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Feasibility study on carbon capture system of LNG-fueled ship-based on comprehensive utilization of heat and cold energy

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Abstract: This study proposed an onboard carbon capture system for a LNG-fueled ship. The design target of the OCCS is to meet the Energy Efficiency Design Index (EEDI) in phase 3. Under this context, an absorption-type OCCS is selected with exhaust gas waste heat and LNG cryogenic cold energy recovery. The CO_2 contained in the exhaust gas is captured and then liquified by the cryogenic cold energy released during LNG regasification. The effects of exhaust gas mass flow rate, the solvent mass flow rate and regeneration temperature on the OCCS performances are investigated. The results demonstrate that the specific heat consumption of the CO_2 capture varies in the range of 10.9~12.2 GJ/tCO_2. The feasibility of the OCCS to satisfy the IMO regulation required EEDI in phase 3 is validated.

Keywords: LNG-fueled bulk carrier; Carbon capture system; EEDI; Waste heat; LNG cold energy

1. Introduction

To be able to achieve the Paris climate agreement goal, the International Maritime Organization (IMO) has called for 50% decarbonization of the shipping industry from 2008 levels by the end of 2050, which means approximately an 85% reduction of CO_2 for each ship. Liquefied Natural Gas (LNG) is regarded as the most potential fuel for international shipping. Compared with heavy oil, LNG can reduce SOx by 90%, NOx by 80%, CO_2 by 20%, and particulate matter by 100%(S Lion et al., 2020). With the improvement of global refueling vessel layout and the development of dual-fuel engines, LNG-fueled ships have developed to large ocean vessels. According to Sharples, the number will be doubled by 2026 and will account for 32% of the total ship demand by 2050(J Sharples, 2019). LNG is stored at a cryogenic temperature of -162°C and needs to be regasified before entering the DF engine, which releases about 830 kJ/kg of cold energy(BB Kanbur et al., 2017).

LNG, to some extent, could be treated as clean fuel except for the CO_2 emission. To overcome this shortage, post combustion carbon capture system (CCS) for dealing with the tail gas is mostly recommended. As for the CCS, the alcohol-amine-based absorption method has become the main decarbonization method because of the characteristics of high absorption load, recyclable absorbent and low cost. Inspired by the cryogenic cold energy and waste heat, the feasibility of the onboard carbon capture system (OCCS) attracts attention. With the OCCS, the CO_2 contained by the exhaust gas would be captured and concentrated. For the convenience of storage and transport, the gaseous CO_2 is liquified and transported to the port for commercial utilization.

The research on the alcohol-amine-based absorption OSSC has been widely studied. Seo et al. (Y Seo et al., 2015) developed several CO_2 liquification processes and evaluated the availability of the ship-based CCS from a life cycle cost perspective. Feenstra et al. (M Feenstra et al., 2019) investigated the feasibility of ship-based CCS on a cargo ship. 30 wt% aqueous monoethanolamine (MEA) and 30 wt% aqueous piperazine (PZ) were used as solvents. The carbon capture cost was in the range of 98 to 389 €/tCO_2. Fang et al. (S Fang et al., 2019) proposed an optimal sizing model to determine the capacity of the shipboard CCS. They pointed out that a 6MW OCCS could reduce124 tons CO_2, which was 55.8% of the total shipping GHG emission. Long et al. (NVD Long et al., 2021) developed a system using MEA/PZ and MDEA/PZ as solvents for CO_2 capture, compression and liquefaction onboard a 3000 kW diesel engine. The results demonstrated that CO_2

removal could be up to 1348 kg/h under the optimum configuration. Ros et al. (JA Ros et al., 2022) designed a ship-based CCS considering solvent selection, heat integration and ship movement. The techno-economic analyses showed that the cost of CO_2 capture for the Sleipnir varied within 119-133 €/tCO_2. Einbu et al. (A Einbu et al., 2022) alleged that the waste heat recovered from the engine exhaust gas was not sufficient for the demand of an absorption-based CCS operating 50% capture rate with 30 wt% MEA as solvent. From the literature review, even though the waste heat from the exhaust gas has been widely applied in OCCS, the utilization of cryogenic cold energy released by the LNG regasification process is seldomly reported.

EEDI is an index representing the CO_2 generated from ships for transporting 1 ton of cargo per nautical mile (nm). The MEPC agreed on intensifying the phase 3 EEDI requirements during the 74th meeting. The decarbonization results of the OCCS should be considered in the EEDI calculation and baseline set. Lee et al. (S Lee et al., 2021) designed a chemical absorption-type OCCS with an ammonia refrigeration system for a container ship. The results demonstrated that the carbon capture amount from the exhaust gas could reach the target line of EEDI in phase 3. The main goal of this paper, which clearly shows the novelty as well, is to introduce the LNG cold energy utilization for OCCS. This study aims to explore the feasibility of MEDA/PZ absorption-based OCCS in satisfying the IMO regulation for EEDI in phase 3 for a LNG-fueled ship.

2. EEDI analysis method

2.1 Reference EEDI and phases

EEDI is not a performance-based but a goal-based technical standard encouraging improvement in the new ship design. From 1 January 2013, an initial 2-year "phase 0" started with the required EEDI. Since then, three phases with more progressive requirements are established to reach 30% reduction between 2025 to 2030. The EEDI reference line represents the average efficiency for ships built between the years 1999 and 2009, which is determined by the ship type and size. The EEDI regression equation for Bulk carrier is described as Eq. (1). The Required EEDI is calculated with the reduction factor *X* in different phases, as shown in Eq. (2).

$$Reference\ EEDI = 961.79 \times DWT^{-0.477} \quad \text{for Bulk carrier} \tag{1}$$

$$Requireed\ \ EEDI = (1 - X/100) \times 961.79 \times DWT^{-0.477} \tag{2}$$

2.2 Attained EEDI calculation for bulk carrier

According to Chapter 4 of Annex 6 in the International Convention for the Prevention of Marine Pollution from Ships (MARPOL) guideline, the attained EEDI of international sailing ships with a gross tonnage of 400 tons should be estimated. The attained EEDI should be calculated with the technical guidelines and verified by the recognized official organizations during the ship building process. The attained EEDI calculation formula provided by IMO is shown in Eq. (3).

$$EEDI\left(gCO_2/ton.nm\right) = \frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}\right) + PTI + EFF}{f \cdot Capacity \cdot V_{ref}} \tag{3}$$

2.3 Reference ship

To effectively predict the effect of the EEDI baseline on the design of future bulk carrier, a typical Kamsarmax ship with a dual-fuel main engine (Wärtsilä 12V50DF) is selected as the reference ship. The specifications of the reference ship are listed in Table 1. The compositions of the exhaust gas obtained from the main engine are Nitrogen 75 wt %, Oxygen 16.6wt%, Water 4wt% and CO_2 4.4wt%. Considering the energy balance, only part of the exhaust gas passed through the OCCS, while the rest was discharged to the environment. The LNG fuel is stored in the tank with the cryogenic temperature of -162℃ at 100kPa. The required inlet temperature and pressure of the main engine are 60℃ and 600kPa. The exhaust gas data and LNG data for the Wärtsilä 12V50DF are given in Table 2.

Table 1 Main specifications of the reference ship

Parameter	Value	Parameter	Value
Type	Bulk	LNG tank	600 m^3
Ship length overall	229 m	Heavy oil tank	1800 m^3

Ship beam	32 m	Marine diesel oil tank	400 m^3
Deadweight	81190 DWT	Main engine type	Wärtsilä 12V50DF
Reference speed	14 knots	MCR rating of main engine	9930 kW

Table 2 Exhaust gas and LNG data for Wärtsilä 12V50DF

Exhaust gas	Engine load			LNG	Engine load		
	100%	75%	50%		100%	75%	50%
Mass flow rate (kgh^{-1})	68400	52560	41040	Mass flow rate (kgh^{-1})	2196	1728	1260
CO_2 concentration (%)	4.8	4.6	4.2	Cold energy (kW)	602.4	474	345.6
CO_2 production (kgh^{-1})	3283.2	2417.8	1723.7	Available cold ($kWhkg^{-1}$)	0.18	0.19	0.20
Inlet temperature (℃)	383	303	285				
Outlet temperature (℃)	120	120	120				
Heat energy (kW)	3106.3	2679.8	1886.6				
Available heat ($kWhkg^{-1}$)	0.95	1.11	1.09				

This study uses Ψ to reflect the captured CO_2 via the OCCS. Thus, ψ could be calculated from Eq. (4). The proposed factor ψ provides suitable criteria for OCCS design. The required EEDI, attained EEDI and the CO_2 captured by OCCS are summarized in Table 3.

$$Required\ EEDI\left(gCO_2/ton.nm\right) = Attained\ EEDI - \frac{\Psi/1000}{f \cdot Capacity \cdot V_{ref}} \tag{4}$$

Table 3 Attained EEDI and required EEDI for the reference ship.

	Phase 0	Phase 1	Phase 2	Phase 3
Attained EEDI ($gCO_2(tn\cdot m)^{-1}$)	3.61			
Required EEDI ($gCO_2(tn\cdot m)^{-1}$)	4.38	3.94	3.51	3.07
Ψ (kgh^{-1})	---	---	113.7	613.8

3. Modelling and simulation

3.1 Overall concept design of the OCCS

The OCCS aims at capturing CO_2 from the engine exhaust gas of the LNG-fueled ship. The captured CO_2 is compressed and liquified before being stored in the tank. The liquified CO_2 would be further transported to a chemical plant for utilization or to an underground injection site for permanent storage. The content of CO_2 in the exhaust gas of diesel or LNG is usually no more than 5 vol%. Therefore, CO_2 separation from the exhaust gas and concentration improvement is the first step for further treatment. CO_2 separation and capture need significant energy input. Ideally, the waste heat from the ship engine exhaust gas should be considered. The electricity consumed by the compressor comes from the ship as well. Compared with the waste heat, the applicable cold energy is much smaller. Therefore, the capacity of OCCS is limited by the cold source conditions. As for the CO_2 liquification process, the cryogenic temperature is required. Considering the temperature range, the LNG cold energy is used for the concentrated CO_2 cooling and liquification. The supplementary cold energy is provided by the seawater. Figure 1 illustrates the block diagram of the overall concept design of the OCCS.

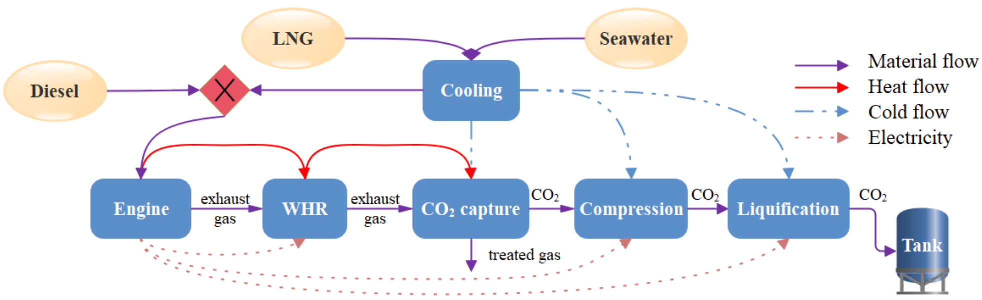

Figure 1 The block diagram of the overall concept design of the OCCS.

3.2 Simulation basis

Aspen HYSYS V12 software is utilized to simulate the carbon capture process. The Acid Gas thermal property package and Peng-Robinson equation are applied for equilibrium calculation and kinetic reactions. The isentropic efficiencies of the compressor and the pump are assumed as 85% and 75%, respectively. The main design and operating parameters for the OCCS are shown in Table 4.

Table 4 Design and operating parameters for the OCCS

Main equipment	Value
Absorber	float valve tower; trays number :10; diameter: 1.372m; tray space: 0.6096m; weir height: 0.05m; calculation method: Murphree's efficiency; lean solvent flow rate: $16000kgh^{-1}$; inlet temperature: 30°C; inlet pressure: 450kPa; upper pressure: 190kPa; lower pressure: 200kPa
Stripper	float valve tower; trays number :10; diameter: 1.5m; tray space: 0.6096m; weir height: 0.05m; calculation method: Murphree's efficiency; lean solvent inlet temperature: 80°C; inlet pressure: 300kPa; upper pressure: 150kPa; lower pressure: 200kPa; reflux ratio: 10
Internal heat exchanger	shell-tube type
Pumps	lean pump: from 190 to 300kPa and isentropic efficiency of 75% rich pump: from 200 to 450kPa and isentropic efficiency of 75%
Compressor	from 150 to 1500kPa, isentropic efficiency of 75%, outlet temperature is cooled to 60°C
HEX	shell-tube type; HEX1 hot side: from 60 to 30°C and pressure drop is 0kPa; HEX2 outlet temperature 60°C and pressure drop is 0kPa
Cooler	shell-tube type; coolant: water

The exhaust gas from the main engine passes through the absorption column and only CO_2 is absorbed. The treated gas is vented to the air, and the solvent becomes rich solvent. The rich solvent is pumped to the stripper column for regeneration. Before the stripper column, the rich solvent recovers heat from the lean solvent, which returns from the bottom of the re-boiler. After which, the working medium is supplemented to the original composition. The lean solvent is returned to the absorption column. The CO_2 is discharged in the gaseous state from the column upper. For the convenience of storage and transportation, the separated CO_2 is liquified. Instead of using the complex multi-stage compression process, the cryogenic cold energy released by the LNG regasification process is utilized. The CO_2 storage pressure influences the density and boiling point, which would affect the energy supplied to the OCCS.

The methyldiethanolamine (MDEA) is regarded as the ideal solvent for CCS because of its high CO_2 solubility, acceptable reaction kinetics and friendly cost. After the 1980s, MDEA was widely used in CO_2 absorption process. German BASF company added different activators (such as piperazine, butylamine, imidazole or methyl imidazole, etc.) to the MDEA solvent and successfully developed activation methods for MDEA. MDEA acts as both an electrolyte and a mixed solvent system, so both chemical absorption and physical absorption occur at the same time. MDEA does not react with CO_2 directly but catalyzes the hydrolysis of CO_2. In this study, to improve reaction rate and reduce column height, the MDEA with PZ as the activator is used as the working medium for CO_2 capture. The activated solvent is with the solubility of 22 wt% MDEA and 8 wt% PZ.

3.3 System performance

An important factor is the carbon capture rate that can be attained with the OCCS. The carbon capture rate heavily depends on the available heat provided by the exhaust gas and the cold energy supplied by the LNG regasification process. The OCCS is designed to be able to deal with the full engine load. The heating capacity required for OCCS (GJ/tCO_2) is evaluated via:

$$\varepsilon_{heat} = \frac{3.6Q_{stripper}}{m_{CO2,ca}} \tag{5}$$

4. Results and discussion

The study of the main parameter influencing the capacity of the OCCS focus on the exhaust gas mass flow rate, the lean solvent inlet temperature and mass flow rate at the absorber inlet. The effect of lean solvent temperature at the absorber inlet on the CO_2 capture and required energy capacity is demonstrated in Figure 2. At the fixed mass flow rate of exhaust gas and solvent, the total required heat amount (Q_{reg}) is decreased from 1916.4 to 1813.9 kW when the lean solvent temperature increases from 20 to 60°C. The captured CO_2 amount ($m_{CO2,ca}$) satisfies the reduction in phase 3 even though it slightly decreases as the column shows. The specific heat consumption (ε_{heat}) decreases from 10.9 to 10.5 GJ/tCO_2. Therefore, the lean solvent temperature at the absorber inlet should be maintained at a relatively higher value. The other limitation of the solvent temperature is the desorb temperature in the stripper. Meanwhile, the higher temperature requires more insulation on the facilities and tubes, which also increases the initial investment and maintenance charge.

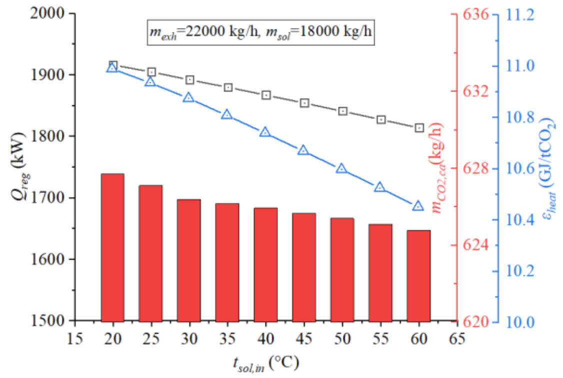

Figure 2 CO_2 capture and required energy capacity

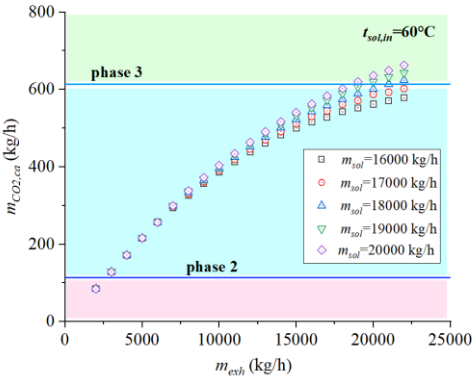

Figure 3 Variation of captured CO_2 mass flow rate

The variation of captured CO_2 mass flow rate with the exhaust gas and solvent mass flow rate is illustrated in Figure 3. The required CO_2 reduction to meet the requirement of phase 2 and phase 3 is also marked. As can be seen, the capture CO_2 obviously increases with the increase of exhaust gas, which proves the capacity of the designed OCCS. However, the increase rate decreases. In addition, increasing the solvent mass flow rate could increase the CO_2 capture amount, and the deviation becomes more pronounced. It concludes that when the solvent mass flow rate is lower than 18000 kg/h, the OCCS could not meet the CO_2 reduction in phase 3.

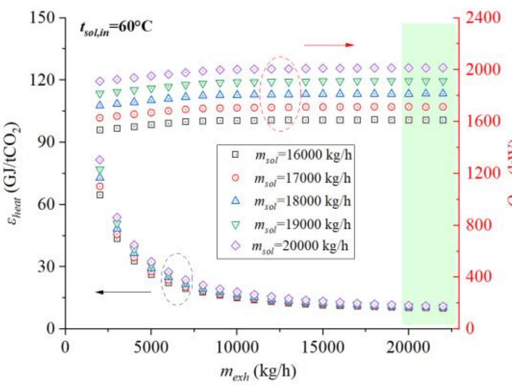

Figure 4 Heat consumption of OCCS

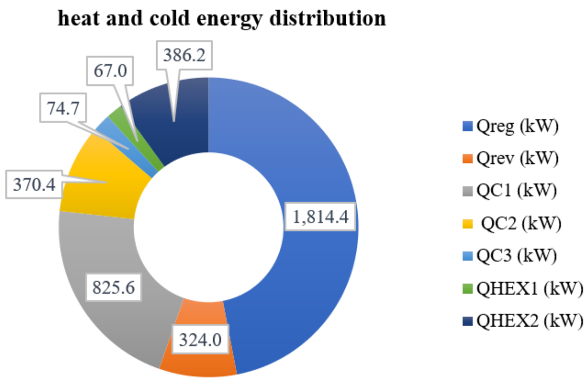

Figure 5 Energy distribution of the optimum condition

The results of heat consumption of OCCS are demonstrated in Figure 4. The total required heat amount (Q_{reg}) varies in the range of 1547.3~2102.7 kW. With the increase of exhaust gas mass flow rate, the amount of CO_2 is accordingly increased, and the total heat consumption by the stripper is slightly increased. At the fixed exhaust mass flow rate, the larger the solvent mass flow rate, the larger the heat amount would be. The total heat consumption determines the facility volume and installation space. At the same time, the specific heat consumption per unit ton CO_2 (ε_{heat}) represents the energy efficiency of the OCCS. The specific heat consumption declines sharply and leveled off gradually with the increasing of exhaust gas mass flow rate. In the region meeting the requirement of CO_2 reduction in phase 3, the specific heat consumption varies in the range of 10.9~12.2 GJ/tCO_2. The smallest specific heat consumption is obtained with the exhaust gas mass flow rate of 22000 kg/h and the solvent mass flow rate of 18000 kg/h. Thus, the optimum working condition is verified. Under the optimum working condition, the mass flow rate of the captured CO_2 is 625.6 kg/h.

Figure 5 shows the heat and cold energy distribution of the optimum condition. The total heat required is 1892.7 kW, which is afforded by the exhaust gas heat recovery. The cooling capacity is supplied by the LNG cold energy and seawater. The recovery cold energy is 453.2 kW and the cooling capacity offered by the seawater is 1853.4 kW. Meanwhile, it is noticed that the cooling capacity for CO_2 capture is 1778.5 kW and that is 528.1 kW for CO_2 liquification. Under the optimum working condition, the MEDA, PZ and water supplement mass flow rates are 1.2, 1.1 and 1140.9 kg/h, respectively.

5. Conclusion

This study proposed an onboard carbon capture system (OCCS) with the integration of exhaust gas waste heat and LNG cryogenic energy recovery for a LNG-fueled bulk carrier. The solvent-based OCCS is designed with the ship constraints and the onboard feasibility is validated. The 22%wt MEAD solvent with 8%wt PZ as the activator is used as the working medium for CO_2 capture. The LNG cryogenic energy is used for CO_2 liquification. The effect of the OCCS on promoting greenhouse gas emission control is evaluated with the energy efficiency design index (EEDI). The effects of exhaust gas mass flow rate, the solvent mass flow rate and the regeneration temperature on the OCCS performances are studied. With the OCCS, the LNG-fueled bulk carrier could satisfy the required EEDI in phase 3 with the specific heat consumption varies in the range of 10.9~12.2 GJ/tCO_2. The possibility of using OCCS to meet the IMO strategy required EEDI is validated for the reference ship. Future studies could be focused on OCCS optimization and economic analysis, which would further promote its practical application. Other types of ships should be taken into consideration as well. The results would provide guidelines for the EEDI reference set.

Acknowledgements

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