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Preliminary Study and Review of Oxy-fuel Combustion with Cryogenic Onboard CO_2 Capture for LNG-Driven Ships

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The maritime industry faces growing pressure to reduce greenhouse gas emissions in line with the International Maritime Organization’s 2030 and 2050 decarbonization targets. This study proposes a novel onboard CO_2 capture solution for LNG-powered ships, integrating oxy-fuel combustion with a Turbo-Expander-based Cryogenic Distillation Technology (CryoDT). By increasing CO_2 partial pressure through oxy-fuel combustion and utilizing cold energy from onboard LNG and low-purity oxygen or Crude Liquid Oxygen (CLOX) from a simplified Air Separation Unit (ASU), the system eliminates solid CO_2 formation and external utility requirements. A hybrid approach incorporating process simulations using Aspen HYSYS and P-HENS was developed to generate several feasible heat exchanger networks. Among the generated networks, a compact, low-cost design that minimizes Total Annualized Cost (TAC) from utility energy consumption and heat transfer area was selected for its spatial and operational advantages. Results indicate that with 80 mol.% oxygen purity, a 35 % reduction in energy penalty and a capture efficiency of 92 % can be achieved. This integrated approach offers a highly compact, energy-efficient and practical pathway for onboard CO_2 capture, tailored to maritime constraints.

1. Introduction

The maritime industry accounts for 2.9 % of global greenhouse gas emissions, a 20 % increase over the past decade (UNCTAD, 2023). Large vessels face increasing pressure to meet the International Maritime Organization’s carbon intensity reduction targets, , which are 40 % by 2030 and 70 % by 2050 relative to 2008 levels (IMO, 2023). Current ships are built to last more than 20 years. Retrofitting these ships with onboard CO_2 capture is a promising solution to comply with the planned regulations. For newly built ships, different options need to be evaluated, and onboard CO_2 capture is definitely one of them. However, conventional onshore technologies are not directly adaptable to ships, which operate with limited space and available energy.

Cryogenic CO_2 capture offers a potential advantage, as it directly produces liquid CO_2 suitable for onboard storage and later offloading. In contrast, absorption, adsorption, and membrane methods yield low-pressure CO_2 gas, requiring additional energy-intensive compression and liquefaction. Cryogenic systems, which separate CO_2 via condensation or desublimation at low temperatures, can leverage higher pressures from oxy-fuel combustion to minimize compression needs, although significant refrigeration demands remain a challenge. Recent studies have explored cryogenic capture for maritime applications. Willson (2020) evaluated the Advanced Cryogenic Carbon Capture process, emphasizing compactness and energy efficiency via waste heat recovery. The decarbonICE project proposed capturing CO_2 as dry ice for seabed storage (Ahmed et al., 2025). Oil and Gas Climate Initiative and Netherlands Organization for Applied Scientific Research highlighted LNG cold energy utilization to reduce liquefaction energy on LNG-powered ships (Lebedevas et al., 2024). TECO 2030 ASA et al. (2021) developed a system capturing and liquefying ship exhaust CO_2 for onboard storage. Collectively, these efforts highlight the potential of cryogenic technologies for onboard carbon capture. However, many proposed systems still face major energy efficiency challenges. Recently, Turunawarasu et al. (2025)

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introduced the Turbo-Expander-based Cryogenic Distillation (CryoDT) process, which maximizes internal heat recovery using P-HENS-generated heat exchanger networks, reducing energy consumption by up to 67 % compared to conventional cryogenic methods. Yet, CryoDT was originally designed for high-CO_2 natural gas, not the ship exhaust associated with low CO_2 partial pressure, risking operational issues like CO_2 solid formation and line plugging. To address this gap, the present study extends and adapts the CryoDT concept by proposing onboard oxy-fuel combustion to increase exhaust CO_2 concentration, streamlining liquefaction, eliminating intermediate solid formation, and enabling high-purity liquid CO_2 recovery at lower energy cost. A detailed simulation-based evaluation was carried out to assess the feasibility, performance, and energy efficiency of the adapted CryoDT process for maritime applications.

2. Process Description and Problem Statement

One of the fundamental challenges in implementing carbon capture on LNG-powered ships lies in the low partial pressure of CO_2 when combusting LNG with air. In a conventional post-combustion capture scenario, this low CO_2 partial pressure significantly increases the energy required for liquefaction. In some cases, it may even necessitate the formation of solid CO_2, which must subsequently be converted into liquid form. This phase change introduces operational complexity and the risk of process upsets, such as line plugging due to solid CO_2 formation, especially under transient conditions. To overcome this barrier, the use of oxy-fuel combustion has been proposed. By combusting LNG with oxygen-enriched air instead of atmospheric air, the resulting flue gas contains a much higher concentration of CO_2, increasing its partial pressure. This elevated CO_2 concentration streamlines the liquefaction process, avoids the intermediate solid phase, and enables the recovery of high-purity liquid CO_2 at a significantly lower energy cost. Figure 1(a) illustrates the oxy-fuel combustion cryogenic capture configuration tailored for newly built LNG ships. The innovation introduced in this paper is highlighted in yellow in the schematic to distinguish it from the design proposed by Yao et al. (2023). A central feature of this updated process is the integration of CryoDT, as shown in Figure 1(b) and developed by Turunawarasu et al. (2025). Traditional cryogenic distillation methods are known for their high energy demands, primarily due to the utilities consumed by condensers, reboilers, and pre-cooling stages. To address these inefficiencies, CryoDT introduces a novel turbo-expander into the distillation system. This component plays dual roles: it depressurizes and cools the flue gas stream while recovering energy that can be internally recycled. This significantly reduces reliance on external utilities for the reboiler and condenser. Furthermore, the system leverages the captured CO_2 as a refrigerant in the feed gas pre-cooler, minimizing the requirement for external refrigerants and further lowering operational costs. The efficiency of CryoDT is further enhanced by leveraging the cold energy available from the onboard LNG and the Crude Liquid Oxygen (CLOX) produced by a simplified Air Separation Unit (ASU). By utilizing these integrated cold sources, the system effectively eliminates the need for external cooling utilities, including those for the feed pre-cooler. As a result, the process proposed in this paper is energetically self-sustaining.

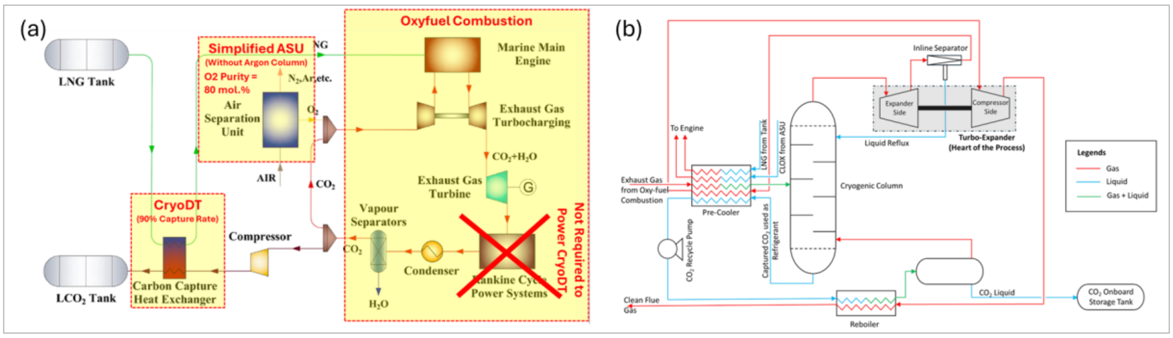

Figure 1 : (a) Modified oxy-fuel combustion cryogenic CO_2 capture configuration based on Yao et al. (2023); (b) CryoDT Concept (Turunawarasu et al., 2025)

3. Methodology

This study utilized process simulation to evaluate the feasibility and performance of oxy-fuel combustion integrated with CryoDT technology for CO_2 capture onboard LNG-powered ships. The simulations focused on evaluating the energy demands of key unit operations across six oxygen purities (75, 80, 85, 90, 95, and 99 mol.%) and identifying opportunities for internal energy recovery through innovative process configurations. The simulation was performed in Aspen HYSYS v14 using the Peng–Robinson–Boston–Mathias model with default binary interaction parameters to accurately represent the vapor-liquid equilibrium of the cryogenic CO_2–light gas mixture as recommended by AspenTech (AspenTech, 2001).

An initial base case was modelled without heat integration to establish baseline heating and cooling demands. This was followed by pinch analysis to identify minimum utility requirements, forming the basis for Heat Exchanger Network (HEN) synthesis using P-HENS. P-HENS is an open-source HEN synthesis tool based on graph-theoretical principles. It systematically generates all combinatorially feasible HEN configurations that achieve the minimum energy consumption target (Orosz et al., 2022). Unlike conventional methods, P-HENS not only identifies the optimal design but also simultaneously ranks multiple near-optimal alternatives (Orosz et al., 2020). This feature makes it particularly suitable for HEN synthesis, as near-optimal designs can offer practical advantages during real-world implementation, where the theoretically optimal solution may not always be the most viable. In configuring the process, the system was deliberately designed to operate with relaxed oxygen purity requirements. Specifically, the ASU was simplified to exclude the argon column, producing CLOX with 60–80 % purity from the medium- and low-pressure columns. The proposed approach is estimated to reduce ASU's Capital Expenditure (CAPEX) by approximately 20 % and energy consumption by 35 %. Figures 2(a) and 2(b) illustrate the trade-offs observed between oxygen purity and total system energy consumption. Lower oxygen purity reduces ASU energy demand but dilutes CO_2 in the flue gas, increasing cryogenic purification load, whereas higher purity has the opposite effect. Therefore, integrating CryoDT achieves a synergistic reduction in overall energy demand, with moderate oxygen purity striking a balance between ASU efficiency and CO_2 purification, providing a cost-effective strategy for onboard CO_2 capture.

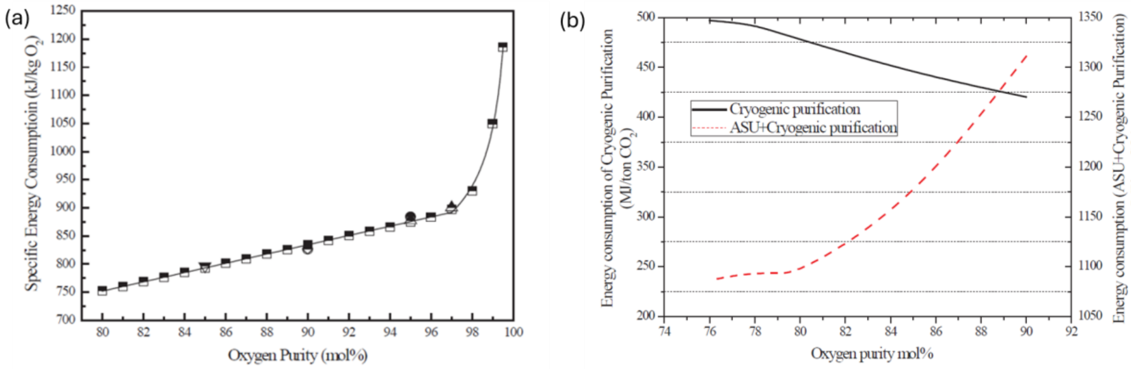

Figure 2: (a) Energy Consumption of ASU Under Different Oxygen Purities (Li et al., 2013); (b) The Energy Consumption of ASU and Cryogenic Purification (Li et al., 2013)

The process design basis used in modelling the system is presented in Table 1, with the objective of meeting the CO_2 onboard storage specifications outlined in Table 2.

Table 1: Process Design Basis

Parameter	Value
Marine Engine Power/Unit	21.93 MW – Based on 85 % average load (Ballout et al., 2024)
Ship Propulsion Power	50 MW (Powered by 2 engines based on full load)
LNG Onboard Storage Condition	5 bara, -162 °C
CO_2 Onboard Storage Condition	15 bara, -30 °C

Table 2: CO_2 Specification for Onboard Storage

Components	Threshold Limits
CO_2	Balance
N_2	Propose limits to be set at the saturation level for specified P and T at storage conditions to avoid boil-off gas and CO_2 remaining in the liquid phase
Ar	
O_2	10 ppm-mol
H_2O	30 ppm-mol (Northern Lights, 2024)

4. Results and Discussion

Figure 3 shows the oxy-fuel cryogenic capture process with the optimal HEN (Structure #1) on the CryoDT process, identified by P-HENS shown in Figure 4, with the assumption that engine load and exhaust composition remain constant. As shown in Figure 2b, reducing O_2 purity to 80 mol.% lowers the energy penalty and was selected for oxy-fuel combustion. This approach shifts part of the separation burden from the ASU to the downstream cryogenic capture stage, where nitrogen is later separated from CO_2 more efficiently, resulting in substantial energy savings of 35 %. To control combustion temperature, approximately 90 % of the CO_2 produced from oxy-fuel combustion is recycled, while the remaining 10 % is directed to CryoDT. The CO_2 stream entering CryoDT has a purity of approximately 66 mol.%, with simulations indicating a capture efficiency of 92 %, outperforming the 65.9 % reported for a conventional cryogenic CO_2 capture process (Ballout et al., 2024).

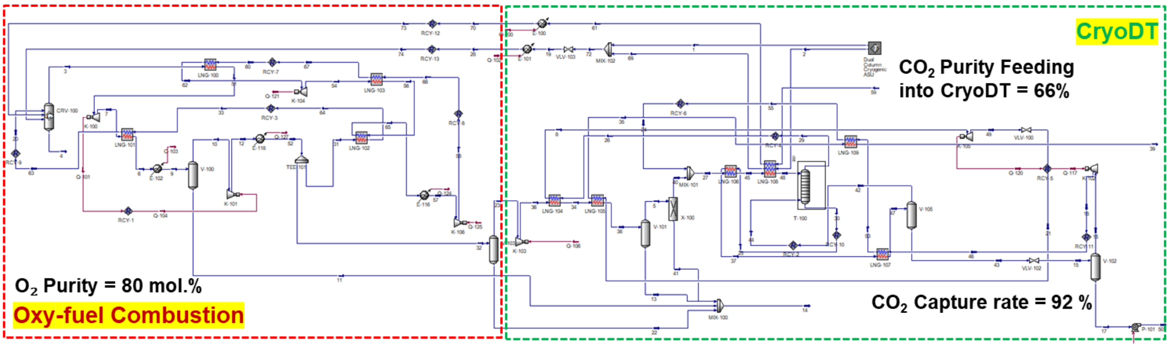

Figure 3: Oxy-fuel Combustion Cryogenic Capture Process Simulation Model with Optimal HEN Incorporated on CryoDT Process

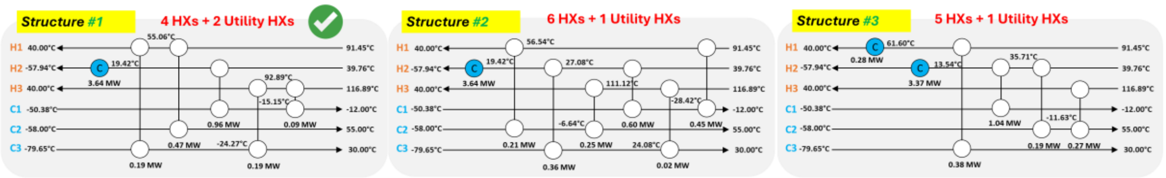

Figure 4: Top 3 HEN Structured Generated from P-HENS

P-HENS generates feasible solution structures through structure generation and ranks them based on Total Annualized Cost (TAC) as outlined in section 3 (Orosz et al., 2022). TAC in P-HENS considers two aspects: (i) energy costs due to utility consumption and (ii) capital costs based on the total heat transfer area. In this study, P-HENS generated over 50 feasible HENs, with the top 3 networks shown in Figure 4. These HENs achieve maximum energy recovery while minimizing TAC. Although the 3 HENs have the same energy consumption, which leads to identical energy cost, the capital investment needed varies due to the differences in network topology (note: matching different streams would lead to different log-mean temperature differences and result in different heat transfer area requirements). Each structure varies in the number of Heat Exchangers (HXs), utility HXs, and energy exchange processes. These structures are evaluated and compared based on several criteria, including the number of heat exchangers, utility requirements, spatial footprint, maintenance implications, and overall operational efficiency. Structure #1, with 5 HXs and a single utility HX, is recommended as the optimal solution due to its balance of energy efficiency, simplicity, and cost-effectiveness. The reduced number of HXs decreases the spatial footprint by 20 % compared to Structure #2, making it more suitable for onboard ships due to space constraints. Additionally, the single utility HX and fewer HXs in Structure #1 simplify maintenance, reduce downtime, and lower operational complexity by minimizing components requiring inspection and repair, all contributing to less frequent maintenance scheduling.

4.1 CryoDT Heat Integration

A closer look at the CryoDT section (Figure 5) reveals that substantial cold energy is required for pre-cooling during CO_2 liquefaction. Traditionally, this would require significant external utility input. However, in this system, those needs are fully met through internal heat integration, utilizing cold energy from LNG and CLOX produced by the simplified ASU. This integration, shown in Figure 6, allows the process to operate without external cooling utilities, significantly enhancing system efficiency and reducing operating costs.

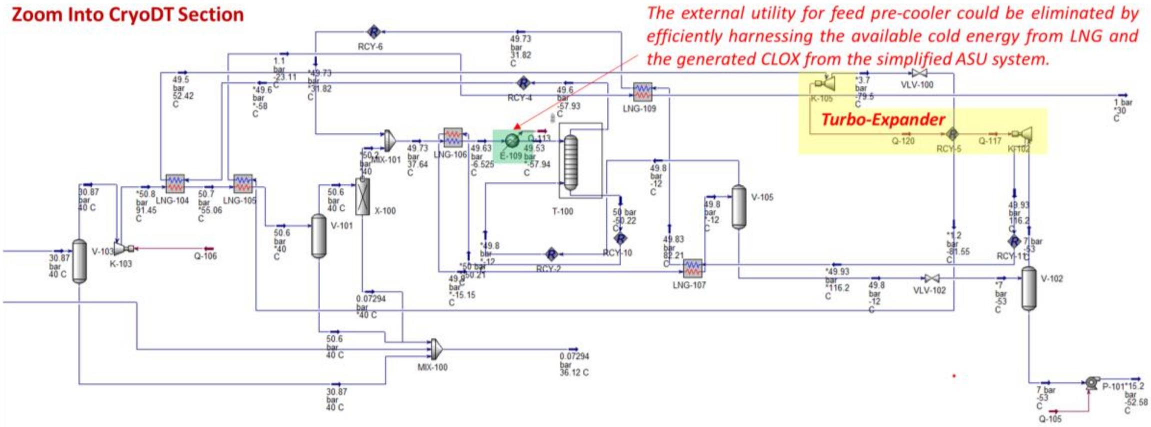

Figure 5: Pre-Cooling Demand Before LNG and CLOX Integration

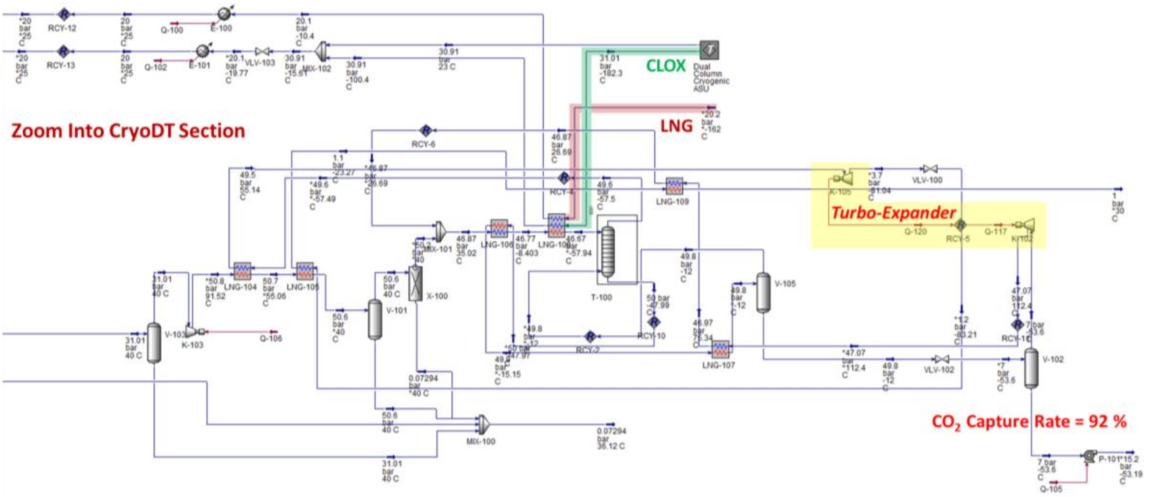

Figure 6: Fully Integrated CryoDT with Internal Cold Energy Recovery

4.2 Energy Profile of the System

Figure 7(a) presents the system energy breakdown for the entire oxy-fuel combustion cryogenic capture process, including the ASU, with a total power requirement of 76.4 MW for LNG-driven ships. In a typical Net Power Allam cycle (Figure 7(b)), approximately 90 % of the CO_2 from oxy-fuel combustion is compressed to 80–100 bar using one or two stages, then pumped to 200–400 bar to control combustion temperature (Allam et al., 2013), resulting in substantial compression demands as shown in Figure 7(a).

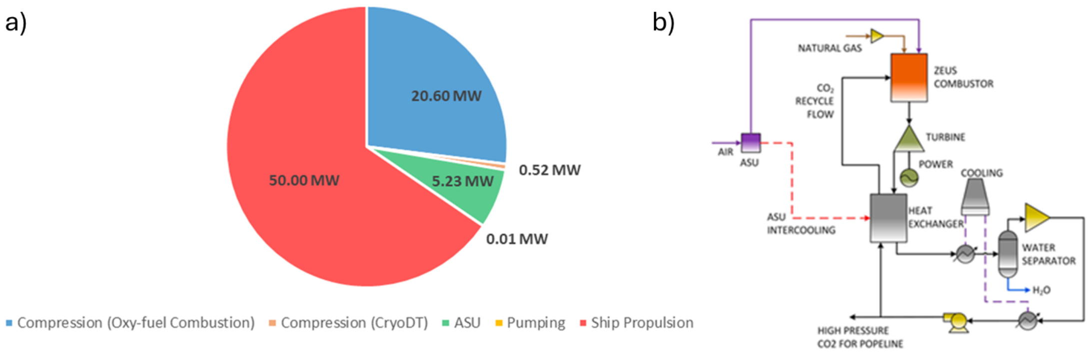

Figure 7: (a) System Energy Breakdown of Oxy-fuel Combustion Cryogenic Capture (b) Simplified Allam Cycle/NET Power Schematic (Allam et al., 2013)

5. Conclusions

This study proposes a novel CO_2 capture concept for LNG-powered ships, combining oxy-fuel combustion with CryoDT. By harnessing cold energy from LNG and CLOX from a simplified ASU, the process eliminates external utility requirements, offering a self-sustaining, energy-efficient solution. Lowering oxygen purity from 99 to 80 mol.% reduces energy penalties by up to 35 % and CAPEX by 20 % by simplifying ASU design and removing the argon column. Nitrogen and argon separation is instead managed efficiently downstream in the CryoDT unit. Optimized heat integration using P-HENS identified a compact, low-cost heat exchanger network (Structure #1), ideal for space-constrained shipboard environments. Unlike conventional systems, CryoDT operates without an external power cycle, relying on internal energy recovery. This preliminary study demonstrates that CryoDT offers a promising path toward practical onboard CO_2 capture. Future work will involve detailed techno-economic analysis, spatial and operability assessments under dynamic maritime conditions to address real-world variability (e.g., variable engine loads and exhaust composition), benchmarking against alternatives and strategies to reduce the high energy demand of oxy-fuel compression cycle, currently approaching 50 % of the ship's load. Pilot-scale trials on commercial vessels will also be essential for validation and optimization.

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