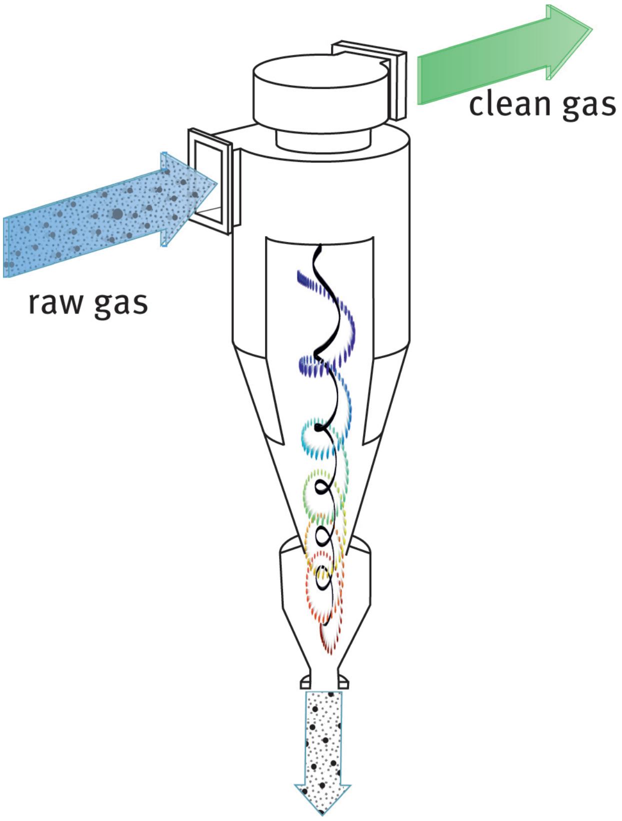

Figure 7: Schematic flow diagram of a standard centrifugal separator – cyclone (inspired by [25]).

Cyclones are sized on the basis of centrifugal force, F_c

$$F_c = \frac{m{v_c}^2}{r} = m\omega_c r \tag{31}$$

where m is mass, v_c is velocity, r is radius and ω_c is angular velocity for rotational motion of particle inside the cyclone. Using a centrifugal equivalent of Stokes' law, i.e. after substitution of the gravitational force by the centrifugal force in eq. (20) it is possible to calculate the settling velocity of particle for the centrifugal settling [15]:

$$v_t = \frac{{v_c}^2}{r}\frac{{d_p}^2\rho_p}{18\mu} \tag{32}$$

The cyclone diameter is important design parameter that has the highest effect on the cyclone separation efficiency. For a given pressure drop, smaller the diameter, greater is the efficiency, because centrifugal action also increases with decreasing radius of rotation. The efficiency of a cyclone can be increased by the use of a large number (up to seven thousand) or a battery of smaller cyclones (with a diameter ranging between 0.005 m and 0.3 m) operating either in parallel or serial. This kind of cyclone arrangements with a common inlet chamber, outlet plenum and collection system is known as multiple cyclones or multi-clones. The separation efficiency will also increase with increasing particle size, particle density, inlet particle loading, cyclone body length and ratio of body diameter to gas outlet tube diameter [10, 15, 26]. However, as efficiency increases the operating costs also increase because of the higher pressure drops. Common problems related to the work of the cyclone are erosion, corrosion and a dust cake builds up on the cyclone walls, especially if the dust is hygroscopic [26]. Cyclones are usually designed by set of procedures. More information on design considerations can be found out in the literature [15, 23, 26].

3.3.2 Electrostatic precipitator

An electrostatic precipitator (ESP) is a separation devices like gravity settler or cyclone, but it use electrostatic force to move particles entrained within a waste gas stream to the walls of the collector plates. It is very useful for the removal of fine dusts (between 1 and 10 µm, but mostly less than 5 µm) from different kind of waste gases with very high efficiency (approaching even 100 %) [10, 26]. The principle behind all electrostatic precipitators is to give electrostatic charge to particles in a given gas stream and then pass the particles through an electrostatic field that drives them to a collecting electrode of opposite charge. The overall process of dust separation in the ESP consists of the following steps: generation of electric field, generation of electric charges, transfer of electric charge to a dust particle, movement of a charged dust particle in an electric field to the collection electrode, adhesion of the charged dust particle to the surface of the collection electrode and mechanical removal of the dust layer from the collection electrode (by rapping, vibration or washing) to a hopper.

The electrostatic precipitators require maintenance of a high potential difference (20–100 kV, but mostly 40–60 kV) between the two electrodes: discharging electrode and collecting electrode. The applied voltage depends on the distance between electrodes. The high voltage between electrodes results in a strong electric field and electric discharge of ions from the discharging electrode called the corona. Besides on process conditions (flow rate, composition, temperature, dew point) and properties of particles such as concentration, size distribution, hygroscopy and tendency to agglomerate, the efficiency of ESP significantly depends on the particle resistivity. The particle resistivity is a measure of the resistance of the dust layer to the passage of a current. For efficient work of ESP, the resistivity should be between 10^7 and 10^{10} ohm-cm [10, 23]. Operation at the lower or higher resistivity leads to a decrease in removal efficiency. To improve efficiency it is possible to perform chemical conditioning of the flue gases (with moisture, by addition SO_3 gas, sodium or ammonium salts) or to work at the lower operating temperature (with caution because of the possible condensation and corrosion) [15].

The most important challenge in consideration of ESP design is calculation of collection efficiency or collection area. The collection efficiency and/or the collection area of an ESP can be estimated using several equations and one of them is known as the Deutch-Anderson equation [16, 26]:

$$\eta = 1 - \exp(-\frac{\omega A}{Q}) \tag{33}$$

where A is the effective collecting plate area of the precipitator (m^2), ω is the drift velocity or the particle migration in an electric force field (m s^{-1}) and Q is volumetric gas flow through the precipitator (m^3 s^{-1}). More accurate estimates of collection efficiency can be obtained by modifying the eq. (32) or by decreasing the calculation of collection efficiency by a factor of k. The resulting Matts–Ohnfeldt equation is given by [15, 26]:

$$\eta = 1 - \exp\,(-\frac{\omega A}{Q})^k \tag{34}$$

where k is constant (usually 0.4 to 0.6). The particle migration velocity is the speed at which a particle, once charged, migrates toward the grounded collection electrode. Variables affecting ω are particle size, the strength of the electric field and the viscosity of the gas. The theoretical drift velocity of a spherical particle (or particle settling velocity in ESP) subjected to constant gas flows and electrostatic fields in an ESP is given by

$$\omega = \frac{Cd_p}{\mu}\varepsilon_0\frac{\varepsilon}{(\varepsilon + 2)}E^2 \tag{35}$$

C is the Cunningham correction factor, μ is gas viscosity (kg m^{-1} s^{-1}), ε_0 is permittivity of free space (8.85 10^{-12} C V^{-1} m^{-1}), ε is dielectric constant for the particle relative to free space and E is average field strength (V m^{-1}). The drift velocity is also related to the corona power, P_c (W):

$$\omega = \frac{kP_c}{A} \tag{36}$$

where k is an adjustable constant. The drift velocities are usually in the range 0.03 and 0.2 m s^{-1} [27]. After substitution of eq. (32) into **the Deutsch-Anderson equation**, eq. (32) the collection efficiency can be calculated as

$$\eta = 1 - \exp\left(-\frac{kP_c}{Q}\right) \tag{37}$$

Based on the shape of the collection electrode and depending on the mode of operation there are several types of ESPs: dry and wet wire-plate ESPs as well as dry and wet wire-pipe (or tubular) ESPs [10]. The discharge electrodes are commonly in the form of a wires (made from noncorrosive materials like tungsten or alloys of steel and copper), because of small radius of curvature. In the wire-plate ESP the high voltage electrodes are long wires (discharge electrodes) that are weighted and hang between the plates (collection electrodes). In this case the waste gas flows horizontally and parallel to vertical plates of ESP. Plates are usually 1–2 m wide, 3–6 m high and plates are at distance between 15 and 35 cm [10]. In the wire-pipe type precipitator the discharge electrodes are in the form of wires and the collecting electrodes consist of parallel pipes which may be round, square and octagonal. The pipe electrodes are 2–5 m high and about 30 cm (or less) in diameter. The space between the electrodes is in the range 8–20 cm. In dry ESPs the PM is removed from the collecting electrodes by rapping, while in the wet precipitator water or any other fluid can be used for removal of the solid particulates. Wet precipitators are more efficient, but dry type plate precipitators are mostly used in the practice. The most important fields of their application are: cement factories, steel plants, chemical industry, petroleum industry.

3.3.3 Fabric filters

Fabric filtration is a well-known physical technique in which a gas stream containing **dry particles** passes mostly through a porous fabric medium, which retains the solids. During this process, the contaminated gas flows into and passes through a number of filter bags placed in parallel, leaving the solid particles retained by the fabrics. The air pollution control equipment where this process takes place is called bag house. The fabric is a filter medium; however it is also a support for the layer of dust (dust cake or filter cake) that accumulates on it. This dust layer can significantly increase the efficiency of filtering, especially for very small particles. However, these filter bags must be periodically cleaned, because with the increase in the thickness of the filter cake also increases the pressure drop or the air resistance through the filter. The filter bags are usually cleaned by rapping, shaking or vibration as well as by the reverse air flow, causing falling of the filter cake into the hopper. Generally, the economy of filtration depends on separation efficiency, pressure drop and lifetime. According to some opinions, fabric filters belong to the most effective dust removal devices. Therefore, they are widely used in industrial application (steel industry, foundry, cement industry, power stations, etc.), although depending on the applied filter medium, they may be quite sensitive to high temperatures and humidity.

According to the chemical composition filter medium can be natural or man-made fibers, plastic, ceramic, glass or metals. The choice of fabrics is determined by the following conditions: temperature, gas composition and/or presence of acids or alkalis in a gas streams, gas flow rate as well as size and shape of dust particles and its concentration. The filter medium can be fibrous (e. g. cloth), granular (e. g. sand), a rigid solid (e. g. screen) and a mat (e. g. a field pad). It can be made in different forms, i.e. in the shape of a bag (the most common form), tube or sheet with a number of the individual filter units housed together in a bag house as well as in the form of bed or fluidized bed. Generally, filters can be divided into the following types: fabric or cloth filters (surface filters) and fibrous or deep bed filters (depth filters). *Surface filters* usually compete with cyclones and ESPs for treatment of gas stream contaminated with particulates. In the cloth filters, the filter is in the form of tubular bags, while in the case of deep-bed filters, a fibrous material (cotton, wool, cellulose, etc.) has the role of separator and the collection of particulates takes place in the interstices of the bed. The number of filter bags may vary between a few hundred and a few thousand. The diameter of a bag filter ranges from 0.1 to 0.4 m and the height may be up to 10 m. The velocities at which a gas stream is passed through the bags are very low 0.4–1 m min^{-1} [26]. **The total pressure drop through a filter bag**, ΔP ($\mathrm{N\,m^{-2}}$) is given as the sum of the pressure drop owing to the fabric, ΔP_f and the drop owing to the caked or adhered particles, ΔP_p [22]:

$$\Delta P = \Delta P_f + \Delta P_p = u\mu\left(\frac{x_f}{60K_f} + \frac{x_p}{60K_p}\right) \tag{38}$$

where u is superficial filtering velocity (m min^{-1}), μ is gas viscosity (kg $\mathrm{m^{-1}s^{-1}}$), x_f *and* x_p are thicknesses of the filter and the particulate layer (m), K_f and K_p are permeabilities of the filter and the particulate layer ($\mathrm{m^2}$) (values of K_f and K_p must be determined experimentally for each type of fabric and type of dust removed) and 60 is conversion factor (s min^{-1}). The superficial filtering velocity, u is also known as **the air/cloth ratio** and can be determined as the ratio of the volumetric gas flow rate, Q ($\mathrm{m^3\,min^{-1}}$) and the cloth area, A ($\mathrm{m^2}$). Excessive air/cloth ratio lowers particulate removal efficiency.

Ceramic and metal filters also belong to the surface filters. There are more resistant at much higher temperature than fabric filters (up to 1000 °C in the case of metal filters) and also they have higher chemical resistance. The process of filtering and removal of particles from the contaminated gas is comparable to that on fabric filters and only significant difference is in the filtering material. There are some special designs applicable for removal of compounds such as HCl, NO_x, SO_x and dioxins, but the process of filtering in these cases involve the presence of catalysts and the injection of some reagents [10].

Deep-bed filters can be filled with granular materials as well as with fibers. They are usually composed of mats of wood, cellulose, glass or iron fibers. The most important filed of their application is in air conditioning, heating and ventilating systems as well as for the cleaning under the conditions of light dust loads. The advantage of a granular bed over a fiber filter bed can be the greater structural strength of a packed bed. Deep-bed fiber filters have the potential to remove the particles that are too small to be removed efficiently by any other type of surface filters. The low capital costs of small fiber filters make them very attractive for small gas streams (e. g. household furnace filters, air filters for automobiles).

3.3.4 Wet dust scrubbers

Wet collectors or scrubbers have several important advantages in comparison to other air pollution control devices. The most important advantages of scrubbers are: low initial cost, moderately high collection efficiency for small particles and applicability for the high temperature installations. They can handle large volume of gases and collect dust particulates like flammable, sticky and explosive dusts with a little risk. Additionally, wet scrubbing (or absorption) is process which can be used for the removal of gaseous pollutants (such as SO_2, NH_3, H_2S, hydrogen halides, VOCs) as well as for the removal of mists, fumes, heavy metals and suspended dusts [28]. They also provide cooling hot gases and neutralization of corrosive gases and dust. Based on the main purpose of their using, scrubbers can be divided on the wet gas scrubbers and the wet dust scrubbers. Special configurations of the so called dry scrubbers belong to the additional group scrubbers, which are very efficient for the elimination of the problematic liquid waste stream, acid and odorous gases by means of a dry sorbent injection (mostly alkaline material) into a gas stream. The dry scrubber is usually followed by a bag house to clean the effluent to acceptable levels.

Wet dust scrubbers are devices that remove PM by direct contact of the dirty gas stream with liquid drops (mostly water) (Figure 8). Scrubbing is usually carried out by intensively mixing of the incoming gas stream with water in combination with the removal of particles by means of centrifugal force. The absorption of particles into the liquid phase can be both physical and chemical absorption, depending on the particle and liquid phase and gaseous properties. By replacement of water with other aqueous solutions (lime, potassium carbonate or slurry of MgO) it is possible to perform simultaneous removal of gaseous and solid pollutants from a gas streams. Different types of scrubbers can be found on the market. Most of them can be grouped according to the contacting mechanism with liquid. The most popular scrubber designs which vary in terms of both function and performance are: spray tower scrubber, Venturi scrubbers, cyclone scrubbers, packed scrubbers and mechanically aided scrubber. According to energy requirements they can be classified as low-, moderate- and high-energy scrubber units. The simpler types of scrubbers with low energy requirements are efficient in collecting particles above 5–10 µm in diameter, while the more efficient, high energy input scrubbers are favorable for separation of very small particles (1–2 µm). Energy requirements are related to the pressure drop across the scrubber or to the level of contacting power. Obviously, the disadvantages of scrubbers are previously mentioned high power consumption for higher efficiency, moderate to high maintenance costs (corrosion and abrasion) as well as disposal of waste sludge which can be very expensive.

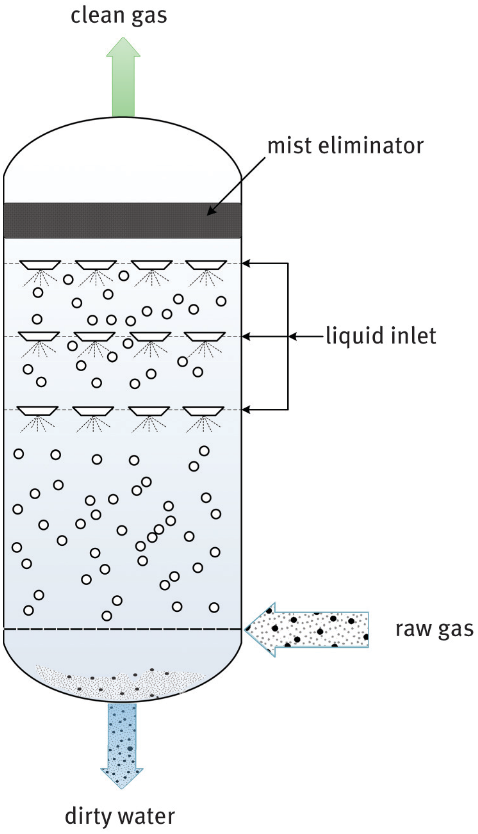

Figure 8: Spray tower with counter-current flow (inspired by [29]).

A key parameter in the design of scrubbers is the liquid-to-gas ratio (L/G). This ratio is determined by the solubility of the gas pollutants, concentrations of pollutants and particulates in the gas stream and the mass transfer properties of the scrubber. The increase in the (L/G) increases the separation efficiency of the system, so finding the optimum ratio is very important for the balancing of performance with operation costs. Besides energy needs and requirements for performance efficiency, the other important parameters for the selection of scrubber for a particular application include compatibility of materials used in the construction of the scrubber with the chemical (acidity, reactivity), physical properties of the gas stream (abrasivity), optimal operating temperature, need for addition reagents, etc.

In the *spray tower scrubber* the washing liquid is sprayed by spray nozzles, fast-spinning nebulizer disk or rotating sprays, creating a large contact surface for the drops and the inlet gas. Droplet size is controlled to optimize particle-liquid contact and to provide easy separation of droplets from the air stream. Very high (L/G) are required ($>3\,\mathrm{l\,m^{-3}}$) to capture fine particles. Power consumption for spray tower scrubber is low and they operate with a low pressure drop. Spray tower are capable for removal of particles <8 µm with 90 % efficiency [22]. *Cyclone spray scrubbers* combine the capture techniques of cyclones and spray towers. Gas streams enter into the device tangentially at high speeds. The high speeds in combination with the centrifugal force promote droplets separation, allowing the use of a smaller droplet size, which also increases collection efficiency (95 % for particles >5 µm). They are more efficient than spray towers and have lower liquid requirements, but require more power, due to higher pressure drop. They are preferred over spray towers for gas streams with heavier particulate loads. *Venturi wet scrubbers* are applied for removal of fine particulate from corrosive, high temperature, hazardous or volatile gas streams. These are scrubbers with a Venturi-shaped chamber including converging and diverging sections. Water is injected at low pressure into the throat of the Venturi, through which the gas stream passes at high velocities. The energy from the gas atomizes the liquid, allowing particles and pollutants to be entrained in droplets. Venturi jet scrubbers use a modified design in which liquid at high velocity is jetted (injected) into the throat of a Venturi, rather than the gas stream. Venturi scrubbers have very high separation efficiencies for particulate pollution (>98 % for particles >0.5 µm) and are simple to install and maintain. However, they require large pressure drops leading to higher power requirements than other scrubber designs. Other often used designs involve packed scrubbers and mechanically aided scrubber. Packed scrubbers are occasionally used for particulate control, but they are restricted to separation of fine and/or soluble particulates, aerosol and mists, because of possible blockage of nozzles and plugging of bed. In line with this, they are limited to applications with low particle content ($<0.5\,\mathrm{g\,m^{-3}}$). Scrubber can also use mechanically enhanced gas-liquid contact. However, the main disadvantage of mechanical scrubber is high maintenance cost.

3.4 Control of gaseous and vapor pollutants

This section gives an overview of several control devices for handling gaseous pollutants. Gaseous and vaporous pollutants may be removed from the waste gases by changing the process that produces the pollutants or by using the secondary treatment devices with the aim of trapping the pollutants from the waste stream (absorption, adsorption) or changing the physical state of matter from gas phase into liquid phase by cooling (condensation) or changing them chemically or biologically. A large number of gases and vapors which can be present in a gas streams are potentially explosive. Therefore, one of the main factors that must be considered in designing a gaseous contaminant control system is the concentration range at which one or more of the contaminants can be ignited.

3.4.1 Absorption

Absorption (also called gas absorption, gas scrubbing or gas washing) is the standard method of removing any compounds from a gas stream, which can be used if is possible to find a liquid solvent in which the gaseous pollutant is more soluble than the other compounds in the gas stream [10, 25]. The species transferred to the liquid phase are referred to as solutes or absorbate. This is probably one of the most important techniques in the control of gaseous pollutant emission, although the most important disadvantage of this process is the generation of waste water. The most important fields of application this technique include control of SO_2 and NO_x from combustion sources, removal and recovery of NH_3 in fertilizer production, removal of HF from glass furnace exhaust, control of odorous gases from rendering plants, recovery of water-soluble solvents such as acetone and methyl alcohol, etc. Absorption takes place in the absorption unit (absorber or scrubber) and basic principle of this process is the selective mass transfer of gaseous substance from the gas to liquid phase, owing to the preferential solubility of a gaseous component in the liquid. During this process the substance can be only dissolved in the liquid phase (physical absorption) or may react with the liquid or with a specific substance contained in the liquid (chemical absorption). As mentioned previously, water is commonly used liquid or absorbent. However, gases of very little solubility such as SO_x, H_2S and NO_x, can be absorbed readily in an alkaline solution such as NaOH [10]. Thus, when water is used as the solvent, it may contain added species, such as acids, alkaline, oxidants or reducing reagents to react with the gas being absorbed and to enhance its solubility. Absorption is favorable process for the recovery of products or for purification of a gas streams that have high concentration of organic compounds, otherwise the process is not economically acceptable. Generally, absorber can achieve separation efficiency higher than 95 %.

Basic principles of the process operation are described previously (see Section 3.3.4). The packed column absorber/scrubber is most commonly used technical device for separation of gaseous pollutants. The packed absorbers/scrubbers are usually filled with an inert material such as plastic or ceramic with the aim to increase the gas-liquid interface. The adsorbent can be in a wide variety of physical forms such as pellets in a thick bed, small beads in a fluidized bed or fibers pressed onto a flat surface. There are many types of packing and some of the commercially used are Raschig rings, Berl saddles, Pall rings and Intalox saddles. Generally, it is required for the packing to have large surface area per unit volume and low pressure drop of gas through it. Bubble caps and sieve trays can be also used in the interior of the absorption/scrubbing device to enhance counter-current contact between the liquid and gas stream. The main elements of the absorber design are: material balance to determine a liquid circulation rate, calculation of a packed absorber high or number of plates (depending on the type of absorber selected for the process) and determination of the absorber diameter sufficient to handle the required liquid and gas flow rates. The process opposite to the gas absorption is the stripping (Figure 9). After the solubility equilibrium is achieved during the process of absorption, the liquid which contains most of the gaseous compound removed from the waste gas, passes to the stripper – another device which works at much higher temperature and/or at much lower pressure than the absorber. Because of this the solubility of the gas in liquid is reduced, the gas comes out from the liquid and after the cooling it can be sent to storage. At the same time, the stripped or recovered liquid can be sent back to the absorber unit.

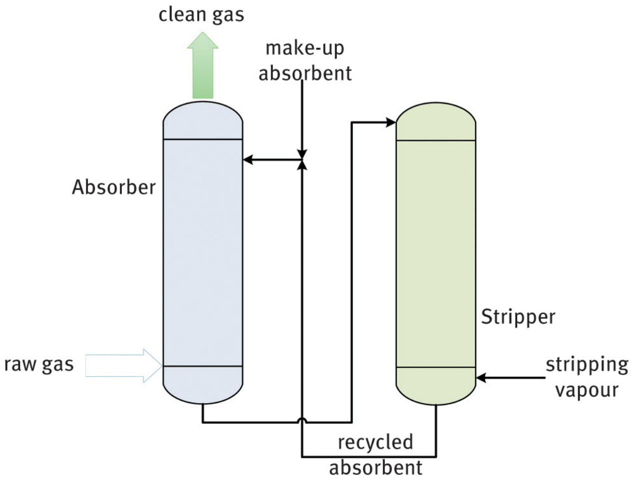

Figure 9: Absorption-stripping system.

3.4.2 Adsorption

Adsorption is another type of equilibrium separation process; in this case it involves a gas-solid equilibrium. Adsorption means the attachment or the binding of gaseous and vaporous molecules to the surface of a solid adsorbent or in the pores or interstices of adsorbent material. The adsorbing solids are usually called *adsorbent*, while the gas which is adsorbed is referred to as the *adsorptive* (Figure 10).

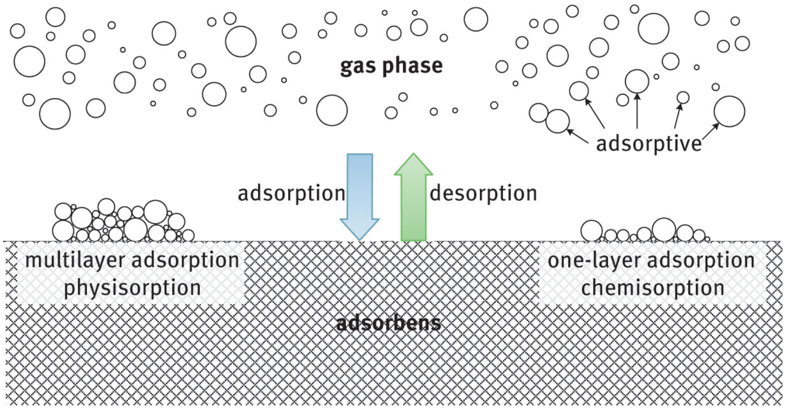

Figure 10: Simple illustration of gas adsorption (adopted from [23]).

Adsorption may be physical or chemical (chemisorption), depending on the strength of molecules binding to a surface of adsorbent. *Physical adsorption* (reversible process) is used primarily for the control of organic compounds, while *chemical adsorption* (irreversible process) is frequently used for the control of acid gases (hydrogen chloride, hydrogen fluoride, hydrogen sulfide) and mercury vapor. Depending on the flow rate of the polluted air, the adsorption process involves one or several adsorbers that operate in parallel. Adsorption is an exothermic process, because in the adsorption process the molecule loses kinetic energy. Contrary, the reverse process of adsorption is desorption and this process is endothermic. Conventional adsorption plant usually consists of two devices: one for the adsorption cycle and another for desorption, because the adsorbent must be regenerated after adsorption in order to be available for another process. Adsorption is mostly used to capture, concentrate and recovery a pollutant that is present in dilute form in waste stream. This means that adsorption may result in the recovery of economically valuable final product or in disposal of pollutants after previous treatment if there is a need. Separation efficiency of 95–99 % can be achieved using the adsorption process based on activated carbon as adsorbent [26].

The most often used adsorbent are activated carbon, silica gel, alumina, molecular sieve, polymer-based materials and zeolites. The common types of *adsorbent equipment* are thin bed absorbers and deep bed adsorbers. As the names of devices imply, the thin bed adsorber consists of a thin layer of adsorbed solid, which is preferable if adsorption is very quick process, while another type of adsorber is usually based on a deep bed of adsorbent to adsorb contaminants from the air that is heavily polluted.

The adsorbers usually work in the temperature range between 30 and 60 °C. Besides on temperature, the rate of adsorption is depended on the concentration of the adsorptive in the gas phase, the surface area and pore volume of the adsorbent and other properties of adsorbent (e. g. porosity, adsorption capacity, selectivity) and adsorptive. Regeneration of the adsorbent is usually carried out by increasing the temperature, by means of water vapor desorption at temperatures of 100 °C (and higher), by contact with a hot inert gas or by decreasing the total pressure (under vacuum). Reactivation of adsorbent in the case of chemisorption can be performed at the high temperatures (ca. 700 °C, depending on adsorbent nature). Design and analysis of adsorption system involves heat and mass transfer, fluid dynamics, process control and chemical analysis. More information on design of adsorbers can be found in [22, 23].

3.4.3 Condensation

Condensation is a separation process used to convert one or more volatile components of a vapor mixture to a liquid through saturation process. Condensation can be accomplished by reducing the temperature or by increasing the pressure. The first approach is more often used in the practice, because an increase in the vapor pressure can be expensive [30]. Condensers are typically used as a pre-treatment device to reduce the volume of the effluent gas before treatment by other devices. They can be also used for the reducing emissions from the high concentration gas streams to recovery of economically valuable products in a waste stream or to remove corrosive components and components that can damage other part of the system. Two most important representatives of condensers are contact condensers and surface condensers. In contact condenser the contaminated gas stream comes into contact with cold liquid by spraying ambient or chilled liquid directly into the gas stream. The direct mixing of the coolant and contaminant causes separation or extraction before coolant reuse. This additional separation process may lead to a disposal problem or secondary emissions. In the surface condensers, the coolant does not mix with the gas stream (which is advantage comparing to contact condensers), but contacts a cooled surface in which cooled liquid or gas is circulated. Surface condensers require less water and generate 10–20 times less condensation than contact condensers do. Removal efficiency of condensers range from 50 % to 95 %, depending on theirs design and application.

3.4.4 Chemical waste gas treatment

Chemical waste gas treatment methods involve process of *incineration* (thermal oxidation and catalytic oxidation) and flaring, in which an organic pollutant can be converted to CO_2, water and some inorganic gases. Incineration (or combustion) refers to the rapid oxidation of pollutants through the combination of oxygen from the air with supplementary combustible fuel in the presence of heat. The chemical conversion of pollutants (mostly gaseous but also solid and liquid particles) contained in waste gases is the most efficient process in the air pollution control which results in the complete degradation of almost all pollutants, independent on their chemical properties. Equipment for control waste gases by incineration can be categorized as: thermal oxidizers or afterburners, catalytic oxidizers and direct combustor or flare.

The thermal oxidizer involves specifying a temperature (650–825 °C) of operation along with a desired residence time (0.5–1.0 s) and then optimum sizing the device to achieve the desired residence time and temperature with proper flow velocity. Efficiency of thermal oxidation can be higher than 99 % when operated correctly. However, if the process of ignition is not complete, some pollutants can be released into the atmosphere, which is undesirable. In *the catalytic oxidation* the presence of catalyst is responsible for achievement of high reaction rate at much lower temperatures (315–485 °C), which results in considerable savings in the fuel costs. The space requirement for operation of the catalytic oxidation is also much smaller. However, the costs of the catalytic systems are higher than those of the thermal oxidation systems, because of expensive catalysts and associates systems. Anyway, application of catalytic afterburners is favorable because of possibility to avoid formation of the thermal NO_x, dioxins and other undesirable products. Thermal NO_x are formed at the high temperatures (>1300 °C) due to complex reaction of oxygen and nitrogen with high energetic free radicals (O, N, OH, H and hydrocarbons that have lost one or more hydrogen). The catalysts are usually based of combination of a noble and other metals (Pd, Pt, Cr, Mn, Cu, Co, and Ni) deposited on an alumina monolithic support to minimize the pressure drop, which is one of the critical parameters of the incinerator designs. Limitation of the catalytic systems is catalyst deactivation, due to the presence of contaminants, attrition or catalyst sintering. Catalytic systems are suited for a gas stream with low VOC content. Depending on the types of heat recovery, both thermal and catalytic incinerators can be classified into two categories: recuperative and regenerative. The recuperative incinerator can recover about 70 % of the waste heat from the waste gases, while the regenerative incinerator can recover up to 95 % of the energy. *Flare gas systems* are used in a wide variety of applications and are generally used to burn off excess gas, usually hydrocarbons. A flare gas system may contain open flame flares or combustors (flame enclosed) with small differences between them. A flare can be used to control almost any emission stream containing VOCs [23, 28]

3.4.5 Biological waste gas treatment

In the biological control systems gaseous pollutants are converted into less harmful or harmless substances by microorganisms. Almost all kind of organic (hydrocarbons, chlorinated hydrocarbons, ketones, esters, aldehydes, odors) and inorganic pollutants (NH_3, NO_x, H_2S, CS_2) can be treated by microorganisms. There are two groups of microorganisms that may be used for this purpose: autotrophic bacteria which are particularly suitable for the conversion of inorganic substances and heterotrophic bacteria which are well suited for the conversion of organic pollutants. The microorganisms oxidize the pollutants and produce cell substrate, CO_2, water and inorganic salts. This process takes place in the presence of water and it is possible only for the very low pollutant concentration. Biological systems are especially suitable for degradation of VOCs, odors and toxic compounds. Obviously, they are similar to biological systems used for treatment of the wastewater and can be divided into three categories: biofilters, biotrickling filters and bioscrubbers (Table 3).

Table 3: Types of biological air pollution control systems [22].

Application	Biomass	Water phase
Biofilter	fixed	fixed
Biotrickling filter	fixed	flowing
Bioscrubber	flowing (suspended)	flowing

Biofilms of microorganisms are grown on porous media in biofilters and biotrickling filter, while a contaminated gas stream is passed through a porous packed bed at a low velocity. The main difference between those two systems is that liquid phase is stationary in a biofilter and moves through the porous media in a biotrickling system. Bioscrubbing combines wet gas scrubbing (absorption) and biodegradation. The scrubbing water with suspended microorganisms is recirculated through the reactor and the absorbed pollutants are degraded in aeration sludge tank. Bioscrubbing is suitable for removing of readily biodegradable compounds, such as NH_3, amines, hydrocarbons, H_2S and odorous pollutants. Biofiltration mainly use compost as the porous media is cheapest and thus widely used biological waste gas treatment for the removal of low concentration of pollutants that are easily soluble in water [10, 22].

Readers interested in the additional information on design and scale-up principles and operational guidance regarding to the control devices for cleaning gaseous pollutants can refer to available literature [5, 10, 13, 15, 23, 31].

Questions and exercises to get you thinking

- What is the difference between primary and secondary air pollutants. Give some examples!
- Explain the greenhouse effect and specify some greenhouse gases!
- What is “sick building syndrome” and what does it link to?
- What are you doing to improve the air quality in your household?
- What are the major parameters that influence dispersion of air pollutants in the atmosphere?
- Describe typical sources and types of air emissions resulting from the oil refineries. What are examples of prevention pollution practice in this industry which kind of and which kind of the emission control equipment are used for the same purpose?
- Compare the major types of air pollution control devices used for particulates removal. Visit the Web and make a list of suppliers for these devices.
- Explain the better efficiency of multiple cyclones in comparison to a single cyclone.
- Describe the processes of absorption and desorption. Explain the similarities and differences of these processes.

- Adsorption isotherms can be described by different equations. List some of them!
- Describe the characteristic types of scrubbers that can be used for the simultaneous removal of particulates and gaseous pollutants.
- Does the Henry's law absorption limit influence the amount of air pollutant that can be absorbed in a wet scrubbing type system?
- Compare the most important advantages and disadvantages of thermal and catalytic oxidizers!
- Explain some heat recovery options during the incineration process.

This article is an excerpt from the textbook Environmental Engineering: Basic Principles (978-3-11-046801-4)

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