Chapter 1

Introductory Chapter: Ozone in the Nature and Practice

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1. Introduction

Ozone (O_3) is a tri-atomic form of oxygen, that is, three atoms of oxygen bonded together. It is an unstable gas with distinctive sharp odor. Under normal conditions, ozone is unstable and rapidly decomposes to a more stable gaseous form of molecular oxygen, O_2. Behavior of ozone shows more "faces" according to the circumstances. The ozone layer protects the Earth from damaging ultraviolet (UV) light; therefore, it is an inevitable compound to save life on Earth. Its applications also present benefits for human welfare. Thanks to its strong oxidizing properties as well as bactericidal, virucidal, and fungicidal effects, it is widely used for water disinfection, wastewater treatment, in various industrial fields, for example, in the pulp and paper industry and the textile industry and progressively for medical purposes as well. Unfortunately, there are also circumstances, mainly due to the activities of humans, when ozone behaves contrary to the mentioned benefits, with negative and harmful influence on human health, and life in nature, as well as to material environment [1]. While stratospheric ozone protects biological life on Earth, ozone in the troposphere is toxic to human health, plants, and trees and it also damages various materials [2].

One may have noticed a smell in the air after thunders and lightning bolts. The pure odor was most likely to the actual ozone formed by flashing atmospheres. Because ozone is unstable and cannot be stored successfully, it must be generated at the application site. To produce ozone sufficiently in the water, wastewater, and sewage treatment plant, ozone generators are used. The simplest method can be ozone generated by the passage of oxygen or oxygen-containing air through the area of electric discharge or spark.

Ozone is a subject of interest and research for a number of reasons. This chapter will deal briefly with related aspects of stratospheric and tropospheric ozone as well as with utilization of ozone in practice.

2. Ozone in the environment

In the case of atmospheric ozone, the main focus is on the decrease in the concentration of stratospheric ozone and the related biological effect, the occurrence, and the detrimental effects of tropospheric ozone.

Ozone is highly toxic, blue to colorless gas with a pungent odor. It is located mainly in the stratosphere (15–50 km above the Earth's surface) and the troposphere (0–11 km above Earth's surface).

2.1. Tropospheric ozone

The most important chemical transformation processes in the atmosphere are photo-dissociation and oxidation. Major atmospheric oxidants include O_3, hydroxyl radical ·OH, and hydrogen peroxide H_2O_2 (together they form the oxidative capacity of the atmosphere). Among possible consequences of transformation, there is a production of substances that are more toxic than their precursors (i.e. the substances leading to their formation). An example is the formation of tropospheric ozone, so-called ground-level ozone, which is harmful and is among the toxic pollutants. Ground-based ozone is one of the most variable atmospheric components that depend on temperature and air pressure [2].

Ground-level ozone is released when various hydrocarbons react with nitrogen dioxide (emissions from public transportation and industry) in the presence of sunlight. The largest source of nitrogen oxides (NO_x) is the combustion of fossil fuels (energy, transport) and therefore the largest share of automotive transport. Exhaust gases from engines include NO_x (approximately 95% NO, 5% NO_2), hydrocarbons (saturated and unsaturated), partially oxidized hydrocarbons (mainly aldehydes, most of them formaldehyde), and CO. Levels of ground-level ozone in the exterior are higher during the summer [3, 4].

High concentrations of ozone adversely affect human health. Ozone as an effective oxidant causes transient irritation of the respiratory system, resulting in coughing, irritation of the nose, throat, eyes, breathing, and chest pain in deep breathing. Chronic exposure to high concentrations of ozone leads to premature aging of the lung tissue, thereby reducing resistance to infections. Up to 95% of ozone inhaled into the lungs remains in the body.

Tropospheric ozone also has an unfavorable effect on vegetation, especially on agricultural crops and forest stands. Smog-induced foliar injury on plants was first identified in the 1950s [2]. Short episodes of high concentrations of ground-level ozone cause acute damage to assimilation organs (reduction of resistance or decay of the plant).

Ground-level ozone effectively decomposes chlorophyll in plants. It also damages various materials. It causes rubber hardening, decoloration of dyes and dyed textiles, and corrosion of metals. Increases in corrosion of construction materials (steel, zinc, copper, aluminum, and bronze) are attributed to the synergistic action of ozone and other substances such as SO_2 and NO_2 [2].

The World Health Organization (WHO) recommends an 8-h limit of 100–120 μg m^{-3} concentration of ozone-exposed to human body [1].

2.2. Stratospheric ozone

Ozone is formed in the stratosphere by the reaction of an oxygen radical with an oxygen molecule. The ozone molecule can absorb radiation in the range of 310–200 nm, after which it is divided into an oxygen molecule and an oxygen radical, followed by a repeat cycle [3].

$$O_2 + UV_{240\ nm} \rightarrow \cdot O + \cdot O \cdot O + O_2 \rightarrow O_3 \tag{1}$$

$$O_3 + UV_{310\text{–}200\ nm} \rightarrow \cdot O + O_2 \tag{2}$$

It can be destroyed by a number of free radicals, the largest of which are: $\cdot OH$ $\cdot NO$, $\cdot Cl$ and $\cdot Br$. While ·OH and ·NO radicals are mostly of natural origin, the halogen radicals are increased due to the human activity by discharging chlorine and fluorine derivatives of hydrocarbons.

$$\text{(CFC, HCFC)}\ CFCl_3 + UV \rightarrow \cdot C + CFCl_2 \tag{3}$$

Subsequently, the radicals act as a catalyst.

$$\cdot C + O_3 \rightarrow ClO + O_2\ ClO + O_3 \rightarrow \cdot Cl + 2\ O_2 \tag{4}$$

2.3. Ozone hole

Ozone hole is a term describing more than 50% temporary loss of ozone in the stratosphere. At poles, the ozone layer is already very thin. The most significant decrease in ozone was recorded in the lower stratospheric levels a decrease up to 70% was recorded over the Antarctic and has continued since 1985. The restoration was recorded in 2016 similarly to the Arctic. The reason why ozone holes are formed more easily over the poles is due to the phenomenon known as polar vortex that allows chemical reactions in the enclosed air mass to be enhanced due to the lack of mixing with other, lower latitude, air masses. The effects of the pollutants in the atmosphere are thus enhanced in these isolated regions of the atmosphere [5]. Another reason is the formation of polar stratospheric clouds that are composed of ice crystals, sometimes greatly enriched in nitrogen oxides enhancing the ozone degradation. During winter, Antarctic is extremely cold due to the absence of sunlight. The temperature here drops to −90°C and creates the stratospheric clouds by freezing the water's vapor. Freon molecules and other ozone-depleting gases above the Antarctic are captured in ice crystals. These ice particles can react with various forms of chlorine in the atmosphere and accumulate the molecule $ClONO_2$, which is a source of ozone-depleting Cl radicals. After two or three months, the mass of air with less ozone is moving from Antarctica to other parts of the world. This creates a harmful ozone hole in the atmosphere of the planet [6].

So far, there has been a small decline in habitat habits, and no direct evidence of health damage due to the reduced concentration has been documented. In the event of a reduction in concentration, the effects could be significantly more dramatic, especially in the southern hemisphere that would be affected by the Antarctic hole. The most negative effects are sunburn, skin cancer, and cataracts. In addition, amount of UV light increases on the Earth surface, which will contribute to ground-level ozone formation, posing another health risks.

Montreal Protocol, a protocol to the Vienna convention for the protection of the ozone layer, the last valid revision of Beijing 1999, contains legally binding emission reduction targets for freon use [6]. As a result of an international agreement, the ozone hole is slowly recovering. Predictions say the situation will return to the pre-1980s in the years 2050–2070.

3. Ozone in water, wastewater, and sludge treatment

Ozone has some advantages for use in water treatment specifically in respect to the use of chlorine, but it also has several disadvantages. It easily reacts with organic and inorganic compounds thanks to its high reduction potential and reactivity [7, 8, 9]. Ozone removes odor, colors, chemical oxygen demand (COD), phenols and cyanides; reduces haze, surfactant and suspended solids content and also increases dissolved oxygen levels. Ozone is easily produced from air or oxygen by electric discharge. A major limitation of the ozonation process is the relatively high costs of ozone generation.

3.1. Ozone reactions and affecting factors

Ozone is able to react through two different reaction mechanisms, direct ozone oxidation, and indirect oxidation with free hydroxyl radicals. Both reactions run simultaneously and it is difficult to distinguish them and study their reaction mechanism.

The rate of ·OH radical's formation is dependent on pH. With increasing pH, the rate of its formation also increases [10]. Usually under acidic conditions (pH <4), direct reaction prevails. At pH ≥ 10, the reaction mechanism changes to indirect. Direct oxidation of organic compounds by ozone is a selective reaction with a low reaction rate constant [11].

The indirect reaction involves oxidation by radicals that are formed by ozone decomposition. The hydroxyl radical (·OH) reacts non-selectively and has a very high-redox potential. For this reason, it is a much more effective oxidant than ozone itself [12]. The resulting OH radical reacts with the dissolved organics. Some functional groups present in organic molecules react with ·OH to form organic radicals, which are oxidized in the presence of oxygen. Many organic and inorganic compounds react with the ·OH radical to form secondary radicals that do not lead to the regeneration of HO_2 and O_2. This leads to termination of the chain reaction [13].

In general, ionized or dissociated forms of organic compounds react as much as non-dissociated forms. Thus, the pH also affects the direct reaction of ozone. Olefins are more reactive than aromatic compounds with the same substituent. The direct reaction with ozone occurs when the radical reaction is inhibited. Therefore, the water either contains a small number of initiators or contains a large number of scavengers that end the chain reaction of ozone decomposition. With an increasing concentration of scavengers, the oxidation mechanism turns to the direct reactions [11].

Although the ozone decomposition rate in aqueous media is known to depend on pH (at high pH, ozone undergoes rapid decomposition), Nakano et al. [14] found that neither the low pH nor the high solubility of ozone affected the degradation rate of the studied substances. Thai et al. [15] studied the effect of chemical properties of organic solvents (acetic acid, ethyl acetate, methyl acetate, propionic acid, and acetonitrile) on the rate of decomposition of non-dissociated and dissociated chlorinated hydrocarbons. They found that the rate of decomposition for dissociated and non-dissociated substances is different, indicating that the rate of ozonation depends on the nature of the organic solvent.

The course of ozonation significantly influences wastewater composition. Substances present in water/wastewater may initiate, promote or inhibit the chain reaction. The initiators include OH^-, H_2O_2/HO^{2-}, Fe^{2+}, formates and humus substances. These substances induce the formation of a superoxide ion $\bullet O_2$ from the ozone molecule. Promoters are, for example, R_2 -CH-OH, aryl-R, formates, and humus compounds. O_3 is responsible for the regeneration of the superoxide ion from the hydroxyl radicals. The main inhibitors are CH_3-COO-, alkyl-R, and HCO^{3-}/CO_3^{2-}. These substances are capable of absorbing hydroxyl radicals without subsequent regeneration to superoxide ion. Carbonates and bicarbonates inhibit ozonation due to reaction with ·OH radicals.

The ozonation of inorganic compounds in wastewater leads to the destruction of toxic substances, mostly cyanides. Cyanides are often used in the metalworking industry and in the electronics industry where cyanides occur as iron and copper complexes. Nitrates (NO^{2-}) and sulfides (H_2S/S^{2-}) are also removed during ozonation in wastewater.

One of the most problematic substances in industrial wastewater is organic compounds. They are often found as a mixture of complexes composed of many different substances present in a wide concentration range (mg–g L^{-1}). The role of ozone associated with wastewater treatment is as follows:

- transformation of toxic compounds (often occurring at relatively high concentrations),
- oxidation of non-biodegradable substances to improve biodegradation,
- removing water stains and odors.

3.2. Ozonation reactors and ozone transfer

The ozonation time, that is, the contact time of ozone with water is a very important factor. With sufficient reaction time, the maximum degradability of biodegradable substances can be achieved with controlled ozonation. There is also a larger drop in values in the indicator of COD, which can lead to complete mineralization. Ozone processes are also affected by the amount of ozone delivered. Increased ozone levels provide more effective oxidation of pollutants in water.

At normal temperature, ozone reacts with a number of substances. Temperature changes generally do not cause a significant change in the rate of these oxidation processes. However, ozone solubility in water decreases with increasing temperature. The limited solubility of ozone in water also causes difficulty in mixing it with water. Mixing ozone with water is most often performed using:

- contact tanks with flooded water column with ozone-containing gas (mixture of ozone with air or oxygen),
- ozone-injected ejectors,
- mixing tanks using mechanical mixing (propeller mixer, turbine) and water jump.

The distribution of ozone in the reaction mixture is most often used with a porous distribution element (diffuser) or venturi ejector. When using porous distribution elements it is an analog of pneumatic aeration. The ozone-containing reaction mixture is fed into the ozonation reactor under elevated pressure and then distributed to the liquid reaction mixture (or slurry) in the form of gaseous bubbles. The main advantage of pneumatic ozone distribution is the simple design of an ozonation reactor that does not require any moving parts. The effectiveness of the use of ozone delivered in such a reaction system generally depends on:

- the interfacial interface area,
- bubble size (type and porosity of the distribution element),
- the time of gas and liquid phase contact, and
- the height of the reaction device (the height of the liquid column).

Pneumatic ozone distribution is therefore particularly advantageous for large volumes of water, for example, for water treatment. Its basic disadvantages are that it does not allow the use of a compact reactor device (distribution elements) as well as the possibility of gradual fouling of the distribution elements and thereby the reduction of ozone utilization efficiency.

3.3. Ozone-based treatment processes

Nowadays, worldwide interest in the development of alternative water reuse technologies, especially in agriculture and industry, has grown steadily throughout the world.

Biological processes do not always produce satisfactory results, especially for industrial wastewater treatment plants, because many of the organic substances produced in the chemical industry are toxic and resistant to biological treatment [16]. Therefore, the only feasible option for these biologically persistent wastewaters is the use of modern technologies based on chemical oxidation. In this context, advanced oxidation processes (AOPs) are considered highly efficient water treatment technologies to remove organic pollutants. In particular, there are substances that are not removable by conventional processes and procedures for their high chemical stability or low biodegradability. These processes degrade organic pollutants by the formation of hydroxyl radicals that are highly reactive and non-selective [17, 18]. One of the possible potential alternatives is the use of these chemical oxidation processes for pre-treatment of wastewater and thus for the transformation of initially persistent organic substances to biodegradable intermediates, which would then be further purified in a biological process of oxidation with significantly lower costs.

Ozone is proven to be an effective degradation reactant of organic pollutants in water and wastewater [19]. High pH ozonation (> 8) also belongs to the AOPs process because it decomposes ozone molecules to stronger hydroxyl radicals. These are relatively new technologies for water treatment and wastewater treatment. Hydroxyl radicals produced by AOPs processes have a higher oxidation potential (2.8 V) than molecular ozone, therefore, they attack organic and inorganic molecules non-selectively at a very high reaction rate [20].

3.3.1. Combined ozonation and biological processes

The main task of chemical pre-treatment is the partial oxidation of biologically persistent substances to produce biodegradable intermediates. The percentage of mineralization should be minimal during pre-treatment to avoid unnecessary expenditures on chemicals and energy. This is important because electricity costs account for about 60% of the total operating costs. Another goal is detoxification of wastewater prior to biological treatment. Therefore, the extent of partial oxidation, as well as detoxification of wastewater by ozone, needs only to be sufficient enough to facilitate subsequent biodegradation of the converted organic matter. Thus, reductions in operating costs can be achieved by combining them with biological treatment [21]. Studies have shown that biodegradation in wastewater will increase when subjected to chemical oxidation first.

Another way to wider applications of ozone is to use ozone in combination with other techniques such as ultrasonic/UV radiation, hydrogen peroxide, or other hybrid methods [17]. State of the art of AOPs for wastewater treatment was presented by Poyatos et al. [22].

3.3.2. Integrated process

The major drawbacks of biological wastewater treatment processes include the high production of excess sludge. Solving the problem of sludge disposal is very important for wastewater treatment plants (WWTPs), especially from an economic and ecological point of view [23]. In recent years, research and development of new methods and strategies for the use of minimization and disposal of sludge have been intensively developed. One of the studied and to a certain extent applied processes of reducing the production of excess activated sludge is the use of ozone. In the ozonation of the sludge, cell membranes are disrupted and the intracellular material is released into the liquid phase [24]. Ozonation of sludge is presented as the most cost-effective technology with the highest disintegration performance [25, 26]. In addition, the ozonated sludge could be used as an additional carbon source for the biological removal of nitrogen, which would save a considerable part of the cost of the external carbon source [27].

Derco et al. [28] presented the results of research into the use of ozone for an integrated 2-mercaptobenzothiazole (2-MBT) degradation process after its adsorption to activated sludge and simultaneous disintegration of surplus sludge cells in order to reduce its production. During the laboratory research of the integrated process, 99% removal of 2-MBT from the activation mixture was observed after 20 min of ozonation.

Although the values of the 2-MBT removal efficiency were approximately the same for different reaction times (20 and 60 min), the effect of the samples taken on the respiration activity of the activated sludge microorganisms was significantly different. With the increase of the reaction time, less inhibitory effects of the ozonated sample on activated sludge microorganisms activity were observed, as well as greater tolerance of these microorganisms to larger substrate concentration values and higher specific respiratory rate values with the ozonated substrate, that is, with the ozonated activation mixture with the 2-MBT present.

Transformation of the pollutants does not have to eliminate the toxic effects of the resulting reaction products. However, the toxicity of wastewater can be decreased significantly. In addition to this benefit, the integrated approach to the multi-purpose use of the ozonation process increases the environmental and economic efficiency of the process [28].

3.4. Ozone-based processes in water treatment

Ozone has very strong oxidizing and disinfecting properties; therefore, it is increasingly used for water treatment. It is used to improve sensory properties and for removal of various bacteria and organic and inorganic substances [29]. The use of chlorine for disinfection leads to the production of hazardous byproducts, and the use of ozone is in many cases a more suitable alternative. Ozone was first used for water treatment in 1886 [12, 30]. The ozonation is usually followed by filtration on granular activated carbon, which is a standard method of surface water treatment for the preparation of drinking water.

Camel and Bermond [31] summarized the main applications of ozonation and related oxidation processes in the treatment of surface and ground natural waters for production of drinking water. The most important step in drinking water production is the removal of organic substances, for example, humic substances and micropollutants in order to prevent degradation processes in the distribution of drinking water. These processes could result in bad odors and tastes and formation of trihalomethanes could initiate microbial re-growth in the distribution system. Complete mineralization is hardly achieved. Consequently, additional treatment processes such as sand or granular activated carbon filtration are required to meet the drinking water requirements.

Gunten [32] describes the oxidation of various organic and inorganic compounds during the ozonation process. The mechanism of these reactions is based on ozone as a highly selective electrophile or OH radical's formation or a combination of both. When treating drinking water with ozone, the reactions between ozone, and inorganic compounds present in water are usually fast and occur by transfer of oxygen atom.

Reaction of ozone and organic micropollutants is selective. Ozone as an electrophile can react with electrons of activated aromatic systems, compounds with double bonds, and non-protonated amines. The degree to which oxidation process by ozone and ·OH radicals goes is determined by the corresponding kinetics.

Audenauert et al. [33] describe the full-scale ozonation reactor for water treatment with a simplified mathematical model. To describe the ozonation process, they developed the model involving basic processes such as organics removal, ozone decomposition, disinfection, and bromate formation. According to results of the simulations, the model describes the behavior of the reactor at different operational scenarios and conditions.

3.5. Ozone-based processes in wastewater treatment

Wastewater treatment plants are mainly designed to remove organic pollutants and nutrients. However, attention is increasingly focused on micropollutants, because even low concentrations of these substances can have an adverse effect on the aquatic ecosystem. Wastewater ozonation appears to be a promising option for the removal of these substances as part of tertiary wastewater treatment.

Laboratory tests have shown that ozone can be successfully used to remove micro-pollutants from sewage [34]. One of the examples is an application to a wastewater treatment plant in Regensdorf, Switzerland. It has been shown that ozonation is an effective way of removing a wide range of organic micropollutants from wastewater. More than 90% of substances have been degraded at relatively low ozone doses of about 0.6–0.8 g g^{-1} (O_3/DOC). Antibiotics, hormones, analgesics and so on were almost completely removed. The experience of the Regensdorf wastewater treatment plant, based on the results of the operation of this plant is that after the ozonation a further step is required: for example, sandblast sand filtration to remove reactive oxidation products. In addition to removing micropollutants, another advantage of this process is that ozone removes also bacteria scent, color, and foam. The costs associated with ozonation in the WWTP's technological line were approximately 10–20% higher than the costs required to operating the original technology.

Removal of pesticides from industrial wastewater is an important process because pesticides are resistant to biological degradation and are capable of accumulation in the environment and also exhibit possible carcinogenic and mutagenic properties. Appropriate key technologies for degradation and reduction of these pollutants in water and wastewater are ozonation and basic oxidation processes such as O_3/H_2O_2, O_3/UV, and O_3/H_2O_2/UV [35].

Ormad et al. [36] monitored the effectiveness of pesticide removal by processes commonly used in drinking water treatment technologies in Spain and in the river Ebro. The studied pesticides were: alachlor, aldrin, ametryn, atrazine, chlorfenvinphos, chlorpyrifos, pp'-DDD, op'-DDE, op'-DDT, desethylatrazine, 3,4dichloraniline, 4,40- dichlorobenzophenone, dicofol, dieldrin, diuron, endosulfan, endosulfansulfate, endrin, α-HCH, β-HCH, γ-HCH, δ-HCH, heptachlor, heptachlor epoxide, heptachlor β-epoxide, hexachlorobenzene, isodrine, 4-isopropylaniline, isoproturon, metolachlor, parathion-methyl, parathion ethyl, prometone, prometryline, propazine, simazine, terbuthylazine, terbutrine, trifluralin, and tetradifon. The following processes have been investigated: chlorine or ozone oxidation, chemical precipitation with aluminum sulfate, and adsorption on activated carbon. Oxidation with chlorine removed 60% of the pesticides studied. This process can be combined with coagulation, flocculation, and decantation, which contributes to higher pesticide removal efficiency. The disadvantage of this process is the formation of trihalomethane. Ozone oxidation was able to remove 70% of the pesticides studied. Combined with the processes of coagulation, flocculation, and decantation, the efficiency of the process was not improved; however in combination with the adsorption on activated carbon, 90% of the studied pesticides were removed.

Xue et al. [37] presented the results of a study aimed at removing hexachlorobenzene (HCB) in water using advanced UV, O_3, and UV/O_3 oxidation processes. The results showed that UV radiation itself does not contribute to the removal of HCB. HCB is better degraded by O_3 and a combination of UV/O_3. During ozonation and the combination of UV/O_3, a higher HCB removal efficiency was achieved. During 40 min a 50% HCB removal efficiency with an initial concentration of 0.2 mg was achieved.

4. Ozone in medicine

Medical ozone is a mixture of ozone and oxygen, prepared via silent electrical discharge, within a concentration range of 0.05 volume % O_3 to max. 5.0 volume % O_3. Ozone has toxic effects on the pulmonary epithelium; therefore, the exposure of the respiratory tract needs to be avoided at all times [38]. Ozone therapy is the use of medical ozone to treat a wide variety of health problems. It has been practiced for many years in Europe, the United Kingdom, Egypt, and Cuba. In the United States, the practice is not widely used because of current regulations and concerns over misapplication. Due to its strong antimicrobial effects, some hospitals use ozone to disinfect rooms, it has long been used as a water disinfectant and ozonated water can be efficiently used for disinfection of various medical tools, for example, endoscopes, as an alternative to the conventional techniques [39, 40].

The most common form of medical ozone use is ozonated autohemotherapy. The principle is to take about 250 ml of blood from a patient, expose it to ozone and drip it back intravenously. Medical ozone can also be delivered by insufflation, where the ozone mixture is applied rectally, vaginally or in the ear [39]. Mechanism of actions is by inactivation of bacteria, viruses, fungi, yeast and protozoa; stimulation of oxygen metabolism; and activation of the immune system [41]. Medical ozone application in the form of the low-dose concept is established and proven as a complementary medical method in the treatment of chronic inflammations or diseases associated with chronic inflammatory conditions [42].

Although not many controlled clinical studies have been reported, ozone therapy seems to be useful in infectious diseases, immune depression, vascular disorders, degenerative diseases, orthopedics, and for hyperuricemia and arthritis. Various studies have demonstrated that ozonated autohemotherapy exhibits beneficial effects in patients with hepatitis B, diabetes, degenerative eye disease, complex regional pain syndrome, ischemic peripheral vascular disease and osteonecrosis of the jaw and can be used also for pain alleviation of cancer patients [43, 44].

Modern technologies allow precise determination of ozone concentrations as well as evaluation of toxicity and mechanisms of action. Ozonated autohemotherapy was not proved to have acute or chronic side effects so far, and it is a very interesting and promising technology.

5. Conclusions

Ozone has an important and irreplaceable position in nature and in human society. In one case, it can preserve life on Earth; in other, it can harm or do some damage, dependent on its location. The most important role of stratospheric ozone is to preserve human health and life on Earth as such. In the last few decades, this protection is endangered by excessive release of pollution in the air (freons mainly), which causes the destruction of ozone in the stratosphere. Economical activities worldwide contribute to the significant decrease of concentration of stratospheric ozone and therefore ozone hole formation. Anthropogenic activities need to take active steps to minimize the emissions of problematic substances into the atmosphere and to repair the damage, which has been done mainly by us.

Tropospheric (ground) ozone is created in the air by the photochemical reaction of sunlight and NO_x. This process is supported by the presence of various photochemically active volatile organic compounds (VOC). The main anthropogenic source of NO_x is the exhaustions from car engines. Other sources of VOC are emissions from chemical and oil industry. Considerable amount of NO_x has its origin in burning fossil fuels in power stations, industry and in our households. The ground ozone can cause health problems, has a negative effect on living organisms and damages all kinds of materials. Also, in this case, the solution is to reduce the gas emissions, which are the precursors of ground ozone creation.

Bactericidal effects of ozone are utilized for drinking water disinfection instead of chlorine or chlorite. Ozone is also used to disinfect the water in swimming pools and to treat technological and cooling water.

Ozone also has strong oxidative effects, which result in many practical applications such as drinking water treatment, wastewater treatment and, latest, the excess sludge treatment.

Strong oxidative effects of ozone are used in the removal of organic substances during the water treatment process (humic substances), wastewater treatment process and treatment of municipal landfill leachates (various organic and inorganic substances), odor and color removal and also in the cellulose-paper industry during the whitening process.

The main limitation of ozone applications is relatively high costs of ozone generation and very short half-time of decomposition. This can be solved by new high-efficient ozone generator development, new reactors with higher ozone use efficiency, increasing the reaction rate by combining ozone with other reagents, homogenic and heterogenic catalysts and other processes.

Ozone is also used in medicine to sterilize instruments. Ozone therapies for cell and tissue regeneration are now getting very popular and develop quickly. The effects of this method are discussed, because of health risk due to the high reaction rate of ozone and its toxicity.

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Conflict of interest

There is no potential conflict of interest.

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