A Case Ship Study on Practical Design and Installation of Carbon Absorption and Solidification System

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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 a case ship study on design and installation of a practical carbon absorption and solidification system which was proposed in authors' previous work (Peilin and Haibin, 2014). The design process is based on authors' previous work of simulation on lab-scale experiment. The specifications of the selected ship will be presented and utilized for its modelling. The processes of simulation illustrate modifications of simulation model, design of physical model, application of orthogonal design method, introduction of equipment and software and analysis of results. This paper also presents tank design, positioning and CAD drawing of the system on board after all processes and systems are derived. This paper demonstrates general processes of carbon absorption and solidification system design for a case ship so that design of the system for a new ship could follow the same procedures.

Keywords: Carbon emission control, numerical simulation system design

NOMENCLATURE

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

1. INTRODUCTION

Greenhouse gases (GHG) are the main reason for climate change. It leads to many disasters to our human beings. Melting of glaciers, rising of 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 Figure 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 (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, 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)

Since the simulation of lab-scale experiment is achieved in previous paper of authors' (Peilin and Haibin, 2014), the CFD model built can be applied for real ship system simulation. It is essential to carry out a real ship system simulation because theory in laboratory should be verified its feasibility on a real ship. In this paper, a case ship will be selected and a carbon absorption system will be designed and simulated for this target ship. The specifications of the selected ship will be presented and utilized for its modelling. The modifications of simulation model, design of physical model, application of orthogonal design method, introduction of equipment and software and analysis of results will be illustrated during the processes of simulation. After deriving simulation results of absorption process, the following processes are designed: precipitation process, separation process and storage process. The weight and volume required for these processes are obtained according to case ship specifications and absorption system requirements. After all details of processes and systems are derived, this paper presents tank design, positioning and CAD drawing of system on board. This paper demonstrates general processes of carbon absorption and solidification system design for a case ship and design of this system for other vessel could follow the same procedures.

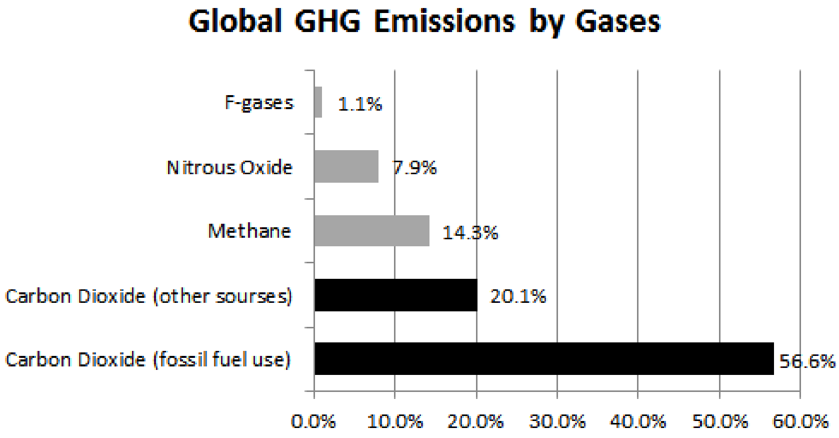

Figure 1Contributions of different GHG gases to global emissions.

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 Eqs. 2 (Pflug et al., 1957; Mahmoudkhani and Keith, 2009):

CO_2 (g) + 2NaOH (l) = Na_2CO_3 (l) + H_2O (l) - ΔH_1 (1)

Na_2CO_3 (l) + $Ca(OH)_2$ (s) = $CaCO_3\downarrow$(s) + 2NaOH (l) -ΔH_2 (2)

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

CO_2 (g) + $2H_2O$ (l) = HCO_3^- + H_3O^+ - ΔH_3 (3)

CaO (s) + H_2O (l) = $Ca(OH)_2$ - ΔH_4 (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 (Eqs. 2) and can be reused as absorbent in the process in Eqs. 1. In this paper, only the absorption process is analysed 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. Currently, there is no project providing similar comparisons between chemical method and liquefaction method for ships. It is because that not only the energy and chemical cost but also the transportation penalty of the vessel should be considered. Our previous work (Peilin and Haibin, 2014) has a comprehensive consideration on these costs for both methods and the results are presented in that paper as well.

3. METHODOLOGY

3.1 SIMULATION MODEL IN CFD (ANSYS FLUENT)

Chemical process comprises two main components: species transportation and multiphase flow. To simulate a chemical process with CFD tools, both components should be considered. Species transportation is considered

in the numerical simulation by transferring masses, energy and momentum of reactants into products. Multiphase flow is simulated as bubble column effects due to the mixing of liquid and gas of reactants. CO_2 and air are in a gas phase and NaOH and Na_2CO_3 solutions are in liquid forms.
ANSYS Fluent solves conservation equations for chemical species by predicting the local mass fraction of each species, through the solution of a convection-diffusion equation for specified species (ANSYS Fluent theory guide 14.5, 2012) as shown in the following:

$$\frac{\partial}{\partial t}(\rho Y_i)+\nabla\cdot(\rho\vec{v}Y_i)=-\nabla\cdot\vec{J}_i+R_i+S_i \qquad (5)$$

where Y_i is the local mass fraction of each species. R_i is the net rate of production of species i by chemical reaction and S_i is the rate of creation from the dispersed phase and sources. J_i is the mass diffusion flux. $\vec{v}$ is the overall velocity vector (m/s). t represents time and ρ is the density of species.
For an Eulerian multiphase model, the concept of phasic volume fractions is introduced and the volume of one phase can be defined as:

$$V=\int_V a\,dV \qquad (6)$$

where a is the volume fraction of phases.
The continuity equation of phase q (for fluid-fluid mass exchange) is:

$$\frac{\partial}{\partial t}(a_q\rho_q)+\nabla\cdot(a_q\rho_q\vec{v}_q)=\sum_{p=1}^{n}(\dot{m}_{pq}-\dot{m}_{qp}) \qquad (7)$$

where $\vec{v}_q$ is the velocity of phase q; $\dot{m}_{pq}$ is the mass transferred from the phase p to q and $\dot{m}_{qp}$ is the mass transferred from phase q to phase p.
The energy conservation equation in Eulerian model is:

$$\frac{\partial}{\partial t}(a_q\rho_q h_q)+\nabla\cdot(a_q\rho_q\vec{u}_q h_q)=a_q\frac{\partial p_q}{\partial t}+\bar{\tau}_q:\nabla\vec{u}_q-\nabla\cdot\vec{q}_q+S_q+\sum_{p=1}^{n}(Q_{pq}+\dot{m}_{pq}h_{pq}-\dot{m}_{qp}h_{qp}) \qquad (8)$$

where h_q is the specific enthalpy of the q^{th} phase; $\vec{q}_q$ is the heat flux, S_q is a source term that includes sources of enthalpy, such as from chemical reaction; Q_{pq} is the intensity of heat exchange between p^{th} and q^{th} phases, and h_{pq} is the interphase enthalpy (for example, the enthalpy of the vapor at the temperature of the droplets, in the case of evaporation). The heat exchange between phases must comply with the local balance conditions $Q_{pq}=-Q_{qp}$ and $Q_{qq}=0$.
The conservation of momentum for a fluid phase is:

$$\frac{\partial}{\partial t}(a_q\rho_q\vec{v}_q)+\nabla\cdot(a_q\rho_q\vec{v}_q\vec{v}_q)=-a_q\nabla p+\nabla\cdot\bar{\bar{\tau}}_q+a_q\rho_q\vec{g}+\sum_{p=1}^{N}(K_{pq}(\vec{v}_p-\vec{v}_q)+\dot{m}_{pq}\vec{v}_{pq}-\dot{m}_{qp}\vec{v}_{qp})+(\vec{F}_q+\vec{F}_{lift,q}+\vec{F}_{wl,q}+\vec{F}_{vm,q}+\vec{F}_{td,q}) \qquad (9)$$

where ρ is the density; p is the pressure shared by all phases; g is gravitational acceleration, $\vec{v}_{pq}$ is the interphase velocity and K is the momentum exchange coefficient between fluid phases. $\vec{F}_q$ is an external body force, $\vec{F}_{lift,q}$ is a lift force, $\vec{F}_{wl,q}$ is wall lubrication force, $\vec{F}_{vm,q}$ is a virtual mass force, $\vec{F}_{td,q}$ is a turbulent dispersion force (for turbulent flow only).
$\bar{\bar{\tau}}$ is the stress-strain tensor of q^{th} phase:

$$\bar{\bar{\tau}}_q=a_q\mu_q(\nabla\vec{v}_q+\nabla\vec{v}_q^{\,T})+a_q\left(\lambda_q-\frac{2}{3}\mu_q\right)\nabla\cdot\vec{v}_q\bar{\bar{I}} \qquad (10)$$

where μ_q and λ_q are the shear and bulk viscosity of phase q and I is the unit tensor.
Reaction rate, r, between phases can be derived by following equation:

$$r=k(T)[A]^m[B]^n \qquad (11)$$

Where $k(T)$ is the reaction rate constant that depends on temperature, $[A]$ and $[B]$ are the concentrations of substances A and B in moles per volume of solution (assuming the reaction is taking place throughout the volume of the solution) and exponents m and n are partial orders of reaction which depend on reaction mechanism.
Reaction rate constant, k, is estimated by using Arrhenius expression:

$$k=AT^{\beta}e^{-Ea/RT} \qquad (12)$$

where A is the pre-exponential factor; T is the temperature of reactants; β is the temperature exponent; Ea is the activation energy for reaction and R is the universal gas constant.
The surface tension is involved in modelling of the bubbling effect:

$$\Delta p = \frac{2\sigma}{R} \tag{13}$$

where Δp is the pressures difference between two sides of the surface; σ is the surface tension coefficient; and R is the radius of bubbles.
Wall adhesion is also considered for bubbling effect and the surface normal at the live cell next to the wall is:

$$\hat{n} = \hat{n}_w \cos\theta_w + \hat{t}_w \sin\theta_w \tag{14}$$

where $\hat{n}_w$ and $\hat{t}_w$ are the unit vectors normal and tangential to the wall; θ_w is the tangent angle of the gas bubbles or liquid droplets to the wall as indicated in Figure 2.

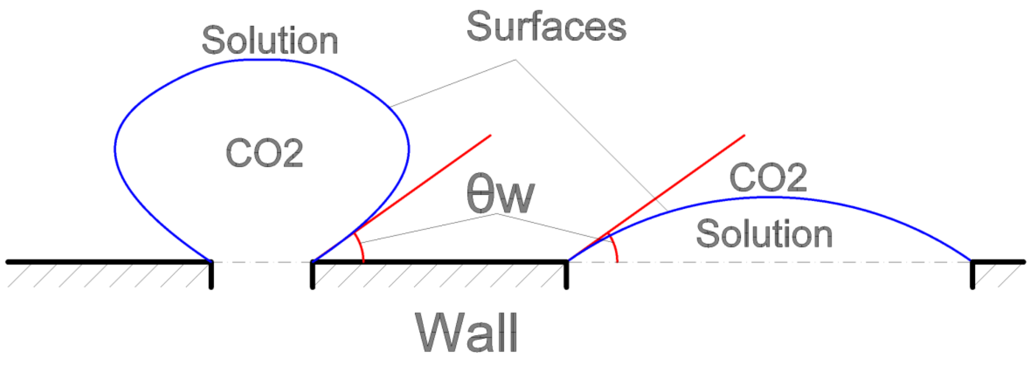

Figure 2 Demonstration of contact angle between gas-solution surface and wall.

3.2 ORTHOGONAL DESIGN METHOD INTRODUCTION AND APPLICATION

Orthogonal design method is experimental processes applied to test and compare the effectiveness of multiple different factors on a target process or system. It is an efficient way to find out new phenomenon, materials or regular pattern during scientific researching and with these findings researches can be developed to discover more meaningful results. Design of experiment (DOE) was established by Ronald Aylmer Fisher in 1920s. (Ronald A.F., 1935) Further DOE was developed and improved by Genichi Taguchi research team during 1940~1950 and Taguchi methods were established by his team. Orthogonal design method has been widely used in many different fields. Ming Q. and et al. applied this method on their slewing bearing models to test the performance of connecting bolts with analysing significant factors. (Ming Q. and et al, 2011) Orthogonal design method is also applied to improve optimization algorithm and find out an optimal solutions in Wenyin and his colleagues' research. (Wenyin G. and et al, 2008) Se-Jong and his colleagues utilized orthogonal design method to develop and test a dual phase steel. Three levels of three controllable factors were considered: intercritical annealing, aging and galvanizing temperatures during the heat treatment (Se-Jong K. and et al, 2009).

4. SIMULATION PROCESSES

To design a system for practical vessel, the simulation of the system can be a good start and feasible analysis can also be figured out. The practical system can apply the simulation models of lab-scale experiment established and analysed in previous publication of authors' (Peilin and Haibin 2014). The results from simulation matches well with experiment data which indicates the model can present the reaction processes properly.
The design of carbon solidification system should consider both engine specifications and practical feasibility on ships so that a reasonable physical model can be achieved. In this stage of simulation, orthogonal design method is applied to reduce the considerable simulation numbers. The computing equipment and software will be briefly introduced which are the same as previous stage of simulation. The results from simulation will give an optimal design of the practical system. After analysing significant factors, an analysis optimal design will be compared with the optimal case. According to the comparison results, the better design will be utilized for further case ship study procedures.

4.1 SIMULATION MODEL MODIFICATIONS

The simulation model for lab-scale experiment is applied for practical system simulation. Due to its matching with experiment, the reaction model can present the practical reaction between gas and solution phases so that it can be directly used for practical system simulation. Other internal models, such as multiphase model and species model will be remained as chemical materials used in practical design are not changed. It is simply because the difference between two different scales of simulation is the physical parameters, such as container sizes, structure, additional gas and solution inlet and outlet and so on. Therefore, no reaction related model is changed. With only physical model changed, previous simulation model can be applied for further system design and simulation.

Physical model will be enlarged from the lab-scale system because the capacity of carbon absorption system should meet the requirement of case ship exhaust gas flow. Hence, the dimension of the system should be well considered. Moreover, industrial processes usually apply packed or tray column to increase the contact area between two phases, for example in oil refinery industry. There are also many researches on CFD simulation of flow in packing and tray columns. Gao and his colleagues modelled and analysed flow in random packing columns for seawater desulfurization. (Gao and et al, 2011) Research team from Tianjin University modelled and investigated the flow behaviour of two phase flow in a structured packing distillation column. (Chen and et al, 2009) The hydrodynamic characteristics of sieve trays in distillation columns were studied by Teleken and his colleagues. (Teleken and et al, 2009) A suitable physical design of the system should be selected and designed to satisfy the requirements of absorption efficiency and ship performances.

Other changes in this physical model are the flow rate of two phases. Apparently, inlet flow rate of gas and solution should be adjusted since the gas inlet is from engine exhaust gas. Solution inlet flow rate should be controlled to prevent flooding and keep high contact area between two phases. Physical model design will be presented in next section.

4.2 PHYSICAL MODEL DESIGN

Physical model is designed as a cylindrical container. Gas outlets and solution inlets are on top while gas inlets and solution outlets are on bottom. In laboratory, a measuring cylinder was used as the absorption reaction container. The simulation of lab-scale experiment is in 2-dimensional and the results from simulation are matched well with those from experiments. While simulating the practical absorption system, a 2-dimensional model is built and simulated. Hence, this new model is presenting the results for a practical cylindrical container for case ship.

4.2.1 ABSORPTION SYSTEM SELECTION

Currently, there are two popular absorption system structures used for chemical absorption on scrubbers: packing column and tray column. Comparing with tray columns, packing column has many advantages according to Perry’s handbook of chemical engineering. (James, 2008):

- Low initial cost;
- Corrosion resistant (plastics and ceramics materials are available);
- Low pressure drop (which can be an advantage when a fan or compressor is applied for the tower);
- Easy and economic adaptability to small-diameter (less than 0.6-m or 2-ft) columns;
- Excellent handling of foams.

Based on Klemas and Bonilla’s research, comparisons between column types are listed in Table 1. It agrees with that packing can be anti-corrosion, low pressure drop, and good at foam handling. (Klemas and Bonilla, 2000) Furthermore, packing column is able to work with high capacity. At low liquid rate (less than $136m^3/h$), packing column also has a better performance than tray column. The disadvantages of packing are also presented in this table:

- Low performance at high pressure;
- Bad performance with high liquid rate ($408\ m^3/h$);
- Anti-fouling system requires improvements;
- High inspection and maintenance costs.

Table 1 Packing and tray columns comparisons

Application in distillation	*Random packing*	*Structured packing*	*Traditional trays*	*High-capacity trays*
Pressure drop	2	1	3	3
Efficiency at high pressure	2	4	2	1
Efficiency at low pressure	2	1	2	3
Efficiency at low liquid rate [a]	2	1	3	4
Efficiency at high liquid rate [b]	3	4	2	1
Foaming systems	2	2	3	3
Non-metallic services	1	2	4	4
Fouling systems	4	2	1	1
Inspection and maintenance	3	4	1	1
Low cost	2	4	1	3

Application rating: 1, best; 2, good; 3, fair; 4, poor.
a. Systems below 136 m^3/h; b. Systems over 408 m^3/h

Since both packing column and tray column has advantages according to industrial experiences, further consideration of applying them on ships will be made. The stability of vessels is greatly important simply because it relates to the safety of vessels. Considering ship stability, tray column is not preferred because there are large quantities of liquid accumulating on each tray until the liquid height reaches the height of weir. The large quantities of liquid could be sloshing with the movement of vessels and it is definitely a potential risk for safety transportation. For packing column, liquid will be separated and obstructed by packing material from accumulating so that the sloshing effect is small comparing to tray column. Therefore, considering both the industrial experience and practical situation on ships, packing column is a better option.

4.2.2 ABSORPTION SYSTEM DESIGN

A common packing column can increase the contact area between liquid and gas so that high absorption rate is assured. For most of packing column application, a counter flow design is preferred. One reason is that gravity can be utilized to separate gas and liquid phase as liquid is driven to move downwardly by gravity. If using parallel flow, it requires more power output to maintain either liquid moving upwardly with gas or gas moving downwardly with liquid.

Due to counter flow design, the position of inlets and outlets are set as introduced in previous section. However, even though gravity effect is utilized, it is hard to make sure both liquid and gas leaving the designed outlets. To prevent liquid from leaving from gas outlets, mist eliminators are applied. The mist eliminators are nets equipped inside the reaction tank right before the gas outlets. When liquid mist touches the net, liquid mist will attach, accumulate and drop until the net can't hold it. This is also another reason why counter flow is preferred. To prevent gas leaving from liquid outlets, a pump is fitted with outlets which can control the liquid outflow rate. A liquid seal on liquid outlet will keep gas leaving from gas outlets. In simulation, the gas outlets are covered by a region of porous medium as the mist eliminator. Porous medium provides resistance to liquid phase, which prevents liquid from moving upwardly. Pressure outlet boundary condition is applied on these outlets. For liquid outlet, mass flow inlet boundary condition is utilized to simulate the pump which only constantly pumps liquid out from the reaction tank.

As the packing column will be applied in the absorption system, designed system will be filled with spherical packing to increase the contact area. The size of the packing material will be under researching to find out its impact on absorption process. A support will be included in the design so that the spherical packing can be fixed in the middle of the reaction tank.

Seven main factors are considered while designing the absorption system. For each factor, three different values will be selected in order to determine their impact on absorption processes and find out an optimal case for practical design:

- Tower height (H):

1.5, 1.75 and 2 meter are selected. These heights are selected considering the height of container on the vessel and volume onboard is limited.

- Tower diameter (D):

Three different diameters are selected, 2, 2.25 and 2.5 meter, considering volume onboard is limited and small diameter is preferred when liquid quantity is same.

- Sprayer number and position (S_n and S_p):

Three different sprayer number and position are chosen: 9, 10 and 11; 0.1, 0.125 and 0.15 meter. These two factors are considered together. When design sprayers, the distance between the left most and right most sprayers should be smaller than tower diameter and also leaves enough space for gas outlets.

- Packing material diameter (d):

Generally the packing material size is ranging from 0.015 to 0.07 meter. Therefore, three general sizes are selected: 0.02, 0.03 and 0.04 meter.

- Solution flow rate (m_s):

These solution flow rates are designed to prevent flooding and keep a reasonable contact area. After testing, 40, 60 and 80 kg/s of liquid flow rate are selected.

- Gas flow rate (m_g):

20% of CO_2 from engine exhaust gas is designed to be removed. The flow rate of CO_2 is about 1.6 kg/s so gas flow rates of 1.2, 1.6 and 2 kg/s are selected for further analysis.

One example of the design system is presented in Figure 3. It indicates the position of gas and liquid outlets and inlets, mist eliminators, packing materials and supports in reaction tank. The blue lines present tank walls and the grey sections are the flow regions. The practical system can be derived by swirling this 2-D model and the liquid distributor and gas outlets are presented in Figure 4. After designing the system, the next step will be simulating with CFD software. However, there are too many possible combinations of these factors to be tested in a limited time. Orthogonal design method will be introduced in next section to reduce the numbers of combinations and save computing time.

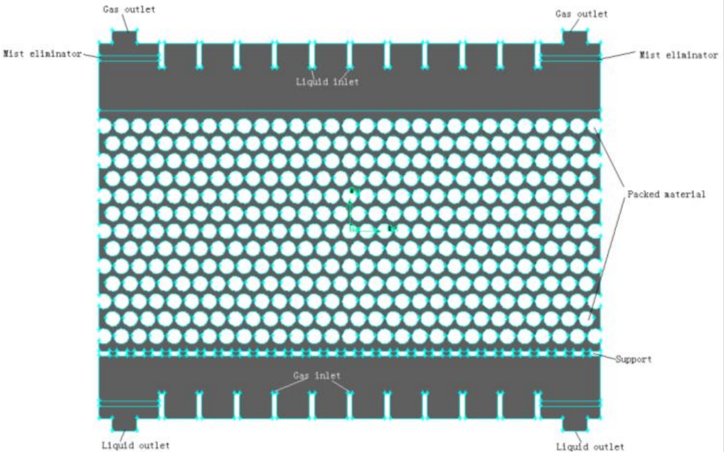

Figure 3Example physical model of absorption system design.

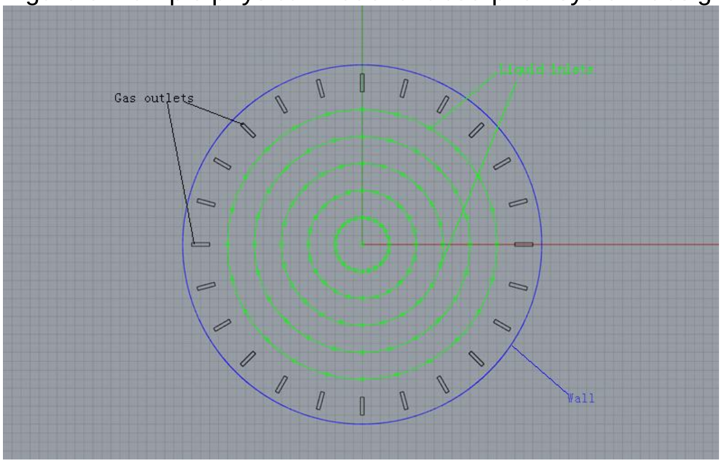

Figure 4 Schematic of liquid distributors and gas outlets.

4.3 ORTHOGONAL DESIGN METHOD INTRODUCTION AND APPLICATION

Orthogonal design method will be applied and to find out how the selected factors would impact the absorption rate during the absorption process. The application of orthogonal design method is utilizing normalized table to design experiments. It is efficient accurcy and realiable to find out optimal conclusions with relatively small amount of trials. With this method, 18 different cases are required to be carried out by utlizing normalized orthogonal design method table. The selected factors are considered because they are important ones and also controllable. A seven factors with three level orthogonal design method table ($L_{18}\,3^7$) is designed as shown in Table 2. (Hong Z. and et al, 2012) According to previous section, the factors and their levels are set up and presented in Table 3.

Table 2 Seven factors with three level orthogonal design method table ($L_{18}\,3^7$)

	A	*B*	*C*	*D*	*E*	*F*	*G*
1	1	1	1	1	1	1	1
2	1	2	2	2	2	2	2
3	1	3	3	3	3	3	3
4	2	1	1	2	2	3	3
5	2	2	2	3	3	1	1
6	2	3	3	1	1	2	2
7	3	1	2	1	3	2	3
8	3	2	3	2	1	3	1
9	3	3	1	3	2	1	2
10	1	1	3	3	2	2	1
11	1	2	1	1	3	3	2
12	1	3	2	2	1	1	3
13	2	1	2	3	1	3	2
14	2	2	3	1	2	1	3
15	2	3	1	2	3	2	1

16	3	1	3	2	3	1	2
17	3	2	1	3	1	2	3
18	3	3	2	1	2	3	1

Table 3 Orthogonal design factors and levels

Factor code	*Factors*	*Levels*		
		1	2	3
A	Tower height(m)	1.5	1.75	2
B	Diameter(m)	2	2.25	2.5
C	Sprayer number	9	10	11
D	Sprayer position(m)	0.1	0.125	0.15
E	Packed material size (m)	0.02	0.03	0.04
F	Solution flow rate(kg/s)	40	60	80
G	Gas flow rate (kg/s)	1.2	1.6	2

4.4 RESULTS AND ANALYSIS

The absorption rate in practical system simulation is derived based on the same method to lab-scale experiment which monitoring the concentration of Na_2CO_3. The absorption rate at 10 second of every case is derived and presented in Table 4. It is obvious that case 12 has the highest absorption rate so this case is the optimal case among all simulation cases.

Table 4 Results of absorption rates under different cases.

Test number	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*
Absorption rate	12.97%	16.95%	13.42%	15.77%	16.22%	15.18%	20.65%	9.35%	19.63%	16.30%	13.61%	23.05%	18.27%	20.15%	11.45%	21.52%	18.26%	9.78%

4.4 (a) SIGNIFICANCE OF FACTORS (R VALUE):

After deriving the absorption rates for all cases, analyses are carried out to find the impacts of different factors on absorption rates. For each level of every factor, a sum of absorption rate value (K) is introduced. Also average values and the ranges of average values (R) are derived and presented in Table 5. The R value is applied to present the significance of factors to absorption rate. As shown in the table, the changing of factor G, the gas flow rate, has the most significant impact on absorption rate. Therefore, the significance of these factors on absorption rate can be derived: Gas flow rate > Solution flow rate> Sprayer number > Width > Sprayer position > Tower height > Packed material size (G>F>C>B>D>A>E). For different factors, their impacts on absorption rate are presented in Figure 5.

Table 5 Results of analysis from orthogonal design

Target	*Factor code*	*A*	*B*	*C*	*D*	*E*	*F*	*G*
Absorption rate	K_1	96.30%	105.48%	91.68%	92.35%	97.08%	113.55%	76.07%
	K_2	97.04%	94.54%	104.92%	98.09%	98.59%	98.79%	105.16%
	K_3	99.20%	92.51%	95.93%	102.09%	96.86%	80.19%	111.30%
	$K_1/6$	16.05%	17.58%	15.28%	15.39%	16.18%	18.92%	12.68%
	$K_2/6$	16.17%	15.76%	17.49%	16.35%	16.43%	16.47%	17.53%
	$K_3/6$	16.53%	15.42%	15.99%	17.01%	16.14%	13.37%	18.55%
	Range (R)	0.48%	2.16%	2.21%	1.62%	0.29%	5.56%	5.87%

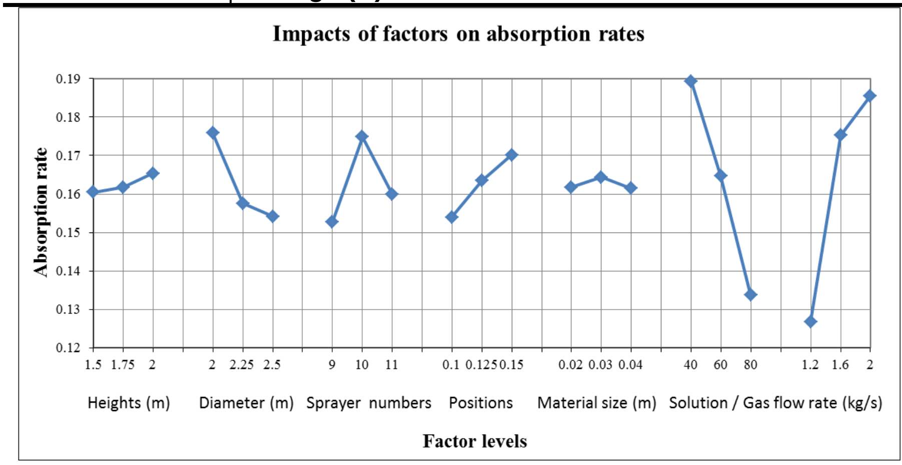

Figure 5 Impacts of factor levels on absorption rates

4.4 (b) Comparison between analysis and optimal case

After the significance of different factors is derived, the optimal levels for every factor are also obtained from the results in last section. Therefore another optimal case based on analysis can be derived and presented in Table 6. This analysis optimal case is compared with simulation optimal case derived in last section.

Table 6 Comparisons of simulated and analysis optimal cases

Cases	*H(m)*	*D (m)*	S_n	S_p*(m)*	*d (m)*	m_s *(kg/s)*	m_g *(kg/s)*
From analysis	2	2	10	0.15	0.03	40	2
Optimal case	1.5	2.5	10	0.125	0.02	40	2

From Table 6, levels of some factors are exactly the same in both cases and some are a little bit different. Considering the significance of these factors, gas and solution flow rate and sprayer numbers are three most effective factors that could impact on absorption rate. In this table, these three factors are the same. Since these three factors could mostly impact the absorption rate, it is reasonable to ignore the effect of other factors so that these two optimal cases from simulation and analysis have a good agreement. Therefore, the design of practical system for case ship is feasible and reliable. As long as the absorption system is designed, the following parts of the system can be designed in turn. Next section will give some detail information about the design of whole system for a selected case ship.

5. CASE SHIP STUDY

5.1 CASE SHIP SPECIFICATION AND MODELLING

Before designing the dimensions of different tanks, the modelling of selected container ship is conducted first. The selected ship is a 6300 TEU (twenty-foot equivalent unit) class container carrier, Sealand Michigan, from Hyundai. The details of this vessel and the engine specification are listed in Table 7 and Table 8 respectively.

Table 7 Container ship details

LOA	*303.96*	*m*
LBP	292.00	m
Breadth	40	m
Depth	24.2	m
Draught	12	m
Voyage duration	16	days
Shipping capacity	6300	TEU

Table 8 Main engine specification

Engine type	*B&M 10K98MC-C*	
MCR	57059	kW
SFOC	171	g/kWh
Fuel carbon factor	3.021	

According to the drawing provided by Hyundai, the CAD model of this containership is established and presented in Figure 6 and Figure 7. The red and light blue parts present the ship hull below and above the water line. The pink part is the superstructure and the dark blue part is the funnel. The grey sections in Figure 7 are carried containers on ship. In next section, all the tanks will be designed and positioned on this CAD model.

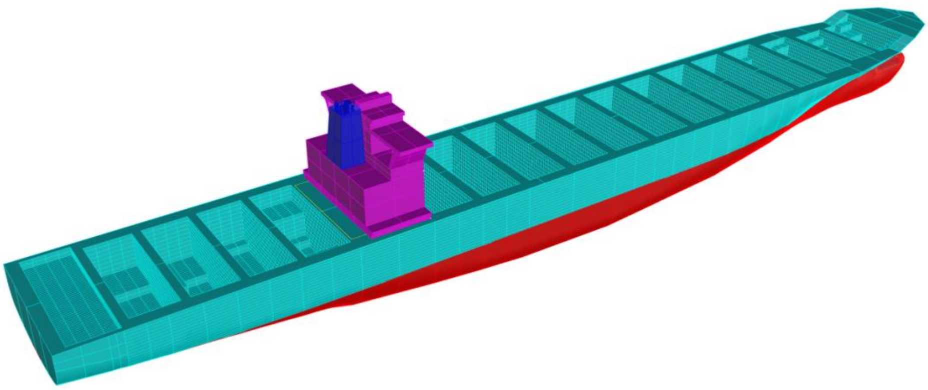

Figure 6 CAD model of the selected containership: empty load case.

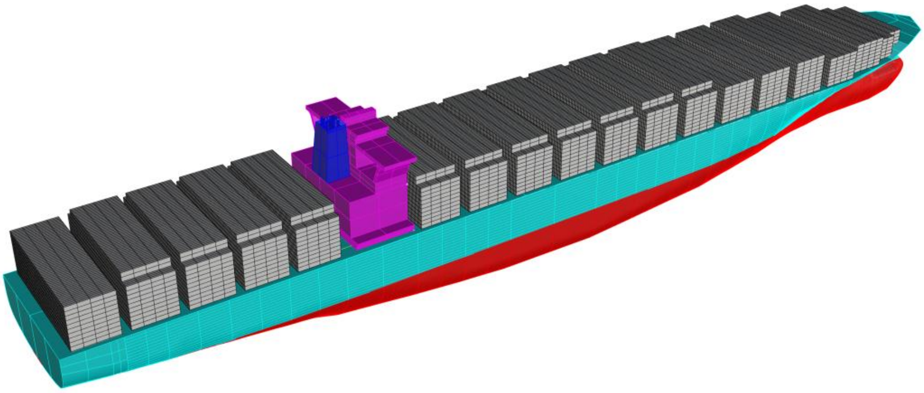

Figure 7 CAD model of the selected containership full load case.

5.2 System design, position and drawing

- Absorption tanks:

The dimension of absorption tanks is fixed based on the simulation and analysis results. The volume taken by the absorption tank is only about 0.2 container volumes. To make sure the there is enough place for pipelines, blowers and pumps, 1 container volume is distributed to absorption tanks. The position of these tanks should be near the main engine and the funnel so that exhaust gas could be by-passed from them and the power required for transportation is low.

- Precipitation tank:

Precipitation tank is aiming to deal with the product from absorption hourly so that the volume taken by precipitation tank is larger than that from absorption process. To ensure the volume is enough for precipitation process, a 20% margin is added and the final volume of this tank is 302.54 m^3. Hence 10 times of container volume is assigned to each precipitation tank. The total container volume required by precipitation tanks are 20 container volumes. The location of this tank should be next to the absorption tank because the precipitation process deals with the product from absorption process.

- Centrifugation separation:

Centrifugation separation system has a fixed dimension and the data are derived from manufacture. It takes about 0.7 time of container volume for two sets of systems. Hence, 1 container volume will be designed considering the fitting to systems to precipitation tank and $CaCO_3$ storage tanks. Since centrifugation separation systems are fitted with these tanks, it is cost-effective to locate them near each other.

- NaOH, CaO and $CaCO_3$ storage tanks:

If NaOH, CaO and $CaCO_3$ are designed to be stored in containers, the limitation of the containers should be considered. Since the net weight of a container is limited, the numbers of containers required as NaOH, CaO and $CaCO_3$ storage tanks can be derived. It is about 57 containers for NaOH, 134 for CaO and 239 for $CaCO_3$. It is about 7.02% of the total cargos in this container ship. To reduce the containers occupied by these storage tanks, a modified tank is designed. The weight limitation of containers is significant because the working load of cranes for container loading and unloading is limited. Therefore, considering the working load of crane, a new container can be designed with acceptable weight and volume.

The cranes usually have a working load of 24 ton which is also the weight limitation of standard containers. The maximum weight of a new designed container with full load should be 24 ton. The tare weight of a standard 20 foot container is 2.44 ton so the cargo in the container is 21.56 ton. 21.56 ton of NaOH has a volume of 10.12m^3. Same weight of CaO has a volume of 6.43 m^3 and that of $CaCO_3$ take 7.95 m^3. They are all less than one third of a container inside volume. To keep the original arrangement of containers on ship, several new containers should share one slot of a standard container. Hence the new container will be designed to have 1/3 volume of a standard container. It is selected also considering the thickness of the container wall. In this way, not only the volume on ship is saved with no change on container arrangement but also the weight of new container still meets the requirement of crane working load.

Since the total weight of CaO and $CaCO_3$ is related to operation time, the total weight reaches the maximum at the voyage destination. Therefore, although the total weight of NaOH, CaO and $CaCO_3$ are 9239.56 ton, the instant weight is increasing from 4096.63 ton to 6358.40 ton. It is because the consumed NaOH and CaO are finally contained in $CaCO_3$. The locations of NaOH storage tanks are above absorption reaction tank. The locations of these containers with CaO and $CaCO_3$ are at the bottom of each container hold on the container ship. With this arrangement of storage tanks, their weights are distributed along the ship so that the risk of overload in one section of ship hull is eliminated.

Considering the dimensions of all tanks and assigned containers, a CAD drawing is derived. In Figure 8, 385 designed containers for CaO and $CaCO_3$ are assigned to 18 container holds which will have 21.39 containers in every hold. A 10% margin is added so 23.53 containers are required and 24 are assigned in every hold.

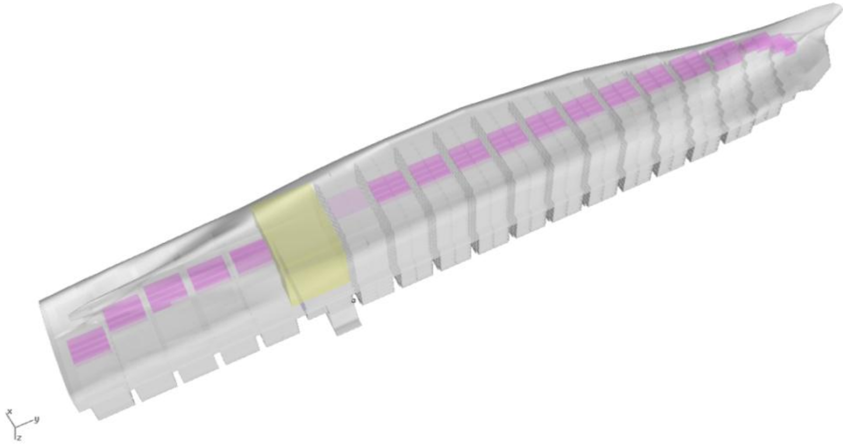

Figure 8 Storage tanks installation of carbon solidification system on container ship.

Figure 9 presents the location of all tanks with systems before the process. These systems include a separation system for removing CO_2 from exhaust gas and a pipeline which transports the purified CO_2 in to absorption reaction tank. The separation system is in light blue colour. The pipeline is in dark blue. The container in green is the absorption reaction tanks and the orange ones are the precipitation tanks. The red one is the centrifuge separation system. The yellow compartment is the engine room and the pink one is the superstructure. All the grey compartments with grids are containers.

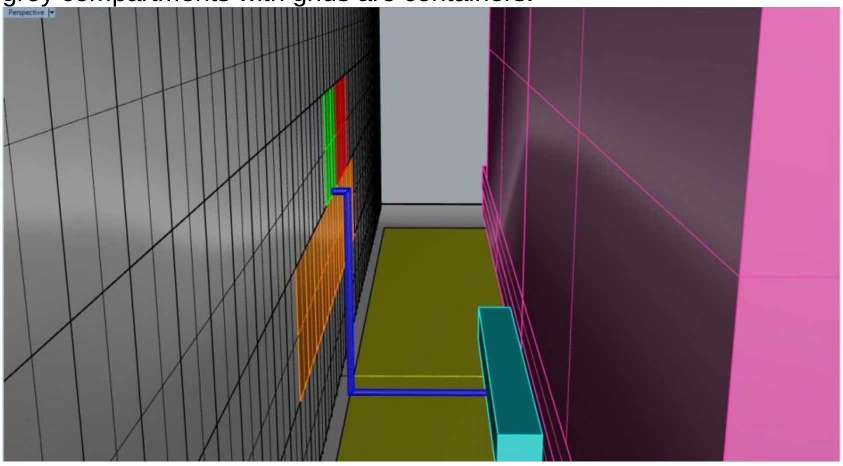

Figure 9 CAD drawing of carbon absorption and solidification system.

6. CONCLUSIONS

This paper introduces and presents a case study of carbon solidification system design and application on a selected ship, based on previous works of CFD simulation on lab-scale experiment. The simulation processes apply the CFD model in previous simulation processes for experiment. A physical model of absorption reaction tank is designed according to the limitations on ship board and also analysed using orthogonal design method. After simulation and analysis, a simulation optimal case and an analysis optimal case are obtained. The analysis optimal case is eventually selected. This model occupies fewer volumes than simulation optimal model and the levels of significant factors are kept the same. Based on the output from the physical absorption tank model, the tanks and systems in following processes can be derived. Then the case ship is selected and modelled with CAD software and the positions of all the tanks and systems are designed and presented on a CAD drawing.

This paper is a good guideline for practical design, analysis and installation of carbon solidification system. However, further works are still required. Time required for precipitation may need further consideration. Future works can also target on designing the fittings between all tanks and the systems before absorption reaction process, like gas blower and CO_2 separator.

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