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Experimental and numerical analysis on impacts of significant factors on carbon dioxide absorption efficiency in the carbon solidification process

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ABSTRACT

Onboard carbon capture and storage is an excellent solution to reduce the greenhouse gas emissions from shipping. This paper focuses on the absorption process and CO_2 gas flow rate, the geometry of absorption tank and the concentration of absorption solution are key factors affecting the absorption efficiency. This paper will illustrate the experimental results of the impacts of these factors on the CO_2 absorption efficiency. Meanwhile, results from CFD simulations of effects of the key factors on CO_2 absorption rates will be presented in this paper. Pressure distributions, solution concentration and velocity of CO_2 gas and solution are derived from the simulations. The results of the simulations provide fundamentals and insight understanding of the design of a proto-type demonstration system onboard a case ship. In addition to the key factors, the effect of atmosphere temperature was simulated and analyzed. Comparisons between the experiment and simulation have been conducted and the results have shown a good agreement. Optimized values of the factors are obtained from the comparisons and analyses. The numerical simulations of temperature effects on CO_2 absorption rate and optimized temperature for the absorption process are also presented in the paper.

1. Introduction

Greenhouse gases (GHG) are the main reason for climate change. It leads to many disasters to our human beings. Melting glaciers, rising sea levels and extinction of endangered species keep impacting our living conditions on the earth. These phenomena are resulting from the temperature rising continuously due to the thermal insulation effect of GHG. The heat received by earth cannot be rapidly released into the space and resulting in global warming. The GHG emission has to be reduced in order to guarantee the safety of our planet in the future. There are many kinds of GHG existing, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases (F-gases). Among all the GHG, presented in Fig. 1, CO_2 is the most influential one which contributes 76.7% of the anthropogenic GHG emissions to atmosphere (IPCC, 2007). Nowadays, there are a large number of research projects focusing on different methods to mitigate the effect of global warming by reducing CO_2 gas emission. One of the most effective and popular methods is the carbon capture and storage (CCS). CCS is considered to be an effective way to mitigate and even eliminate the global warming effect through capturing the CO_2 emission and storing them underground for Enhanced Oil Recovery (EOR) or in deep seas (World Resources Institute (WRI), 2008). However, CCS system currently is only applied on onshore power plants and some industrial processes. There are few marine applications. About 938 million tons of CO_2 emission is estimated from shipping and 796 million tons are contributed by international shipping in 2012 (Third IMO GHG Study, 2014). 20% reduction of carbon emission from ships is also set up as a global target to be achieved in 2020 by United Nations (Shipping, World Trade and the Reduction of CO_2 Emissions, 2014). Although it is about 2.2% of the global CO_2 emissions, International Maritime Organization (IMO) has already taken actions to reduce GHG emissions from ships, such as EEDI, EEOI and SEEMP, aiming to increasing the energy efficiency of ships (MARPOL Annex VI, Chapter IV, 2011).

By the end of the 2012, there have been 14 active CCS industrial projects on shore (Global CCS Institute 2012, 2012). Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project is an active CCS project launched in 2014 in Canada. The target is on the power station. An amine based post-combustion capture method is applied for capture. The transport type is using pipeline

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Nomenclature

CCS	Carbon capture and storage
CFD	Computing Fluid Dynamic
CPCS	Chemical Processes for Carbon Solidification
DNV	Det Norske Veritas
EEDI	Energy efficiency design index
EEOI	Energy efficiency operational indicator
EOR	Enhanced oil recovery
GHG	Greenhouse gases
IMO	International maritime organization
IPCC	Intergovernmental panel on climate change
SEEMP	Ship energy efficiency management plan
WRI	World Resources Institute

and EOR is selected for carbon storage (Boundary Dam Integrated Carbon Capture and Storage Demonstration Project, 2014). Gorgon Carbon Dioxide Injection Project is an Australian project under execute and will be in operated in 2016. The target is on natural gas processing and this CCS project will apply pre-combustion capture method (natural gas processing), pipeline and EOR (Gorgon Carbon Dioxide Injection Project, 2015). FutureGen 2.0 Project is an under defined CCS project and will apply oxy-fuel combustion capture method on power station in USA. Compression method will be applied for separation. Pipeline and dedicated geological storage will be utilized for CO_2 transportation and storage (FutureGen 2.0 Project, 2013).

For Marine applications, Det Norske Veritas (DNV GL) and Process Systems Enterprise Ltd have launched projects on maritime CCS applications and a report has indicated that, with CCS on ship, CO_2 emission can be reduced by 65% (DNV and PSE report on ship carbon capture & storage, 2013). It also proves that CCS is not only an excellent supplement of energy improvement methods but also an effective CO_2 emission reduction method. From previous work of the authors, it indicates the feasibility of proposed CCS method to reduce marine CO_2 emission by separating and storing them in a solid form on ships. Case study from previous work also have illustrated the proposed solidification processes is more cost effective than the traditional liquefaction method for CO_2 storage onboard (Peilin and Haibin, 2014).

In order to design a reasonable and feasible CFD model, several literatures are reviewed. Horvath and his research group have successfully modeled and simulated a cuboid bubble column using the VOF model. VOF model is suitable to present immiscible phase interaction and the computation cost is quite small. Their results are close to the experiment data (Horvath et al., 2009). The investigation from Mohammad and Mohammad tests both mixture and Eulerian approaches on a bubble column reactor at unsteady state conditions and low gas flow rates. The results from simulation have a good consistency with experiment data. It also indicates similar outputs are derived from mixture and Eulerian model but the Eulerian model has a better convergence and stability (Mohammad et al., 2011). Asendrych and his colleagues applied a two-fluid Eulerian model for an amine based carbon capture system. A 2D axisymmetric CFD model was designed and analyzed. The results illustrate the ratio of solution to gas has a significant impact on efficiency. They also achieved a good agreement of numerical results and experiment data (Asendrych et al., 2013).

This paper presents the experiment conducted to estimate the effects of various factors on the CO_2 absorption rate. Numerical simulations of the absorption process are also illustrated. An Eulerian model will be selected and a 2D model will be applied. The comparisons of experiment results with that of simulation are also presented, leading to optimized operational factors for CO_2 absorption. The numerical simulations will provide fundamentals of the design of a proto-type demonstration system on ships.

2. Carbon solidification processes

Carbon solidification processes only deal with part of exhaust gases from marine engines as the target is to comply with various regional and international CO_2 emission regulations. Part of the exhaust gas from the funnel is firstly bypassed into a separation system to obtain high purity CO_2 gas. Since it is not attached to main engine, the impact of this system on engine efficiency is very much slight. There are many different methods available to achieve the separation so this paper will focus on the absorption processes dealing with concentrated CO_2 gas. The concentrated CO_2 gas after separation is fed into a reaction tank which contains alkaline solution. Following the absorption of CO_2 by the alkaline solution, calcium oxide (CaO) is added to solidify the CO_3^{2-} ions from the solution. The chemical reaction processes are presented below by Eqs. (1) and (2) (Pflug et al., 1957; Mahmoudkhani and Keith, 2009):

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

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

There are two intermediate reactions containing in the above processes shown in Eqs. (3) and (4) (Chambers and Holliday, 1975; Hessabi, 2009):

$$CO_2(g)+2H_2O(l)=HCO_3{}^-+H_3O^+-\Delta H_3 \quad (3)$$

$$CaO(s)+H_2O(l)=Ca(OH)_2-\Delta H_4 \quad (4)$$

Sodium hydroxide (NaOH) solution is selected as the absorbent because it naturally reacts with acid gas (CO_2, SO_2 and NO_2). After sodium carbonate (Na_2CO_3) is generated, CO_2 is captured in the form of CO_3^{2-} ions in solution. After adding in CaO, it firstly reacts with water to generate calcium hydroxide ($Ca(OH)_2$). When Ca^{2+} meets with CO_3^{2-} in the solution, sediment calcium carbonate ($CaCO_3$) is produced. The sediments are separated from the solution and then dried for storage on ship. The sediment will be discharged off ship at end of a voyage in port. Calcium carbonate can be traded to medical industry as calcium supplement or building industry as primary substance of building materials. NaOH solution is regenerated during the precipitation (Eq. (2)) and can be reused as absorbent in the process in Eq. (1). In this paper, only the absorption process is analyzed and further consideration on separation and solidification processes will be made in future research works.

This project is a very much forefront idea to apply chemical method on ship for the purpose of carbon emission reduction.

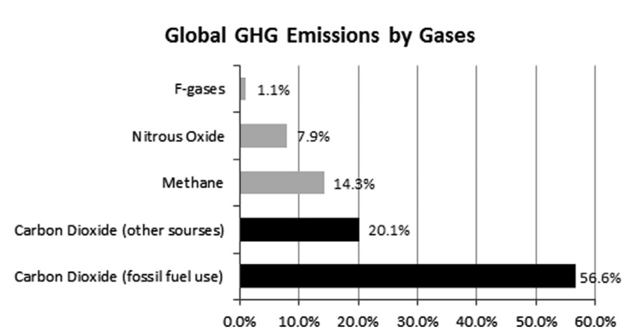

Fig. 1. Contributions of different GHG gases to global emissions.