Carbon Capture and Storage – Solidification and Storage of Carbon Dioxide Captured on Ships

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Abstract

To meet the International Maritime Organization (IMO) target of 20% reduction of CO_2 emissions from marine activities by 2020, application of Carbon Capture and Storage (CCS) on ships is considered as an effective way to mitigate CO_2 emissions while other low carbon shipping technologies being developed. Literature reviews on CCS methods for onshore applications indicate that the current CCS technologies could not be implemented on boards directly due to various limitations on ships. A novel chemical CO_2 absorption and solidification method for CO_2 storage on-board is proposed, presented and analyzed. Technical feasibility with explanation of principles and cost assessment are carried out for a case ship with a comparison to a conventional CCS method. The paper also presents results obtained from laboratory experiment including factors that affect the absorption. Theoretical study and laboratory experiment illustrate the proposed CO_2 solidification method is a promising, cost effective and feasible method for CO_2 emissions reduction on ships.

Keywords

Emissions reduction; carbon capture, solidification and storage; chemical absorption; environment protection.

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1. Introduction

Climate change has become a popular topic simply because it leads the melting glaciers, rising sea levels and the extinction of endangered species. It is well-known that greenhouse gases (GHG) are the cause of the climate change which is mainly contributed by the carbon dioxide (Houghton, 2004). According to IPCC report, the current CO_2 concentration in the atmosphere is increased by 100 ppm which is about 34% increment compared with the pre-industrial level (Ronger et al., 2007). Fig. 1 presents the growing of CO_2 emissions from 2000 to 2009 (Boden et al., 2010). Although the emissions are a little bit declined from 2008 to 2009, the tendency of the curve is obviously climbing.

For the global economy, international shipping have an immeasurable effect as it is the most effective way for large quantity and long distance transportation of international trade. Referring to the report of Second IMO GHG Study 2009, international shipping is estimated to have 870 million tones CO_2 emitted in 2007 which is about 2.7% of the global CO_2 emissions (Buhaug et al., 2009). There are numbers of methods to reduce the ship GHG emissions. EEDI, EEOI and SEEMP stipulated by IMO are focusing on increasing the energy efficiency. With high energy efficiency, the fuel consumed will be reduced so that the CO_2 generated will be decreased. EEDI, EEOI and SEEMP regulations are proposed to be entered into force on 2013 with an aim to reduce about 180 million tons of CO_2 emissions from international shipping annually by 2020. It is about 20% of the current emissions level. Thus, so many projects emerge with a target of 20% reduction of CO_2 emissions.

 -- Insert Figure 1 here --

Fig. 1 Tendency of CO_2 emissions from 2000 to 2009

CCS is an effective way to mitigate and even eliminate the effect of global warming caused by CO_2 emissions. It is now only used on shore based power plants and industrial processes (Global Carbon

Capture and Storage Institute). Fig. 2 presents three general ways of CCS that are available for onshore application. The principles of pre-combustion method are to remove carbon component from the fossil fuel priory to its combustion. Oxy-fuel capture method is to burn the fossil fuel with pure oxygen rather than oxygen in air so that only CO_2 and water vapor are produced after combustion and CO_2 can be easily captured by condensing the flue gases. Post-combustion capture method is to have CO_2 captured from the flue gases after the combustion of the fossil fuel.

-- Insert Figure 2 here --

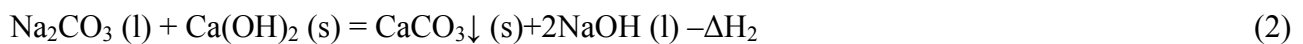**Fig. 2** General carbon capture methods

Although these methods could help capture carbon from fuel oil, mechanically installation of the systems on ships will bring great impacts on shipping performance. For instance, additional power consumption will increase fuel consumption, more space taken leads a reduction of cargo transported and storage of CO_2 on ships in a form of gas or liquid state is difficult and unsafe. No matter what kind of method is considered, the impacts on shipping performance should be minimized.

A novel carbon capture method is proposed in order to reduce the power requirement, save spaces on board and avoid CO_2 storage in a gas or liquid form on ships. This method applies two chemical processes and a physical step to absorb CO_2 from exhaust gases, precipitate the CO_3^- ion and separate $CaCO_3$ from the absorption solution on ship board.

In this study, the results obtained from laboratory experiment are extended to apply on a case ship. An economical assessment is presented by comparing the chemical processes for carbon solidification (CPCS) with the CO_2 compression and liquefaction method used commonly for the case ship, together with the results obtained from the experiment.

2. Chemical processes for carbon dioxide solidification

There are two chemical processes involved which include CO_2 absorption and CO_3^- ions precipitation. The reactions related to these two processes are shown in equation (1) and (2) (Pflug et al., 1957; Mahmoudkhani and Keith, 2009):

$$CO_2 (g) + 2NaOH (l) = Na_2CO_3 (l) + H_2O (l) - \Delta H_1 \qquad (1)$$

$$Na_2CO_3 (l) + Ca(OH)_2 (s) = CaCO_3 \downarrow (s) + 2NaOH (l) - \Delta H_2 \qquad (2)$$

In the first reaction, the carbon dioxide is absorbed by sodium hydroxide (NaOH, caustic soda). Sodium hydroxide reacts with acid gases, such as CO_2, SOx and NOx, is a natural process. The products from this reaction are sodium carbonate (Na_2CO_3, washing soda) and water. Na_2CO_3 is a relative stable compound so that CO_2 can be stored as CO_3^- ions in the Na_2CO_3 solution. After the absorption reaction, the Na_2CO_3 solution will react with calcium oxide (CaO, quicklime) and water. Finally, the precipitated calcium carbonate ($CaCO_3$, limestone) is produced, as shown in reaction (2). The CO_3^- ions are precipitated in the form of $CaCO_3$ compound. After filtering, washing and drying processes, the powders of precipitated calcium carbonate will be obtained which can be stored safely on-board and unloaded at the destination of a voyage. The reaction presented in equation (3), generating calcium hydroxide ($Ca(OH)_2$, hydrate lime), is an internal reaction of reaction (2). It is an exothermal reaction where reaction heat can be recovered and reused (Souto et al., 2008).

$$CaO (s) + H_2O (l) = Ca(OH)_2 (s) - \Delta H_3 \qquad (3)$$

The heat released during three reactions is 109.4, 5.3 and 65 kJ per mol CO_2 respectively (Mahmoudkhani and Keith, 2009). While dissolving NaOH into water, there are heat released as well which is 35.82 kJ per mol NaOH (Japan Soda Industry Association, 2006).

Based on these reactions, CO_2 from the exhaust gases are eventually captured and stored in a solid form. Referring to the conservation of mass, the masses of reactants are equal to the masses of the

products. As masses are related to molecule masses and molar numbers, the relationships between different substances are shown as following equation:

$$m_1/m_2 = (n_1 \times M_1) / (n_2 \times M_2) \tag{4}$$

Where:

m_1 = total mass of substance 1 (ton);

m_2 = total mass of substance 2 (ton);

n_1 = molar number of substance 1 (mol);

n_2 = molar number of substance 2 (mol);

M_1 = molar mass of substance 1 (kg/mol);

M_2 = molar mass of substance 2 (kg/mol).

This relationship will be used to derive the masses of different chemical substances involved in the reactions.

As the $CaCO_3$ is generated from the solution, what obtained from reactions is $CaCO_3$ mud which is a mixture of NaOH solution and $CaCO_3$ (Metso, 2011). To separate the sediment from the solution, a filtration process is applied. After filtration and drying, solid sediment will be available for storing on ship.

Other than being able to retrofit on existing ships, there are many advantages when applying CPCS comparing to CO_2 compression and liquefaction for shipboard application. The final product precipitated $CaCO_3$ from the solidification processes can be used by many applications in industry, for instance, paper making, construction and plastic industries. Due to a large quantity of precipitated $CaCO_3$ produced, profits made by selling the product could be considerable. When storing liquefied CO_2 on board, issues like ship stability, spaces occupied and high requirement for storage tank due to the instability of liquefied CO_2 are serious problems. With the application of CPCS, all these

problems will be solved. These advantages will be presented in detail in the section of case ship study.

3. Experiment and results

Based on the principles of the solidification processes introduced above, two steps of experiment are designed: chemical absorption and precipitation, and physical filtration. In the chemical processes, pure CO_2 is used.

A flow chart of the experimental rig is shown in Fig. 3. Fig. 4 is a picture of the experiment rig. The flow of CO_2 gas contained in a CO_2 bottle is controlled by a regulator. The gas is piped into NaOH solution inside a measuring cylinder. A diffuser is used to increase the contact area between the gas and solution by generating gas bubbles. Inside the measuring cylinder, the gas is absorbed by the solution. After the absorption, CaO powders are added into the measuring cylinder so that the CO_3^- ions can be precipitated.

-- Insert Figure 3 here --

Fig. 3 Schematic of the experiment systems

After the precipitation, the mixture of sediment and solution goes through a funnel with filter paper where the sediment and solution are separated. After the filtration, the sediment obtained will be dried for further measurement.

-- Insert Figure 4 here --

Fig. 4 Pictures of experiment rig

Table 1 presents the results of gas absorption rate, NaOH regeneration rate and $CaCO_3$ filtration efficiency achieved from experiment. The CO_2 absorption rate is a ratio between gases absorbed and that gas fed in. The regeneration rate of NaOH is defined as the ratio of NaOH regenerated and that

initially supplied. The $CaCO_3$ filtration efficiency is determined by ratio of $CaCO_3$ separated to theoretical formatted from reaction.

Table 1 Experiment results

-- Insert Table 1 here --

From the table, the gas absorption rate is nearly 68% but it is only the rate under laboratory conditions. For an industrial application, a much better mixing process of gas and solution can be obtained by using a mechanical stirrer so that the absorption rate will be higher than that under laboratory conditions. Another factor will be considered in the industrial processes is the purity and concentration of CO_2 gas. Due to the impurities in exhaust gases in a practical application, further treatments may be required for purification so the absorption rate will be varied.

Whatman grade 589/3 qualitative filtration papers are used for the separation of NaOH solution and $CaCO_3$ in the experiment. This type of filter paper is suitable for high retention of fine particles and have an excellent resistance from strong alkali solution. The filter papers with a diameter of 125mm are selected to match the funnel. The particle size of $CaCO_3$ ranges from 1 to 3 μm and pore size of filter papers is less than 2 μm which is the smallest one for laboratory use. The small pore size does not only lead a long period of filtration processes but also result in a small amount of $CaCO_3$ slipping through the filter. The $CaCO_3$ filtration efficiency is expected to be much higher in practical application because industrial filtration method, such as pressure disc filter or centrifugal separation. To simplify the study, the filtration efficiency used in the case ship study is taken as 100%.

In order to estimate the CO_2 absorption rate, four parameters were examined during the experiment: gas input flow rate, change of absorption cylinder diameter with fixed volume of solution, change of absorption cylinder diameter with solution column height unchanged and change of solution column height with the same diameter of cylinder.

3.1. Impact of gas flow rate on absorption rate

To find out effect of the gas flow rate on the CO_2 absorption rate, three runs of experiment with different gas flow rates are conducted. The selected gas flow rates are 1, 2 and 3 L/min. The selection of gas flow rate is restricted by the experiment equipment because higher flow rate will lead to an unstable pipe connection and even disconnected. To ensure the accuracy of reading on flow meter, only integer scales are selected for comparison. For these three sets, the same quantity solution is used with the solution column height of 30 cm. The diameter of the measuring cylinder is 6 cm. The results are presented in Table 2 and Fig. 5.

Table 2 Change of absorption rate with gas input flow rate

-- Insert Table 2 here --
-- Insert Figure 5 here --

Fig. 5 CO_2 absorption rate vs. gas flow rate

According to the experimental results, the CO_2 absorption rate increases as the input gas flow rate decreases. The reason being a small gas flow rate allows more time for contact of the gas and the solution. As the gas flow increases, the amount of CO_2 slipped from the absorption process will be increased. However, the reduction rate is only 2.7% when the gas flow rate is increased from 1 L/min to 3 L/min. Hence, it is concluded that the flow rate has no significant effect on absorption rate under the conditions used in the experiment.

3.2. Impact of cylinder diameters on absorption rate with fixed volume of solution

Table 3 Changing of absorption rate with container diameters (solution quantity unchanged)

-- Insert Table 3 here --
-- Insert Figure 6 here --

Fig. 6 Effect of container diameter on gas absorption rate with unchanged solution quantity

According to Table 3 and Fig. 6, the absorption rate is decreased while the container has a larger diameter. It is easy to find that container with a large diameter leads a short time for CO_2 gas

contacting with the solution. It is because column height is reduced as the cylinder diameter is increased when the volumes of the solution are fixed. When the diameter is changed from 6 to 8 cm, less than 3% of the gas are released and wasted. The percentage grows to 6.64% when the diameter is increased from 8 to 10 cm. From the curve above, it is obviously that declining of the curve is faster along the X axis. Hence, the absorption rate will be increasingly reduced when enlarging the diameter. On the contrary, narrowing the diameter will lead a greatly increasing on absorbing gas when changing diameter of cylinder without changing volume of the solution. It is a feasible and effective way of enhancing CO_2 absorption rate by increasing the contact rate between gas and solution.

3.3. Impact of cylinder diameters on absorption rate with solution column height unchanged

According to the result above, a better mixing and long contact time between gas and solution will bring a higher absorption rate of CO_2 gas. Results in Table 4 and Fig. 7 show the effect of change of the cylinder diameter (cross-section area) on absorption rate with fixed height of solution column height.

Table 4 Changing of absorption rate with container diameters (same solution column height)

-- Insert Table 4 here --
-- Insert Figure 7 here --

Fig. 7 Effect of container diameter on gas absorption rate with fixed solution height

Results shows when the cylinder diameter varies from 6 to 10 cm with the same column height of 10.5 cm, the highest absorption rate takes place when the diameter is 10cm. When the diameter is changed from 6 to 8cm, the absorption rate is increased by 9.7%. A further increase in the diameter from 8 cm to 10cm, the rate is increased only by 1.91%. It is understandable that the absorption rate will be increasing when the solution column cross-section area is increased. For the given test rig set up, the results indicate that a too large cross-section area does not help to increase the absorption rate

much. This could be because the diffuser size is not increased as the diameter increases. Hence, when the cross-section is too large the gas bubble could not reach to the edge area of the cylinder. This means there is room for test rig optimization to achieve the best match of solution column cross-section area, diffuser size and column height.

3.4. Impact of column height on absorption rate with a fixed cylinder diameter

Table 5 Change of absorption rate with solution column heights (fixed container diameter)

-- Insert Table 5 here --
-- Insert Figure 8 here --
Fig. 8 Effect of solution column height on gas absorption rate with same cylinder diameter

According to Table 5 and Fig. 8 above, the absorption rate is increased while the height of the solution column is increased. This is because as the solution height increased, the path of gas are increased, resulting in an increase in the contacting time between the gas and solution. Hence, more gas will be absorbed. When the height is increased from 10.5 to 18cm, the absorption rate is raised by 16.09%. The rate grows only 5.02% when the solution column is changed from 18 to 30cm. It is because with small solution column height, the path of gas is too short to have a good contact with solution. When the solution height increased, the change will be significant at the beginning and then will be very slightly. This indicates that there is an optimal match between the column height and gas supply rate.

4. Case Ship Study

Nowadays, there are two technologies used onshore for the storage and transportation of CO_2 captured, i.e. compressed CO_2 and liquefied CO_2. For pipeline transportation, compressed CO_2 is a preferred option (Ciferno et al., 2010; Witkowski and Majkut, 2012). If captured CO_2 is transported by a ship, both compressed CO_2 and liquefied CO_2 technologies can be used, where the latter is achieved by a combination of increased pressure and reduced temperature (Bert et al., 2005).

Currently, only the liquefied CO_2 method has been used for ship transportation (Aspelund et al., 2006) due to the factor of some 580 times of volume reduction from gas form CO_2 to liquid form CO_2.

There are some technical challenges in storing and transporting CO_2 in liquid form on ships.

In addition to the requirement of low temperature and high pressure, liquefied CO_2 has a triple phase point. The triple phase point is an unstable state of CO_2 which means a phase change of CO_2 may take place from liquid state to solid or gas without a change in temperature or pressure. Storage of CO_2 liquid also has special requirements on the materials of storage tanks in order to cope with high pressure and low temperature. It is essential to make sure that there is no water or moisture contained in liquefied CO_2 to prevent corrosion of tank materials. Compared with the method of CPCS, the volume taken by liquefied CO_2 is 3% more than that of $CaCO_3$ (EIGA, 2010). In addition, carrying liquefied CO_2 causes a ship stability problem – sloshing, due to its viscosity is about 1/3 of water (Wischnewski; ITTC, 2011). In summary, in a comparison with CO_2 liquid, storing solid CO_2 in the form of $CaCO_3$ on ships has the following advantages:

    a. $CaCO_3$ can be reused or land disposal;

    b. No particular requirements on storage tank materials;

    c. No corrosion problems;

    d. Less volume taken;

    e. No impact on ship stability.

Other than the above ship operational and CO_2 storage advantages, a case study on a selected ship indicates that applying CPCS on ships will bring an economical profit by selling the by-products of CPCS. The following section presents a feasibility study of applying CPCS on the case ship.

The specifications of the case ship are listed in Table 6, along with the details of voyage of the vessel. Since the power output of auxiliary alternators is only about 8.4% of the main engine power, fuel consumption and CO_2 emissions of the auxiliary engines are not considered in the case ships study.

Table 6 Specifications of the case ship

-- Insert Table 6 here --

a: Sources of data: Significant Ships of 2011: Hyundai Trust.

4.1. Cost estimation of CPCS

4.1.1. Total CO_2 generated during a voyage

According to the project guide of the selected engine and fuel type used, the gas flow rate of CO_2 emissions can be estimated as equation (5):

$$\dot{m}_{CO_2} = C_{HSFO} \times P \times SFOC \tag{5}$$

$$= 3.021 \times 18,660 \times 174 \times 1000 / 3600$$

$$= 2.72 \text{ kg/s}$$

Where:

$\dot{m}_{CO_2}$ = mass of CO_2 in exhaust gas (ton);

SFOC = specific fuel oil consumption (g/kWh);

P = power output of main engine (kW);

C_{HSFO} = carbon factor of HSFO (MEPC, 2010).

With this flow rate of CO_2, the total CO_2 generated during a voyage (16 days) is 3,766.54 ton.

4.1.2. Exhaust gas by-pass into CPCS system

Based on the IMO target of 20% CO_2 emissions reduction by 2020, the CPCS system will be designed to absorb and store 20% of CO2 emitted from the engine of the case ship, i.e. 753.31 ton of

CO_2. According to the experiment results, the average CO_2 absorption rate is 67.85%. To achieve 20% reduction of CO_2 emissions, the amount of exhaust gases by-passed to the CPCS system can be derived with equation (6):

$$R_{by\text{-}pass} = R_{target} / R_1 \tag{6}$$

$$= 20\%/67.85\%$$

$$= 29.48\%$$

Where:

   $R_{by\text{-}pass}$ = percentage of exhausted gas by-pass into the CPCS system;

   R_{target} = targeted CO_2 reduction required by IMO regulations;

   R_1 = absorption rate of CO_2.

According to the above estimation, there is about 30% of exhaust gas should be fed into the CPCS system in order to achieve the target of 20% CO_2 reductions from the main engine exhaust gas. The mass flow rate of CO_2 fed into the CPCS can be derived: $2.72 \times 29.48\% = 0.80$ kg/s. The quantity of CO_2 bypassed per voyage is 1,110 ton.

4.1.3. Initial quantities of chemical substances required

The quantities of all chemical substances involved in the reaction can be derived by applying the equation (4) in conjunction with the equation (1), (2) and (3). Thus, the quantities of caustic soda (NaOH) and quicklime (CaO) required per voyage are 86 ton and 959 ton, respectively. The limestone $CaCO_3$ finally produced per voyage is 1,712 ton.

4.1.4. Consumption of NaOH by CPCS system

In the CPCS system, NaOH solution will be regenerated after the causticizing reaction. For the case ship, the NaOH is assumed to be replenished on a daily basis. Since its regeneration rate is 85.37%

according to the experiment results, the daily consumption of NaOH can be calculated by the following equation:

$$m_{refilled} = m_{system} \times (1 - R_2) \tag{7}$$

$$= 85.60 \times (1 - 85.37\%)$$

$$= 12.52 \text{ ton/day}$$

Where:

$m_{refilled}$ = daily consumption of NaOH (ton);

m_{system} = the theoretical quantity of NaOH needed by system (ton);

R_2 = regeneration rate of NaOH.

The total NaOH consumed during a voyage can be derived as following:

$$m_{total} = m_{refilled} \times t \tag{8}$$

$$= 12.52 \times 16$$

$$= 200.34 \text{ ton}$$

Where:

m_{total} = total NaOH required during a voyage (ton);

t = duration of a voyage (days);

4.1.5. Operational cost of CPCS system

Operational cost of the CPCS is made of 3 components, i.e. cost of chemicals consumed; cost of fuel operating the CPCS and cost of cargo lost penalty due to space taken by the chemical reactant and CPCS product.

4.1.5.1. Cost estimation of chemical substances

Table 7 presents the quantities of chemicals consumed and their unit prices.

Table 7 Quantities of substances consumption and costs

-- Insert Table 7 here --

a: Sources of data: Prices achieved from Alibaba.com.

4.1.5.2.Energy consumption and fuel costs

The energy consumed for CPCS process includes energy required for CO_2 separation from the engine exhaust gas; energy for CO_2 gas and chemical solutions' transfer through the CPCS system; and energy used for handling and storing solid chemicals and end product of CPCS ($CaCO_3$) on ships. Since the energy consumed in handling solids materials are much smaller compared with that in CO_2 gas separation and transportation, the energy consumed for solid materials handling is ignored in estimating the system energy consumption.

The power required by gas separation is due to the application of membrane device which is about 0.5 MJ/kg CO_2 separated (Barbieri et al., 2011). Thus, the energy consumption by the membrane system can be obtained as the following:

$$P_M = \dot{i}_{} \quad m_{CO_2} / t \tag{9}$$

$$= 0.5 \times 10^3 \times 3766.54 \times 10^3 \times 29.48\% / (16 \times 24 \times 3600)$$

$$= 401.59 \text{ kW}$$

Where:

P_M = power required by membrane device (kW);

$\dot{i}_{}$ = energy required for CO_2 separation (kJ/kg CO_2);

m_{CO_2} = mass of CO_2 separated (kg);

t = operation time of membrane device (s).

CO_2 gas pumps (blowers) are used to feed the CO_2 gas after the separation unit to pass through the CPCS. The solution height of the reaction tank designed is about 6.44 meter. The blowers should provide enough pressure to feed gas into the bottom of the tank. Other than head loss due to solution

height in tank, there are friction loss and fitting loss for CO_2 to go through the duct system. Assuming the diameter and the length of the duct from the outlet of membrane device to reaction tank are 1 m and 10 m respectively and there are one baffler and two 90° bends along the system. The pressure drops due to friction and fitting estimated at about 0.99 Pa (Massey and Ward-Smith, 2012). The power required for gas input can be obtained with equation (10):

$$P_B = \dot{r}_{CO_2} \Delta P_B / \rho_{CO_2} \tag{10}$$

$$=0.80 \times (0.99 + 1.815 \times 9.81 \times 6.5)/ 1.815/1000$$

$$= 0.05 \text{ kW}$$

Where:

P_B = power required by gas blower (kW);

$\dot{r}_{CO_2}$ = mass flow rate of CO_2 (kg/s);

ΔP_B = pump pressure required to transfer fluid or gas (Pascal);

ρ_{CO_2} = density of CO_2 (kg/m^3).

Thus, the total power consumption for CO_2 separation and CPCS is 401.64 kW. The fuel oil consumed due to gas blower and membrane is 29.15 ton per voyage and the fuel cost is estimated to be $18,072.66.

4.1.5.3. Cargo penalty due to CPCS system application

Table 8 lists the density and volume of the chemicals involved in CPCS. The total volume taken by the chemicals is 1,112.49 m^3. The density of coal is 929kg/m^3 so the mass of coal cargo in an equivalent volume is 1,033.50 tons (Anval Valves Ltd.). According to the current coal shipping price15 $/ton (ChinaCCM, 2013), the total cost of cargo freight penalty due to CPCS system application is 15 × 1033.50 = $ 15,502.48.

Table 8 Volumes and mass of coal losses due to storage of chemicals

-- Insert Table 8 here --

4.2. Profits made by selling by the product from CPCS system

There are two parts of profits resulting from applying of the CPCS system:

a. Profit made from selling the final product of CPCS

b. Saving from carbon credits.

The final product from CPCS is $CaCO_3$ (limestone) which is an industrial raw material widely used in many different industries, such as paper making, construction and plastic industries. The commercial price of limestone is 50 \$/ton. The carbon credit is15 \$/ton based on the report of '2012 Carbon Dioxide Price Forecast' (Wilson et al., 2012). Thus, the profits made from selling $CaCO_3$ and saving of CO_2 credits are \$85,603.23 and \$11,299.63.

4.3. Cost comparison between CPCS and liquefaction method

Having conducted the above cost analysis, Table 9 is resulted to present costs and profits of CPCS in a comparison with the conventional liquefied CO_2 storage method.

Table 9 Costs and profits comparison

-- Insert Table 9 here --
a: Negative sign means earning profits; b: Wischnewski; The physics hyper textbook, 1998; c: Melzer, 2012.
It can be seen that if the $CaCO_3$ were sold at the destination of a voyage, applying CPCS can make \$ 35,981.07 profit while capturing 20% CO_2 emissions from engine exhaust.

The operation cost and profit made from liquefaction method are listed in the table above. There are no chemical substances involved in liquefaction method so there is no cost due to purchase chemical substances. However, energy cost due to CO_2 liquefaction processes is considerable referring to liquefaction cost in the table. The freight reduction is resulted from the storage of liquefied CO_2. The

profits are made from saving carbon credits and selling CO_2 for enhanced oil recovery (EOR) which is about 25$/ton (Melzer, 2012).

5. Conclusions

The laboratory experiment examined the impacts of four key factors in CPCS. The results show that the CO_2 absorption rate varies with various parameters, such as solution volume, height, cross-section area and CO_2 gas flow rate. The results provide an insight of CPCS effectiveness and offer a useful reference in onboard system design.

The comparative study between CPCS and liquefaction for CCS onboard ships has shown that the liquefaction method has a merit of low running cost. The CPCS method has a higher profit from selling the end product. The profit is sufficient to overweight the running cost and freight penalties. The study proves that, CPCS for marine CO_2 capture and storage offers advantages of fewer requirements for captured CO_2 storage and transportation; safety and stability of ship operation are not affected. It is a cost-effective method bringing profits every single voyage if the product of $CaCO_3$ were sold. Conclusions can be made that the proposed chemical absorption processes for carbon dioxide solidification is a feasible and cost effective method for ship CO_2 emissions reduction.

Further studies should be conducted to analyses the factors that could improve the CO_2 absorption rate. Factors that can increase NaOH regeneration rate and filtration efficiency of $CaCO_3$ should also be investigated and analyzed in order to increase the total efficiency of the system. To verify the results from experiment, Computing Fluid Dynamic (CFD) study is underway for system simulation and onboard system design.

Acknowledgment

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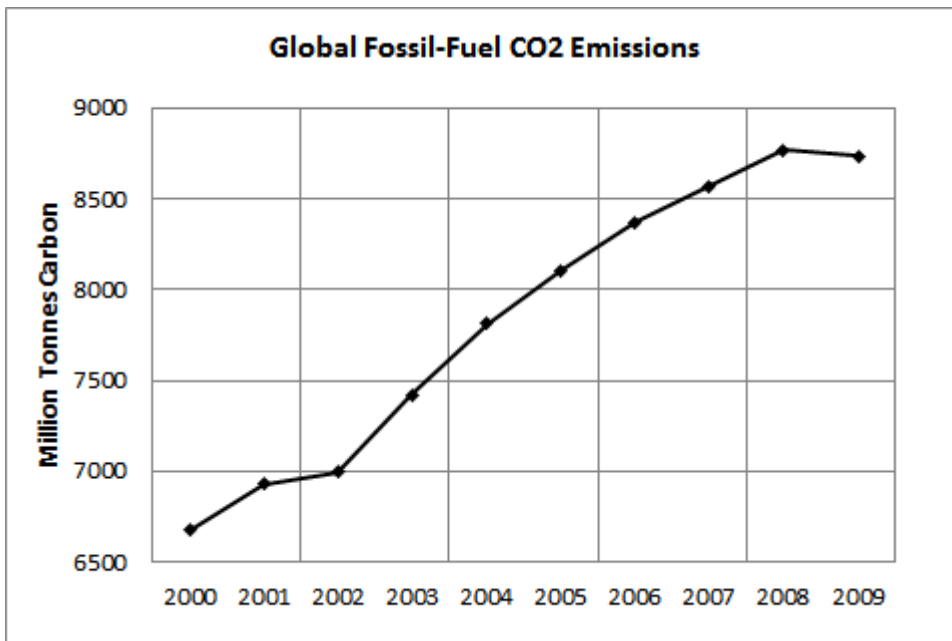
Figures

Fig. 9 Tendency of CO$_2$ emissions from 2000 to 2009
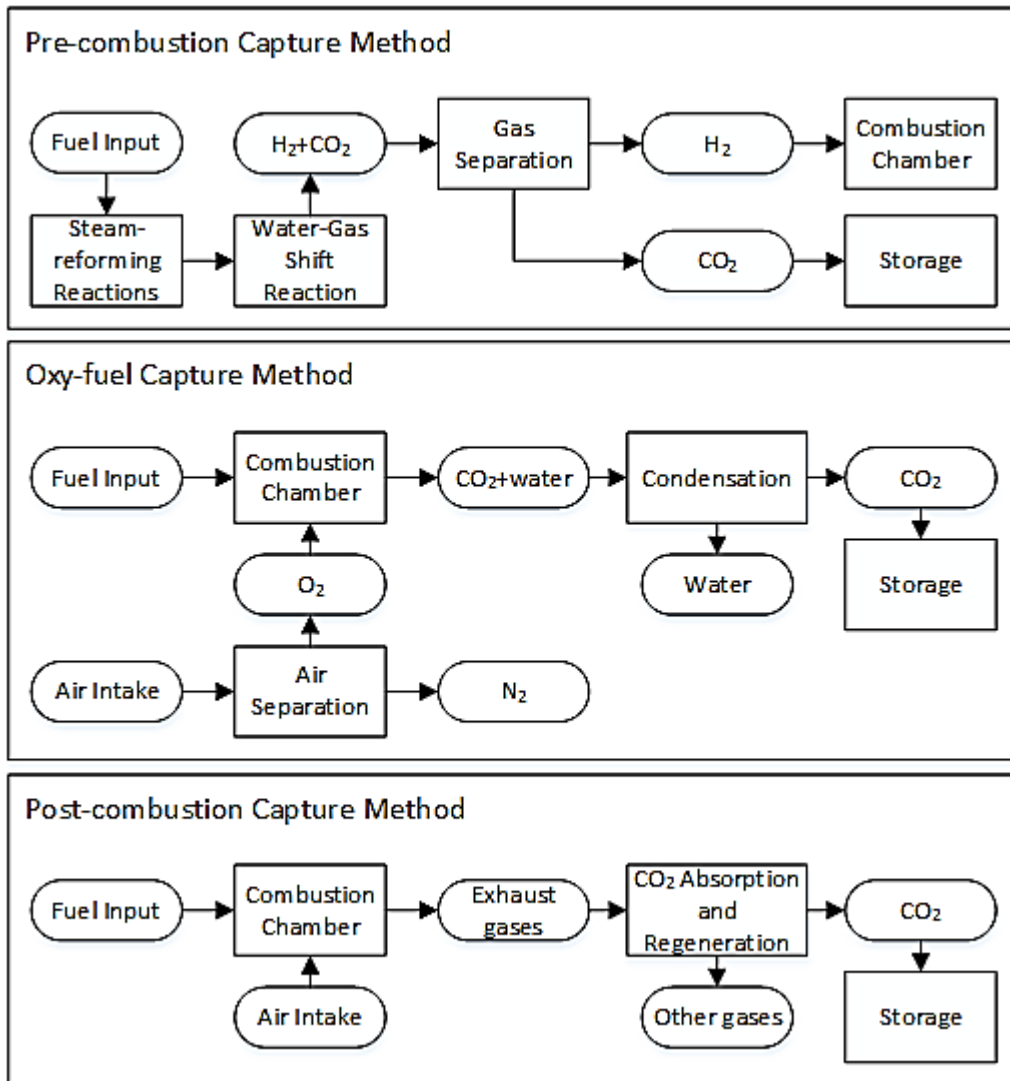
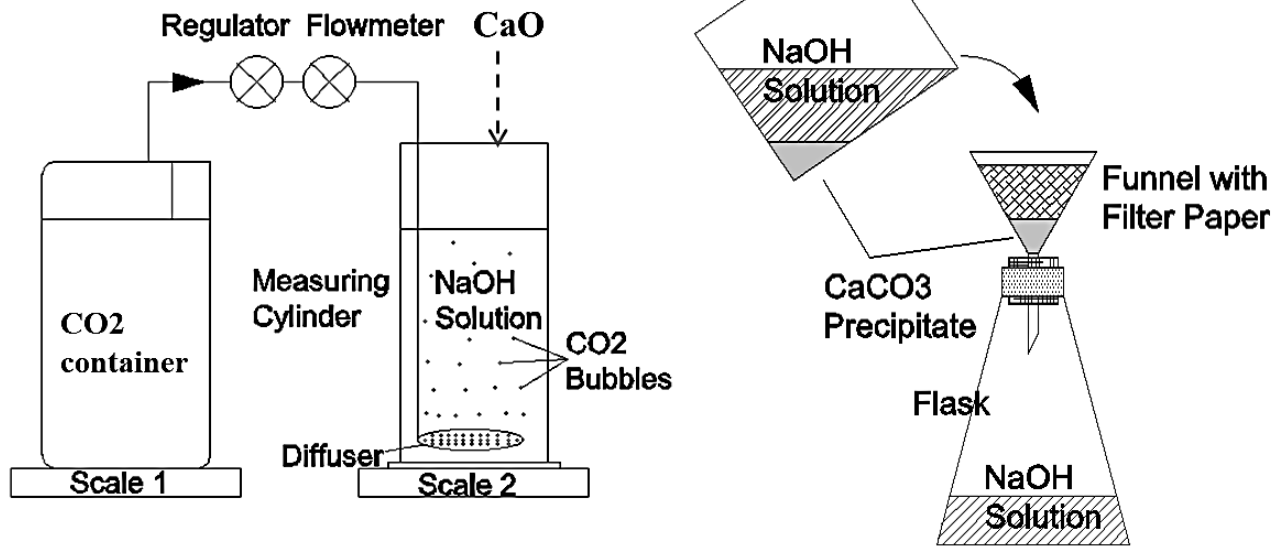**Fig. 10 General carbon capture methods**

Fig. 11 Schematic of the experiment systems
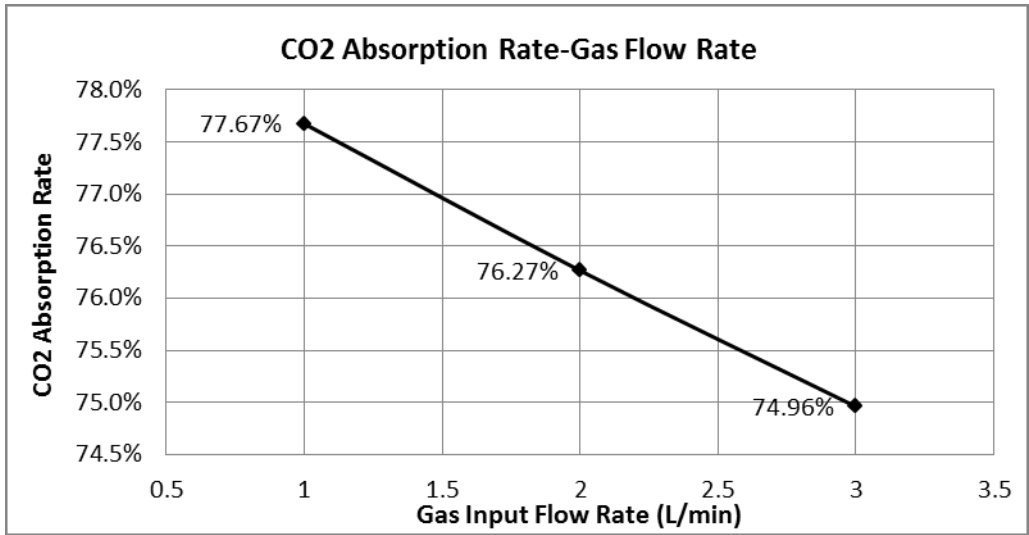
Fig. 12 Pictures of experiment rig

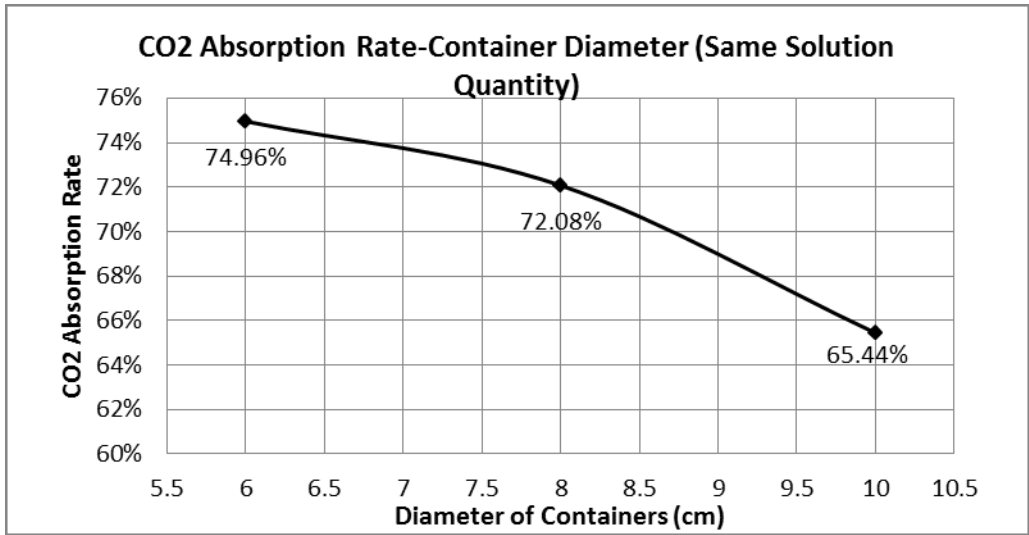**Fig. 13 CO_2 absorption rate vs. gas flow rate**

Fig. 14 Effect of container diameter on gas absorption rate with unchanged solution quantity
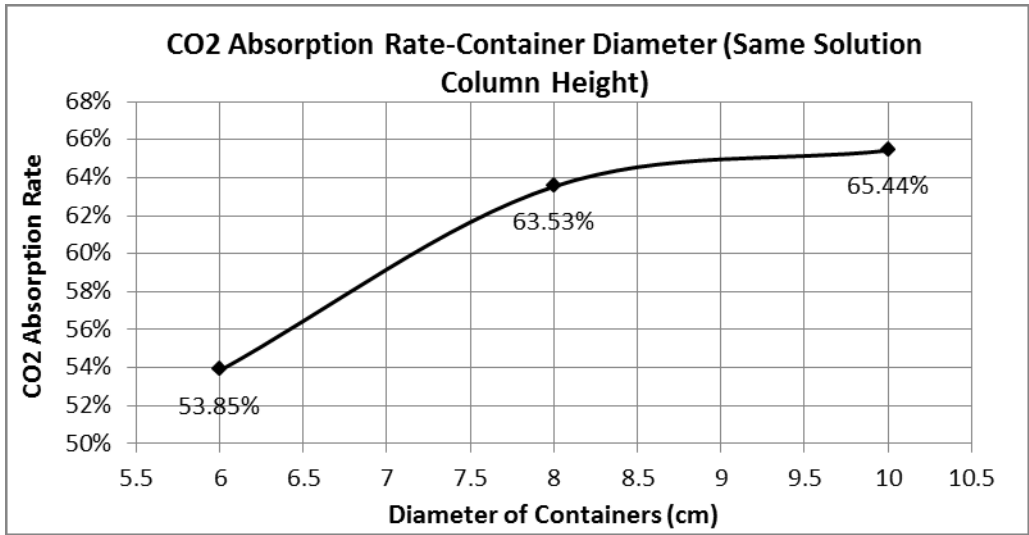
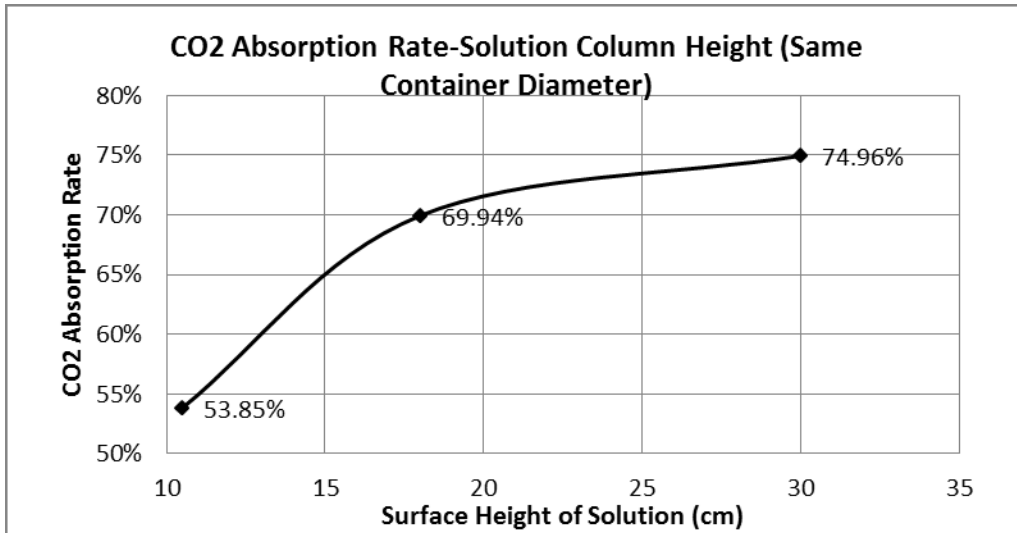**Fig. 15 Effect of container diameter on gas absorption rate with fixed solution height**

Fig. 16 Effect of solution column height on gas absorption rate with same cylinder diameter

Tables

Table 1. Experiment results

Experiments Rates	Results
CO_2 Absorption Rate	67.85%
NaOH Regeneration Rate	85.37%
$CaCO_3$ filtration efficiency	82.17%

Table 2. Change of absorption rate with gas input flow rate.

Solution volume (ml)	Solution column height (cm)	Cylinder diameter (cm)	CO_2 Flow Rate (L/min)	CO_2 Absorption Rate
~900	30	6	1	77.67%
			2	76.27%
			3	74.96%

Table 3. Changing of absorption rate with container diameters (solution quantity unchanged).

Solution volume (ml)	Solution column height (cm)	Cylinder diameter (cm)	CO_2 Flow Rate (L/min)	CO_2 Absorption Rate
~900	30	6		74.96%
	18	8	3	72.08%
	10.5	10		65.44%

Table 4. Changing of absorption rate with container diameters (same solution column height).

Solution volume (ml)	Solution column height (cm)	Cylinder diameter (cm)	CO_2 Flow Rate (L/min)	CO_2 Absorption Rate
296.88		6		53.85%
527.79	10.5	8	3	63.53%
824.67		10		65.44%

Table 5. Change of absorption rate with solution column heights (fixed container diameter).

Solution volume (ml)	Solution column height (cm)	Cylinder diameter (cm)	CO_2 Flow Rate (L/min)	CO_2 Absorption Rate
848.23	10.5			53.85%
508.94	18	6	3	69.94%
296.88	30			74.96%

Table 6. Specifications of the case ship.

Route details			Vessel dimensions			Engine and generator specifications		
Origin	Port of Qinhuangdao		Type	Bulk Carrier [a]		Main Engine	MAN B&W: 6S70MC-C7	
Destination	Port of San Francisco		LOA	292	m	No. of main engine	1	
Range	5,547	Nm	LBP	283.5	m	Engine Speed	91	rpm
Service Speed	15.2	Knot	Breadth	45	m	MCR	18,660	kW
Duration	16	Day	Depth	24.8	m	SFOC	174	g/kWh
			Draught	16.5	m	Generators	HHI/Himsen: 7H17/28	
			Gross	94,360	ton	No. of generators	3 (1 stand-by)	
			DWT	157,500	ton	Engine Speed	900	rpm
			Water ballast	78,000	m^3	Output	780	kW
			Fuel type	HSFO		SFOC	189	g/kWh

Table 7. Quantities of substances consumption and costs.

Chemicals	Quantities (ton)	Unit price ($/ton)	Cost ($)
Caustic soda (NaOH) consumed	200	83.33[a]	16,695
Quicklime (CaO) consumed	959	11.11	10,652
Sum			27,347

Table 8. Volumes and mass of coal losses due to storage of chemicals. (Bunker Price of Hong Kong, November 2013.)

Chemical substances	Density (kg/m^3)	Volume (m^3)
NaOH	2,130	94
CaO	3,355	286
CaCO$_3$	2,711	632
Sum		1,112

Table 9. Costs and profits comparison.

Costs per voyage ($)	Operation costs				Profits			Total costs
	Capture cost	Chemicals cost	Liquefaction cost	Freight reduction	Carbon credits	CaCO$_3$	CO$_2$	
CPCS	18,073	27,347	-	15,502	-11,300[a]	-85,603	-	-35,981
Liquefaction	18,073	-	21,021[b]	9,932	-11,300	-	-18,833[c]	6,758

Nomenclature

Nomenclature			
CCS	Carbon capture and storage	**Chemical substances**	
CFD	Computing Fluid Dynamic	$Ca(OH)_2$	Calcium hydroxide
CPCS	Chemical Processes for Carbon Solidification	$CaCO_3$	Calcium carbonate
D	Diameter	CaO	Calcium oxide
DWT	Deadweight tonnage	CO_2	Carbon dioxide
EEDI	Energy efficiency design index	CO_3^-	Carbonate ion
EEOI	Energy efficiency operational indicator	H_2O	Water
EIGA	European Industrial Gases Association	Na_2CO_3	Sodium carbonate
EOR	Enhanced oil recovery	NaOH	Sodium hydroxide
GHG	Greenhouse gases	NO_x	Nitrous oxides
H	Height	SO_x	Sulphur oxides
HSFO	High sulphur fuel oil		
ICP	Inductively coupled plasma	**Atomic and molar weight**	
IMO	International maritime organization	Carbon (C)	12
IPC	Inductively coupled plasma	Hydrogen (H)	1
IPCC	Intergovernmental panel on climate change	Oxygen (O)	16
ITTC	International Towing Tank Conference		
LBP	Length between perpendiculars	$Ca(OH)_2$	74
LOA	Length overall	$CaCO_3$	100
M	Molar mass	Calcium (Ca)	40
m	Mass	CaO	56
MCR	Maximum continuous rating	CO_2	44
n	Molar number	H_2O	18
P	Power	Na_2CO_3	106
p	Profit	NaOH	40
R	Rate	Sodium (Na)	23
SEEMP	Ship energy efficiency management plan		
SFOC	Specific fuel oil consumption	**Units**	
t	Time	L	Litre
V	Volume	L/min	Litre per minute
π	pi	mol	Mole number
ρ	density	ppm	Parts per million