SYSTEM AND METHOD FOR CAPTURING AND STORING CO2

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of and priority to U.S. Provisional Application No. 63/557,231 filed February 23, 2024, the entire disclosure of which is hereby incorporated by reference herein.

TECHNICAL FIELD

[0002] The present disclosure is generally related to a system and method for capturing and storing carbon dioxide from a gas moving through a modular containerized carbon capture system.

BACKGROUND

[0003] The capture and permanent storage of carbon dioxide (CO_2) is a useful climate change mitigation tool for decarbonizing fossil-fuel based industries, providing pure CO_2 for industrial uses, and even transforming processes into negative emission systems when they are fueled by biomass, carbon neutral waste, or CO_2 directly captured from the atmosphere.

[0004] Calcium Looping is a CO_2 capture technology that uses CaO (and/or $Ca(OH)_2$) as regenerable calcium (Ca) sorbent of CO_2. The state of the art of the fundamental properties of the materials, reactor design and process integration of Calcium Looping has greatly progressed in recent years. A wide variety of patents and technical publications have been published to apply Calcium Looping to power plants and industries. For example, U.S. Patent No. 8,226,917 B2 shows that these materials can carbonate fast (in particular $Ca(OH)_2$) when in small particle form (i.e., particle diameter of less than 3 mm), at temperatures between 600 and 700°C and in a wide range of CO_2 concentrations reach a maximum carbonation conversions of between 0.5-0.7. Such limit to the carbonation conversion is known to be limited by porosity ($CaCO_3$ molecular volume density is 27100 mol/m^3, $Ca(OH)_2$ is 29900 mol/m^3 while

CaO is 59642 mol/m^3) and by the formation of a product layer of $CaCO_3$ on the internal surface of CaO. The thickness of the product layer is known to decrease with temperature (Y.A. Criado et al, Effect of the carbonation temperature on the CO_2 carrying capacity of CaO, Ind. Eng. Chem. Res. 2018, 57, 12595-12599). From a practical point of view, this means that for flue gases with CO_2 content between 1-30%v of CO_2 the maximum level of conversion of 0.5-0.7 is reached when the surface area of the Ca-containing material is higher than 10 m^2/g and the porosity of active Ca-containing material is higher than 0.45.

[0005] Calcium Looping processes making use of such Ca-containing materials typically use fluidized beds, circulating fluidized beds, or entrained bed carbonator reactors, where the Ca-sorbents will typically carbonate in seconds to several minutes while in contact with the gas containing CO_2. Once carbonated, the particles containing $CaCO_3$ need to be brought to temperatures typically within 900-950°C to produce CaO (that eventually returns to the carbonator reactor or is purged for cement manufacture or other uses), and a gas stream rich in CO_2 (suitable for purification and disposal or use).

[0006] There are also Calcium Looping systems using packed bed reactors, where gases can move through the bed, but solids do not move and are not carried or entrained by the gas. All known packed bed Calcium Looping systems work in cyclic stages of reaction, with at least one carbonation stage aimed at the generation of a gas with a low content of CO_2 at the exit of the reactor, until the bed of CaO-containing solids is converted to $CaCO_3$ and a sharp breakthrough in the gas composition at the exit of the reactor occurs. For example, U.S. Patent No. 5,509,362 discloses a fuel gas reforming method with steam, using an adiabatic packed bed reactor filled with CaO sorbent, in which the removal of CO_2 forming $CaCO_3$ shifts the gas reactions towards a higher production of H2. A subsequent calcination stage of $CaCO_3$ in the same solid bed is carried out using an oxidation/reduction chemical loop and air, so that CO_2 is emitted to the atmosphere in diluted form. U.S. Publication No. 2012/0164032 A1 discloses an adiabatic Calcium Looping system to reduce the carbon content in a syngas using a packed-bed reactor holding a calcium-based sorbent.

[0007] Another process to capture CO_2 that uses stagnant solids during carbonation is a system proposed for the direct CO_2 capture from air (Abanades et al., An air CO_2 capture system based on the passive carbonation of large $Ca(OH)_2$ structures, Sust. Energ. & Fuels, 2020, 4, 3409-3417), where the carbonation of porous plates or Ca-containing solids of $Ca(OH)_2$ takes place in the open atmosphere, arranged in vast stationary infrastructures that passively carbonate in weeks to months when left to expose to ambient air. The $Ca(OH)_2$ porous structures can take virtually any form and, once carbonated, can be transported to a centralized calcination plant to manufactured again the $Ca(OH)_2$ while producing pure CO_2. Mortars containing $Ca(OH)_2$ have been extensively used in construction from Roman times, usually mixed up with other materials to enhance mechanical and other properties. The porosity of $Ca(OH)_2$ mortars when settled and dry can be high (between to 0.5-0.7) and this allows almost complete carbonation in ambient air. However, the carbonation mechanism of Ca-containing solids at low temperatures (from ambient air to 100°C) is known to be different than at 600-700°C referred above for Calcium Looping applications. Beruto et al. (Liquid-like H_2O adsorption layers to catalyze the $Ca(OH)_2/CO_2$ solid-gas reaction and to form a non-protective solid iroduct layer at 20°C. J. Eur. Ceram. Soc. 2000, 20 (4), 497-503) show the need of high relative humidity (80-100%) in the gas to promote fast carbonation of $Ca(OH)_2$. On the other hand, when $Ca(OH)_2$ is flooded in liquid water (for example $Ca(OH)_2$ as “lime putty” used in the building industry), the carbonation rates become again extremely slow. In these conditions, the carbonation rate of $Ca(OH)_2$ dry porous mortars, or other structures containing $Ca(OH)_2$, is governed by CO_2 gas diffusion through the open pores, with a carbonation front moving inwards from the external surface of the porous Ca-containing solids. It must be noted that direct carbonation of CaO at ambient temperatures is so slow that it cannot have practical applications. CaO carbonation in humid air is first converted to $Ca(OH)_2$ by hydration and then form $CaCO_3$.

[0008] An example of an existing industrial application of passive carbonation of $Ca(OH)_2$ to capture CO_2 from air, or vitiated air, comes from the need to remove CO_2 in fruit stores to extend the lifetime of the fruit. A porous bed of $Ca(OH)_2$ in powder form

is located inside porous bags for this purpose (FRUITCAL® http://www.carmeuse-agriculture.com/our-products/fruitcal). The bags are simply replaced when fully carbonated. Curing of lime mortars and other cementitious materials containing $Ca(OH)_2$ by the CO_2 contained in air, or accelerated curing with gases containing CO_2, is also part of the state of the art in the manufacture of extruded bricks or other prefabricated construction structures of a variety of shapes.

[0009] Lisbona et al. (Technoeconomic feasibility study of cement plants as reference facilities for centralized CO_2 capture in industrial sites; 15th International Conference on Greenhouse Gas Control Technologies, GHGT-15, 15th- 18th March 2021, Abu Dhabi, UAE) proposes the use of centralized cement plants with CO_2 capture (for example by oxycombustion in the calciner fed with $CaCO_3$) as centralized producers of CaO-containing solids, that are then transported (at temperatures close to ambient temperature) to an industrial site to be carbonated in a carbonator reactor operating at around the optimum temperature for Calcium Looping carbonation, i.e. around 650°C. The CaO must be transported at close to ambient temperature and the resulting carbonate requires cooling before being transported for regeneration in the cement plant. Such carbonator is therefore energy and resource inefficient, because it needs arranging additional heat exchanging steps to preheat the CaO-containing solids, the stack flue gases (usually emitted at temperatures below 150°C) and to recover the energy released in the carbonator or when cooling the carbonated solids exiting the carbonator. Such level of thermal integration may be uneconomic for many industrial applications of relatively small scale, served by the decentralized CO_2 capture carbonation method. A higher level of energy efficiency and compactness would be desirable for such decentralized carbonation method, combined with centralized regeneration to produce CO_2. Indeed, in all applications mentioned above, when the CO_2 sorbent and the resulting carbonate need to be transported at ambient temperature from the regeneration plant to the CO_2 capture plant and vice versa, it would be desirable to have a CO_2 capture method by carbonation being highly energy efficient and economic when preheating and cooling reactants and products from carbonation taking place at optimum temperatures around 650°C. Alternatively, it would be

desirable to be able to operate the carbonator at low temperatures, so that transport of sorbent Ca-containing materials and $CaCO_3$ product would be feasible without expensive and energy inefficient heating and cooling steps.

[0010] In this context, there is interest to note the widespread commercial availability of vertical shaft kilns of limestone to produce porous CaO, with the highest energy efficiencies and lowest footprint. This is achieved in lime kilns by arranging the solids and the gases to move in countercurrent mode in a moving bed apparatus, so that the hot gases leaving the calcination zone (which is overall exothermic because of the firing of a fuel in air to drive the endothermic calcination reaction) preheat the solids entering at ambient temperature at the top of the kiln and the hot solids moving downwards from the calcination zone preheat the air flowing upwards towards the burning zone (H. Piringer, Lime Shaft Kilns, Energy Procedia 120, 2017, 75-95). These moving bed kilns can treat large stones of limestone and lime (from 1 to 15 cm of diameter) to minimize gas pressure drop. They also provide solid residence time of the solids as long as 24 hours, which are needed to achieve the desired calcination degrees of the stones and the effective heat transfer between the gases and the solids in the preheating regions of gases and solids surrounding the calcination zone. In contrast, the gases reside in the kiln less than 20 seconds, moving upwards at superficial gas velocities of 1-3 m/s at the conditions of the calcination zone. The design techniques of cocurrent and countercurrent moving bed reactors are well known, and there are recent moving bed reactors applications in the CO_2 capture field, using special materials and set ups for effective adsorption of CO_2 by the solids (Mondino et al., Moving bed temperature swing adsorption for CO_2 capture from a natural gas combined cycle power plant, International Journal of Greenhouse Gas Control, 85, 2019, 58-70).

[0011] From the previous review of the state of the art, it can be concluded that despite recent advances developing Calcium Looping CO_2 capture methods at high temperatures (using 600-700°C for carbonation and 900-950°C for calcination), and the industrial experience related to the producing of porous CaO and $Ca(OH)_2$ materials in stone or Ca-containing solids form, or in the form of porous mortars of $Ca(OH)_2$ of different shapes, or even in the form of porous bags of $Ca(OH)_2$ material for passive

carbonation in contact with air, there is a lack of techno-economically viable and energy efficient CO_2 carbonation methods when the Ca-containing solids entering the carbonator are at low temperature and the exiting carbonated solids must also be at low temperatures (i.e., for transport to a centralized calciner). Accordingly, there is a continuing need for capturing and storing CO_2, for instance, from exhaust gas of a sea vessel, such as a cargo ship.

SUMMARY

[0012] Advantages of the subject technology include a system and method of capturing and storing CO_2, such as capturing CO_2 from a gas stream using calcium and/or magnesium (Ca/Mg) containing solids arranged in a packed bed. The system and method advantageously can employ a modular carbonator reactor. The modularity of the carbonator reactor furthermore allows for easy installation to a gas source via minimal retrofitting, as well as easy storage and transportation of the captured CO_2 and regeneration of the Ca/Mg containing solids. Such systems and methods of capturing CO_2 by carbonation can be used in a wide range of applications, such as cleaning flue gases emitted from a cargo ship during freight transport.

[0013] According to some implementations, a system for capturing carbon dioxide from a gas comprises a modular carbonator comprising a storage container defining an internal storage chamber; a gas inlet manifold configured to direct a flow of the gas into the internal storage chamber; a gas outlet manifold configured to direct the flow of the gas out of the internal storage chamber; and a packed bed reactor disposed within the internal storage chamber, the packed bed reactor including a plurality of Ca/Mg containing solids configured to capture carbon dioxide from the flow of the gas within the internal storage chamber.

[0014] According to other aspects of the system, an access portion is connected to the storage container and comprises a gas manifold including the gas inlet manifold and the gas outlet manifold.

[0015] According to other aspects of the system, the gas manifold further includes a bypass valve disposed between the gas inlet manifold and the gas outlet manifold, the

bypass valve being configured to allow the flow of gas directly from the gas inlet manifold to the gas outlet manifold when in an open configuration, thus preventing or minimizing the flow of gas from entering the internal storage chamber.

[0016] According to other aspects of the system, the access portion is attached to a front endwall of the storage container, and wherein the access portion extends from the front endwall of the storage container.

[0017] According to other aspects of the system, a rear endwall of the storage container comprises an access door configured to provide access to the internal storage chamber.

[0018] According to other aspects of the system, a gas diffuser is disposed within a lower portion of the storage container, the gas diffuser being in fluid communication with the gas inlet manifold.

[0019] According to other aspects of the system, the gas diffuser is configured to uniformly direct the flow of gas into the internal storage chamber from the gas inlet manifold.

[0020] According to other aspects of the system, the gas diffuser includes a diffuser plate having spaced apart holes, and wherein the holes located farther away from the gas inlet manifold have a larger diameter than the holes located closer to the gas inlet manifold.

[0021] According to other aspects of the system, the gas diffuser extends from a first end of the storage container to a second end of the storage container.

[0022] According to other aspects of the system, the gas diffuser further includes a mesh or perforated plate configured to prevent or minimize the Ca/Mg containing solids within the internal storage chamber from entering the gas inlet manifold.

[0023] According to other aspects of the system, a gas collector is disposed within an upper portion of the storage container and in fluid communication with the gas outlet manifold, such that the gas collector is configured to direct the flow of gas out of the internal storage chamber and into the gas outlet manifold.

[0024] According to other aspects of the system, the gas collector includes a baffle plate configured to extend across the gas outlet manifold for restraining, regulating, and/or redirecting the flow of gas.

[0025] According to other aspects of the system, the storage container is thermally insulated.

[0026] According to other aspects of the system, the Ca/Mg containing solids can comprise CaO, $Ca(OH)_2$, MgO, $Mg(OH)_2$, or two or more combinations thereof, or any mixture thereof. In addition to calcium oxides and/or magnesium oxides, the Ca/Mg containing solids optionally can comprise one or more alkali metal compounds such as one or more alkali metal hydroxides, e.g., LiOH, NaOH, KOH, one or more alkali metal carbonates, e.g., Na_2CO_3, $NaHCO_3$, etc. Further, according to other aspects of the system, the Ca/Mg containing solids can be porous.

[0027] According to other aspects of the system, a fan is configured to pull or push the gas through the modular carbonator.

[0028] According to other aspects of the system, a filtration device is configured to remove particulate from the gas after the gas has passed through the modular carbonator.

[0029] According to other aspects of the system, at least three modular carbonators are fluidly connected in series in a vertically stacked and/or horizontally linked arrangement.

[0030] According to other aspects of the system, the gas inlet manifold is configured to receive exhaust gas from an internal combustion engine of a shipping vessel.

[0031] According to other aspects of the system, the gas inlet manifold is configured to receive flue gas from a land-based factory plant.

[0032] In some implementations, a method for capturing carbon dioxide from a gas comprises moving the gas through a plurality of modular carbonators connected to each other in a vertically stacked and/or horizontally linked arrangement such that the plurality of modular carbonators are arranged in series and in fluid communication with each other, wherein each modular carbonator comprises a storage container defining an

internal storage chamber; a gas inlet manifold configured to direct the flow of the gas into the internal storage chamber; a gas outlet manifold configured to direct the flow of the gas out of the internal storage chamber; and a packed bed reactor disposed within the internal storage chamber, the packed bed reactor including a plurality of Ca/Mg containing solids configured to capture carbon dioxide from the flow of the gas within the internal storage chamber; and capturing the carbon dioxide from the flow of the gas via the Ca/Mg containing solids disposed within each modular carbonator; wherein the gas is moved through each modular storage container sequentially, such that the gas exiting the gas outlet manifold of one of the modular carbonators subsequently enters the gas inlet manifold of another one of the modular carbonators.

[0033] According to other aspects of the method, the Ca/Mg containing solids can comprise CaO, $Ca(OH)_2$, MgO, $Mg(OH)_2$, or two or more combinations thereof, or any mixture thereof. In addition to calcium oxides and/or magnesium oxides, the Ca/Mg containing solids optionally can comprise one or more alkali metal compounds such as one or more alkali metal hydroxides, e.g., LiOH, NaOH, KOH, one or more alkali metal carbonates, e.g., Na_2CO_3, $NaHCO_3$, etc. Further, according to other aspects of the method, the Ca/Mg containing solids can be porous.

[0034] According to other aspects of the method, the storage container of each modular carbonator is thermally insulated.

[0035] According to other aspects of the method, each modular carbonator comprises an access portion connected the corresponding storage container for providing access to a corresponding gas manifold.

[0036] According to other aspects of the method, each gas manifold of the respective access portion includes the corresponding gas inlet manifold and gas outlet manifold.

[0037] According to other aspects of the method, each gas manifold further comprises a bypass valve located between the gas inlet manifold and the gas outlet manifold, the bypass valve being configured to allow the flow of gas directly from the gas inlet manifold to the gas outlet manifold of the corresponding carbonator when in

an open configuration, thus preventing or minimizing the flow of gas from entering the internal storage chamber.

[0038] According to other aspects of the method, the flow of gas is uniformly directed into the internal storage chamber from the corresponding gas inlet manifold.

[0039] According to other aspects of the method, flow of gas is pulled or pushed through the series of connected modular carbonators by a fan.

[0040] According to other aspects of the method, particulate is removed from the gas via a filtration device after passing the gas through the series of modular carbonators.

[0041] According to other aspects of the method, the plurality of modular carbonators connected to each other in a vertically stacked or horizontally linked arrangement includes at least three modular carbonators arranged in series and in fluid communication with each other.

[0042] According to other aspects, the gas moved through modular storage containers can be exhaust gas from an internal combustion engine, e.g., from an internal combustion engine of a shipping vessel. In other aspects, the gas moved through modular storage containers can be flue gas, e.g., flue gas from a land-based facility such as a factory plant.

[0043] Another implementation of the present disclosure includes a method of regenerating Ca/Mg containing solids disposed within a modular storage container after CO_2 is captured from a gas by such solids. The Ca/Mg containing solids can have CO_2 captured from a gas according to systems and methods disclosed herein. In some aspects, the method can include releasing captured carbon dioxide such as by heating the Ca/Mg containing solids to release the CO_2. In other aspects, the method can further include regenerating the Ca/Mg containing solid sorbents. Regeneration can include hydrating and shaping, e.g., pelletizing, the solids to form or reform Ca/Mg containing solids configured to capture carbon dioxide. The regenerated Ca/Mg containing solids can then be disposed within a modular storage container of the present disclosure.

[0044] There has thus been outlined certain aspects of the subject technology so that the detailed description thereof may be better understood, and in order that the

present contribution to the art may be better appreciated. Details associated with these aspects as well as additional implementations of the subject technology will be described below, and which form the subject matter of the claims appended hereto.

[0045] In this respect, before explaining at least one aspect of the system and method of capturing and storing CO_2 in detail, it is to be understood that the subject technology is not limited in its application to the details of construction and to the arrangements of the components set forth in the following description or illustrated in the drawings. The system and method of capturing and storing CO_2 are capable of aspects in addition to those described, and of being practiced and carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein, as well as the abstract, are for the purpose of description and should not be regarded as limiting.

[0046] As such, those skilled in the art will appreciate that the conception upon which the technology is based may readily be utilized as a basis for the designing of other structures, methods, and systems for carrying out the several purposes of the system and method of capturing and storing CO_2.

BRIEF DESCRIPTION OF THE DRAWINGS

[0047] Aspects of the system and method of capturing and storing CO_2 of the present technology are illustrated by way of examples in the accompanying drawings, in which like parts are referred to with like reference numerals throughout.

[0048] FIG. 1 depicts a front perspective view of a modular carbonator according to an implementation of the subject technology.

[0049] FIG. 2 depicts a rear perspective view of the modular carbonator of FIG. 1.

[0050] FIG. 3 depicts a rear elevation view of the modular carbonator of FIG. 1.

[0051] FIG. 4 depicts an example of a damper valve according to an implementation of the subject technology.

[0052] FIG. 5 depicts an example of an electrical interface according to an implementation of the subject technology.

[0053] FIG. 6 depicts a cross-sectional view of the carbonator taken along lines 6-6 in FIG. 3.

[0054] FIG. 7 depicts a cross-sectional view of the carbonator taken along lines 7-7 in FIG. 6

[0055] FIG. 8 depicts an example of a gas diffuser according to an implementation of the subject technology.

[0056] FIG. 9 depicts an example of a gas collector according to an implementation of the subject technology.

[0057] FIG. 10 depicts an example of a baffle plate according to an implementation of the subject technology.

[0058] FIG. 11 depicts an example of a gas inlet manifold according to an implementation of the subject technology.

[0059] FIG. 12 depicts an example of a gas outlet manifold according to an implementation of the subject technology.

[0060] FIG. 13 depicts an example of a process for capturing CO_2 from a flue gas using a series of modular carbonators according to an implementation of the subject technology.

[0061] FIG. 14 depicts the process for capturing CO_2 from a flue gas using a series of modular carbonators according to an implementation of the subject technology.

[0062] FIG. 15 depicts the process for capturing CO_2 from a flue gas using a series of modular carbonators according to an implementation of the subject technology.

[0063] FIG. 16 depicts the process for capturing CO_2 from a flue gas using a series of modular carbonators according to an implementation of the subject technology.

[0064] FIG. 17 depicts a schematic diagram of the carbon capture system according to an implementation of the subject technology.

[0065] FIG. 18 depicts a flow diagram for capturing carbon dioxide from a gas and releasing the captured carbon dioxide according to implementations of the subject technology.

DETAILED DESCRIPTION

[0066] The present disclosure relates to systems and methods to capture CO_2 from a gas entering a container including a packed bed reactor of calcium and/or magnesium sorbents, obtain a gas reduced or even depleted in CO_2 at a reactor gas exit. The Ca-sorbents and/or Mg-sorbents can comprise solids of CaO, $Ca(OH)_2$ MgO, $Mg(OH)_2$, or any combination or mixtures thereof that can react to form carbonates such as $CaCO_3$ and/or $MgCO_3$. In addition to calcium oxides and/or magnesium oxides, the calcium and/or magnesium (Ca/Mg) containing solids optionally can comprise one or more alkali metal compounds such as one or more alkali metal hydroxides, e.g., LiOH, NaOH, KOH, etc., one or more alkali metal carbonates, e.g., Na_2CO_3, $NaHCO_3$, etc. Further, according to other aspects of the method, the Ca/Mg containing solids can be porous. Ca/Mg containing solids can include, for example, lime rocks, extruded cylindrical pellets, bricks or plates made with CaO or $Ca(OH)_2$, MgO, $Mg(OH)_2$, or any combination or mixtures thereof, or porous bags containing the Ca/Mg sorbent in powder form, to avoid their entrainment into the gas. Advantageously, the Ca/Mg containing solids can have internal porosities connected to the exterior surface of the solids ranging from about 0.45 to about 0.7 and/or internal surface areas higher than about 10 m^2/g. Such properties allow a maximum molar carbonation conversion of CaO and $Ca(OH)_2$ higher than about 0.5, at temperatures of carbonation of from about 600°C to about 700°C for CaO and from about 400°C to about 600°C for $Ca(OH)_2$, or at ambient temperature as long as there is 80-100% humidity in the air, for example.

[0067] In an implementation of the present disclosure, CO_2 can be captured from a gas such as a flue gas or exhaust gas, e.g., exhaust gas of an internal combustion engine of a marine vessel such as a cargo ship. The method can include moving the gas through a plurality of modular carbonators, such as modular storage containers, which are connected to each other in series and in fluid communication with each other, and each modular storage container including a plurality of Ca/Mg containing solids disposed therein. In an aspect of the method, the gas can be moved through each modular storage container sequentially, such that the gas exiting one of the modular storage containers subsequently enters another one of the modular storage containers. The modular

storage containers can be in a vertically stacked arrangement and/or horizontally linked arrangement. Advantageously, CO_2 can be captured from the flow of the gas via the Ca/Mg containing solids disposed within each of the connected modular storage containers.

[0068] In some implementations, Ca/Mg containing solids having an effective particle diameter or thickness from about 10 mm to about 100 mm. The residence time of gas flow through each modular storage container can range from about 1 hour to about 20 hours depending on the amount of Ca/Mg containing solids in a particular modular storage container.

[0069] The choice of Ca/Mg containing solids will depend on several factors including the amount of carbon dioxide in the gas. For example, the equilibrium of CO_2 on CaO does not allow for high CO_2 capture efficiencies when the concentration of CO_2 in the gas is low. Therefore, operation of the method targeting maximum temperatures in the carbonation zone, T_{max}, below 100°C are preferred for gases with volume fraction of CO_2 lower than 0.02, where it is known that $Ca(OH)_2$ can achieve high carbonation conversion under the right reaction conditions and gas-solid contact times. In these conditions, $Ca(OH)_2$ and/or $Mg(OH)_2$ or combinations thereof are also the preferred material, and operating conditions must be such as to have in the central carbonation region of the reactor a high relative humidity in the gas while avoiding the formation of liquid water that could flood the $Ca(OH)_2$ pore network, reducing the carbonation rates.

[0070] In another embodiment, flue gases at close to ambient temperature with a CO_2 content between 500 to 5000 ppmv and relative humidity between 80-100% enter the reactor at 5-10 m/s, and the solids are $Ca(OH)_2$ preferably with a surface area higher than 30 m^2/g, contained in a form of honeycombs, extruded bricks, plates or bags with a geometry to allow an effective depth of the carbonated layer of from about 1 mm to about 10 mm. The emphasis on high velocities and solid forms offering low pressure drop is necessary to accommodate the vast flows of air required to capture meaningful flow rates of CO_2 for climate change mitigation purposes. The use of porous solids in the method of the present disclosure advantageously minimizes entrainment of solids

into the gas and facilitates CO_2 capture devices with a lower footprint (i.e., lower cross-sections).

[0071] In some implementations, CO_2 is captured from a flue gas such as exhaust gas from an internal combustion engine, or from a flue gas from a factory plant or other land-based applications, among others. In one aspect, CO_2 may be captured from an exhaust gas from an internal combustion engine of a marine vessel, such as a cargo ship. Advantages of the systems and methods of the present disclosure employing modular carbonator reactors are that the capture and subsequent release of carbon dioxide can be decoupled. That is, carbon dioxide capture can occur at the source of the gas and release of the captured carbon dioxide can occur at a different location and facility.

[0072] FIGS. 1-3 illustrate a modular carbonator (100) for capturing and storing CO_2 from a gas, e.g., an exhaust gas or flue gas, moving therethrough. The modular carbonator (100) comprises a storage container (110) connected to an access portion (120), such as an access manifold or access compartment. The overall envelope and attachment points, including the corner castings, of the modular carbonator (100) conform with ISO 668 standard for intermodal shipping containers having a standard width of 8 feet, a height of 8.5 feet, and a length of either 20 feet or 40 feet. The storage container (110) defines a thermally insulated internal storage chamber (112). A packed bed reactor is disposed within the internal storage chamber (112). The packed bed reactor comprises a plurality of Ca/Mg containing solids, such slaked lime (i.e., calcium hydroxide, $Ca(OH)_2$) and/or a bed of pebble lime (i.e., calcium oxide, CaO), among others. According to some aspects, a volume of approximately 18-28 m^3, or a mass of approximately 19-30 metric tons of Ca/Mg containing solids may be disposed within the internal storage chamber (112).

[0073] Ca/Mg containing solids containing active CaO and/or $Ca(OH)_2$, for example, can carbonate at temperatures ranging from about 600°C to about 700°C for CaO and about 400°C to about 600°C for $Ca(OH)_2$ when contacted with CO_2 to form $CaCO_3$. Under such conditions, active CaO and/or $Ca(OH)_2$ can reach maximum calcium molar conversions between about 0.5 to about 0.7 when the specific surface

area of the solids is higher than 10 m^2/g, so as to allow sufficient build-up of a thin carbonate layer in the interior of the Ca/Mg containing solids. On the other hand, porous $Ca(OH)_2$ is also known to carbonate up to calcium molar conversions exceeding 0.9 at temperatures ranging from about 400°C to about 600°C, or in ambient air, in particular when relative humidity is higher than 80%. Taking into account these optimum carbonation conditions, different embodiments of this method are defined, depending on the CO_2 concentration and temperature of the gas to be treated, so that optimum conditions are reached in the carbonator reactor used for efficient CO_2 capture by carbonation. Embodiments of the system and methods apply to the capture of CO_2 from a flue gas, engine exhaust gas, or industrial gas with CO_2 concentrations between 2-25%v, targeting a carbonation temperature between 600°-700°C for CaO and 400°-600°C for $Ca(OH)_2$ in the core reaction region of the carbonator.

[0074] In some implementations, the Ca/Mg containing solids used in the reactor are lime rocks produced from the calcination of natural limestone rocks or from recycled carbonated materials, or manufactured from powdered CaO or $Ca(OH)_2$ in the form of porous pellets or extruded, brick-type or honeycombs with holes or channels. Such channels can be separated by a solid wall of from about 20-30 mm (allowing a depth of the carbonated layer of 10-15 mm in each side of the wall) and a bed porosity (determined in this case by the fraction of free cross-section area occupied by the holes or channels) of between 0.15-0.35 sufficient to moderate the pressure drop in the reactor when the gas has CO_2 concentrations between 2-25%v. Pozzolanic additives for mechanical strength can be included with the Ca/Mg containing solids as well as other additives to enhance porosity and mechanical strength.

[0075] The storage container (110) includes a first end (102) defining a first endwall panel connected to the access portion (120), and a second end (104) defining a second endwall panel comprising an access door (105). The access door (105) is configured to open and close for providing selective access to the internal storage chamber (112) where the packed bed reactor filled with Ca/Mg containing solids is stored. The access portion (120) comprises a gas manifold including a gas inlet manifold (122) and a gas outlet manifold (124). The gas inlet manifold (122) is

configured to receive a flow of gas containing CO_2, such as exhaust gas from a cargo ship or other sources of industrial flue gas. The gas inlet manifold (122) is configured to direct the flow of gas containing CO_2 into the internal storage chamber (112) of the storage container (110). The gas outlet manifold (124) is configured to expel a flow of decarbonized gas from the internal storage chamber (112) of the storage container (110). In some implementations, the gas inlet manifold and the gas outlet manifold may be disposed at the opposite ends of the storage container. For instance, the first end of the storage container may include the gas inlet manifold, and the second end of the storage container may include the gas outlet manifold, or vice versa. Thus, various configurations for placement of the gas inlet manifold and the gas outlet manifold are possible.

[0076] The storage container (110) includes a thermally insulated storage chamber (112) containing a packed bed reactor filled with Ca/Mg containing solids, as previously discussed above. The access portion (120) is attached to the front endwall panel (102) of the storage container (110), and furthermore extends from the front endwall panel of the storage container. Such an extension may be from approximately 0.5 meter (m) to about 2.5 m, such as approximately 1 m. The access portion (120) is furthermore configured to serve as an access area for one or more valve and pipe interfaces (126), as well as one or more electrical interfaces (128).

[0077] With reference to FIGS. 6 and 7, the gas inlet manifold (122) is in fluid communication with a gas distribution manifold or gas diffuser (130) disposed within the storage container (110). The gas diffuser (130) extends from the first end (102) of the storage container (110) to the second end (104) of the storage container, and is configured to uniformly direct a flow of gas into the internal storage chamber (112) from the gas inlet manifold (122). A gas collection manifold or gas collector (140) is also disposed within the storage container (110) and extends from the first end (102) of the storage container (110) to the second end (104) of the storage container. The gas collector (140) is configured to direct a flow of gas decarbonized gas out of the internal storage chamber (112) of the storage container and into the gas outlet manifold (124). Thus, the gas inlet manifold (122) is configured to receive a flow of gas containing CO_2

and uniformly direct the flow of gas into the internal storage chamber (112) of the storage container (110) via the gas diffuser (130). The gas outlet manifold (124) is configured to receive the flow of gas from the gas collector (140) after CO_2 has been captured by the Ca/Mg containing solids of the packed bed reactor within the internal storage chamber (112) of the storage container (110). According to some aspects, the gas inlet manifold is configured to receive flue gas from a sea vessel, such as a cargo ship, and the gas outlet manifold is configured to expel clean exhaust gas to the atmosphere. In some implementations, the gas diffuser includes a mesh or perforated plate configured to prevent or minimize the Ca/Mg containing solids within the internal storage chamber from entering the gas inlet manifold. In some implementations, the gas collector includes a mesh or perforated plate configured to prevent or minimize the Ca/Mg containing solids within the internal storage chamber from entering the gas outlet manifold.

[0078] Various configurations of the shape of the gas diffuser and the gas collector are possible. For instance, FIG. 8 depicts an implementation of the gas diffuser (130). The gas diffuser (130) includes a first layer, such as a diffuser plate (132) having spaced apart holes to allow for uniform gas distribution and to keep gas velocity even and relatively constant through the Ca/Mg containing solids disposed within the internal storage chamber (112) of the storage container (110). The holes are spaced in a certain way near each end of the diffuser plate. For instance, the diffuser plate may include different zones, with each zone having a different pattern and/or size of holes. In one implementation, the holes located closer to the gas inlet manifold (122) are smaller than the holes located farther away from the gas inlet manifold. Stated another way, the holes closer to the second end (104) of the container are larger in diameter than the holes closer to the first end (102) of the container. Thus, the size of the diameter of the holes increases in the direction away from the gas inlet manifold, such that the holes farther from the gas inlet manifold are larger in diameter than the holes closer to the gas inlet manifold. This arrangement ensures sure that the gas is evenly distributed to the packed bed reactor through the base of the container via the holes in the diffuser plate.

[0079] A plurality of channels (134) underneath the diffuser plate directs the flow of gas to the spaced apart openings. In one implementation, the spaced apart openings may be holes in the diffuser plate for gas to pass through. In another implementation, the gas diffuser may include an initial layer, such as a mesh or perforated plate, to prevent or minimize the Ca/Mg containing solids from falling through the first layer. The gas diffuser may also include a second layer having a reduced cross-sectional area to distribute gas evenly and to keep gas velocity even and relatively constant through the Ca/Mg containing solids of the packed bed reactor disposed within the internal storage chamber (112). Accordingly, in some implementations the initial layer, the first layer, and the second layer may be used together as a three-layer system.

[0080] Turning to FIG. 9, an implementation of the gas collector (140) is shown. In one implementation, the gas collector includes a plurality of channels (144) for corralling the decarbonized gas into the gas outlet manifold (124). The gas collector also includes a baffle plate (145) that extends across the gas outlet manifold (124). FIG. 10 depicts an implementation of the baffle plate (145), which includes a plurality of holes (147) configured to restrain, regulate, and/or redirect the flow of decarbonized gas into the gas outlet manifold (124) from the gas collector (140).

[0081] In some implementations, a bypass valve (150) may be provided between the gas inlet manifold (122) and the gas outlet manifold (124). The bypass valve (150) is configured to allow gas to flow directly from the gas inlet manifold to the gas outlet manifold when in an open configuration, thus bypassing the internal storage chamber (112) of the storage container (110). When the bypass valve (150) is in a closed configuration, gas flows from the gas inlet manifold (122) to the internal storage chamber (112) of the storage container via the gas diffuser (130). In some implementations, the bypass valve is a butterfly valve, or other type of flow regulating valve, as shown in FIG. 4. It should be appreciated that such a bypass valve, when in an open configuration, may naturally allow a small amount stagnant engine exhaust into the carbonator which is unlikely to result in any large scale reactions with the Ca/Mg containing solids of the packed bed reactor contained in the internal storage chamber (112). In some implementations, the bypass valve (150) is manually controllable via

the valve interface (126) located in the access portion (120) of the modular carbonator (100).

[0082] Each modular carbonator (100) includes an electrical enclosure (128) with an electrical interface (i.e., to provide an electrical communication to the ship). In one implementation, the electrical interface (129) is a heavy duty 6 pin locking connector at the bottom of the electrical enclosure, as shown in FIG. 5. In some implementations, a dedicated cable is provided on the ship for each carbonator, with the male end of the cable being plugged into a female connector housing located at the bottom of the electrical panel. Latches on the connector are used for locking the connector in place. When the connectors are not joined, covers are latched into place for further protection.

[0083] The storage container (110) also includes an insulating layer disposed around the perimeter of the internal storage chamber (112) in order to regulate a temperature within the internal storage chamber (112). In particular, the insulation is located between the internal and external walls of the storage container in order to keep the external walls and structure below 80° C. In some implementations, the insulation used in between the internal and external walls is a primary layer of Pyrogel® XTE which is rated for use up to 650° C and Rockwool® which can withstand a service temperature of up to 250° C. Advantageously, such a thermally insulated modular storage container can be configured to allow an internal temperature of the container to be from about 400 °C to about 700 °C and exterior temperature of the container to be no more than about 80 °C, for example. Other aspects of the system and methods of the subject technology may include a fan prior to the gas inlet manifold (122) and/or a fan after the after the gas outlet manifold (124) to minimize backpressure of the flow of gas containing CO_2, such as exhaust gas from a cargo ship or other sources of industrial flue gas, into the internal storage chamber (112). In some aspects, the backpressure of such exhaust gas is not increased by more than about 15 kPa, e.g., no more than about 5 kPa, 3, kPa, 1 kPa, etc.

[0084] Further, a plurality of modular carbonators, including corresponding storage containers and access portions, can be configured to be connected in series, such as in a vertically stacked and/or horizontally linked configuration, wherein each respective

gas outlet manifold of a first carbonator is connected to a corresponding gas inlet manifold of a vertically stacked or horizontally linked second carbonator. Each modular carbonator is fitted with ISO 1161 corner castings on all eight corners which are configured to interface with standard twist locks. Depending on the onboard configuration, the carbonators may be secured to the ship as well as each other using standard lashings or within cell guides. In one implementation, a maximum assessed stacking height is eight carbonators, which is limited by the maximum gross weight of each carbonator according to ISO 668. This may be further limited by structural limitations of the ship, which would be assessed on a case by case basis. Each carbonator is securable to other carbonators or base locks on the ship. In some implementations, each carbonator is connected to other carbonators as well as the corresponding piping system onboard the ship via DN700 flanges. A non-standard bolt pattern is used on these flanges to reduce the overall diameter and provide clearance for installation and removal of flange hardware, as shown in FIGS. 11 and 12. This is made possible by the low internal pressure of the piping system, which is max 15 kPa gauge. On the bottom of the container a flange (123) of the gas inlet manifold (122) is recessed by 10 mm from the bottom plane of the container to allow for the carbonator to be placed on uneven ground without damaging the flange. In some implementations, a flexible bellow rated for high temperatures (i.e., up to 650 °C) is provided on the top of the container to allow for any misalignment or relative motion between the container and the flange it is connected to. Thus, according to some aspects, the gas outlet section of a gas manifold of a first carbonator container can direct the flow of gas into the gas inlet section of a gas manifold of a second storage container. According to some implementations, the access portion may further include a ladder and/or a manhole for workers to access through a stacked and/or linked configuration of carbonators. Thus, when the carbonators are connected to each other by a manual quick release valve, for example, workers are able to go through the access portion to manually attach any gas connections and electrical connections between stacked and/or linked carbonators.

[0085] The modularity of each storage container further allows for minimal retrofitting of the carbonator to a source of exhaust (e.g., from an exhaust manifold of

an internal combustion engine such as in a shipping vessel), since the gas is moved to meet the Ca/Mg containing solids in the packed bed reactor rather than moving the Ca/Mg containing solids towards the gas, as in moving bed systems. A plurality of modular carbonators can be connected to each other in a stacked and/or linked arrangement and in fluid communication with each other such that the gas exiting one of the modular carbonators subsequently enters another one of the modular carbonators. The modularity of each carbonator (100) advantageously allows two or more carbonators to be connected in series. For instance, FIG. 13 depicts six storage containers (i.e., 110a, 110b, 110c, 110d, 110e, 110f) connected in series in a stacked and/or linked configuration. During use in such an arrangement where a plurality of storage containers are connected in series, a first gas inlet manifold connected to a first storage container (110a) receives a flow of gas containing CO_2, such as exhaust gas from an internal combustion engine having CO_2 concentrations between 2-25%v. The flow of gas containing CO_2 enters a first internal storage chamber (112a) of the first storage container (110a), where the gas is preheated by contacting with a stationary first packed bed reactor including high-temperature Ca/Mg containing solids (200) as the gas moves through the first internal storage chamber. An initial carbonation stage of the Ca/Mg containing solids occurs as the flow of gas moves through the bed of solids in the first internal storage chamber (112a). The preheated flow of gas then exits the first internal storage chamber (112a) through a first gas outlet manifold connected to the first storage container.

[0086] A second gas inlet manifold connected to a second storage container (110b) then receives the preheated flow of gas, which enters a second internal storage chamber (112b) of the second storage container (110b), where a core reaction stage occurs to achieve effective capture of the CO_2 in the moving gas flow by the carbonation of the high temperature Ca/Mg containing solids (200) of the second packed bed reactor within the second internal storage chamber (112b). In this core reaction stage, the Ca/Mg containing solids are heated to a carbonation temperature from about 600° to about 700°C for CaO and from about 400° to about 600°C for $Ca(OH)_2$. The CO_2 diluted flow of gas then exits the second internal storage chamber (112b) through a

second gas outlet manifold connected to the second storage container. A third gas inlet manifold connected to a third storage container (110c) then receives the CO_2 diluted flow of gas, which enters a third internal storage chamber (112c) of the third storage container (110c), where the Ca/Mg containing solids (200) of a third packed bed reactor are preheated. A final carbonation stage of the Ca/Mg containing solids occurs as the CO_2 diluted flow of gas moves through the packed bed of Ca/Mg containing solids in the third internal storage chamber (112c), thus resulting in a flow of decarbonized gas that exits the third internal storage chamber (112c) through a third gas outlet manifold connected to the third storage container.

[0087] The modularity of each carbonator 100 further allows individual storage containers to be connected or disconnected during the carbonation process. For instance, with reference to FIG. 14, once CO_2 is captured by the Ca/Mg containing solids (200) within the first internal storage chamber (112a) via carbonation, the first storage container (110a) may be disconnected from the second storage container (110b), and the carbonated solids of the first packed bed reactor are able to cool down so that they can be disposed or transported via the first storage container to a secondary location, such as a centralized regeneration plant to obtain pure CO_2 from decomposition of $CaCO_3$. In this arrangement, the second gas inlet manifold connected to the second storage container (110b) now receives the flow of gas containing CO_2, such as cargo ship exhaust gas having CO_2 concentrations between 2-25%v. The flow of gas containing CO_2 enters the second internal storage chamber (112b) of the second storage container (110b), where the gas is preheated by contacting with stationary high-temperature Ca/Mg containing solids (200) of the second packed be reactor as the gas moves through the second internal storage chamber. The initial carbonation stage of the Ca/Mg containing solids thus occurs as the flow of gas moves through the packed bed of Ca/Mg containing solids in the second internal storage chamber (112b). The preheated flow of gas then exits the second internal storage chamber (112b) through a second gas outlet manifold connected to the second storage container.

[0088] A third gas inlet manifold of the third storage container (110c) then receives the preheated flow of gas, which enters a third internal storage chamber (112c)

connected to the third storage container (110c), where the core reaction stage occurs to achieve effective capture of the CO_2 in the moving gas flow by the carbonation of the high temperature Ca/Mg containing solids (200) of the third packed bed reactor within the third internal storage chamber (112c). In this core reaction stage, the Ca/Mg containing solids are heated to an optimum target carbonation temperature between 600°-700°C for CaO and between 400°-600°C for $Ca(OH)_2$. The CO_2 diluted flow of gas then exits the third internal storage chamber (112c) through a third gas outlet manifold connected to the third storage container.

[0089] A fourth gas inlet manifold connected to a fourth storage container (110d) then receives the CO_2 diluted flow of gas, which enters a fourth internal storage chamber (112d) of the fourth storage container (110d), where the Ca/Mg containing solids (200) of the fourth packed bed reactor are preheated. A final carbonation stage of the Ca/Mg containing solids occurs as the CO_2 diluted flow of gas moves through the bed of solids in the fourth internal storage chamber (112d), thus resulting in a flow of clean gas that exits the fourth internal storage chamber (112d) through a fourth gas outlet manifold connected to the fourth storage container. Accordingly, once CO_2 is captured by the Ca/Mg containing solids (200) within the second internal storage chamber (112b) via carbonation, the second storage container (110b) may be disconnected from the third storage container (110c), and the carbonated solids are able to cool down so that they can be disposed or transported via the second storage container to the secondary location, such as a centralized regeneration plant to obtain pure CO_2 from decomposition of $CaCO_3$.

[0090] This process can be repeated for any number of storage containers connected in series. For instance, FIG. 15 depicts the flow of gas containing CO_2 as entering the third storage container (110c), moving through the fourth storage container (110d), and finally exiting from a fifth storage container (110e) as clean exhaust gas resulting from the sequential carbonation processes occurring within each consecutive packed bed reactor of the corresponding storage container. Similarly, FIG. 16 depicts the flow of gas containing CO_2 as entering the fourth storage container (110d), moving through the fifth storage container (110e), and finally exiting from a sixth storage container (110f)

as clean exhaust gas devoid of CO_2, which results from the sequence of carbonation processes occurring within each consecutive packed bed reactor of the corresponding storage container.

[0091] In each of these examples of FIGS. 13-16, a set of three modular carbonators are active at any given time, wherein the third modular carbonator is stacked on top of the second modular carbonator, which is stacked on top of the first modular packed be reactor. The first, or bottommost, modular carbonator is the first to react with the exhaust gas to remove CO_2. This reaction is an exothermic reaction. Further, this reaction is thermally insulated. Thus, the Ca/Mg containing solids, which have a high thermal mass, are able to transfer heat to the gas, which is cooler because it comes from the ship's exhaust. This gas is then heated up through the heat transfer in the gas preheating carbonator. Meanwhile, in the second, or intermediate, modular carbonator, the Ca/Mg containing solids have not been fully reacted yet, and so they interact with high temperature gas with CO_2. These solids in the second modular carbonator are still predominantly non-limestone at this point, but rather are predominantly calcium, and thus they react more efficiently. In the third, or final, carbonator, the Ca/Mg containing solids are much cooler than the gas that has little or no CO_2 in it, which is conducive for heat transfer that enables the solid pellets to heat up and cool down the gas. Once the control system senses that the reaction is complete, i.e., by sensing the outlet temperature at the first carbonator is the same as the inlet temperature, then this means there is no real heat transfer or the Ca/Mg containing solids in the bottom container are no longer able to benefit by preheating the gas. At this point, the first carbonator is shut off and a fourth carbonator that is stacked on top of the third carbonator can be activated. . Moreover, the modularity of the carbonators allows each respective carbonator to be turned on and off so that certain carbonators can be isolated during the carbon capture process.

[0092] There are general quantitative estimations of the carbonator reactor performance. For instance, heat transfer between solids and gases is of sufficient quality so that temperature difference between gas and solids is assumed to be negligible inside the reactor, with step changes in temperature between gas-solid heat exchange or

preheating zones and carbonation zone at high temperature. The rate of carbonation reaction follows the shrinking core model, controlled by the diffusion of CO_2 through the gas phase occupying the voids in the external carbonated layers of the Ca/Mg containing solids, with an effective diffusivity of CO_2 that is the product of the diffusion coefficient of CO_2 at the temperature of the Ca/Mg containing solids and the porosity of the carbonated layer of the Ca/Mg containing solids. And the molar conversion of CaO to $CaCO_3$ is assumed to be 0.6 in the external layer of carbonated Ca/Mg containing solids, when the carbonation temperature is between 600-700°C (i.e., consistent with maximum carbonation conversion of lime resulting from a first calcination of limestone). The molar conversion is assumed to be 0.7-0.9 when the solids are $Ca(OH)_2$ and the temperature of operation is either between 400°-600°C or below 100°C and the relative humidity above 80%.

[0093] These examples are based on a well-known control of the progress of carbonation by Fick's diffusion law in porous Ca-materials of large diameter (i.e., characteristic carbonation lengths >1 cm) at optimum temperatures of carbonation of 650°C. For example, Ca/Mg containing solids having an effective particle diameter or thickness between 10 to 100 mm are able to reach their carbonation conversion close to their maximum (0.5-0.7 at temperatures between 600-700°C) when in contact with a wide range of CO_2 content in the gas, as long as there is gas-solid contact time of between 1-30 hours.

[0094] Turning to FIG. 17, a schematic diagram of the carbon capture system according to the present disclosure is depicted. The carbon capture system employs a Calcium Looping process to remove CO_2 from exhaust gas, such as exhaust gas from a ship. The system comprises a bank of modular carbonators to capture and store CO_2, as well as some related process equipment that aids in the pre-conditioning, treatment and measurement of the exhaust gas. In the example shown, a series of four modular carbonators (100a, 100b, 100c, 100d) are installed on a ship in a stacked configuration. Exhaust gas flows from an inlet (300), such as a cargo ship's engine, toward the first modular carbonator (100a). A bypass line (304) is also provided that would prevent the flow of gas from being blocked in the event of any sort of failure in the

decarbonization process. A first measurement system (310), such as a continuous emission monitoring system (CEMS), includes various sensors to measure properties of the exhaust gas, such as CO_2, SO_2, and H_2O. The exhaust gas then goes through an isolation valve of the system, such as a butterfly valve, where a first pressure sensor and temperatures sensor obtain the respective pressure and temperature values of the exhaust gas. In some implementations, the exhaust gas may then go through a section of pipe (312) that is heated in order to maintain the exhaust temperature. This depends on the ship's specific engine, as it might have an exhaust temperature that's high enough that the pipe does not need to be heated further. The exhaust gas then reaches the stack of modular carbonators. When the bypass valve (150a, 150b, 150c, 150d) of each respective carbonator is closed, the exhaust gas is directed in and out of each adjacent carbonator as previously discussed above. The exhaust gas reacts with the calcium hydroxide pellets to capture CO2, which is stored or locked in the calcium carbonate. Each carbonator is capable of capturing up to a total of 20 metric tonnes of CO_2 at a time. Inside each container is a packed bed reactor filled with sorbent, such as Ca/Mg containing solids. According to some implementations, the sorbent used inside the container for carbon capture is pelletized calcium hydroxide ($Ca(OH)_2$). The volume capacity of the container is approximately 20.58 m^3 and with a bulk density of approximately 886 kg/m^3 the payload capacity is approximately 18,234 kg. When the sorbent reacts to form calcium carbonate it increases in weight by up to 4,395 kg for a total payload weight of approximately 22,719 kg. As the engine exhaust flows through the calcium hydroxide, it reacts with the CO_2 to form calcium carbonate, $CaCO_3$, according to the following equation:

$$CO_2 + Ca(OH)_2 \Leftrightarrow CaCO_3 + H_2O$$

[0095] The water that is released by the reaction remains a vapor that safely exits through the ship's exhaust into the atmosphere. This carbon capture reaction is an equilibrium reaction, so as the temperature increases, the reaction rate slows down and releases less heat, thus any possibility of overheating is eliminated. There is insulation between the internal and external walls of the storage container of each carbonator, which is designed to maintain the external walls and structure below 80° C. The

reaction in each container takes about twelve hours to complete, depending on the ship's exhaust gas temperature and flow rate. Once complete, the valve on the carbonator is opened, which allows that corresponding container to be bypassed. When the ship arrives back into port, the carbonators are disconnected, offloaded and transported to a facility where the calcium carbonate is emptied and replenished with fresh calcium hydroxide. The carbonators are then sent back to the ship to capture more CO_2.

[0096] The stacked and/or linked modular arrangement of the plurality of carbonators allows the flow of gas to move through multiple carbonators. During the carbon capture process, an exothermic reaction is created within the carbonator, so each subsequent carbonator will increase the temperature of the gas flowing through it, which is advantageous because the ship's exhaust temperature is generally a little lower than the ideal temperature for the reaction. Thus, the more containers the gas goes through, the more preheating is happening with the gas, and thus the reaction becomes more efficient. Moreover, additional sensors, such as pressure and temperature, are provided with each successive carbonator in order to monitor a corresponding parameter of the exhaust gas as it travels through each successive carbonator.

[0097] Once the gas has exited the last of the modular carbonators (100d), it may enter a filtration system (330), such as a cyclone filter, to filter out and remove dust or other fine particles that were swept out of the carbonators and entrained in the flow of gas. A fan (340) may be provided to pull or push the gas through the entire stacked and/or linked arrangement of carbonators. A venturi tube or other flow measurement instrument (350) may be provided to measure the flow rate of the gas prior to, or as it passes through, an outlet (370), such as an exhaust stack. A second measurement system (360), such as a second CEMS, includes sensors to measure various properties of the exhaust gas, such as CO_2, SO_2, and H_2O. By measuring the flow rate, as well as measuring the initial CO_2 concentration from the ship engine and the resulting CO_2 concentration after the gas has passed through the stack of carbonators, then the amount of CO_2 captured can be determined by subtracting the flow rate of CO_2 at the outlet (370) from the flow rate of CO_2 at the inlet (300).

[0098] When the carbon capture system is activated, the isolation valves (302, 306) are open and the fan (340) is running, which causes exhaust from the ship engine to flow through the system. If the fan were to stop working or the isolation valves were to unexpectedly shut, the exhaust would flow through its normal path in the engine casing and out to the atmosphere. This design ensures complete safety for the ship engine and eliminates potential failure which could result in loss of propulsion.

[0099] Under nominal operating conditions, exhaust is measured by the first measurement system (310) which determines the CO_2 and SO_2 content. The exhaust then flows through the first isolation valve (302) through a section of pipe which may be heated to maintain its temperature. The carbon capture system is configured to handle exhaust with a minimum temperature of 280 °C but higher temperatures may result in more efficient CO_2 removal. Temperature and pressure are measured after the exhaust passes through the first isolation valve (302) by a first pressure sensor (307) and a first temperature sensor (308). A second isolation valve (305) is provided along the inlet pipe which can be opened to add ambient dilution air into the carbon capture system. This is performed during system shut down to ensure the pipe connections between stacked and/or linked carbonators are at a safe temperature for the ship's crew to handle. Once the exhaust gas passes through the inlet piping it reaches the bank of stacked and/or linked modular carbonators (100a, 100b, 100c, 100d). Each carbonator can either be bypassed by opening each corresponding valve (150a, 150b, 150c, 150d), or activated by closing each corresponding valve. At any given time, a maximum of three carbonators are active which limit fan power draw. Reaction progress in each carbonator is monitored by corresponding temperature sensors. For instance, two thermocouples inside the sorbent compartment of each carbonator monitor the progression of the heat front and/or reaction front. When the temperature of these thermocouples exceeds a certain threshold, the control system, which is installed on the ship and separate from the container, will activate the subsequent stacked and/or linked carbonator by closing its damper valve. If these thermocouples or the valve fails, the container will remain active, which will result in less carbon dioxide captured but no other negative or dangerous consequences.

[0100] When the reaction is complete in a particular carbonator (100a, 100b, 100c, 100d), the control system bypasses the container by opening the corresponding valve (150a, 150b, 150c, 150d). After the passing through the stack of modular carbonators, the exhaust gas flows through the filtration device (330), such as a cyclone filter, to remove any dust that may have accumulated in the exhaust gas while inside the containers. More particularly, the filtration device removes any calcium-based particulates that escape from the modular carbonators. The filtration device is a passive device that uses inertial separation to extract dust particulate from the gas. A collection barrel may be provided underneath the filter which can be unloaded from the ship and emptied if it is full.

[0101] The exhaust gas then reaches the fan (340), which causes the pressure differential that draws the exhaust gas into the carbon capture system. In some implementations, a centrifugal fan is used to draw the ship's exhaust through the carbon capture system. Finally, the exhaust gas flows through the venturi tube (350) which measures its flow rate. The venturi tube is a passive device that measures exhaust gas flow rate using Bernoulli's principle. When flow rate and CO_2 concentration at the inlet and outlet of the system are known, the CO_2 capture rate can be determined. Fan speed is controlled via a variable frequency drive which receives as feedback the flow rate as measured by the venturi tube as well as the pressure measurements at P00 and P05. P05 is placed at the outlet of the exhaust and measures atmospheric pressure. If the pressure at P00 is less than at P05, then the engine exhaust flow rate is too low and air is being drawn down the ship's exhaust to compensate, or recirculated from the outlet of the carbon capture system. In this situation the fan speed will be automatically reduced. The second measurement system (360) measures the CO_2 and SO_2 content at the outlet, and the third isolation valve (306) allows the decarbonized gas to return back into the exhaust line (370) in the engine casing to be released into the atmosphere.

[0102] A control system comprising an industrial PLC, an industrial PC, networking equipment, field IO devices and an HMI are used to monitor and control the carbon capture system. The industrial PLC runs a set of control routines that monitor temperatures, pressures, flow rates and gas concentrations of the process equipment,

and controls the heating system, damper valves and centrifugal fan in order to maintain safe and efficient operation of the carbon capture system. As the reaction takes place, the control routine monitors the progress of the reaction by measuring the temperature inside the sorbent compartment of the container of each carbonator and automatically activates and deactivates segments of the respective packed bed reactor by opening and closing the corresponding damper valves of each carbonator. The control system allows for observation of the process variables, safety information and general status of the system via an HMI station, and also provides for the manual control of the controlled components of the system by a system operator. Further, the control system monitors for any process conditions or equipment failures that would impede the safe or normal operation of the system and raises visual and audible alarms accordingly. The context for such alarms is made available on the HMI, and alarms can be dismissed via the HMI. Additionally, any alarms and the events that triggered them are logged by a logging system. The subject technology advantageously, allows a large margin to adapt the design of the reactor to the specific characteristic of the ppmv CO_2 in the flue gas.

[0103] Advantages of the systems and methods of the present disclosure employing modular carbonator reactors are that the processes of (1) capture and (2) subsequent release of carbon dioxide can be decoupled. That is, carbon dioxide capture can occur at the source of the gas and release of the captured carbon dioxide can occur at a different location and facility. Hence, in some implementations, the subject technology includes methods of regenerating Ca/Mg containing solids disposed within a modular storage container after CO_2 is captured from a gas by such solids. For example, FIG. 18 depicts a flow chart illustrating a method of releasing captured carbon dioxide from Ca/Mg containing solids. A system of the present technology can be connected to a gas stream and used to capture carbon dioxide (steps 1802, 1804). The carbonator modules can then be disconnected from the gas stream (step 1806). Advantageously, when used on a transport vessel such as a marine vessel, each carbonator module can be removed from the vessel and transported to one or more facilities to release the captured carbon dioxide (1808) and regenerate the sorbent (1810). For example, in one facility the Ca/Mg containing solids can be removed from a carbonator and put in an oven or kiln

and heated to release the CO_2 captured by the Ca/Mg containing solids to form desorbed solids. Such an oven or kiln can further be equipped to store the released CO_2. The released CO_2 can then be permanently stored or used as a reagent, such as for material preparations, etc. In the same or different facility, the sorbents can be regenerated (1810) by rehydrating the desorbed solids and shaped in to particles such as pellets with appropriate sizes and porosities to form regenerated Ca/Mg containing solids. The regenerated Ca/Mg containing solids can then be disposed within a modular storage container of the present disclosure (1812). Carbonator modules with regenerated Ca/Mg containing solids can then be employed again in the systems and method of the present technology so that the process can be repeated and cycled multiple times. In addition, the subject technology advantageously allows a large margin to adapt the design of the Ca/Mg containing solids to the specific characteristic of the ppmv CO_2 in the flue gas.

[0104] While a modular carbonator system and a corresponding method of capturing CO_2 from flue gas has been described in terms of what may be considered to be specific aspects, the present invention is not limited to the disclosed aspects. Additional modifications and improvements to the carbonator system and corresponding method of the device may be apparent to those skilled in the art. Moreover, the many features and advantages of the disclosure are apparent from the detailed specification, and thus, it is intended by the appended claims to cover all such features and advantages of the present invention which fall within the spirit and scope of the disclosure. Further, it is not desired to limit the disclosure to the exact construction and operation illustrated and described, and accordingly, all suitable modifications and equivalents may be resorted to, falling within the scope of the disclosure. The present disclosure should therefore be considered as illustrative and not restrictive. As such, this disclosure is intended to cover various modifications and similar arrangements included within the spirit and scope of the claims, which should be accorded their broadest interpretation so as to encompass all such modifications and similar structures.

CLAIMS

What is claimed is:

1. A system for capturing carbon dioxide from a gas, the system comprising:

a modular carbonator comprising a storage container defining an internal storage chamber;

a gas inlet manifold configured to direct a flow of the gas into the internal storage chamber;

a gas outlet manifold configured to direct the flow of the gas out of the internal storage chamber; and

a packed bed reactor disposed within the internal storage chamber, the packed bed reactor including a plurality of Ca/Mg containing solids configured to capture carbon dioxide from the flow of the gas within the internal storage chamber.

2. The system according to claim 1, further comprising an access portion connected to the storage container for providing access to a gas manifold including the gas inlet manifold and the gas outlet manifold.

3. The system according to claim 2, wherein the gas manifold further includes a bypass valve disposed between the gas inlet manifold and the gas outlet manifold, the bypass valve being configured to allow the flow of gas directly from the gas inlet manifold to the gas outlet manifold when in an open configuration, thus preventing or minimizing the flow of gas from entering the internal storage chamber.

4. The system according to claim 2, wherein the access portion is attached to a front endwall of the storage container, and wherein the access portion extends from the front endwall of the storage container.

5. The system according to claim 4, wherein a rear endwall of the storage container comprises an access door configured to provide access to the internal storage chamber.

6. The system according to any one of the preceding claims, further comprising a gas diffuser disposed within a lower portion of the storage container, the gas diffuser being in fluid communication with the gas inlet manifold.

7. The system according to claim 6, wherein the gas diffuser is configured to uniformly direct the flow of gas into the internal storage chamber from the gas inlet manifold.

8. The system according to claim 7, wherein the gas diffuser includes a diffuser plate having spaced apart holes, and wherein the holes located farther away from the gas inlet manifold have a larger diameter than the holes located closer to the gas inlet manifold.

9. The system according to any one of claims 6-8, wherein the gas diffuser extends from a first end of the storage container to a second end of the storage container.

10. The system according to any one of claims 6-9, wherein the gas diffuser further includes a mesh or perforated plate configured to prevent or minimize the Ca/Mg containing solids within the internal storage chamber from entering the gas inlet manifold.

11. The system according to any one of the preceding claims, further comprising a gas collector disposed within an upper portion of the storage container and in fluid communication with the gas outlet manifold, such that the gas collector is configured

to direct the flow of gas out of the internal storage chamber and into the gas outlet manifold.

12. The system according to claim 11, wherein the gas collector includes a baffle plate configured to extend across the gas outlet manifold for restraining, regulating, and/or redirecting the flow of gas.

13. The system according to any one of the preceding claims, wherein the storage container is thermally insulated.

14. The system according to any one of the preceding claims, wherein the Ca/Mg containing solids are porous.

15. The system according to any one of the preceding claims, further comprising a fan configured to pull or push the gas through the modular carbonator.

16. The system according to any one of the preceding claims, further comprising a filtration device configured to remove particulate from the gas after the gas has passed through the modular carbonator.

17. The system according to any one of the preceding claims, further comprising at least three modular carbonators fluidly connected in series in a vertically stacked and/or horizontally linked arrangement.

18. The system according to any one of the preceding claims, wherein the gas inlet manifold is configured to receive exhaust gas from an internal combustion engine of a shipping vessel.

19. The system according to any one of claims 1-17, wherein the gas inlet manifold is configured to receive flue gas from a land-based factory plant.

20. A method for capturing carbon dioxide from a gas, the method comprising:

moving the gas through a plurality of modular carbonators connected in series and in fluid communication with each other, wherein each modular carbonator comprises:

a storage container defining an internal storage chamber;

a gas inlet manifold configured to direct the flow of the gas into the internal storage chamber;

a gas outlet manifold configured to direct the flow of the gas out of the internal storage chamber; and

a packed bed reactor disposed within the internal storage chamber, the packed bed reactor including a plurality of Ca/Mg containing solids configured to capture carbon dioxide from the flow of the gas within the internal storage chamber; and

capturing the carbon dioxide from the flow of the gas via the Ca/Mg containing solids disposed within each modular carbonator;

wherein the gas is moved through each modular storage container sequentially, such that the gas exiting the gas outlet manifold of one of the modular carbonators subsequently enters the gas inlet manifold of another one of the modular carbonators.

21. The method of claim 20, wherein the Ca/Mg containing solids comprise CaO, $Ca(OH)_2$, MgO, $Mg(OH)_2$, or any combination or mixture thereof and optionally any one or more alkali metal compounds.

22. The method according to any one of claims 20-21, wherein the storage container of each modular carbonator is thermally insulated.

23. The method according to any one of claims 20-22, wherein each modular carbonator comprises an access portion connected to the corresponding storage

container for providing access to a gas manifold including the corresponding gas inlet manifold and gas outlet manifold.

24. The method according to claim 23, wherein each gas manifold further comprises a bypass valve located between the gas inlet manifold and the gas outlet manifold, the bypass valve being configured to allow the flow of gas directly from the gas inlet manifold to the gas outlet manifold of the corresponding carbonator when in an open configuration, thus preventing or minimizing the flow of gas from entering the internal storage chamber.

25. The method according to any one of claims 20-24, further comprising uniformly directing the flow of gas into the internal storage chamber from the corresponding gas inlet manifold.

26. The method according to any one of claims 20-25, further comprising pulling or pushing the flow of gas through the series of connected modular carbonators by a fan.

27. The method according to any one of claims 20-26, further comprising removing particulate from the gas via a filtration device after passing the gas through the series of connected modular carbonators.

28. The method according to any one of claims 20-27, wherein the plurality of modular carbonators are connected to each other in a vertically stacked and/or horizontally linked arrangement.

29. The method according to any one of claims 20-28, wherein the plurality of modular carbonators connected to each other includes at least three modular carbonators.

30. The method according to any one of claims 20-29, wherein the gas is exhaust gas from an internal combustion engine of a shipping vessel.

31. The method according to any one of claims 20-30, wherein the gas is flue gas from a land-based factory plant.

32 The method according to any one of claims 20-31, further comprising releasing the captured carbon dioxide and/or regenerating the Ca/Mg containing solids.