IS CARBON CAPTURE A VIABLE SOLUTION TO DECARBONISE THE SHIPPING INDUSTRY?

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Abstract

This work presents some insights into two different options for onboard carbon capture and storage (OCCS). Previous studies have shown that solvent-based carbon capture is feasible, and that the new equipment installed for CO_2 capture would not debilitate the ship stability. This work assesses the potential for cryogenic carbon capture on LNG-fired engines due to the availability of cold conditions through a thermal analysis.

Keywords: *shipping, carbon capture and storage, maritime sector, cryogenic separation*

1. Introduction

The maritime sector is emitting about 2.5% of global GHG emissions. As a respond, the International Maritime Organization (IMO) has committed to a reduction of at least 40% of CO_2 emissions by 2030 from international shipping and by at least 50% by 2050 compared to 2008 emissions [1]. This need to reduce the emissions of greenhouse gases (GHG) from the shipping sector has enthused the first all-electric ferry that started operation between the island ports of Fynshav and Søby in southern Denmark to powered by a 4.3-MWh battery travels a distance of 40 km between charges [2]. Also, plans for the first liquid hydrogen fuel cell of 3.2MW with battery storage is expected by retrofitting a cruise ship by 2023 in Norway [3]. As an alternative, various options are being assessed including: fuel switching to liquified natural gas (LNG) or other fuels such as biofuels, methanol, hydrogen; electric propulsion systems, and nuclear marine propulsion; vessel improvements such as wind propulsion assistance, slow steaming, low resistance hull coatings, waste heat recovery systems; or exhaust gas treatment (e.g. carbon capture) [4]. However, some of these solutions will require adaptation of engines to new fuels and resolving sustainability challenges of those biofuels. Therefore, this work will focus on exhaust gas treatment measures.

1.1 Background on shipping decarbonisation

The CO_2 intensity of shipping is approximately 13.9gCO_2 tonne^{-1} km^{-1} [5]. Thus, a study has shown that the switch to LNG is not enough to achieve the target of 50% reduction of GHG emissions. The study highlights that this option will require to be combined with efficiency measures; whilst bio-based fuels that struggle to derive from sustainable sources will rely more on efficiency measures to reduce their consumption [4]. Balcombe et al. [4] and Bouman et al. [6] presented the CO_2 reduction potential from different methods to decarbonise shipping, none included carbon capture as a potential measure.

Onboard carbon capture and storage (OCCS) systems have been proposed to treat exhaust gases emitted from the internal combustion engines on board of ships. The stored CO_2 can be unloaded at ports, and then stored underground, undergo methanation or other conversion routes for CO_2 utilisation [7]. In addition, the IMO 2020 regulation has set a cap for sulphur content on fuel from 3.5% to 0.5%, where vessels will need to either change to low sulphur fuels or be fitted with scrubbers to comply such targets [1]. Awoyowi et al. [8] proposed scrubbing using aqueous ammonia for the simultaneous removal of CO_2 and SO_2 from the flue gas from a 10,800 kW Wärtsilä 9L46F marine diesel engine and found that through waste heat recovery a 70% CO_2 capture rate at 85% load is achievable. They showed that a 75% carbon capture rate is possible to recover heat using WHRS (waste heat recovery system) for the reboiler (ammonia requires less heat for regeneration than MEA), but 12.88% more fuel was needed to deliver the same power output of 8.7 MWe at 85% load, due to power requirements for CO_2 capture and compression for storage.

In addition to ammonia, other solvents have been considered. Feenstra el al. [9] proposed carbon capture from diesel and LNG-fuelled vessels (1,280 kW dual fuel Wärtsilä 8L20DF and 3,000 kW Wärtsilä 6L34DF). They used MEA as reference case, which was evaluated against 30 wt.% aqueous piperazine (PZ). PZ showed lower costs compared to MEA cases due to the higher pressure used in the desorption process and consequently lower CO_2 compression costs. They concluded that after considering the weight of equipment and stored CO_2, equipment could be fit onboard the ship with some space reconfiguration. They compared carbon capture rates of 60 – 90%, and in most cases, it was possible to recovery heat from exhaust gases for use in the reboiler to regenerate the solvent. However, it is not clear if the compression power and NH_3 refrigeration power are provided by using more fuel or reducing the engine power output.

As a potential alternative to chemical absorption with aqueous-based solvents, cryogenic carbon capture (CCC) is emerging as a CO_2 separation technology based on phase change at very low temperatures. The CCC method consists of the separation of CO_2 as a solid frost at conditions below its sublimation temperature (-78°C at 1 bara). The CO_2 frost is then warmed leaving a pure CO_2 stream ready for reuse or storage. One CCC approach uses packed beds to separate both water and CO_2 on the packing surface. The packed bed consists of chilled beads where water condenses, then the fuel gas is further cooled for CO_2 deposition as frost, the bed is warmed to release the CO_2, and finally the bed is cooled down ready for a new cycle. Thus, the process makes use of multiple parallel beds to allow continuous operation [10]. Another approach uses a moving bed of metallic beads, the advanced cryogenic carbon capture (A3C) process, that avoids the switching of multiple beds. This provides intensive heat transfer while avoiding the effects of heavy frost deposition, but it will need the appropriate handling of solids [11].

The A3C process has been evaluated for a shipping application. Two case studies were assessed, an LNG fuelled pure car and truck carrier (12,614 kW dual-fuel 7S60ME-C10.5-GI two stroke diesel engine), and a hybrid diesel (1,200 kW engine that burns marine gas oil, MGO) - electric/battery ferry. The study by PMW Technology found that integration of the A3C process into new built or retrofitted vessels is feasible. However, the A3C process showed that the total fuel consumption increased by 17% for LNG and 24% for MGO when capturing 90% of carbon emissions from main and auxiliary engines, and an additional load on the vessel by the liquid CO_2 storage tanks. The report concludes claiming that the cost of the A3C process for shipping could be up to 50% lower than the conversion of vessels to zero carbon fuels [12].

Carbon capture could aid decarbonise the maritime transport, whilst avoiding major design changes needed in fuel switching to ammonia or hydrogen. This sector is important worldwide. For instance, in the UK economy the maritime transport involves around 95% of imports and exports, 25% of the energy supply and 48% of food supply [13], and within the EU 40% of freight exchanges are carried out by sea.

1.1.1 Motivation and aims of this study

OCCS offers a route that avoids changes or replacement of ship engines. However, there is limited open literature on carbon capture for shipping applications.

Previous works [9], [14] have tested the use of OCCS by scrubbing using aqueous solvents, though this option will require the handling of hazardous chemicals onboard. A report [12] evaluating the cryogenic A3C process featured the potential and benefits of cryogenic separation, but the process will require refrigerants, and energy consumption for compression and liquefaction of CO_2. This works aims to compare solvent-based carbon capture against cryogenic separation. These technologies greatly depend on highly integrated configurations that intend to minimise energy consumption; therefore, identifying the benefits of hot versus cold heat integration could aid selecting the OCCS options with more potential.

2. Methodology

LNG is used as fuel, which is stored at -163ºC. Table 1 shows the composition of the LNG consumed onboard. Table 2 shows the exhaust gas compositions and flow rates used in this work with and without exhaust gas recirculation (EGR). In order to reduce the energy requirements linked to the lower CO_2 content in the exhaust gases, EGR can be implemented to increase the concentration of CO_2 and thus the overall performance of the carbon capture unit, as shown in Table 2.

Table 1**:** Liquified natural gas composition [14].

LNG	% wt.	% mol
Methane	91	95.41
Ethane	6.5	3.64
Propane	2.5	0.095
	100% load	85% load
Flow (kg/s)	0.55	0.45

Table 2**:** Data for exhaust gases of main engine Wartsila 9L46DF at 85% load and with EGR [14].

(mol %)	85% load	EGR (30%)
CO_2	4.88	6.45
N_2	75.24	74.04
O_2	10.37	6.97
H_2O	9.50	12.54
Flow (kg/s)	16.35	12.30

2.1 Ship-based carbon capture

Figure 1 shows the proposed integrated system of cryogenic post-combustion carbon capture in an LNG fuelled engine. The system consists of an LNG storage tank, a vaporiser to regasify LNG, the ship engine, and direct contact cooler to cool down exhaust gases. Before the CCC process, the exhaust gases are further cooled and dried. The shade area shows the CO_2 capture unit, where CO_2 is desublimed at temperatures below -100°C depending on the CO_2 content and at atmospheric pressure, and sublimed for CO_2 release using packed columns, and finally the CO_2 is compressed, liquified and stored.

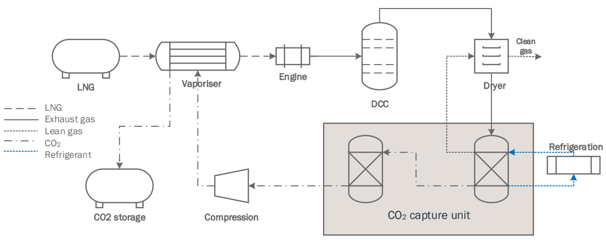

Figure 1**:** Schematic representation of the proposed OCCS using cryogenic packed columns

The desublimation/sublimation (CO_2 separator and CO_2 sublimer) steps could be designed to operate according to the two configurations shown in Figure 2, currently at technology readiness level (TRL) 3. One option shown in figure 2a employs alternating processes, that is whilst one precooled column is used for CO_2 removal the other columns are releasing the previously captured CO_2 and/or being cooled to the required temperatures. This system has been previously tested at laboratory scale [10]. Another option is to make use of moving beds as proposed in the A3C process [11], where the desublimation step has been tested experimentally using precooled metallic beads as packing material [15]. This configuration would allow continuous operation, but it requires complex handling of particles, as shown in Figure 2b.

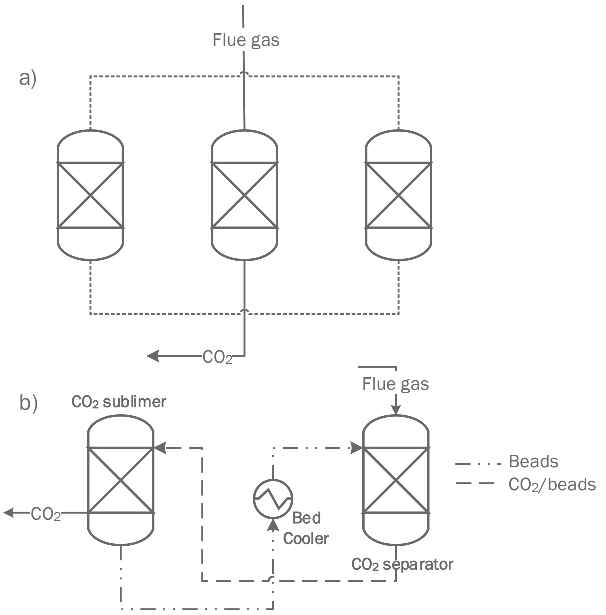

Figure 2: Schematic representation of cryogenic CO_2 capture unit: a) fixed packed columns and b) moving packed beds

In both configurations from Figure 2, prior to CO_2 desublimation, the packing material is cooled below the sublimation temperature, for an exhaust gas with 6.45% mol CO_2 content at -118°C for 95% CO_2 removal. For the fixed packed column, the packing cooling stage is switched between columns once each reach saturation. Whilst for the moving packed bed, the packing is cooled in a heat exchanger prior to entering the CO_2 separator, as shown in Figure 2b. This work aims to integrate cold sinks to minimise the need for external refrigeration. Figure 1 also shows that the evaporation of LNG could provide the cooling duty for liquifying CO_2; whilst the CCC process is integrated between the CO_2 desublimation and sublimation steps, and the cooling and drying of exhaust gases. The direct contact column (DCC) is designed so that the maximum sea water temperature rise is 5°C.

The cryogenic OCCS process was modelled using Aspen Plus® software V10. The thermodynamic method used was the Peng Robinson equation-of-state. Since only Gibbs reactors (RGibbs) can handle solids, these were used to represent the desublimation and sublimation of CO_2. The desublimation column was represented by a series of ten RGibbs blocks using phase and chemical equilibrium, allowing solids formation at each stage [16], and the standard enthalpy of formation and free energy of formation of solid CO_2 were entered to achieve more accurate energy estimations.

3. Results and Discussions

3.1 Performance of the Integrated System

3.1.1. Thermal integration of OCCS process

Feenstra el al. [9] showed that there is enough cold from the regasification of LNG to cool and liquify CO_2 at 22 bar with a storing temperature of -16ºC. An analysis of heat and cold sinks made possible the integration of the cold from LNG as previously done plus other cold streams from the cryogenic process. Since the cryogenic packed column delivers a cold CO_2 at around the sublimation temperature, the cold from this stream could be recovered to cool the compressed CO_2 at a lower pressure of 11 bar to reach the temperature of -36ºC needed for CO_2 liquefaction. Figure 3 shows the composite curve for hot and cold streams. Table 3 shows the duties and the streams matched.

Table 3: Heat balance analysis.

	Parameter to achieve	Duty (kW)	Supplied by
CO_2 cooling	-36ºC	80.8	Cold CO_2
CO_2 liquefaction	Liquid CO_2	379.6	LNG vaporisation

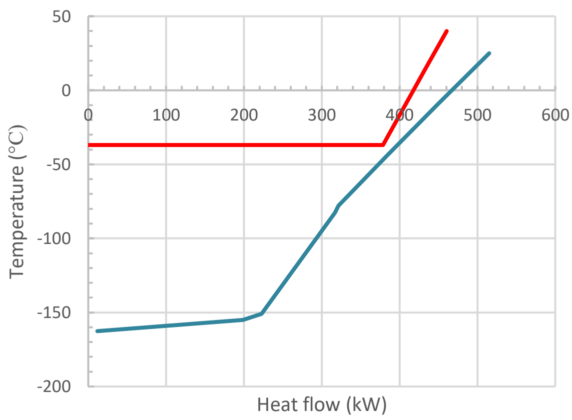

Figure 3: Composite curve for heat integration

Other alternative CCC process, developed by Sustainable Energy Solutions (SES), makes use of a cryogenic liquid to provide the cold for the desublimation of CO_2 [16]. Their Cryogenic Carbon Capture™ technology has been tested using real flue gas from power generation sources, positioning it at TRL 5. The SES CCC process has the advantage that a slurry, a mixture of the cooling liquid and solid CO_2, is produced. The slurry can then be compressed to the desired storage pressure, avoiding the need for electric power for gaseous CO_2 compression that would be further transported for permanent underground storage. However, the process requires highly integrated refrigerant loops to provide the cooling for CO_2 desublimation and for cooling the cryogenic contact liquid.

3.1.2. Performance of OCCS process

Table 2 shows the exhaust gas composition including the use of exhaust gas recirculation (EGR) that helps increasing the CO_2 content and reduces the gas flow rate. EGR was considered in this work, since Awoyowi et al. [14] reported that the engine power output was maintained similar to that without EGR.

Table 4 compares the OCCS performance with and without EGR. The results do not show a significant difference between the two cases. However, power consumption for CO_2 capture is higher for the cryogenic cases due to compression in the refrigeration unit, thus this will require higher NG consumption of around 11% to provide the same engine power output. With solvent scrubbing, the decreased gas flow rate and increased CO_2 content reduced the reboiler duty due to less solvent used, thus reducing operating costs.

This work found that the power requirements for CO_2 compression remained the same for EGR and no EGR cases. For CO_2 capture with scrubbing, the electric power consumption for CO_2 compression decreased from 0.4 MW_e with no EGR to 0.25 MW_e with EGR [14].

Table 4: Comparison of performance results.

	no EGR	with EGR	no EGR [14]	with EGR [14]
CO_2 capture technology	cryogenic		solvent	
CO_2 capture rate (%)	94.8	94.6	90	90
CO_2 stored pressure (bar)	11	11	7	7
Electric power for CO_2 compression (MW)	0.181	0.179	0.4	0.25
Specific energy consumption for CO_2 capture (MJ/kg-CO_2)				
electrical	0.91	0.87	0.09	0.06
thermal	-	-	3.4	2.7

Awoyowi et al. [14] also reported that less CO_2 is captured with EGR. In this work, the amount of CO_2 captured remained the same, since the increased CO_2 concentration was compensated by the reduced gas flow rate. This observation aligns with other EGR studies on gas turbines [17].

The OCCS process was also assessed through an exergy analysis. One parameter analysed was the exergy destruction, the difference between the total amount of exergy into and out of the system, which measures the unrecoverable lost capability to do work [18]. Thus, Figure 4 shows the exergy destruction contribution of different equipment in the cryogenic configuration with EGR. As can be seen, the exhaust gas cooling equipment has the most significant contribution of exergy destruction in the process (39.5%). After that, the CO_2 capture equipment has the largest impact on the exergy destruction in the system (34.7%).

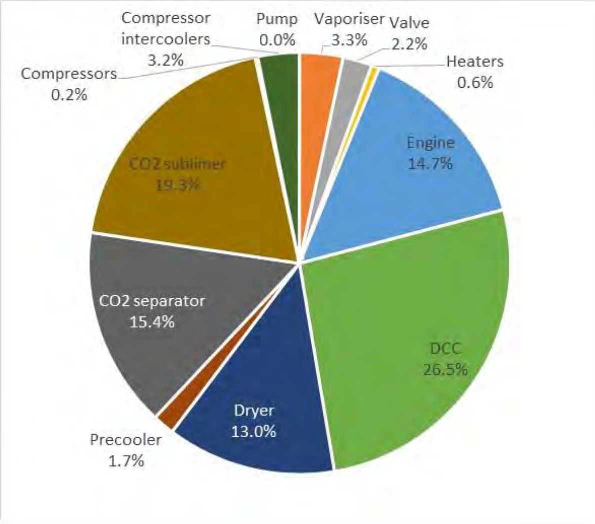

Figure 4: Percentage shares of exergy destruction based on the types of equipment in the cryogenic EGR case

4. Conclusions

This work addresses the increasing need to reduce GHG emissions from the maritime sector, this is in alignment with current targets of 50% reduction by 2050 compared to 2008 levels. Previous work evaluated the integration of solvent-based carbon capture onboard for LNG-fired ships. Thus, this work assessed the incorporation of novel cryogenic systems that complement well with the cold conditions available from LNG regasification. It was found that with a capture rate of 95%, the energy released from LNG regasification is sufficient to liquify CO_2, but the precooling needed to reach the near liquefaction temperature could be achieved from recovering cold from the cold CO_2 captured stream. Further work should look more closely into the dynamics of the integrations as well as the economic evaluation.

Acknowledgements

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