

CO₂ CAPTURE PROCESS WITH ELECTROLYTIC REGENERATION

Technical field

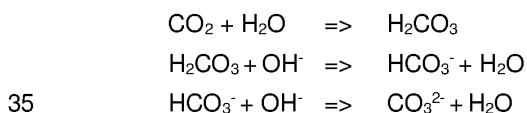
The present invention relates to a method of scrubbing a gas, such as flue gas
5 comprising carbon dioxide (CO₂), to deplete the gas of carbon dioxide, comprising
regenerating spent aqueous scrubbing liquid. Further, the present invention relates to a
system for such scrubbing of a gas, such as flue gas, comprising carbon dioxide.

Background

10 Carbon dioxide (CO₂) is a gas that when emitted into the atmosphere is
damaging to the climate as it contributes to the green-house effect and rise in global
temperature. It is for example produced as a byproduct when fossil fuel, e.g. coal,
gasoline or diesel, is burned. Coal- and gas-fired power plants accounts for a large
share of CO₂ emissions. It is a goal for many sectors to lower carbon dioxide
15 emissions.

Emitted gases resulting from combustion and comprising CO₂ are typically
denoted flue gases or exhaust gases. Depleting such emitted gases of CO₂ by lowering
the CO₂ content in the emitted gases, can be done by so called scrubbing of the gases,
i.e. removing the CO₂ from the gas stream by absorbing/dissolving CO₂ in a liquid. The
20 primary application for CO₂ scrubbing is for removal of CO₂ from the exhaust (i.e. flue
gas) of coal- and gas-fired power plants, downstream of a power station, before the
gas is released into the atmosphere. By using such a process, it would be possible to
significantly lower the CO₂ emissions involved in coal-fired power generation. In the
chemical industry, CO₂ scrubbing is used to separate CO₂ from natural gas, for use in,
25 for example, the beverage or fertilizer sector.

In a CO₂-scrubbing system, a scrubbing solution takes up the carbon dioxide
from the flue gas, at low temperatures, in an absorber. Most common is scrubbing of
the flue gas using a chemical absorption medium, such as an alkaline, aqueous liquid.
In an alkaline, aqueous liquid, CO₂ will dissolve and partly be hydrolyzed into carbonic
30 acid (H₂CO₃). Given the alkaline pH, formed carbonic acid (H₂CO₃) will be shifted into
hydrogen carbonate (HCO₃⁻) and/or carbonate (CO₃²⁻), as outlined below.



The technology being primarily developed for this process involves the use of aqueous amines, e.g. aqueous monoethanolamine, as absorption solvent. Amine scrubbing has been used to separate carbon dioxide (CO₂) from natural gas and hydrogen since 1930. However, it is not yet used on a larger scale for CO₂ capture from coal-fired power plants. The process is energy consuming and the technology has not been implemented in large scale because of the capital costs of installing the facility and the operating costs. Scrubbers using aqueous monoethanolamine as absorption solvent for example use large amounts of heat for regeneration of the solvent used in the scrubber. Presently, there are no other industrial applicable technologies that will provide energy-efficient or timely solutions to CO₂ emission from conventional coal-fired power plants.

Further key areas in development work on the carbon capture process include process integration and optimization for applications in large-scale power plants.

There is an imperative need for improved scrubbing systems that preferably require less heat for CO₂ capture.

Summary

Accordingly, there is, according to a first aspect, provided a method of scrubbing a gas comprising carbon dioxide (CO₂) to deplete the gas of carbon dioxide. The gas comprising carbon dioxide (CO₂) may typically be a result from combustion, such as flue gas or exhaust gas. However, also other gases comprising carbon dioxide (CO₂) may be scrubbed by the present method. An example would be to capture CO₂ from a power plant that generates heat and power from biomass.

The method comprises the steps of scrubbing the gas in a scrubber with a first alkaline, aqueous scrubbing liquid to dissolve carbon dioxide (CO₂) as hydrogen carbonate (HCO₃⁻) and/or as carbonate (CO₃²⁻) in the first alkaline, aqueous scrubbing liquid, thereby providing a first spent aqueous scrubbing liquid comprising hydrogen carbonate (HCO₃⁻) and/or carbonate (CO₃²⁻). The first spent aqueous scrubbing liquid has a pH from about 7 to about 9, in order to optimize the subsequent regeneration.

The method further comprises the step of feeding the first spent aqueous scrubbing liquid to an anode chamber of an electrolytic cell with an anode and a cathode. The anode and the cathode of the electrolytic cell are separated by a membrane to provide the anode chamber and a cathode chamber. The membrane is permeable to alkali metals, such as lithium, sodium and potassium, but has no or low permeability to hydrogen carbonate (HCO₃⁻) and/or to carbonate (CO₃²⁻). Typically, the

membrane is permeable only to cations. The membrane may be a cation-exchange membrane. In the electrolytic cell, the first spent aqueous scrubbing liquid is regenerated by electrolysis. In regenerating the spent aqueous scrubbing liquid, a number of electrolytic cells connected in parallel may be used. Before being fed to the anode chamber, the spent aqueous scrubbing liquid may be filtered to remove particulate matter.

In electrolysis, water is converted into oxygen and hydronium ions (H_3O^+) at the anode, whereas water is converted into hydrogen and hydroxide ions (OH^-) at the cathode. The electrolysis thus increases the pH of the first spent aqueous scrubbing liquid in the cathode chamber and depletes the first spent aqueous scrubbing liquid of hydrogen carbonate (HCO_3^-) and of carbonate (CO_3^{2-}) in the anode chamber, by decreasing the pH to shift the equilibrium towards carbonic acid in turn shifted into carbon dioxide. The regeneration further comprises generating gaseous hydrogen in the cathode chamber and a gaseous mixture of oxygen and carbon dioxide in the anode chamber by electrolysis. The chemical reactions and description of the operation of the processes are further described in the Detailed Description herein further below.

The method further comprises the step of withdrawing regenerated alkaline, aqueous scrubbing liquid from the cathode chamber and re-circulating it to the scrubber.

One key difference from the set-up of commercially available amine scrubbers is that the scrubbing liquid in the present method is regenerated by electrochemistry, while scrubbers in the art typically use large amounts of heat for regeneration of the scrubbing liquid used in the scrubber.

According to the present method, in regenerating the scrubbing liquid its pH is increased. Further, the regeneration, as already explained, also generates carbon dioxide and hydrogen, which may be used downstream for synthesis of organic compounds, such as methanol, thus adding further value to the process. The process is ideal for processes such as downstream Power-to-X processes.

The gaseous hydrogen is withdrawn from the cathode chamber and the gaseous mixture of oxygen and carbon dioxide is withdrawn from the anode chamber.

Withdrawing hydrogen, oxygen and carbon dioxide from the regeneration process is advantageous as hydrogen and oxygen can be used to generate electricity, e.g. by a fuel cell, to operate the process partly. Further, hydrogen and carbon dioxide (CO_2) can be used for synthesis of organic compounds, e.g. methanol, thereby compensating for the cost of running the process.

The carbon capture reaction in the scrubbing step takes place automatically. The operation of the scrubber is thereby an automatic process and requires no power apart from one needed to circulate the liquids. The regeneration process that takes place in the cathode and anode chambers of the electrolytic cell are electrochemical reactions, which inherently require electrical power. The electrochemical process regenerates the solvent, produces hydrogen at the cathode and a mixture of carbon dioxide (CO₂) and oxygen at the anode.

The actual power consumption will depend on the technical implementation of the process. Overall, the process requires a large amount of electrical energy rather than heat. This is positive, as electrification of the regeneration in carbon capture processes is highly desired. Further, some of the energy may be recovered as heat for district heating. Regeneration of amine-based scrubbing liquids reduces the overall efficiency of a power plant as some of the heat generated rather than being distributed, has to be used to re-generate the scrubbing liquid. Regeneration of alkaline scrubbing liquids comprising dissolved metal hydroxides may be regenerated electrical energy thus not affecting the overall efficiency of a power plant.

In order to dissolve carbon dioxide and shift the equilibrium towards hydrogen carbonate (HCO₃⁻) and of carbonate (CO₃²⁻), the first aqueous scrubbing liquid needs to be alkaline, i.e. have a pH exceeding 7, such as 8 or higher.

Thus, the first alkaline, aqueous scrubbing liquid may comprise a metal hydroxide. According to an embodiment of the method, the first alkaline, aqueous scrubbing liquid comprises one or more of dissolved potassium hydroxide (KOH), dissolved sodium hydroxide (NaOH) and dissolved lithium hydroxide (LiOH). The first alkaline, aqueous scrubbing liquid may comprise potassium hydroxide (KOH). Given its high solubility in water, potassium hydroxide (KOH) is a preferred metal hydroxide.

In the anode chamber, a gaseous mixture of oxygen and carbon dioxide is formed. The ratio between carbon dioxide and oxygen may be approximately 4:1, which allows for an efficient separation of CO₂ and O₂. The method may thus further comprise a step of separating this gaseous mixture of oxygen and carbon dioxide into a first stream, rich in oxygen and/or depleted of carbon dioxide, and a second stream, rich in carbon dioxide and/or depleted of oxygen. The gaseous mixture of oxygen and carbon dioxide may be compressed and/or cooled to provide for separation of liquid carbon dioxide (CO₂) from gaseous (O₂). According to one embodiment of the method,

carbon dioxide (CO_2) and/or oxygen (O_2) withdrawn from the anode chamber is compressed into liquid carbon dioxide and/or compressed oxygen (O_2).

Further, hydrogen formed in the cathode chamber is withdrawn. Hydrogen withdrawn from the cathode chamber may be used as a fuel to provide electricity, either internally or externally. Hydrogen and oxygen may be used to fuel a fuel cell. The electricity formed may optionally be used to operate the electrolytic cell regenerating the spent aqueous scrubbing liquid. This is advantageous as it at least partly compensates for the electricity consumption of running the process. Further, it may also be of interest to sell hydrogen on the open market.

The anode chamber is typically not operated such that all hydrogen carbonate (HCO_3^-) is converted to carbon dioxide. The method may thus further comprise withdrawing an aqueous stream still comprising some hydrogen carbonate (HCO_3^-) from the anode chamber. This stream may be concentrated, such as by reversed osmosis. The resulting concentrated stream comprising hydrogen carbonate (HCO_3^-) may be re-circulated to the electrolytic cell, thus facilitating further removal of hydrogen carbonate (HCO_3^-).

Typically, the gas comprising carbon dioxide and the scrubbing liquid are fed in contraflow manner to the scrubber to provide for efficient removal of carbon dioxide.

According to one embodiment of the method, the scrubbing of the gas comprising carbon dioxide is performed in at least a first stage and in a second stage. This provides for efficient removal of carbon dioxide, while still providing for optimizing the pH of the spent scrubbing liquid to be regenerated. The scrubbing may be performed in more than two stages.

In scrubbing the gas comprising carbon dioxide in a first stage and in a second stage, the regenerated alkaline, aqueous scrubbing liquid, withdrawn from the cathode chamber, is fed as a second alkaline, aqueous scrubbing liquid to the second stage of scrubbing downstream of the first stage of scrubbing. A second spent scrubbing liquid, resulting from the second stage of scrubbing, is at least partly, fed as the first alkaline, aqueous scrubbing liquid to the first stage of scrubbing upstream of the second stage of scrubbing.

In scrubbing the gas comprising carbon dioxide in several stages, spent scrubbing liquid, resulting from a downstream stage of scrubbing, may be, at least partly, fed as the alkaline, aqueous scrubbing liquid to an upstream stage of scrubbing. Further, the regenerated alkaline, aqueous scrubbing liquid, withdrawn from the cathode chamber, may be fed as an aqueous scrubbing liquid to the last stage of

scrubbing downstream. Furthermore, spent scrubbing liquid from the first stage of scrubbing may be fed to the electrolytic cell to be regenerated.

5 In scrubbing the gas comprising carbon dioxide in a first stage and in a second stage, the pH of the second alkaline, aqueous scrubbing liquid is preferably higher than the pH of the first alkaline, aqueous scrubbing liquid in order to remove carbon dioxide efficiently. The pH of the second alkaline, aqueous scrubbing liquid may be in the range 12 to 14, such as about 13.5. Further, the pH of the first alkaline, aqueous scrubbing liquid may be in the range 8 to 10, such as about 9.

10 In scrubbing the gas comprising carbon dioxide in several stages, the pH of the aqueous scrubbing liquid will be lower in up-stream stages than in down-stream stages.

15 In one exemplary embodiment, the first spent aqueous scrubbing liquid may be fed into the electrolytic cell, where the first spent aqueous scrubbing liquid may have a pH from about 7 to about 9 when the first spent aqueous scrubbing liquid enters the electrolytic cell. This means that the method may provide a recirculation arrangement and/or regeneration arrangement, where the arrangement is configured to reduce the pH value of the first spent aqueous scrubbing liquid to a pH of about 7 to about 9, in order to optimize CO₂ regeneration. The reduction of the pH value may be achieved by utilizing liquids or compositions that are regenerated during the electrolytic process, in order to ensure that the reduction of pH of the first spent aqueous scrubbing liquid occurs in a closed circulation system, where the electrolytic process regenerates the necessary components for the reduction in pH. Alternatively, the reduction of the pH value of the first spent aqueous scrubbing liquid may be obtained by mixing the scrubbing liquid during the scrubbing process to reduce the pH to about 7 to 9.

25 In one exemplary embodiment, the alkaline solution introduced into the cathode chamber may be have a pH of between about 12 to about 14. Thus the difference in pH between the anode chamber and the cathode chamber may be between about 5 and about 7. Thus the alkaline solution introduced into the cathode chamber may have a pH that is about 5 to about 7 higher than the pH of the first spent aqueous scrubbing liquid introduced into the anode chamber.

30 In embodiments according to which the scrubbing of the gas comprising carbon dioxide is performed in a first stage and in a second stage, regenerated alkaline, aqueous scrubbing liquid withdrawn from the cathode chamber may be mixed with a part of the second spent scrubbing liquid to provide the second alkaline, aqueous scrubbing liquid. By mixing these liquids, the pH of the second alkaline,

aqueous scrubbing liquid is lower than the pH of the regenerated alkaline, aqueous scrubbing liquid withdrawn from the cathode chamber. The pH of the second alkaline, aqueous scrubbing liquid may thus be adjusted by changing the ratio of regenerated alkaline, aqueous scrubbing liquid withdrawn from the cathode chamber to the second spent scrubbing liquid. Further, part of the second spent scrubbing liquid may be mixed with a part of a first spent scrubbing liquid, resulting from the first stage of scrubbing, to provide the first alkaline, aqueous scrubbing liquid. By mixing these liquids, the pH of the first alkaline, aqueous scrubbing liquid will be higher than the pH the first spent scrubbing liquid, and the first spent scrubbing liquid may be partly re-cycled.

10 In order to further optimize the pH within the electrolytic cell, part of the regenerated alkaline, aqueous scrubbing liquid may be re-circulated to the cathode chamber. The regenerated alkaline, aqueous scrubbing liquid may be diluted by an aqueous stream before re-circulating it to the cathode chamber. This aqueous stream may be provided by withdrawing an aqueous stream still comprising some hydrogen carbonate (HCO_3^-) from the anode chamber and concentrating it, such as by reversed osmosis, to provide an aqueous stream depleted of hydrogen carbonate (HCO_3^-) and a concentrated stream comprising hydrogen carbonate (HCO_3^-).

According to a second aspect, there is in corresponding manner provided a system for scrubbing a gas, such as flue gas or exhaustive gas, comprising carbon dioxide to deplete the flue gas of carbon dioxide. The system comprises a scrubber arrangement for scrubbing a gas with an alkaline, aqueous scrubbing liquid to dissolve carbon dioxide as hydrogen carbonate (HCO_3^-) and/or as carbonate (CO_3^{2-}) in the alkaline, aqueous scrubbing liquid. The system further comprises a regeneration arrangement for regenerating spent aqueous scrubbing liquid by electrolysis.

25 The scrubber arrangement comprises a scrubber. The scrubber has an inlet for the gas to be scrubbed and an outlet for a gas depleted of carbon dioxide. The scrubber further has an inlet for receiving the alkaline, aqueous scrubbing liquid and an outlet for withdrawing spent aqueous scrubbing liquid. Preferably, the inlets and outlets are arranged to provide for scrubbing in a counterflow manner.

30 The regeneration arrangement comprises an electrolytic cell, or a number of electrolytic cells connected in parallel. The electrolytic cell comprises an anode chamber and a cathode chamber separated by a membrane. The membrane is permeable to alkali metals, such as lithium, sodium and potassium, but has no or low permeability to hydrogen carbonate (HCO_3^-) and/or carbonate (CO_3^{2-}). Typically, the membrane is permeable only to cations. The membrane may be a cation-exchange

membrane. The anode chamber comprises an anode inlet for receiving the spent aqueous scrubbing liquid from the scrubber arrangement and an anode outlet for withdrawing oxygen and carbon dioxide. The regeneration arrangement may further comprise a filter for filtering spent aqueous scrubbing liquid to be fed to the anode inlet of the anode chamber. Further, the cathode chamber comprises an outlet for withdrawing regenerated aqueous scrubbing liquid and hydrogen. The outlet for spent aqueous scrubbing liquid of the scrubber is in flow communication with the inlet for the spent aqueous scrubbing liquid of the anode chamber. Similarly, the outlet for regenerated aqueous scrubbing liquid of the cathode chamber is flow communication with the inlet for the alkaline, aqueous scrubbing liquid of the scrubber.

An advantage of this system is that it comprises both a scrubber arrangement and a regeneration arrangement where output from the scrubber arrangement can be regenerated by electrolysis and reused in the scrubber arrangement, enabling and optimizing a complete, energy and cost efficient system of depleting gas of carbon dioxide, driven by electrical power.

According to one embodiment, the scrubber arrangement comprises a first and a second buffer tank for alkaline, aqueous scrubbing liquid. Further, the scrubber comprises at least a first and a second absorber. It may comprise more than two absorbers. Further, a number of scrubbers may be used. A number of scrubbers may be either connected in series or in parallel.

The first absorber comprises an inlet for receiving alkaline, aqueous scrubbing liquid from the first buffer tank. Further, the first absorber comprises an outlet for withdrawing spent aqueous scrubbing liquid from first absorber to feed to an inlet of the first buffer tank. Thus, alkaline, aqueous scrubbing liquid may be circulated between the first absorber and the first buffer tank. While the presence of the first buffer tank is preferred, it may according to some embodiments be dispensed with and the alkaline, aqueous scrubbing liquid may be re-circulated over the first absorber by a first pipe system connecting the inlet and the outlet of the first absorber. Further, the first buffer tank is in flow communication with the inlet for the spent aqueous scrubbing liquid of the anode chamber.

The second absorber comprises an inlet for receiving alkaline, aqueous scrubbing liquid from the second buffer tank. Further, the second absorber comprises an outlet for withdrawing spent aqueous scrubbing liquid from second absorber to feed to an inlet of the second buffer tank. Thus, alkaline, aqueous scrubbing liquid may be circulated between the second absorber and the second buffer tank. While the

presence of the second buffer tank is preferred, it may according to some embodiments be dispensed with and the alkaline, aqueous scrubbing liquid may be re-circulated over the second absorber by a first pipe system connecting the inlet and the outlet of the second absorber. Further, the outlet for regenerated aqueous scrubbing liquid of the cathode chamber is in flow communication with the inlet of the second absorber. Furthermore, the outlet of the second absorber is in flow communication with the inlet of the first absorber.

If the scrubber arrangement comprises more than two absorbers, they may be arranged such that the outlet of a downstream absorber is in flow communication with the inlet of an upstream absorber. Further, an inlet of the last absorber (i.e. the most downstream absorber close to an outlet for scrubbed gas) is in flow communication with the outlet for regenerated aqueous scrubbing liquid of the cathode chamber. Furthermore, an outlet of the first absorber (i.e. the most upstream close to an inlet for the gas to be scrubbed) is in flow communication with an inlet for the spent aqueous scrubbing liquid of the anode chamber. Typically, the alkaline, aqueous scrubbing liquid may be re-circulated over each absorber by means of a pipe system connecting the inlet and the outlet of the respective absorber. Similar to the first and second absorber, any further absorbers may be in flow communication with a corresponding buffer tank.

To further provide for adjusting flows independently, the scrubber arrangement may further comprise a third buffer tank for regenerated aqueous scrubbing liquid. The third buffer tank is in flow communication with the outlet for regenerated aqueous scrubbing liquid of the cathode chamber and with the inlet of the second absorber. Further, the scrubber arrangement may comprise a fourth buffer tank for spent aqueous scrubbing liquid. The fourth buffer tank is in flow communication with the first buffer tank and with an inlet for the spent aqueous scrubbing liquid of the anode chamber.

This design enables regenerated aqueous scrubbing liquid of the cathode chamber to be reused in the scrubbing process and enables optimization of the pH of the liquids before being recycled into the scrubber.

The regeneration arrangement may further comprise a first compressor unit for compressing hydrogen withdrawn from the cathode chamber and/or a second compressor unit for compressing oxygen and carbon dioxide withdrawn from the anode chamber. Further, regeneration arrangement may comprise a first gas separator for separating oxygen and carbon dioxide withdrawn from the anode chamber from each

other. Typically, the first gas separator is arranged downstream the second compressor unit to separate liquid carbon dioxide from gaseous oxygen.

This way the system can provide compressed hydrogen, compressed oxygen and carbon dioxide, as well as separated oxygen and carbon dioxide, for commercial
5 exploration.

According to one embodiment, the regeneration arrangement further comprises a concentrator, such as a filter, for concentrating an aqueous stream comprising some hydrogen carbonate (HCO_3^-) withdrawn from the anode chamber to provide a concentrated stream comprising hydrogen carbonate (HCO_3^-) and an
10 aqueous stream depleted of hydrogen carbonate (HCO_3^-). The concentrator is arranged in flow communication, typically by pipes, with the electrolytic cell such that:

- the aqueous stream comprising some hydrogen carbonate (HCO_3^-) may be withdrawn from the anode chamber and fed to the concentrator;
- the concentrated stream comprising hydrogen carbonate (HCO_3^-) may be
15 withdrawn from the concentrator and fed to the anode chamber; and/or
- the aqueous stream depleted of hydrogen carbonate (HCO_3^-) may be withdrawn from the concentrator and fed to the cathode chamber.

The regeneration arrangement may further comprise a first balance tank for regenerated alkaline, aqueous scrubbing liquid. The first balance may be arranged in
20 flow communication, typically by pipes, with the electrolytic cell and it may have:

- a first inlet for receiving regenerated alkaline, aqueous scrubbing liquid from the cathode chamber;
- a second inlet for receiving the aqueous stream depleted of hydrogen carbonate (HCO_3^-) withdrawn from the concentrator; and/or
25 - an outlet for feeding diluted regenerated alkaline, aqueous scrubbing liquid to the cathode chamber of electrolytic cell.

Further, the regeneration arrangement may comprise a second balance tank for spent aqueous scrubbing liquid. The second balance may be arranged in flow communication, typically by pipes, with the electrolytic cell and it may have:

- 30 - a first inlet for receiving spent aqueous scrubbing liquid from the scrubber arrangement;
- a second inlet for receiving the concentrated stream comprising hydrogen carbonate (HCO_3^-) from the concentrator; and/or
- an outlet for feeding spent aqueous scrubbing liquid to the anode chamber of
35 the electrolytic cell.

In scrubbing flue gas in a power plant, the scrubbing and the regeneration are typically run continuously at the plant. It is however possible to run the scrubbing separately from the regeneration. As an example, the scrubbing may be operated in a vehicle, whereas the regeneration takes place at a central unit, which may serve
5 several vehicles. The vehicle may be provided with a scrubber arrangement comprising a third buffer tank for regenerated aqueous scrubbing liquid and a fourth buffer tank for spent aqueous scrubbing liquid. By providing the vehicle with such a scrubber arrangement, it may be run independently of the rearrangement until the third buffer tank runs empty and/or the fourth buffer tank becomes full.

10 According to a third aspect, there is thus provided scrubber arrangement for scrubbing a gas, such as flue gas, comprising carbon dioxide to deplete the flue gas of carbon dioxide. As already described above, the scrubber arrangement comprises a scrubber having an inlet for the gas to be scrubbed and an outlet for gas depleted of carbon dioxide. The scrubber further has an inlet for receiving the alkaline, aqueous
15 scrubbing liquid and an outlet for withdrawing spent aqueous scrubbing liquid. The scrubber arrangement comprises a first and a second buffer tank for alkaline, aqueous scrubbing liquid, and the scrubber at least comprises a first and a second absorber. The first absorber comprises an inlet for receiving alkaline, aqueous scrubbing liquid from the first buffer tank and an outlet for withdrawing spent aqueous scrubbing liquid
20 and feed it to an inlet of the first buffer tank. Thus, alkaline, aqueous scrubbing liquid may be circulated between the first absorber and the first buffer tank. While the presence of the first buffer tank is preferred, it may according to some embodiments be dispensed with and the alkaline, aqueous scrubbing liquid may be re-circulated over the first absorber by a first pipe system connecting the inlet and the outlet of the first
25 absorber. The second absorber comprises an inlet for receiving alkaline, aqueous scrubbing liquid from the second buffer tank and an outlet for withdrawing spent aqueous scrubbing liquid from the second absorber to feed to an inlet of the second buffer tank. Thus, alkaline, aqueous scrubbing liquid may be circulated between the second absorber and the second buffer tank. While the presence of the second buffer
30 tank is preferred, it may according to some embodiments be dispensed with and the alkaline, aqueous scrubbing liquid may be re-circulated over the second absorber by a second pipe system connecting the inlet and the outlet of the first absorber. The outlet of the second absorber is in flow communication with the inlet of the first absorber.

If the scrubber arrangement comprises more than two absorbers, they may be
35 arranged such that the outlet of a downstream absorber is in flow communication with

the inlet of an upstream absorber. Further, an inlet of the last absorber (i.e. the most downstream absorber close to an outlet for scrubbed gas) is in flow communication with the outlet for regenerated aqueous scrubbing liquid of the cathode chamber.

Furthermore, an outlet of the first absorber (i.e. the most upstream close to an inlet for the gas to be scrubbed) is in flow communication with an inlet for the spent aqueous scrubbing liquid of the anode chamber. Typically, the alkaline, aqueous scrubbing liquid may be re-circulated over each absorber by means of a pipe system connecting the inlet and the outlet of the respective absorber. Similar to the first and second absorber, any further absorbers may be in flow communication with a corresponding buffer tank.

According to one embodiment, the scrubber arrangement further comprises a third buffer tank for regenerated aqueous scrubbing liquid. The third buffer tank has an inlet for receiving regenerated aqueous scrubbing liquid, such that the third buffer tank may be filled up with regenerated aqueous scrubbing liquid. Further, the third buffer tank is in flow communication with the inlet of the second absorber. Furthermore, the scrubber arrangement may comprise a fourth buffer tank for spent aqueous scrubbing liquid. The fourth buffer tank is in flow communication with the first buffer tank, such that the fourth buffer tank may be filled up with regenerated aqueous scrubbing liquid in operating the scrubber arrangement. The fourth buffer tank further has an outlet for withdrawing spent aqueous scrubbing liquid, such that the fourth buffer tank may be emptied.

By providing such a scrubber arrangement, it can be utilized without being directly connected to any regeneration arrangement. It may for example be installed in a vehicle for scrubbing an exhaust gas obtained in the operation of the vehicle. The third buffer tank can be filled with alkaline, aqueous scrubbing liquid to be used in the scrubbing process. Spent aqueous scrubbing liquid can be withdrawn from the fourth buffer tank to empty it at a convenient time point, such as when re-fueling the vehicle, for it to be emptied after being filled up during the process.

Correspondingly, there is, according to a fourth aspect, provided a regeneration arrangement for regenerating a spent aqueous scrubbing liquid comprising hydrogen carbonate (HCO_3^-) and/or carbonate (CO_3^{2-}) used in electrolysis to provide alkaline, aqueous scrubbing liquid. The regeneration arrangement has already been described herein above. It comprises an electrolytic cell. The electrolytic cell comprises an anode chamber and a cathode chamber separated by a membrane. The anode is present within the anode chamber and the cathode is present within the cathode chamber. The anode chamber comprises an anode inlet for receiving the

spent aqueous scrubbing liquid and an anode outlet for withdrawing oxygen and carbon dioxide. The regeneration arrangement may further comprise a filter for filtering spent aqueous scrubbing liquid to be fed to the anode inlet of the anode chamber. The cathode chamber comprises an outlet for withdrawing regenerated aqueous scrubbing liquid and hydrogen. The regeneration arrangement further comprises a concentrator for concentrating an aqueous stream comprising some hydrogen carbonate (HCO_3^-) withdrawn from the anode chamber to provide a concentrated stream comprising hydrogen carbonate (HCO_3^-) and an aqueous stream depleted of hydrogen carbonate (HCO_3^-). The concentrator is arranged in flow communication with the electrolytic cell such that the aqueous stream comprising some hydrogen carbonate (HCO_3^-) may be withdrawn from the anode chamber and fed to the concentrator, the concentrated stream comprising hydrogen carbonate (HCO_3^-) may be withdrawn from the concentrator and fed to the anode chamber, and the aqueous stream depleted of hydrogen carbonate (HCO_3^-) may be withdrawn from the concentrator and fed to the cathode chamber.

The regeneration arrangement may further comprise a first balance tank for regenerated alkaline, aqueous scrubbing liquid. The first balance tank has a first inlet for receiving regenerated alkaline, aqueous scrubbing liquid, and a second inlet for receiving the aqueous stream depleted of hydrogen carbonate (HCO_3^-) withdrawn from the concentrator. Further, the first balance tank has an outlet for feeding diluted regenerated alkaline, aqueous scrubbing liquid to the cathode chamber of electrolytic cell. Furthermore, regeneration arrangement may comprise a third buffer tank for storing regenerated aqueous scrubbing liquid. The third buffer tank has an inlet for receiving regenerated aqueous scrubbing liquid, such that the third buffer tank may be filled up with regenerated aqueous scrubbing liquid. Further, the third buffer tank has an outlet for withdrawing regenerated aqueous scrubbing liquid in filling up a corresponding buffer tank of the scrubbing system.

The regeneration arrangement may further comprise a second balance tank for spent aqueous scrubbing liquid. The second balance tank has a first inlet for receiving spent aqueous scrubbing liquid from the scrubber arrangement, a second inlet for receiving the concentrated stream comprising hydrogen carbonate (HCO_3^-) from the concentrator, and an outlet for feeding spent aqueous scrubbing liquid to the anode chamber of electrolytic cell. Furthermore, the regeneration arrangement may comprise a fourth buffer tank for spent aqueous scrubbing liquid. The fourth buffer tank is in flow communication with the anode chamber, such that spent aqueous scrubbing

liquid to be regenerated, may be withdrawn from the fourth buffer tank. Furthermore, the fourth buffer tank has inlet for receiving spent aqueous scrubbing liquid. Thus, the fourth buffer tank may be filled up in emptying a corresponding buffer tank of the scrubbing system.

5 The regeneration arrangement may further comprise a first compressor unit for compressing hydrogen withdrawn from the cathode chamber. Further, the regeneration arrangement may comprise a second compressor unit for compressing oxygen and carbon dioxide withdrawn from the anode chamber, and/or a first gas separator for separating oxygen and carbon dioxide withdrawn from the anode
10 chamber from each other. Typically, the first gas separator is arranged downstream the second compressor unit to separate liquid carbon dioxide from gaseous oxygen.

Although the present invention has been described above with reference to specific embodiments, it is not intended to be limited to the specific form set forth herein. Rather, the invention is limited only by the accompanying claims and other
15 embodiments than the specific embodiments described above are equally possible within the scope of these appended claims.

In the claims, the term "comprises/comprising" does not exclude the presence of other elements or steps. Additionally, although individual features may be included in different claims, these may possibly advantageously be combined, and the inclusion in
20 different claims does not imply that a combination of features is not feasible and/or advantageous.

In addition, singular references do not exclude a plurality. The terms "a", "an", "first", "second" etc. do not preclude a plurality.

25 **BRIEF DESCRIPTION OF THE DRAWINGS**

These and other aspects, features and advantages of which the invention is capable of will be apparent and elucidated from the following description of embodiments of the present invention, reference being made to the accompanying drawings, in which:

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Fig. 1 shows a flow path between a scrubber and an electrolytic cell;

Fig. 2 shows a process scheme of a system for scrubbing flue gas;

Fig. 3 shows a scrubber arrangement of the process scheme of Fig. 2;

Fig. 4 shows a regeneration arrangement of the process scheme of Fig. 2;

Fig. 5 shows test results of the overall generation of gas flow in the electrolytic cell and the pH-value over time;

Fig. 6 shows test results of the gas flow of CO_2 and O_2 in relation to the pH-value over time;

5 **Fig. 7** shows test results of the gas production of CO_2 and O_2 in relation to the energy consumption over time; and

Fig. 8 shows test results of the relationship between the production of gases leaving the electrolytic cell over time.

10 DETAILED DESCRIPTION

With reference to **Fig. 1**, a system 100 according to an embodiment is shown having a scrubber arrangement 200 and a regeneration arrangement 300. Here, a method of scrubbing a gas, such as flue gas or an exhaustive gas, comprising carbon dioxide CO_2 , is illustrated. The gas enters the scrubber through the scrubber inlet 213.

15 To deplete the flue gas from carbon dioxide CO_2 , the scrubbing method can be described as follows. The gas is scrubbed in the scrubber 210 in a counter flow manner with a first alkaline, aqueous scrubbing liquid to dissolve carbon dioxide CO_2 as hydrogen carbonate HCO_3^- and/or as carbonate CO_3^{2-} in the first alkaline, aqueous scrubbing liquid. A first spent aqueous scrubbing liquid comprising dissolved hydrogen

20 carbonate HCO_3^- and/or carbonate CO_3^{2-} results. The first spent aqueous scrubbing liquid has a pH from about 7 to about 9 when it leaves at the outlet 211" for withdrawing spent aqueous scrubbing liquid of the scrubber 210. The first spent aqueous scrubbing liquid is then fed to an anode chamber 313 of an electrolytic cell 310 via an anode inlet 313'.

25 The electrolytic cell 310 has apart from the anode chamber 313 also a cathode chamber 312. The anode chamber 313 and the cathode chamber 312 are separated by a membrane 311. This membrane 311 may be a semi-permeable membrane, being permeable to cations, but essentially impermeable to anions. Thus, the membrane cation-exchange membrane. The electrolysis increases the pH of the first spent aqueous scrubbing liquid in the cathode chamber 312. The electrolysis

30 concentrates the alkaline solution at a pH between 12 and 14 in the cathode chamber. In the anode chamber 313, the electrolysis further depletes the first spent aqueous scrubbing liquid of hydrogen carbonate HCO_3^- and of carbonate CO_3^{2-} by decreasing the pH-value to release gaseous carbon dioxide. The outlet 211" for spent aqueous scrubbing liquid of the scrubber 210 is in flow communication with the inlet 313' for the

35 spent aqueous scrubbing liquid of the anode chamber 313. Moreover, the outlet 312"

for regenerated aqueous scrubbing liquid of the cathode chamber 312 is flow communication with the inlet 212' for the alkaline, aqueous scrubbing liquid of the scrubber 210.

One can say that the first spent aqueous scrubbing liquid is regenerated by
5 generating gaseous hydrogen H_2 and dissolved hydroxide ions OH^- in the cathode chamber 312 and a gaseous mixture of oxygen O_2 and carbon dioxide CO_2 in the anode chamber 313 by electrolysis. This is indicated by the upwards pointing arrows from the cathode outlet 312'' and the anode outlet 313'' in **Fig. 1**, respectively. The gaseous hydrogen H_2 and dissolved hydroxide ions OH^- is withdrawn from the cathode
10 chamber 312 and the gaseous mixture of oxygen O_2 and carbon dioxide CO_2 is withdrawn from the anode chamber 313. For instance, the hydrogen H_2 may be used in downstream processes (not shown) such as in fuel or methanol production. The regenerated alkaline, aqueous scrubbing liquid from the cathode chamber 312 is then recirculated via the inlet 212' for receiving the alkaline, aqueous scrubbing liquid to the
15 scrubber 210. Gas depleted of carbon dioxide CO_2 then exits the scrubber 210 via the scrubber outlet 214.

In **Fig. 2**, a detailed view of the system 100 described in relation to **Fig. 1** is shown. The system is separated into two parts; the scrubber arrangement 200 and the regeneration arrangement 300. These two arrangements are also shown separately in
20 **Figs 3** and **4**, respectively. For increased understanding, the scrubber arrangement 200 and the regeneration arrangement 300 will now be described separately. The dotted arrows in **Figs 3** and **4** indicate where the scrubber arrangement 200 and the regeneration arrangement 300 may meet in **Fig. 2** to form the system 100 in its entirety. Alternatively, the scrubber arrangement 200 and the regeneration arrangement 300,
25 may be operated independently.

With reference to **Fig. 3**, the scrubber arrangement 200 has a first buffer tank 230 and a second buffer tank 240 for alkaline, aqueous scrubbing liquid. The scrubber 210 has a first absorber 211 and a second absorber 212 for scrubbing the gas of carbon dioxide. Scrubbing liquid may be re-circulated to the first absorber 211 via the
30 first buffer tank 230. Further, scrubbing liquid may be re-circulated to the second absorber 212 via the second buffer tank 240. The first absorber 211 thus has an inlet 211' for receiving alkaline, aqueous scrubbing liquid from the first buffer tank 230, and an outlet 211'' for withdrawing spent aqueous scrubbing liquid and feeding it to the inlet 313' for the spent aqueous scrubbing liquid of the anode chamber 313 directly (as
35 shown in **Fig. 1**) or via the first buffer tank 230, as shown in **Figs 2** and **3**. The second

absorber 212 has an inlet 212' for receiving alkaline, aqueous scrubbing liquid from the second buffer tank 240 and an outlet 212'' for withdrawing spent aqueous scrubbing liquid and feeding it to the inlet 211' of the first absorber and/or to the second buffer tank 240. The outlet 212'' of the second absorber is in flow communication with the
5 second buffer tank 240 and the inlet 211' of the first absorber 211. Thus, regenerated alkaline, aqueous scrubbing liquid may be mixed with spent aqueous scrubbing liquid from the second absorber 212 before being fed as alkaline, aqueous scrubbing liquid to the second absorber 212. Further, spent aqueous scrubbing liquid from the second
10 absorber 212 may be mixed with spent aqueous scrubbing liquid from the first absorber 211 before being fed as alkaline, aqueous scrubbing liquid to the first absorber 211. By controlling the flow rates in the scrubber arrangement 200, as well as the mixing ratios, not only the scrubbing efficiency, but also the pH of the spent aqueous scrubbing liquid to be regenerated may be controlled.

15 In accordance with the description of Fig. 1, flue gas enters the scrubber 210 via the scrubber inlet 213. The scrubbing is then performed in two stages. The first stage takes place in the first absorber 211 and the second stage takes place in the second absorber 212. The scrubbing is performed in a counter flow manner, with the second absorber 212 arranged downstream of the first absorber 211.

As mentioned, the scrubber arrangement 200 also has a third buffer tank 220
20 for regenerated aqueous scrubbing liquid. This third buffer tank 220 is in flow communication with the outlet 312'' for regenerated aqueous scrubbing liquid of the cathode chamber 312 and with the inlet 212' of the second absorber 212. The scrubber arrangement 200 also has a fourth buffer tank 250 for spent aqueous scrubbing liquid. This fourth buffer tank 250 is in flow communication with the first buffer tank 230 and
25 with the inlet 313' for the spent aqueous scrubbing liquid of the anode chamber 313. The fourth buffer tank 250 also has an outlet for withdrawing spent aqueous scrubbing liquid and delivering to the electrolytic cell 310 via the anode inlet 313'.

If the scrubber arrangement 200 is arranged separately from the regeneration arrangement 300, such as in a vehicle, also the regeneration arrangement 300, such
30 as a charging station or vehicle depot, may comprise a third buffer tank 220 and a fourth buffer tank 250 as shown in **Fig. 4**.

Now turning to the regeneration arrangement 300 in **Fig. 4**. Other than the electrolytic cell 310 and its components, which have been previously described in relation to **Fig. 1**, the regeneration arrangement 300 further comprises a first
35 compressor unit 320 for compressing hydrogen gas withdrawn from the cathode

chamber 312. Moreover, the regeneration arrangement 300 further comprises a second compressor unit 330 for compressing oxygen and carbon dioxide withdrawn from the anode chamber. Furthermore, the regeneration arrangement 300 also comprises a first gas separator 340 for separating oxygen O_2 and carbon dioxide CO_2 withdrawn from the anode chamber 313 from liquid. The first gas separator 340 is arranged upstream the second compressor unit 330. The regeneration arrangement 300 also comprises a second gas separator 380 for separating gaseous hydrogen H_2 and, for instance, liquid aqueous potassium hydroxide KOH, withdrawn from the cathode chamber 312. When the system 100 is operating, the oxygen O_2 and carbon dioxide CO_2 leaving the first gas separator 340 is compressed. The composition is then typically around 75% CO_2 and 25% O_2 . They may for instance be compressed at about 50 bar at 10 °C where carbon dioxide CO_2 is liquefied and oxygen O_2 still is in gaseous phase. An advantage of keeping CO_2 in a liquid phase is that it is practical during transportation. For instance, a third separator 390 is present downstream of the compressor to separate the oxygen from the liquefied carbon dioxide.

Furthermore, the regeneration arrangement 300 has a separator 350, such as a filter. For instance, the filter may be a reversed osmosis filter. This concentrator 350 is arranged downstream of the first gas separator 340. After passing the first gas separator, the fluid contains an aqueous stream comprising some hydrogen carbonate HCO_3^- withdrawn from the anode chamber 313. The concentrator is configured to provide, such as by filtration, a concentrated stream of hydrogen carbonate HCO_3^- and an aqueous stream depleted of hydrogen carbonate HCO_3^- . The concentrator 350 is in flow communication with the electrolytic cell 310 such that the aqueous stream comprising some hydrogen carbonate HCO_3^- is withdrawn from the anode chamber 313 and fed to the concentrator 350. The concentrated stream of hydrogen carbonate HCO_3^- may be withdrawn from the concentrator 350 and fed to the anode chamber 313. Further, the aqueous stream depleted of hydrogen carbonate HCO_3^- may be withdrawn from the concentrator 350 and fed to the cathode chamber 312.

The regeneration arrangement 300 also has a first balance tank 360 for regenerated alkaline, aqueous scrubbing liquid. The first balance tank 360 has a first inlet 361 for receiving regenerated alkaline, aqueous scrubbing liquid from the second gas separator 380. The first balance tank 360 also has a second inlet 362 for receiving the aqueous stream depleted of hydrogen carbonate HCO_3^- from a third balance tank 351, withdrawn from the concentrator 350. Further, it has an outlet 363 for feeding

diluted regenerated alkaline, aqueous scrubbing liquid to the cathode chamber 312 of the electrolytic cell 310.

The regeneration arrangement 300 may also have a second balance tank 370 for spent aqueous scrubbing liquid. The second balance tank 370 has a first inlet 371 for receiving spent aqueous scrubbing liquid from the scrubber arrangement 200, in particular via the fourth buffer tank 250. Further, it has a second inlet 372 for receiving the concentrated stream comprising hydrogen carbonate HCO_3^- from the concentrator 350. It also has an outlet 373 for feeding spent aqueous scrubbing liquid to the anode chamber 313 of the electrolytic cell 310.

To further describe the relationship between the scrubber arrangement 200 and the regeneration arrangement 300, the following description is provided. The regenerated alkaline, aqueous scrubbing liquid withdrawn from the cathode chamber 312 of the electrolytic cell 310 is fed as a second alkaline, aqueous scrubbing liquid to the second stage of scrubbing downstream of the first stage of scrubbing. The second stage of scrubbing may be defined as the process of the second absorber 212. A second spent scrubbing liquid, resulting from the second stage of scrubbing in the second absorber 212, is at least partly fed as the first alkaline, aqueous scrubbing liquid to the first stage of scrubbing upstream of the second stage of scrubbing, i.e. in the first absorber 211.

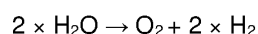
The pH-value of the second alkaline, aqueous scrubbing liquid entering the second absorber 212 is rather high. Preferably, the pH of the second alkaline, aqueous scrubbing liquid is about 12 to 14. This is higher than the pH of the first alkaline, aqueous scrubbing liquid leaving the first absorber 211 on its way to the electrolytic cell 310. Preferably, the pH of the first alkaline, aqueous scrubbing liquid is about 8 to 10.

It is to be noted that the electrolytic cell may be sensitive to impurities in the fluid flowing through the anode and cathode chambers. Hence, there may also be a separate cleaning unit (not shown), which serves to remove impurities such as for instance nitrogen oxides NO_x and sulfur oxides SO_x from the spent aqueous scrubbing liquid before it enters the electrolytic cell 310. As an example, the cleaning unit may include a filter to remove particulate matter.

It should be noted that in all Figs 1-4, the direction of the arrows corresponds to the direction of flow of the fluids circulating in the system 100. Further, the lines of the arrows indicate a fluid or flow communication between the elements of the system.

Chemical processes

The chemical processes occurring in the system 100 may be divided into two different parts, namely carbon capture and electrochemical regeneration, respectively. The overall reaction electrochemically splits water to oxygen and hydrogen according to the
5 following formula:



The chemical reactions have been balanced for the overall process of capturing 4 ×
10 CO₂ molecules.

The scrubber

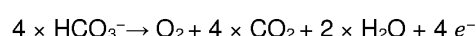
In short, carbon is captured in the scrubber 210 by dissolving carbon dioxide in the alkaline, aqueous scrubbing liquid. This reaction takes place automatically in
15 accordance with the following formula:



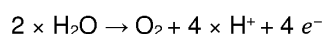
The solvent is then regenerated in the regeneration arrangement 300 using
20 electrochemistry. In general, the electrochemical reaction can be split into two parts; the anode reaction and the cathode reaction. These reactions will be described below.

The anode

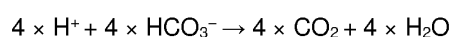
In the anode chamber 313, O₂ and CO₂ is generated in two different steps. First, O₂ is generated at the anode together with 4 H⁺. Then, the H⁺ decreases the pH-value of the solvent and releases CO₂. Simultaneously, O₂ is generated at the anode and the two gases are mixed in a ratio of 4:1, CO₂ to O₂. The overall reaction at the



The reaction at the anode is:



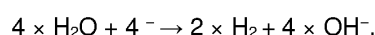
This reaction decreases the pH-value locally. This decrease in pH-value pushes the HCO₃⁻/CO₂ equilibrium to the right, such that:



which results in the release of gaseous CO₂ from the solvent.

The cathode

At the cathode, H₂ is produced together with OH⁻. This reaction both generates valuable H₂ for downstream applications and regenerates the alkaline solvent comprising hydroxide ions (OH⁻) for the carbon capture process. The cathode chamber reaction 312 is:

*Scrubbing liquid*

Ethanolamine (MEA) is an amine used for carbon capture used in conventional scrubbers. It has been suggested that MEA may act as a promoter for the process of scrubbing for instance flue gas. MEA indeed is known to capture CO₂ faster than a hydroxide solution. An envisaged idea has therefore been to combine the carbon capture capabilities of MEA with the electrochemical properties of the hydroxide solution. However, experimental tests have indicated that MEA unfortunately behaves undesirably in an electrochemical cell. MEA appears to be reduced at the cathode,

which would reduce the carbon capturing capabilities of the solvent, which is highly unwanted. Thus, using a metal hydroxide, e.g. potassium or sodium hydroxide, is preferred in the system 100 disclosed herein.

5 *Power need*

The electrochemical reaction in the electrolytic cell 310 requires electrical power. The actual power consumption will depend on the technical implementation of the process of the system 100. Assuming 100 % efficiency, the minimum current required for the process can be calculated using Faraday's law of thermodynamics: $I =$
 10 mFz/tM . With the parameters as listed in **Table 1** below, the current can be calculated.

Table 1 – parameters for calculating the minimum current required for the process

Symbol	Quantity	Value
<i>m</i>	Mass of O ₂	182 kg
<i>F</i>	Faraday's constant	96485 C/mol
<i>z</i>	Valency number of electrons	2
<i>t</i>	Time	1 s
<i>M</i>	Molar mass of O ₂	32 g/mol

15 The current can thus be calculated to $I = 1.09 \times 10^9$ A. With a minimum voltage of 2 V assumed, the theoretical minimum power consumption for 1 ton of CO₂ will be:

$$P_{\min} = 2 \text{ V} \times 1.09 \times 10^9 \text{ A} = 2.18 \times 10^9 \text{ J} = 2.18 \text{ GJ.}$$

20

*With alternative parameters as listed in **Table 1b** below, with the Valency number of electrons as 4, opposite to 2 shown in Table 1, the current can be calculated*

Table 2b – parameters for calculating the minimum current required for the process

Symbol	Quantity	Value
<i>m</i>	Mass of O ₂	182 kg
<i>F</i>	Faraday's constant	96485 C/mol
<i>z</i>	Valency number of electrons	4

t	Time	1 s
M	Molar mass of O ₂	32 g/mol

The current can thus be calculated to $I = 2.19 \times 10^9$ A. With a minimum voltage of 1.2 V assumed, the theoretical minimum power consumption for 1 ton of CO₂ will be:

5

$$P_{\min} = 1.2 \text{ V} \times 2.19 \times 10^9 \text{ A} = 2.63 \times 10^9 \text{ J} = 2.86 \text{ GJ}.$$

The theoretical minimum power consumption for 1 ton of CO₂ may be seen as producing 182 kg O₂ and 22 kg H₂.

10

For real chemical reactions, a higher energy consumption is expected. As suggested by a model based on experiments the ultimate power consumption for the capture of CO₂ and regeneration of the solvent is predicted to 5.88 GJ per 1 ton of CO₂. This process regenerates the solvent, produces H₂ at the cathode 312 and a mixture of CO₂ and O₂ at the anode.

15

Further energy is required for the separation of the CO₂ and O₂ from the first gas separator 340. This separation may for instance be done cryogenically. Energy consumption for CO₂ cryogenically separated from CH₄ has been studied in the literature for biogas purposes. For cryogenic separation, CH₄ and O₂ have similar physio-chemical properties, as the CO₂ is removed by cooling. The energy consumption for separation of O₂ and CO₂ in the first gas separator 340 is expected to be 1.4 ± 0.4 MJ per kg CO₂.

20

CO₂ and H₂ is typically produced in a ratio of 2:1. If the downstream application is methanol production, the suitable stoichiometric ratio is 1:3 and additional H₂ is required for this process. Commercial electrolysis equipment produces H₂ with an energy consumption of 55 kWh/kg. For 1 ton of CO₂, the H₂ requirements are therefore $(m_{\text{CO}_2} M_{\text{CO}_2}) \times 3 = 68182 \text{ mol}$, which equals: $68182 \text{ mol} \times 2 \text{ g/mol} \times 55 \text{ kWh/kg} = 7500 \text{ kWh} = 26.98 \text{ GJ}$. The carbon capture regeneration process produced H₂ corresponding to 4.5 GJ, and the remaining energy requirements for H₂ production is therefore: $26.98 \text{ GJ} - 4.50 \text{ GJ} = 22.48 \text{ GJ}$.

25

30

The power consumption of the carbon capture process is determined primarily by the electrochemical cell. The purification of CO₂ requires additional energy. However, the substantially largest energy consumption comes from the H₂ production. The carbon capture and purification alone is expected to cost in the order of 7.28 GJ

per ton of CO₂. This includes the production of H₂ corresponding to 4.5 GJ as already mentioned. Commercial values for CO₂ capture with amine scrubbers are currently 3.7 GJ per ton of CO₂. This is without the generation of H₂ and the CO₂ purification. Hence, if the CO₂ is used downstream of the electrolytic cell 310 together with H₂ to make for instance methanol, the process disclosed herein will be beneficial.

Using the values from an experimental model, the methanol produced from 1000 kg of CO₂ would costs about 2.5 kr/l, see Table 2 below. This price (Danish krone) is calculated based only on energy consumption and does not take material and personal into account.

Table 3 – Energy consumption of producing methanol from 1000 kg of CO₂

Process	Energy consumption
Case:	1000 kg CO ₂
Carbon capture and regeneration	5.88 GJ
CO ₂ purification	1.4 GJ
H ₂ production	22.48 GJ
Overall	29.76 GJ = 8267 kWh
Production	728 kg = 919 l methanol
Electricity price	0.3 kr/kWh
Carbon tax (saved)	182 kr
Price	2.5 kr/l

Currently, methanol made from non-renewable sources is sold at the price of 1.66 kr/l. The price of 2.5 kr/l is higher than 1.66 kr/l. However, currently, it is expected that green methanol would have a higher price than black methanol. Furthermore, the price is highly linked to the electricity price. However, as the carbon tax is expected to increase, as well as the cost for emission rights, the need and request for methanol production will increase in the industry and the system 100 provided herein will be beneficial to meet this increased demand.

EXPERIMENTAL SECTION

Example 1

In the following, a CO₂ capture from a power plant generating 10 MW heat and power from biomass is presented in relation to three process steps; "scrubber",

"regeneration" and "separation", see **Table 3**. Overall, the process requires a large amount of electrical energy. This is positive, as electrification of the carbon capture process is highly wanted and completely new. Some of the energy may be recovered as heat for district heating.

5

Table 4 – 10 MW power plant CO₂ capture

Process	Scrubber	Regeneration	Separation
In	- Gas with ~10% CO₂ 2 ton CO₂/h - Lean liquid 400 m³/h	- Saturated liquid 400 m³/h - Power 3.2 MW	- Gas: 80% CO₂ and 20% O₂ 2 ton/h CO₂ - Power 0.76 MW
Out	- Gas without CO₂ - Saturated liquid 400 m³/h	- Lean liquid 400 m³/h - Gas: H₂ 45 kg/h - Gas: 80% CO₂ and 20% O₂ 2 ton/h CO₂	Gas: pure CO₂ 2 ton/h CO₂
Operation	Automatic process	Uses power	Uses power

Example 2

To verify the applicability of the process using the system 100 as described herein, laboratory tests have been performed.

In the laboratory tests, a standard electrolysis cell from EC Electrocell, model Electro MP Cell was used. The electrolysis cell was provided with a Nafion 117 membrane. In operating the cell, a 1,5 M KHCO₃ solution was circulated over the anode side from a combined degassing/circulation tank. The liquid was circulated at 1.5 L/min. Similarly, a 1.5 M KOH solution was circulated over the cathode side from a combined degassing/circulation tank. The liquid was circulated at 1.5 L/min. Standard flowmeters and lab pumps were used. Gas flow from the degassing tanks were measured by an Aalborg GFM gas flow meter. CO₂ content were measured using a Guardian NG from Edinburgh Sensors. A standard heat plate was used to keep a constant temperature of the liquid at 40 degrees Celsius during the experiments. The pH and temperature were measured in the circulation tanks using standard online pH

and temperature meters. The current density applied to the electrolyzer were varied between 1-4 kA/m², using a standard power converter.

The results from the tests are presented in **Figs 5-8**. It is clear that the pH-value of the scrubbing liquid entering the electrolytic cell 310 plays an important part in the production of gases.

Fig. 5 shows the overall gas generation in the electrolytic cell and the pH-value over time. As is shown, the gas flow on the anode side of the electrolytic cell is fairly low at the beginning of the trial. Here, the pH-value of the scrubbing liquid is around 9.5. As the pH-value drops, the gas flow increases until it reaches its maximum level at a pH of about 8.5. Thereafter, the gas flow stabilizes at about 290 ml gas/min and the pH-value at about 8.

In **Fig. 6**, the gas flow of CO₂ and O₂ is illustrated in relation to the pH-value over time. As can be seen, in the beginning, only O₂ is produced and there is no release of CO₂. However, as soon as the pH-value begins to drop, the process starts to produce CO₂ gas and the collective rise in gas flow is substantially due to the rise in CO₂. The gas then has the composition of approximately 25% O₂ and 75% CO₂. Thus, it is shown once again that the pH-value plays an important role in the gas composition and in the production of CO₂ from the scrubbing liquid and hence also in the regeneration of scrubbing fluid. Preferably, the process is operated to provide the spent aqueous scrubbing liquid with a pH-value of about 8.5. This is where an optimal gas production and generation of CO₂ occurs.

Hence, the scrubber 210 may be seen not only as a scrubber, but importantly also as a pH-regulator. The scrubber 210 is preferably divided into several steps or absorbers, such as the first and second absorbers 211, 212 depicted with dashed lines in Fig. 2. The scrubber fluid entering the second absorber 212 has a higher pH-value than the fluid exiting the first absorber 211 to the anode chamber 313 of the electrolytic cell 310. This is also clear from **Fig. 7** where the gas production of CO₂ and O₂ is shown in relation to the energy consumption. Here, the current has been decreased in three steps, marked by the blue line which has a step-like shape.

Fig. 8 shows the relationship between the production of gases leaving the electrolytic cell per hour as measured over time. It is clear that the production of O₂, H₂ and KOH starts immediately, whereas the CO₂ production begins as the pH-value is decreased to an appropriate level as previously described. The production of H₂ follows

the production of O₂ in a ratio of 2 parts H₂ per one part O₂. Moreover, the production of KOH follows the production of H₂ in a ratio of 2 parts KOH per part H₂.

- From **Table 4** it is clear that essentially no additional energy is required for generating CO₂ and producing KOH for the regeneration of the scrubbing fluid, when compared to conventional H₂ electrolysis. This way, the H₂ production actually can compensate substantially for the energy required for the CO₂ capture.

Table 4 – Power consumption in the production of CO₂.

CO₂-production:	0.59	mol/h	(aim in the trials)
Power consumption	40	Watt	(aim and assumed from industrial standards)
Power consumption pr. mol:	67.8	Watt/mol	calculated
Power consumption pr. ton CO₂:	1541	kW	calculated
Total production of H₂	26.7	kg/ton CO ₂	calculated
Power consumption pr. kg H₂	57.5	kW	calculated

- In summary, the disclosure intends to describe a system 100 which reduces the cost (per ton of CO₂) for capturing CO₂ as compared to existing technologies, where the costs are associated with green electrical power, CO₂ quota or tax costs as well as hydrogen sales price.

Example 3

- The applicability of the process using the system of the aforementioned example has also been verified on a scale that is larger.

- The large scale test setup was installed on a site where flue gas from a biogas fueled engine was available. CO₂ removal from a flue gas originating from biogas may be an application where a system similar to that disclosed Fig. 2 and the corresponding disclosure may be installed.

- The large scale test comprised a scrubber tower from Puretec which was used to capture CO₂ from the flue gas and a 1.6 m² electrolysis cell from EC electrocell model "Electro Prod Cell" with a Nafion Cation exchange membrane was used. The pilot plant included buffer tanks, balance tanks and gas separators as described in the system shown in Fig. 2. The process plant was equipped with sensors to monitor pH,

liquid flows, gas flows, temperature, density, pressure, CO₂ %, currents and voltages, the sensors where used for monitoring and process control.

The results of the experimental results disclosed in Fig. 5-8, have been confirmed in the large scale test using the following parameters. First spent scrubbing
5 fluid consisting of a 1,5 M KHCO₃ solution that was circulated over the anode side from a combined degassing/circulation tank. The liquid was circulated at 60 L/min. Similarly, a 1.5 M KOH solution was circulated over the cathode side from a combined degassing/circulation tank. The liquid was circulated at 60 L/min. Flowmeters from Endress&Hauser and circulation pumps from Iwaki were used. Gas flow from the
10 degassing tanks were measured by gasflowmeters from VPinstruments and Sierrainstruments. CO₂ content were measured using a Guardian NG from Edinburgh Sensors. Inline heaters were used to keep the liquids at a temperature of 50 degrees Celsius. The pH and temperature were also measured in the circulation tanks using standard online pH and temperature meters. The current density applied to the
15 electrolyzer were varied between 0-4 kA/m₂, using a power converter from Flex Kraft.

The larger scale pilot plant test confirmed that the scrubber may both be utilized for both CO₂ capture as well as pH regulation of the scrubber liquid. The larger scale pilot plant test confirmed that the Alkaline scrubbing liquid, using KOH as part of the scrubbing liquid can be regenerated in the electrolytic cell while releasing CO₂, O₂
20 and H₂

CLAIMS

1. A method of scrubbing a gas, such as flue gas or exhaust gas, comprising carbon dioxide to deplete the gas of carbon dioxide (CO_2), the method comprising the steps of:
- scrubbing the gas in a scrubber (210) with a first alkaline, aqueous scrubbing liquid to dissolve carbon dioxide (CO_2) as hydrogen carbonate (HCO_3^-) and/or as carbonate (CO_3^{2-}) in the first alkaline, aqueous scrubbing liquid, thereby providing a first spent aqueous scrubbing liquid comprising hydrogen carbonate (HCO_3^-) and/or carbonate (CO_3^{2-}), the first spent aqueous scrubbing liquid having a pH from about 7 to about 9;
 - feeding the first spent aqueous scrubbing liquid to an anode chamber of an electrolytic cell (310) comprising the anode chamber (313) and a cathode chamber (312) separated by a membrane (311);
 - regenerating the first spent aqueous scrubbing liquid in the electrolytic cell (310) by electrolysis, the electrolysis increasing the pH of the first spent aqueous scrubbing liquid in the cathode chamber (312), the electrolysis further depleting the first spent aqueous scrubbing liquid of hydrogen carbonate (HCO_3^-) and of carbonate (CO_3^{2-}) in the anode chamber (313) by decreasing the pH, the regeneration further comprising generating gaseous hydrogen in the cathode chamber (312) and a gaseous mixture of oxygen and carbon dioxide (CO_2) in the anode chamber (313) by electrolysis; and
 - withdrawing regenerated alkaline, aqueous scrubbing liquid from the cathode chamber (312) and re-circulating it to the scrubber (210);
- wherein:
- the gaseous hydrogen is withdrawn from the cathode chamber (312); and
 - the gaseous mixture of oxygen and carbon dioxide is withdrawn from the anode chamber (313).
2. The method according to claim 1, wherein the first alkaline, aqueous scrubbing liquid comprises a dissolved metal hydroxide, such as one or more of dissolved potassium hydroxide (KOH), dissolved sodium hydroxide (NaOH), and dissolved lithium hydroxide (LiOH); preferably the first alkaline, aqueous scrubbing liquid comprises potassium hydroxide (KOH).

3. The method according to claim 1 or 2, wherein the method further comprises a step of separating the gaseous mixture of oxygen and carbon dioxide into:

- a first stream rich in oxygen and/or depleted of carbon dioxide; and
- a second stream rich in carbon dioxide and/or depleted of oxygen.

5

4. The method according to any one of the preceding claims, wherein hydrogen withdrawn from the cathode chamber (312) is used as a fuel to provide electricity; preferably in a fuel cell.

10

5. The method according to any one of the preceding claims, wherein the method further comprises:

- withdrawing an aqueous stream still comprising some hydrogen carbonate (HCO_3^-) from the anode chamber (313);
 - concentrating, such as by reversed osmosis, the withdrawn aqueous stream
- 15 comprising some hydrogen carbonate (HCO_3^-) to provide a concentrated stream comprising hydrogen carbonate (HCO_3^-); and
- re-circulating the concentrated stream comprising hydrogen carbonate (HCO_3^-) to the electrolytic cell (310).

20

6. The method according to any one of the preceding claims, wherein the scrubbing of the flue gas is performed at least in a first stage and in a second stage, the regenerated alkaline, aqueous scrubbing liquid withdrawn from the cathode chamber (312), being fed as a second alkaline, aqueous scrubbing liquid to the second stage of scrubbing downstream of the first stage of scrubbing, and wherein a second spent scrubbing liquid, resulting from the second stage of scrubbing, at least partly is

25 fed as the first alkaline, aqueous scrubbing liquid to the first stage of scrubbing upstream of the second stage of scrubbing, the pH of the second alkaline, aqueous scrubbing liquid being higher than the pH of the first alkaline, aqueous scrubbing liquid; preferably the pH of the second alkaline, aqueous scrubbing liquid being 12 to 14 and

30 the pH of the first alkaline, aqueous scrubbing liquid being 8 to 10.

7. The method according to claim 6, wherein:

- the regenerated alkaline, aqueous scrubbing liquid withdrawn from the cathode chamber (312) is mixed with a part of the second spent scrubbing liquid to
- 35 provide the second alkaline, aqueous scrubbing liquid, whereby the pH of the second

alkaline, aqueous scrubbing liquid is lower than the pH of the regenerated alkaline, aqueous scrubbing liquid withdrawn from the cathode chamber (312); and/or

- part of the second spent scrubbing liquid is mixed with a part of a first spent scrubbing liquid, resulting from the first stage of scrubbing, to provide the first alkaline, aqueous scrubbing liquid, whereby the pH of the first alkaline, aqueous scrubbing liquid being higher than the pH the first spent scrubbing liquid.

8. The method according to any one of the preceding claims, wherein part of the regenerated alkaline, aqueous scrubbing liquid is re-circulated to the cathode (312) chamber; optionally the regenerated alkaline, aqueous scrubbing liquid being diluted by an aqueous stream before re-circulating it to the cathode chamber (312), preferably said aqueous stream being provided by withdrawing an aqueous stream still comprising some hydrogen carbonate (HCO_3^-) from the anode chamber (313) and concentrating it, such as by reversed osmosis, to provide an aqueous stream depleted of hydrogen carbonate (HCO_3^-) and a concentrated stream comprising hydrogen carbonate (HCO_3^-);.

9. The method according to any one of the preceding claims, wherein carbon dioxide (CO_2) and/or oxygen (O_2) withdrawn from the anode chamber (313) is compressed into liquid carbon dioxide and/or compressed oxygen (O_2).

10. A system for scrubbing a gas, such as flue gas or exhaustive gas, comprising carbon dioxide to deplete the flue gas of carbon dioxide, the system comprising:

- a scrubber arrangement (200) for scrubbing a gas with an alkaline, aqueous scrubbing liquid to dissolve carbon dioxide as hydrogen carbonate (HCO_3^-) and/or as carbonate (CO_3^{2-}) in the alkaline, aqueous scrubbing liquid; and
- a regeneration arrangement (300) for regenerating spent aqueous scrubbing liquid by electrolysis, wherein:
 - the scrubber arrangement comprises a scrubber (210), the scrubber having an inlet (213) for the gas to be scrubbed and an outlet (214) for gas depleted of carbon dioxide, the scrubber (210) further having an inlet (212') for receiving the alkaline, aqueous scrubbing liquid and an outlet (211'') for withdrawing spent aqueous scrubbing liquid; and

- the regeneration arrangement comprises an electrolytic cell (310), comprising an anode chamber (313) and a cathode chamber (312) separated by a membrane (311), the anode chamber (313) comprising an anode inlet (313') for receiving the spent aqueous scrubbing liquid and an anode outlet (313'') for withdrawing oxygen and carbon dioxide, and the cathode chamber (312) comprising an outlet (312'') for withdrawing regenerated aqueous scrubbing liquid and hydrogen; wherein the outlet (211'') for spent aqueous scrubbing liquid of the scrubber (210) is in flow communication with the inlet (313') for the spent aqueous scrubbing liquid of the anode chamber (313), and the outlet (312'') for regenerated aqueous scrubbing liquid of the cathode chamber (312) is in flow communication with the inlet (212') for the alkaline, aqueous scrubbing liquid of the scrubber (210).

11. The system according to claim 10, wherein the scrubber arrangement (200) comprises a first (230) and a second (240) buffer tank for alkaline, aqueous scrubbing liquid, the scrubber (210) further comprising at least a first (211) and a second (212) absorber, wherein

the first absorber (211) comprises an inlet (211') for receiving alkaline, aqueous scrubbing liquid from the first buffer tank (230), and an outlet (211'') for withdrawing spent aqueous scrubbing liquid from the first absorber (211) to feed to an inlet of the first buffer tank (230), whereby aqueous scrubbing liquid may be circulated between the first absorber (211) and the first buffer tank (230);

the first buffer tank (230) is in flow communication with the inlet (313') for the spent aqueous scrubbing liquid of the anode chamber (313);

the second absorber (212) comprises an inlet (212') for receiving alkaline, aqueous scrubbing liquid from the second buffer tank (240), and an outlet (212'') for withdrawing spent aqueous scrubbing liquid from second absorber (212) to feed to an inlet of the second buffer tank (240), whereby aqueous scrubbing liquid may be circulated between the second absorber (212) and the first buffer tank (230);

the outlet (312'') for regenerated aqueous scrubbing liquid of the cathode chamber (312) is in flow communication with the inlet (212') of the second absorber (212); and

the outlet (212'') of the second absorber (212) is in flow communication with the inlet (211') of the first absorber (211).

12. The system according to claim 11, wherein the scrubber arrangement further comprises:

a third buffer tank (220) for regenerated aqueous scrubbing liquid, the third buffer tank (220) being in flow communication with the outlet (312'') for regenerated aqueous scrubbing liquid of the cathode chamber (312) and with the inlet (212') of the second absorber (212); and/or

a fourth buffer tank (250) for spent aqueous scrubbing liquid, the fourth buffer tank (250) being in flow communication with the first buffer tank (230) and with an inlet (313') for the spent aqueous scrubbing liquid of the anode chamber (313).

13. The system according to claim 10 or 11, wherein the regeneration arrangement (300) further comprises:

- a first compressor unit (320) for compressing hydrogen withdrawn from the cathode chamber (312); and/or

- a second compressor unit (330) for compressing oxygen and carbon dioxide withdrawn from the anode chamber (313), and/or a first gas separator (340) for separating oxygen and carbon dioxide withdrawn from the anode chamber (313) from each other.

14. The system according to claim 10 to 13, wherein the regeneration arrangement (300) further comprises a concentrator (350), such as a filter, for concentrating an aqueous stream comprising some hydrogen carbonate (HCO_3^-) withdrawn from the anode chamber (313) to provide a concentrated stream comprising hydrogen carbonate (HCO_3^-) and an aqueous stream depleted of hydrogen carbonate (HCO_3^-), the concentrator (350) being in flow communication with the electrolytic cell (310) such that:

the aqueous stream comprising some hydrogen carbonate (HCO_3^-) may be withdrawn from the anode chamber (313) and fed to the concentrator (350);

the concentrated stream comprising hydrogen carbonate (HCO_3^-) may be withdrawn from the concentrator (350) and fed to the anode chamber (313); and

the aqueous stream depleted of hydrogen carbonate (HCO_3^-) may be withdrawn from the concentrator (350) and fed to the cathode chamber (312);

optionally the regeneration arrangement (300) further comprising:

- a first balance tank (360) for regenerated alkaline, aqueous scrubbing liquid,

the first balance tank (360) having a first inlet (361) for receiving regenerated alkaline,

aqueous scrubbing liquid, a second inlet (362) for receiving the aqueous stream depleted of hydrogen carbonate (HCO_3^-) withdrawn from the concentrator (350), and an outlet (363) for feeding diluted regenerated alkaline, aqueous scrubbing liquid to the cathode chamber (313) of electrolytic cell (310); and/or

- 5 - a second balance tank (370) for spent aqueous scrubbing liquid, the second balance tank (370) having a first inlet (371) for receiving spent aqueous scrubbing liquid from the scrubber arrangement (200), a second inlet (372) for receiving the concentrated stream comprising hydrogen carbonate (HCO_3^-) from the concentrator (350), and an outlet (373) for feeding spent aqueous scrubbing liquid to the anode
10 chamber (313) of electrolytic cell (310).

- 15 15. A scrubber arrangement for scrubbing a gas, such as flue gas, comprising carbon dioxide to deplete the flue gas of carbon dioxide, the scrubber arrangement (200) comprising a scrubber (210) having an inlet (213) for the gas to be scrubbed and an outlet (214) for gas depleted of carbon dioxide, the scrubber (210) further having an inlet (212') for receiving the alkaline, aqueous scrubbing liquid and an outlet (211'') for withdrawing spent aqueous scrubbing liquid; wherein the scrubber arrangement (200) comprises a first (230) and a second (240) buffer tank for alkaline, aqueous scrubbing liquid, and the scrubber comprises at least a first (211) and a second absorber (212),
20 wherein:
 the first absorber (211) comprises an inlet (211') for receiving alkaline, aqueous scrubbing liquid from the first buffer tank (230) and an outlet (211'') for withdrawing spent aqueous scrubbing liquid and feed it to an inlet of the first buffer tank (230), whereby aqueous scrubbing liquid may be circulated between the first absorber
25 (211) and the first buffer tank (230); and
 the second absorber (212) comprises an inlet (212') for receiving alkaline, aqueous scrubbing liquid from the second buffer tank (240) and an outlet (212'') for withdrawing spent aqueous scrubbing liquid from the second absorber (212) to feed to an inlet of the second buffer tank (240), whereby aqueous scrubbing liquid may be
30 circulated between the second absorber (212) and the second buffer tank (240);
 wherein
 the outlet (212'') of the second absorber is in flow communication with the inlet (211') of the first absorber.

16. A scrubber arrangement according to claim 15, wherein the scrubber arrangement (200) further comprises:

a third buffer tank (220) for regenerated aqueous scrubbing liquid, the third buffer tank having an inlet (220') for receiving regenerated aqueous scrubbing liquid, the third buffer tank (220) further being in flow communication with the inlet (212') of the second absorber (212); and/or

a fourth buffer tank (250) for spent aqueous scrubbing liquid, the fourth buffer tank being in flow communication with the first buffer tank (230), the fourth buffer tank (250) further having an outlet (250'') for withdrawing spent aqueous scrubbing liquid.

17. A regeneration arrangement for regenerating a spent aqueous scrubbing liquid comprising hydrogen carbonate (HCO_3^-) and/or carbonate (CO_3^{2-}) used in electrolysis to provide alkaline, aqueous scrubbing liquid, the regeneration arrangement (300) comprising an electrolytic cell (310), comprising an anode chamber (313) and a cathode chamber (312) separated by a membrane (311), wherein the anode chamber (313) comprises an anode inlet (313') for receiving the spent aqueous scrubbing liquid and an anode outlet (313'') for withdrawing oxygen and carbon dioxide, and the cathode chamber (312) comprises an outlet (312'') for withdrawing regenerated aqueous scrubbing liquid and hydrogen; wherein

the regeneration arrangement (300) further comprises a concentrator (350) for concentrating an aqueous stream comprising some hydrogen carbonate (HCO_3^-) withdrawn from the anode chamber (313) to provide a concentrated stream comprising hydrogen carbonate (HCO_3^-) and an aqueous stream depleted of hydrogen carbonate (HCO_3^-), the concentrator (350) being in flow communication with the electrolytic cell (310) such that:

the aqueous stream comprising some hydrogen carbonate (HCO_3^-) may be withdrawn from the anode chamber (313) and fed to the concentrator (350);

the concentrated stream comprising hydrogen carbonate (HCO_3^-) may be withdrawn from the concentrator (350) and fed to the anode chamber (313); and

the aqueous stream depleted of hydrogen carbonate (HCO_3^-) may be withdrawn from the concentrator (350) and fed to the cathode chamber (312);

optionally the regeneration arrangement (300) further comprises:

- a first balance tank (360) for regenerated alkaline, aqueous scrubbing liquid, the first balance tank having a first inlet (361) for receiving regenerated alkaline, aqueous scrubbing liquid, a second inlet (362) for receiving the aqueous stream

depleted of hydrogen carbonate (HCO_3^-) withdrawn from the concentrator (350), and an outlet (363) for feeding diluted regenerated alkaline, aqueous scrubbing liquid to the cathode chamber (312) of electrolytic cell (310); and/or

- a second balance tank (370) for spent aqueous scrubbing liquid, the second
- 5 balance tank (370) having a first inlet (371) for receiving spent aqueous scrubbing liquid from the scrubber arrangement (200), a second inlet (372) for receiving the concentrated stream comprising hydrogen carbonate (HCO_3^-) from the concentrator (350), and an outlet (373) for feeding spent aqueous scrubbing liquid to the anode chamber (313) of electrolytic cell (310).

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18. The regeneration arrangement according to claim 19, wherein the regeneration arrangement (300) further comprises:

- a first compressor unit (320) for compressing hydrogen withdrawn from the cathode chamber (312); and/or
- 15 - a second compressor unit (330) for compressing oxygen and carbon dioxide withdrawn from the anode chamber (313), and/or a first gas separator (340) for separating oxygen and carbon dioxide withdrawn from the anode chamber (313) from each other.