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Research on the Applicability and Process of Ship-Based Carbon Capture Technology

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Abstract. Shipping is one of the most energy-efficient modes of transport, and its carbon emissions are second only to road transportation. Applying carbon capture technology on vessels using carbon-based fuels not only meets the Carbon Intensity Indicator (CII) requirements proposed by the International Maritime Organization (IMO) but also avoids the modification of ship internal combustion engine power systems, thereby reducing investment costs. However, ship-based carbon capture technology still faces problems such as unclear process parameters, high energy consumption, and limited research on optimal performance regulation under different operating conditions. Aiming at the ship-based carbon capture system using Monoethanolamine (MEA) solution as an absorbent, this paper focuses on reducing operational energy consumption, comparatively analyzes the development of carbon capture technology and ship-based carbon capture processes, and proposes improvement measures for technical research.

Keywords: Ship-based Carbon Capture, Carbon Intensity Indicator, Chemical Absorption, Energy Consumption, Process Optimization

1. Introduction

The International Maritime Organization's Fourth Greenhouse Gas Study, published in 2020, points out that global shipping emitted 1.056 billion tons of greenhouse gases in 2018, representing a 9.3% increase compared with 2012 [1]. Although the COVID-19 pandemic temporarily influenced global cargo transport, shipping-related carbon emissions are still expected to grow steadily [2]. Under mounting pressure to decarbonize, over the past few years, the IMO has implemented a range of actions to limit greenhouse gas emissions from maritime transport. At present, CO_2 reduction in the maritime sector mainly focuses on three pathways: energy substitution, process optimization, and end-of-pipe treatment. Energy substitution mainly refers to the shift toward lowcarbon and zerocarbon fuels, along with the gradual electrification of ships. LNG and methanol are already being used to replace traditional heavy fuel oil, while hydrogen and ammonia are increasingly viewed as potential zerocarbon fuels for future applications [3]. However, because energy substitution and process optimization often require substantial investment while offering limited emissionreduction benefits, the use of relatively mature CCUS technologies at the exhaust end is gaining importance as a practical pathway for reducing emissions in the shipping sector.

2. Carbon capture technology

Carbon capture technologies have become increasingly mature through their long-term development in land-based coal-fired power applications. Because carbon capture approaches can be logically and systematically categorized according to the technological pathway, they can be conveniently grouped into pre combustion capture, oxy fuel combustion, post combustion capture, bioenergy with carbon capture, fuel cell based conversion, and direct air capture(DAC) [4]. Importantly, the first three of these approaches have already been validated at the pilot scale, whereas fuel-cell conversion and DAC are still at earlier stages. pre-combustion capture is a well-established or early-stage concept in which fossil fuels are gasified to syngas (mainly H_2 and CO), CO is converted to CO_2 via the water–gas shift reaction, and the CO_2 is then separated. Therefore it has the major advantages of high CO_2 purity and relatively low capture costs (13 – 37 USD per ton of CO_2), but it also has the notable drawbacks of requiring large installation space and involving high capital investment for the necessary equipment [5]. Oxy-fuel combustion burns fossil fuels in an oxygen-enriched or pure-oxygen environment, the combustion process produces flue gas basically composed of water vapor, CO_2, and inert components [6], and by condensing the water vapor and employing low-temperature flashing, CO_2 concentrations above 90% can be readily achieved. However, it is also well recognized that the technology has two major drawbacks: high oxygen production costs and the complexity of the system equipment. Direct air capture(DAC) separates CO_2 directly from ambient air. The text presents several novel materials and processes, emphasizing that the most important advantage of DAC is its independence from emission source type and location, hence avoiding the infrastructure hurdles inherent in deploying CCUS near populated areas [7]. But it also clearly states that DAC's application is presently limited by its high operating costs. In contrast, BECCS provides a straightforward negative emission route by capturing CO_2 from biomass combustion or conversion, but it is still subject to technical, economic, and social challenges and remains in the research and demonstration phase [8]. High-temperature fuel-cell-based conversion is another emerging technology that eliminates nitrogen from the reaction stream, thereby greatly simplifying CO_2 capture, though it has not yet been scaled up beyond the laboratory level [9].

Post combustion capture removes CO_2 from flue gas after combustion and therefore has excellent applicability and selectivity, which is why it is currently the most commonly used and technically most mature carbon capture approach. Importantly, within post-combustion capture, only chemical absorption has achieved commercialization, while all other methods are still in the pilot or demonstration phase [10]. Compared with pre combustion and oxy fuel technologies, since post combustion capture requires only moderate modifications to the exhaust gas treatment system and leaves the engine, power system, and combustion process unchanged, it avoids high-temperature or hazardous operations and therefore has a much simpler exhaust-gas treatment route. More importantly, it has high technological maturity, excellent capture performance, low installation cost, and good adaptability to different operating conditions [11]， because of its overall safety and stability, post-combustion capture is generally regarded as the most promising CO_2 capture option for maritime applications [12]. Among various post-combustion technologies, chemical absorption has a distinct advantage: it adapts very well to flue-gas conditions and is easy to scale up, so it is the most developed and most commercially deployed technology, making it particularly well-suited for low concentration CO_2 capture [13].

3. Applicability research of ship-based carbon capture technology

As landbased CCUS technologies continue to advance, their adaptation to maritime scenarios is viewed as a promising option for reducing emissions from ships. According to Ros et al. [14], fuelsaving strategies alone cannot achieve significant reductions, while shipbased carbon capture (SBCC) offers a nearterm solution with the potential for notable emission decreases.

Wang et al. [15] first demonstrated the feasibility of carbon solidification for maritime emission reduction by means of real ship tests and numerical simulations, thus convincingly showing that shipboard carbon capture and storage is a very promising route for reducing greenhouse gas emissions in shipping. Building on this, Wang et al. [16] examined the operating costs and profits of a solidification-based reduction scheme on a bulk carrier, demonstrating the economic feasibility of applying SBCC on ships while utilizing simulation to prove the feasibility of installing SBCC on a container vessel. fang et al. [17] presented a clear, logically structured optimization approach for determining the optimal SBCC capacity under EEOI constraints, and they explicitly separated the problem into two well-defined stages: the first stage finds the required SBCC capacity and the necessary additional energy storage capacity to support its continuous operation, while the second stage is a joint onboard power generation and demand-side management model that resolves power shortages resulting from SBCC installation. From this, they naturally and convincingly conclude that carbon capture systems are a viable option for reducing greenhouse gas emissions from ships prior to the maturity of renewable energy technologies.

Stec et al. [18] have done a systematic analysis of the energy demand for the full marine carbon capture chain, namely SO_2 removal, CO_2 capture, and compression. Through scenario simulations conducted in both tropical and Arctic conditions, they found that postcombustion carboncapture technology shows strong potential for improving the Energy Efficiency Design Index (EEDI). Oh et al. [19] further indicated that their marine membranebased capture and liquefaction system could become a competitive option for meeting the IMO's 2050 greenhousegas reduction targets.

García-Mariaca et al. [20] pointed out that shipboard carbon capture and storage systems may be the preferred choice for achieving zero-carbon emissions in transport equipment driven by internal combustion engines. Their case analysis of carbon capture for internal combustion engine-powered transport demonstrated that operating CCUS systems on maritime and road freight equipment is feasible. Guirma et al. [21] suggested that shipbased carboncapture technology offers a highly effective means of reducing emissions from large offshore LNGpowered vessels, particularly when evaluated under specific boundary conditions, shipowners have significant potential to achieve the IMO 2030 and IMO 2050 targets. Qu Ziyi analyzed the feasibility and compatibility of several maritime carbon reduction technologies and very clearly concluded that postcombustion capture is the most compatible with existing energy systems, hence the most direct and effective option for current ship emission mitigation [22]. Building on this, Zhang et al. [23] examined CO_2 capture from LNG ship exhaust using carbon based adsorbents and found that trace quantities of CH_4, H_2O, and NO enhance adsorption performance, whereas O_2 and N_2 inhibit CO_2 removal. Therefore, they naturally and convincingly argue that carbon based adsorption is a promising approach for CO_2 capture in LNG fueled vessels.Li Heming et al. [24-25] have made a thorough analysis of the merits and drawbacks of precombustion, oxy fuel, and post combustion carbon capture technologies in marine applications, and therefore quite naturally concluded that CCS still has major cost and technical barriers to overcome before it can be applied on ships, summarizing existing issues such as installation and retrofitting difficulties, high capture and storage costs, and insufficient attention to storage and transportation safety; they provided solution analyses regarding CCUS technical progress, multi-energy coupling utilization, and government policies. Jin Ding [26] analyzed the application prospects of key marine CCUS technologies from a technical standpoint, concluding that while breakthroughs have been made in some key technologies of shipboard carbon capture and storage, they have not yet reached the stage of commercial application.

4. Process research of ship-based carbon capture

Efficiency and cost remain key considerations when selecting a technical pathway for shipbased carbon capture (SBCC). Since onboard capture accounts for more than 70% of the total energy consumption in the CCS chain, it is clear that the factors related to onboard capture play a decisive role in system design and feasibility.[27] Hence, both capture rate and energy consumption are fundamental performance indicators of SBCC. It is therefore not surprising that the current international research effort is directed at improving capture efficiency and reducing energy use via advanced solvents and optimized process configurations, as discussed by Awoyomi et al. [28], the authors examined SBCC using an ammonia-based solvent and convincingly showed that at an 85% engine load, approximately 4 MW of recoverable waste heat was sufficient to achieve a 70% capture rate with a solvent circulation of 90 – 100 kg/s, thereby illustrating very clearly the economic promise of waste heat utilization. In contrast, Long et al. [29] achieved an 87.4% capture rate on a 3 MW diesel vessel using MEA and then systematically explored mixed solvent systems along with process optimizations such as intercooling, multi-stage feeding, and heat integration.

Akker [30] presented a well-thought-out conceptual SBCC design for LNG carriers that integrates LNG regasification cold energy with exhaust waste heat without sacrificing cargo capacity or vessel stability. Building on this, Luo et al. [31] carried out the first systematic MEA-based absorption design for a 35，000 GT cargo vessel and conclusively showed that the limited onboard energy supply limited the capture rate to 73%，with a corresponding cost of 77.50 EUR/t CO_2.

The gas turbine increased the capture rate to 90%， but the accompanying increase in fuel consumption raised the cost to 163.07 EUR/t CO_2. Feenstra et al. [32] performed a rigorous Aspen Plus simulation of MEA and PZ systems for diesel and LNG ships and consequently showed that while higher capture rates require larger capital investments, the cost per ton of CO_2 captured actually decreases. Moreover, because PZ operates at a higher desorption pressure, switching from MEA to PZ further lowers the overall SBCC cost. Ros et al. [33] gave a systematic review of SBCC design considerations and analyzed the"Sleipnir"LNG carrier from the DerisCO₂ project, thereby clearly and rigorously concluding that CO_2 capture and liquefaction have only minor effects on vessel operation: higher exhaust temperatures improve capture rates, higher liquefaction pressures increase liquid CO_2 output, static heel angles reduce capture efficiency, and dynamic ship motion has almost no effect. Other studies have already examined economic performance from the viewpoints of solvent selection, membrane systems, and system scale, and two recent papers stand out in this regard: Zhou et al. [34] proposed absorbing CO_2 with sodium hydroxide to form sodium carbonate, which then reacts with quicklime to give solid calcium carbonate, thus presenting a compact, economical onboard storage solution. In contrast, Lee et al. [35] developed an EEDI evaluation method that incorporates SBCC and applied it to a 53，000 DWT LNG fueled container feeder using an activated MDEA+PZ solvent. They considered 45%, 55%, and 70% CO_2 reduction scenarios, finding that only part of the exhaust stream needed treatment and the capture unit achieved 92% efficiency. Most importantly, they rigorously concluded that the process capture rate must surpass the required EEDI reduction to offset cargo loss and extra energy use [36].

Oh et al. [37] dealt with the problem of low CO_2 concentration (≈ 3%) and high O_2 content (≈ 16%) in LNG exhaust by designing a compact, energy-efficient membrane-based capture and liquefaction system and then systematically comparing its performance with amine-based processes. In a complementary approach, Güler et al. [38] used process simulation to analyze the effect of hydraulic parameters in the separation column on solvent-based SBCC performance, and they compared the costs for oil tankers, Q Max, Q Flex, and conventional LNG carriers. Their conclusion is clear and important: for high value, high speed LNG carriers such as Q Max and Q Flex, SBCC is more cost-effective than speed reduction or switching solely to LNG fuel.

5. Conclusions

This paper gives a clear, systematic review of the technical routes toward carbon neutrality in the shipping industry, and then proceeds to analyze the applicability and process bottlenecks of Ship-Based Carbon Capture (SBCC) technology. Based on the discussion, it logically and convincingly concludes that, given the present constraints of source substitution and process reduction regarding cost and technical maturity, post-combustion capture technology, particularly the chemical absorption method, is the most realistic and direct solution for current maritime emission reduction. The reasons are its compatibility with existing marine power systems, low installation cost, and established technical readiness.

Since SBCC systems have fundamental problems of excessive energy demand, low capture efficiency, and limited installation space, the present process research is quite logically directed toward the development of high performance composite solvents, the optimization of thermal integration using exhaust gas waste heat and LNG cold energy, and the design of compact membrane separation and solid state carbon storage devices.

Since there are several clear areas that call for further investigation: the stability of SBCC under vessel motion conditions, the degradation of absorbents, and compatibility with global carbon emission regulations, it is logical and important in the future to strengthen real ship validation of high-efficiency, compact capture processes. Integrating SBCC with green fuels provides a natural path toward a more complete emission reduction framework, thus accelerating progress toward the IMO's 2050 net zero greenhouse gas goal.

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