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(72) Inventeurs/Inventors:
VERMA, MAUSAM, CA;
FRADETTE, LOUIS, CA;
FRADETTE, SYLVIE, CA;
LEFEBVRE, SYLVAIN, CA

(73) Propriétaire/Owner:
SAIPEM S.P.A., IT

(74) Agent: ROBIC

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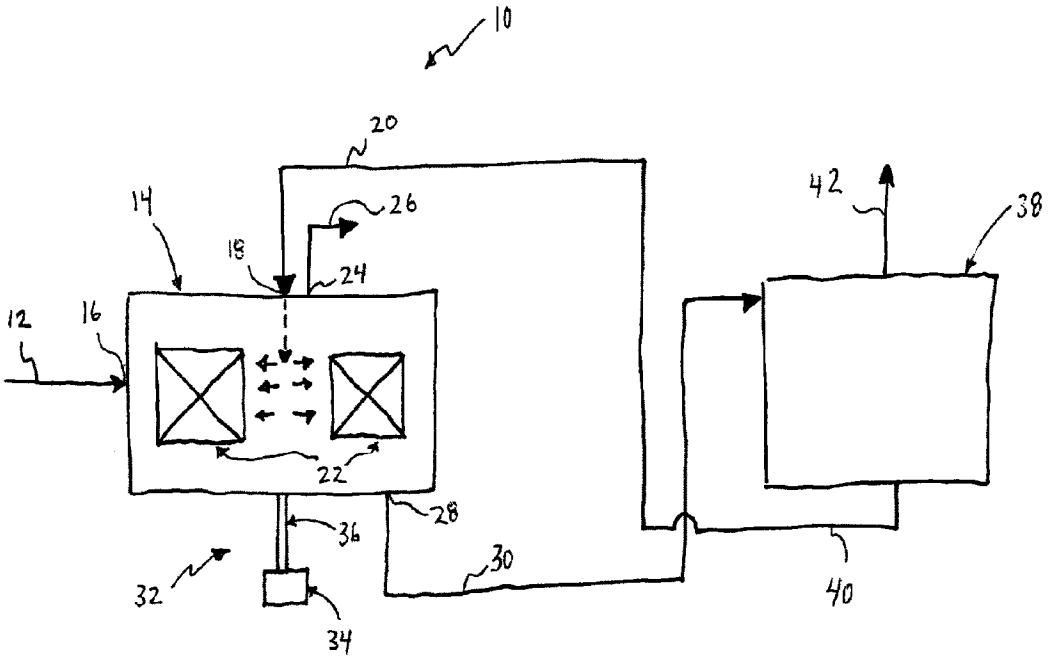

(57) Abrégé/Abstract:
Biocatalytic techniques for treating a CO_2 containing gas can include supplying CO_2 containing gas into a high intensity reactor comprising a reaction chamber; supplying an absorption solution into the high intensity reactor; contacting the CO_2 containing gas and the absorption solution within the reaction chamber, in the presence of carbonic anhydrase, for converting dissolved CO_2 into bicarbonate and hydrogen ions to form a CO_2 depleted gas and an ion enriched solution; and withdrawing the CO_2 depleted gas and an ion enriched solution from the high intensity reactor. The techniques may include elevated biocatalytic concentrations, various absorption compounds in the solution, a rotating packed reaction chamber, a defoamer, biocatalyst being immobilized with respect to particles carried with the absorption solution, and/or various operating conditions of the high intensity reactor.

ABSTRACT

Biocatalytic techniques for treating a CO_2 containing gas can include supplying CO_2 containing gas into a high intensity reactor comprising a reaction chamber; supplying an absorption solution into the high intensity reactor; contacting the CO_2 containing gas and the absorption solution within the reaction chamber, in the presence of carbonic anhydrase, for converting dissolved CO_2 into bicarbonate and hydrogen ions to form a CO_2 depleted gas and an ion enriched solution; and withdrawing the CO_2 depleted gas and an ion enriched solution from the high intensity reactor. The techniques may include elevated biocatalytic concentrations, various absorption compounds in the solution, a rotating packed reaction chamber, a defoamer, biocatalyst being immobilized with respect to particles carried with the absorption solution, and/or various operating conditions of the high intensity reactor.

INTENSIFICATION OF BIOCATALYTIC GAS ABSORPTION

TECHNICAL FIELD

The technical field generally relates to process intensification of biocatalytically enhanced operations, and more particularly to CO_2 absorption enhanced by carbonic anhydrase and intensification techniques such as the use of rotating contactors.

BACKGROUND

Conventional technology for gas absorption mainly consists of contacting a gas and a liquid inside a contactor, such as a packed column or a spray column, in such a way that the liquid phase contacting the gas phase absorbs a gaseous species of interest. The liquid phase can be selected for its ability to absorb the gaseous species of interest and to carry the absorbed gaseous species. To enable a high contact surface area between the gas and the liquid phase, a solid support known as a packing, can be present in packed column type contactors. The packing is fixed within the reaction chamber and its geometry may differ depending on the process conditions and thus provide different contact surface areas and/or flow regimes inside the liquid film flowing at the surface of the packing to promote the mass transfer of the gaseous species of interest into the liquid phase. The packing can be random or structured and can have different geometries.

Such conventional gas absorption technology is used for CO_2 capture operations. In this application, the gas phase containing CO_2, which may be a process gas, a gas effluent or another CO_2 containing gas, can be fed to a packed column absorption unit where it is contacted with a liquid phase. Depending on the pressure, temperature of the CO_2 containing gas, the nature of the liquid phase may differ. For example, for a gas phase available at high pressure, physical solvents or ionic liquids may be used, while for cases where the gas phase is available a low pressure, which typical of post-combustion CO_2-containing gas effluent, chemical solvents may be beneficial. Once the gaseous species is absorbed into the liquid it can be transferred to a second unit for regeneration of the solution by desorption/stripping techniques or mineralization. For both high and low pressure applications for CO_2 capture, the use of the conventional contactor technology can result in the use of large size equipment, large installation footprints

which can, in turn, lead to large capital investment and operating costs. This scenario is a challenge with respect to deployment of CO_2 capture installations.

Most enhancements related to CO_2 capture are focused on (i) improving the formulation of the absorption solution to maximize absorption rate, absorption solution carrying capacity (or solution cyclic capacity) and energy requirements for the regeneration of the solution and release of the absorbed CO_2, as well as (ii) optimizing equipment and process configurations in order to maximize heat integration in the process and thus reduce the process energy requirement. Most of the enhancements so far have not been able to dramatically reduce the equipment size, installation footprint and energy requirements.

In recent years, process intensification has been considered to enhance various processes. Some process intensification techniques have been proposed for CO_2 capture operations, and some research has been conducted at the laboratory scale using conventional liquid solutions such as aqueous solutions including MEA or NaOH.

There is a need for a technology that further enhances gas absorption, such as CO_2 absorption from a CO_2 containing gas.

SUMMARY

In some implementations, there is provided a biocatalytic process for treating a CO_2 containing gas, comprising: supplying CO_2 containing gas into a high intensity reactor comprising a reaction chamber; supplying an absorption solution into the high intensity reactor; contacting the CO_2 containing gas and the absorption solution within the reaction chamber, in the presence of carbonic anhydrase at elevated biocatalytic concentration, for converting dissolved CO_2 into bicarbonate and hydrogen ions to form a CO_2 depleted gas and an ion enriched solution; and withdrawing the CO_2 depleted gas and an ion enriched solution from the high intensity reactor.

In some implementations, the absorption solution comprises a slow absorption compound. In some implementations, the slow absorption compound comprises tertiary amines, tertiary alkanolamines, tertiary amino-acids, tertiary amino-acid salts, carbonates or a mixture thereof.

In some implementations, the absorption solution comprises an absorption compound comprising primary, secondary and/or tertiary amines; primary, secondary and/or tertiary alkanolamines; primary, secondary and/or tertiary amino acids; carbonates.

In some implementations, the absorption compound comprises piperidine, piperazine and derivatives thereof which are substituted by at least one alkanol group, monoethanolamine (MEA), 2-amino-2-methyl-i-propanol (AMP), 2-(2-aminoethylamino)ethanol (AEE), 2-amino-2-hydroxymethyl-i,3-propanediol (Tris), N-methyldiethanolamine (MDEA), dimethylmonoethanolamine (DMMEA), diethylmonoethanolamine (DEMEA), triisopropanolamine (TIPA) and triethanolamine), dialkylether or dimethylether of polyethylene glycol; glycine, proline, arginine, histidine, lysine, aspartic acid, glutamic acid, methionine, serine, threonine, glutamine, cysteine, asparagine, leucine, isoleucine, alanine, valine, tyrosine, tryptophan, phenylalanine, and derivatives such as taurine, N,cyclohexyl 1,3-propanediamine, N secondary butyl glycine, N-methyl N-secondary butyl glycine, diethylglycine, dimethylglycine, sarcosine, methyl taurine, methyl-a-aminopropionic acid, N-(β- ethoxy)taurine, N-(β-aminoethyl)taurine, N-methyl alanine, 6-aminohexanoic acid, including potassium or sodium salts of aforementioned amino acids; potassium carbonate, sodium carbonate, ammonium carbonate; or mixtures thereof.

In some implementations, at least a portion of the carbonic anhydrase is free in the absorption solution. In some implementations, at least a portion of the carbonic anhydrase is provided on or in particles flowing with absorption solution through the high intensity reactor. In some implementations, at least a portion of the carbonic anhydrase is provided immobilized with respect to supports fixed within the reaction chamber.

In some implementations, the high intensity reactor comprises internals fixed within the reaction chamber. In some implementations, the internals comprise packing material.

In some implementations, the high intensity reactor comprises a rotating packed bed reactor comprising the packing material housed in the reaction chamber. In some implementations, the packing material comprises metal foam.

In some implementations, the packing material has between 80% and 95% porosity. In some implementations, the packing material has between 85% and 90% porosity.

In some implementations, the internals comprise discs. In some implementations, the high intensity reactor comprises a rotating disc reactor having the discs housed within the reaction chamber.

In some implementations, the carbonic anhydrase is immobilized with respect to the internals.

In some implementations, the carbonic anhydrase is immobilized by covalent bonding, adsorption, ionic bonding, entrapment or encapsulation.

In some implementations, the carbonic anhydrase is immobilized with respect to an immobilization material that is provided as a coating on the internals.

In some implementations, the carbonic anhydrase is immobilized with respect to the particles by covalent bonding, adsorption, ionic bonding, entrapment or encapsulation.

In some implementations, the carbonic anhydrase is immobilized with respect to an immobilization material that is provided as a coating on the particles.

In some implementations, the elevated concentration of the carbonic anhydrase is at least 2 g/L, and the high intensity reactor is operated to provide mass transfer of CO_2 into the absorption solution at a rate such that biocatalytic impact on CO_2 hydration rate is below a plateau.

In some implementations, the elevated concentration of the carbonic anhydrase is at least 3 g/L, and the high intensity reactor is operated to provide mass transfer of CO_2 into the absorption solution at a rate such that biocatalytic impact on CO_2 hydration rate is below a plateau.

In some implementations, the elevated concentration of the carbonic anhydrase is at least 4 g/L, and the high intensity reactor is operated to provide mass transfer of CO_2 into the absorption solution at a rate such that biocatalytic impact on CO_2 hydration rate is below a plateau.

In some implementations, the elevated concentration of the carbonic anhydrase is at least 6 g/L, and the high intensity reactor is operated to provide mass transfer of CO_2

into the absorption solution at a rate such that biocatalytic impact on CO_2 hydration rate is below a plateau.

In some implementations, there is provided a biocatalytic system for treating a CO_2 containing gas, comprising: a gas inlet receiving CO_2 containing gas; a liquid inlet receiving an absorption solution; a high intensity reaction chamber in fluid communication with the gas inlet and the liquid inlet, the reaction chamber being configured to enable contact of the CO_2 containing gas and the absorption solution; carbonic anhydrase present in the reaction chamber at elevated biocatalytic concentration, and catalysing the conversion of dissolved CO_2 into bicarbonate and hydrogen ions to form a CO_2 depleted gas and an ion enriched solution; a gas outlet in fluid communication with the reaction chamber for withdrawing the CO_2 depleted gas; and a liquid outlet in fluid communication with the reaction chamber for withdrawing the ion enriched solution from the high intensity reactor.

In some implementations, the absorption solution comprises a slow absorption compound. In some implementations, the slow absorption compound comprises tertiary amines, tertiary alkanolamines, tertiary amino-acids, tertiary amino-acid salts, carbonates or a mixture thereof. In some implementations, the absorption solution comprises an absorption compound comprising primary, secondary and/or tertiary amines; primary, secondary and/or tertiary alkanolamines; primary, secondary and/or tertiary amino acids; carbonates. In some implementations, the absorption compound comprises piperidine, piperazine and derivatives thereof which are substituted by at least one alkanol group, monoethanolamine (MEA), 2-amino-2-methyl-i-propanol (AMP), 2-(2-aminoethylamino)ethanol (AEE), 2-amino-2-hydroxymethyl-i,3-propanediol (Tris), N-methyldiethanolamine (MDEA), dimethylmonoethanolamine (DMMEA), diethylmonoethanolamine (DEMEA), triisopropanolamine (TIPA) and triethanolamine), dialkylether or dimethylether of polyethylene glycol; glycine, proline, arginine, histidine, lysine, aspartic acid, glutamic acid, methionine, serine, threonine, glutamine, cysteine, asparagine, leucine, isoleucine, alanine, valine, tyrosine, tryptophan, phenylalanine, and derivatives such as taurine, N,cyclohexyl 1,3-propanediamine, N secondary butyl glycine, N-methyl N-secondary butyl glycine, diethylglycine, dimethylglycine, sarcosine, methyl taurine, methyl-a-aminopropionic acid, N-(β- ethoxy)taurine, N-(β-aminoethyl)taurine, N-methyl alanine, 6-aminohexanoic acid, including potassium or

sodium salts of aforementioned amino acids; potassium carbonate, sodium carbonate, ammonium carbonate; or mixtures thereof.

In some implementations, at least a portion of the carbonic anhydrase is free in the absorption solution. In some implementations, at least a portion of the carbonic anhydrase is provided on or in particles flowing with absorption solution through the high intensity reactor. In some implementations, at least a portion of the carbonic anhydrase is provided immobilized with respect to supports fixed within the reaction chamber.

In some implementations, the high intensity reactor comprises internals fixed within the reaction chamber.

In some implementations, the internals comprise packing material. In some implementations, the high intensity reactor comprises a rotating packed bed reactor comprising the packing material housed in the reaction chamber. In some implementations, the packing material comprises metal foam. In some implementations, the packing material has between 80% and 95% porosity. In some implementations, the packing material has between 85% and 90% porosity.

In some implementations, the internals comprise discs. In some implementations, the high intensity reactor comprises a rotating disc reactor having the discs housed within the reaction chamber.

In some implementations, the carbonic anhydrase is immobilized with respect to the internals. In some implementations, the carbonic anhydrase is immobilized by covalent bonding, adsorption, ionic bonding, entrapment or encapsulation. In some implementations, the carbonic anhydrase is immobilized with respect to an immobilization material that is provided as a coating on the internals. In some implementations, the carbonic anhydrase is immobilized by with respect to the particles by covalent bonding, adsorption, ionic bonding, entrapment or encapsulation. In some implementations, the carbonic anhydrase is immobilized with respect to an immobilization material that is provided as a coating on the particles.

In some implementations, the elevated concentration of the carbonic anhydrase is at least 2 g/L. In some implementations, the elevated concentration of the carbonic anhydrase is at least 3 g/L. In some implementations, the elevated concentration of the

carbonic anhydrase is at least 4 g/L. In some implementations, the elevated concentration of the carbonic anhydrase is at least 6 g/L.

In some implementations, there is provided a use of carbonic anhydrase at elevated biocatalytic concentration in a rotating packed bed reactor for biocatalytically enhancing CO_2 absorption from a gas into an absorption solution.

In some implementations, there is provided a biocatalytic process for treating a CO_2 containing gas, comprising: supplying CO_2 containing gas into a high intensity reactor comprising a reaction chamber; supplying an absorption solution into the high intensity reactor; contacting the CO_2 containing gas and the absorption solution within the reaction chamber, in the presence of carbonic anhydrase immobilized with respect to particles that are carried with the absorption solution through the reaction chamber, for converting dissolved CO_2 into bicarbonate and hydrogen ions to form a CO_2 depleted gas and an ion enriched solution; and withdrawing the CO_2 depleted gas and an ion enriched solution from the high intensity reactor.

In some implementations, there is provided a biocatalytic system for treating a CO_2 containing gas, comprising: a gas inlet receiving CO_2 containing gas; a liquid inlet receiving an absorption solution; a high intensity reaction chamber in fluid communication with the gas inlet and the liquid inlet, the reaction chamber being configured to enable contact of the CO_2 containing gas and the absorption solution; carbonic anhydrase immobilized with respect to particles that are carried with the absorption solution through the reaction chamber, and catalysing the conversion of dissolved CO_2 into bicarbonate and hydrogen ions to form a CO_2 depleted gas and an ion enriched solution; a gas outlet in fluid communication with the reaction chamber for withdrawing the CO_2 depleted gas; and a liquid outlet in fluid communication with the reaction chamber for withdrawing the ion enriched solution from the high intensity reactor.

In some implementations, there is provided a biocatalytic process for treating a CO_2 containing gas, comprising: supplying CO_2 containing gas into a high intensity reactor comprising a rotating reaction chamber; supplying an absorption solution into the high intensity reactor; contacting the CO_2 containing gas and the absorption solution within the rotating reaction chamber, in the presence of carbonic anhydrase, for converting

dissolved CO_2 into bicarbonate and hydrogen ions to form a CO_2 depleted gas and an ion enriched solution; operating the high intensity reactor at a liquid-to-gas (L/G) ratio, a carbonic anhydrase concentration, and a rotation speed of the rotating reaction chamber, such that the rotation speed is at or below an upper rotation speed limit at which biocatalytic acceleration of the hydration reaction reaches a maximum plateau for the L/G ratio; and withdrawing the CO_2 depleted gas and an ion enriched solution from the high intensity reactor.

In some implementations, the absorption solution comprises a carbonate absorption compound. In some implementations, the carbonic anhydrase concentration is between about 3 g/L and about 6 g/L based on the volume of the absorption solution prior to enzyme addition. In some implementations, the L/G ratio is between about 30 and about 300 on a w/w basis. In some implementations, the rotation speed is between about 300 RPM and about 750 RPM. In some implementations, the rotating reaction chamber comprises a packing material having a voidage between about 80% and about 95%.

In some implementations, there is provided a biocatalytic process for treating a CO_2 containing gas, comprising: supplying CO_2 containing gas into a high intensity reactor comprising a rotating reaction chamber; supplying an absorption solution into the high intensity reactor; contacting the CO_2 containing gas and the absorption solution within the rotating reaction chamber, in the presence of carbonic anhydrase, for converting dissolved CO_2 into bicarbonate and hydrogen ions to form a CO_2 depleted gas and an ion enriched solution; operating the high intensity reactor at a liquid-to-gas (L/G) ratio; operating the high intensity reactor at a rotation speed for the rotating reaction chamber, wherein the rotation speed is based on the L/G ratio to maximize biocatalytic acceleration of the hydration reaction; and withdrawing the CO_2 depleted gas and an ion enriched solution from the rotating reaction chamber.

In some implementations, the rotation speed is below an upper rotation speed limit at which biocatalytic acceleration of the hydration reaction reaches a maximum plateau for the L/G ratio.

In some implementations, there is provided a biocatalytic process for treating a CO_2 containing gas, comprising: supplying CO_2 containing gas into a high intensity reactor comprising a reaction chamber comprising internals; supplying an absorption solution

into the high intensity reactor to flow over the internals; contacting the CO_2 containing gas and the absorption solution within the reaction chamber, in the presence of carbonic anhydrase immobilized with respect to the internals, for converting dissolved CO_2 into bicarbonate and hydrogen ions to form a CO_2 depleted gas and an ion enriched solution; and withdrawing the CO_2 depleted gas and an ion enriched solution from the high intensity reactor.

In some implementations, the reaction chamber is configured for rotation and the internals comprise packing material or discs.

In some implementations, there is provided a biocatalytic process for treating a CO_2 containing gas, comprising: supplying CO_2 containing gas into a high intensity reactor comprising a reaction chamber; supplying an absorption solution into the high intensity reactor; contacting the CO_2 containing gas and the absorption solution within the reaction chamber, in the presence of carbonic anhydrase, for converting dissolved CO_2 into bicarbonate and hydrogen ions to form a CO_2 depleted gas and an ion enriched solution, wherein the high intensity reactor comprises a rotating packed bed reactor and the carbonic anhydrase is provided free in the absorption solution and flows therewith through the reaction chamber; operating the high intensity reactor at conditions that cause foam production; providing a defoamer in the high intensity reactor to inhibit the foam production; and withdrawing the CO_2 depleted gas and the ion enriched solution from the high intensity reactor.

In some implementations, the carbonic anhydrase is provided free in the absorption solution at a concentration sufficiently high to increase foam production in the high intensity reactor. In some implementations, the concentration of the carbonic anhydrase is above 0.2 g/L.

In some implementations, the defoamer comprises an oil-in-water emulsion. In some implementations, the defoamer comprises a water-in-oil emulsion, polyol based compounds, a polyol based dispersion, silicon based compounds, a non-ionic silicon emulsion, and/or a silica particle suspension.

In some implementations, the defoamer is provided in a concentration of at least 50 mg/L based on the volume of the absorption solution. In some implementations, the defoamer is provided in a concentration of at least 200 mg/L based on the volume of the absorption solution. In some implementations, the defoamer is provided in a concentration of between 100 and 300 mg/L based on the volume of the absorption solution.

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In some implementations, there is provided a biocatalytic system for treating a CO_2 containing gas, comprising: a gas inlet receiving CO_2 containing gas; a liquid inlet receiving an absorption solution; a high intensity reaction chamber in fluid communication with the gas inlet and the liquid inlet, the reaction chamber being configured to enable contact of the CO_2 containing gas and the absorption solution, wherein the high intensity reactor comprises a rotating packed bed reactor; carbonic anhydrase present in the reaction chamber and catalysing the conversion of dissolved CO_2 into bicarbonate and hydrogen ions to form a CO_2 depleted gas and an ion enriched solution, wherein the carbonic anhydrase is provided free in the absorption solution to flow therewith through the reaction chamber; a defoamer present in the high intensity reactor to inhibit foam production; a gas outlet in fluid communication with the reaction chamber for withdrawing the CO_2 depleted gas; and a liquid outlet in fluid communication with the reaction chamber for withdrawing the ion enriched solution from the high intensity reactor.

There is also provided the use of carbonic anhydrase and a defoamer in a rotating packed bed reactor for biocatalytically enhancing CO_2 absorption from a gas into an absorption solution, the carbonic anhydrase being free in the absorption solution and flowing therewith through the rotating packed bed reactor

In some implementations, there is provided a biocatalytic process for treating a gas stream comprising a target gas component, comprising: supplying the gas stream into a high intensity reactor comprising a reaction chamber; supplying an absorption solution into the high intensity reactor; contacting the gas stream and the absorption solution within the reaction chamber, in the presence of a biocatalyst, for converting dissolved target gas component into ions to form a gas stream depleted in the target gas component and an ion enriched solution; and withdrawing the depleted gas stream and an ion enriched solution from the high intensity reactor. One or more aspects of the processes or systems described herein for CO_2 absorption can also be applied to target gas components in general as well as various specific target gas components that may benefit from implementation of such aspects, such as particles high intensity reactor structural features, use of absorption compounds and/or defoamers, and operating parameters. In addition, other biocatalytically enhanced unit operations can also be used in connection with high intensity reactors and various adapted features described herein, for a variety of unit operations that may include reactions, phase separation, scrubbing, stripping, and so on, where use of biocatalyst and high intensity reactor cooperate to enhance the biocatalytic impact and the mass transfer in the unit operation.

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It should be noted that various features describe above and herein can be combined with various other features, processes and systems described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic representation of an absorption and desorption system including a rotating packed bed absorber.

Figure 2 is a schematic representation of a rotating discs contactor.

Figure 3 is a graph of Acceleration of the CO_2 absorption rates in a packed column using a 1M K_2CO_3 absorption solution in combination with 4 different carbonic anhydrase concentrations.

Figure 4 is a graph of Acceleration of the CO_2 absorption rates in a packed column using a 1.45M K_2CO_3 absorption solution in combination with 4 different carbonic anhydrase concentrations.

Figure 5 is a graph of Acceleration of the CO_2 absorption rates in a rotating packed bed using a 1.45 M K_2CO_3 in combination with 3 different enzyme concentrations at L/G of 30, 149 and 297 (w/w). The rotational speed of the contactor is 450 rpm.

Figure 6 is a graph showing Acceleration of the CO_2 absorption rates in a rotating packed bed using a 1.45 M K_2CO_3 at an enzyme concentration of 0 and 4 g/L, for L/G of 30, 149 and 297 (w/w) and rotational speed of the contactor of 450, 1000 and 1500 rpm.

Figure 7 is a graph showing a comparison of the CO_2 absorption performance obtained using a 5M MEA solution (lean CO_2 loading of 0.28 mol C/mol MEA) and using a 1.45 M K_2CO_3 solution (lean CO_2 loading of 0.62 mol C/mol potassium ions) containing 4 or 5.7 g/L of carbonic anhydrase enzyme for different L/G. The rotational speed of the contactor is 450 rpm.

DETAILED DESCRIPTION

Various techniques are described for enhancing gas component capture operations, such as CO_2 absorption. While the techniques will be described in detail with respect to the absorption and desorption of CO_2 in particular, using carbonic anhydrase enzyme for biocatalytic enhancements, it should be understood that the techniques can also apply to

other catalytic processes where a liquid stream and a gas stream containing a gas component are supplied to an intensification reactor, such as a rotating packed bed, such that mass transfer limitations between the gas and liquid phases are reduced to facilitate enhanced catalytic impact on the process of transferring the gas component from the gas phase to the liquid phase.

Intensification of biocatalytically enhanced CO_2 capture

Referring to Figure 1, a biocatalytic system 10 for removing a gas component, such as CO_2, from a gas stream 12 by absorption is illustrated. The CO_2 containing gas 12 is supplied to a high intensity reactor, such as a rotating reactor 14. The rotating reactor 14 can be a rotating packed bed reactor, a rotating disc reactor, or another type of reactor that uses rotation to increase mass transfer rate. The rotating reactor 14 can be a rotating packed bed reactor including a gas inlet 16 for receiving the CO_2 containing gas 12, a liquid inlet 18 for receiving an absorption solution 20, a reaction chamber 22 including packing material, a gas outlet 24 for withdrawing a CO_2 depleted gas 26, and a liquid outlet 28 for withdrawing an ion enriched solution 30. The rotating reactor 14 can also include a rotation mechanism 32 including a motor 34 and a drive shaft operatively connecting the motor to the reaction chamber for providing the torque for rotating the reaction chamber around a rotational axis.

The ion enriched solution 30 can then be supplied to a regeneration unit 38 for regenerating the solution by desorption or mineralisation, to produce a regenerated solution 40. In the case of desorption, a CO_2 enriched gas stream 42 is produced, whereas in the case of mineralization a solid mineral stream (e.g., solid carbonates) is produced. The regenerated solution 40 can then be recycled in whole or in part to the absorption stage, which in Figure 1 includes the rotating reactor 14. The regeneration unit can have various constructions and may take the form of various types of reactors, such as a conventional packed column or a high intensity reactor, such as an RPBs. Carbonic anhydrase may be present in the desorption unit, for example immobilized with respect to internals of the desorption unit or micro-particles flowing with the ion rich solution, or free in the solution. The high intensity desorption unit can be operated in conjunction with the high intensity absorption reactor such that the temperature, pressure, pH, and solvent concentration conditions do not substantially denature the carbonic anhydrase.

Techniques described herein can facilitate increasing the impact of biocatalysts in a gas absorption process. For instance, in operations where a liquid phase is contacted with a gas phase to absorb a component of interest, biocatalysts may be provided free or immobilized on particles that are carried with the liquid phase. In order to increase the kinetic impact of the biocatalyst, the contact between the gas phase and the liquid phase (containing the biocatalyst) takes place in a high intensity gas-liquid contactor to intensify the mass transfer of the gaseous component of interest toward the liquid phase, employing process intensification principles. A significant option for intensifying the mass transfer in a gas-liquid contactor is to use a rotating contactor, which may include a cyclone/vortex or a rotor, under enhanced acceleration conditions. This enhanced acceleration facilitates formation of thinner films, smaller bubbles and droplets, and increased flooding velocities for counter-current systems. In some implementations, the enhanced acceleration can result in an increase in the gas-liquid mass transfer by a factor of 10 to 100 compared to conventional techniques.

Intensification reactors and techniques

Various types of intensification techniques may be used in conjunction with carbonic anhydrase for enhanced CO_2 capture. The techniques can include intensification equipment and/or intensification methods. Rotating reactors, such as rotating packed beds and rotating disc reactors, can be used. In addition, other types of high intensity reactors can be used in connection with some implementations of the techniques described herein, such as gas-liquid jet reactors, swirling gal-liquid contactors, or contactors as described in US patent application published as No. 2010/0320294.

Process intensification techniques typically rely on the intensification of various different process parameters with a view of accelerating the process and reducing the size of equipment required for unit operations. Some potential intensification parameters, such as elevated pressures and temperatures, have been leveraged to accelerate unit operations by enhancing the kinetics of various mass transfer and reaction phenomena in the process. However, the intensification of some process parameters can lead to detrimental effects on some biocatalytic processes that employ biocatalysts that can denature at elevated temperature conditions for example. Nevertheless, some process intensification techniques focus on "fluid dynamic" intensification parameters, such as reducing the liquid film thickness flowing over packing material by leveraging rotational

force to drive the liquid instead of reliance on gravitational force. Contactors that leverage fluid dynamic intensification parameters can therefore increase mass transfer rates to take advantage of biocatalytic reaction kinetics while avoiding detrimentally impacting the biocatalysts. In this regard, the term "high intensity" reactor or "high intensity" contactor used herein refers to units that leverage fluid dynamic intensification parameters, rather than parameters such as high temperature that could have detrimental effects on the biocatalyst, to enhance mass transfer rates.

Referring to Figures 1 and 2, the rotating contactor 14 may include rotating discs or rotating packing. The rotating disc contactor is also known as a spinning disc contactor, and the rotating packed contactor is also known as a Higee contactor or rotating packed bed (RPB). Various different configurations and constructions of rotating discs or RPBs, can be used. For both high intensity contactor types, the method includes feeding a gas phase, containing a gas species of interest to absorb, to the contactor. The gas phase is fed via an outer part of the contactor. The liquid phase that will absorb the gaseous species of interest is fed via an inner part of the contactor. Because of the centrifugal force coming from the rotation of the reaction chamber housing the packing or the discs, the liquid will flow outwardly through the packing or form a film on the surface of the discs. The rotational speed can be adjusted in such a way as to minimize the liquid film thickness and maximize the contact surface area between the gas and the liquid phases, to enhance removal of the gas species of interest.

Regarding high intensity reactors that have discs or packing material, the process may be operated using biocatalytic particles that flow with the solution through the reactor and/or the process may be operated such that bicarbonate precipitates form in the solution and area carried out of the reactor. In scenarios where the particles and/or precipitates are nanosized, the reactor may be an RPB or a spinning disc reactor. In scenarios where the particles and/or precipitates are micron sized or larger, a spinning disc reactor may be preferred for handling such larger solid particulates.

Regarding high intensity reactors that have packing material provided in the reaction chamber(s), the packing that is used can have certain characteristics to benefit the mass transfer and biocatalytic impact on CO_2 absorption. In some implementations, the packing material can be a reticulated packing material, which can be composed of metal for example. The reticulated packing material can have large surface area per unit

volume and/or enable high voidage characteristics. For example, the specific surface area of the packing material can be between about 500 ft^2/ft^3 to about 1000 ft^2/ft^3, optionally between about 700 ft^2/ft^3 to about 800 ft^2/ft^3, still optionally about 750 ft^2/ft^3. The voidage of the packing material can be above about 80%, above about 85%, above about 90%, or between about 85% and about 95%, for example.

Some combinations of carbonic anhydrase biocatalyst, with absorption compounds of interest, for CO_2 absorption in a packed column as part of a CO_2 capture process have resulted in CO_2 capture rates, installation footprint and energy requirement comparable to conventional chemical solvent based processes. One advantage of such enzyme enhanced processes is that the solutions being used (e.g., carbonate based solutions) are less reactive than conventional primary alkanolmanines, more stable, and present less environmental issues. One finding with respect to the impact of the carbonic anhydrase enzyme in processes based on the use of a packed column as an absorber, is that the enzyme impact appears to be limited by the CO_2 mass transfer rate provided in this conventional absorber type. Therefore, fluid dynamic intensification techniques combined with carbonic anhydrase can enhance the impact of the enzyme on the CO_2 capture system and thus further benefit from both the intensification and biocatalytic effects.

Absorption solutions and compounds

In some implementations, the techniques can generally include removing a selected gas component from a gas phase, using a liquid phase that is contacted with the gas phase. The contact between the gas and the liquid will result in the absorption of the selected gas component by the liquid phase. This liquid phase can be selected and formulated based on its ability to absorb and store the absorbed selected gas component, and may therefore include one or more absorption compounds. The liquid phase composition can be formulated specifically to efficiently absorb the gas component of interest. The liquid phase may include water and other absorption compounds species that will absorb and react with the absorbed gaseous species. The liquid can also include other compounds such as de-foaming compounds. In some cases, the liquid phase can also contain the biocatalysts which are carried with the liquid through the reactor.

In some implementations, the absorption solution can be formulated to include one or more absorption compounds in addition to water to facilitate CO_2 absorption. In some implementations, the absorption compound can have a slow reaction rate with CO_2, but provide high cyclic capacity, no carbamate formation and/or lower energy requirement for their regeneration as compared to primary alkanolamines commonly used in post-combustion CO_2 capture process. The absorption compounds of interest can include, for example, slow reactive compounds. In some implementations, the absorption compound includes tertiary amines, tertiary alkanolamines, tertiary amino-acids, tertiary amino-acid salts, carbonates or a mixture thereof.

In some implementations, the biocatalyst is used in conjunction with an absorption compound which may include primary, secondary and/or tertiary amines (including alkanolamines); primary, secondary and/or tertiary amino acids; and/or carbonates. The absorption compound may more particularly include amines (e.g. piperidine, piperazine and derivatives thereof which are substituted by at least one alkanol group), alkanolamines (e.g. monoethanolamine (MEA), 2-amino-2-methyl-i-propanol (AMP), 2-(2-aminoethylamino)ethanol (AEE), 2-amino-2-hydroxymethyl-i,3-propanediol (Tris), N-methyldiethanolamine (MDEA), dimethylmonoethanolamine (DMMEA), diethylmonoethanolamine (DEMEA), triisopropanolamine (TIPA) and triethanolamine), dialkylether of polyalkylene glycols (e.g. dialkylether or dimethylether of polyethylene glycol); amino acids which may include potassium or sodium salts of amino acids, glycine, proline, arginine, histidine, lysine, aspartic acid, glutamic acid, methionine, serine, threonine, glutamine, cysteine, asparagine, leucine, isoleucine, alanine, valine, tyrosine, tryptophan, phenylalanine, and derivatives such as taurine, N,cyclohexyl 1,3-propanediamine, N secondary butyl glycine, N-methyl N-secondary butyl glycine, diethylglycine, dimethylglycine, sarcosine, methyl taurine, methyl-a-aminopropionic acid, N-(β- ethoxy)taurine, N-(β-aminoethyl)taurine, N-methyl alanine, 6-aminohexanoic acid; and which may include potassium carbonate, sodium carbonate, ammonium carbonate, promoted potassium carbonate solutions and promoted sodium carbonate solutions or promoted ammonium carbonates; or mixtures thereof. Absorption compounds can be added to the solution to aid in the CO_2 absorption and to combine with the catalytic effects of the carbonic anhydrase.

Biocatalysts and delivery methods

The biocatalysts considered for CO_2 capture operations is the enzyme carbonic anhydrase. This enzyme is one of the fastest known enzymes, and catalyses the interconversion of CO_2 and bicarbonate according to the following reaction:

$$CO_2 + H_2O \overset{CA}{\Leftrightarrow} H^+ + HCO_3^-$$

Carbonic anhydrase is not just a single enzyme form, but includes a broad group of metalloproteins that exists in genetically unrelated families of isoforms, α, β, γ, δ and ε. Different classes, isoforms and variants of carbonic anhydrase have been used in order to catalyze the hydration reaction of CO_2 into bicarbonate and hydrogen ions and the bicarbonate dehydration reaction into CO_2 and water. Under optimum conditions, the catalyzed turnover rate of the hydration reaction can reach 1×10^6 molecules/second.

In some implementations, the biocatalyst can be immobilized directly onto the surface of the packing material via chemical fixation of the biocatalyst. In some implementations, the biocatalyst or of an aggregate of the biocatalysts, such as CLEAs or CLECS, can be used in the high intensity reactor. In some other implementations, particles with the biocatalyst at their surface or entrapped inside the particles can be used.

In terms of particle delivery methods, the biocatalysts can be immobilized or otherwise delivered via particles that are carried with the absorption solution through the reaction chamber. In a conventional packed reactor, there is reliance on gravity as a driving force for establishing the liquid film that flows over the packing material. In the high intensity reactors, the biocatalytic particles may be provided to have a size and concentration in the absorption solution to flow with the liquid and to be smaller than the liquid film flowing on the surfaces of the packing material, which may be reticulated packing material as described above. The biocatalytic particles may also have other characteristics to remain distributed in the absorption solution in a generally uniform manner under the rotational force. In some implementations, the density of the biocatalytic particles is provided to be low enough such that the particles are carried with the liquid upon the substantial acceleration of the liquid within the rotating reactor. In addition, the particles can be sized in accordance with the thin liquid film, and may be for example at least an order of magnitude smaller than the thickness of the liquid film.

In some implementations, the biocatalyst can be immobilized with respect to the internals (e.g., packing material, discs, etc.) in the high intensity reactor. For RPB

reactors, the biocatalyst can be immobilized on the packing material using various techniques, such as entrapment, covalent bonding, and so on. In some scenarios, the biocatalyst can be immobilized in an immobilization material that is provided on the packing material as a coating, and may be spray coated onto the packing material. The immobilization material may include polysulfone and/or polysulfone grafted with polyethylene glycol and/or any one or a combination of polymeric materials described in US patent No. 7,998,714. The immobilization material may include micellar and/or inverted micellar polymeric materials, such as micellar polysiloxane material and/or micellar modified polysiloxane materials described in PCT patent application No. WO 2012/122404 A2. In some implementations, the immobilization material may include chitosan, polyacrylamide and/or alginate.

In some scenarios, the biocatalyst present in the packed reactor can lose activity over time, and techniques for replenishing activity of the biocatalytic reactor may be employed. Various activity replenishment technqiues can be used depending on the type of the reactor and the delivery method of the biocatalyst. Some activity replenishment techniques are described, for example, in US patent application No. 14/401,609. In the case of smaller sized high intensity reacotrs, such as RPBs, activity replenishment can be facilitated for various reasons. In some implementations, the packing material including immobilized biocatalyst can be more easily removed and replaced. In some implementations, the packing material can be reactivated in situ within the reaction chamber by supplying one or more biocatalyst activation solution into the reaction chamber to contact the packing material. For example, such in situ reactivation can include a series of solutions to pre-treat, clean, functionalize, etc., and eventually provide the immobilized enzyme onto the packing material. Since the volume of the high intensity reaction chamber is significantly smaller than conventional packed columns, for example, solutions requirements for in situ reactivation can be reduced and reactivation can be generally facilitated.

Biocatalyst can be provided at various concentrations in the high intensity reactor, in part depending on the delivery method of the biocatalyst.

In some scenarios, the biocatalyst is provided free in the absorption solution supplied to the high intensity reactor, at an elevated concentration. In this context, "elevated concentration" means that the concentration of the biocatalyst is greater than the

maximum concentration of the same biocatalyst under similar conditions in a conventional reactor, where such maximum concentration corresponds to a plateau of biocatalytic impact on the reaction. For example, as will be explained in the Examples section, in conventional packed columns the biocatalyst impact reaches a plateau at lower biocatalyst concentrations (e.g., see plateau in Figure 4) while in a RPB high intensity reactor the biocatalyst can be provided at significantly higher concentrations without reaching such a plateau (e.g., see Figure 5).

In addition, the biocatalyst can be provided in the high intensity reactor at a concentration (which may be an elevated concentration) that is below an upper concentration limit corresponding to a plateau of biocatalytic impact in the high intensity reactor. While the upper concentration limit is not shown in the Examples section, at certain high concentrations of biocatalyst there will be a plateau of biocatalytic impact on the hydration reaction. For example, at certain high concentrations of biocatalyst the absorption solution may become more susceptible to foaming and/or may have a high viscosity that would begin to limit mass transfer in the high intensity reactor. By keeping the biocatalyst concentration below such a plateau enables more efficient use of biocatalyst in the system.

In some scenarios, the biocatalyst can be provided at other concentrations depending on various factors, such as operating conditions, biocatalyst delivery method, type of biocatalyst, type of high intensity reactor, type of input gases and liquids, and so on. For example, carbonic anhydrase concentrations can range from 0.5 g/L to 10 g/L, 1 g/L to 8 g/L, 2 g/L to 6 g/L, or 3 g/L to 5 g/L. In addition, the biocatalyst concentration can be maintained to be relatively constant, or may be modified over time which may be accomplished by in-line addition of biocatalyst to the absorption solution.

Process additives and operation

In some implementations, the absorption solution can include additives that may be in addition to one or more absorption compounds and/or biocatalysts. In some scenarios, the additives can include a defoamer. Such defoamer or "anti-foam" compounds can be used in various scenarios where the biocatalyst and/or the process operating conditions are such that the absorption solution tends to have foam production. The presence of foam can negatively affect gas-liquid mass transfer and therefore can reduce

performance of the CO_2 absorption. For example, higher concentrations of biocatalyst (e.g., carbonic anhydrase) can increase the tendency of foam production, which was observed during experiments.

Various different types of defoamers can be used, depending on the given application of the process and operating conditions. The defoamer can include an oil-in-water emulsion, water-in-oil emulsion, polyol based compounds which may be in the form of a polyol based dispersion, silicon based compounds which may be in the form of a non-ionic silicon emulsion, or silica particle suspension, or a combination thereof.

The defoamer can be provided in various concentrations, for example a concentration of at least 50 mg/L based on the volume of the absorption solution, a concentration of at least 200 mg/L based on the volume of the absorption solution. Or a concentration of between 100 and 300 mg/L based on the volume of the absorption solution.

It should also be noted that various aspects of the processes and/or systems for removing CO_2 from a gas can also be applied to the removal of a gas component from a mixed gas stream and employing a catalyst (e.g., biocatalyst such as an enzyme) in a high intensity reactor. Examples, aspects and implementations described herein for CO2 capture and using carbonic anhydrase can be adapted using, for example, other biocatalysts having high turnover rates for a given reaction in order to covert a dissolved gas component into an ionic compound in the absorption solution.

EXAMPLES & EXPERIMENTATION

Experimentation series 1

A CO_2 absorption test series was conducted using a carbonic anhydrase as a biocatalyst in combination with a 1 M potassium carbonate solution (K_2CO_3); the lean CO_2 loading of the solution was 0.81 mol carbon/mol potassium ions. An antifoam agent, AF-204 (Sigma Aldrich) which is a polyol-based dispersion, was added to the carbonate solution at a concentration of 200 mg/L. The CO_2 concentration in the gas phase was 8% (v/v) dry basis. The absorber consists in a packed column containing 16mm polypropylene Pall rings as a packing to provide the gas/liquid contact surface area. The column has a diameter of 0.175 m and a height of 6.85 m. The L/G ratio was 7 (w/w). Tests were

conducted at 30°C temperature. The impact of carbonic anhydrase on the CO_2 transfer rates was evaluated at 4 different enzyme concentrations.

Results reported in Figure 3 show that increasing the enzyme concentration translates into an acceleration of the CO_2 mass transfer rate. However, the impact of the enzyme is greater at lower concentration. This seems to indicate that the CO_2 mass transfer from the gas phase to the liquid phase may be limiting the enzyme impact at higher enzyme concentration.

Experimentation series 2

Another CO_2 absorption test series was conducted using a carbonic anhydrase as a biocatalyst in combination with a 1.45M potassium carbonate solution (K_2CO_3); the lean CO_2 loading of the solution was 0.62 mol carbon/mol potassium ions. An antifoam agent, AF-204 (Sigma Aldrich) which is a polyol-based dispersion, was added to the carbonate solution at a concentration of 200 mg/L. The CO_2 concentration in the gas phase was 10% (v/v) dry basis. The absorber consists in a packed column containing 4.57m of Metal Mellapak M250Y packing and 3.05m IMTP Metal 25 packing for a total packing height of 7.62m. The column has a diameter of 0.254 m. The L/G ratio was 10 (w/w). Tests were conducted at a 30°C temperature. The impact of carbonic anhydrase on the CO_2 capture efficiency was evaluated at 4 different enzyme concentrations.

Results are reported in Figure 4. Data show that increasing the enzyme concentration translates into an acceleration of the CO_2 mass transfer for enzyme concentration up to 1 g/L. This clearly indicates that the CO_2 mass transfer from the gas phase to the liquid phase is limiting the enzyme impact at enzyme concentrations around 1 g/L and higher.

Experimentation series 3

CO_2 absorption tests were conducted using a carbonic anhydrase as a biocatalyst in combination with a 1.45M potassium carbonate solution (K_2CO_3) in a rotating packed bed; the CO_2 loading of the solution was adjusted to 0.62 mol carbon /mol potassium ions. An antifoam agent, AF-204 (Sigma Aldrich) which is a polyol-based dispersion, was added to the carbonate solution at a concentration of 200 mg/L. The CO_2 concentration in the gas phase was 9.5% (v/v) dry basis. The packing consisted of steel foam with 90% porosity. The dimensions of the packing are the following: height 2.54 cm, outer

diameter: 29.85 cm and inner diameter: 8.89 cm. The L/G ratios were 30, 149 and 297 (w/w). Tests were conducted at room temperature for 3 enzyme concentrations. The packed bed rotational speed was adjusted at 450 rpm. Results are shown in Figure 5. It can be observed that for this absorber configuration, the increase of the enzyme concentration results in an increase in the acceleration of the CO_2 capture rate as compared to a solution without enzyme. Moreover, a comparison with results presented in Figure 4, shows that a rotating packed bed reactor enables an increase in the CO_2 mass transfer rate as compared to a packed column as the impact of enzyme is still significant for concentration of enzymes higher than 1 g/L, value where mass transfer becomes limiting in a packed column.

Experimentation series 4

Additional tests were performed in the same unit as described in Experimentation series 3. For these tests, a 1.45 M potassium carbonate solution (K_2CO_3) having a CO_2 loading adjusted to 0.62 mol carbon / mol potassium ions was used. An antifoam agent, AF-204 (Sigma Aldrich) which is a polyol-based dispersion, was added to the carbonate solution at a concentration of 200 mg/L. The tests included measuring the CO_2 absorption rate, at different rotational speeds (450, 1000 and 1500 rpm) of the RPB, and at different L/G ratios (30, 149 and 297 (w/w). Two solutions were tested, the first solution did not contain enzyme whereas the second had an enzyme concentration of 4 g/L). Results are shown in Figure 6.

Regarding the results obtained for the solution not containing enzyme, it can be observed that the CO_2 absorption rate increases with the rotational speed up to 1000 rpm for an L/G of 297 (w/w) and then the Acceleration stays at a plateau. However, for the 4 g /L enzyme solution, the rotational speed has an impact at lower L/G whereas at higher L/G ratios the maximum CO_2 absorption rate at the tested process conditions is already reached at 450 rpm. This indicates that the optimal rotational speed depends on the L/G of the system and also on the presence of the enzyme. Acceleration is reported as the CO_2 absorption rate divided by the CO_2 absorption rate obtained for the solution not containing the enzyme at L/G 297 (w/w) and a rotational speed of 450 rpm.

Experimentation series 5

In order to compare the performance of the rotating packed bed to the performance obtained in the packed columns described in Examples 1 and 2, specific CO_2 absorption rates per unit packing volume were calculated for each system. RPB performance considered for comparison was obtained at an enzyme concentration of 4 g/L, rotational speed of 450 rpm and a L/G of 296 (w/w). Results are shown in Table 1.

Table 1. Ratio of the performance of RPB vs. packed columns

	Specific CO_2 absorption rates $\frac{(\mathbf{mg\ CO_2\ m^{-3}s^{-1}})_{RPB}}{(\mathbf{mg\ CO_2\ m^{-3}s^{-1}})_{PaCo}}$
RPB/packed column (Example 1)	54000/2400 = 22
RPB/packed column (Example 2)	98000/5000 = 20

These data clearly show that using a rotating packed bed increases mass transfer intensity as the absorption rates are 20 times higher than in a packed column for a same volume of packing. It is a clear indication that there is a synergy in using CA containing absorption solution with a rotating packed bed for CO_2 capture.

Experimentation series 6

For the sake of comparison and benchmarking, the performance obtained using carbonic anhydrase in combination with a potassium carbonate solution, 5M MEA solutions were also tested in the rotating packed bed described in Experimentation series 3 under the same L/G. Tests were conducted at 40°C. The CO_2 loading of the MEA solution was adjusted to 0.28 mol C/mol MEA, which is typical of values encountered in industrial MEA-based CO_2 capture processes. Results are shown in Figure 7 together with some of the data previously report on Figure 6. Acceleration values are calculated as the ratio of the CO_2 absorption efficiency of a given solution to the CO_2 capture efficiency observed with a 1.45 M K_2CO_3 solution at a lean CO_2 loading of 0.62 mol C/ mol potassium ions under same L/G conditions and at room temperature.

It can be first surprisingly observed that MEA absorption rates under the tests conditions are only 1.5 X higher than the corresponding absorption rates obtained in a 1.45 M K_2CO_3 (loading 0.62 mol/mol) at room temperature. A second surprising observation is

that the addition of carbonic anhydrase to the potassium carbonate solution leads to a significant increase in the acceleration of CO_2 absorption rates, the increase being more important when the enzyme concentration is higher. The acceleration is about 3.5 X more important using 4 g/L enzyme and 5 X more important using 5.7 g/L enzyme. These results were surprising notably since previous work using a packed column indicated that the packed column height should be higher when the enzyme was used in combination with potassium carbonate as compared to a MEA-based system for a same CO_2 capture efficiency as the L/G for the absorber. This demonstrates that a rotating packed bed, a high intensity contactor, enables enhanced impact of carbonic anhydrase in the CO_2 absorption process. This also clearly indicates that using carbonic anhydrase in combination with an absorption solution of interest (as described above) in a rotating packed bed is an advantageous option to reduce equipment size, installation footprint and process energy requirements in CO_2 absorption processes.

Some of the advantages related to process intensification of biocatalytically enhanced absorption operations over conventional technology can include equipment size reduction, higher kinetics, capital cost reduction, raw material cost reduction, increased process flexibility and maintenance, and enhanced environmental impact.

CLAIMS

1. A biocatalytic process for treating a CO_2 containing gas, comprising:

   supplying CO_2 containing gas into a high intensity reactor comprising a reaction chamber;

   supplying an absorption solution into the high intensity reactor;

   contacting the CO_2 containing gas and the absorption solution within the reaction chamber, in the presence of carbonic anhydrase, for converting dissolved CO_2 into bicarbonate and hydrogen ions to form a CO_2 depleted gas and an ion enriched solution, wherein the high intensity reactor comprises a rotating packed bed reactor and the carbonic anhydrase is provided free in the absorption solution and flows therewith through the reaction chamber;

   operating the high intensity reactor at conditions that cause foam production;

   providing a defoamer in the high intensity reactor to inhibit the foam production; and

   withdrawing the CO_2 depleted gas and the ion enriched solution from the high intensity reactor.

2. The biocatalytic process of claim 1, wherein the concentration of the carbonic anhydrase is above 0.2 g/L.

3. The biocatalytic process of claim 1 or 2, wherein the defoamer comprises an oil-in-water emulsion.

4. The biocatalytic process of claim 1 or 2, wherein the defoamer comprises a water-in-oil emulsion.

5. The biocatalytic process of claim 1 or 2, wherein the defoamer comprises polyol based compounds.

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6. The biocatalytic process of claim 5, wherein the defoamer comprises a polyol based dispersion.

7. The biocatalytic process of claim 1 or 2, wherein the defoamer comprises silicon based compounds.

8. The biocatalytic process of claim 7, wherein the defoamer comprises a non-ionic silicon emulsion.

9. The biocatalytic process of claim 7, wherein the defoamer comprises a silica particle suspension.

10. The biocatalytic process of any one of claims 1 to 9, wherein the defoamer is provided in a concentration of at least 50 mg/L based on the volume of the absorption solution.

11. The biocatalytic process of any one of claims 1 to 9, wherein the defoamer is provided in a concentration of at least 200 mg/L based on the volume of the absorption solution.

12. The biocatalytic process of any one of claims 1 to 9, wherein the defoamer is provided in a concentration of between 100 and 300 mg/L based on the volume of the absorption solution.

13. A biocatalytic system for treating a CO_2 containing gas, comprising:

a gas inlet receiving CO_2 containing gas;

a liquid inlet receiving an absorption solution;

a high intensity reaction chamber in fluid communication with the gas inlet and the liquid inlet, the reaction chamber being configured to enable contact of the CO_2 containing gas and the absorption solution, wherein the high intensity reactor comprises a rotating packed bed reactor;

carbonic anhydrase present in the reaction chamber and catalysing the conversion of dissolved CO_2 into bicarbonate and hydrogen ions to form a CO_2 depleted gas and an ion enriched solution, wherein the carbonic

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anhydrase is provided free in the absorption solution to flow therewith through the reaction chamber;

a defoamer present in the high intensity reactor to inhibit foam production;

a gas outlet in fluid communication with the reaction chamber for withdrawing the CO_2 depleted gas; and

a liquid outlet in fluid communication with the reaction chamber for withdrawing the ion enriched solution from the high intensity reactor.

14. The biocatalytic system of claim 13, wherein the concentration of the carbonic anhydrase is above 0.2 g/L.

15. The biocatalytic system of claim 13 or 14, wherein the defoamer comprises an oil-in-water emulsion.

16. The biocatalytic system of claim 13 or 14, wherein the defoamer comprises a water-in-oil emulsion.

17. The biocatalytic system of claim 13 or 14, wherein the defoamer comprises polyol based compounds.

18. The biocatalytic system of claim 17, wherein the defoamer comprises a polyol based dispersion.

19. The biocatalytic system of claim 13 or 14, wherein the defoamer comprises silicon based compounds.

20. The biocatalytic system of claim 19, wherein the defoamer comprises a non-ionic silicon emulsion.

21. The biocatalytic system of claim 19, wherein the defoamer comprises a silica particle suspension.

22. The biocatalytic system of any one of claims 13 to 21, wherein the defoamer is provided in a concentration of at least 50 mg/L based on the volume of the absorption solution.

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23. The biocatalytic system of any one of claims 13 to 21, wherein the defoamer is provided in a concentration of at least 200 mg/L based on the volume of the absorption solution.

24. The biocatalytic system of any one of claims 13 to 21, wherein the defoamer is provided in a concentration of between 100 and 300 mg/L based on the volume of the absorption solution.

25. The biocatalytic process of any one of claims 1 to 12, wherein the absorption solution comprises water and an absorption compound.

26. The biocatalytic process of claim 25, wherein the absorption compound comprises tertiary amines, tertiary alkanolamines, tertiary amino-acids, tertiary amino-acid salts, carbonates or a mixture thereof.

27. The biocatalytic process of any one of claims 1 to 12, wherein the absorption solution comprises an absorption compound comprising primary, secondary and/or tertiary amines; primary, secondary and/or tertiary alkanolamines; primary, secondary and/or tertiary amino acids; carbonates; or a combination thereof.

28. The biocatalytic process of claim 27, wherein the absorption compound comprises piperidine, piperazine and derivatives thereof which are substituted by at least one alkanol group, monoethanolamine (MEA), 2-amino-2-methyl-i-propanol (AMP), 2-(2-aminoethylamino)ethanol (AEE), 2-amino-2-hydroxymethyl-i,3-propanediol (Tris), N-methyldiethanolamine (MDEA), dimethylmonoethanolamine (DMMEA), diethylmonoethanolamine (DEMEA), triisopropanolamine (TIPA) and triethanolamine), dialkylether or dimethylether of polyethylene glycol; glycine, proline, arginine, histidine, lysine, aspartic acid, glutamic acid, methionine, serine, threonine, glutamine, cysteine, asparagine, leucine, isoleucine, alanine, valine, tyrosine, tryptophan, phenylalanine, and derivatives such as taurine, N,cyclohexyl 1,3-propanediamine, N secondary butyl glycine, N-methyl N-secondary butyl glycine, diethylglycine, dimethylglycine, sarcosine, methyl taurine, methyl-a-aminopropionic acid, N-(β- ethoxy)taurine, N-(β-aminoethyl)taurine, N-methyl alanine, 6-aminohexanoic acid, including potassium or sodium salts of aforementioned amino acids; potassium carbonate, sodium carbonate, ammonium carbonate; or mixtures thereof.

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29. The biocatalytic process of any one of claims 1 to 12 or claims 27 to 28, wherein the rotating packed bed reactor comprises packing material housed in the reaction chamber.

30. The biocatalytic process of claim 29, wherein the packing material comprises metal foam.

31. The biocatalytic process of claim 29 or 30, wherein the packing material has between 80% and 95% porosity.

32. The biocatalytic process of claim 31, wherein the packing material has between 85% and 90% porosity.

33. The biocatalytic process of any one of claims 1 to 12 or claims 25 to 32, wherein the concentration of the carbonic anhydrase is at least 2 g/L.

34. The biocatalytic process of any one of claims 1 to 12 or claims 25 to 32, wherein the concentration of the carbonic anhydrase is at least 3 g/L.

35. The biocatalytic process of any one of claims 1 to 12 or claims 25 to 32, wherein the concentration of the carbonic anhydrase is at least 4 g/L.

36. The biocatalytic process of any one of claims 1 to 12 or claims 25 to 32, wherein the concentration of the carbonic anhydrase is at least 6 g/L.

37. The biocatalytic process of any one of claims 1 to 12 or claims 25 to 36, wherein the high intensity reactor is operated to provide mass transfer of CO_2 into the absorption solution at a rate such that biocatalytic impact on CO_2 hydration rate is below a plateau.

38. The biocatalytic system of any one of claims 13 to 24, wherein the absorption solution comprises water and an absorption compound.

39. The biocatalytic system of claim 38, wherein the absorption compound comprises tertiary amines, tertiary alkanolamines, tertiary amino-acids, tertiary amino-acid salts, carbonates or a mixture thereof.

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40. The biocatalytic system of any one of claims 13 to 24, wherein the absorption solution comprises an absorption compound comprising primary, secondary and/or tertiary amines; primary, secondary and/or tertiary alkanolamines; primary, secondary and/or tertiary amino acids; carbonates; or a combination thereof.

41. The biocatalytic system of claim 40, wherein the absorption compound comprises piperidine, piperazine and derivatives thereof which are substituted by at least one alkanol group, monoethanolamine (MEA), 2-amino-2-methyl-i-propanol (AMP), 2-(2-aminoethylamino)ethanol (AEE), 2-amino-2-hydroxymethyl-i,3-propanediol (Tris), N-methyldiethanolamine (MDEA), dimethylmonoethanolamine (DMMEA), diethylmonoethanolamine (DEMEA), triisopropanolamine (TIPA) and triethanolamine), dialkylether or dimethylether of polyethylene glycol; glycine, proline, arginine, histidine, lysine, aspartic acid, glutamic acid, methionine, serine, threonine, glutamine, cysteine, asparagine, leucine, isoleucine, alanine, valine, tyrosine, tryptophan, phenylalanine, and derivatives such as taurine, N,cyclohexyl 1,3-propanediamine, N secondary butyl glycine, N-methyl N-secondary butyl glycine, diethylglycine, dimethylglycine, sarcosine, methyl taurine, methyl-a-aminopropionic acid, N-(β- ethoxy)taurine, N-(β-aminoethyl)taurine, N-methyl alanine, 6-aminohexanoic acid, including potassium or sodium salts of aforementioned amino acids; potassium carbonate, sodium carbonate, ammonium carbonate; or mixtures thereof.

42. The biocatalytic system of any one of claims 13 to 24 or claims 38 to 41, wherein the rotating packed bed reactor comprises the packing material housed in the reaction chamber.

43. The biocatalytic system of claim 42, wherein the packing material comprises metal foam.

44. The biocatalytic system of claim 42 or 43, wherein the packing material has between 80% and 95% porosity.

45. The biocatalytic system of claim 44, wherein the packing material has between 85% and 90% porosity.

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46. The biocatalytic system of any one of claims 13 to 24 or 38 to 45, wherein the concentration of the carbonic anhydrase is at least 2 g/L.

47. The biocatalytic system of any one of claims 13 to 24 or 38 to 45, wherein the concentration of the carbonic anhydrase is at least 3 g/L.

48. The biocatalytic system of any one of claims 13 to 24 or 38 to 45, wherein the concentration of the carbonic anhydrase is at least 4 g/L.

49. The biocatalytic system of any one of claims 13 to 24 or 38 to 45, wherein the concentration of the carbonic anhydrase is at least 6 g/L.

50. Use of carbonic anhydrase and a defoamer in a rotating packed bed reactor for biocatalytically enhancing CO_2 absorption from a gas into an absorption solution, the carbonic anhydrase being free in the absorption solution and flowing therewith through the rotating packed bed reactor.

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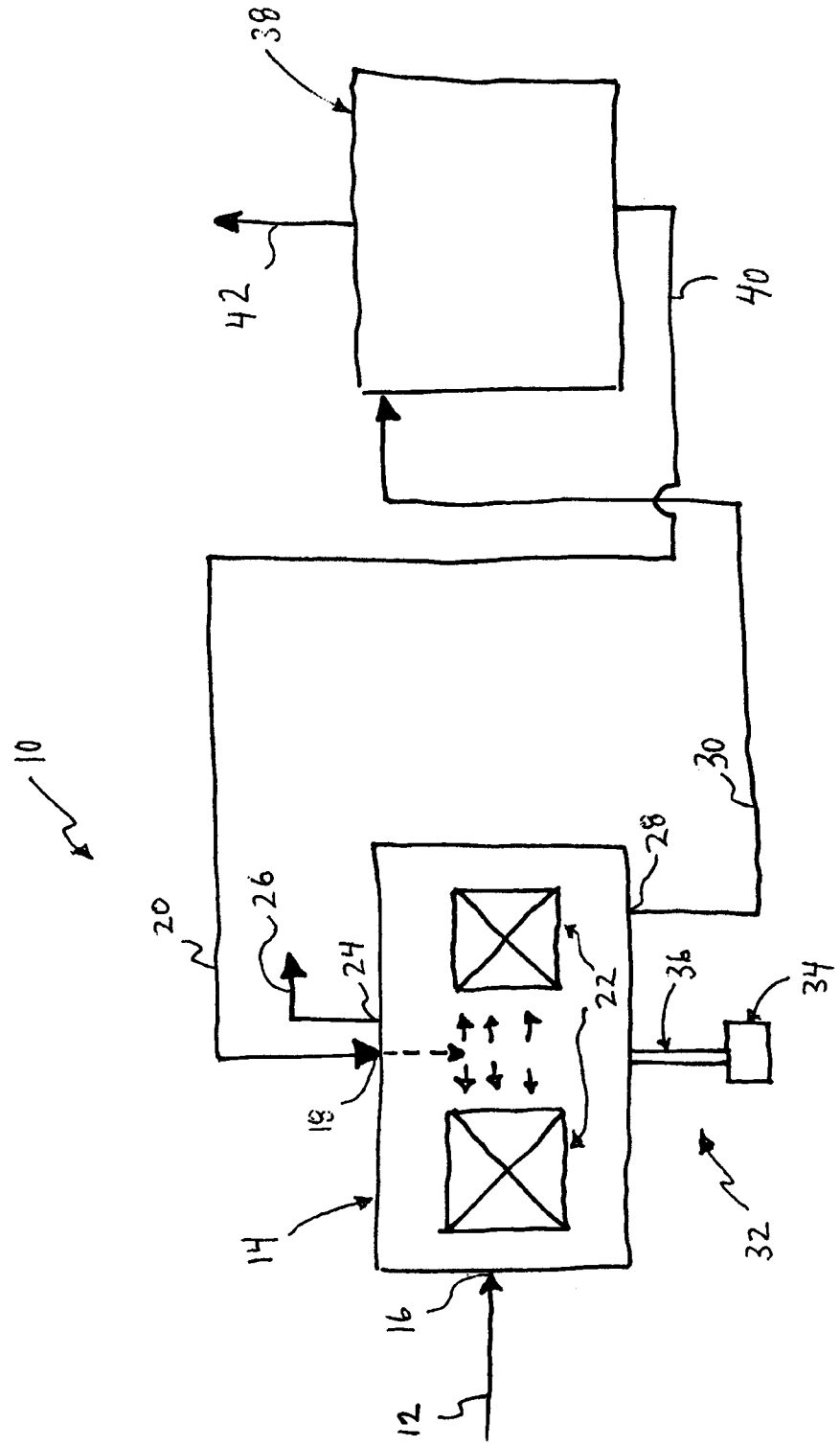


Fig. 1

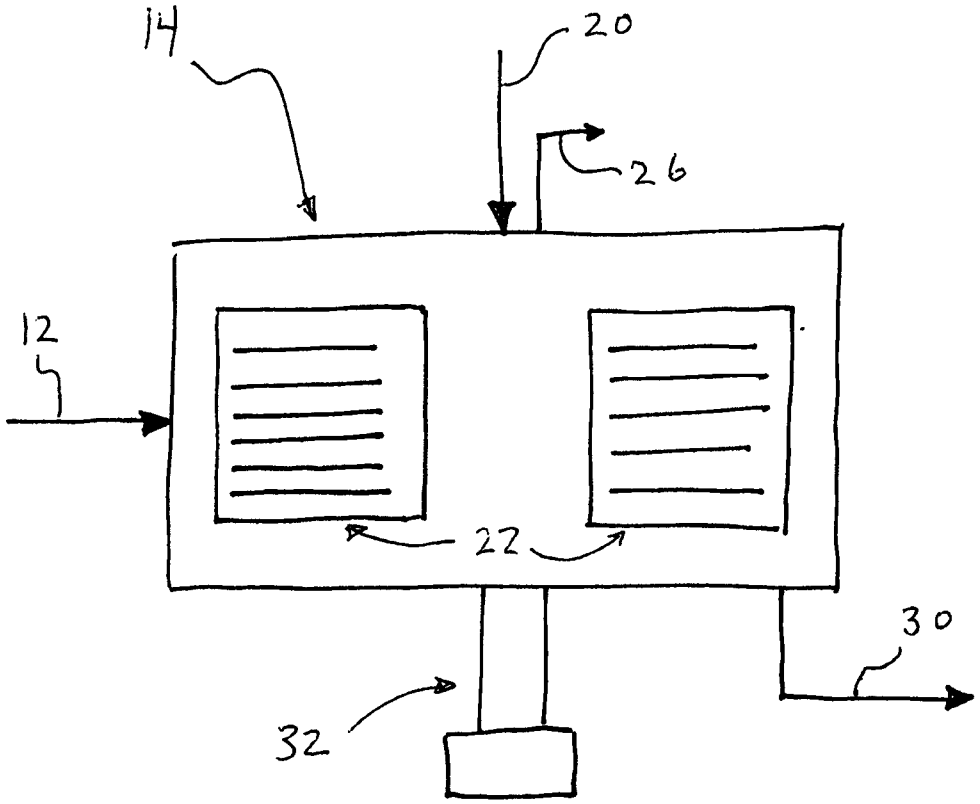


FIG. 2

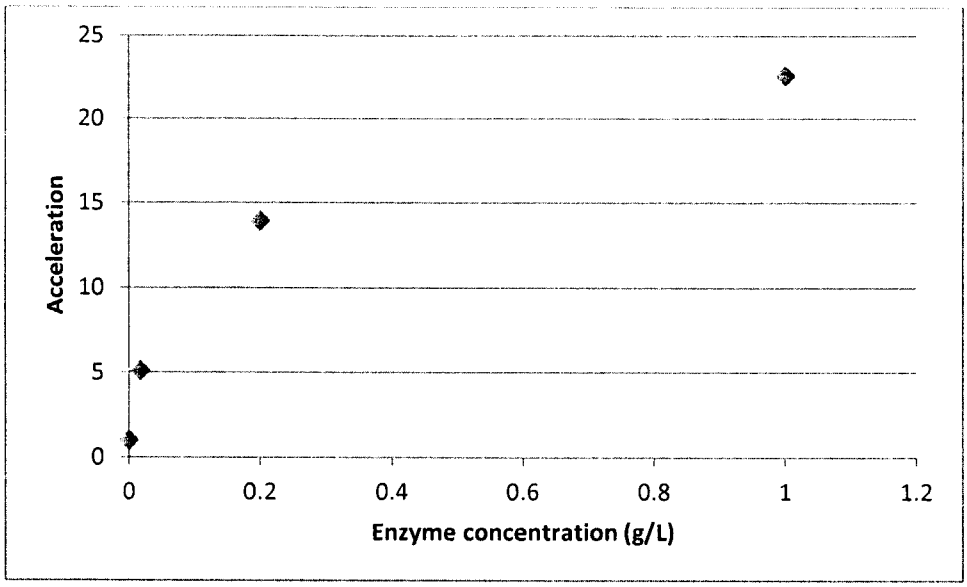

25
20
15
10
5
0
Acceleration
0
0.2
0.4
0.6
0.8
1
1.2
Enzyme concentration (g/L)

Figure 3

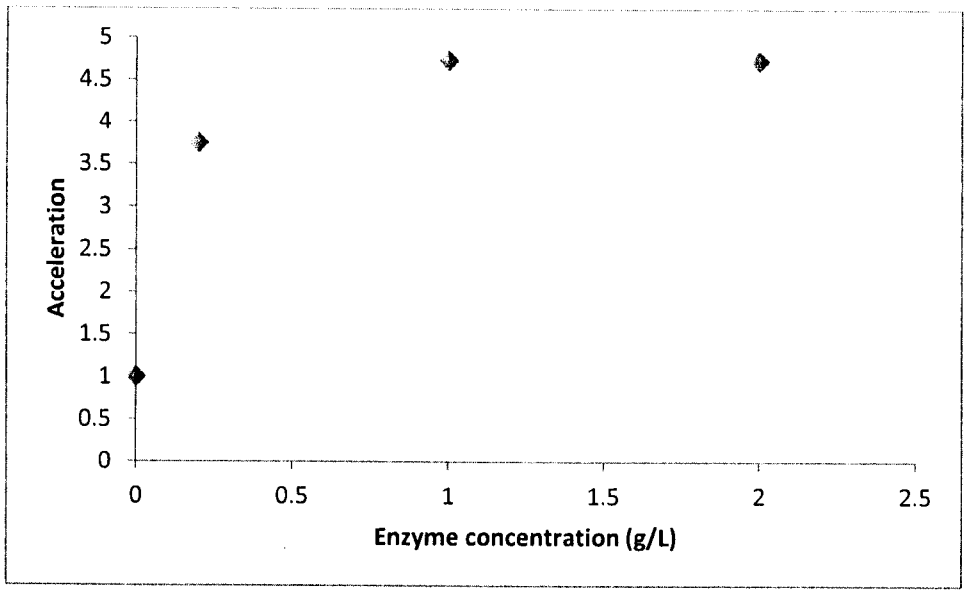

5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Acceleration
0
0.5
1
1.5
2
2.5
Enzyme concentration (g/L)

Figure 4

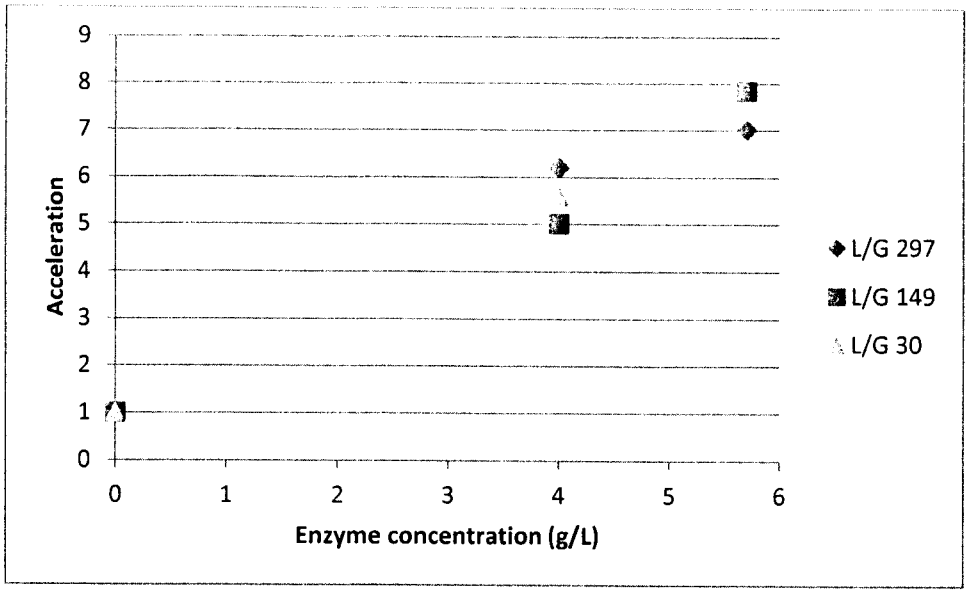

9
8
7
6
5
4
3
2
1
0
Acceleration
0
1
2
3
4
5
6
Enzyme concentration (g/L)
L/G 297
L/G 149
L/G 30

Figure 5

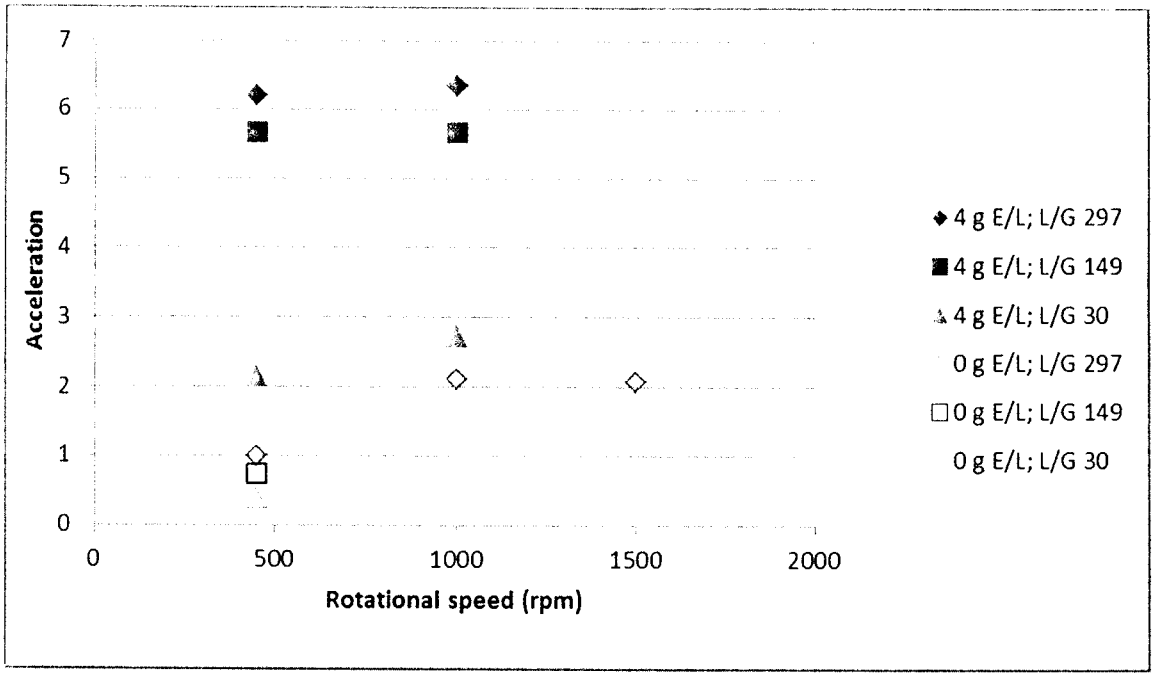

Acceleration
Rotational speed (rpm)
0
1
2
3
4
5
6
7
0
500
1000
1500
2000
4 g E/L; L/G 297
4 g E/L; L/G 149
4 g E/L; L/G 30
0 g E/L; L/G 297
0 g E/L; L/G 149
0 g E/L; L/G 30

Figure 6

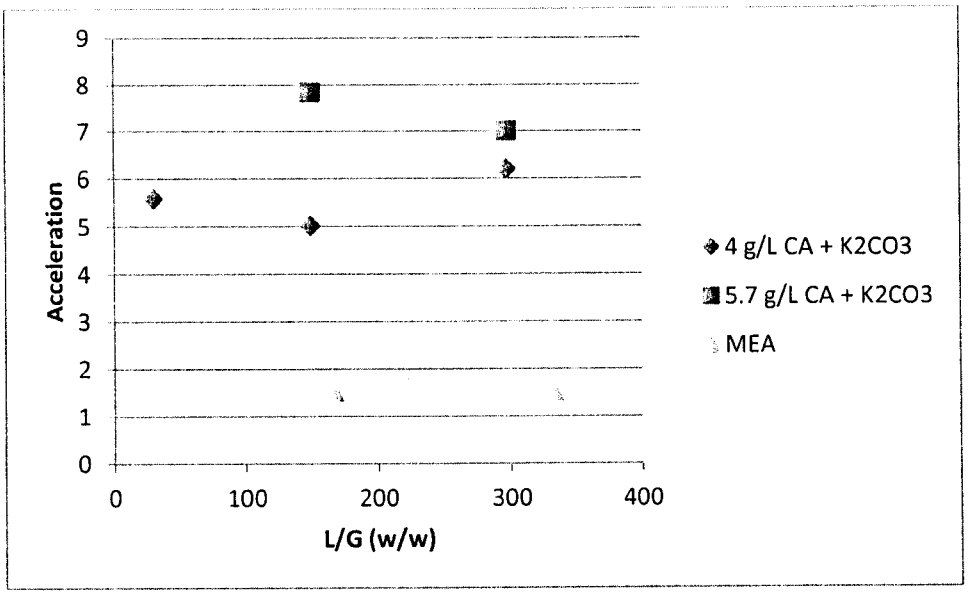
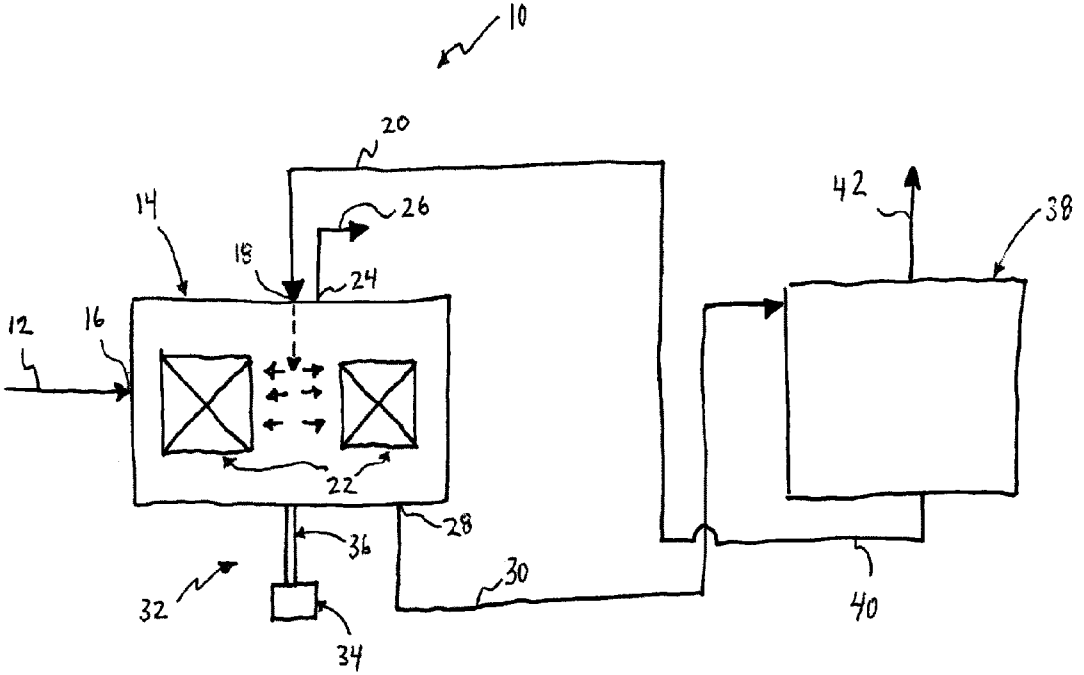

Acceleration
9
8
7
6
5
4
3
2
1
0
0
100
200
300
400
L/G (w/w)
4 g/L CA + K2CO3
5.7 g/L CA + K2CO3
MEA

Figure 7


10
20
14
26
18
24
12
16
22
28
36
32
30
34
42
38
40