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Energy assessments of onboard CO_2 capture from ship engines by MEA-based post combustion capture system with flue gas heat integration

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ABSTRACT

An early phase feasibility study was carried out for offshore CO_2 capture from ship engines of a CO_2 transport ship. A flexible in-house process simulator was applied in the assessments. Parametric studies of the overall onboard process were enabled by a fast data-driven capture plant model derived from supervised machine learning by PLS regression of a large dataset of rigorous simulations. The results show, based on the given models and assumptions, that the thermal energy coming from the ship engine exhaust gas is not sufficient alone to cover the thermal energy demand of an absorption-based CO_2 capture unit operating above 50% capture rate using 30 wt% MEA (mono-ethanolamine) as solvent. The thermal energy demand can be met using a fuel afterburner as heat source. The added fuel consumption is estimated to increase the fuel consumption by 6–9% when operating with liquefied natural gas (LNG) as fuel source, while an increase of 8–12% is expected with diesel as fuel source. The effect of absorber height on energy consumption at a given CO_2 capture rate is limited, especially for lower capture rates, and may be an important degree of freedom for optimizing the CAPEX/OPEX trade-offs. Use of state-of-the art solvents with lower specific energy consumptions will shift the results towards higher capture rates before a fuel afterburner is required to meet the thermal energy demands.

Introduction

Carbon Capture and Storage (CCS) is addressed by the International Energy Agency (IEA) as one of the key technologies of reaching the Paris Agreement 2 °C goal. In the IEA 2 °C scenario 1 $GtCO_2$/year will need to be captured by 2030 ramping up to 5 $GtCO_2$/year in 2045 (IEA, 2020). CO_2 emissions from global shipping contributed to an approximate 3% of the total emissions in 2012 and are projected to rise with 50–250% up to 2050 (IMO, 2014).

In a CCS full-scale value chain, the CO_2 is first captured and then transported to a suitable permanent storage site. The transport element could either be by pipeline, ship, or a combination of both. Transport of CO_2 by ship represents an alternative when pipelines are too expensive due to distance, volume, and depreciation period (IEA, 2018). CO_2 has been transported with ships for decades, but these volumes are rather small compared to the required scales for CCS. In the ongoing Norwegian Northern Lights project (Equinor, 2021), the transport concept under planning is shipping of CO_2 from one or two emission sites to an import hub located at Kollsnes, Norway, with pipeline transport to permanent storage offshore.

Monteiro (2020) presents a technical and economic feasibility study from a recently completed EU project where CO_2 capture from LNG-fueled ships was investigated using MEA absorption technology. CO_2 capture rates in the range 54–75% were considered technically feasible for the three use cases which were evaluated. Both waste heat from the engine exhaust gas and cooling from LNG vaporization was utilized for solvent regeneration and CO_2 liquefaction, respectively. The reported levelized CO_2 capture costs were reported in the range of 115 – 300 EUR/ton CO_2 depending on use-case.

Previous studies on ship-based CO_2 capture have been published (Luo et al., 2017; Feenstra et al., 2019; Sharma et al. 2019; Lee et al., 2021). Feenstra et al. (2019) performed a feasibility study of onboard capture from diesel and LNG ship engines. The study applied Aspen Plus simulations with 30 wt% aqueous MEA and 30 wt% aqueous piperazine (PZ) as solvents. The authors reported findings that OPEX and CAPEX were reduced by integrating the thermal energy of the

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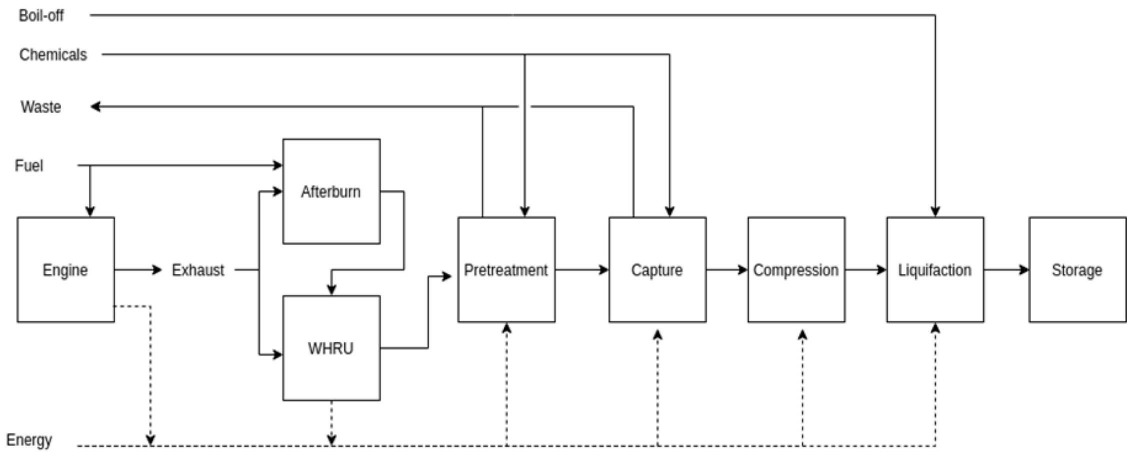


Fig. 1. Overall concept flow diagram of onboard capture and handling of CO_2 from ship engine exhaust applied in the current feasibility study.

exhaust gas with the stripper reboiler with up to 90% capture rate achievable by recovering the heat from the exhaust.

The Energy Efficiency Design Index (EEDI) for ships made mandatory for new ships by the International Maritime Organization (IMO) in 2011 (IMO, 2011), is the most important technical measure for promoting the use of more energy efficient (less polluting) equipment and engines on ships. The EEDI requires a minimum energy efficiency level per capacity mile (e.g., tonne mile) for different ship types. This regulation currently proposed by the IMO do not reflect the introduction of onboard CO_2 capture systems. Lee et al. proposed a novel EEDI estimation method considering a ship-based carbon capture and storage system satisfying the upcoming GHG emission regulations for ships. Chemical absorption with methyl-diethanolamine (MDEA) activated with piperazine was used as CO_2 capture solvent in the analysis. The results demonstrated that the required carbon capture ratio in the CO_2 capture process is higher than the actual EEDI reduction rate.

Capture of CO_2 from ship engines is a challenging task, especially considered the significant energy required for the capture process and the logistics involved in bringing the captured CO_2 to a storage site. In this relation, CO_2 transport ships could be a special case that is viable, since the CO_2 capture plant would be located next to an available storage that is heading for a permanent storage site. The aim of the current study was to explore the possibility of capturing CO_2 from the exhaust gas emitted by the engines of the CO_2 transporting ships. The study is done as part of the CO2LOS II (CO_2 Logistics by Ship Phase II) project (SINTEF, 2020), aimed at reducing the cost of CO_2 ship transportation by utilizing new technology and investigate optimization possibilities in the logistic chain.

The current work describes an assessment of options for onboard absorption-based CO_2 capture and establishes a basis for developing a concept for onboard capture, including energy supply for capture, and onboard CO_2 storage. An overall assessment of energy balances for cases of process flowsheets including ship engine, waste heat recovery unit (WHRU), flue gas afterburner, CO_2 capture, compression and liquefaction was performed in addition to preliminary size estimations of main units of the CO_2 capture process.

2. Methods

2.1. Selected concept for post combustion CO_2 capture from the ship engines of a CO_2 transport ship

The onboard capture concept studied aims at capturing CO_2 from the engines of a CO_2 transport ship followed by compression and addition of the captured CO_2 to and then compressed and added to the ships CO_2 storage tanks for further transport to an injection site for permanent underground storage. Fig. 1 illustrates the overall concept flow diagram for CO_2 capture from ship engines of a CO_2 transport vessel.

The case explored involves ship engines with a flue gas CO_2 content in flue gas in the range from 3.5 to 5.5 vol% for a 25% and 100% engine load, respectively. Normal engine operation is in the lower range of this interval. The base case for the current capture technology assessment is therefore capture from a flue gas for a ship engine running at 66% load producing 20,000 Nm^3/h flue gas with a CO_2 content of 3.7 vol%(wet) with LNG as fuel or 4.9 vol%(wet) with Diesel as fuel.

All CO_2 capture processes require significant energy input, bound by the fact that it takes energy to separate mixed gases. This specific energy demand increases with reduced CO_2 concentration in the flue gas. Ideally the energy required for the CO_2 capture process should come from the ship engines waste heat and onboard electricity production. In cases where the available surplus heat is insufficient, afterburning of fuel in the engine exhaust gas has been studied as an option for increasing the flue gas CO_2 capture ratio. The after burner will both increase the CO_2 content of the flue gas and increase the available waste heat in the flue gas.

The aspects of the base case with capture from a flue gas with low CO_2 content, limited onboard energy available and limited onboard space are critical factors restricting the available options for ship-based CO_2 capture. An initial technology screening assessment of available capture technologies at hand, concluded that absorption processes are by far the most viable option for the capture case at hand, given the low partial pressure of CO_2 in the flue gas, limited electric power onboard and waste heat from the engines as the main available energy source for the capture process. Application of an additional onboard power source dedicated for the capture process was not an option on the current case study.

2.2. Pragmatic approach for modeling and simulation of the overall process

SimpleSIM is a Python-based flexible simulator framework for feasibility assessments developed at SINTEF. In the current work, this simulator framework was applied for solving the mass and energy balances for the process concept outlined in Fig. 1. In SimpleSIM, each module (process block) is defined as an object and information (input, parameters and/or outputs) are connected to adjacent modules as required by the process flowsheet topology. The convergence of the overall process flowsheet is accomplished by consecutively solving each process block and checking for convergence when while updating selected recycle streams (so called tear streams) with direct substitution. This is similar to the approach used in conventional (commercial) sequential process simulators. However, the flexibility of a programming language like Python allows for more degrees of freedom, different level of process block detailing, advanced investigations, and fast

Table 1
Inputs, parameters, and outputs for each model of modules.

Module	Inputs	Parameters	Outputs
Engine module	Engine load - [-] fraction of max. power	Fuel type (LNG or Diesel)	Fuel consumption [kg/h] Flue gas flow rate [Nm^3/h] Flue gas CO_2 concentration [mol%] Flue gas temperature [°C]
Afterburner module	Flue gas flow rate [Nm_3/h] CO2 concentration in flue gas (mol fraction) [-] Flue gas temperature in [°C] Flue gas temperature out [°C] (after mixing from afterburner) Thermal energy demand in Capture unit [kW] Waste heat recovered from WHRU unit [kW] Engine fuel consumption [kg/h]	Flue gas heat capacity [kJ/(Nm^3K)] Fuel type (LNG or Diesel) Excess air factor	Heat produced [kW] Fuel consumption afterburner [kg fuel/h] Afterburner relative fuel consumption [%] Flue gas outlet flow rate [Nm^3/h] Outlet CO_2 mole fraction
Waste heat recovery unit module	Flue gas flow rate FG - [Nm3/h] leaving the Afterburner unit. Typically, in the range 36 000 – 100 000 Nm3/h depending on Engine load and fuel type. Flue gas inlet temperature TFG_{In} - [C] leaving the Afterburner unit. Typically, in the range 200 – 300 °C.	Flue gas exit temperature TFG_{Out} - [C] leaving the WHRU. Assumed to be 150 °C Thermal efficiency qEff - [-] compensating for heat loss and steam venting. Assumed to be 0.97 Flue gas heat capacity CpFG - [kJ/(Nm^3*K)]. Assumed to be 1.43 kJ/(Nm^3*K)	Thermal energy recovered Q_{WHRU} - [kW] Q_{WHRU} = FG / 3600 *Cp_{FG} * (TFG_{In} – TFG_{Out}) * qEff
Pre-treatment module	Flue gas flow rate FG - [Nm3/h] leaving the WHRU unit Flue gas inlet temperature TFGIn - [C] leaving the WHRU unit. Set to 150 °C	Flue gas exit temperature TFG_{Out} - [C] to enter the absorber. Set to 50 °C Flue gas heat capacity CpFG - [kJ/(Nm^3*K)]. Assumed to be 1.34 kJ/(Nm^3*K)	Gas cooling demand qCool - [kW]. q_{Cool} = FG / 3600 *Cp_{FG} * (TFG_{In} – TFG_{Out}) * qEff
The SINTEF SimpleSIM capture process module	Flue gas flow rate FG - [Nm^3/h] Flue gas CO_2 content [vol %] - model covers 1-12 vol % with best resolution in the range 1-6 vol % Desired CO_2 capture ratio [%] - model covers 40-95 % capture Absorber packing height [m] - model covers 5 -> 20-meter packing height Flue gas temperature into absorber [°C] – Current model only covers 30 and 50 °C. Dataset can be expanded. Gas side pressure drop between engine and absorber inlet, 10 [mbar]		Specific reboiler duty (SRD) [MJ/ton CO_2] Solvent circulation rate [l/min] - not applied in current simulator framework Required absorber cross-section area [m2] - derived from desired column superficial gas velocity and total flue gas flow. Capture plant flue gas blower electric duty [MW] - from absorber flue gas pressure drop and adiabatic compression work.
Compression and liquefaction modules	Gas flow rate [Nm^3/h] Gas temperature in [°C] Pressure out [bar]	Exergy efficiency Ambient temperature, [°C]	Power consumption [kW] Outlet liquid temperature [°C]

visualization of the parameter space.

The design parameters and assumptions embedded in each of the applied SimpleSIM process modules are described below and inputs, parameters and the output information are shown in the Table 1. The feasibility study investigated a range of design parameters, where each set of values represent a unique design point. The following design parameters were varied over the given ranges in the parametric study:

- Engine fuel type: LNG versus Diesel.
- Engine load: variations between 25 and 100%.
- Absorber CO_2 capture rate: variations between 50 and 90%.
- Absorber height: variations between 5 and 20 m absorber packing height.

Each point in the set of design parameters represents a unique design point. For a given design point analysis of transient behavior with respect to engine load could be performed. This has, however, not been part of the current scope of work.

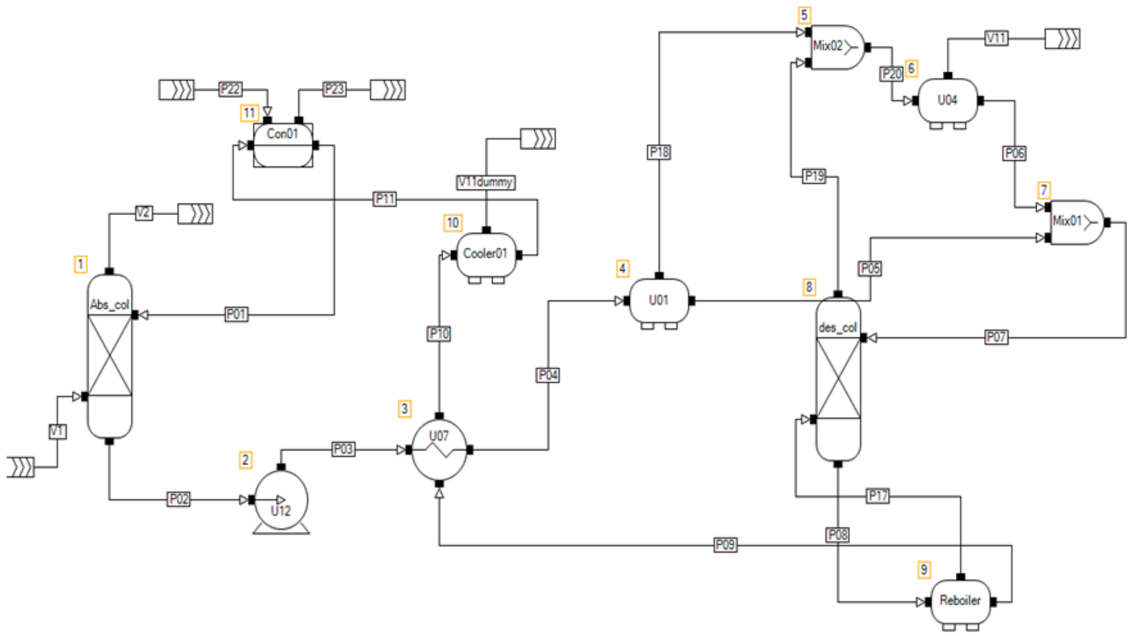


Fig. 2. Capture plant process flowsheet from the CO2SIM process simulator applied in the study.

2.2.1. *Engine module*

The engine used in the study is a MAN B&W S40ME-C9.5-GI, 5-cylinder L1. 5675 kW, which is a two-stroke, dual fuel engine. The engine selection is part of the ship concept D with 77,500 m^3 CO_2 transport capacity for shore-to-shore transport from Rotterdam to the Gulf of Mexico (Port Arthur) (SINTEF 2021), Engine calculations using MAN's web interface and engine datasheets have been performed by Brevik Engineering and the results are used for the simulations.

2.2.2. *Afterburner module*

In the afterburner unit, extra fuel is assumed to be burned with air and mixed with the flue gas from the engine. The amount of excess air is specified, and the outlet temperature calculated from the combustion enthalpy of the fuel (LHV), assuming ideal gas behavior and constant heat capacity.

2.2.3. *Waste heat recovery module*

The waste heat recovery unit (WHRU) cools down flue gas from the afterburner unit while producing hot water or saturated steam that is subsequently used in the CO_2 capture unit, party covering the solvent thermal regeneration requirement. The steam production rate (measured as thermal effect) of the WHRU is described by a simple energy balance for the flue gas, including a thermal efficiency loss due to heat loss and steam venting.

2.2.4. *Flue gas pre-treatment module*

Flue gas pre-treatment has not been considered in detail in this study and is expected to be very simple at least if LNG is used as engine fuel. However, since the main purpose of the WHRU unit is to recover sufficient heat to be used for operating the thermal regeneration of solvent in the capture unit, the exit flue gas temperature from the WHRU has been limited to 150 °C. This is too high as input temperature for the downstream absorber column, and a direct contact cooler (DCC) is therefore placed prior to the absorber to lower the input temperature to the target temperature of 50 °C and provide water saturation. The main purpose of the pre-treatment block is to lower the flue gas temperature which gives the cooling requirement. The DCC can also potentially function as a SO_x scrubber, by pH-regulation of the circulating water. This has not been assessed further in the current work.

2.2.5. *CO_2 capture module*

In the current feasibility study, special attention has been given to the CO_2 capture process unit of the flowsheet in Fig. 1. To allow for fast multi-parametric studies of the overall flow diagram, integrating the capture plant with ship engines and post treatment of CO_2, a data driven hybrid model of the capture unit was developed. The model (described in Chapter 2.2.5.2) was derived by supervised machine learning of a large data set of inputs and outputs of thousands of rigorous process simulations in CO2SIM (described in Chapter 2.2.5.1) with operating conditions spanning across the parametric ranges of interest. The resulting model enables very fast parametric studies of the CO_2 capture process. This new capture unit model thus represents the rigorous absorption-based capture unit subsequently as part of the feasibility framework allowing for fast and accurate calculations for parametric studies covering the full onboard capture process.

The SINTEF CO2SIM process simulator: CO2SIM is an in-house flow sheet simulator framework developed by SINTEF and NTNU (Tobiesen et al., 2007). CO2SIM provides a flexible and extensive simulation framework for solving a wide range of chemical processes related to CO_2 capture technologies. This rate-based simulator has been used for solvent development and process configurational studies and applied for simulations of system performance assessments of various solvents systems for post combustion CO_2 capture absorption processes. The simulator has robust computation numerical solvers and enables simulation of advanced process configurations for process optimization. The simulation models can describe the details of the system including rigorous vapor liquid equilibrium (VLE), reaction kinetics and transport properties. Further description of the specifics of underlying models used in CO2SIM can be found in Tobiesen et al. (2007, 2008, 2018) and Tobiesen and Schumann-Olsen (2011). The framework is also applied for dynamic simulations for advanced process control (Tobiesen et al., 2012). The simulator includes optimization procedures and methods for automatic handling of data obtained from different sources, such as pilot plants or industrial process data.

The CO_2 capture unit assessed in the current study is a generic absorption plant with absorber column, stripper column and reboiler. Fig. 2 shows the generic capture plant flowsheet applied in the study from CO2SIM.

The assessments have been based on application of MEA as CO_2 absorption solvent. MEA has become the benchmark solvent for CO_2

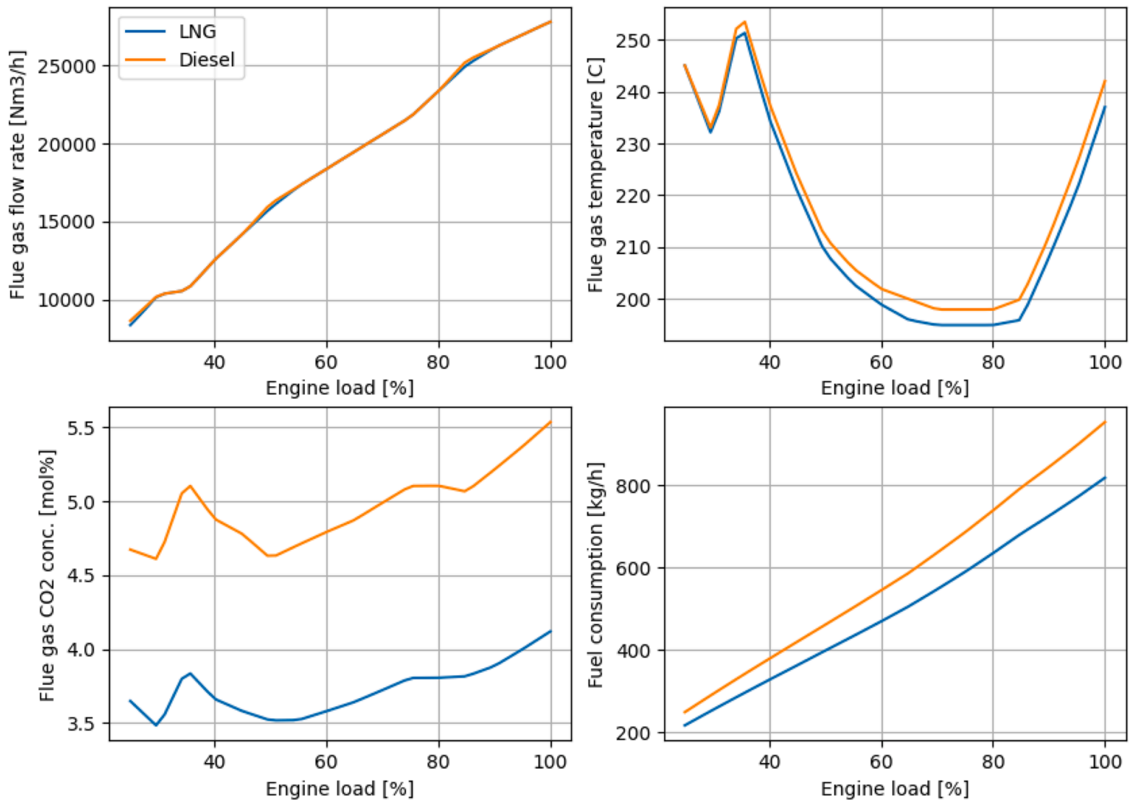


Fig. 3. Key engine performance parameters relevant for the waste heat recovery system.

absorption processes. State-of-the-art solvents may result in significantly lower energy consumption in the capture process, in some cases down to as much as 40% reduction compared to MEA (Tobiesen et al., 2018), however, MEA was chosen as basis for this study since it is so widely used, and proprietary solvents are not covered in the current study. The base case process as well as unit sizes have been determined from a standardized case with an inlet flue gas CO_2 content ranging from 1 to 12 vol%. It is assumed that the sizing of the plant is given, i.e., a range is given for the absorber height (all parameter and variable perturbations are shown in Table 1 which are inputs to the simulations). The CO_2 capture plant in Fig. 2 includes a flash which behaves as a water wash unit with a given cooling amount (a water wash assuming one full equilibrium stage, which is adequate for this study). This is equivalent to a water wash and has been done to reduce complexity and thus process calculations). The unit ensures water balance by returning reflux back to the main circulating solvent at a set temperature and pressure. The exit temperature from the absorber was assumed equal to the entrance temperature to the absorber (50 °C).

The crossflow heat exchanger lean approach was set to 8 °C), lean trim cooler temperature set to 40 °C (Cooler01), condenser temperature set to 40 °C (U04) and reboiler pressure to 195 kPa. The loadings are therefore calculated for each case, rich loading based on the absorber performance, whereas the lean loading by the reboiler duty and circulation rate. A control block (Con01) ensures that the full flow sheet can be solved, with MEA concentration, plant water balance and overall material balances maintained. During optimization, circulation rate and reboiler duty is minimized at a given capture rate such that the absolute minimum SRD is found at the given CO_2 input partial pressure. It is therefore assumed that the sizing of the plant is given, i.e., absorber and desorber height and internal diameter, cross flow heat exchanger lean pinch temperature (set to 8 °C), lean trim cooler temperature, condenser temperature and reboiler pressure. The loadings are therefore calculated for each case – rich loading based on the absorber performance (calculated), whereas the lean loading by the reboiler duty and circulation rate. An overview of such an optimization procedure can be found in Tobiesen and Schumann-Olsen (2011).

For each core capture simulation with different process conditions, the same base case flow sheet is thus used, which allows for creating a rapid trained model contained within the "Capture" unit of the SimpleSIM flow diagram, as shown in Fig. 1.

Machine learning model for fast calculations of the CO_2 *capture unit*: As the CO2SIM simulator is based on rigorous sub-systems for vapor liquid equilibrium, mass transfer and reaction kinetics, the flowsheet simulations take significant time to converge, each flow sheet simulation takes about 30 s. The Python- based SimpleSIM framework is a simulator based on a concept of rapid calculations in each module of the process flowsheet enabling fast assessments of parametric ranges. To include a rigorous capture module in SimpleSIM with fast simulations of CO2SIM quality outputs, a data-driven machine learning capture model was developed. A heuristically similar approach to machine learning of CO2SIM simulator outputs has previously been performed, but with the use of an artificial neural network model (Sipöcz et al., 2011) for creating the hybrid model. A REST-API (Representational State Transfer Application Programming Interface) was established to allow for remote simulator calls from Python to a central CO2SIM server. Through this API, CO2SIM simulation cases were automatically collected, with input parameters spanning over a large operational range, as depicted in Table 1. A "data-mining" script was written to create a dataset of more than 15,000 CO2SIM simulations of the capture process, running calculations over several days. The simulations covered variations in flue gas CO_2 contents, absorber bed heights, solvent circulation rates, reboiler duties and flue gas inlet temperatures for a capture process based on 30 wt% aqueous MEA. From this dataset, a refined dataset was produced, selecting cases of optimum solvent circulations rates for minimum specific reboiler duty result for each reboiler duty setting.

Based on the refined dataset of optimum simulation cases (Tobiesen and Schumann-Olsen, 2011), a multivariate PLSR (Partial Least Squares Regression) model was built for predicting optimized SRD (specific

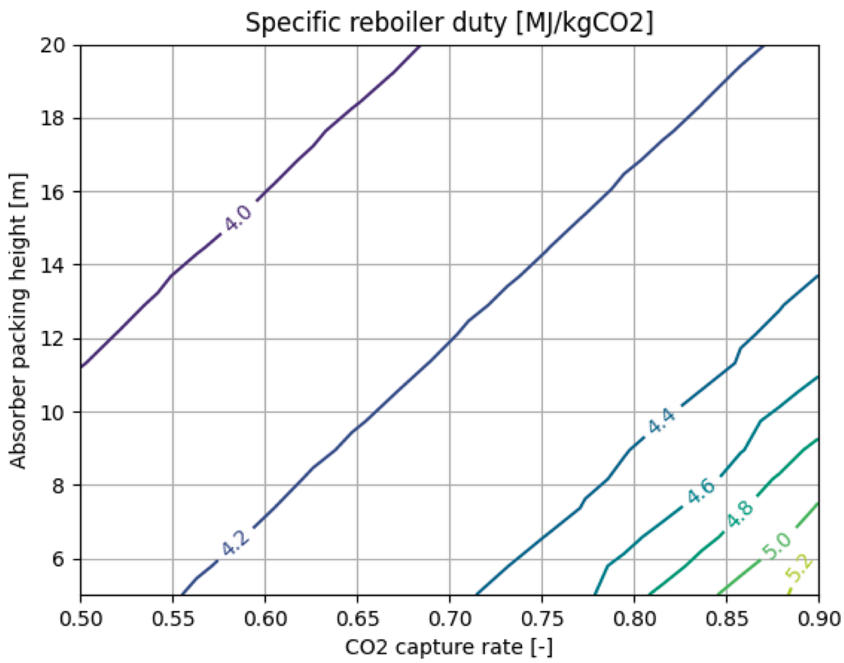


Fig. 4. Design trade-off between absorber height and CO_2 capture rate with respect to specific reboiler duty for a feed gas composition of 3.6 vol% CO_2 representative for engine exhaust operating on LNG as fuel.

reboiler duty) as a function of flue gas CO_2 content, absorber bed height and desired capture ratio (percent CO_2 captured from the flue gas). This data-driven hybrid model allows for very immediate estimates of SRD and was applied, derived from CO2SIM, as the core function in the capture process module of the SimpleSIM framework.

The created capture unit model also calculates estimates of electric flue gas blower duty, based on resulting absorber column pressure drop from a simple model derived from data from Sulzer MellapakCC-2 structured packings, and can return solvent circulation rates for the estimated SRD cases.

2.2.6. Compression and liquefaction module

Compression and liquefaction were calculated based on the thermodynamic theoretical minimum work and an exergy efficiency. The theoretical minimum work possible is the difference of the available work, $h\text{-}T_{0}s$, between the uncompressed CO_2 before the liquefaction and the final cold, liquid CO_2. Enthalpy, *h*, and entropy, *s*, are based on table interpolation. In practice, the liquefaction process is only about 45% efficient. Dividing by the efficiency we get the real work requirement of the liquefaction.

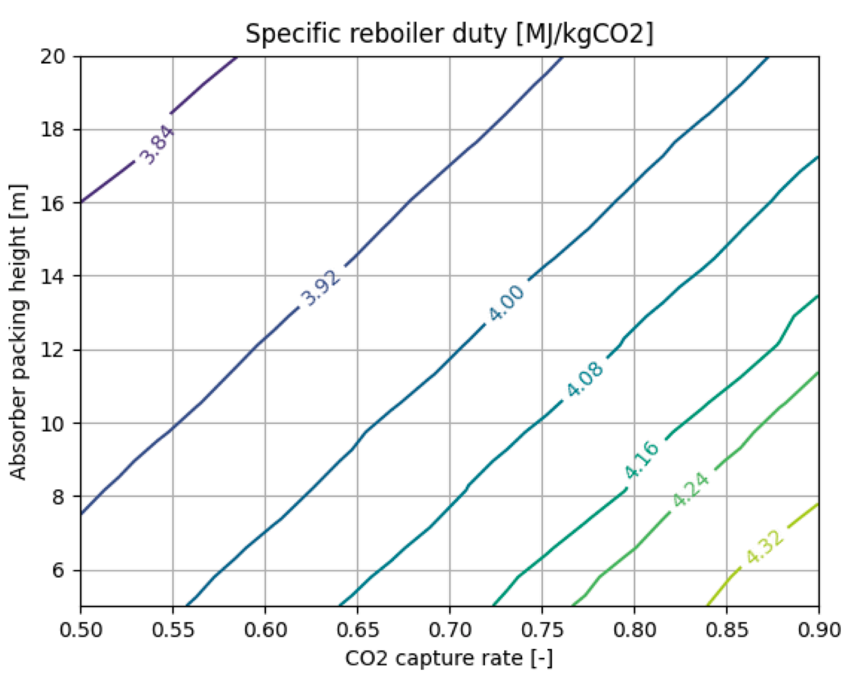


Fig. 5. Design trade-off between absorber height and CO_2 capture rate with respect to specific reboiler duty for a feed gas composition of 4.8 vol% CO_2 representative for engine exhaust operating on Diesel as fuel.

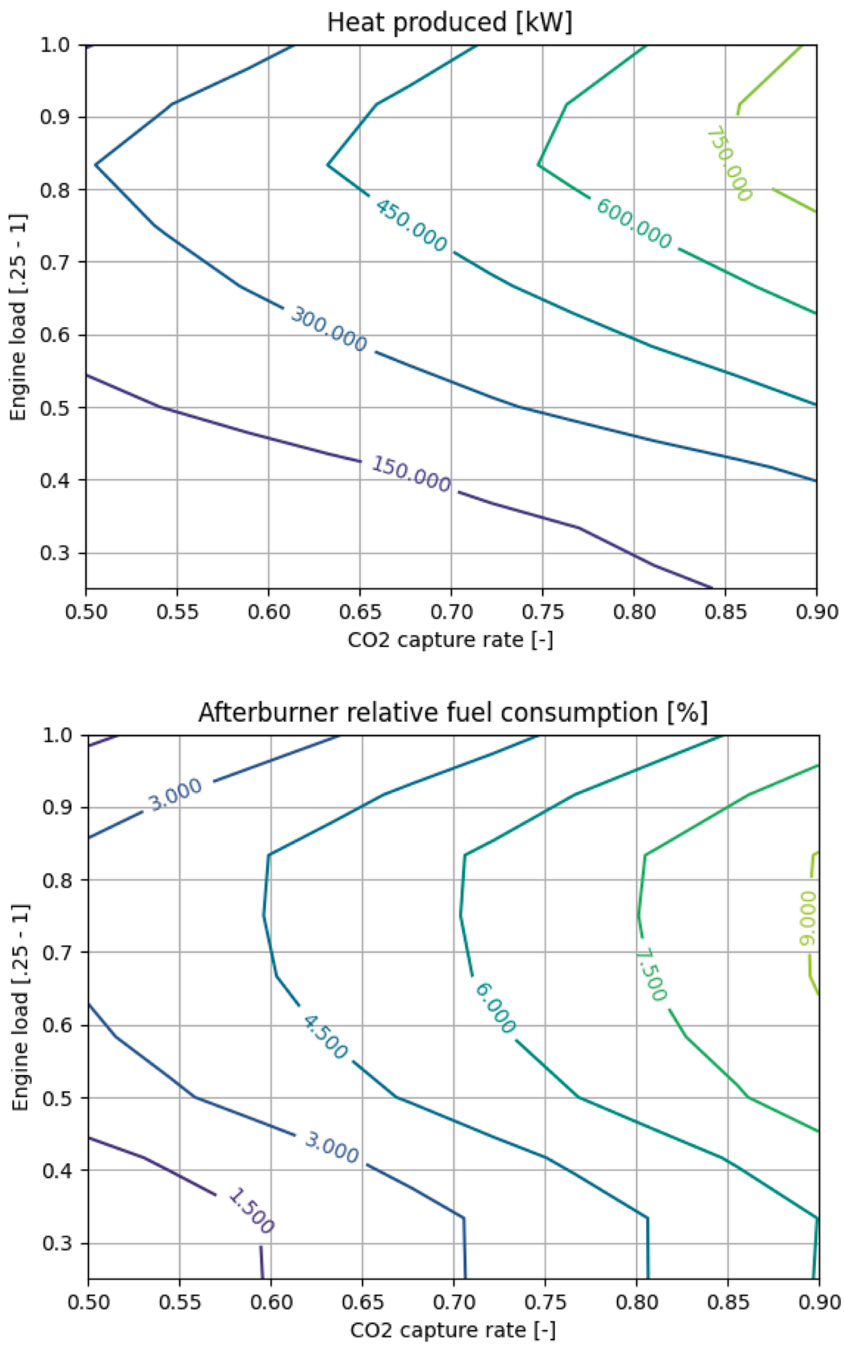


Fig. 6. Thermal energy production in afterburner required to match energy production in the waste heat recovery unit with the thermal energy demand in the CO_2 capture unit and afterburner relative fuel consumption. Assumptions: Absorber packing height = 20 m. Fuel source: LNG.

3. Results

3.1. *Engine performance and waste heat recovery*

Fig. 3 shows the results for estimated flue gas flow rate, temperature, CO_2volume fraction and fuel consumption as function of engine load for both LNG and Diesel fuels.

The ship engine is expected to be operating 66% engine load during normal operation, i.e., during normal sailing conditions. Thus, for each fuel type, the flue gas conditions (temperature, flow rate and CO_2 concentration) at 66% engine load was used as nominal design criteria for the capture process.

The recoverable waste heat from the engine to be provided to the CO_2 capture plant was found to be insufficient for 90% CO_2 capture. One possibility, for obtaining the additional heat required, is to burn extra fuel in an afterburner.

3.2. *CO_2 capture process performance*

A CO_2 capture plant can be designed with significant flexibility with respect to the engine flue gas conditions above and below the nominal point, however a detailed analysis of the capture performance away from the engine nominal point is not reported here.

Capture process specific reboiler duty (SRD) of the process was investigated as a function of absorption tower bed packing height and CO_2 capture ratio (% of CO_2 in flue gas captured) for diesel and LNG as engine fuel. Fig. 4 shows resulting capture unit estimates of SRD as a function of capture ratio and absorber height for a flue gas of 3.6 vol%

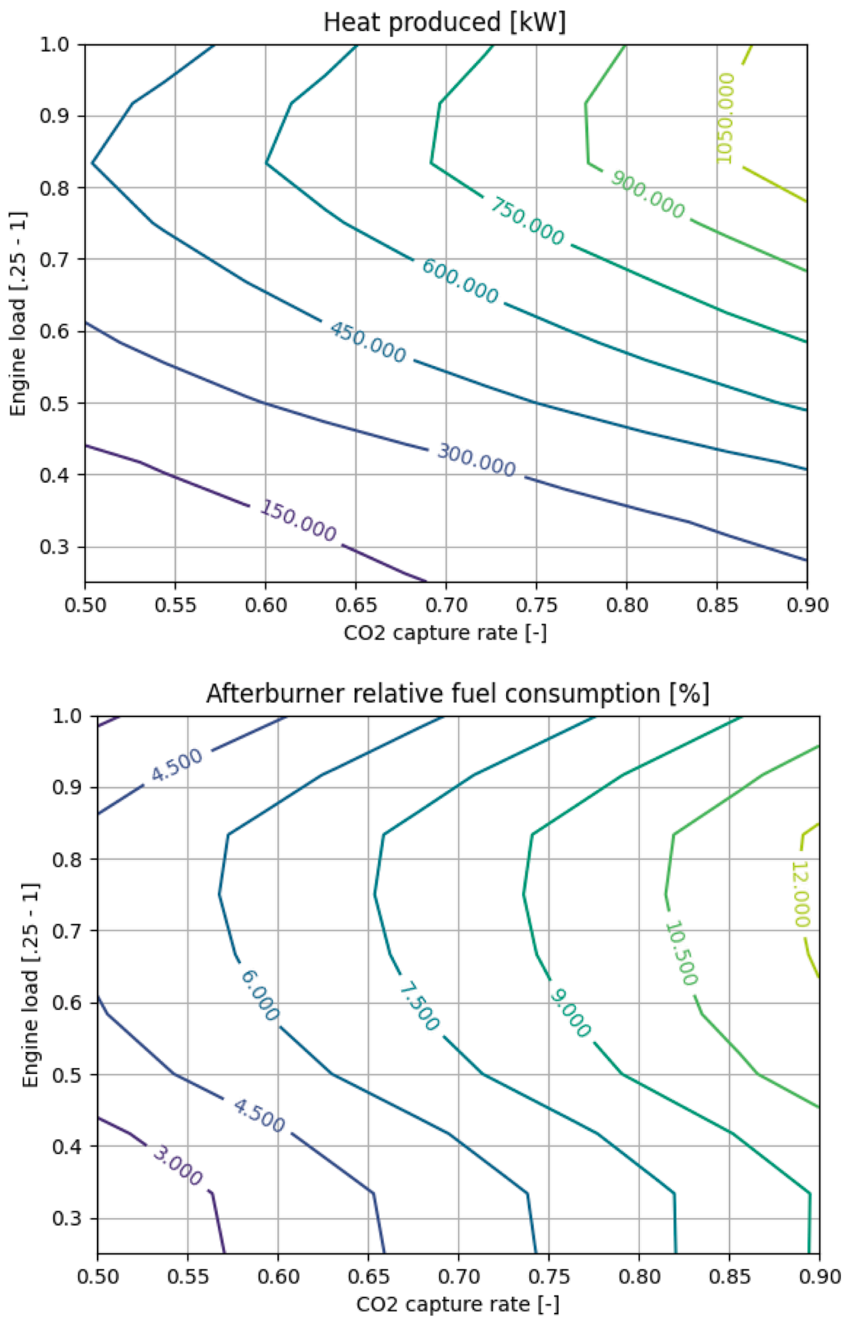


Fig. 7. Thermal energy production in afterburner required to match energy production in the waste heat recovery unit with the thermal energy demand in the CO_2 capture unit and afterburner relative fuel consumption. Assumptions: Absorber packing height = 20 m; Fuel source: Diesel.

CO_2 which is representative for a ship engine operating on LNG fuel.

The results show that a 70% CO_2 capture ratio when applying a reboiler duty of 4 MJ/kg CO_2 will require more than 20 m absorber packing height when applying 30 wt.% MEA as a solvent with LNG as engine fuel.

Fig. 5 shows resulting capture unit estimates of SRD as a function of capture ratio and absorber height for a flue gas of 4.8 vol% CO_2 which is representative for a ship engine operating on diesel fuel.

The results show that a 70% CO_2 capture ratio when applying a reboiler duty of 4 MJ/kg CO_2 only requires a 12 m absorber packing height when applying 30 wt.% MEA as a solvent with diesel as engine fuel. The reduction in needed packing height for diesel as engine fuel compared to LNG, is due to the increase CO_2 content in the flue gas for the diesel case.

As seen in Figs. 4 and 5, the minimum energy penalty option would require an absorber bed height of approximately 20 m, resulting in a total absorber tower height of more than 30 m. The overall process energy requirements, and not equipment sizing, has been the focus of this study. The onboard capture case at hand is challenging due to limited onboard energy available and a flue gas with low CO_2 content. These limitations are directly connected to the sizing of the absorber, which traditionally is the largest unit of the capture plant. The absorber height is a function of the required separation stages and depends on the solvent characteristics such as kinetics and capture capacity as well as the plant separation requirements.

3.3. Energy balance

An important question to answer is if waste heat recovery from the ship engine exhaust gas will be sufficient to cover for the thermal energy

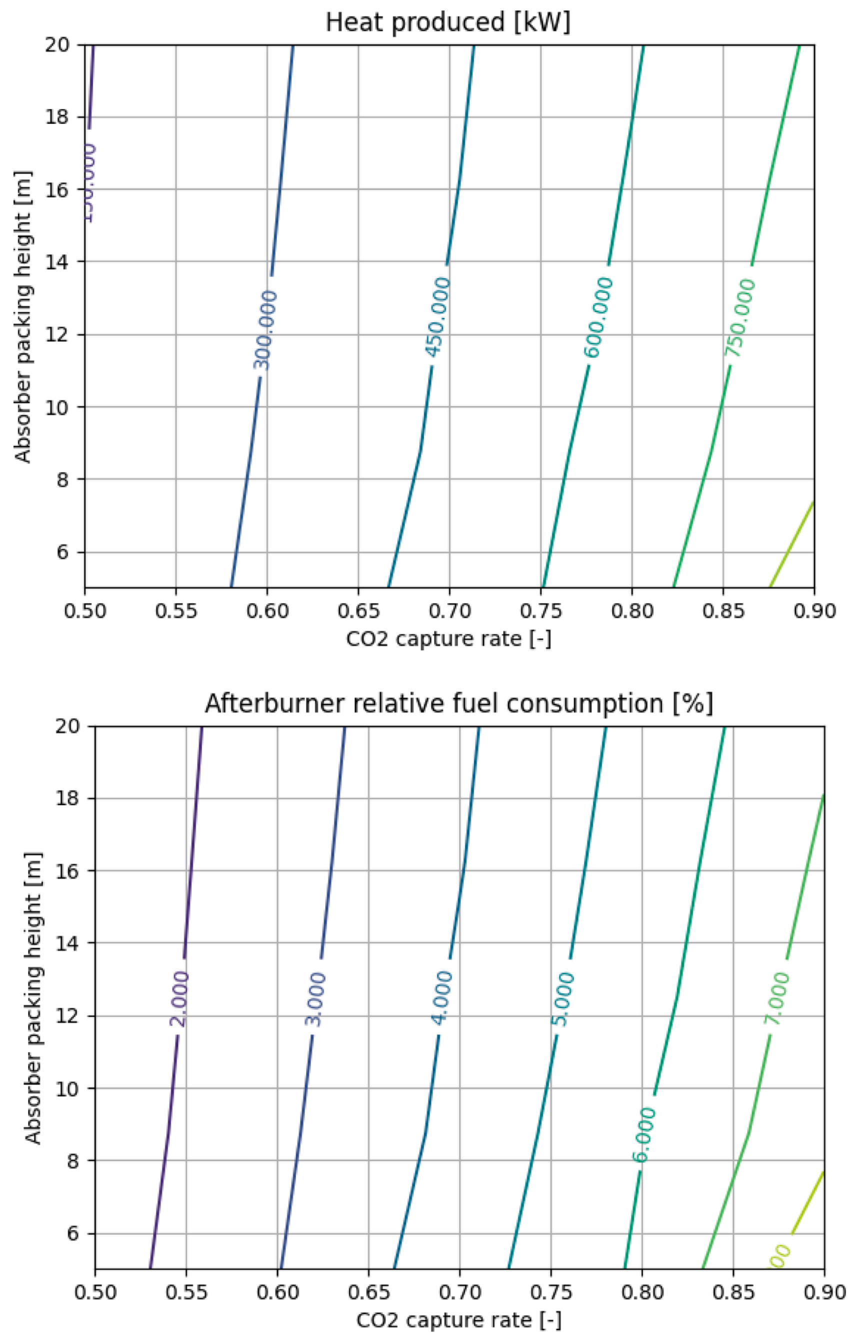


Fig. 8. Thermal energy production in afterburner required to match energy production in the waste heat recovery unit with the thermal energy demand in the CO_2 capture unit and afterburner relative fuel consumption. Fuel source: LNG. Nominal engine load: 66%.

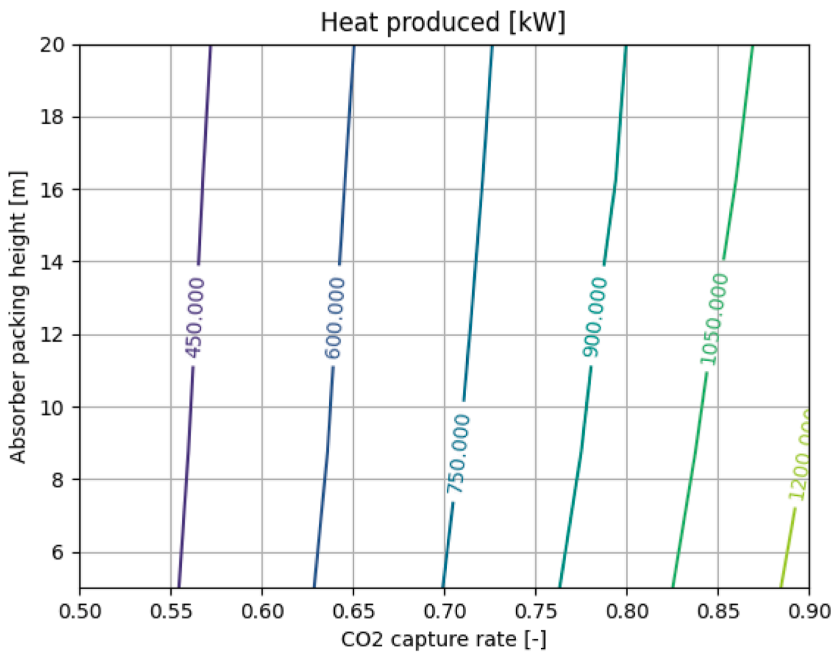
demand in the CO_2 capture unit. In the simulation model, the duty of the afterburner is adjusted to ensure that the energy produced in the waste heat recovery unit match the thermal energy demand from the CO_2 capture process. Fig. 6 shows the afterburner duty as a function of engine load and CO_2 capture rate when operating with LNG as fuel source.

The afterburner is required as an extra energy source even with CO_2 capture rates as low as 50%. The afterburner duty varies from 200–800 kW with a CO_2 capture rate of 90%. At 50% CO_2 capture rate the required afterburner duty is lower with a maximum around 300 kW at 85% engine load. The afterburner duty represents an increase in fuel consumption for the ship. The lower plots show how much the afterburner duty represents in fuel consumption relative to the fuel consumption in the ship engine at a given engine load. The fuel penalty from the afterburner represents 6–9% of the engine fuel consumption at 90% CO_2 capture rate. At 50% CO_2 capture rate the fuel penalty is below 3%.

Fig. 7 shows the corresponding results with diesel as fuel source. Even though diesel results in an exhaust gas with higher CO_2 concentration (Fig. 3) which results in lower a specific reboiler duty (Figs. 4 and 5), the amount of CO_2 to capture increases. Thus, the energy demand in the afterburner increases when switching from LNG to diesel as fuel. With diesel, the fuel penalty at 90% capture rate is in the range 9–12% (as opposed to 6–9% with LNG).

3.4. Absorber height for a nominal engine load

The CO_2 capture process needs to be designed for operation at a nominal engine load. In this work we have selected 66% engine load as the design point. Once the engine load is determined the effect of



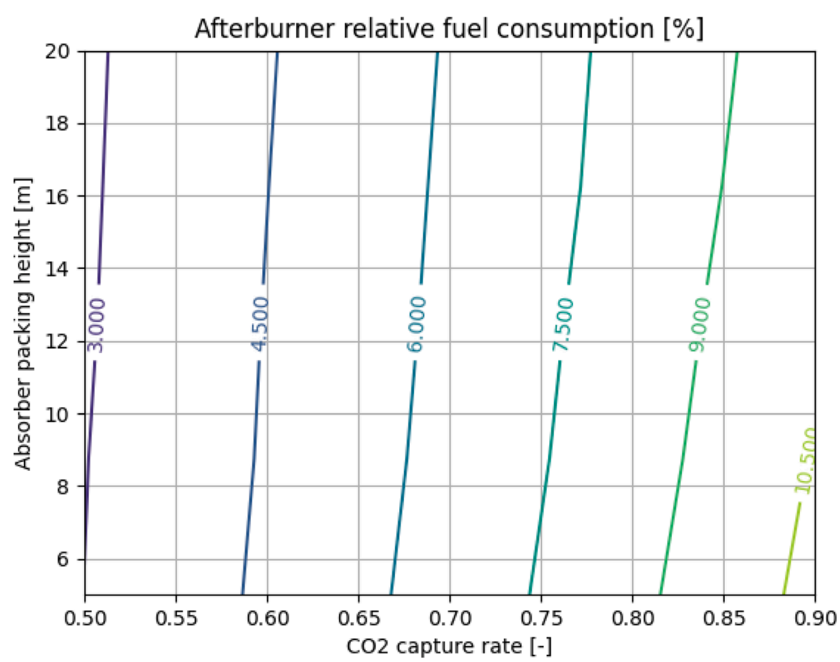


Fig. 9. Thermal energy production in afterburner required to match energy production in the waste heat recovery unit with the thermal energy demand in the CO_2 capture unit and afterburner relative fuel consumption. Fuel source diesel. Nominal engine load: 66%.

absorber height can be investigated for different CO_2 capture rates. Again, the main focus will be the fuel penalty for CO_2 capture versus the potential capital costs benefits which can be achieved by installing a short absorber. Fig. 8 shows the thermal energy production in the afterburner as a function of CO_2 capture rate and absorber packing height for an LNG engine.

As seen in the results, the dominant design parameter is the CO_2 capture rate. At any given capture rate, a reduction in the absorber height will result in relatively small increases in energy penalty, reflecting the fast CO_2 absorption kinetics of the MEA solvent. At 90% capture rate the relative fuel penalty increases from 6.5% with 20 m column packing up to slightly above 8% with a 5 m column packing. This allows for an interesting trade-off between capital and operating costs. Fig. 9 shows qualitatively similar results with diesel as fuel source.

Main outputs for estimation of capture plant size and footprint, were estimated based on absorber packing height and cross-sectional area. In addition to the absorber bed, it consists of a sump section, gas inlet section, liquid feed distribution sections, redistributor sections, water wash sections and demister sections (typically between absorber and water wash, between water was sections and on absorber flue gas outlet. The assessment performed shows that a tower with 20 m absorber packing will require a total tower height of more than 30 m. For a 10 m absorber packing section, total height could be around 20 m. The treated flue gas exiting the absorber also needs to be vented well above the ship deck. If the gas outlet of the absorber is on deck level (absorber located inside the hull), an additional chimney would require an additional blower or heating of the flue gas to create flue gas lift.

The absorber tower can also be split into several columns, depending

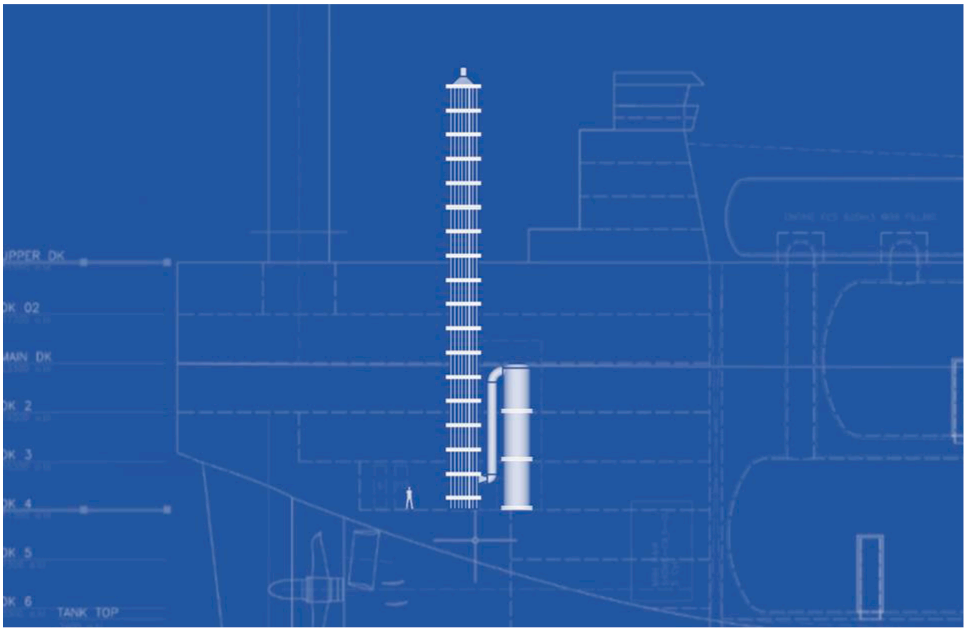


Fig. 10. A 35 m total height absorber tower and its DCC based within the ship hull (Ship drawing provided by Brevik Engineering).

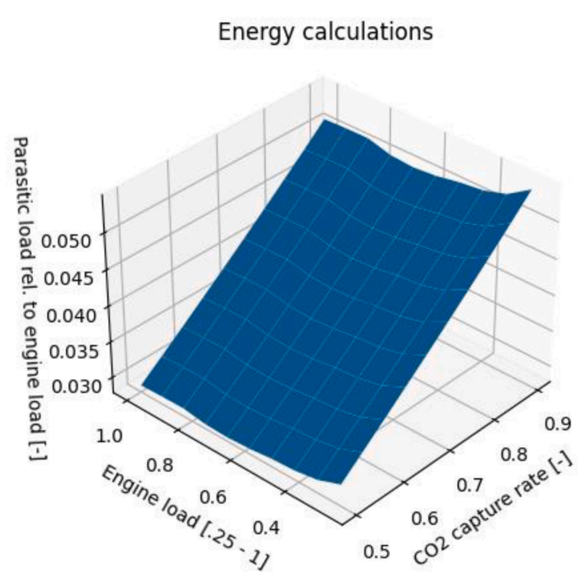


Fig. 11. Electric parasitic load relative to engine load with LNG as fuel. Absorber packing height 20 m.

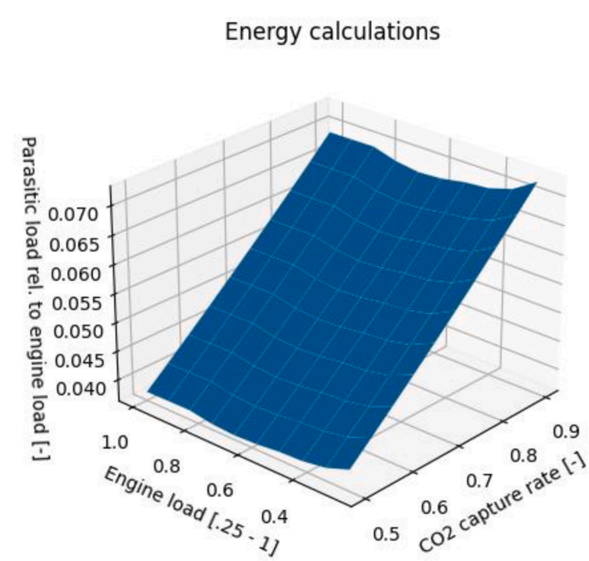


Fig. 12. Electric parasitic load relative to engine load with diesel as fuel. Absorber packing height 20 m.

on the available onboard space. Offshore operation might require additional redistributor sections to avoid potential liquid maldistribution in the packing. Design selection for absorber tower height will be a trade-off between energy penalty, CAPEX and physical integration of the onboard capture plant. Reducing the absorber tower height is an option, but the ship has room for application of a 'full-height' absorber minimizing the capture process energy penalty.

An illustration of a full-height onboard absorber is shown in Fig. 10. This tall absorber structure also allows room for additional redistributor sections in the column if needed for reducing liquid mal-distribution due to tilt during off-shore operation. Based on a parametric 3D CAD model – the figure shows the two largest process units of the capture plant positioned inside the ship, with the upper part reaching over deck as the ships chimney. The absorber tower with a total height 35 m absorber tower (20 m absorber packing) and the DCC for a capture scenario with column cross-sectional area according to a case of CO_2 capture from 36,000 Nm3/h flue gas.

The capture plant reboiler (not shown) is connected to the stripper, integrated with the steam system of the WHRU. One interesting option for further studies, could be to perform assessments of integrating the WHRU boiler in the reboiler design.

3.5. Electrical parasitic load

Electrical parasitic load was calculated with contributions from the units involving the capture process, compression, and liquefaction.

The main contributors to electrical parasitic load in the capture process outlined in Figs. 11 and 12 are linked to operation of the flue gas fan and the compression and liquification. Based on the assumptions outlined previously, the compression and liquefaction process represent more than 90% of the parasitic load. Figs. 11 and 12 shows the total electrical parasitic load relative to the engine duty as a function of engine load and CO_2 capture rate for either LNG or diesel as fuel. The CO_2 capture rate is the dominant factor and with LNG as fuel the total electric parasitic load vary from 3 to 5% with CO_2 capture rates from 50 to 90%. With diesel as fuel the corresponding variation range is 4–7%.

4. Conclusions

A technical initial phase feasibility study has been carried out for ship-based CO_2 capture. The results show that thermal energy extracted from the ship engine exhaust alone is not sufficient to cover the thermal energy demand of an MEA absorption-based CO_2 capture unit operating above 50% capture rate. This result contradicts Feenstra et al. (2019) reported findings that up to 90% capture rate was feasible by recovering the heat from the exhaust. This is clearly not the case in our analysis, and the application of piperazine, which is a more energy efficient solvent than MEA, cannot alone explain the difference in the results.

The thermal energy demand can be met using a fuel afterburner as supplying the additional heat required. The added fuel consumption from applying afterburning is estimated to increase the fuel consumption in the range of by 6–9% when operating with LNG as fuel source, while an increase of 8–12% is expected with use of diesel as fuel source. The effect of absorber height on energy consumption at a given CO_2 capture rate is limited in this particular case using MEA, especially for lower capture rates, and may be an important degree of freedom for optimizing the CAPEX/OPEX trade-offs. Integration of the ship engine WHRU in the capture plant reboiler design is seen as an interesting option for further studies to optimize the overall heat integration of the onboard capture system.

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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