AN APPARATUS FOR CONDUCTING AN ELECTRO-FENTON REACTION FOR DECOMPOSING ORGANIC CHEMICAL COMPOUNDS

Background

[01] Organic chemical compounds with phenol and other aromatic groups commonly appear as components of a multitude of compositions such as medicaments, paints, solvents, etc.. Thus, such compounds frequently appear in the waste water from various industries. Compounds with phenol, benzyl, or chlorinated aromatic groups have been identified as Persistent Organic Pollution (POP) and forbidden in waste water by UNEP, as listed in the Stockholm Convention. POP waste water has become an international problem dramatically effecting human life and ecology.

[02] It has been proven that phenolic compounds have both an anticarcinogenic-proapoptotic effect and a carcinogenic, DNA damaging, mutagenic effect, inducing DNA mutations in animal and human genome, for example, leading to such diseases like neonatal acute leukemia (blood cancer). Once phenolic or similar compounds are discharged into municipal water systems, not only humans would suffer therefrom, but also the anaerobic bacteria in such systems would be deactivated and mutated, leading to the whole systems in waste water treatment plants losing their function.

[03] Various organic solvents including phenol are vastly used in pharmaceutical industry. However, currently no effective and efficient on-site measure for the removal of such compounds from plant waste water is known. This is mainly due to the fact that most of the chemical removal processes need customized research based on the properties of the specific chemical mixtures (such as customized functional groups on membranes surface vs certain chemical property) which complicates the separation processes.

[04] The electro-Fenton technology which will be described in more detail herein below, is particularly effective for the decomposition of aromatic chemical compounds, such as phenol, aniline, bisphenol and polyphenols, without secondary waste produced.

[05] The electro-Fenton technology provides a pragmatic solution for the treatment of industrial waste water which is heavily polluted by POP compounds. It allows individual factories to decompose various POP compounds on-site. The produced effluent only contains non-toxic precipitate and salt water. Some chlorine and other gases produced by

the electro-Fenton reaction can be absorbed by caustic or acidic solutions. Therefore, the electro-Fenton technology can effectively help industries to reduce the COD level (chemical oxygen demand) from waste water.

[06] However, H_2O_2 and electrical energy consumption is still a major concern for applying the electro-Fenton technology to waste water treatment on an industrial scale.

Summary of the invention

[07] Accordingly, the object of the present invention is to significantly reduce H_2O_2 and electrical energy consumption of the electro-Fenton technology to make it a cost-effective and ecological approach for decomposition of water-soluble, in particular aromatic organic pollution in waste water.

[08] The application of graphene as electrode material has been studied for solar cell counter electrodes. However, the application as a reactive membrane in a reactor has not been fully studied. Some researchers have tried different carbon materials such as carbon felt, carbon foam, etc., and have proven that such carbon cathodes could produce H_2O_2 when oxygen flow is continuously supplied under a flow rate lower than 300 ml/min.L (see reference 1 to 11).

[09] The present inventors have conducted extensive experimentation on various materials and have found that commercial graphite sheet, carbon felt or carbon foam does not provide for satisfying results in the electro-Fenton technology. Commercial graphite sheet showed a fast peel-off layer by layer after applying a strong current above 10 A/m². Carbon foam coated on e.g. a titanium support was only able to give a very small fabrication area, and was not able to be applied in an industrial scale reactor because of the limitation of physical size.

[10] The object of the present invention has now been solved by an apparatus for conducting an electro-Fenton reaction for decomposing organic, preferably aromatic, chemical compounds in polluted waste water, comprising at least one electrochemical cell having a cathode, and an anode, wherein at least the area of the cathode which comes into contact with the polluted waste water when in use, is covered by at least one graphene layer having a nanoporous structure.

[11] Preferably, the graphene layer over the cathode has a thickness between 2 nm and 70 μm.

[12] The pore size of the graphene layer preferably ranges from 1 nm to 10 nm.

[13] In a preferred embodiment, the graphene layer is a sheet material.

[14] According to the invention, it is preferred that at least the area of the cathode and/or the anode which comes into contact with the polluted waste water when in use, is covered by a protective layer.

[15] In a specific embodiment, the protective layer over the cathode is located between the graphene layer and the cathode.

[16] Preferably, the protective layer comprises a sintered powder of any metal selected from the following group, any oxide of such metal or any combination thereof: titanium, tantalum, zirconium, vanadium, niobium, hafnium, aluminium, silicon, tin, chromium, molybdenum, tungsten, lead, manganese, beryllium, iron, cobalt, nickel, platinum, palladium, osmium, iridium, rhenium, technetium, rhodium, ruthenium, gold, silver, cadmium, copper, zinc, germanium, arsenic, antimony, bismuth, boron, scandium and any metals of the lanthanide and actinide series.

[17] In a preferred embodiment of the invention, the space between the cathode and the anode within the electrochemical cell is divided by a membrane or spacer to form a cathode chamber and an anode chamber, respectively.

[18] The apparatus of the present invention preferably comprises two or more electrochemical cells in series.

[19] Preferably, the apparatus of the present invention can be provided in either a plate-frame design or a spiral wound design.

[20] In a specific embodiment, the spiral wound design is a packing structure embedding the electrodes in a packing material.

[21] Preferably, the packing material is selected from fibreglass, ceramic and fluoro-polymer materials.

[22] The present invention is also related to a system for cleaning polluted waste water from organic chemical compounds comprising an apparatus according to the invention as described hereinabove.

[23] Moreover, the present invention is related to a process for conducting an electro-Fenton reaction in an apparatus or a system according to the invention, wherein the operation current density applied to the electrochemical cell(s) is between 0.1 A/m^2 and 4000 A/m^2.

[24] Preferably, the operation pH range in the electrochemical cell(s) is between 1 and 10.

[25] In a specific embodiment of the process according to the invention, the polluted waste water is pre-treated, before entry into the electrochemical cell(s), by plasma gas or direct arc discharge through a high frequency power supply at 50 Hz to 30 kHz for a period of 1 to 120 minutes.

[26] According to the invention, the pre-treatment can be conducted either inside or outside of the apparatus of the present invention.

[27] Very surprisingly, the inventors have found that a graphene layer with a nanoporous structure over the cathode of an electrochemical cell used in electro-Fenton technology dramatically reduces the H_2O_2 and electrical energy consumption. Comparison of graphene covered and non-graphene covered cathodes, used in decomposition processes of electro-Fenton technology, showed a reduction of electrical energy consumption of 27% to 56%, depending on the process conditions, for the graphene-covered cathodes. See Fig 5.

[28] It appears that the nanostructure of the graphene-cover over the cathode plays an important role in the generation of H_2O_2 as the reactive agent over an extended time period (from few minutes to few days).

[29] One way of covering the cathode by a graphene layer is by applying a pre-fabricated graphene sheet over the cathode.

[30] Another way is to directly apply the nanoporous graphene layer as a coating onto the cathode according to processes known from the prior art per se. Typically, a water-soluble homogenous solution in a concentration range of 0.1 µg/l to 200 g/l carbon is coated onto the cathode, with coating times from 10 s to 1 h. Chemical reduction of the graphene oxide is conducted under strong reducing agents such as typically hydrazine or hydroiodic acid. The preferred annealing temperature for the graphene layer is between 100°C and 700°C.

[31] The graphene layer is at least applied over that part of the cathode which comes into contact when in use, with the polluted waste water to be treated in the electrochemical cell. However, more of the cathode surface or even the complete cathode surface may be covered by the graphene layer.

[32] Preferably, the apparatus of the present invention comprises a series of electrochemical cells. In the system of the present invention, the polluted waste water is delivered to the electrochemical cells by common inlets, and the treated waste water is discharged from the electrochemical cells by similar common outlets (manifold).

Moreover, the system of the present invention typically comprises a common anode gas collector and a common cathode gas collector.

[33] In a specifically preferred embodiment of the present system, a pre-treatment of the polluted waste water is done before the entry into the electrochemical cell(s) as mentioned hereinabove.

Brief description of the drawings

[34] Fig. 1 is a schematic diagram of the concept of the electro-Fenton reaction.

[35] Fig. 2 shows the design of an electro-Fenton system of the present invention.

[36] Fig. 3a and 3b show an example of a plate-frame design of the apparatus of the invention.

[37] Fig. 4a and 4b show an example of a spiral wound design of the apparatus of the invention.

[38] Fig. 5 is a table illustrating the performace of the E-Fenton system in accordance with an embodiment of the invention; and

[39] Fig. 6 is a table comparing the power consumption with and without hi-frequency pre-treatment.

Detailed description of the invention

[40] Working principle of the electro-Fenton technology

[41] A radical (more precisely, a free radical) is an atom, molecule, or ion that has unpaired valance electrons or an open electron shell, and therefore may be seen as having one or more “dangling” covalent bonds.

[42] This unpaired valence electron makes free radicals highly chemically reactive towards other substances or towards themselves. Indeed, radicals are intermediate stages in many chemical reactions.

[43] Free radicals may be created in a number of ways, including synthesis with very dilute or depleted reagents, reactions at very low temperatures, or breakup of larger molecules. The latter can be effected by any process that puts enough energy into the parent molecule such as ionizing, radiation, heat, electrical discharges, electrolysis, and chemical reactions. Sometimes, the free radical generation can be catalyzed by ferric ions.

[44] In the electro-Fenton reaction, free radicals are generated by hydrogen peroxide (H_2O_2) and the free radical (R.) is generated by extra electrical energy exerted on parent molecules. The combination of hydroxyl radicals and free radicals R. will produce

organic precipitation. In the case of the electro-Fenton reaction, the free radical R. includes primary, secondary, or tertiary alkyl, allyl, phenol, or benzyl radicals as well as the breakup species of larger molecules.

[45] Phenol and benzyl radicals represent the chemical compounds that are most difficult to be decomposed. The above radicals show a tendency of increasing potential energy. Once the phenol or benzyl pollutant could be decomposed, other types of chemical compounds would be surely easier to be decomposed under the same conditions.

[46] At the cathode surface, hydrogen peroxide is generated and could last until the battery action is finished.

[47] In the present invention, the above described electro-Fenton reaction is confined in the cathode chamber and all of the precipitation will be discharged from the common outlet (manifold) thereof. The toxic gas will be collected and absorbed in wet scrubbers of the system. The Joule heat is dramatically reduced and the electrical energy is used at a much higher efficiency to produce organic precipitation as in an electro-Fenton system without a graphene layer over the cathode.

[48] Design of the electrochemical cell of the electro-Fenton system

[49] Fig. 1 is a conceptual draft for an electro-Fenton reaction.

[50] Both the anode and the cathode are coated, the anode by a protective coating which may or may not have a nanoporous structure, and the cathode by the graphene layer of the present invention. Between the graphene layer and the cathode base material, an additional protective layer may be located which may be identical to or different from the protective layer on the anode.

[51] In contrast to the electro-Fenton reaction directly on the metal surface of the cathode or on the protective layer, the graphene layer of the present invention dramatically reduces the electrical resistance on the cathode, thus significantly reducing the Joule heat, and noticeably improves the reaction efficiency. At the same time, the nanoporous graphene layer over the cathode produces hydrogen peroxide, continuously providing the reagent for the electro-Fenton reaction, resulting in a drop of costs on hydrogen peroxide by up to 80%.

[52] Fig. 2 shows an industrial plate-frame design 200 (see also Fig. 3a and 3b) of an electro-Fenton system according to the present invention. In this system, the potential of the first cathode equals the potential of the second anode. Therefore, the electrochemical

cells can be arranged back-to-back or just simply share the two sides of one plate.

[53] Fig. 3a shows the industrial plate-frame design while Fig. 3b shows the industrial plate-frame in a suitable housing. The nozzle shown in Fig. 3b is operable to pump in original waste water mixed with H_2O_2.

[54] The electro-Fenton system includes, in addition to the series of electrochemical cells, an anode manifold 202, a cathode manifold 204, an anode gas collector 206, a cathode gas collector 208 and a circulation tank 210 of cathode liquid, heat exchanger (chiller) 212, air compressor 214 and membrane aeration system 216.

[55] After the reaction starts, organic precipitation appears in the cathode chamber. The cathode liquid will be circulated through a circulation tank, precipitating organic sludge from the bottom of the tank, and returning the clear liquid after membrane filtration 220.

[56] A gas produced on the anode will be collected in a common collector 206 and absorbed by a wet scrubber 218. The cathode gas (H_2) will be collected in a common collector 208 and released into the atmosphere.

[57] The body of the frame and plate cells are made of stainless steel coated with polymer for corrosion resistance purpose. All fittings and connections are coated with the same or a different polymer for anti-corrosion.

[58] The electrode material of the anode and the cathode is selected from a relatively inexpensive metal having a high conductivity and oxidation resistance. In particular, the electrode material is selected from the group consisting of brass, amorphous carbon , graphite, graphene, copper, copper graphite, copper tellurium, copper tungsten, copper zirconium diboride, gold or gold alloy, electrographite, metal graphite, molybdenum, palladium or palladium alloys, platinum or platinum alloys, plated base metal, resin bonded graphite, silver or silver alloys, silver copper, silver cadmium oxide, silver graphite, silver molybdenum, silver nickel, silver tin oxide, silver tungsten, silver tungsten carbide, ruthenium or ruthenium oxide, iridium or iridium oxide, and tungsten or tungsten carbide.

[59] The electrode material is treated or coated with anti-corrosion treatments or anti-corrosion coatings to make it suitable for the electrochemical environment. The anti-corrosion materials form protective layers on the electrode surface, having electrical conductivity, the ability to cohere to the electrode material, and surface reaction under a

strong electrochemical environment. The protective layer on the anode and on the cathode may be identical or different. The protective layer on the electrodes comprises a sintered powder of any metal selected from the following group, any oxide of such metal or any combination thereof: titanium, tantalum, zirconium, vanadium, niobium, hafnium, aluminium, silicon, tin, chromium, molybdenum, tungsten, lead, manganese, beryllium, iron, cobalt, nickel, platinum, palladium, osmium, iridium, rhenium, technetium, rhodium, ruthenium, gold, silver, cadmium, copper, zinc, germanium, arsenic, antimony, bismuth, boron, scandium and any metal of the lanthanide and actinide series.

[60] Except for a minor amount of hydrogen peroxide to be added at the beginning of the reaction, the major amount of hydrogen peroxide will be generated on the nanoporous graphene coating or cover on or over the cathode, under an operation current density of 0.1m A/m² to 4000 A/m².

[61] Preferably, the electro-Fenton system of the present invention comprises an aeration tube as a gas source for H_2O_2 formation on the cathode. The gas source either is compressed oxygen or compressed air, releasing along the surface of the cathode in a rate of 2-300ml/l.min.

[62] Preferably, the electro-Fenton system of the present invention comprises a series of electrodes and a series of homogenous membranes applied in parallel between the cathode and the anode within a matrix 222, the membrane pore size ranging from 2 nm to 500 μm. The material of the homogenous membrane of the electrochemical cells may be any material which is conventionally used for membranes in electrochemical cells.

[63] The homogenous membranes in the electrochemical cells of the electro-Fenton system may either be wound in a spiral or provided as a homogenous flat sheet porous membrane which could be fabricated under standard industrial processes in bulk amounts.

[64] The reaction process is controlled by a feedback pH adjusting system. The combination of pH online monitoring and the membrane partitions enables a stable pH to last up to 24 hours. The pH operation range will be 1 to 10.

[65] Ultra-thin chambers in series with good circulation allow the reaction to be finished in very short time. A spiral wound design of the membranes provides means to

obtain a thin chamber and large reaction area simultaneously. The reaction area for such approach could reach more than 10 m^2. All of the electrodes and membranes are wrapped in one compact cylinder. The electrodes in such a system are usually embedded in packing material, preferably selected from fiberglass, ceramic material and fluoro-polymers. See Fig. 4a and Fig. 4b for a spiral wound design, where Fig. 4b is illustrates a perspective view of the house housing the spiral wound reaction surface. The nozzle shown in Fig. 4b is operable to pump in original waste water mixed with H_2O_2.

Example 1 Performance test for organic drug polluted waste water

[66] Materials: Real case waste water donated by a pharmaceutical company, with an original COD of 55,000 ppm. H_2O_2 solution and $FeSO_4$. Electrodes coated with nano-structure conductive film, membranes, and tape water. DC power supply max 8000 W, 100 A DC output. Peristaltic pump, 6 mm silicon tubing and 1l beakers.

[67] The original waste water mixed with 20 ml H_2O_2 was directly pumped into the cathode chamber, and tape water was pumped in the anode chamber. 5 ml - 50 ml of 0.1M of $FeSO_4$ was added into the cathode chamber. The electro-Fenton reaction starts with an electric loading of 10 A on a pair of flat sheet electrodes with an area of 20cmx30cm. When the precipitation became obviously, 30% of the cathode liquid was released into the 1L beaker, and the clear liquid return was pumped back into the cathode chamber. The precipitation sludge shows grey brown color. After 10 h, both the cathode and anode chamber change their colors. The anode chamber became colorless, and the cathode chamber became bright green. After filtration, the liquid from the cathode chamber turns into colorless and odorless. The precipitation is a green colored solid.

Example 2. Performance test for fluorescence paint polluted waste water

[68] Materials: Real case waste water donated by an aerospace company, with an original COD of 12,000 ppm, and a bright yellow color. H_2O_2 solution and $FeSO_4$. Electrodes coated with nanostructure conductive film, membranes, and tape water. DC power supply max 8000 W, 100 A DC output. Peristaltic pump, 6 mm silicon tubing and 1l beakers.

[69] The original waste water mixed with H_2O_2 was directly pumped into the cathode

chamber, and tape water was pumped into the anode water. 5 ml - 50 ml of 0.1M $FeSO_4$ was added into the cathode chamber. The electro-Fenton reaction starts with an electric loading of 10 A on a pair of flat sheet electrodes with an area of 20cmx30cm. When the precipitation became obviously, 30% of the cathode liquid was released into the 1L beaker, and the clear liquid return pumped back into the cathode chamber. No much precipitation appeared in the beaker. After 20 min, both the cathode and anode chamber became colorless.

Example 3. Performance test for ink polluted waste water.

[70] Materials: Real case waste water donated by an ink company, with an original COD of 8,000 ppm, black coloured waste water. The original waste water mixed with H_2O_2 was directly pumped into the cathode chamber, and tape water was pumped into the anode water. 5 ml - 50 ml of 0.1M of $FeSO_4$ was added into the cathode chamber. The E-Fenton reaction starts with an electric loading of 10 A on a pair of flat sheet electrodes with an area of 20cmx30cm. When the precipitation became obviously, 30% of the cathode liquid was released into the 1L beaker, and the clear liquid return pumped back inthe cathode chamber. Only very little precipitation appeared in the beaker. After 30 min, both the cathode and anode chamber became colorless.

[71] Example 4

[72] All of the waste water samples as in Examples 1, 2, and 3.

[73] The original waste water was pre-treated by plasma gas or direct arc discharge through a high frequency power supply. The lower COD waste (COD < 10,000 ppm) is treated for 0.5-10 min; the waste water with higher COD (COD > 10,000 ppm) is treated for 10-30 min, cooling by chilled tape water. After the pre-treatment, the waste water is pumped into the electro-Fenton reactor. The electro-Fenton reaction time also depends on the COD level. The low COD sample may only need 10-20 min. The high COD sample may need 30 min-5h to reduce the COD to 600ppm.

[74] This process with pre-treatment significantly benefits to high COD waste. It improves the reaction efficiency and reduces the power consumption up to 70% -80% compared to that without pre-treatment See Fig. 6.

[75] Those skilled in the art will appreciate that the invention described herein is susceptible to variations and modifications other than those specifically described. The invention includes all such variation and modifications. The invention also includes all

of the steps, features, formulations and compounds referred to or indicated in the specification, individually or collectively and any and all combinations or any two or more of the steps or features.

[76] Each document, reference, patent application or patent cited in this text is expressly incorporated herein in their entirety by reference, which means that it should be read and considered by the reader as part of this text. That the document, reference, patent application or patent cited in this text is not repeated in this text is merely for reasons of conciseness.

[77] Any manufacturer's instructions, descriptions, product specifications, and product sheets for any products mentioned herein or in any document incorporated by reference herein, are hereby incorporated herein by reference, and may be employed in the practice of the invention.

[78] The present invention is not to be limited in scope by any of the specific embodiments described herein. These embodiments are intended for the purpose of exemplification only. Functionally equivalent products, formulations, methods and designs are clearly within the scope of the invention as described herein.

[79] The invention described herein may include one or more range of values (e.g. size, concentration, frequency, current density etc.). A range of values will be understood to include all values within the range, including the values defining the range, and values adjacent to the range which lead to the same or substantially the same outcome as the values immediately adjacent to that value which defines the boundary to the range.

[80] Throughout this specification, unless the context requires otherwise, the word "comprise" or variations such as "comprises" or "comprising", will be understood to imply the inclusion of a stated integer or group of integers but not the exclusion of any other integer or group of integers. It is also noted that in this disclosure and particularly in the claims and/or paragraphs, terms such as "comprises", "comprised", "comprising" and the like can have the meaning attributed to it in U.S. Patent law; e.g., they can mean "includes", "included", "including", and the like; and that terms such as "consisting essentially of" and "consists essentially of" have the meaning ascribed to them in U.S. Patent law, e.g., they allow for elements not explicitly recited, but exclude elements that are found in the prior art or that affect a basic or novel characteristic of the invention.

[81] Other definitions for selected terms used herein may be found within the detailed

description of the invention and apply throughout. Unless otherwise defined, all other scientific and technical terms used herein have the same meaning as commonly understood to one of ordinary skill in the art to which the invention belongs.

[82] While the invention has been described with reference to specific methods and embodiments, it will be appreciated that various modifications and changes may be made without departing from the invention.

[83] **References:**

1 P.V. Nidheesh, R. Gandhimathi, Trends in electro-Fenton process for water and wastewater treatment: An overview, Desalination 299 (2012) 1–15.

2 Alexander Kraft, Doped Diamond: A Compact Review on a New, Versatile Electrode Material Int. J. Electrochem. Sci., 2 (2007) 355 – 385.

3 Jin Anotai, Sermpong Sairiam, Enhancing Treatment Efficiency Of Wastewater Containing Aniline By Electro-Fenton Process, Sustain. Environ. Res., 21(3), 141-147 (2011).

4 Susana Silva Martı´nez,*, Cristina Lizama Bahena, Chlorbromuron urea herbicide removal by electro-Fenton reaction in aqueous effluents, water r e s e arch 4 3 (2 0 0 9) 3 3 – 4 0.

5 Carlos A. Martı´nez-Huitle , Enric Brillas , Decontamination of wastewaters containing synthetic organic dyes by electrochemical methods: A general review, Applied Catalysis B: Environmental 87 (2009) 105–145.

6 E. Brillas, C. Arias, degradation of Organic Contaminants by Advanced Electrochemical Oxidation Methods, Portugaliae Electrochimica Acta 24(2006)159-189.

7 Ali OZCAN, Degradation of Hazardous Organic Compounds by Using Electro-Fenton Technology, Thesis, 2010.

8 J.M. Peralta-Hernández, C. A. Martínez-Huitle, Recent Advances in the Application of Electro-Fenton and Photoelectro-Fenton Process for Removal of Synthetic Dyes in Wastewater Treatment, J. Environ. Eng. Manage., 19(5), 257-265 (2009).

9 G. R. Agladze, G. S. Tsurtsumia, Comparative study of chemical and electrochemical Fenton treatment of organic pollutants in wastewater, J Appl Electrochem (2007) 37:985–990.

10 C. Barrera-Díaz,B. Bilyeu, Physicochemical Aspects of Electrocoagulation, Separation & Purification Reviews, 40:1–24, 2011.

11 J.M. Friedrich a, C. Ponce-de-Leon, Reticulated vitreous carbon as an electrode material, Journal of Electroanalytical Chemistry 561 (2004) 203–217.

CLAIMS

1. An apparatus for conducting an electro-Fenton reaction for decomposing organic, preferably aromatic, chemical compounds in polluted waste water, comprising at least one electrochemical cell having a cathode, and an anode,
wherein at least the area of the cathode which comes into contact with the polluted waste water when in use, is covered by at least one graphene layer having a nanoporous structure, wherein the pore size of the graphene layer ranges from 1 nm to 10 nm.

2. The apparatus according to claim 1, wherein the graphene layer over the cathode has a thickness between 2 nm and 70 μm.

3. The apparatus according to claims 1 or 2, wherein the graphene layer is a sheet material, a coating layer attached to metal plate, or 3D graphene (carbon) foam.

4. The apparatus according to any of the preceding claims, wherein at least the area of the cathode and/or the anode which comes into contact with the polluted waste water when in use, is covered by a protective layer.

5. The apparatus according to claim 4, wherein the protective layer over the cathode is located between the graphene layer and the cathode.

6. The apparatus according to claim 4 or 5, wherein the protective layer comprises a sintered powder of any metal selected from the following group, any oxide of such metal or any combination thereof: titanium, tantalum, zirconium, vanadium, niobium, hafnium, aluminium, silicon, tin, chromium, molybdenum, tungsten, lead, manganese, beryllium, iron, cobalt, nickel, platinum, palladium, osmium, iridium, rhenium, technetium, rhodium, ruthenium, gold, silver, cadmium,

copper, zinc, germanium, arsenic, antimony, bismuth, boron, scandium and any metals of the lanthanide and actinide series.

7. The apparatus according to any of the preceding claims, wherein the space between the cathode and the anode within the electrochemical cell is divided by a membrane or spacer to form a cathode chamber and an anode chamber, respectively.

8. The apparatus according to any of the preceding claims, comprising two or more electrochemical cells in series.

9. The apparatus according to any of the preceding claims, in a plate-frame design.

10. The apparatus according to any of claims 1 to 8, in a spiral wound design.

11. The apparatus according to claim 10, wherein the spiral wound design is a packing structure embedding the electrodes in a packing material.

12. The apparatus according to claim 11, wherein the packing material is selected from fibreglass , ceramic and fluoro-polymer materials.

13. A system for cleaning polluted waste water from organic chemical compounds comprising an apparatus according to any of the preceding claims.

14. A process for conducting an electro-Fenton reaction in the apparatus according to any of claims 1 to 12 or in the system according to claim 13, wherein the operation current density applied to the electrochemical cell(s) is between 0.1 A/m^2 and 4000 A/m^2.

15. The process according to claim 14, wherein the operation pH range in the electrochemical cell(s) is between 1 and 10.

16. The process according to claim 14 or 15, wherein the polluted waste water is pre-

treated, before entry into the electrochemical cell(s), by plasma gas or direct arc discharge through a high frequency power supply at 50 Hz to 30 kHz for a period of 1 to 120 minutes.

17. The process according to claim 16, wherein the pre-treated step of the process is conducted inside the apparatus according to any of claims 1 to 12.

18. The process according to any of claims 16, wherein the pre-treatment step of the process is conducted outside the apparatus according to any of claims 1 to 12.