ATMOSPHERIC OZONE AND CLIMATE CHANGE. SYNTHETIC OZONE AND ITS APPLICATIONS. 21TH CENTURY AND ROLE OF OZONE

R.Munter
Department of Chemical Engineering, Tallinn University of Technology, ESTONIA

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Summary

Ozone is an interesting substance that touches on our modern society in many ways. First, it plays a significant role in stratosphere protecting the earth and all living organisms from the very dangerous UV-B (280-320 nm) radiation. In the stratosphere,

ozone is continuosly created and destroyed by the sun's radiations. This results in an equilibrium concentration of ozone. The equilibrium is, however, disturbed when reactive chlorine atoms, released from photolysis of chlorofluorocarbons (CFCs), waft into the atmosphere. These atoms create an imbalance by destroying ozone molecules. The loss of ozone molecules in the upper atmosphere is termed „*depletion of stratospheric ozone*". On another side, ozone may be formed in troposphere due to atmospheric pollution with nitrogen oxides (NO_X) and hydrocarbons (C_nH_m) as a constituent of the photochemical smog. Troposheric ozone is expected to continue to increase through the 21st century. In the 21st century, an increase in both temperature and water vapour in the atmosphere is anticipated. The increased water vapor would lead to a higher concentration of the OH° radical which would mute the increases in tropospheric ozone. The ability of ozone to disinfect water was recognized already in 1886. Ozone may also be used for different purposes in wastewater treatment: for disinfection, color removal, toxic and biologically resistant compounds (detergents, pesticides, nitrocompounds, oil products etc.) partial destruction before biological oxidation. Ozone in medicine is used for disinfection, wound cleansing, improved would healing, modulation of the immune system, activation of antioxidative enzymes as radical scavengers, activation of RBC metabolism with an improvement of oxygen release etc. In the 21st century several new applications of ozone were discovered: odor control, fumigation, restoration of homes/buildings that have experienced fires, mildew control, elimination of cat urine odors in homes and cars, mold/spore control on stored foodstuffs, packaing of pharmaceuticals, treatment of plastic films prior to lamination (bonding) with aluminium, cleansing surfaces of semiconductors, etc., etc.

1. Introduction

Ozone is an interesting substance that touches on our modern society in many ways. First of all, ozone is stratospere screens the surface of earth from biologically damaging ultraviolet radiation. But at the same time ozone as a strong oxidizing agent is also present in dangerous photochemical smog in troposphere. Synthesized ozone is used in many water/wastewater treatment and other industrial processes as a disinfectant and oxidant. And now, when we have entered Century 21, more and more ozone is being used around the world. It is also clear that more and more new applications for this versatile gas are being found. Potable water and wastewater treatment now can be called the "classical" applications for ozone. Ozone use for odor control, fumigation of homes and buildings, packaging of pharmaceuticals, cleansing of semiconductor chips, bleaching of pulp, kaolin and textile, regeneration of polymerization catalysts, oxidation of flue gas constituents, washing clothes, treatment, storage and processing of foods and agricultural products, medical therapy etc., etc. might be termed "non-classical". All of these uses emerge from our basic understanding of ozone that began with the recognition by German chemist Christian Schönbein in 1840 that ozone was a unique substance produced in a variety of processes.

Like most areas of science, the discovery of ozone did not come as a bolt from the blue. In the 1770s, Priestly, in England, and Scheele, in Sweden, were studying the properties of air. They were able to separate air into two parts, one that supported combustion at an increased rate over normal air, and one that did not support combustion. They both tried to interpret their experiments in terms of the existing phlogiston theory and did not realize that they had discovered a new element. In 1776, Lavoisier repeated many of their experiments and correctly recognized the elementary nature of the gas that he named oxygen (Stolarski, 2001).

In 1785 Van Marum passed electric sparks through oxygen and noted a peculiar smell and that the resulting gas reacted strongly with mercury. The peculiar odor in the air after a lightning strike had been known for centuries, including references in the Odyssey and Iliad. Van Marum and others attributed the odor to the electricity, calling it the „electrical odor“. It was C.Schönbein in 1840 who recognized that the odor was not due to the electricity, but was due to the properties of a substance produced during the electrical process. He named this substance ozone (from *ozein*, Greek for „to smell“) (Stolarski, 2001).

For the few decades immediately following Schönbein’s discovery of ozone, many studies were carried out regarding the identity of ozone, its properties, and its possible uses. In 1845 Marignac and De la Rive interpreted their experiments as indicating that ozone was just oxygen, modified by its passage through a peculiar electrical state. But in 1848, T. Sterry Hunt put forward a hypothesis that is close to our present understanding - he described the molecule of ozone (O_3) consisting from three oxygen atoms (O_3 = (OOO) (Leeds, 1880).

By the middle of the 1870s, ozone was established as a potentially important component for the normal atmosphere. Several tests had been developed to measure the amount of ozone in the air. Debates raged over the accuracy of these measurements that used litmus-type papers. Did they measure just ozone, or was there a significant contribution from hydrogen peroxide in the air ? Ozone was a very important and lively topic for research at this time. In his book „Ozone and Antizone“ Corenelius Fox (Fox, 1873) wrote:
„*To the Philosopher, the Physician, the Meteorologist, and the Chemist, there is perhaps no subject more attractive than that of ozone*“. And it has remained attractive even in the 21st century !

2. Stratospheric Ozone and Human-induced Trends

In 1801, Johann Ritter discovered that the intensity of the sun’s radiation dropped off rapidly at wavelengths below about 300 nm. He demonstrated that the wavelength of the „cutoff“ increased as the sun set and the path through the atmosphere increased. He correctly interpreted that the cutoff was the result of an absorbing substance in the atmosphere. In 1880, W.N.Hartley (1880) suggested that the atmospheric absorber was ozone. This conclusion was based on his laboratory studies of the ultraviolet absorption by ozone. He even asked the question: „*Is ozone a constant constituent of the higher atmosphere, and, if so, in what proportion is it probably present ?“*

In 1918 R. Strutt (1918) attempted to measure the absorption by ozone from a light source located four miles across a valley. He could not detect no absorption and concluded that: „*There must be much more ozone in the upper air than in the lower.“*

By this time it was further established that ozone was not near the ground, but was in the upper atmosphere, and a quantitative estimate of the amount of ozone had been made which was reasonably close to the amount now known to be in the atmosphere.

The next era of atmospheric ozone research started with the classic theory paper of Chapman, published in 1930 (Chapman, 1930). For several decades, laboratory measurements had been carried out to determine the mechanism responsible for ozone decomposition, but arguments persisted as to the correct mechanism. In 1930, H. Schumacher (1930) published a review of the laboratory work on ozone decomposition and concluded that the key intermediary formed in the initial absorption by ozone was atomic oxygen. Chapman (1930), in the same year, applied this knowledge to the first model of the distribution of ozone as a function of altitude in the atmosphere.

Chapman’s mechanism can be described by the following equations (Sodhi, 2000).
Photolysis of oxygen molecule into the reactive oxygen atoms by the ultraviolet light from the sun:

$$O_2 + h\nu \rightarrow 2O \qquad (1)$$

This reaction is followed by another in which a reactive oxygen atom recombines with an oxygen molecule:

$$O_2 + O \rightarrow O_3 \qquad (2)$$

The ozone formed in reaction (2) distributes itself in the stratosphere, forming a layer which is thin in some places, and thick in others. If to recalculate the amount of all ozone distributed in the stratosphere to the even gaseous homogeneous layer, it appears that the thickness of this layer around the earth will be only 3 mm (!). This layer of stratospheric ozone absorbs harmful ultraviolet radiations:

$$O_3 + h\nu \rightarrow O_2 + O \qquad (3)$$

In absence of ozone these damaging solar radiations would have reached the earth, causing several ill effects: blindness of animals and humans, skin cancer etc. Thus, the ozone layer filters the incoming ultraviolet radiations and affords our natural protection. No doubt, reaction (3) destroys ozone, but it also produces reactive oxygen atoms, which combine with oxygen (reaction (2)) producing more ozone to compensate the loss.

Thus, in the stratosphere, ozone is continuosly created and destroyed by the sun’s radiations. This results in an equilibrium concentration of ozone. The equilibrium is, however, disturbed when reactive chlorine atoms, released from photolysis of chlorofluorocarbons (CFCs), waft into the atmosphere. These atoms create an imbalance by destroying ozone molecules. The loss of ozone molecules in the upper atmosphere is termed „*depletion of stratospheric ozone*“.When it happens, the ozone layer’s capacity to filter out the harmful ultraviolet rays (< 300 nm) from the sun decreases.

The inert nature of the chlorofluorocarbons, a group of chemicals having wide industrial applications, imparts them enormous stability. Their residence times in the atmosphere are very long. For example, two most commonly used CFCs, CFC-11 (CCl_3F) and CFC-12 (CCl_2F_2) persist in the environment for about 75 and 110 years, respectively. Thus, even if the release of these chemicals to the atmosphere were to stop with immediate effect, they would continue depleting ozone well into the next century. In 1987 the Montreal Protocol was adopted as a completion of the Vienna Convention. Forty six countries signed an agreement aimed at a step-by-step reduction of the production and use of fully halogenized CFCs to 50% of the 1986 level by 1999.

When the CFCs are emitted and reach stratosphere, the solar radiation splits them into reactive chlorine atoms. This is followed by the next chain reactions (Sodhi, 2000):

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

$$ClO\cdot + ClO\cdot + M \rightarrow (ClO)_2 + M \tag{5}$$

$$(ClO)_2 + h\nu \rightarrow Cl\cdot + ClOO\cdot \tag{6}$$

$$ClOO\cdot + M \rightarrow Cl\cdot + O_2 + M \tag{7}$$

$$Cl\cdot + O_3 \rightarrow ClO\cdot + O_2 \tag{8}$$

The net reaction is:

$$2O_3 + h\nu \rightarrow 3O_2 \tag{9}$$

The species M represents here another molecule (for example, N_2) that absorbs the energy of reaction and remains unchanged.

As a result of this mechanism, ozone hole is formed mainly over Antarctica during spring time (September-October) and replenishes after spring (November-December). Scantly depletion, however, also occurs over Arctic and a few pockets of non-polar regions.

There is also a different, so-called dynamical theory of atmosphere according to which stratospheric air tends to circulate from higher altitudes in the tropics to lower altitudes in polar regions, carrying ozone along with it. This circulation depends on the temperature gradient between the tropics and the polar zones (Sodhi, 2000). As a result of this natural phenomenon, the concentration of ozone in non-polar regions decreases temporarily during the time following Antarctic spring. Ozone is a greenhouse gas. That is, it causes a warming of the atmosphere in its vicinity. When the concentration of ozone decreases, the temperature of the stratosphere over the non-polar regions also decreases. This means that the temperature difference between the non-polar and polar regions decreases. Due to this the circulation of stratospheric air weakens. In the years that follow, air carries lesser amounts of ozone to the Antactica after each spring. In fact, a decrease in the stratospheric air circulation activity has been recorded since 1979, and since that period the size of the ozone hole over Antarctica has consistently increased.

Thus, according to dynamical theory of atmosphere, ozone is not depleted by a chemical process. In fact, it is not depleted at all. It is only redistributed by a geographical phenomenon. However, this theory fails to explain as to how the ozone hole, wherever it occurs, is embedded with above-normal concentrations of reactive chlorine atoms and chlorine monoxide.

Over the past few years, the atmospheric concentration of nitrous oxide has recorded a consistent increase. This has been attributed to large scale combustion of fossil fuels and enhanced use of nitrogenous fertilizers. Nitrous oxide, as well as other oxides of nitrogen, are also emitted by supersonic transport aircrafts (Sodhi, 2000). Like CFCs, nitrous oxide is quite inert, in stratosphere it may be photochemically converted into more reactive nitric oxide:

$$N_2O + h\nu \rightarrow NO+N \qquad (10)$$

NO so formed then undergoes the following chain reactions:

$$NO+O_3 \rightarrow NO_2+O_2 \qquad (11)$$

$$O_3 + h\nu \rightarrow O_2+O \qquad (12)$$

$$NO_2+O \rightarrow NO+O_2 \qquad (13)$$

Net reaction:

$$2O_3 + h\nu \rightarrow 3O_2 \qquad (14)$$

This mechanism has been ruled out because the oxides of nitrogen, rather than depleting ozone, act as scavengers for the ozone depleting reactive chlorine atoms.

Now let’s discuss some consequences of ozone depletion. Solar ultraviolet radiations are composed of mainly UV-A (240-280 nm) and UV-B (280-320 nm) types. The UV-A radiations are absorbed both by oxygen (reaction (1)) and ozone (reaction (3)). However, the UV-B radiations are absorbed only by ozone. Exposure of the earth’s environment to UV-B radiations results in more deleterious effects than exposure to UV-A radiations. The penetration of UV-B radiations through the ozone hole has the following environmental implications (Sodhi, 2000):

Human health

UV-B radiations are sufficiently energetic to break apart imporatant biological molecules, including proteins and DNA. Exposure to UV-B radiations also causes the connective tissue of the skin to damage. As a result, the skin becomes finely wrinkled and loses its elasticity. It has been estimated that a 1% decline in ozone layer could lead to a 4-6% increase in the incidence of *malignant melanoma*, a form of skin cancer. Eyes too are vulnerable to excessive UV-B exposure. Melanoma of eyes, blindness and even death can result. The UV-B radiations also damage the lens of the eye. A *cataract* may be formed, one of the most preventable cause of blindness.

Crop yields

More than two-third of the crop species are damaged by ultraviolet rays. An increased level of UV-B radiations, therefore, adversely affects crop yield. A 1% increase in UV-B radiations is estimated to cause a 1% decline in the yield of soya beans, peas and beans.

Phytoplankton

Phytoplankton, the tiny drifting plants that live near the surface of the sea, seeking light for photosynthesis, are vulnerable to UV-B damage too. These organisms are the bottom link in the marine food chain and support all other forms of life in the sea. There is thus a potential for a major upheaval in the marine ecology, which could, in turn, affect human food sources.

Are there any possibilities to abate ozone depletion? Two sets of compounds are being developed as substitutes for CFCs. These are: the *hydrochlorofluorocarbons* (HCFCs) and even better, the *hydrofluorocarbons* (HFCs) (Sodhi, 2000). These compounds have the following advantages:

a) Their ozone depletion potential is far less than that of the cfcs.
b) The alternative fluorocarbons carry hydrogen atoms that make them susceptible to degradation in the lower regions of atmosphere, unlike the fully halogenated cfcs, whose long lives let them survive until they reach the stratospheric ozone layer.
c) The physical properties of alternative fluorocarbons are similar to those of cfcs, so that they could be substituted mostly without a major redesign or refitting of existing equipment.

It must be appreciated that the world moved fast to agree to phase out the CFCs once their dangers were demonstrated. This offers a hopeful precedent for international action on other threats to the global environment.

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Bibliography

Bin, A., Annusewicz, A., Konopczynski, A. (2001). *Swimming pool water treatment with ozone as a standard of the highest water quality in the newly constructed swimming pools in Poland.* Proc. 15th

Ozone World Congress, vol.**1**, London, UK, International Ozone Association. 390- 409. [A good overview on ozone properties and application for recreation purposes].

Bocci, V., Aldinucci, C., Borelli, E., Corradeschi, F., Diadori, A., Fanetti, G., Valacchi, G. (2001). Ozone in medicine. *Ozone: Sci. and Engng*. **23**(3):207-217. [An overview on ozone therapy used as a complementary medical approach].

Chapman, S. (1930). *On Ozone and Atomic Oxygen in the Upper Atmosphere*. Phil.Mag. 10:369-383. [This work proves that the key intermediary formed in the initial absorption by ozone is atomic oxygen].

Clark, T., Ruiz, J.D., Fan, H., Brinker, C.J., Swanson, B.I., Parikh, A.N. (2000). A new application of UV-Ozone treatment in the preparation of substrate-supported mesoporous thin films. *Chem.Mater*., **12**:3879-3884. [A paper on ozone use for semiconductor cleansing].

Crutzen, P.J. (1973). A discussion of the chemistry of source minor constituents in the stratosphere and troposphere. *Pure Appl. Geophys*. **106/108**: 1385-1399. [A study where is shown that photochemical production of ozone can take place everywhere in the troposphere in the course of oxidation of CO and CH_4]

Enhalt D.H. (2001). Tropospheric ozone, chemistry and Human-induced trends. *Ozone: Sci. and Engng.* **23**(6):445-453. [This is an overview on tropospheric ozone formation chemistry and anthropogenic impact].

Fox, C.B. (1873). *Ozone and Antozone: Their History and Nature*, London, England: J & A Churcill. [This is a description of ozone applications in America].

Gottschalk, C., Libra, J.A., Saupe A. (2000). *Ozonation of Water and Waste Water*. Berlin, Germany: Wiley-VCH Verlag GmbH. (A contemporary overview on ozonation of water and wastewater].

Hartley, W.N. (1880). On the probable absorption of the solar ray by atmospheric ozone. *Chem.News*, Nov. **26**, p.268. [This presents the laboratory studies of Hartley on ultraviolet absorption by ozone].

Horvath, M., Bilitzky, L., Hüttner, J. (1985) *Ozone, Monograph 20*, Oxford, UK, Elsevier Publishers. 292 p. [An handbook on ozone properties, synthesis and application for inorganics and organics oxidation].

Inui, Y., Ichiyanagi, I. (2001). *Ozone Cleaner for Bedding, Bedclothes, etc*. Japanese Patent 161797 A2, issued 19.06.2001. [A paper demonstrating ozone efficiency for bedding and bedclothes disinfection].

Kilham, L.B., Dodd, R.M. (2001). *The application of ozone for air treatment (case study of a Bingo Hall HVAC system)*. Proc. 14th Ozone World Congress, Deaborn MI, vol.2, Stamford, CT: Intl.Ozone Assoc., Pan American Group, 1999, pp.49-56. [The study on ozone use for pharmaceuticals packaging].

Lacis, A.A., Wuebbles, D.J., Logan, J.A.(1990). Radiative forcing by changes in the vertical distribution of ozone. *J.Geophys.Res.* **95**:9971-9981. [A study where is shown the vertical distribution of ozone in the atmosphere].

Leeds, A.R. (1880). Lines of discovery in the history of ozone. *Annals of the New York Academy of Sciences* **1**(3):363-391. [This work provides a good overview on the earlier decades of ozone history].

Maggiolo, A., Blair, E.A. (1959). *Ozone oxidation of sulfides and sulfooxides.* In: Ozone Chemistry and Toxicology. Advances in Chemistry Series, vol.**21,** Washington, DC., American Chemical Society, 1959, pp. 200-201. [A study on hydrogen sulfide and sulfides oxidation with ozone].

Maggiolo, A., Niegowski, S.J. (1959). *Preparation of tertiary amine oxides by ozonation*. In: Ozone Chemistry and Toxicology. Advances in Chemistry Series, vol.**21,** Washington, DC., American Chemical Society, 1959, pp. 202-204. [This is a description of ozone use for tertiary amine oxides synthesis].

Margosan, D.A., Smilanick, J.L. (2000). *Mortality of spores of Botyritis cinerea, Monilinea, Penicillium digitatum and Rhizopus stolonifer after exposure to ozone gas*. Proc. of Postharvest Integrated Pest Management Meeting, Univ. of California, Davis, CA. [A study on gaseous ozone use for spores killing].

Ozonek, J., Fijalkowski, S., Pollo, I. (1994). *A new approach to energy distribution in industrial ozonizers.* Proc. of the International Ozone Symposium „Application of Ozone in Water and Wastewater Treatment“, May 26-27: 218-227. Warsaw, Poland. [In this paper ozone synthesis in industrial ozone generators and energy consumption are discussed].

Palou, L., Smilanick, J.L., Crisoto, C.H., Mansour, M. (2001). Effect of gaseous ozone exposure on the development of green and blue molds on cold stored citrus fruit. *Plant Disease* **85**(6):632-638. [A study on ozone application for fruits and vegetables storage].

Pryor, A. (2001). *Ozone as a gaseous soil treatment agent as an alternative to methyl bromide for pre-plant fumigation.* Proc. International Ozone Association PAG Conference, Newport Beach, CA. [A study on replacement of methyl bromide with ozone in agriculture for fumigation of soil].

Ramanathan, V., Callis, L.B., Boughner, R.E. (1976). Sensitivity of surface temperature and atmospheric temperature to perturbations in the stratospheric concentration of ozone and nitrogen dioxide. *J.Atmos.Sci*. **33**:1092-1112. [A study where is shown that human activity changes stratospheric ozone concentrations].

Ramanathan, V., Dickinson, R.E. (1979). The role of stratospheric ozone in the zonal and seasonal energy balance of the earth-troposphere system. *J.Atmos.Sci*. **36**:1084-1104. [A work on the role of ozone in the energy balance of the earth-troposphere system].

Razumovski, S.D., Zaikov, G.E. (1974). *Ozone and its Reactions with Organic Compounds*. Moscow, Russia, Science, 322 p. [in Russian]

Rice, R.G. (2002a). Ozone and anthrax - knowns and unknowns. *Ozone: Sci. and Engng*. **24**(3):151-158. [This is a paper discussing ozone use for a dangerous *Bacillus anthracis* killing]

Rice, R.G. (2002b). Century 21 – pregnant with ozone. *Ozone: Sci. and Engng*. **24**(3):1-15.

Rounsaville, J., Rice, R.G. (1997). Evolution of ozone for bleaching of paper pulps. *Ozone: Sci. and Engng*. **18**(6):549-566. [An overview on ozone use in pulp and paper industry instead of chlorine].

Schumacher H.J. (1930). The mechanism of the photochemical decomposition of ozone. *J. Amer. Chem. Soc*. **52**:2377-2391. [A review on ozone decomposition mechanism].

Shine, K.P. (2001). Atmospheric ozone and climate change. *Ozone: Sci. and Engng*. **23**(6):429-435. [A paper on links between changes of atmospheric ozone content and climate change].

Snyder, S.A., Wert, E.C., Rexing, D.J., Zegers, R.E., Drury, D.D. (2006). Ozone oxidation of endocrine disruptors and pharmaceuticals in surface water and wastewater, *Ozone:Sci.and Engng*. **28**(6): 445-460. [A discussion on the possibilities to use ozone for endocrine disruptors and pharmaceutical chemicals removal from water].

Sodhi, G.S. (2000). *Fundamental Concepts of Environmental Chemistry*, Pangbourne, UK, Alpha Sci. Internat. Ltd. [A good book on fundamental concepts of environmental chemistry].

Viebahn-Haensler, R. (2001). *Milestones of Medical Ozone*. Proc. 15th Ozone World Congress, vol.1. London, UK, International Ozone Association. 20-27. [An historical overview on ozone application in medicine].

Vosmaer, A. (1916). *Ozone: Its Manufacture, Properties and Uses*. Van Nostrand Publishers, New York. [A book on ozone manufacture, properties and application on the basis of knowledge at the beginning of 20th century].

Wang, W.C., Yung, Y.L., Lacis, A.A., Mo, T., Hansen, J.E. (1976). Greenhouse effects due to Human-made perturbations of trace gases. *Science*. **194**:685-690. [This presents links between global warming and human activities].

Wang, W.C., Sze, N.D. (1980). Coupled effects of atmospheric N_2O and O_3 on the earth's climate. *Nature*. **286**:589-590. [A study showing that N_2O and O_3 are both global warming gases]

WMO Scientific Assessment of Stratospheric Ozone Depletion, 1998: Global Ozone Research and Monitoring Project, Report Nr.44, World Meteorological Organisation, Geneva, Switzerland, 1999. [A discussion on atmospheric ozone possible recovering over the next decades].

Yasuda, K., Fujimoto, Y., Shinohara, I., Kobayashi, M., Hamano, S., Nagaya, K. (2001). *Treatment of Dioxin-Containing Flue Gases*. Japanese Patent 137656 A2 (Assignee: Hitachi Shipbuilding and Engineering Co., Ltd), issued 22.05.2001. [A paper on flue gas constituents oxidation with ozone and dioxin abatement].

Biographical Sketch

Rein Munter was born in Tallinn, Estonia in 1936. Received degrees: Diploma in Chemical Engineering *Cum Laude*, Tallinn University of Technology (TUT), Tallinn, Estonia, 1960; Candidate of Technical Sciences of the USSR (equal to a Ph.D), Chemical Engineering, TUT, Tallinn, Estonia, 1968; Doctor of Technical Sciences of the USSR, Water Chemistry and Technology, Kiev Institute of Colloidal and Water Chemistry (Ukraine), 1991. Since 1992 Professor of Environmental Technology, TUT.

His work experience includes: Researcher at the Institute of Chemistry (Estonian Academy of Sciences); Assistant, Senior Lecturer, Associate Professor, Chair of Environmental and Chemical Technology, Head of Chemical Engineering Department (TUT).

Trapido M., Munter R., Veressinina Y., Kulik N. Oil shale semicoke leachate treatment using ozonation and the Fenton oxidation. Environmental Technology, 27, 2006. pp. 307-315.

Munter R., Trapido M., Veressinina Y., Goi A. Cost effectiveness of ozonation and AOPs for aromatic compounds removal from water: a preliminary study. Ozone Science & Eng., 28(5), 2006. pp. 287-293.

Trapido M., Veressinina Y., Munter R., Kallas J. Catalytic ozonation of m-dinitrobenzene. Ozone Science & Eng., 27(5), 2005. pp. 359-363.

Munter R., Ojaste H., Sutt J. Complexed iron removal from groundwater. Journal of Environ. Eng. – ASCE, 131(7), 2005. pp. 1014-1020.

Research interests: Ozonation of water/wastewater, advanced oxidation processes (AOPs) in water treatment, drinking water production, sustainable technology