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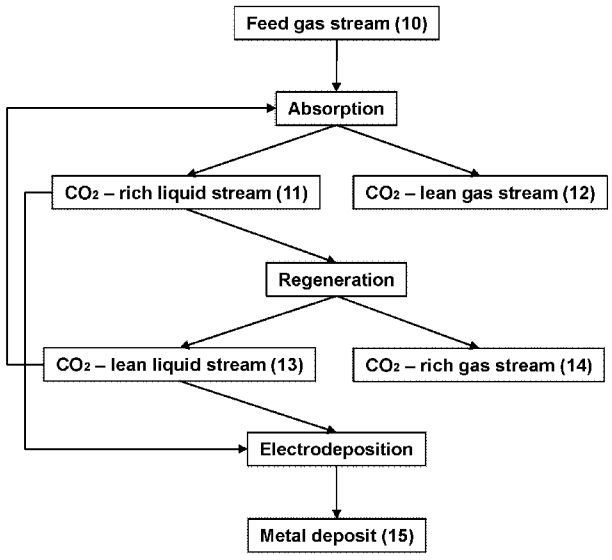

FIG 1

(57) Abstract: The invention is in the field of CO_2 capture. In particular the invention relates to a method for capturing CO_2 from a CO_2-containing feed gas stream, wherein the method comprises at least partially removing dissolved transition metal ions by electrodeposition. The invention further relates to a system for the method.

WO 2023/018331 A1

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Title: Electrochemical metal removal

The invention is in the field of CO_2 capture. In particular the invention relates to a method to remove metal ions from a solvent from CO_2 capture processes, and a system for the method.

It is widely acknowledged that it is desirable to minimize carbon dioxide emission and move towards a sustainable economy. A method to minimize emission is to capture and optionally regenerate the carbon dioxide. Conventional CO_2 capture include processes as described in US1783901 and for absorption based technologies the carbon dioxide containing gas (*e.g.* a flue gas) is fed to an absorber wherein it is contacted with a solvent. The solvent are typically amine-based aqueous solvents, such as alkanolamines. The CO_2 reacts with the solvent to form *i.a.* carbamate and/or carbonate and/or bicarbonate ions and protonated alkanolamines, and a CO_2-lean gas which leaves the absorber. The CO_2-rich stream can be fed to a regenerator (*e.g.* stripper), wherein typically a reboiler is present at the bottom to remove the CO_2 from the solvent. Typically, the highest temperature in the regenerator is around 120°C.

The high temperature in the stripper can cause degradation of the amine (thermal degradation). Moreover, the feed gas typically comprises oxygen and the presence of oxygen cause solvent degradation (*e.g.* through an oxidative degradation pathway). As described *i.a.* by H. Liu & G. Rochelle (Oxidative degradation of amine solvents for CO_2 capture, Master Thesis UT Austin (2015)), the oxidative degradation pathway is the main degradation mechanism and it is responsible for about 70% of total amine losses. This may be severe and a wide variety of volatile products *(e.g.* ammonia) and heat-stable salts can be formed. Further, the degradation products can be corrosive to the material of the CO_2 capture plant (*i.a.* absorber, regenerator, pipes), which typically comprise stainless steel. The corrosion may be monitored by the amount of metal that originate from the

material of the CO_2 capture plant. The particular metals and what metal may be predominantly present may for instance depend on *i.a.* the type of stainless steel and/or the degree of stainless steel. Typically, iron, chromium and nickel can be found as dissolved ions in the capture solvent. The dissolved metal ions can further be considered as a catalyst for the oxidative degradation, which will subsequently lead to more degradation and that will lead to more corrosivity of the solvent. This cycle can be considered as an autocatalytic process.

To recover the solvent quality by removing impurities, reclaiming processes can be employed. Reclaiming processes are typically operated batch-wise and may be costly.

An example of a solvent reclaiming process is thermal reclaiming, wherein heat is used to distill a part of the non-degraded solvent (*e.g.* amines) from the solution. However, more solvent may degrade during the reclaiming and thermal reclaiming is typically paired with significant losses of the non-reclaimed solvent. Additionally, thermal reclaiming is energy intensive and typically results in a hazardous waste stream comprising impurities, degradation products and salts. A further drawback is the limited throughput, roughly 1-2% of the total solvent flow can be subjected to thermal reclaiming.

Another method comprises ion-exchange resins, which are often used to remove charged contaminants. The principle is based on the use of cation exchange resins to replace cationic species with protons and anion exchange resins to replace anionic species with hydroxyl ions. An example hereof is disclosed in US4795565. Herein heat stable salts are removed from ethanolamine gas purification process units using ion-exchange resins. A further example, in particular for anion exchange resins, is disclosed in EP0430432. Herein an alkanolamine solution containing heat stable alkanolamine salts of acidic anions is contacted with an anion exchange resin to remove the acidic anions. Small amounts of metal cations may also

be captured by the resin. However, ion-exchange resins may require aggressive regeneration cycles, typically leading to large amounts of strong acids and bases that have to be recycled or disposed of. Accordingly, the use of ion-exchange resins may be paired with increasing complexity of the solvent and waste management. Additionally, there is typically a risk that some of the carbamate ions and protonated alkanolamines are captured by the resins.

A further example is electrodialysis. Electrodialysis can be employed to remove charged species from aqueous solvents. Herein a stack of alternating cation exchange membranes and anion exchange membranes are typically used to drive charged species through the selectively permeable membranes under an applied potential difference. A drawback of using electrodialysis is membrane fouling which increases ohmic resistance and accordingly reduces efficiency. Additionally, the carbamate ions and protonated amines may permeate through the membranes leading to a loss of solvent. This may be particularly unbeneficial at high CO_2 loading as a high concentration of carbamate and protonated amines may be present.

A need however remains on the removal of the metal ions as these seem to be a major contributor to solvent degradation. One way to remove metal from an amine-based solvent from a CO_2 capture process is disclosed in US2015/0258497. Herein a metal ion chelator is used to form a coordination complex with the metal ion. However, the metal ion chelator is in the form of a resin which requires the use of chemical eluents for the regeneration of the chelator and accordingly creates another waste stream or, alternatively, requires frequent refreshing of the chelator. Additionally, with increasing cationic amine species the selectivity of the chelator may decrease.

Activated carbon is also a proposed solution to remove degradation products from CO_2 capture solvents. The throughput is variable, from approximately 1-2% up to 10-20% of the total solvent flow. In

a campaign at a large pilot plant operating with monoethanolamine, no effect of the active carbon on the iron content was observed (Morken *et al.* International Journal of Greenhouse Gas Control (2019) Vol. 82 175-183). Further, the activated carbon typically needs to be replaced or regenerated. As the activated carbon may absorb degradation compounds safety issues are typically associated with replacing the activated carbon.

It is an object of the present inventors to provide an improved method for removing transition metal ions (herein also referred to as metal ions) from CO_2 capture liquids that overcomes at least part of the above-mentioned drawbacks. The present inventors surprisingly found that such a method can be obtained by using electrodeposition, such as electroreduction or electro-oxidation, of the metal ions.

Figure 1 illustrates a schematic flow-chart of a preferred method according to the present invention.

Figure 2 illustrates a schematic flow-chart of a preferred method according to the present invention.

Figure 3A illustrates an electrochemical cell suitable for a preferred method according to the present invention.

Figure 3B illustrates an electrochemical cell suitable for a preferred method according to the present invention.

Figure 4 illustrates a bipolar membrane suitable for the method according to the present invention.

Figure 5-10 illustrate schematic overviews of alternative embodiments of a system according to the present invention.

Figure 11 illustrates a schematic overview of a preferred system according to the present invention.

Figure 12 illustrates the iron concentration over time at different cell potentials.

Figure 13 illustrates the iron concentration over time for different starting concentrations.

Figure 14 illustrates the iron concentration over time for different starting concentrations and long-term operation (> 20h).

Thus, in a first aspect the present invention is directed to a method for CO_2 capture from a CO_2-containing feed gas stream (10). The method is schematically illustrated as flow-chart in Figure 1. The method accordingly comprises providing the feed gas stream in an absorber (101) comprising an solvent to absorb CO_2 in the solvent to obtain a CO_2-rich solvent stream (11) and a CO_2-lean gas stream (12). The solvent typically reacts with the CO_2 present in the feed gas. The CO_2-rich solvent stream can be led to a regenerator (104). In the regenerator the reaction of the solvent with CO_2 is typically reversed to obtain a CO_2-lean solvent stream (13) and a CO_2-rich gas stream (14). Further illustrated in Figure 1, the CO_2-lean solvent stream is preferably led back to the absorber. Generally, oxygen is present in the feed gas which may cause solvent degradation. The solvent degradation products can be corrosive. This can lead to the generation of metal ions into solution. The origin of the metal ions can be from the metallic parts of the capture plant (*e.g.* absorber, heat exchangers, stripper, piping, packing material). Accordingly, the CO_2-rich solvent stream and/or the CO_2-lean solvent stream comprise dissolved transition metal ions. The method further comprises at least partially removing these dissolved transition metal ions. Removal of the dissolved metal ions comprises electrodeposition of the dissolved transition metal ions in an electrochemical cell (1) to obtain a metal deposit (15). Electrodeposition is herein used to describe electroreduction and/or electro-oxidation, preferably electroreduction. The metal deposit may comprise metallic metal, metal oxides, metal (oxy)hydroxides (herein also referred to as metal oxide hydroxides). It may be appreciated that the metal oxide and/or metal (oxy)hydroxide may be unary, binary or tertiary (see *e.g. J. Am. Chem. Soc.* 2016, 138, 28, 8946-8957).

The method may be performed at ambient temperature and pressure, but as well at temperature and pressure conditions present in the capture plant. The method according to the present invention may allow for a reduced waste management, avoid fast degradation of the solvents and increase the lifetime of both solvent and industrial equipment.

The CO_2-containing feed gas stream may be any feed gas that comprises carbon dioxide. Examples include, but are not limited to flue gasses from industrial processes, air, exhaust gasses and natural gas. The feed gasses may further comprise other gasses such as molecular oxygen and/or molecular nitrogen.

The feed gas enters an absorber in which during use a solvent is provided and reacts with the carbon dioxide to absorb the CO_2. Such solvents typically comprise amine-based solvents. Preferably the solvent comprises a CO_2 capture solvent (*i.e.* a liquid that reacts with the CO_2), herein also referred to as capture solvent. Examples of suitable CO_2 capture solvent include amine-based liquids such as piperazine, glycol-based liquids and/or liquids comprising an amino-acid. More specific examples are for instance alkanolamines, such as monoethanolamine (MEA), aminomethyl propanol (AMP), methyl diethanolamine (MDEA)and combinations thereof such as a blend of 27 wt% AMP and 13 wt% piperazine (CESAR1). The CO_2 reacts with such solvents to produce *i.a.* charged species, in particular carbamate, bicarbonate and carbonate ions and protonated amines. Accordingly, the solvent streams typically comprises these solvents. The solvent may further comprise water but it may also be anhydrous. The solvent may for instance be an aqueous solution of MEA.

It may be preferred to subject the CO_2-lean solvent stream to electroreduction. Considering MEA as capture solvent, for example, the CO_2-lean loading is preferably around 0.2mol CO_2/mol amine.

The CO_2 plant, in particular the absorber, regenerator and/or the pipes, typically comprise stainless steel housing. Accordingly, the corrosion

due to the degradation products typically result in the release of transition metal ions in the liquid. These transition metal are typically iron cations, nickel cations, chromium cations, cobalt cations and/or manganese cations. Cations are herein used to refer to any individual or combination of oxidation states of the metal. For instance iron cations refer to Fe(II), Fe(III), Fe(IV) and/or Fe(VI). Similarly, nickel cations may refer to Ni(I), Ni(II), Ni(III) and/or Ni(IV). Chromium cations is used for Cr(I), Cr(II), Cr(III), Cr(IV), Cr(V) and/or Cr(VI). Cobalt cations may refer to Co(I), Co(I), Co(III), Co(IV) and/or Co(V). Manganese cations may be Mn(I), Mn(II), Mn(III), Mn(IV), Mn(V), Mn(VI) and/or Mn(VII). Generally, in the solvent the metal ions include Fe(II), Fe(III), Ni(II), Ni(III), Cr(III), Cr(VI), Co (II), Co(III) and/or Mn(II). Typically, the metal ions are iron cations, nickel cations and/or chromium cations, mainly iron cations. Iron cations are typically present in higher concentrations and accordingly, the transition metal cations are typically Fe(II) and/or Fe(III). The Roman numerals in the brackets indicate the oxidative state, *e.g.* Fe(II) is Fe^{2+}.

Typically, the transition metal concentration in the CO_2-rich solvent stream and/or the CO_2-lean solvent stream depends on the nature of the feed gas and solvent used. For a stable operation with minimal corrosion and degradation, a metal concentration of less than 5 mg/kg is typically preferred. If no reclaiming process is used, the iron concentration increases over time, typically reaching values much higher than 5 mg/kg, up to 50-100 mg/kg, a point at which operation of the plant needs to be stopped. Accordingly, the method of the present application can be applied to a transition metal concentration in the CO_2-rich solvent stream and/or the CO_2-lean solvent stream of at least 5 mg/kg, preferably at least 15 mg/kg, such as at least 20 mg/kg.

The dissolved metal ions are at least partially removed through electrodeposition, such as electroreduction or electro-oxidation of the dissolved transition metal ions in an electrochemical cell (1) to obtain a

metal deposit. The electrodeposition is carried out in an electrochemical cell. Electroreduction is generally based on the application of an electric current or a reductive potential to discharge cationic species in an electrolyte via an electron-accepting step at the cathode. Electro-oxidation is generally based on the application of an electric current or an oxidative potential to increase the positive charge of a species in an electrolyte via an electron-donating step at the anode. The cells typically comprise a cathode and an anode that are separated by an electrolyte and/or membrane. Additionally, as conventional in the art, the cell may comprise one or more reference electrodes that may be used to control the cathode and/or anode potential. The process can be run galvanostatically (*i.e.* by applying a current) or potentiostatically (*i.e.* by applying a potential on either the cathode, anode or cell).

During electroreduction, a reductive potential or a reductive current is typically applied to the cathode. The reductive potential or current may be specifically chosen such that it allows for the selective reduction of the targeted species (*i.e.* the metal ion(s)). Accordingly, the reductive potential typically varies depending on the conditions such as the cathode material, the cation(s) to be reduced and the electrolyte composition. During electro-oxidation, an oxidative potential or a oxidative current is typically applied to the anode. The oxidative potential or current may be specifically chosen such that it allows for the selective oxidation of the targeted species. Accordingly, the oxidative potential typically varies depending on the conditions such as the anode material, the species to be oxidized and the electrolyte composition.

Generally, the potential applied at the cathode is preferably between -3 and +3V vs Ag/AgCl, preferably between 0 and -3V vs Ag/AgCl. As an example, for the reduction of Fe(II) to Fe(0) on a graphite electrode in a 30% MEA aqueous solution with Ag/AgCl as reference electrode, the reductive potential applied may be between -0.8 and -1.5V, such as between

-1.0 and -1.4V. This potential is particularly favorable for reduction of iron cations. Further, the potential may be amended over time, to for instance first reduce or oxidize a first metal followed by the reduction or oxidation of a second metal. Alternatively or additionally, multiple electrochemical cells may be employed to selectively reduce or oxidize the individual metal ions. As the metals may be similar (*i.e.* close in the period table) the metals may have an overlapping reduction and/or oxidation potential that may result in the reduction or oxidation of more than one metal ion at a particular applied reduction potential.

A combination of electro-oxidation and electroreduction may also be applied. For instance, when multiple electrochemical cells are employed. A first electrochemical cell may be used to oxidize a first metal and a second electrochemical cell may be employed to reduce a second metal or vice versa.

In order to minimize or prevent any losses of oxidizable species in the solvent, such as carbamate ions, amines or protonated amines, the electrochemical cell is preferably a two-compartment electrochemical cell. However, a one-compartment cell comprising a cathode and an anode may suffice for a capture solvent that is stable. A suitable two-compartment electrochemical cell is illustrated in Figure 3A. The two-compartment electrochemical cell preferably comprises a cathodic compartment (2) comprising a cathode (3) and an anodic compartment (4) comprising an anode (5). Further, the electrochemical cell preferably comprises a bipolar membrane (6) that separates the anodic compartment and the cathodic compartment. The reduced losses of charged species may contribute to an increased solvent stability, such as increased lifetime and electrochemical stability of the solvent.

A bipolar membrane is schematically illustrated in Figure 4. The bipolar membrane (6) typically comprises an anion exchange layer (AEL) (7), a cation exchange layer (CEL) (8) and an interface layer (9). Cation

exchange layers are typically permeable to cationic species and anion exchange layers are typically permeable to anions. The interface layer can generally be considered a bipolar junctional and forms the interface between the CEL and AEL. Different morphologies for such an interface layer may be possible as can be seen in *e.g.* Pärnamäe *et al.,* Journal of Membrane Science, 617, 2021, 118538. Charged species can therefore typically not be transported through all layers of bipolar membrane, however neutral species may be transported through the layers. Typically, the anion exchange layer faces the cathodic compartment. The bipolar membrane is accordingly preferably operated under forward-bias mode.

It is even more preferred that the electrochemical cell is a two-compartment electrochemical flow cell. In such a flow cell, the to be treated liquid (*i.e.* the CO_2-lean solvent and/or the CO_2-rich solvent) is typically fed to and flows through the cathodic compartment. The anodic compartment may comprise any conventional electrolyte.

Another two-compartment electrochemical cell is illustrated in Figure 3B. Here the to be treated liquid may be fed and flow through the anodic compartment (4). The cathodic compartment (2) may, in such cases, comprise any conventional electrolyte. This configuration may be particularly favorable for metal removal in *e.g.* water treatment. Figure 3B also illustrates that the cathodic compartment may be separated from the anodic compartment by a membrane (6), such as a bipolar membrane.

In the two-compartment flow cell as illustrated in Figure 3A the to be treated liquid is provided in the cathodic compartment (2). A potential difference can be applied between the cathode and a reference electrode. Alternatively, a current can be applied. The method may accordingly be run galvanostatically or potentiostatically. A reduction potential may be applied to the cathode (3). Due to the potential at the cathode and anode (5), water may split at both the anode and cathode into H^+ and OH^-, respectively. Water splitting at the cathode and/or anode may however be preferably

minimized, as this reaction may compete with the reduction and/or oxidation of the metal ions. Accordingly, due to the bipolar membrane only a positively or negatively charged species may permeate through the exchange layers. In other words, from the cathodic compartment only the hydroxyl anions may permeate through the anionic exchange layer but are typically blocked by the cation exchange layer. Similarly, from the anodic compartment only H^+ may permeate through the cation exchange layer and are typically blocked by the anion exchange layer. Both ions typically meet in the interface layer. Here, the hydroxyl anions and protons may recombine and the neutral water molecules may permeate back to the anodic and/or cathodic compartments through the exchange layers.

The preferred bipolar membrane configuration may beneficially assist in resisting a pH change in the compartments as protons generated in the anodic compartment will consume the hydroxyl anions present in the cathodic compartment in the membrane interfacial layer. Preferably, the electrodeposition comprises electroreduction and an electrochemical cell according to Figure 3A is employed. Due to the presence of the preferred bipolar membrane positively charged amines and carbamate ions are typically prevented to transport to the anodic compartment. Accordingly, oxidation of the amines is typically minimized or prevented resulting in less degradation and solvent loss. Additionally, the bipolar membrane may block metal cations to permeate through the membrane to the anodic compartment.

In a preferred embodiment a reduction potential or current is applied. In such cases, the metal cations are typically reduced. The metal cations may be reduced to *e.g.* its elemental state, hydroxide, oxide and/or oxide hydroxide. For instance, Fe(II) may accept two electrons from the cathode and form a metal deposit of elemental iron. Alternatively or additionally, the Fe(II) may form a metal deposit of iron hydroxide, iron oxide or iron oxide hydroxide. Without wishing to be bound by theory the

present inventors believe that the reduced metal at the cathode may re-oxidize after the reductive potential is removed. Accordingly, the metal deposit may comprise metallic metal, metal oxide, metal oxide hydroxide and/or metal hydroxides.

Dependent on the metal deposit, the metal deposit may be removed from the electrochemical cell for instance by filtration and/or electrochemical regeneration of the electrodes. Filtration may for instance be used in case the metal deposit is not too strongly adhered to the cathode and/or anode but present as *e.g.* a precipitate, while for a more strongly adhered metal deposit to the cathode and/or anode the metal deposit is typically removed by electrochemical regeneration of the electrodes. The metal is typically removed from the CO_2-capture plant and thus tends to break the autocatalytic solvent degradation cycle. As the metal deposit typically forms on the cathode and/or the anode, the cathode and/or anode may also be replaced and/or removed, cleaned or regenerated (*e.g.* scraping and/or electrochemical treatment) and placed back. The cathode and/or anode may comprise any suitable material including for example carbon and/or metals such as titanium, nickel, and/or iron. A further suitable material for the anode comprises gold-coated quartz crystals. Preferably, the cathode and/or anode comprises graphite. See *e.g.* Van Khanh Nguyen and Yeonghee Ahn, *Journal of Environmental Management* 211 (2018) 36-41 and Carlos G. Morales-Guio *et al.*, *J. Am. Chem. Soc.* 2016, 138, 28, 8946–8957. Graphite electrodes are preferred as they are typically cheap. The electrode surface area may be amended to allow for a more optimal metal ion removal.

Further, as the transition metal ions are deposited a metal-lean fraction (16) remains. The metal-lean fraction typically comprises the solvent that can be reused in the absorber of the CO_2 capture system. The metal-lean fraction may accordingly be less corrosive and an increased life-time of the industrial equipment as well as the solvent may be achieved.

Accordingly, it is preferred that the metal-lean fraction is fed to the absorber. A schematic overview is illustrated in Figure 2.

In a preferred embodiment, the method is a continuous method as this typically allows for the CO_2 capture process to remain active. If the method is employed continuously, the anolyte may require occasional or continuous refreshing.

The invention is further related to a method for at least partially removing transition metal ions from a solution. The method comprises electrodeposition, preferably electroreduction, of the metal ions in a two-compartment electrochemical cell comprising a bipolar membrane (6). The bipolar membrane separates a cathodic compartment (2) from an anodic compartment (4). Preferably wherein the anion exchange layer faces the cathodic compartment.

In a further aspect, the invention is related to a system (100) for the method according to the present invention. Several embodiments are illustrated in Figures 5-10. The system comprises an absorber (101) comprising a feed fluid inlet (102) and CO_2-rich solvent outlet (103). During use the absorber typically comprises an amine-based capture solvent, which can react with CO_2 (*vide supra*). The system further comprises a regenerator (104) comprising a CO_2-rich solvent inlet (105) and a CO_2-lean solvent outlet (106). Additionally, the system comprises an electrochemical cell (1) comprising a metal-rich fraction inlet (108) and a metal-lean fraction outlet (109). As can be seen in Figure 5, the CO_2-rich solvent outlet (103) is in fluid connection with the CO_2-rich solvent inlet (105) and in fluid connection with the metal-rich fraction inlet (108). The metal-lean fraction outlet (109) is in fluid connection with the feed fluid inlet (102). The metal-lean fraction obtained from the electroreduction can thus be fed (*e.g.* recycled) to the absorber. Additionally, in Figure 5 it is further illustrated that the CO_2-lean solvent outlet (106) is in fluid connection with the feed fluid inlet (102). Figure 5 accordingly illustrates that the metal removal may be employed for

a part of the CO_2-rich solvent stream. It may be appreciated that the metal-lean fraction outlet (109) may also be in fluid connection with the CO_2-rich liquid inlet (105).

An alternative embodiment is illustrated in Figure 6, herein the CO_2-lean solvent outlet (106) is in fluid connection with the feed fluid inlet (102). The CO_2-rich solvent outlet (103) is in fluid connection with the metal-rich fraction inlet (108). The metal-lean fraction may be lead from the metal-lean fraction outlet (109) to the CO_2-rich solvent inlet (105). Accordingly, Figure 6 illustrates that all of the CO_2-rich solvent may be subjected to electrodeposition, such as electroreduction.

Figure 7 illustrates yet another alternative embodiment. Herein, the CO_2-rich solvent outlet (103) is in fluid connection with the CO_2-rich solvent inlet (105) and in fluid connection with the metal-rich fraction inlet (108). The CO_2-lean solvent outlet (106) is in fluid connection with the feed fluid inlet (102) and with the metal-rich fraction inlet (108). The metal-lean fraction outlet (109) is in fluid connection with the feed fluid inlet (102). Figure 7 accordingly illustrates an embodiment wherein at least part of the CO_2-rich solvent and at least part of the CO_2-lean aqueous solvent may be subjected to the electrodeposition, preferably electroreduction. It may be appreciated that the metal-lean fraction outlet (109) may also be in fluid connection with the CO_2-rich liquid inlet (105).

Figure 8 illustrates another alternative embodiment wherein the CO_2-rich solvent outlet (103) is in fluid connection with the CO_2-rich solvent inlet (105). The CO_2-lean solvent outlet (106) is in fluid connection with the feed fluid inlet (102) and with the metal-rich fraction inlet (108). The metal-lean fraction outlet (109) is in fluid connection with the feed fluid inlet (102). Figure 8 illustrates that at least part of the CO_2-lean solvent is subjected to electrodeposition, preferably electroreduction. It may be appreciated that the metal-lean fraction outlet (109) may also be in fluid connection with the CO_2-rich liquid inlet (105).

In another alternative embodiment, the electrochemical cell may be placed between the regenerator and the absorber as for instance illustrated in Figure 9. Herein the CO_2-rich solvent outlet (103) is in fluid connection with the CO_2-rich solvent inlet (105). The CO_2-lean solvent outlet (106) is in fluid connection with the metal-rich fraction inlet (108). The metal-lean fraction outlet (109) is in fluid connection with the feed fluid inlet (102). In this preferred embodiment, all of the CO_2-lean solvent is subjected to electrodeposition, such as electroreduction, to allow for optimal metal removal and optimal recyclability.

A schematic overview of a suitable system is illustrated in Figure 10. Herein several pumps (20, 22) are shown, a heat exchanger (21) and a heater (23). Further, it illustrates that the CO_2-rich gas stream (14) may be further led to a condenser (24) to obtain a CO_2 gas stream (17). The electrochemical cell (1) is placed such that at least part of the CO_2-rich solvent stream is subjected to electrodeposition, preferably to electroreduction.

Accordingly, the electrochemical cell for the method according to the present invention may be located at any place in the solvent loop of a CO_2 capture system, to allow for *in-situ* metal removal. Part of the liquids may for instance be tapped or bypassed to be subjected to electrodeposition. As at least part of the liquids is subjected to electrodeposition, the metal ions may be removed from these liquids allowing for a sufficient purification to continue the process with minimal corrosion and degradation.

A schematic overview of a preferred system is illustrated in Figure 11. Similarly to Figure 10, several pumps (20, 22) a heat exchanger (21) and a heater (23) are shown. It further illustrates that the electrochemical cell is preferably placed such that at least part of the CO_2-lean solvent stream (*e.g.* a slip stream) is subjected to electrodeposition, preferably electroreduction.

For the purpose of clarity and a concise description features are described herein as part of the same or separate embodiments, however, it will be appreciated that the scope of the invention may include embodiments having combinations of all or some of the features described.

The invention may further be illustrated by the following non-limiting examples.

Example 1 – cell potential

Two batch experiments were performed using an aqueous MEA solution with approximately 30 ppm Fe^{2+} concentration and a CO_2 loading of approximately 0.48 mol CO_2/mol MEA (typical rich loading). In a first two-compartment cell a potential of -1.3V was applied. In the second two-compartment cell a potential of -0.6V was applied. Graphite cathodes of 1cm^2 surface area were used in both cells.

Figure 12 illustrates the concentration of Fe over time. At a potential of -1.3V the iron concentration is reduced from roughly 31 to 24 ppm in 5 hours.

Example 2 – electrode surface area

Two experiments were carried out in a two-compartment electrochemical flow cell with 10cm^2 cathode surface area to determine if the increase in cathode surface area from 1cm^2 (Example 1) to 10cm^2 has an effect. Both experiments used aqueous MEA solutions. A first solution comprised approximately 75 ppm Fe^{2+}, the second solution comprised approximately 35 ppm Fe^{2+}. Both solutions had a CO_2 loading of roughly 0.23 mol CO_2/mol MEA (typical lean loading). The applied potential in both two-compartment cells was -1.3 V.

The results are illustrated in Figure 13. The iron concentration is reduced in three hours from roughly 75 to 60 ppm in the first cell. In the

second cell the iron concentration is reduced from approximately 35 to 30 ppm in three hours.

Example 3 –duration

Two batch experiments were carried out using aqueous MEA solutions in a two-compartment electrochemical flow cell. The first solution had an Fe^{2+} concentration of approximately 35 ppm and the second solution approximately 15 ppm. Both solutions had a CO_2 loading of roughly 0.25 mol CO_2/mol MEA. The applied potential in both cells was -1.3V. The cathode was a polished graphite cathode plate with a surface area of 10cm^2 and the anode was a Pt anode plate.

The iron concentration over time is illustrated in Figure 14. As illustrated after roughly 21 hours the iron concentration is reduced from approximately 15 to 0.1 ppm in the second cell. After approximately 22 hours the iron concentration in the first cell is reduced from roughly 35 to 3 ppm.

Claims

1. A method for capturing CO_2 from a CO_2-containing feed gas stream, wherein the method comprises:

- providing the feed gas stream (10) in an absorber (101) comprising a solvent to absorb CO_2 in the solvent to obtain a CO_2-rich solvent stream (11) and a CO_2-lean gas stream (12);

- leading the CO_2-rich solvent stream to a regenerator (104) to obtain a CO_2-lean solvent stream (13) and a CO_2-rich gas stream (14);

wherein the CO_2-rich solvent stream and/or the CO_2-lean solvent stream comprise dissolved transition metal ions;

wherein the method further comprises at least partially removing the dissolved transition metal ions from the CO_2-rich solvent stream and/or the CO_2-lean solvent stream comprising electrodeposition, preferably electroreduction, of the dissolved transition metal ions in an electrochemical cell (1) to obtain a metal deposit.

2. Method according to the previous claim, wherein the CO_2-rich solvent stream and the CO_2-lean solvent stream comprises a CO_2 capture solvent, preferably an amine-based liquid such as piperazine, a glycol-based liquid and/or a liquid comprising an amino-acid, more preferably an alkanolamine, most preferably aminomethyl propanol (AMP), methyl diethanolamine (MDEA), monoethanolamine (MEA) or combinations thereof such as a blend of 27 wt% AMP and 13 wt% piperazine (CESAR1).

3. Method according to any the previous claims, wherein the transition metal ions are selected from the group consisting of: iron cations, nickel cations, chromium cations, cobalt cations, manganese cations and a combination thereof, preferably wherein the transition metal ions are

selected from the group consisting of: iron cations, nickel cations, chromium cations and a combination thereof, more preferably the transition metal ions are iron cations.

4. Method according to any of the previous claims, wherein the electrochemical cell (1) is a one-compartment electrochemical cell comprising a cathode (3) and an anode (5).

5. Method according to any of the previous claims 1-3, wherein the electrochemical cell (1) is a two-compartment electrochemical cell comprising a cathodic compartment (2) comprising a cathode (3) and an anodic compartment (4) comprising an anode (5), preferably wherein the electrochemical cell is a two-compartment electrochemical flow cell.

6. Method according to the previous claim, wherein the two-compartment electrochemical cell further comprises a bipolar membrane (6) comprising an anion exchange layer (7), a cation exchange layer (8) and an interface layer (9), wherein the bipolar membrane separates the anodic compartment and the cathodic compartment.

7. Method according to the previous claim, wherein the anion exchange layer (7) of the bipolar membrane (6) faces the cathodic compartment.

8. Method according to any of the previous claims, wherein the transition metal concentration in the CO_2-rich solvent stream and/or the CO_2-lean solvent stream is at least 5 ppm.

9. Method according to any of the previous claims, wherein the method further comprises:

- feeding at least part of the CO_2-rich solvent stream and/or at least part of the CO_2-lean solvent stream to the electrochemical cell (1), preferably to the cathodic compartment (2) of the electrochemical cell;
- applying a reductive potential to reduce and/or an oxidative potential to oxidize the transition metal ions to obtain a metal deposit and a metal-lean fraction (15).

10. Method according to the previous claim, wherein the metal-lean fraction is fed to the absorber.

11. Method according to any of the previous claims, wherein the method further comprises removing the metal deposit.

12. Method according to any of the previous claims, wherein the method is a continuous method.

13. Method for at least partially removing transition metal ions from a solution, wherein the method comprises electrodeposition, preferably electroreduction, of the metal ions in a two-compartment electrochemical cell comprising a bipolar membrane (6) comprising an anion exchange layer (7), a cation exchange layer (8) and an interface layer (9), wherein the bipolar membrane separates a cathodic compartment (2) from an anodic compartment (4), preferably wherein the anion exchange layer faces the cathodic compartment.

14. A system (100) for capturing CO_2 from a CO_2-containing feed gas stream according to the method of any of the previous claims, wherein the system comprises;

- an absorber (101) comprising a feed fluid inlet (102) and CO_2-rich solvent outlet (103);

- a regenerator (104) comprising a CO_2-rich solvent inlet (105) and a CO_2-lean solvent outlet (106);

- an electrochemical cell (1) comprising a metal-rich fraction inlet (108) and a metal-lean fraction outlet (109),

wherein the CO_2-rich solvent outlet (103) is in fluid connection with the CO_2-rich solvent inlet (105) and/or in fluid connection with the metal-rich fraction inlet (108);

wherein the CO_2-lean solvent outlet (106) is in fluid connection with the metal-rich fraction inlet (108) and/or in fluid connection with the feed fluid inlet (102);

wherein the metal-lean fraction outlet (109) is in fluid connection with the feed fluid inlet (102) and/or in fluid connection with the CO_2-rich solvent inlet (105).

15. System according to the previous claim wherein the CO_2-lean solvent outlet (106) is in fluid connection with the metal-rich fraction inlet (108), preferably wherein the CO_2-lean solvent outlet (106) is in fluid connection with the metal-rich fraction inlet (108), the metal-lean fraction outlet (109) is in fluid connection with the fluid inlet (102) and the CO_2-rich solvent outlet (103) is in fluid connection with the CO_2-rich solvent inlet (105).

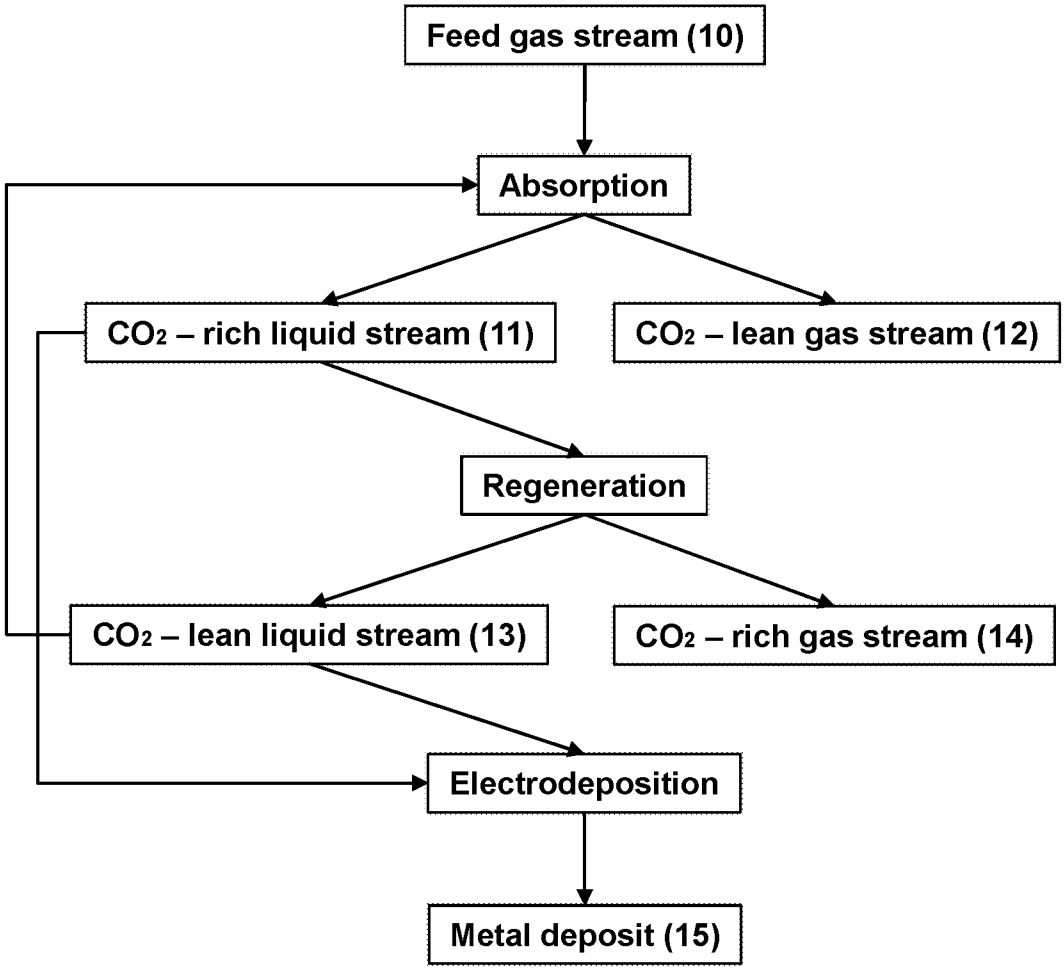

Feed gas stream (10)
Absorption
CO_2 – rich liquid stream (11)
CO_2 – lean gas stream (12)
Regeneration
CO_2 – lean liquid stream (13)
CO_2 – rich gas stream (14)
Electrodeposition
Metal deposit (15)

FIG 1

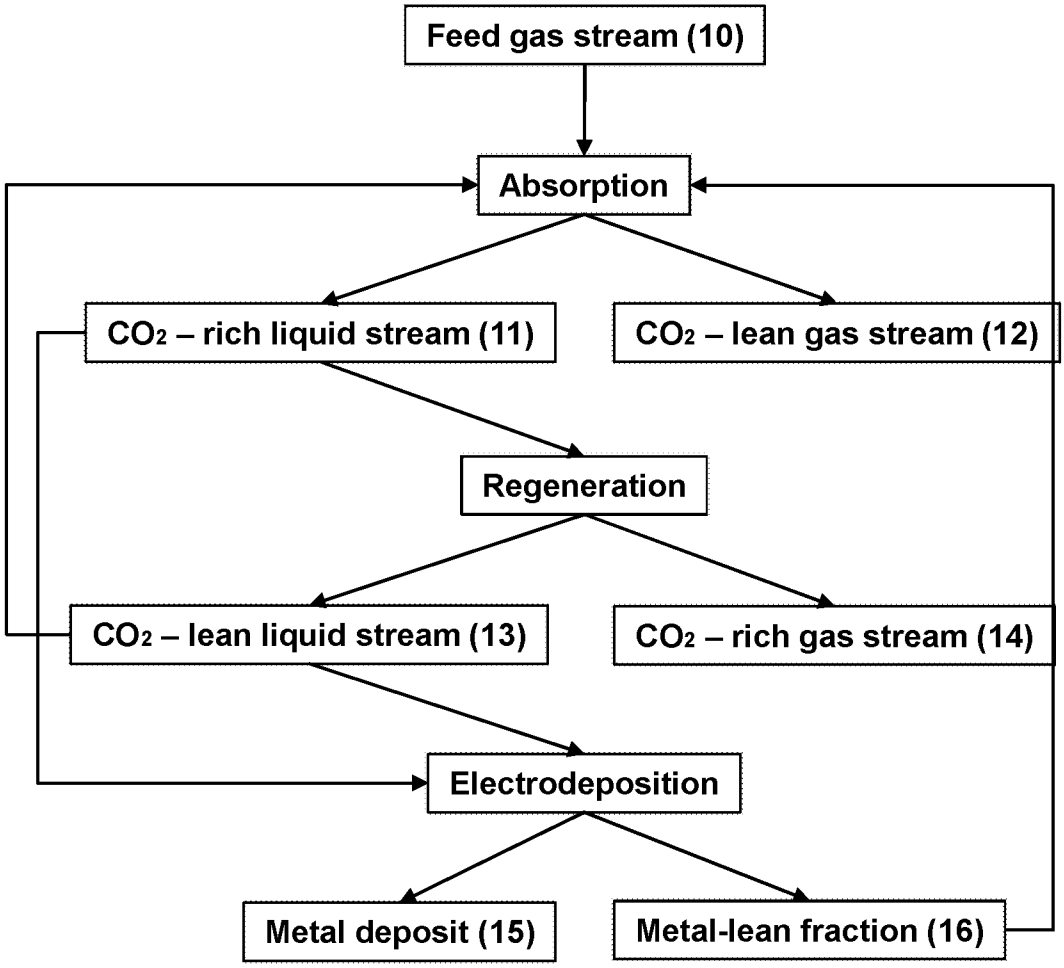

Feed gas stream (10)
Absorption
CO2 – rich liquid stream (11)
CO2 – lean gas stream (12)
Regeneration
CO2 – lean liquid stream (13)
CO2 – rich gas stream (14)
Electrodeposition
Metal deposit (15)
Metal-lean fraction (16)

FIG 2

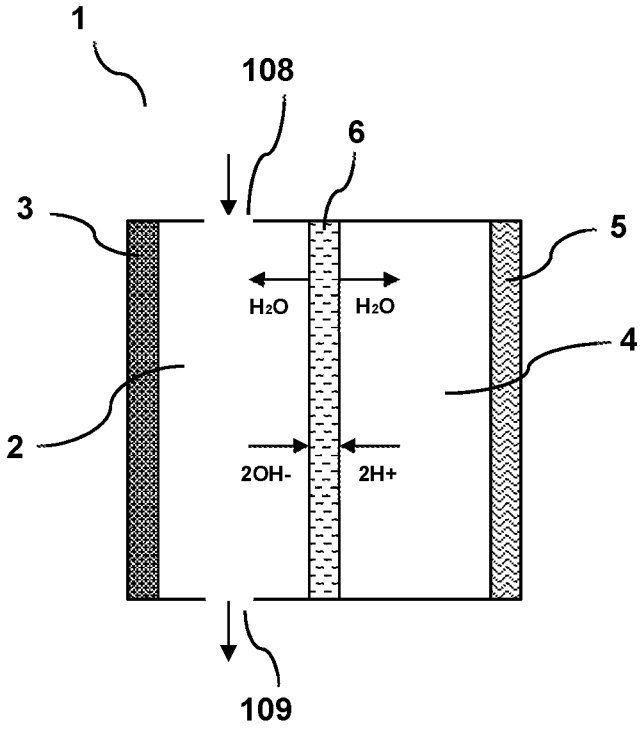


FIG 3A

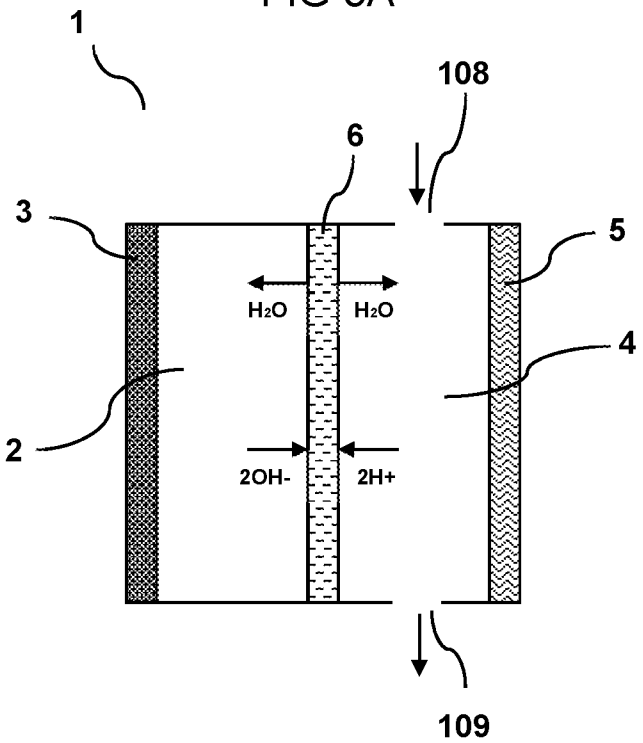


FIG 3B

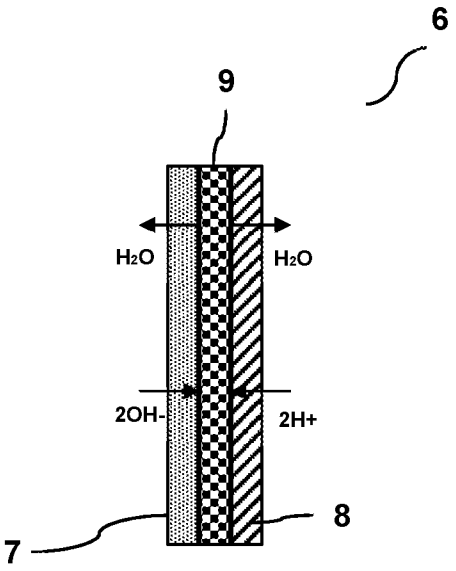


FIG 4

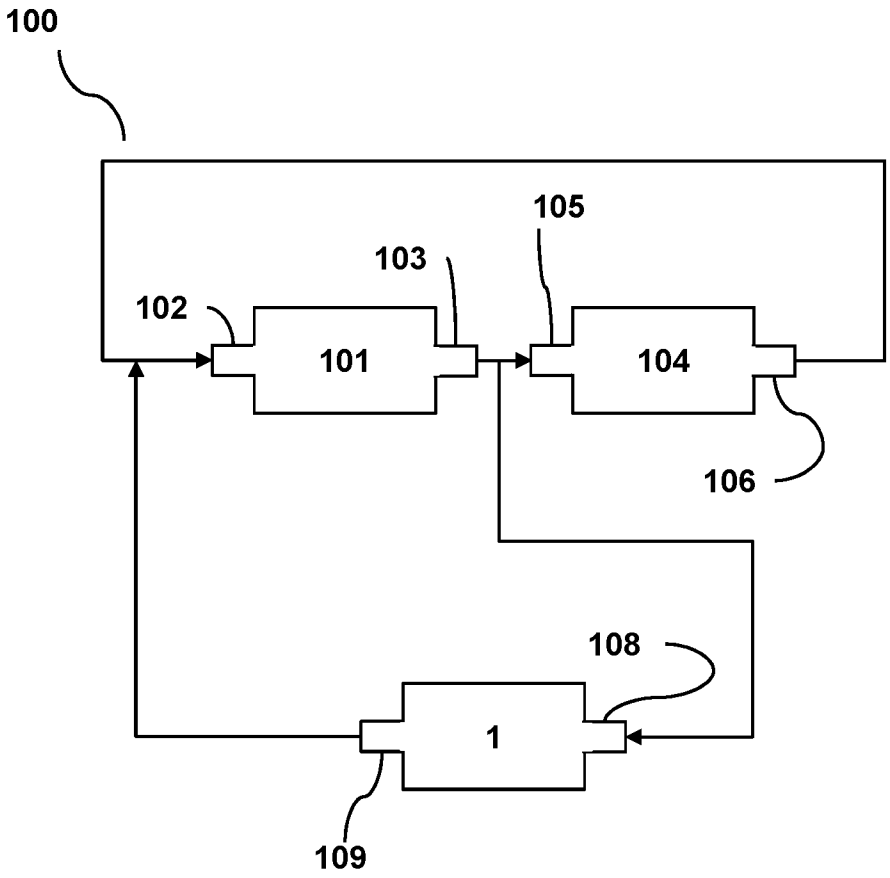


FIG 5

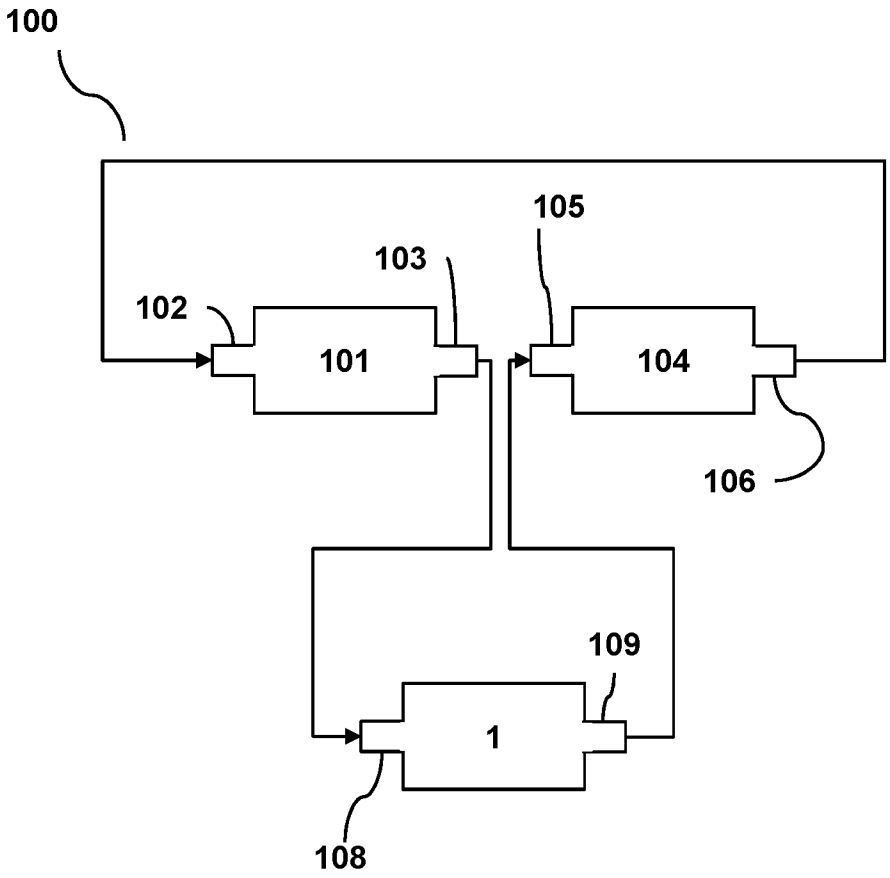


FIG 6

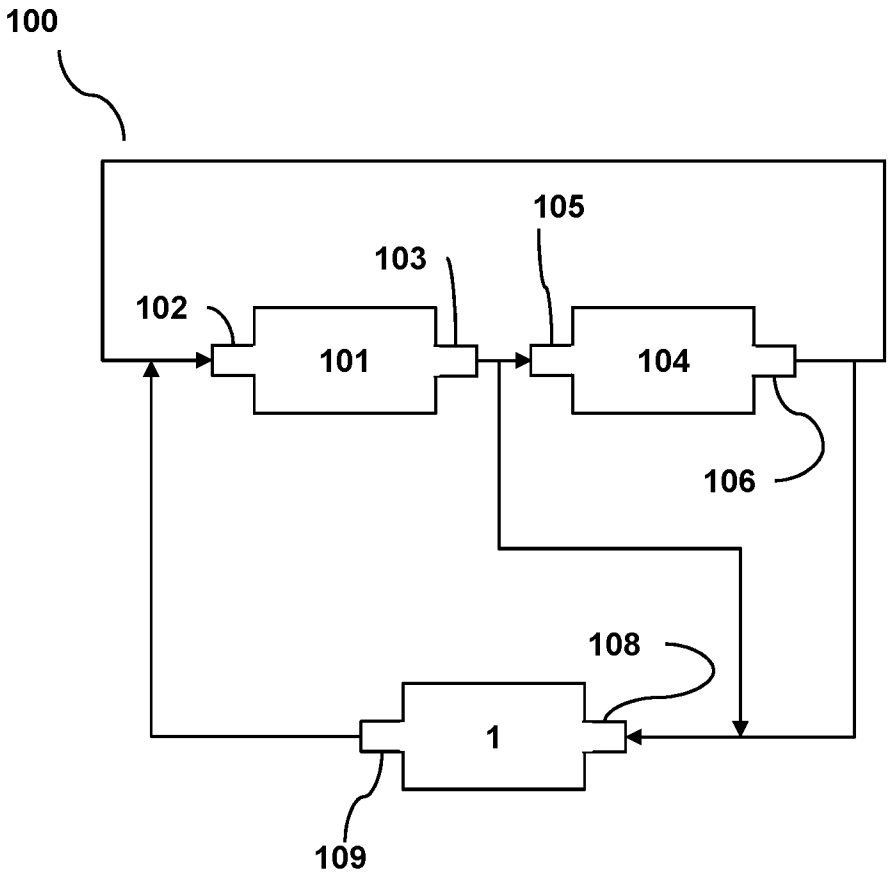


FIG 7

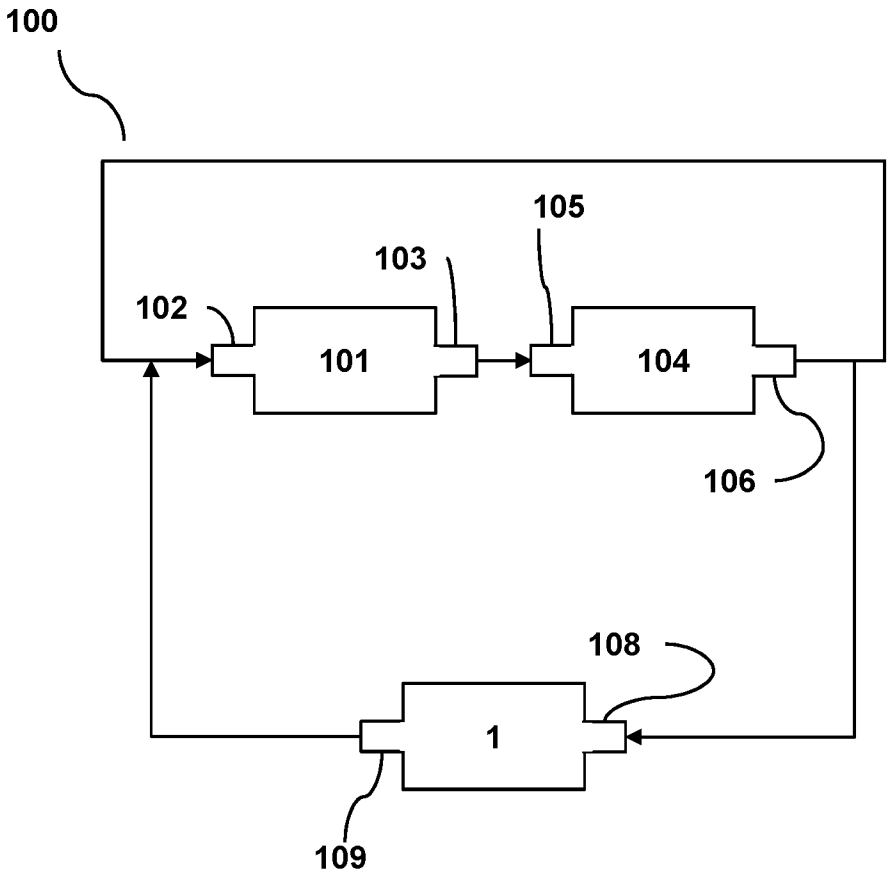


FIG 8

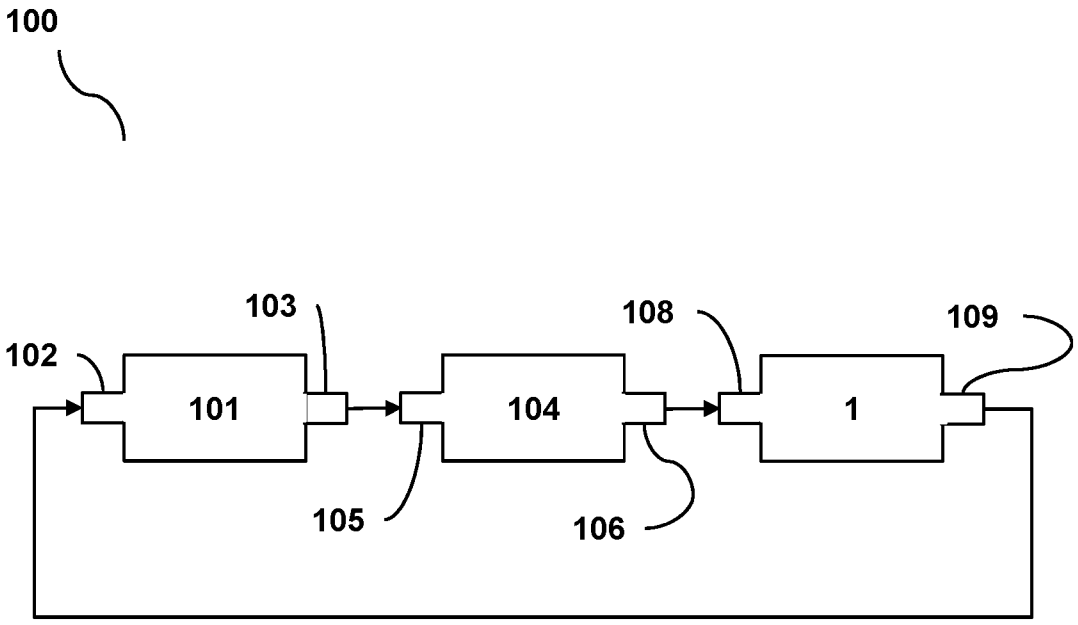


FIG 9

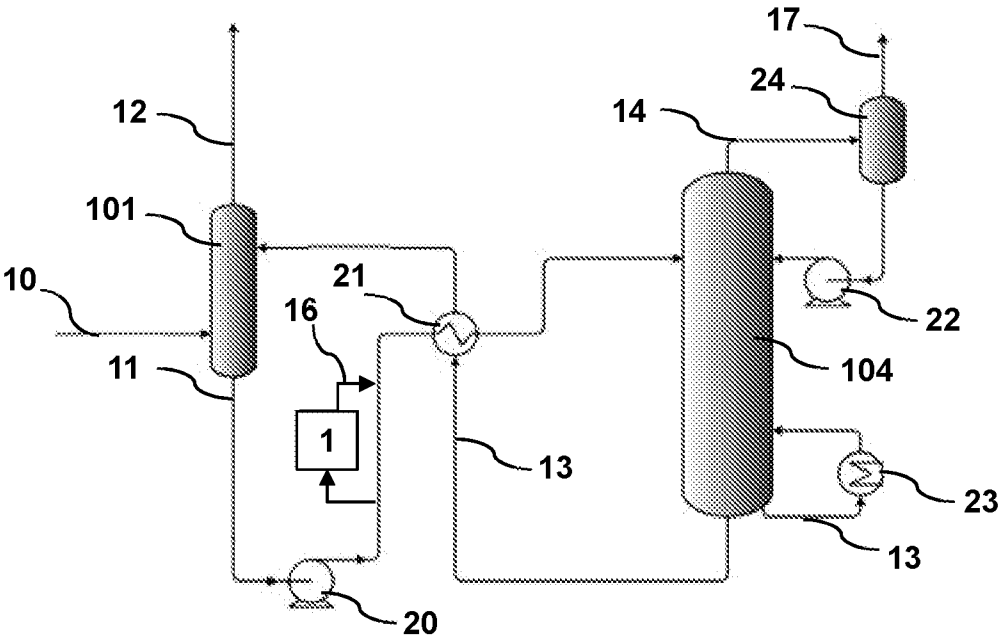


FIG 10

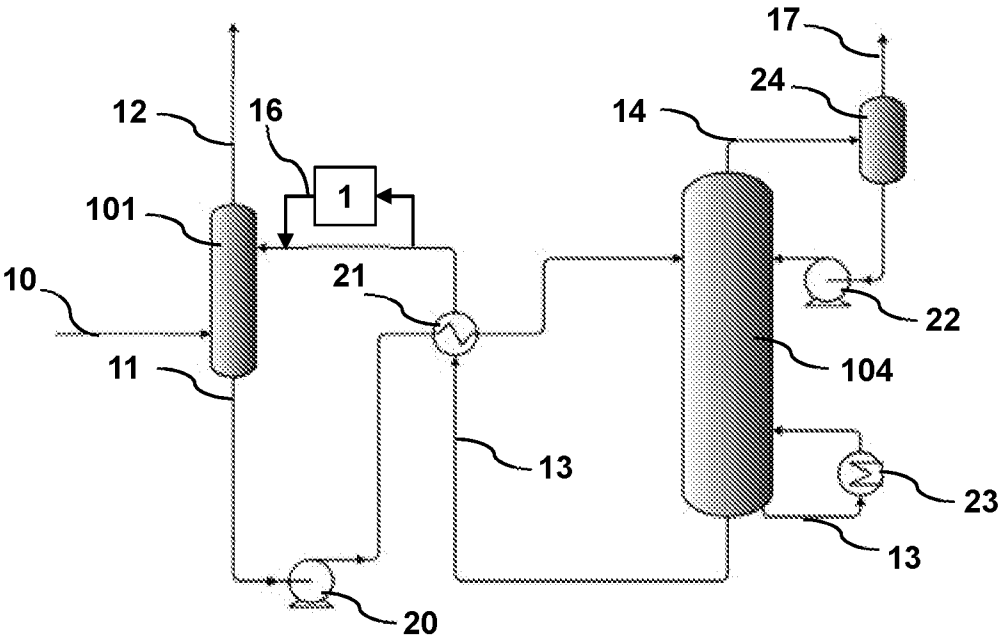


FIG 11

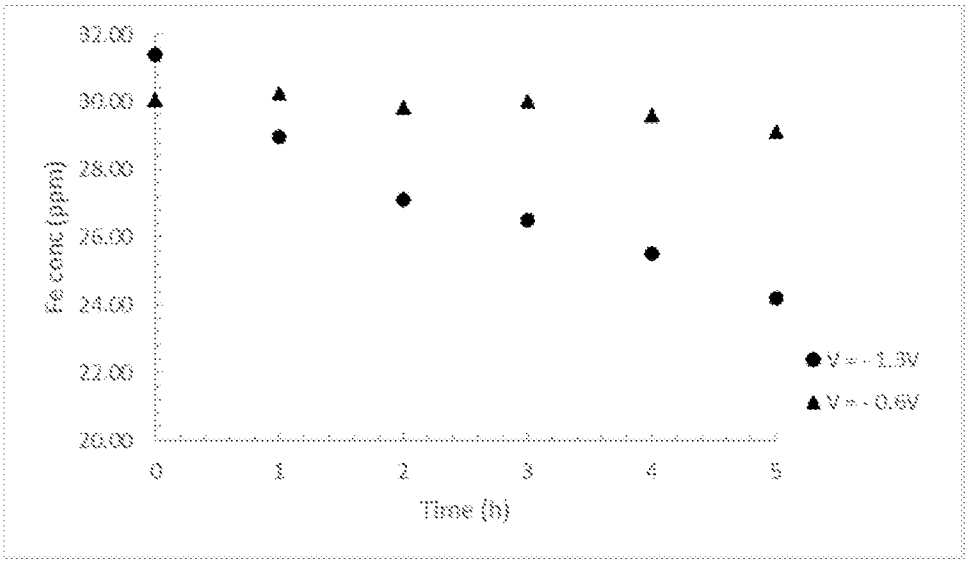
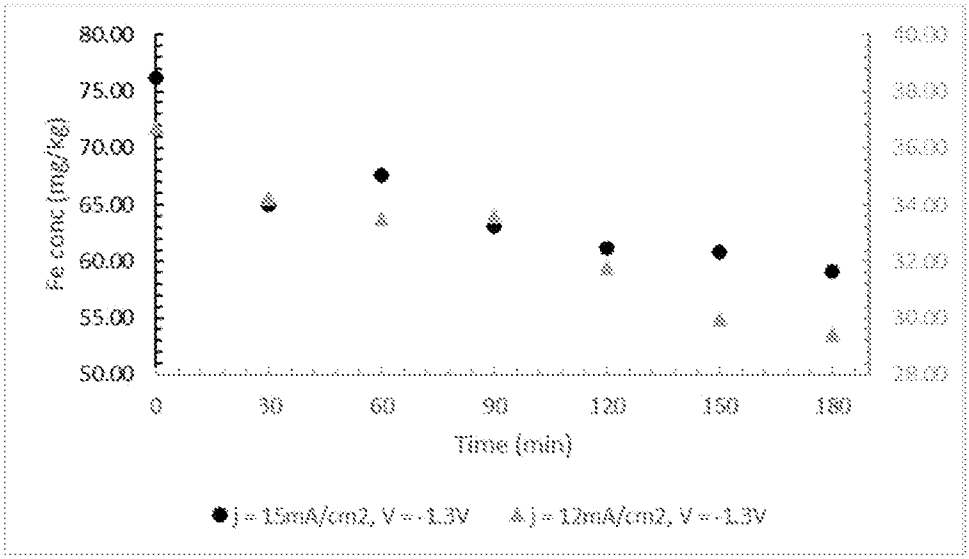


FIG 12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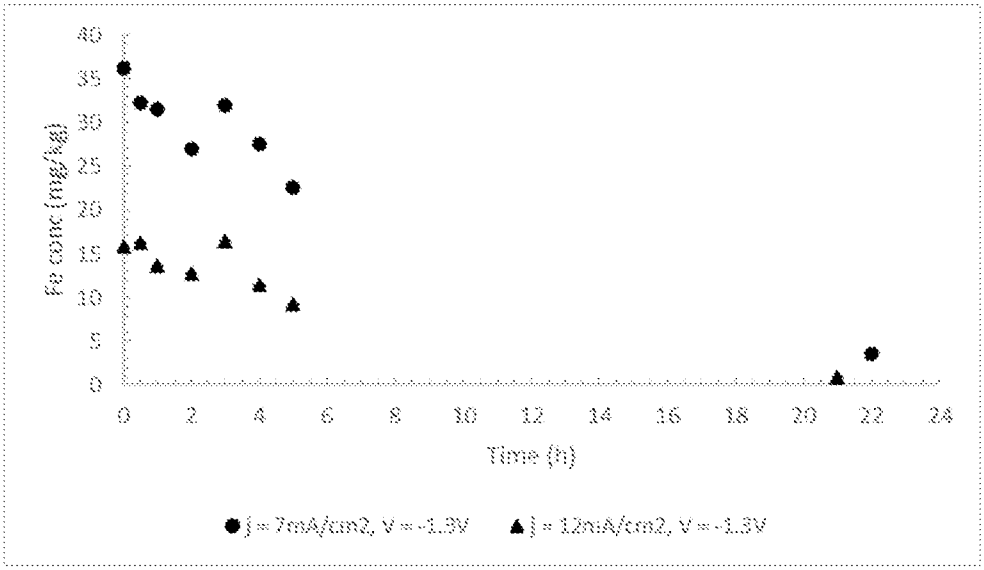
75.00
70.00
65.00
60.00
55.00
50.00
Fe conc (mg/kg)
40.00
38.00
36.00
34.00
32.00
30.00
28.00
0
30
60
90
120
150
180
Time (min)
j = 15mA/cm2, V = -1.3V
j = 12mA/cm2, V = -1.3V

FIG 13


Fe conc (mg/kg)
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35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
22
24
Time (h)
j = 7mA/cm2, V = -1.3V
j = 12mA/cm2, V = -1.3V

FIG 14

INTERNATIONAL SEARCH REPORT

International application No
PCT/NL2022/050466

A. CLASSIFICATION OF SUBJECT MATTER
INV. B01D53/14
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B01D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 622 681 A (GRIERSON JEFFREY G [US] ET AL) 22 April 1997 (1997-04-22) figures 3, 4 column 6, line 5 - line 56 column 7, line 13 - line 24	1-15
A	US 2015/290576 A1 (KIGUCHI AKIRA [JP] ET AL) 15 October 2015 (2015-10-15) figure 1	1-15
X	US 2021/047743 A1 (GOETHEER EARL LAWRENCE VINCENT [BE] ET AL) 18 February 2021 (2021-02-18)	1-4,8-15
A	figures 1-4 paragraphs [0001], [0050], [0066], [0076], [0096] - [0098]	5-7

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
25 November 2022	22/12/2022

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Pöhlmann, Robert

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/NL2022/050466

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		EP 3762522 A1	13-01-2021
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		WO 2019172750 A1	12-09-2019