RTU Zinātniskie raksti
Materiālzinātne un lietišķā ķīmija, 20. sējums 2009

MATERIAL SCIENCE AND APPLIED CHEMISTRY

ISSN 1407-7353 **2009-7353**

MATERIĀLZINĀTNE UN LIETIŠĶĀ ĶĪMIJA

APPLICATION OF ELECTROLYSIS WITH Ti_nO_{2n-1} CERAMIC ELECTRODES FOR DISINFECTION OF DRINKING WATER

DZERAMĀ ŪDENS ELEKTROLĪTISKĀ DEZINFEKCIJA AR Ti_nO_{2n-1} KERAMIKAS ELEKTRODIEM

Linda Mežule, researcher, Msc. biol.
Riga Technical University, Department of Water Engineering and Technology
Address: Azenes 16/20, LV 1048, Riga, Latvia
Phone: +371 67089085
E-mail: linda.m@inbox.lv

Madars Reimanis, researcher, Mg.sc.
Riga Technical University, Faculty of Materials Science and Applied Chemistry
Address: Azenes 14/24, LV 1048, Riga, Latvia
Phone: 371 67089211
E-mail: madars.r@inbox.lv

Juris Mālers, Dr.sc.ing.
Riga Technical University, Faculty of Materials Science and Applied Chemistry
Address: Azenes 14/24, LV 1048, Riga, Latvia
Phone: 371 67089211
E-mail: juris_malers@ktf.rtu.lv

Jurijs Ozoliņš, Asoc., prof., Dr.sc.ing.
Riga Technical University, Faculty of Materials Science and Applied Chemistry
Address: Azenes 14/24, LV 1048, Riga, Latvia
Phone: 371 67089211
E-mail: juris_oz@inbox.lv

Talis Juhna, prof., Dr.sc.ing.
Riga Technical University, Department of Water Engineering and Technology
Address: Azenes 16/20, LV 1048, Riga, Latvia
Phone: +371 67089085
E-mail: talisj@bf.rtu.lv

Keywords: electrolysis, titanium oxide, survival, Escherichia coli

Introduction

Electrochemical disinfection is an alternative for conventional drinking water treatment, which is receiving increasing attention from drinking water production industry. With this approach oxidants are produced from electrolysis of water molecules and some of dissolved chemical compounds (O·, OH·, H_2O_2, O_3, MnO^{2-}, S_2O_8) which are normally present in drinking water. Thus, this method does not require addition of reagents; therefore it is easy to automate and simple to use. In the presence of chlorine ions after being exposed to electrolysis, several species with high disinfection potential, namely, hypochlorous acid and hypochlorites (HClO, ClO^-) [1, 2] are formed. These species have residual disinfection effect; therefore their presence is particularly useful for drinking water as they allow to secure water quality in long water distribution networks.

The efficiency of electrolytic process is affected by many factors including the type of electrodes. At the moment electrodes containing Pt, Ti/Sb-doped SnO_2, IrO_2, Pt-Ir, RuO_2, MnO_2, Ti/boron-doped diamond (BDD), as well as graphite are widely used [3]. Titanium oxide-based ceramic electrode (*viz*. Ti_nO_{2n-1} where n is between 4 and 10) has not been used before in low concentration chlorine solutions, however they appear to be potentially applicable because of their relatively low cost and durability.

The potential application of electrolysis for drinking water disinfection has been investigated. However, until now the studies were limited to analyses on culturability of bacteria [4, 5] whereas other metabolic states in which pathogenic bacteria may occur in drinking water have not been investigated. It has been described that many microorganisms when subjected to stresses such as disinfection can enter "active but nonculturable (ABNC) state" [6], sometimes referred to as "viable but nonculturable" (VBNC) [7], where cells show no potential to divide, they cannot be grown to detectable levels *in vitro* on traditionally used agars but with certain vitality assays show activity [6]. Thus, in addition to traditionally used culture methods several molecular techniques such as Direct Viable Count (DVC) [8] in combination with Fluorescence *in situ* hybridization (FISH) and CTC (5-cyano-2,3-ditolyl tetrazolium chloride) staining [9, 10] could provide more detailed information about changes of viability of microorganisms during disinfection. DVC method is based on the incubation of samples with antimicrobial agents (nalidixic acid for *E. coli*) and nutrients, where nalidixic acid acts as a specific inhibitor of DNA synthesis and prevents cell division without affecting other cellular metabolic activities and causes the formation of long filamentous cells [11]. CTC method is based on incubation of cells with redox dye (CTC) which in the presence of functioning electron transport chain acts as an artificial electron acceptor, resulting in formation of fluorescent insoluble formazan crystals (CTF) inside metabolically active cells [12, 9, 10].

The aim of this study was to estimate the effect of electrolysis with Ti_nO_{2n-1} containing ceramic anode on viability of bacteria in drinking water. The experiments were carried out in laboratory scale using *Escherichia coli* as a model organism for disinfection experiments. The anode was synthesized in the Riga biomaterials innovation and development centre [13].

Materials and methods

Bacterial strains and culture conditions. *Escherichia coli* ATCC 25922 grown on R2A agar (Scharlau, Spain) was inoculated into prefiltered, liquid Luria-Bertrani (LB) media (tryptone 10 g/L, yeast extract 5 g/L, NaCl 10 g/L) and incubated with constant shaking (150 rpm) overnight at 37°C.

Sample preparation. Overnight culture of *E. coli* was centrifuged at 6000 rpm (2500g) for 2 min. Then the pellet was washed twice with sterile phosphate buffered saline (7 mM Na_2HPO_4, 3 mM NaH_2PO_4, 130 mM NaCl, pH 7.2) and resuspended in sterile distilled water. In order to determine the number of cells in suspension, a small volume of suspension (0.1 – 1 µl) was filtered on 25-mm-diameter 0.2-µm-pore-size filters (Anodisc; Whatman plc) and fixed with 3-4% formaldehyde for 15 minutes, washed with sterile distilled water, air-dried and stained with 10 µg/mL DAPI (4',6-diamidino-2-phenylindole, Merck) for 5 minutes. Cell numbers were determined by epifluorescence microscopy by counting 20 random fields of view (Ex: 545 ± 30 nm; Em. 610 ± 75 nm, dichromatic mirror 565 nm, Leica DM, LB). Then a known concentration of cells was added to 0.5 L of sterile synthetic *E. coli*-free water (0.039 M NaH_2PO_4, 0.061 M Na_2HPO_4 and different concentrations of SO_4^{2-} or Cl^-, pH ~7). Maximum concentration of chlorine ions was chosen in order not to exceed the maximum allowable concentration of chlorine ions in drinking water [14]. All samples were analyzed in triple.

Experimental procedure. Water treatment with electrolysis was performed in a specially made electrolytic cell consisting of Ti_nO_{2n-1} containing ceramic anode with an area 12.1 cm^2 and a cathode made of stainless steel, with a total surface area of 18 cm^2. The cathode consisted of two identical plates placed in parallel on either side of the anode, 5 mm away from it [15]. All control samples were left untreated. The amount of released chlorine in the water was determined according to the standard titration method [16].
Power to the electrochemical reactor was supplied by BCA-5A-K (0 – 65V, 0 – 12 A) direct current rectifier. Electrolysis process was carried out at current intensity 0.1 A, temperature 23 ± 2°C and pH 7 with intensive stirring during 15 min. The influence of the sulphate ions and buffer solution on the disinfection process and distributed chlorine variation after electrolysis were investigated. Also the influence of the electrolysis process current intensity and duration time on the disinfection processes, and changes of the extracted chlorine in electrolysis process were investigated.
After the treatment approximately 100 ml of sample were collected in sterile bottles and brought for further processing. To cease the disinfection reaction enough of sodium thiosulphate was added.

Staining of samples with CTC. 0.1 mL of all samples were stained with CTC in accordance with a modification of the procedure described by Rodriguez et al [9]. To 0.1 mL of sample 0.01 mL of 10 times concentrated LB broth and 0.011 mL of CTC (5-cyano-2,3-ditolyl tetrazolium chloride, Fluka, BioChemika) with a final concentration of 4 mM was added. The mixture was continuously stirred for 2 hours in the dark at room temperature (about 20°C). After incubation the sample was filtered through 25-mm-diameter 0.2-µm-pore-size filter, air-dried, fixed with 3-4% formaldehyde for 15 minutes, washed with sterile distilled water and stained with 10 µg/mL DAPI. Actively respiring and non-respiring cell numbers were determined with epifluorescence microscope (Leica DMLB) equipped with a 50-W power supply, mercury lamp, filter sets for DAPI (Ex: 545 ± 30 nm; Em. 610 ± 75 nm) and for fluorescent formazan crystals (Ex: 340/380 nm;. Em: >425 nm or the same channel as for DAPI in order to avoid the counting of any extracellulary fluorescing units) and a camera (CoolSNAP Pro, Media Cybernetics, Inc, USA). For image processing Image Pro Plus 4.5.1. software (Media Cybernetic Inc., Silver Spring, MD) was used.

DVC-FISH procedure. Cell viability was determined by modified DVC method by Kogure et. al. [17] and combined with FISH. To 1 mL of each sample 1 mL of Tryptone Soya broth (Oxoid Ltd., UK) and 10 µg/mL Nalidixic acid mix were added. Then all samples were incubated for 6 h at 30°C. After incubation the samples were centrifuged at 6000 rpm (2500g) for 2 min, supernatant was poured off and replaced with sterile distilled water. Then all samples were fixed with formaldehyde (final

concentration 3-4%) for at least 20 minutes. After fixation the samples were filtered through 25-mm-diameter 0.2-µm-pore-size filter. To remove extra formaldehyde, samples were washed with sterile distilled water. After washing filters were removed from filtering device and air-dried. Then 20 - 30 µL of PNA hybridization mix consisting of hybridization buffer (50 mM Tris-HCl, 10% w/v 50% dextran sulphate, 0.1 mM of NaCl, 30% v/v formamide, 30% v/v tetra-sodium pyrophosphate, 0.2% w/v polyvinylpyrrolidone, 0.2% w/v Ficoll 400, 5 mM Na_2EDTA, 0.1% v/v Triton X-100) and 200 nM of fluorescently labeled ECOLIFILM PNA probe (TCA ATG AGC AAA GGT [18] labeled with CY3 (Ex: 550, Em: 570)) were applied to the filter and covered with cover glass. The samples were incubated in a tight humidified vessel for 60 minutes at 57°C. After hybridization samples were washed with plenty of sterile distilled water and air-dried. Samples were visualized with epifluorescence microscope for detection of *E. coli* with ECOLIFILM probe, a narrow range Y3 filter (Ex: 340/380 nm;. Em: >425 nm, dichromatic mirror 565 nm) was used. For image processing Image Pro Plus 4.5.1. software was used. Cells were counted DVC positive if they were ≥ 1.5 times longer than average length of cells with no DVC treatment (DAPI stained).

Statistical analysis. For CTC assay the enumeration of bacteria was done with direct microscopic counting of 20 random fields of view for each sample. Both respiring and non-respiring bacteria were enumerated in each field of view. For DVC assay at least 20 random pictures were taken from each sample and length measurements of at least 300 cells were done with Image Pro Plus 4.5.1. software. For non-elongated cell length determination DAPI stained samples were analyzed as described above.

Results and discussion

Although *Escherichia coli*, compared to other waterborne pathogens such as *Cryptosporidium*, is not particularly resistant to disinfection, still this bacterium is used as an indicator of hygienic quality of drinking water, therefore it is of interest for water industry. During the last decade especially VBNC forms of bacteria have received attention as they are suspected as "hidden sources" of infection in drinking water.

In order to investigate whether other chemical compounds than chlorine are producing disinfection effect during expose to electricity the changes of viability of *Escherichia coli* were determined by addition of different concentrations of sulphate ions (SO_4^{2-}) to distilled water. All samples were treated for 15 minutes with low current (I – 0.1 A, pH 7 ± 0.2, t^o = 23 ± 2^{o}C) except the control which was untreated. Results showed that the effect of sulphate ions on viability of *E. coli* is minor (Fig. 1). A minor decrease in cultivability and potential for dividing was observed only in samples without sulphate ions or in samples with low sulphate ion concentration. The latter phenomenon should be investigated further.

To test the formation of active chorine from chlorine ions, KCl salt in concentrations similar to those in drinking water was added to water. The solution was electrolyzed using permanent process parameters (I – 0.1 A, pH 7 ± 0.2, t^o = 25^{o}C, t = 15 min) while stirring intensively. To observe the formation of chlorine during electrolysis, samples with different KCl concentrations but without cells were treated (see Fig. 2). Results clearly showed that residual chlorine concentration increases with the increase of chlorine ion concentration in solution. In typical surface waters concentration of chlorine ions is less than 10 mg/L, however, in areas subjected to seawater intrusion, the chorine levels can be much higher. Chlorine can be corrosive to steel pipes at levels of 50 mg/L, whereas at levels above 250 mg/L it causes an objectionable salty taste. From Fig. 2 it can be concluded that at even relatively low energy input (0.5 – 2.5 kWh/m^3, depending on water conductivity) in water samples below 50 mg/L of chlorine Ti_nO_{2n-1} ceramic electrodes generated active chlorine in the range of 0.5-3.5 mgCl_2/L, which is the level of chorine used for drinking water disinfection.

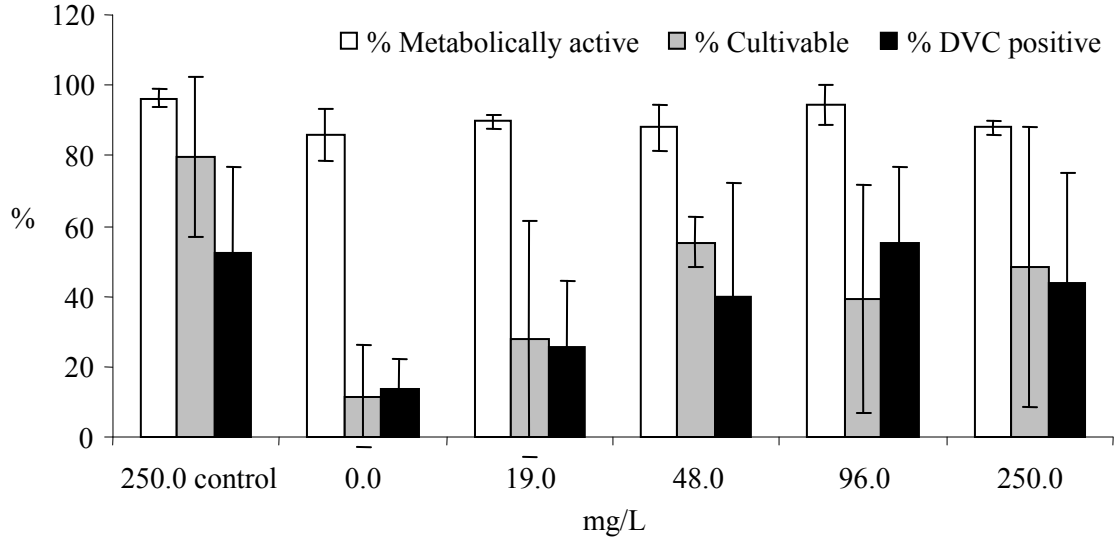

Figure 1. Percent of metabolically active – respiring (white), culturable (grey) and DVC positive – with potential for dividing (black) *Escherichia coli* cells. Standard deviation represents the dispersion of the results of three separate experiments. 100% represents the total population.

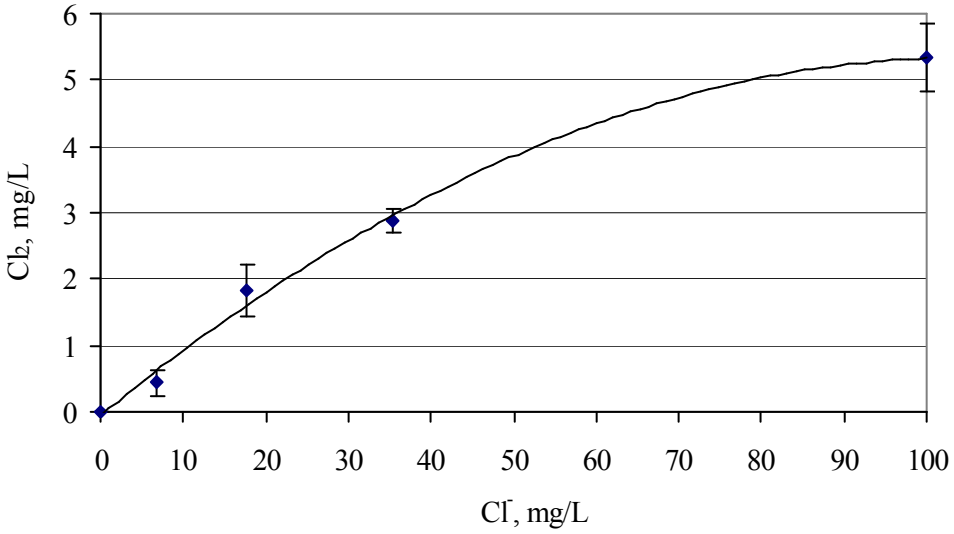

Figure 2. Amount of chlorine formed in samples with different initial concentrations of chlorine ions. Electrolysis was carried out in 0.5 L of solution (I – 0.1 A, pH 7 ± 0.2, $t^o = 23 \pm 2^oC$, t = 15 min).
The results also confirmed that disinfection effect is a result of generation of oxidant species from chlorine rather than effect of electricity *per se*, formation of radicals in water.

Effect of chlorine ion concentration on disinfection efficiency of *E. coli* is presented in Fig. 3. Results clearly showed that at level of about 7 mg/L *E. coli* is not culturable and not VBNC (respiring and able to divide). This concentration is within the range of chloride ion concentration in pristine surface waters and groundwaters.
Effect of current intensity was studied by exposing *E. coli* for 15 minutes at chlorine concentration of 6.8 mg/L (Fig. 4). Results showed that increase of current above 0.02 A was sufficient to inactivate both cultivable and VBNC *E. coli*. Notably, the cell ability to divide (DVC positive) was lost more rapidly than the ability to respire.

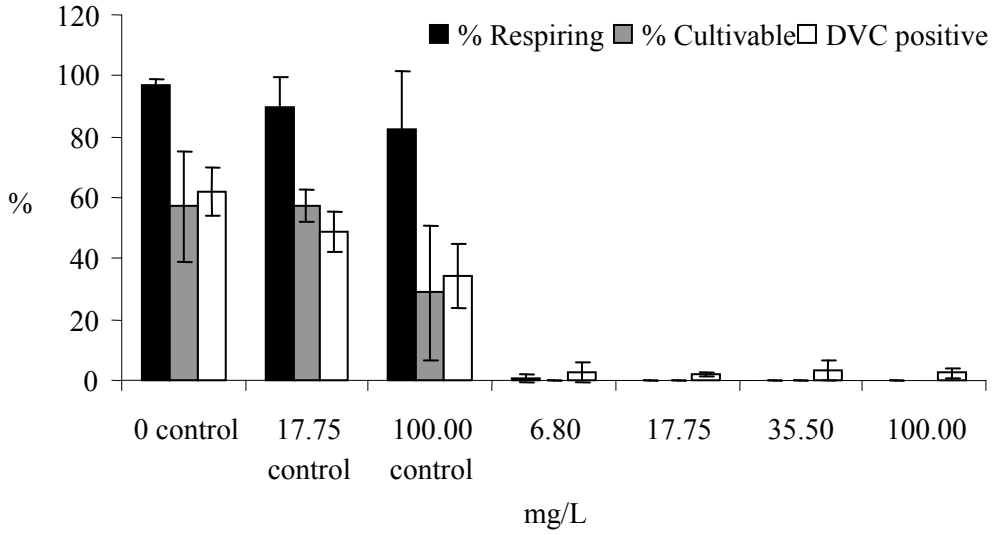

Figure 3. Effect of chlorine ion concentration on disinfection efficiency of *E. coli.* Results represented as percent of metabolically active – respiring (black), cultivable (grey) and DVC positive – with potential for dividing (white) *Escherichia coli* cells. Standard deviation represents the dispersion of the results of three separate experiments. 100% represents the total population. For control samples treatment was not used.

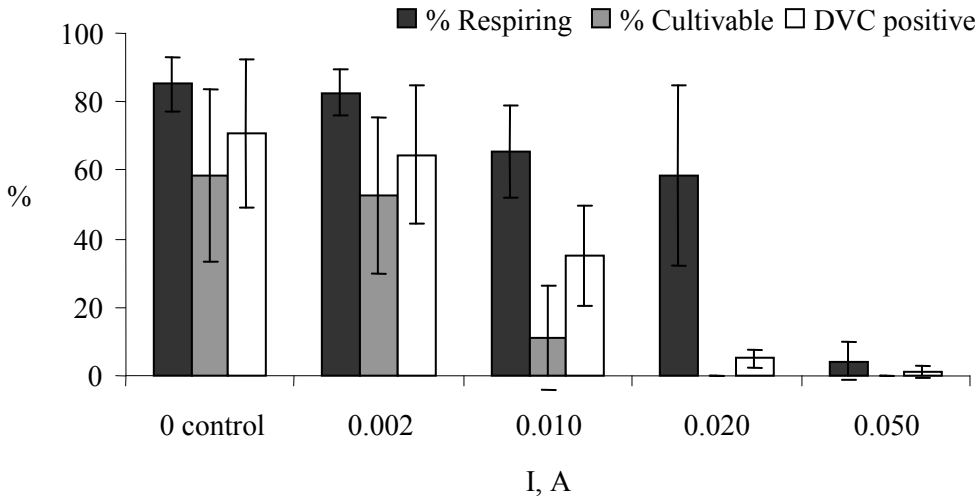

Figure 4. Effect of current intensity on disinfection efficiency of *E. coli.* Results represented as percent of metabolically active – respiring (black), cultivable (grey) and DVC positive – with potential for dividing (white) *Escherichia coli* cells. Standard deviation represents the dispersion of the results of three separate experiments. 100% represents the total population. For control samples no treatment was used.

Kinetics of disinfection was studied in water samples which were treated with 0.02 A at chlorine ion concentration of 6.8 mg/L (Fig.5). Previous experiments (Fig.2) showed that approximate level of

active chlorine formed is around 0.5 mg Cl_2/L. After the sample was exposed to this concentration, *E. coli* concentration decreased rapidly following exponential decay rate (*viz.* first-order rate constant). The rate of decrease was similar for both cultivable and able-to-divide (DVC-FISH) *E. coli*. After about 15 minutes of expose no cultivable or able-to-divide *E. coli* was detected in the sample. However, respiration ability of *E. coli* decreased with different trend: more rapidly at the beginning and nearly stopped after 3 minutes of test. This phenomenon, should be investigated further.

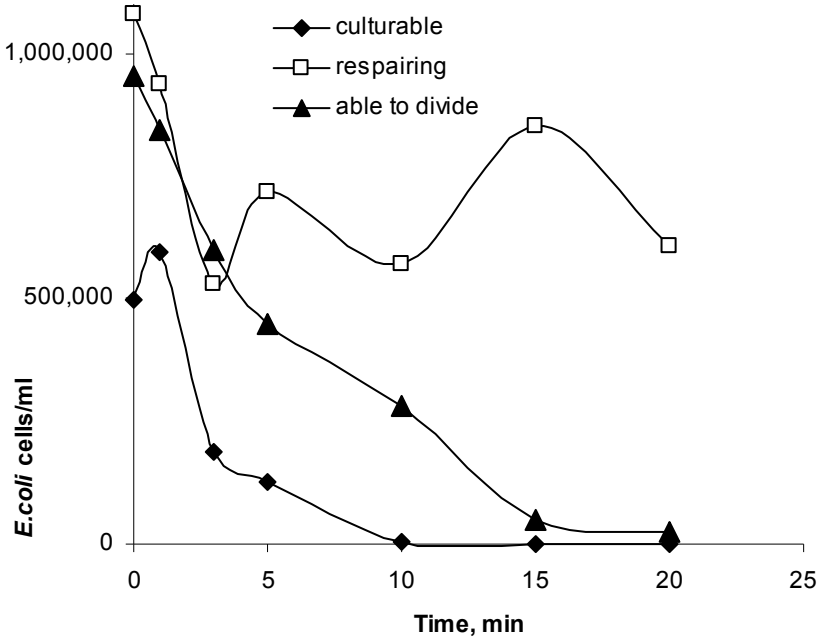

Figure 5. Effect of treatment time on disinfection efficiency (concentrations of chlorine ions 6.8 mg/L, current intensity 0.002 A, pH 7 ± 0.2, $t^o = 23 \pm 2^oC$).

Conclusions

1. The potential application of electrolysis for drinking water disinfection has been investigated. Water treatment with electrolysis was performed in a specially made electrolytic cell with Ti_nO_{2n-1} containing ceramic anode and using *Escherichia coli* as a model organism for disinfection experiments.
2. Using the Ti_nO_{2n-1} electrode in the electrolysis process with the presence of chloride ions, in concentration range which is common in raw waters, a level of active chlorine can be created that kills more than 99% of *E. coli* within 15 minutes.

References

1. A.Kraft, M.Blaschke, D.Kreysig, B.Sandt, F.Schröder and J.Rennau. Electrochemical water disinfection. Part II: Hypochlorite production from potable water, chlorine consumption and the problem of calcareous deposits. *J. Appl. Electrochem*., 1999, 29, 895-902.
2. C. Y. Cheng, G. H. Kelsall. Models of hypochlorite production in electrochemical reactors with plate and porous anodes. *J Appl Electrochem*., 2007, 37, 1203–1217.
3. X.Chen, F.Gao, G.Chen. Comparison of Ti/BDD and Ti/SnO_2–Sb_2O_5 electrodes for pollutant oxidation. *J. Appl. Electrochem.,* 2005, 35, 185–191.
4. C.Feng, K.Suzuki, S.Zhao, N.Sugiura, S.Shimada, T.Maekawa. Water disinfection by electrochemical treatment. *Bioresource Technology*, 2004, 94, 21–25.

5. R.J. Watts, M.S.Wyeth, D.D.Finn, A.L.Teel. Optimization of Ti/SnO2–Sb2O5 anode preparation for electrochemical oxidation of organic contaminants in water and wastewater. *J. Appl. Electrochem.*, 2008, 38, 31–37.
6. Kell, D. B., Kaprelyants, A. S., Weichart, D. H., Harwood, C. R., and Barer, M. R. 1998. Viability and activity in readily culturable bacteria: a review and discussion of the practical issues. *Antonie van Leeuwenhoek*. 73: 169-187.
7. Oliver, J. D. 2005. The Viable but Nonculturable State in Bacteria. *J Microbiol* 43 (S). 93-100.
8. Bjergbaek, L. A., and Roslev, P. 2005. Formation of nonculturable *Escherichia coli* in drinking water. *J App Microbiology*. 99: 1090-1098.
9. Rodriguez, G. G., Hipps, D., Ishiguro, K., and Ridgway, H. F. 1992. Use of a Fluorescent Redox Probe for Direct Visualization of Actively Respiring Bacteria. *Appl Environ Microbiol.* 58 (11). 1801-1808.
10. Schaule, G., Flemming, H., and Ridgway, H. 1993. Use of 5-cyano-2,3-ditolyl tetrazolium chloride for quantifying planktonic and sessile respiring bacteria in drinking water. *Appl Environ Microbiol.* 59 (11). 3850-3857.
11. Goss, W. A., Deitz, W. H., and Cook, T. M. 1964. Mechanism of action of nalidixic acid on *Escherichia coli*. *J Bacteriol*. 88 (4). 1112-1118.
12. Bartosch, S., Mansch, R., Knötzsch, K., and Bock, E. 2003. CTC staining and counting of actively respiring bacteria in natural stone using confocal laser scanning microscopy. *J Microbiol Methods*. 52: 75-84.
13. A.Pavlova, L.Berzina-Cimdina, J.Locs, D.Loca, J.Bossert. Preparation and characterisation of dense TiO_2 ceramics. *Advances in Science and Technology*, 2008, 54, 261-264.
14. 2003.gada 29.aprīļa MK noteikumi Nr.235 "Dzeramā ūdens obligātās nekaitīguma un kvalitātes prasības, monitoringa un kontroles kārtība."
15. M.Reimanis, J.Ozoliņš, J.Mālers. Ūdens bioloģiskā piesārņojuma samazināšana pielietojot elektrolīzes procesā TiOx saturošu keramikas elektrodus. *RTU zinātniskie raksti, Materiālzinātne un lietišķā ķīmija*, 2008, 18, 90.-96.
16. LVS EN ISO 7393-1:2001 „Water quality - Determination of free chlorine and total chlorine - Part 1: Titrimetric method using N, N-diethyl-1, 4-phenylenediamine."
17. Kogure, K., Simidu, U., and Taga, N. 1979. A tentative direct microscopic method for counting living marine bacteria. *Can J Microbiol*. 25 (3). 415-420.
18. Perry-O'Keefe, H., Rigby, S., Oliveira, K., Sorensen, D., Stender, H., Coull, J., and Hyldig-Nielsen, J. 2001. Identification of indicator microorganisms using a standardized PNA FISH method. *J Microbiol Methods*. 47 (3). 281-292.

L. Mezule, M. Reimanis, J. Malers, J. Ozolins, T. Juhna. Application of electrolysis with Ti_nO_{2n-1} ceramic electrodes for disinfection of drinking water. *The potential application of electrolysis for drinking water disinfection has been investigated. Water treatment with electrolysis was performed in a specially made electrolytic cell consisting of Ti_nO_{2n-1} containing ceramic anode and Escherichia coli was used as a model organism for disinfection experiments.*

The influence of the sulphate ion and buffer solution on the disinfection process and distributed chlorine variation after electrolysis, the influence of the electrolysis process current intensity and duration time on the disinfection processes, and changes of the extracted chlorine in electrolysis process were investigated.

Cell viability was determined by cultivation on culture media, by modified Direct Viable Count (DVC) method combined with Fluorescence in situ hybridization (FISH) and cell activity was determined by staining with redox dye 5-cyano-2,3-ditolyl tetrazolium chloride (CTC).

Results showed that the effect of sulphate ions on viability of E. coli is minor. A minor decrease in cultivability and potential for dividing were observed only in samples without sulphate ions or in samples with low sulphate ion concentration.

To test the formation of active chorine from chlorine ions, KCl salt in concentrations similar to those in drinking water was added to water. The solution was electrolyzed using permanent process parameters (I – 0.1 A, pH 7 ± 0.2, $t^o = 25^oC$, t = 15 min) while stirring intensively.

It can be concluded that at even relatively low energy input (0.5 – 2.5 kWh/m^3, depending on water conductivity) in water samples below 50 mg/L of chlorine Ti_nO_{2n-1} ceramic electrodes generated active chlorine in the range of 0.5-3.5 $mgCl_2/L$, which is the level of chorine used for drinking water disinfection. The results also confirmed

that disinfection effect is a result of generation of oxidant species from chlorine rather than effect of electricity per se, formation of radicals in water. Results clearly showed that at level of chlorine ions concentration about 7 mg/L E. coli is not culturable, not respiring and not able to divide.
Results showed that increase of current above 0.02 A at chlorine ion concentration of 6.8 mg/L was sufficient to inactivate both culturable and VBNC E. coli. Notably, the ability to divide (DVC positive) was lost more rapidly than the ability to respire
Kinetics of disinfection was studied in water sample which was treated with 0.02 A at chlorine ion concentration of 6.8 mg/L. After about 15 minutes of exposure no culturable or able-to-divide E. coli was detected in the sample. Respiration ability of E. coli decreased with different trend: more rapidly at the beginning and nearly stopped after 3 minutes of test. This phenomenon should be investigated further.
Using the Ti_nO_{2n-1} electrode in the electrolysis process with the presence of chloride ions, in concentration range which is common in raw waters a level of active chlorine can be created that kills more than 99% of E. coli within 15 minutes.

L. Mežule, M. Reimanis, J. Mālers, J. Ozoliņš, T. Juhna. Dzeramā ūdens elektrolītiska dezinfekcija ar Ti_nO_{2n-1} keramikas elektrodiem. *Darbā pētītas dzeramā ūdens dezinfekcijas iespējas ar izmantojot elektrolīzi. Ūdens apstrāde ar elektrolīzi veikta speciāli izveidotā elektrolīzes šūnā, izmantojot Ti_nO_{2n-1} saturošus keramikas elektrodus. Dezinfekcijas efektivitāte noteikta, izmantojot Escherichia coli baktērijas. Tika pētīta sulfāta jonu un buferšķīduma, elektrolīzes procesā izdalītā hlora daudzuma, kā arī strāvas stipruma un elektrolīzes ilguma ietekme uz ūdens dezinfekciju. Šūnu dzīvotspēja noteikta, izmantojot klasisko mikroorganismu kultivēšanas metodi, uzlabotu tiešās dzīvotspējas skaitīšanas (DVC) metodi apvienotu ar fluorescento in situ hibridizāciju (FISH,) kā arī, veicot parauga iekrāsošanu, ar oksidējošu-reducējošu krāsu 5-ciān-2,3-ditoliyl tetrazolija hlorīdu (CTC), lai noteiktu elpojošās šūnas.*
Iegūtie rezultāti parāda, ka sulfāta jonu ietekme uz E. coli dzīvotspēju ir niecīga. Nedaudz samazināts E. coli kultivēšanas potenciāls tika novērots šķīdumos bez sulfāta joniem un mazās to koncentrācijās.
Lai noteiktu hlora veidošanos no hlorīda joniem, elektrolīzē izmantotajam paraugam tika pievienots KCl koncentrācijās, kādas sastopamas dzeramajā ūdenī. Ūdens šķīduma elektrolīze tika veikta saglabājot nemainīgus parametrus (I – 0,1 A, pH 7 ± 0,2, $t^o = 25^oC$, t = 15 min), to intensīvi maisot.
Iegūtie rezultāti liecina, ka elektrolīzes laikā no ūdens šķīdumiem ar hlora koncentrāciju mazāku par 50 mg/L, izdalās brīvā hlora koncentrācijas robežās no 0,5 – 0,3 mg Cl_2/L , kas atbilst koncentrācijai, ko izmanto dzeramā ūdens dezinfekcijai, patērējot salīdzinoši mazu enerģijas daudzumu (0.5 – 2.5 kWh/m^3, atkarībā no ūdens elektrovadītspējas).
Rezultāti apstiprina, ka ūdens dezinfekciju nodrošina oksidanti, nevis caurplūstošā strāva vai elektrolīzes laikā izveidojušies radikāļi. No rezultātiem redzams, ka pie dotajiem procesa parametriem ūdens šķīdumos ar hlorīda jonu koncentrāciju lielāku par 7 mg/L E. coli baktērijas nav kultivējamas, tās neelpo un nav spējīgas dalīties.
Palielinot strāvas stiprumu virs 0,02 A, ūdens šķīdumam ar hlora jonu koncentrāciju 6,8 mg/L ir pietiekami, lai E. coli kļūtu nekultivējamas. Apstrādes laikā E. coli baktērijas spēja dalīties samazinājās ātrāk nekā elpošana.
Dezinfekcijas kinētika tika skatīta ūdens paraugam ar hlora jonu koncentrāciju 6,8 mg/L, elektrolizējot to pie 0,02 A stipras strāvas. Apstrādājot paraugu 15 minūtes, paraugā nekonstatēja dzīvotspējīgas baktērijas. Eksperimenta laikā E. coli elpošanas spēja samazinājās nevienmērīgi, sākumā straujāk, bet jau pēc 3 minūtēm gandrīz nemainījās. Šis fenomens būtu jāpēta tālākos eksperimentos.
Ti_nO_{2n-1} elektrods var tikt izmantots dezinfekcijas procesam ūdens šķīdumos, kuros hlorīda jonu koncentrācija ir diapazonā, kas satopama neapstrādātā ūdenī, jo spēj izdalīt tādu daudzumu aktīvā hloru, lai nogalinātu vairāk par 99% no E. coli baktērijām 15 minūšu laikā.

Л. Мезуле, М. Рейманис, Ю. Малерс, Ю. Озолиньш, Т. Юхна. Электролитическая дезинфекция питьевой воды с помощью керамических электродов, содержащих Ti_nO_{2n-1}. *В работе были исследованы возможности дезинфекции питьевой воды путём электролиза. Электролиз обрабатываемой воды производился в специально созданной электролизной ячейке, используя Ti_nO_{2n-1} содержащие керамические электроды. Эффективность дезинфекции определялась по бактериям Escherichia Coli. Было изучено влияние ионов сульфата и буферного раствора, количества выделенного хлора в процессе электролиза, а так же силы тока и длительности процесса электролиза на дезинфекцию воды. Жизнеспособность клетки определялась с помощью модифицированного метода прямого подсчёта жизнеспособности бактерий (DVC),в комбинации с гибритизации fluorescenco in situ (FISH), а также производя подкрашивание образца редокс красителем хлоридом 5-циано-2,3-дитолил тетразолия (CTC), для оценки количество дышащих клеток.*
По результатам видно, что действие ионов сульфата на жизнеспособность E. coli незначительно. Небольшое уменьшение потенциала разведения бактерий E. Coli было замечено при отсутствии и при маленьких концентрациях ионов сульфата.

Чтобы определить образование хлора из ионов хлорида, в процессе электролиза к используемому образцу прибавлялся KCl в концентрациях, встречающихся в питьевой воде. Электролиз водного раствора производился при постоянных параметрах (I – 0,1 A, pH 7 ± 0,2, t^o = 25^{o}C, t = 15 min), интенсивно перемешивая.

Полученные результаты показывают, что из водных растворов с концентрацией хлора меньше чем 50 mg/L в процессе электролиза выделяется свободный хлор в пределах концентрации от 0,5 – 0,3 mg Cl_2/L, который соответствует концентрации используемой для дезинфекции питьевой воды, потребляя сравнительно маленькое количество энергии (0.5 – 2.5 kWh/m^3, в зависимости от электропроводности воды).

Результаты подтверждают, что дезинфекцию воды обеспечивает окислитель, образующийся из хлора, а не протекающий ток или во время электролиза образующиеся радикалы. Из результатов видно, что при данных параметрах процесса в водных растворах с концентрацией ионов хлорида больше чем 7 mg/L бактерии E. coli не разводятся, они не способны дышать и делиться .

Увеличив силу тока выше 0,02 A, концентрации ионов хлора 6,8 mg/L в водном растворе достаточно, чтобы инактивировать способность бактерий E. Coli разводиться. Во время обработки способность бактерии E. coli делиться уменьшается быстрее, чем способность дышать.

Была рассмотрена кинетика дезинфекции образца воды с концентрацией хлора 6,8 mg/L, производя электролиз воды при силе тока равной 0,02 A. Обрабатывая образец 15 минут, в нём не констатировали бактерии E. coli, которые способны дышать и делиться. Во время опыта способность бактерий E. coli дышать уменьшалась неравномерно, вначале резко, но уже через 3 минуты почти не менялась. Этот феномен надо исследовать в дальнейших экспериментах.

Ti_nO_{2n-1} электрод может быть использован в процессе дезинфекции воды, концентрация ионов хлорида в которой находится в диапазоне концентраций встречающихся в необрабатаннеой воде, так как способен выделить такое количество активного хлора, которое будет способно за 15 минут убить больше чем 99% бактерий E. coli.