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Study of solvent-based carbon capture for cargo ships through process modelling and simulation

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HIGHLIGHTS

- First systematic study in applying solvent-based carbon capture for ships.
- Discussions on features of onboard carbon capture and storage (CCS).
- Model development of ship energy system integrated with CCS.
- Techno-economic evaluation for different integration options.
- Determination of key process parameters and equipment size of ship CCS process.

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ABSTRACT

Controlling anthropogenic CO_2 emission is crucial to mitigate global warming. Marine CO_2 emissions accounts for around 3% of the total CO_2 emission worldwide and grows rapidly with increasing demand for passenger and cargo transport. The International Maritime Organization (IMO) has adopted mandatory measures to reduce greenhouse gases (GHGs) emissions from international shipping. This study aims to explore how to apply solvent-based post-combustion carbon capture (PCC) process to capture CO_2 from the energy system in a typical cargo ship and to evaluate the cost degrees of different integration options through simulation-based techno-economic assessments. The selected reference cargo ship has a propulsion system consisting of two four-stroke reciprocating engines at a total power of 17 MW. The study first addressed the challenge on model development of the marine diesel engines and then developed the model of the ship energy system. The limitations of implementing onboard carbon capture were discussed. Two integration options between the ship energy system and the carbon capture process were simulated to analyse the thermal performance of the integrated system and to estimate equipment size of the carbon capture process. It was found that the carbon capture level could only reach 73% when the existing ship energy system is integrated with the PCC process due to limited heat and electricity supply for CCS. The cost of CO_2 captured is around 77.50 €/ton CO_2. With installation of an additional gas turbine to provide extra energy utilities to the capture plant, the carbon capture level could reach 90% whilst the cost of CO_2 captured is around 163.07 €/ton CO_2, mainly because of 21.41% more fuel consumption for the additional diesel gas turbine. This is the first systematical study in applying solvent-based carbon capture for ships, which will inspire other researchers in this area.

1. Introduction

1.1. Background

The rapid increase of atmospheric concentration of CO_2 since the beginning of the Industrial Revolution is the main cause for global warming and extreme climate conditions [1]. Therefore, reducing anthropogenic CO_2 emission from major emitters such as combustion of fossil-fuel is vital to achieve the target of limiting average global temperature increase to 2 °C in 2050 [2].

Transport sector contributes second largest CO_2 emission [3]. Marine transport accounts for 11.17% of transport thus approximately 3% of total global CO_2 emission [4]. Fuels such as diesel have been used to drive ships since the 1870s and most marine vessels primarily burn fuels to produce power for propulsion, electricity generation and thermal energy for heating and hot water [5]. With the increase of population and business activities, shipping is an increasingly popular transportation method for travel and industry goods. CO_2 emissions from shipping transport are also

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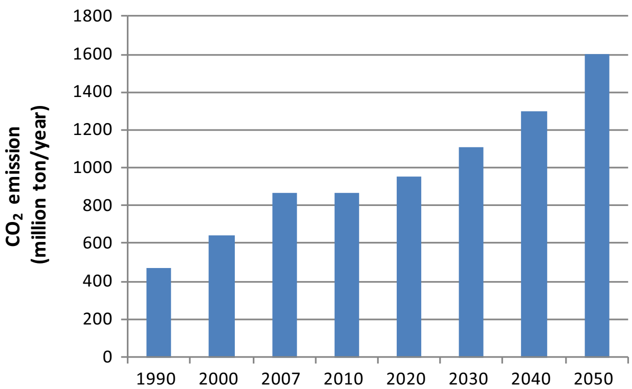

Fig. 1. CO_2 emission trend from ships [8,9].

predicted to rise to 1.6 billion tons by 2050 (see Fig. 1). Thus the International Maritime Organization (IMO) has adopted mandatory measures to reduce GHGs emissions from international shipping [6]. An agreement was also reached for monitoring, reporting and verification of CO_2 emissions from ships throughout Europe [7].

1.2. Marine CO_2 emission reduction

There are several routes to improve thermal efficiency and to reduce CO_2 emission of ship to comply with the environmental protection demands such as optimal design of propulsion system [10,11], replacement with cleaner fuels [12,13], improving thermal efficiency through waste heat recovery [14,15] and carbon capture and storage (CCS) [16].

For the alternative fuels route, liquefied natural gas (LNG) is an attractive condidate, which is widely regarded as a clean and reliable fuel for ship propulsion system. Its combustion emits much less waste gases such as SO_x and NO_x [12]. In addition, the CO_2 - emission reduces around 25–30% because of low carbon to hydrogen ratio of the fuel. One disadvantage of LNG is that the LNG tanks occupy more space and account more weight than marine diesel oil (MDO) because of smaller density of LNG fuel [13,17].

Waste heat recovery (WHR) technology was investigated massively as an approach to improve the thermal efficiency of ship energy system. The temperature of flue gases emitted from the engine is still as high as 350 °C, which provides enough temperature pinches to heat a cold process stream or to generate low pressure steam. Previous studies [18–22] conducted simulation and performance analysis of different circulated fluids in WHR system and the heat integrations with the flue gases and cooling system. Shu et al. [15] made a comprehensive review of the application of WHR system in ships.

Using solvent-based post-combustion carbon capture (PCC) technology to absorb CO_2 in the flue gases is another approach for shipping CO_2 emission reduction. Solvent-based PCC was proven to be the most promising technology for carbon capture for onshore fossil fuel fired power plants by massive studies [23–26]. But significant challenges need to be addressed towards its onboard application because of the natures of marine vessels such as off-shore, constant move and space constraints. In a feasibility study conducted by Det Norske Veritas (DNV) and Process Systems Enterprise Ltd. (PSE), it was found that CCS is feasible for marine vessels and the CO_2 emission can reduce by up to 65% [16,27], but the report is not in public domain. Apart from this, there is no publication on this topic so far.

1.3. Aim of this study and its novelties

This paper aims to explore how to apply solvent-based carbon capture process to capture CO_2 from the energy system in a typical cargo ship and to evaluate the cost degrees of different integration options by simulation-based techno-economic assessments. To serve this aim, the objectives of this study include (1) to develop a steady state process model in Aspen Plus® of ship energy system and to perform model validation; (2) to develop a steady state process model in Aspen Plus® of CCS system including MEA-based PCC process, CO_2 compression and tank storage; (3) to carry out techno-economic evaluations for the integration between ship energy system and the CCS system with and without an additional diesel gas turbine.

To the best knowledge of the authors, this paper presented the first systematical study in applying solvent-based carbon capture for ships, which contributes to an in-depth understanding for the deployment of CCS on ships. This study started from the modelling of the cylinder process of the marine diesel engine, the final models of the integrated system (the energy system of a 35,000 Gt cargo ship integrated with a full function CCS system) were developed in Aspen Plus® at industrial scale. By carrying out simulation-based techno-economic evaluations for different integration options, this study answered key questions related to potential commercial deployment of solvent-based carbon capture on ships, including (1) what are the capture levels that could be reached for the integrated system with or without an additional utilities supply, (2) the selection of CO_2 compression and storage method, (3) the key design features, such as equipment size and process parameters of the CCS system, and (4) the cost degrees of different integration options.

2. Model development of ship energy system

2.1. Reference cargo ship

Table 1 shows the main characteristics of the selected reference ship, which is a middle size cargo ship. The ship has two 9L46 marine diesel engines from Wärtsilä to provide propulsion power of 17 MW and it also supplies 3MW_e electricity by integrating three power generators. The fuel consumed by the engines belongs to heavy marine oil, which is further specified to be diesel in this study.

The sketch of the ship energy system can be seen in Fig. 2. There are three main parts including the propulsion system, auxiliary power generation and WHR system. The propulsion system consists of two four-stroke marine diesel engines, which are directly coupled with two ship propellers through respective gearboxes. Three electricity generators are also connected to the gearboxes to cover a part of electric power demand of the ship. There is one WHR system for each single train of propulsion engine. A typical WHR configuration is a single pressure steam cycle with a steam drum, an integrated heat exchanger and a steam turbine. The steam generated from the steam cycle goes to a steam turbine with a generator to produce another part of electricity.

2.2. Model development of marine diesel engine

2.2.1. Modelling of engine cylinder

Marine diesel engines convert the chemical potential energy of the marine fuel into mechanical energy driving the ship. Most modern ships use reciprocating diesel engines as prime mover

Table 1
Characteristics of the reference cargo ship [28].

Item	Value
Size (Gt)	35,000
Length (m)	220.0
Beam (m)	28.2
Draft (m)	7.0
Propulsion engine	2* Wärtsilä 9L46
Deadweight (mt)	12,500
Propulsion power (MW)	17.0
Auxiliary power (MW_e)	3.0