



Improvement of marine carbon capture onboard diesel fueled ships

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ABSTRACT

There is an urgent need to reduce the CO₂ emissions from global shipping. This study developed efficient sea-based CO₂ capture, CO₂ compression and liquefaction for a 3000 kW diesel engine. Several mixed solvents, an intercooler and multiple feeds are used to improve CO₂ removal in the absorber. A square-shape is adopted to reduce space, which is in scarce supply in marine applications. Heat integration is applied to enhance the performance of the stripper. An effective configuration is developed for marine CO₂ capture to improve the absorber, stripper, CO₂ compression and liquefaction. Mono-ethanolamine/piperazine (MEA/PZ) and N-methyldiethanolamine (MDEA)/PZ increases by 1.7% and 2.8% in terms of CO₂ removal compared to the MEA solution, respectively. The MDEA/PZ process with the intercooler and MDEA/PZ process with multiple feeds achieve 90.6% and 90.5% CO₂ removal, respectively. The configuration using MDEA/PZ as a solvent, and the combined use of the intercooler, multiple feeds and heat integration demonstrate advantages for ship-based carbon capture. The CO₂ removal for the final configuration is 1348 kg/h (94.7%); this is an 8.4% increase compared to the base case. Additionally savings of 100.0%, 18.3%, and 4.0% are achieved in terms of stripper duty, compressor duty in CO₂ compression and CO₂ liquefaction, respectively.

1. Introduction

Global warming and climate change have been caused by anthropogenic carbon dioxide (CO₂) emissions, resulting in increased average global temperatures [1,2]. Emissions from marine transport contribute significantly to current CO₂ emissions of around a billion tons a year, representing 3% of total global emissions [3]. These emissions are also predicted to rise to between two and three billion tons by 2050, so there is an urgent need for global greenhouse gas reduction schemes.

There are several pathways in which to enhance thermal efficiency and decrease the CO₂ emissions of ships such that they comply with environmental protections [4]. These include the optimal design of the propulsion system [5,6], substitution with cleaner fuels [7,8], improvement of thermal efficiency through waste heat recovery [9,10], and carbon capture and storage (CCS) [11]. Whilst zero-emissions technologies such as hydrogen as fuel continue to be developed and implemented,

CCS may be considered an interim, short term solution to lower CO₂ emissions [12,13]. A group of shipping companies have teamed up to develop an onboard CCS solution [12] to meet the International Maritime Organization's 2050 target of a 50% reduction in CO₂ emissions compared to 2008 levels.

To date, there is little research on CO₂ capture in the maritime context. Luo and Wang [4] explored how to apply a solvent-based carbon capture process to capture CO₂ from the energy system in a typical cargo ship. Feenstra et al. [13] evaluated the feasibility of adapting post-combustion CO₂ capture technology for maritime use (herein referred as ship-based carbon capture), using 30% wt. aqueous solution of mono-ethanolamine (MEA) or 30% wt. aqueous piperazine (PZ). Ammonia (NH₃) was used as the solvent for the ship-based carbon capture of liquefied natural gas (LNG)-fueled CO₂ carriers [14]. The captured CO₂ in these studies was reduced the temperature and liquefied for storage purposes. It has been postulated that CO₂ and other greenhouse

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gases (GHGs) in the exhaust from ships are captured on board in a cryogenic process, and converted to dry ice [12]. For the 'Hydrogen-economy' future, it is anticipated that the containerized liquefied CO₂ will be a valuable feedstock to produce synthetic carbon fuels. This is possible when large quantities of hydrogen (H₂) are produced using solar or (excessive) wind-energy, synthetic fuels may be generated from H₂ and CO₂, such as methane (CH₄) or methanol (CH₃OH) [15].

Various solutions were proposed to address some of the drawbacks of land-based carbon capture processes including low vapor loading capacity, high energy consumption during solvent regeneration, large equipment size, high equipment corrosion rate, and solvent degradation [1,16–18]. The process modification technologies include replacing solvents such as amino acid solvents [18] or sodium/potassium carbonate solutions [19], optimizing operating temperature and pressure conditions [20], replacing the internals of a column with a high-performance internals [1], adding an intercooler [21], interheater [17], and a flue gas pre-cooler [22], and using flue gas compression and expansion [23], multiple feeds [24], semi-lean solvent configurations [24], rich solvent recycling schemes [25], and square columns [26]. Technologies in process integration, such as heat pump [27], self-heat recuperation technologies [1] may also be considered. Process intensification techniques, which can be considered to a substantially smaller, cleaner, safer, and more energy-efficient technology, such as reactive absorption [28], swirling gas flow [16], and a rotating packed bed [29] are solutions that show promise in terms of reducing operational costs.

This study develops efficient sea-based CO₂ capture, CO₂ compression and liquefaction for CCS applicable to a 3000 kW diesel engine. Several mixed solvents were tested to improve the performance of CO₂ removal in the reactive absorption, which is one of process intensification techniques. Solutions using an intercooler and/or multiple feeds were utilized to improve the performance of the absorber, whilst the square-shape was used to reduce space; the latter is necessary for marine applications. Heat integration was applied to enhance the performance of the stripper. Finally, an effective configuration based on improving the absorber, stripper, CO₂ compression and liquefaction, was proposed for marine CO₂ capture. The proposed configuration was compared against the base case, and analyzed in terms of total investment cost (TIC), total operating cost (TOC), total annual cost (TAC) and total annual CO₂ emissions (TAE).

2. Base case

Feenstra et al. [13] developed a carbon capture process for the 3000 kW cargo vessel using LNG as fuel. This study developed a base case

adopting the same conditions, with the exception of diesel fuel being used. When diesel was used to run the engine, more flue gas was generated compared to the engine using LNG. At 100% load, the exhaust gas flow rate was 5.5 kg/s or 19 800 kg/h with a CO₂ molar concentration of 4.8%. Note that the temperature following the turbocharger at 100% load was 381 °C. The process included the CO₂ capture, CO₂ compression and CO₂ liquefaction units. All simulations in the CO₂ capture unit were developed using the Aspen Hysys™ V10.0 software with the Acid Gas package. For the CO₂ compression and liquefaction units, the Soave-Redlich-Kwong (SRK) equation of state was employed [30].

2.1. CO₂ capture

The process with aqueous MEA scrubbing is one of the most promising and well-proven technologies to reduce CO₂ emissions [31–33]. Fig. 1 shows that flue gas from the boiler comes into contact with the solvent in the absorber [13]. To compensate the pressure drop in the absorber, a blower can be considered [34]. The base case of CO₂ capture uses 30% wt. MEA as the solvent [13] with a liquid to gas (L/G) ratio of 2.5; the CO₂ wt% from the stripper was 99%. Under these operating conditions, the CO₂ removal was 87.4%. Columns were designed to withstand motion; this means limiting the column height and column diameter, and having a low pressure drop, making the packed-type column designs more suitable than the tray designs [35–36]. In this study, the absorber and stripper were packed with structured packing Mellapak 250X.

2.2. CO₂ compression and liquefaction

The storage of the captured CO₂ should be in liquid phase because this phase is the most energy-efficient condition [4,13]. The liquefied CO₂ storage conditions on a cargo vessel were -16 °C and 22 bar [13]. To generate CO₂ liquid, the process employed a multistage compression followed by condensation. To design of a refrigeration cycle, the selection of an appropriate working fluid was an important task [37–38]. Under the operating conditions, NH₃ was selected as the fluid for the refrigeration cycle. Three design variables including the pressure of the inlet and outlet streams of the compressor, and the working fluid flow rate were adjusted to satisfy the minimum temperature approach of 10 °C in each heat exchanger of the system and the superheating of 3 °C and subcooling of 2 °C [38–39]. Fig. 2 shows simplified flow sheet illustrating ship-based carbon compression and liquefaction.

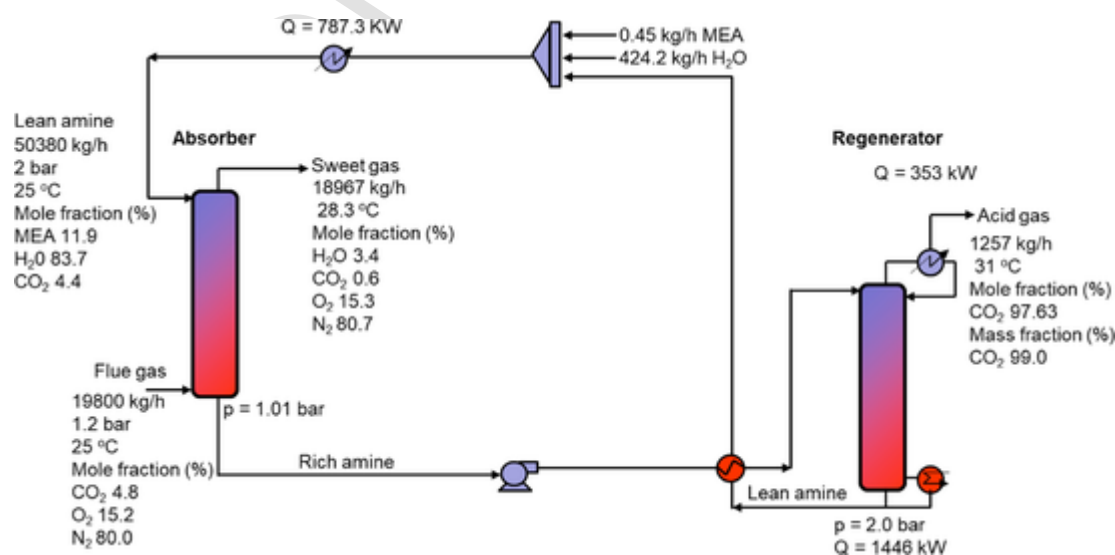


Fig. 1. Simplified flow sheet illustrating the ship-based carbon capture.

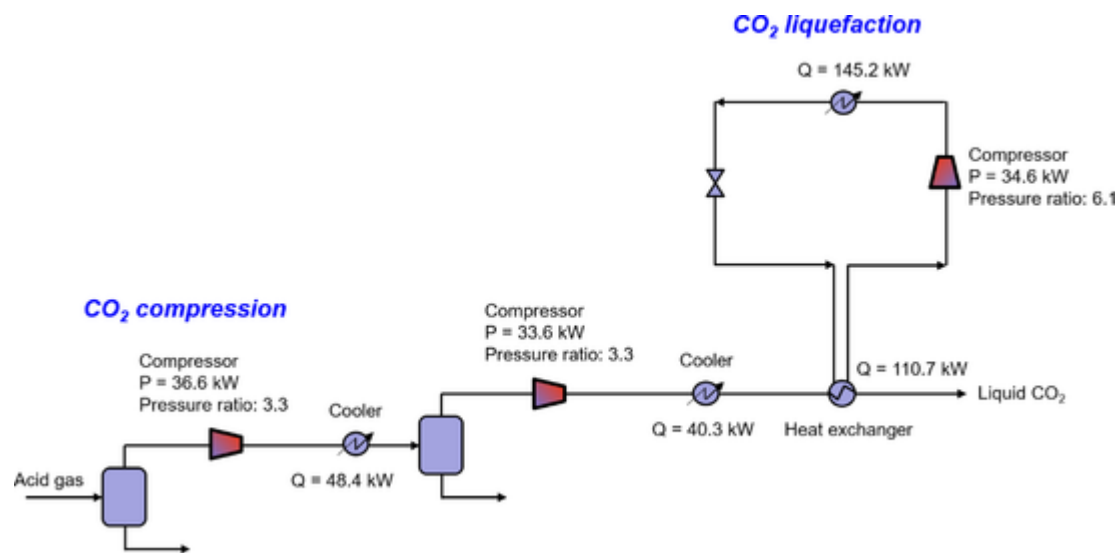


Fig. 2. Simplified flow sheet illustrating ship-based carbon compression and liquefaction.

Note that CO₂ emissions also occur during the CO₂ capture process as this process utilizes energy. Specifically, CO₂ capture processes use steam to run the stripper and electricity to run compressors in the compression and liquefaction sections. The TAE was estimated using the modular method from [40] to assess environmental impact. The results show that to capture 1244 kg/h of CO₂, there is a CO₂ release of 418 kg/h; this is equivalent to 33.6%. This highlights the need to develop a CO₂ capture process that can capture a greater quantity of CO₂ and emit a much lower quantity of CO₂ (or use less energy).

3. Process improvement

3.1. Absorber improvement

3.1.1. Solvent replacement

The solvent used in the CO₂ capture is an important parameter, which directly affects the efficiency and overall cost of the process [41]. To date, MEA is still commonly used as the benchmark to compare CO₂ capture performance [42] as MEA possesses a reasonable reaction rate and absorption capacity. However, MEA is disadvantageous due to its high energy requirement (for reverse reaction-desorption), high corrosivity, toxicity and susceptibility to degradation through reactions with other chemical species [43]. Another major disadvantage of MEA is the need for a much better absorption capacity [41].

PZ is a di-amine that has previously been investigated as a promoter for amine systems to improve kinetics due to its rapid kinetics and low degradation rates [42,44]. As such, it had been used to improve the process performance using only MEA as the solvent. The results indicated that the use of MEA/PZ increased CO₂ removal from 87.4% to 88.9%, compared to a process that only used MEA (shown in Table 1).

Furthermore, the methyl-diethanolamine/PZ (MDEA/PZ) solvent blend has been investigated as an effective alternative for CO₂ capture [45–47]. MDEA/PZ offers advantages over MEA and MDEA alone, due

to its resistance to thermal and oxidative degradation at typical absorption/stripping conditions [46]. The mixed solvent MDEA/PZ contained a low heat of absorption at high CO₂ loading, rendering a reduced solvent regeneration energy. Based on these advantages, this study used MDEA/PZ for marine CO₂ capture, as it is expected to increase CO₂ removal or reduce the energy consumption of the stripper.

The results show that it is possible to achieve a CO₂ removal of up to 90% with a CO₂ purity of 99% when using the MDEA/PZ mixed solvent where 15% is MDEA and 15% is PZ. This proportion of the MDEA/PZ mixed solvent rendered a 2.8% increase in CO₂ removal compared to a 30% MEA solution. This study focused on adopting and improving the MDEA/PZ solvent in the following sections.

3.1.2. Intercooler

One useful means of enhancing CO₂ removal is the application of an external cooler for the absorber columns [20–21,48–50]. Absorption is an exothermic process, which leads to an overall temperature increase of the solvent. This phenomenon can cause a reduction in the driving force for absorption as well as decrease the absorption capacity of the solvent system. The absorption efficiency may be improved by withdrawing a fraction of the solvent in the absorber, and cooling down the solvent prior to returning it to the absorber [17].

The important design parameters for the intercooler design are the location, flowrate and cooling duty [24]. As the temperature in the 10th tray to 12th tray section is highest, the intercooler was installed in that section (Fig. 3a). Seawater was used to cool this stream to 25 °C, and intercooler duty was then used to optimize this (Fig. 3b). Fig. 3b shows that CO₂ removal rapidly increases when the intercooler duty rises from 20 to 40 kW, and slightly elevates when the intercooler duty increases from 40 to 71 kW. Then, CO₂ removal remains stable when the intercooler duty continues to increase thereafter. Based on this relationship, an intercooler duty of 71 kW was adopted in the intercooler design. As shown in Table 1, the use of MDEA/PZ solvent and intercooler raised CO₂ removal from 87.4% to 90.6%, compared to a process that only used MEA.

3.1.3. Multiple feeds

There was only a single feed of solvent fed to the top of the absorber in the base configuration (see Fig. 1). However, the full flow rate of amine was not required in the upper section of the absorber as very little absorption occurred there; the absorption mainly occurs in the bottom section [51]. Thus, the lean amine stream may be split, with most of the amine charged near the bottom of the column [51–52]. The injec-

Table 1
Summary of CO₂ removal performance for various arrangements.

	CO ₂ removal (%)
MEA	87.4
MEA/PZ	88.9
MDEA/PZ	90.0
MDEA/PZ with intercooler	90.6
MDEA/PZ with multiple feeds	90.5
Proposed configuration	94.7

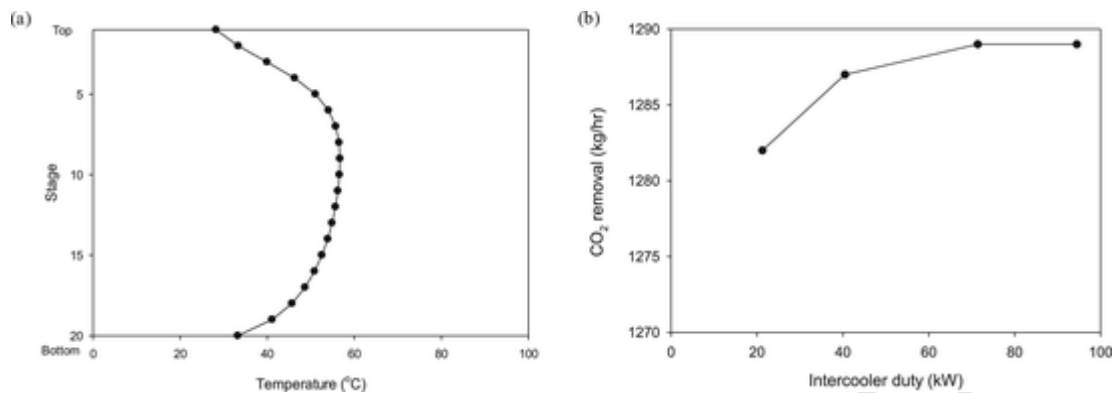


Fig. 3. (a) Temperature profile; (b) influence of intercooler duty on CO₂ removal.

tion of a colder (relative to base configuration), lean solvent in the middle of the absorber prompts a temperature decrease and thermodynamically favors CO₂ absorption in the solution [26,53]. Multi-absorber feeds enable a somewhat higher equilibrium loading [54] and are advantageous for low inlet pressure processes [55].

The maximum CO₂ removal may be achieved at a flow rate of 20 000 kg/h to the top; however, location has a small effect on performance (Fig. 4a). Fig. 4b shows that the 9th tray was selected to achieve the highest CO₂ removal. A process control utilizing multiple feeds was relatively straightforward, and these feed options may prove useful in terms of accommodating a wide range of different acid gas feed compositions [51]. The MDEA/PZ process with the intercooler and the MDEA/PZ process with multiple feeds are able to increase the CO₂ removal by 3.5% compared to the MEA process. However, the MDEA/PZ process with multiple feeds is preferred as the operating cost of the MDEA/PZ process with the intercooler was higher due to cost of pumping seawater.

3.1.4. Using a square absorber

Regarding the shape of the absorber, a cylinder shape is mostly used for small shop assembled and pressurized columns. A square-based shape, which has been widely used for coal boiler flue gas desulphurization systems [56–57], may be considered when the absorber is operated at a low pressure [26]. With a square shape, the field erection and packing installation are simplified [26], and the required space can be reduced. Absorber was sized with a load which is at near 85% of the load at the flooding point to prevent flooding in the columns. As a result, the side of the square shape scrubber (2.3 m) is smaller than the diameter of the cylindrical scrubber (2.6 m).

3.2. Stripper improvement

A large amount of energy used for releasing the CO₂ in the stripper makes this unit an energy intensive process. To enhance the energy recovery efficiently and thoroughly, heat integration was used. In particular, as the temperature of the flue gas after the turbocharger at 100% load is 381 °C, there is extra heat which can be utilized. Furthermore, the simulation indicated that the energy requirement of the re-boiler of the stripper column was 1446 kW. Thus, a heat exchanger was used for heat integration between the hot stream (flue gas) and cold stream (stripper bottom) in order to reduce the hot/cold utilities. The results show that it possible to save 1446 kW in the stripper re-boiler; this amounts to a 100% saving in terms of re-boiler duty.

4. Proposed onboard configuration with improved CO₂ compression and liquefaction

The proposed absorber configuration used MDEA/PZ as the solvent, an intercooler, multiple feeds to improve CO₂ capture, and a square scrubber to save space. It also utilized heat from the flue gas to boil the stripper. Furthermore, the stripper operating pressure was used to reduce compressor duty in the CO₂ compression section. The results show that the final configuration with a higher stripper operating pressure (3 bar instead of 2 bar), was able to achieve a CO₂ removal of 1348 kg/h (94.7%), with an 18.3% saving in terms of compressor duty in the CO₂ compression section.

As the pressure of stripper is higher, the bottom temperature has also increased leading to a reduction in the heat transferred from flue gas (i.e., the savings from the stripper re-boiler duty decreases). Furthermore, the column was more expensive to stand for higher operating pressures; as such, the operating pressure of the stripper was set to 3 bar. Note that in CO₂ liquefaction, the use of a two-stage compressor and intercooler can reduce the power of the compressor. Specifically,

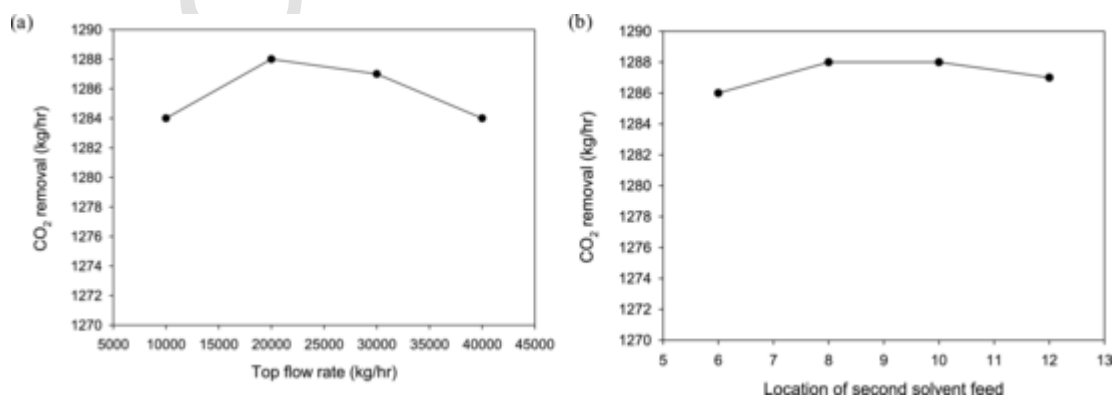


Fig. 4. Influence of the (a) top flow rate; and (b) location of second solvent feed on the CO₂ removal.

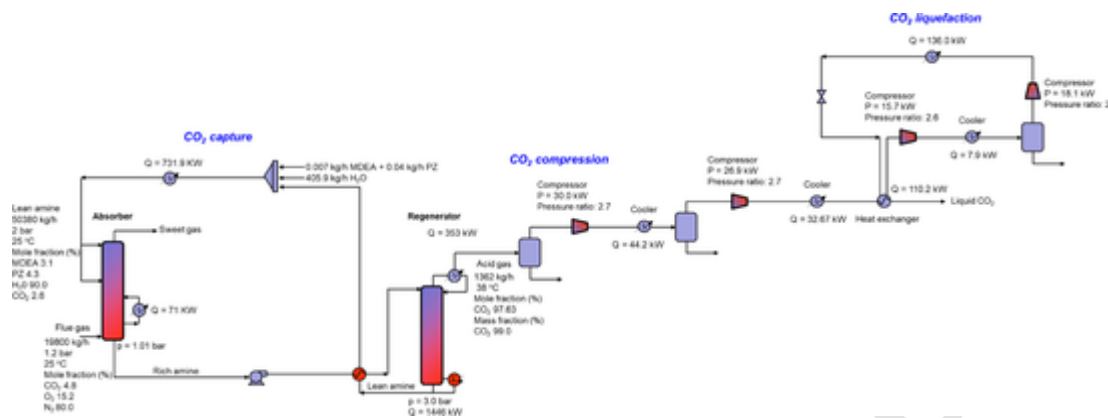


Fig. 5. Simplified flow sheet illustrating the proposed ship-based carbon capture for diesel fueled ships.

the compressor power can reduce by 3.7% (i.e., 35.04 – (15.66 + 18.07) = 1.31 kW).

The investment costs consider all columns, re-boilers, condensers, packing, heat exchangers, coolers, and compressors. The Chemical Engineering Index of 607.5 from 2019 was employed to update the costings. The results indicate that compared to the base case, the proposed configuration (Fig. 5) was able to achieve savings up to 80.3% and 42.1% in terms of the TOC and TAC, respectively. Table 2 shows the utility cost data [58]. Based on the investment cost evaluation, the CO₂ compression and liquefaction for CO₂ storage accounted for approximately one third of the total investment cost of the entire process. The results also demonstrate that the TAE was reduced by up to 85.7%, compared to the base case (shown in Fig. 6). The proposed configuration using MDEA/PZ as the solvent, and the combined use of the intercooler, multiple feeds and heat integration for enhanced performances and the square scrubber to minimize space, proved itself to be an effective solution for ship-based carbon capture.

Table 2
Utilities cost data [58]

Utility	Price (\$/GJ)
Cooling water	0.35
Steam (LP)	6.08
Electricity	16.80

5. Conclusions

This study developed an efficient sea-based CO₂ capture, CO₂ compression and liquefaction process for CCS applicable to a 3000 kW diesel engine. It is demonstrated that it was possible to achieve a CO₂ removal of 87.4% when the L/G was 2.5. Heat released from the flue gas may be used in the stripper re-boiler, where up to 1446 kW may be saved. MEA/PZ and MDEA/PZ are proposed to enhance the performance of the base case. In particular, processes using MEA/PZ and MDEA/PZ can increase CO₂ removal by 1.7% and 2.8% compared to the MEA solution, respectively. An intercooler and multiple feeds are effectively employed to improve CO₂ removal. The results showed that the MDEA/PZ process with an intercooler or the MDEA/PZ process with multiple feeds increases the CO₂ removal by 3.5% compared to the MEA process, and achieving 90.6% and 90.5% CO₂ removal respectively. The MDEA/PZ process with multiple feeds is preferred as the operating cost of the MDEA/PZ process with the intercooler was higher due to cost of pumping seawater. The proposed configuration includes using MDEA/PZ as the solvent, and the combined use of an intercooler, multiple feeds and heat integration for enhanced performance, and a square scrubber to minimize the space required. This configuration provided an effective solution for ship-based carbon capture. In particular, the results show that the final configuration with a relatively higher stripper operating pressure (3 bar versus 2 bar) achieved a CO₂ removal of 1348 kg/h (94.7%) whilst saving up to 18.3% and 100.0% in terms

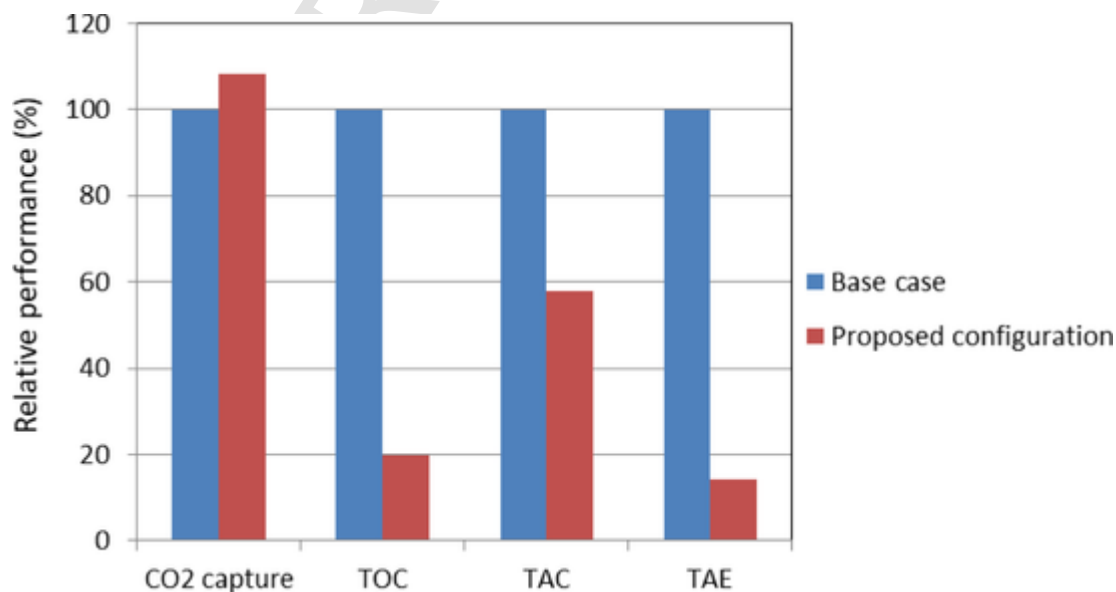


Fig. 6. Economic and environmental evaluation of two structural alternatives for marine carbon capture.

of compression duty and stripper duty, respectively. Furthermore, the compressor power is reduced by 3.7% by utilizing a two-stage compressor in the liquefaction unit. The lower TAC, CO₂ emissions and space requirements demonstrate effectiveness and viability of the proposed configuration for implementation in industrial processes.

Uncited References

[59].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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