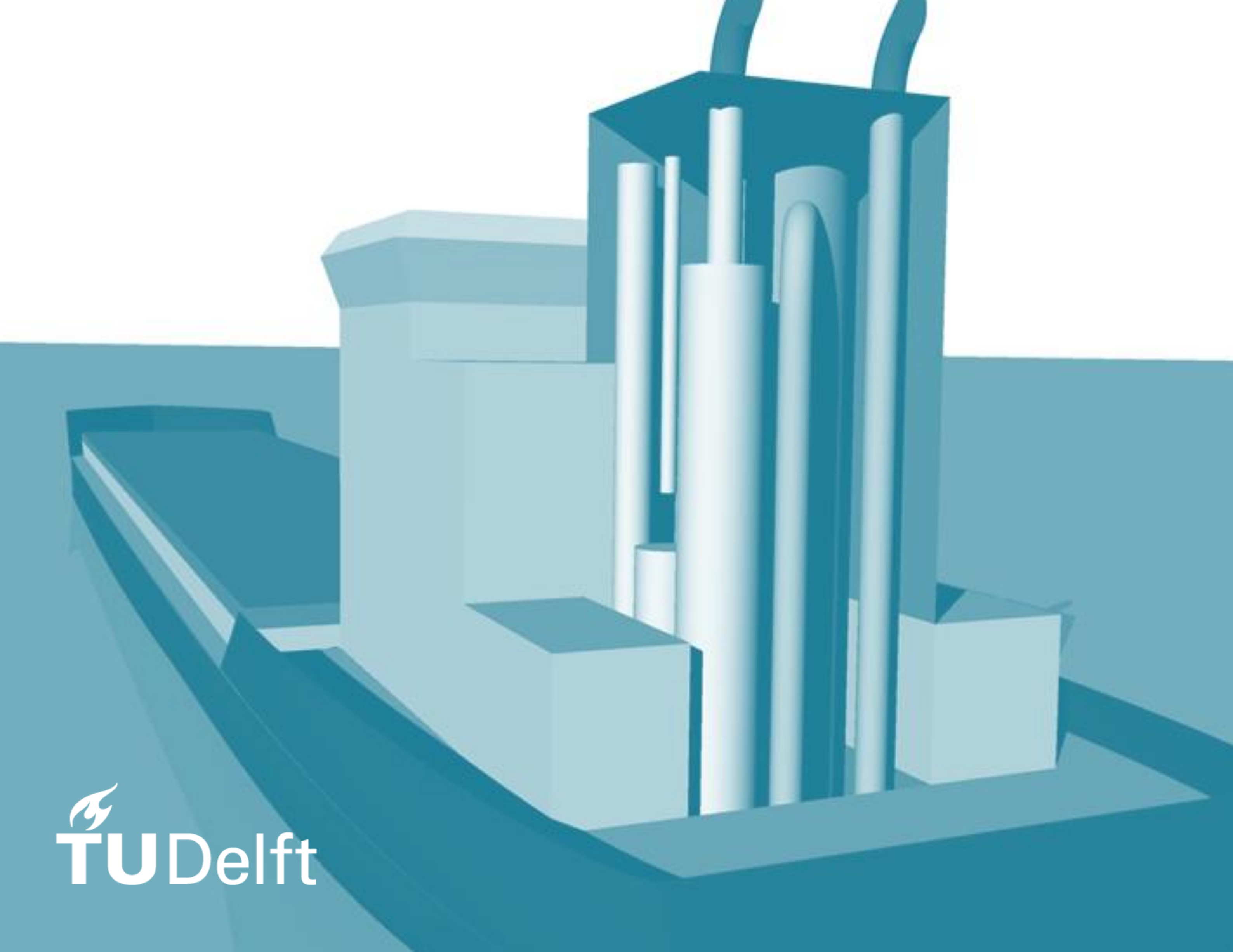
Carbon capture onboard LNG-fueled vessels

A feasibility study

J.T. van den Akker

Master of science thesis

Report number: SDPO.17.028.M



TU Delft

CARBON CAPTURE ONBOARD LNG-FUELED VESSELS

A FEASIBILITY STUDY

By

J.T. VAN DEN AKKER

In partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

IN MARINE TECHNOLOGY

At Delft University of Technology
To be defended publicly on Monday October 2nd, 2017 at 14:00

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An electronic version of this thesis is available at http://repository.tudelft.nl

TU Delft

Voor Huib

Van wie ik de liefde heb meegekregen voor zowel de techniek als de bootjes

ABSTRACT

Although shipping is by far the most carbon efficient mode of commercial transport, greenhouse gas emissions from shipping are estimated to be about 3% of total global emissions and at the moment are predicted to increase by between 50% and 250% in 2050. This is in conflict with cutting global greenhouse gas emissions by at least half in 2050, which is necessary for keeping global warming within the 2 degree limit. If left unregulated, international maritime transport is expected to be responsible for 17% of global greenhouse gas emissions in. To make things worse, renewable energy sources such as wind and solar power are no viable options for shipping yet, so the shipping industry could be stuck with fossil fuels for the coming decades.

A method to further reduce CO_2 emissions from fossil fuels is capturing carbon dioxide and storing it, thus preventing it from entering the earth's atmosphere. The Intergovernmental Panel on Climate Change (IPCC) sees Carbon Capture and Storage (CCS) as an important means of reducing global CO_2 emissions on a short term. Most research concerning CCS is focused on electrical power stations that use fossil fuels, such as coal- and natural gas fired power plants. CCS might however also be a method for reducing CO_2 emissions from shipping.

There are several methods for capturing CO_2 from carbon-based fuel. The one this thesis focuses on is called post-combustion capture, meaning that CO_2 is captured from the flue gases after the fuel has been combusted in a conventional engine. Exhaust gases from LNG fueled engines contain virtually no sulphur. Because of this, there is no need to pretreat the gases before entering the capture process.

The energy required for CO_2 capture and storage is reduced significantly by heat integration: the exhaust gases from the engine used to reheat the solvent in the stripper column. Additionally, the cold required for CO_2 liquefaction is provided for by the LNG, which is stored at -162°C and must be vaporated before entering the engine. Process design and simulation performed at TNO shows that the heat available in the exhaust gases is enough to capture over 90% of the CO_2 produced. Enough cold is provided by LNG vaporisation to store the CO_2 at around -22°C.

To investigate the feasibility of onboard carbon capture a concept design is produced and compared to a reference design. The reference design is an 8000 TDW general cargo vessel with a 3000 kW LNG fueled Wärtsilä 6L34DF engine. The reference vessel was lengthened by nearly 6 meters to accommodate for the system, as well as around 300 tonnes captured CO_2. Some parts of the system require a significant height, which is why most of the capture system is placed in the engine casing and funnel behind the accommodation. A redesign of the accommodation was necessary to make this possible. In order to keep the cryogenic lines as short as possible, the liquefaction of CO_2 takes place close to the LNG tanks, as this is done with the vaporizing LNG. CO_2 is stored below deck to safeguard the stability of the vessel. In order to keep the trim moment from the stored CO_2 low, most of the storage tanks are placed in the cofferdam between holds, near the longitudinal centre of buoyancy. The cofferdam was lengthened for this purpose. The remainder of the required storage space was found between the LNG tanks and the ship side.

Carbon capture combined with LNG as a fuel is very advantageous from an energetic point of view. It is technically feasible. The economic feasibility depends mainly on the capital cost and the economic advantage that can be obtained with the captured CO_2. The extra capital cost for carbon capture on a ship like the one described above is estimated to be 4.79 million euro. This would put the cost of carbon capture on around 74 euro per tonne CO_2 captured. If the captured CO_2 is sold, the net cost is estimated to be around 20 euro per tonne CO_2 captured. Furthermore, governments could help make onboard carbon capture economically feasible by putting in place some sort of climate policy for international shipping.

All in all, onboard carbon capture is a promising opportunity for achieving a more sustainable shipping industry.

PREFACE

This thesis is the result of the work I carried out between October 2016 and August 2017 at TNO in Delft. It also marks the end of my extensive period of studying Marine Technology at Delft University of Technology (TU Delft). I am very grateful to many people at TU Delft for helping me come to this point. A number of people however were vital in the coming about of this thesis. I would like to show my appreciation to them.

The idea of doing a graduation project on onboard carbon capture was sparked by Lex Vredeveldt, during a guest lecture he gave at TU Delft. Given the fact that this lecture had an entirely different subject and, as a matter of fact, was not even attended by me, it can be considered a small miracle that I ended up at TNO writing my thesis about on this. I am very grateful to Lex, not only for sparking the idea for this thesis, but also for allowing me the opportunity to do this graduation work at TNO and for his enthusiastic supervision during this period.

From the beginning, Earl Goetheer and Juliana Monteiro from TNO were more than helpful during my research. Without them, the scientific basis for this thesis would not have been as sound as it is, especially from a process technology point of view. I would like to thank them for allowing me to profit from all the time and effort they were willing to put into the project.

Furthermore, my gratitude goes out to Hans Hopman and Robert Hekkenberg for their feedback.

Lastly, and as events in the past year have made me realize, most importantly, I would like to thank my family and my girlfriend, Annette, for being there.

Joan van den Akker
Delft, September 2017

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LIST OF SYMBOLS

B	Beam
°C	Degrees Celsius
CH_4	Methane
CO_2	Carbon Dioxide
D	Depth
GM	Metacentric height
kW	Kilowatt
kWh	Kilowatt-hour
L_{oa}	Length overall
L_{wl}	Waterline length
NO_x	Nitrous oxides
m	Meter
rpm	Revolutions per minute
T	Draught
∇	Displacement

LIST OF ABBREVIATIONS

CCS	Carbon Capture and Storage
DCC	Direct Contact Cooler
DWT	Deadweight tonnage
ECA	Emission Control Area
ETS	Emissions trading scheme
IMO	International Maritime Organization
INDCs	Intended Nationally Determined Contributions
LNG	Liquefied Natural Gas
MEA	Monoethanolamine
PCC	Post-combustion Capture
PTO	Power take-off
SNG	Synthetic Natural Gas, Substitute Natural Gas
TDW	Tons deadweight
WHR	Waste heat recovery

1 INTRODUCTION

1.1 BACKGROUND

At the Paris climate conference in December 2015, 195 countries adopted a climate deal that aims to avoid dangerous climate change by keeping global warming under 2 degrees Celsius compared to pre-industrial levels. The deal is based on Intended Nationally Determined Contributions (INDCs). However, international aviation and shipping are excluded from this deal. It's up to these industries to cut greenhouse gas emissions themselves. Although shipping is by far the most carbon efficient mode of commercial transport, greenhouse gas emissions from shipping are estimated to be about 3% of total global emissions and at the moment are predicted to increase by between 50% and 250% in 2050. This is in conflict with cutting global greenhouse gas emissions by at least half in 2050, which is necessary for keeping global warming within the 2 degree limit. If left unregulated, international maritime transport is expected to be responsible for 17% of global greenhouse gas emissions in 2050 (Cames et al., 2015). To make things worse, renewable energy sources such as wind and solar power are no viable options for shipping yet, so shipping will be stuck with fossil fuels for the coming decades.

Shipping not only causes emissions of greenhouse gases but also of other harmful substances such as sulfur, nitrous oxides and particulate matter. To minimize the emission of these substances, the International Maritime Organization (IMO) has established Emission Control Areas (ECAs), in which limits are set to the emission of sulfur and nitrous oxides. To meet these limits, some ship owners turn to liquefied natural gas (LNG) as a fuel instead of oil because LNG has a much cleaner combustion. Another advantage of LNG is that CO2 emissions from LNG are slightly lower than those from fuel oil.

A method to further reduce CO_2 emissions from fossil fuels is capturing carbon dioxide and storing it, thus preventing it from entering the earth's atmosphere. The Intergovernmental Panel on Climate Change (IPCC) sees Carbon Capture and Storage (CCS) as an important means of reducing global CO_2 emissions on a short term. A lot of research is done lately regarding the subject. Most research concerning CCS is focused on electrical power stations that use fossil fuels, such as coal- and natural gas fired power plants. CCS might however also be a method for reducing CO_2 emissions from shipping.

Combining the use of LNG as fuel with carbon capture might provide benefits; LNG is a relatively clean-burning fuel, which makes CO_2 capture relatively easy. Moreover, it might be possible to use the ship's LNG tanks to store CO_2 when empty. This thesis focuses on the feasibility of carbon capture onboard LNG fueled ships.

1.2 OBJECTIVE

Following from the introduction given in section 1.1, the objective of this thesis is to investigate the feasibility of carbon capture and intermediate storage onboard LNG-fueled vessels as a means of reducing CO_2 emissions. This objective leads to four main research questions:

Is carbon capture and intermediate storage onboard LNG-fueled vessels technically feasible?
What would be the main design consequences of implementing onboard carbon capture and intermediate storage?
To what extent can CO_2 emissions be reduced by implementing onboard carbon capture and storage?
When is onboard carbon capture and intermediate storage economically feasible?

Each of these main research questions can be further specified. Research question 1 is the first question to be answered in this thesis. It can be split up into two parts, the first part being technical feasibility of onboard carbon capture and the second part being technical feasibility of intermediate (onboard) storage. Regarding this second part, it is interesting to find out whether it is possible to store the captured CO_2 in the ship's fuel tanks, as this would eliminate the need for dedicated CO_2 storage tanks, reducing the volume required for the capture- and storage system. Additionally, the capital investment for the system is expected to be reduced as well if no dedicated CO_2 storage tanks are required.

If question 1 can be answered positively, it is worth investigating how such a system can actually be fitted onboard a ship. How much volume will be required? How should the system be positioned onboard the ship? What are the consequences for the ship's stability? What about the ship's construction? These questions are all interconnected. An important factor in answering question 2 is whether the ship's fuel tanks can be used for CO_2 storage or that separate CO_2 storage tanks are necessary.

Question 3 relates to the main reason for investigating carbon capture: reduction of CO_2 emissions. It seems obvious that when capturing CO_2 from the flue gases, CO_2 emissions are reduced. However, 100% CO_2 capture is not likely to be obtained, and the capture- storage system requires energy, increasing CO_2 emissions. To what extent will the net CO_2 emissions be reduced?

Finally, to have any hope of being implemented, onboard CO_2 capture must be economically feasible. Hence question 4, the answer of which depends highly on the answers to the other three questions. Another relevant factor is whether the captured CO_2 can be sold (e.g. for use in greenhouses) or not. If it turns out that onboard capture is not feasible at the moment, suggestions will be done as to the required conditions to make it economically feasible.

1.3 METHODOLOGY

The first step towards achieving the objective formulated in section 1.2 is to conduct a literature research on the subject. No literature is known to the author regarding onboard carbon capture. However, a lot of research is available on the subject of carbon capture on land-based power plants. There are three main focal points in the literature research:

Capture method: a number of different capture methods exist, all of which have certain advantages and disadvantages. The main capture methods will be briefly analyzed, aiming to find the most suitable method for onboard capture.

Energy penalty: the most suitable capture method will then be further analyzed, focusing mainly on the energy requirements of the method. A good understanding of the working principle of the capture method is to be obtained, as well as an up to date picture of state of the art technology.

CO_2 storage: there are several methods for CO_2 storage. What the best method is depends on several factors. Based on literature, a proposal is done for the storage method to be used onboard ships. To the extent possible, the possibility of using the ship's fuel tanks for CO_2 storage is also investigated.

Once the working principles of the capture method are well understood and a picture has been formed of existing knowledge regarding the subject, a concept system design will be developed. To this purpose, an existing ship design will be selected to act as a reference ship. Based on this ship's required propulsion power, a propulsion plant concept is designed, including a carbon capture and storage system. The system design will be based on state of the art commercially available technology, so that implementation of a similar system on the short term is realistic.

After the dimensions of the system components have been determined, the system is fitted to the reference ship. Based on the premise that the new ship design, including carbon capture and storage system, is equal to the reference ship in terms of propulsive power and transport capacity, the reference ship design is adapted to accommodate for the capture and storage system.

Once the new concept design has been established, it will be evaluated to answer the third research question: how much CO_2 emission is avoided by the new design, compared to the reference ship? Related to this question is the economic feasibility: an estimation is done of the build- and operational costs of the system, so that a cost per tonne CO_2 avoided can be determined. The possibility of selling the CO_2 is also taken into account. A sensitivity analysis is carried out to check for the reliability of these results.

2 CARBON CAPTURE ONBOARD LNG FUELED VESSELS – AN EXPLORATION

As of yet, no ships exist that apply onboard carbon capture. It is thus a novel concept. The idea of carbon capture from exhaust gases itself is not new; the technology of capturing carbon from flue gas of land-based power plants is at an advanced level of development. A number of carbon capture plants are already in operation. In this chapter, the existing literature on carbon capture and storage (CCS) is reviewed and its applicability to the subject of this thesis is assessed. Section 2.1 focuses on the method used to capture CO_2. Section 2.2 discusses the energy required for capturing CO_2. The captured CO_2 must also be temporarily stored onboard, which is the subject of sections 2.3 and 2.4. The CO_2 can however not be stored onboard forever, so some sort of destination is needed for the CO_2 if it is not to be released in the atmosphere. This is what section 2.5 deals with.

2.1 CAPTURE METHOD

There are three basic systems that can be used for capturing CO_2 from fossil fuels: pre-combustion capture, post-combustion capture and oxy-fuel combustion.

In pre-combustion capture, the carbon that is present in the fuel (most fuels, such as oil, coal and gas, consist mainly of carbon and hydrogen) is separated from the hydrogen before combustion, using a sequence of chemical reactions. Consequently, the carbon is then stored or used for other purposes while the hydrogen is used for combustion. To apply this method, a new hydrogen fired engine type would have to be developed, along with a hydrogen production plant (off- or onboard) and hydrogen storage.

The oxy-fuel combustion process uses (nearly) pure oxygen for combustion instead of air. This results in a flue gas that contains mostly CO_2 and water. By cooling the flue gases, the water is then easily separated from the CO_2, after which the CO_2 can be stored. This process requires a supply of pure oxygen. Additionally, using conventional combustion engines for oxy-fuel combustion is impossible, as this would lead to excessively high flame temperatures and problems with flame stability. Hence, a new engine type would have to be designed for this purpose.

Post-combustion capture (PCC) refers to the removal of CO_2 from flue gases produced with the combustion, using air, of (fossil) fuels. Typically the PCC process uses a solvent to capture the CO_2 from the flue gases, although other methods are also studied, such as cooling the flue gas to a temperature at which the CO_2 solidifies, also known as cryogenic carbon capture (Jensen, 2015). PCC can be applied in combination with conventional combustion engines.

In terms of efficiency, the three capture methods have an overall similar performance (Abu Zahra, 2009). Both pre-combustion capture and oxy-fuel combustion however, require a complete redesign of both engine and its surrounding systems, whereas with post-combustion capture conventional combustion engines can be used. For this reason, this thesis will focus on post-combustion capture.

At this moment, the only method that is commercially applied for post-combustion capture of CO_2 is the absorption of CO_2 using chemical solvents. Other methods, such as adsorption and membrane based technologies might be promising for the future but are at the moment not mature enough for commercial application (Sanchez Fernandez, 2013). Another capture method is known as cryogenic carbon capture (Jensen, 2015). This method basically means cooling the gas to a temperature at which the CO_2 becomes liquid or solid. It is especially suited for CO_2-rich gas streams (80-90%). For gas streams with a lower CO_2 content, such as the flue gas from a gas fired internal combustion engine (about 5% CO_2, see Appendix A), this method is not very efficient as the entire gas stream must be cooled to cryogenic temperatures, requiring a lot of energy. Concluding, this thesis will assume absorption as the capture method, as it is the only option that is suitable for implementation on the short term.

Most of the research done for carbon capture is in relation to electrical power stations that make use of coal fired boilers or gas turbines. No research is known to the author concerning carbon capture from gas fired internal combustion engines. The flue gas conditions of gas fired internal combustion engines are however similar, in terms of CO_2 content, to flue gas conditions of gas turbines. Hence, this thesis' literature study makes use of figures from research that is done with regard to carbon capture from gas turbines. Literature concerning carbon capture from coal fired power plants is less relevant because the CO_2 concentration in flue gas from coal fired boilers is much higher than in flue gas from natural gas fired engines.

Figure 2.1 illustrates the PCC process using chemical solvents. Raw flue gas enters the absorber, where the CO_2 from the flue gas is absorbed by the solvent. This happens at relatively low temperatures, typically around 40 to 60 degrees Celsius. From the absorber, the CO_2-rich stream is pumped to the stripper. Here, the CO_2 is separated from the solvent, after which the solvent can be used in the absorber again. The CO_2 is led from the stripper through a condenser, to produce a nearly pure CO_2 stream. To separate the CO_2 from the solvent, heat is added. This added heat is the major energy penalty of the capture process. The stripper typically is operated at 100 to 120 degrees Celsius. By means of a heat exchanger between the lean stream and the rich stream, the energy penalty can be reduced.

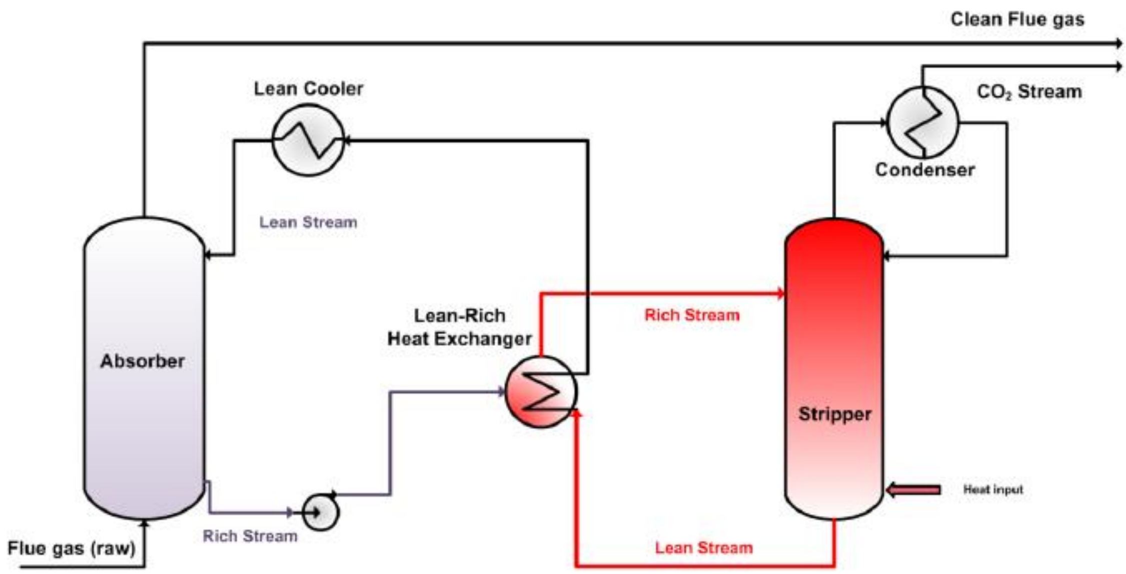


FIGURE 2.1: THE CONVENTIONAL POST-COMBUSTION CAPTURE PROCESS. SOURCE:(SANCHEZ FERNANDEZ, 2013, P. 8)

2.2 ENERGY PENALTY OF THE CAPTURE PROCESS

Efficiency of the capture process is highly dependent on the solvent used in the absorption process, as the desorption energy in the stripper dominates the energy penalty of the capture technology. Monoethanolamine (MEA), which is considered a 'conventional' solvent, requires around 3.5 GJ per tonne CO_2 captured. Literature indicates that for a gas fired power station this would result in an energy penalty of around 16% compared to a reference case with no carbon capture (Sanchez Fernandez, 2013, p. 46). However, significant developments are taking place with respect to the solvent used; the Siemens PostCap process uses Amino Acid salt of which the regeneration energy is reported to be only 2.7 GJ/tonne CO_2(Siemens, 2015). Mitsubishi's amine mixture is also said to have a heat requirement of less than 3 GJ/tonne CO_2 (Sanchez Fernandez, 2013).

Modern gas fired power stations, such as the ones used in the abovementioned studies, have an elaborate system for recovering the energy from the exhaust gases from the gas turbines. As a result, as little as 6% of the thermal power input is left in the exhaust gases when they are released into the atmosphere (calculated from(Sanchez Fernandez, 2013, pp. 39,44), based on an exhaust gas specific heat of 1kJ/kgK). On ships, waste heat recovery (WHR) is much less common. Most ships have no other system for heat recovery from the exhaust gases than the engine's turbocharger. As a result, more than 25% of the thermal energy input is still present in the exhaust gases as they leave the chimney. This provides an opportunity to reduce the extra energy input required for CO_2 capture, as the heat present in the exhaust gases can be put to use in the stripper column.

2.3 ONBOARD STORAGE OF CO_2

Several strategies for onboard CO_2 storage can be explored. Storing the CO_2 in a gaseous state is not an option, as the required storage volume would be much too large. Thus, the CO_2 should be stored either in solid or in liquid state.

2.3.1 SOLID STORAGE

For storing the CO_2 in a solid form, there are two possible strategies. The first one is to cool the CO_2 to a temperature at which it solidifies. At atmospheric pressure, this temperature is -78°C (Figure 2.2). At this pressure and temperature, the enthalpy of sublimation of the gas is 573 kJ/kg (NIST, 2016). That is, apart from cooling the gas to -78°C, another 573 kJ of energy per kilogram of CO_2 has to be removed from the gas in order for it to solidify. This amount of cooling will require a significant amount of energy.

Another way to store CO_2 in a solid form is to bind it chemically to another substance. There is some research that suggests this might be a feasible method of storing CO_2 onboard a ship (Wang, 2017). However, this research remains limited to some lab experiments. It is not yet a mature technology, ready to be applied on a commercial scale. Furthermore, binding the CO_2 to another substance would require this other substance to be available onboard, which would mean a significant increase in weight for the ship to carry.

A downside of storing CO_2 in its solid state is that for it to be practically feasible onboard a ship, whether cooled or chemically bound, a reliable system for handling the solid CO_2 would have to be designed. Specifically for the cooled CO_2 this would have to be a closed system, as sublimating CO_2 could otherwise expel the air from the engine room, creating the hazard of asphyxiation of the crew. Designing such a system could prove to be a challenge.

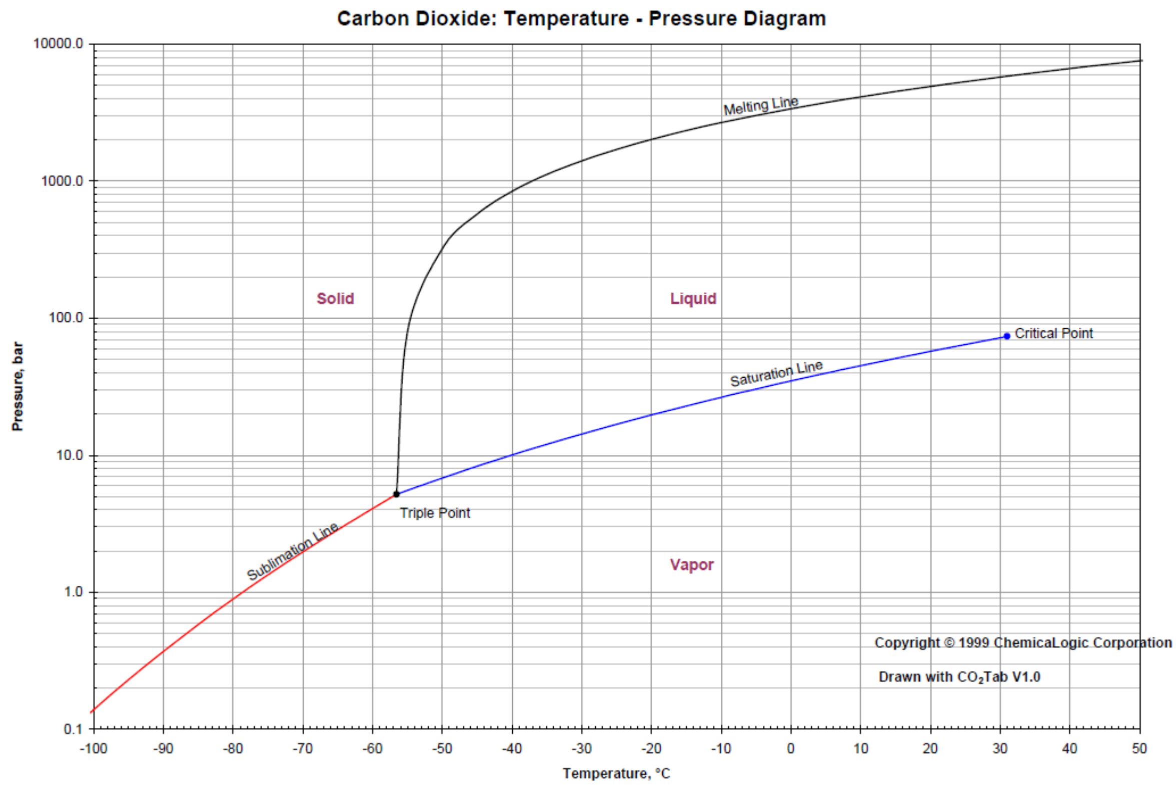


FIGURE 2.2: CARBON DIOXIDE PHASE DIAGRAM

2.3.2 LIQUID STORAGE

Liquid CO_2 has the advantage of being easily handled by means of pumps. To store CO_2 as a liquid, a number of strategies are possible. The difference between these strategies is the temperature (and, consequently, pressure) at which the CO_2 is stored. Carbon dioxide has its triple point at 5.18 bar and -56.6°C. This means that at atmospheric pressure CO_2 only exists in gaseous and solid states. To store it as a liquid, a pressure of at least 5.18 bar is required. However, storing the CO_2 close to its triple point entails the risk of the formation of solid CO_2. This is undesirable, because it could clog the piping and would be hard to remove from the storage tank. Consequently, the CO_2 should be stored well above its triple point.

For ship transport of large volumes (in excess of 10,000 tonnes) of CO_2 the recommended pressure is around 7 bar at -50 degrees Celsius (Mitsubishi Heavy Industries, 2004). This is mainly because a low pressure enables the use of large storage tanks, decreasing the building costs of these tanks. Depending on the size of the gas engine, the required storage volume will be lower than this; a 3000 kW gas engine emits just under 30 tonnes of CO_2 per day (Appendix A). This means that for a 2-week trip approximately 400 tonnes of CO_2 would have to be stored onboard. For volumes this size, a higher pressure and consequently a higher temperature are feasible, requiring less cooling and thus less energy. Initial inquiry indicates that the most economical pressure for storage of this kind of volume is 16-18 bar (Pentair Haffmans, 2016). The temperature would then be -24 to -26 °C. This is consistent with recent research showing that a pressure of around 15 bar would be the most cost effective pressure for CO_2 transport by ship (Seo, Huh, Lee, & Chang, 2016). For this research, it is thus assumed that the captured carbon dioxide is stored as a liquid at 16 bar.

2.3.3 STORAGE OF CO_2 IN FUEL TANKS

To reduce the costs of onboard carbon capture, it is interesting to research the possibility of storing the captured CO_2 in the LNG tanks that are already present onboard, when these run empty. This way, the capital investment could be reduced. Additionally, volume required for the capture system is expected to be smaller, resulting in a higher cargo volume for the ship.

A number of things should be considered when investigating the technical possibility of CO_2 storage in the ship's LNG tanks:

LNG is usually stored and handled at pressures ranging from ambient pressure up to 10 bar. For CO_2, a minimum pressure of around 7 bar is required to prevent it from becoming solid. To reduce the energy required for liquefaction, a higher pressure of 16-18 bar is more favorable. The tank must be able to handle this pressure.

LNG is stored at around -160°C. The liquefied CO_2 will have a temperature of around -26°C. The tank temperature will thus fluctuate between these temperatures. This could lead to fatigue problems. To reduce the temperature difference, it might possible to store the LNG at a higher pressure and temperature, for example 15 bar and -120°C.

The fuel should not be contaminated with CO_2, as this could lead to the fuel lines being clogged with solid CO_2. All CO_2 will thus have to be purged from the tanks before they are refilled with LNG.

Before filling the tank with CO_2, it should be emptied as much as possible, as all fuel left in the tank is rendered useless for propulsion once CO_2 enters the tank. Moreover, when a lot of LNG is present in the tank, CO_2 will solidify upon entering the tank as liquid CO_2 cannot exist at the temperature at which LNG is stored. Adding the heat from the CO_2 to the LNG would make the LNG evaporate, resulting in a high tank pressure.

Liquid CO_2 at 18 bar and -24°C has a density of just over 1 tonne/m^3, which is more than twice the density of LNG (around 0.45 tonne/m^3). The tank and its supporting structure should be able to handle the increased loads that follow from this higher density.

Little literature on using tanks for both LNG and CO_2 is known to the author. Some attention was given to the subject in connection with CO_2 transport (Mitsubishi Heavy Industries, 2004, pp. 19-20). Actual research is lacking, however.

2.4 EXTRA ENERGY PENALTY AS A RESULT OF CO_2 LIQUEFACTION

In the studies mentioned in paragraph 2.2, the captured CO_2 is compressed to a supercritical state, around 100-110 bar at ambient temperature for pipeline transport. As mentioned in paragraph 2.3.2, in this study an onboard storage pressure of 16 bar is assumed, with consequently a temperature of around -26°C. For cooling the CO_2 to this temperature, more energy is required than for compression at ambient temperature to 100 bar.

For compression of CO_2 to 110 bar, around 0.31 GJ_e/tonne CO_2 is required (Sanchez Fernandez, 2013, p. 46). This translates to around 86 kWh per tonne CO_2. As for the liquefaction of CO_2 to 18 bar and 24°C, the required energy is estimated to be around 130 kWh per tonne CO_2 (Pentair Haffmans, 2016), which is 44 kWh more. A lower power requirement is calculated by (Seo, Huh, Lee, & Chang, 2016). Their study mentions a power requirement of 12 MW for the liquefaction of 112 tonnes CO_2 per hour (107 kW/kg CO_2).

In comparison, the energy required for capturing the CO_2 from the flue gases is around 3 GJ/tonne or 830 kWh/tonne (part of this energy, however, can be provided by waste heat in the flue gases). This is much more than the energy required for liquefaction. Consequently, liquefaction of CO_2 is expected to be an important, but not the primary energy consumer in the capture and storage process.

The energy required for compression of the CO_2 is electrical and must be supplied by either a power take-off (PTO) from the main engine or an auxiliary generator. The energy required for cooling the CO_2 to its storage temperature is however thermal energy, which could be supplied by a cold source, if available on the ship. In the case of an LNG powered vessel, the fuel could provide for such a cold source; LNG is stored at -160°C, and must be heated to at least 0°C before it enters the engine. Usually, this is done in an evaporator, using heat from the ship's cooling water. The LNG could however also be evaporated with heat from the CO_2, thereby cooling the CO_2. This would significantly reduce the required power for cooling the CO_2 to its storage temperature.

2.5 DESTINATION FOR THE CAPTURED CO_2

If one does not want to release the captured CO_2 into the atmosphere, which of course would be a waste of effort and energy, it is wise to think about what should be done with the CO_2 when it is offloaded from the ship.

One solution, which is often referenced to when it comes to carbon capture from land based power plants, is to put the CO_2 underground. Depleted oil and gas fields can be used for this purpose. CO_2 can even be used to facilitate oil recovery from oil fields that are nearly depleted, known as enhanced oil recovery (EOR). In fact, this is already being done with captured CO_2 today (Global CCS Institute, 2016). It could however be perceived as ironic that CO_2, captured with the objective of mitigating climate change, is used to pump up fossil fuels.

Another solution, instead of storing the CO_2, is to use the CO_2 for other purposes, such as the food and beverage industry. One possible use is specifically interesting for the Dutch market: the Dutch greenhouse horticulture industry requires large amounts of CO_2 to grow its crops. At the moment, this CO_2 is supplied to the greenhouses in various ways. Most of it is produced by means of combined heat and power (CHP) installations (Mikunda, Neele, Wilschut, & Hanegraaf, 2015). These CHP installations are however not always efficient as CO_2 demand can occur while no heat (or power) is required, especially during the summer months. This is why an external CO_2 supply is preferred from an environmental point of view. External CO_2 is supplied to greenhouses by trucks, but many greenhouses in the Netherlands are connected to a CO_2 pipeline that runs to the greenhouses from the Maasvlakte, where CO_2 is produced as a byproduct at some chemical plants (Mikunda, Neele, Wilschut, & Hanegraaf, 2015). More and more greenhouses are being connected to this pipeline, and the demand for external CO_2 is high (OCAP, 2017). CO_2 from ships calling at the Port of Rotterdam might be used to add to the CO_2 supply via this pipeline.

A third option, which is a very interesting one albeit it might not yet be applied in the immediate future, is the concept of a sustainable carbon circulation: as the use of fossil fuels is likely to be phased out in the coming decades, surrogates for these fuels are being devised, such as biofuels or synthetic natural gas (SNG) produced from CO_2 and electric energy from renewable sources(Sterner, 2009). In the future it might be possible to have a ship sailing on synthetic natural gas, while capturing the CO_2 from the exhaust gas, so that this captured CO_2 can be supplied to the SNG plant which in turn produces fuel for the ship. This way, a sustainable carbon cycle could be realized.

Summarizing, several options exist as a final destination for the captured CO_2. This thesis however, the focus is on the ship and its technology onboard. Hence, for the purpose of this thesis no assumptions are made about the exact destination of the CO_2 and it is assumed that a suitable destination exists, along with an infrastructure for offloading it from the ship.

3 CAPTURE SYSTEM DESIGN

In this chapter, the design of the capture system is described. Before a capture system can be designed, it is necessary to know the amount of exhaust gases that need to be treated, as well as the characteristics of these exhaust gases, such as temperature and composition. In other words, the engine type and its characteristics must be known. The engine type in turn depends on the type of vessel, so the first steps in designing a capture system are determining the vessel type and selecting an engine. This is described in section 3.1. After that a description is given in section 3.2 of the system that was designed at TNO, based on the supplied engine data.

3.1 THE VESSEL

In this section the vessel type and engine are described. First, a description of the vessel type is given and the choice for this type of vessel is motivated. Next, the engine and its characteristics are discussed. Again, the choice for the engine is motivated.

3.1.1 VESSEL TYPE

To be able to evaluate the technical and economic feasibility of onboard carbon capture and intermediate storage, the choice is made to base the concept design on a benchmark design for an LNG-powered vessel. This way, the new design can be compared to the original design.

The benchmark is an 8000 DWT general cargo vessel design by Conoship. This type of ship is very common in European waters.

There are a number of considerations that led to this specific benchmark design:

- Availability: preferably, an existing design is used. Apart from saving out the effort of designing a complete LNG powered vessel as a benchmark design, it also ensures that the design is realistic.
- Commonness: to make this study broadly applicable, a very common ship type is chosen; the general cargo ship is the workhorse of European shipping. If onboard CCS proves to be feasible in this study, it is plausible that it could successfully be applied on a lot of general cargo ships.
- Waste heat recovery: the heat left in the flue gas is used for the capture process. To maximize the available heat, a design is used that has no extensive provisions for waste heat recovery. This requirement is not unrealistic, as general cargo vessels of this size typically don't have any provisions for waste heat recovery from the flue gases.
- Simplicity: for an initial feasibility study, a relatively simple ship type is preferred. This reduces the number of complicating factors in adapting the design, and allows for comparison between the concept and the benchmark design.

3.1.2 ENGINE CHARACTERISTICS

The benchmark ship is powered by a 3000 kW Wärtsilä 6L34DF dual fuel engine. This engine size is broadly applied in general cargo ships. This specific engine type is capable of running on LNG (with a small amount of diesel as a pilot fuel) and marine diesel oil (MDO). Engine characteristics are publicly available and are shown in Appendix B.

It is assumed that the maximum power supplied by this engine is sufficient for any extra power consumption required by the CCS system, because the capture system will be designed to function without adding any extra heat apart from the heat available in the flue gas. The system will only need electric power for pumps, fans and compressors.

Based on the engine characteristics the flue gas composition is calculated with a focus on the CO_2 content of the flue gas. For these calculations, some assumptions are made regarding the composition of the LNG used for combustion.

The CO_2 content in the flue gas is dependent on the composition of the LNG that is combusted. LNG consists mostly of methane (CH_4). Other components are ethane (C_2H_6), propane (C_3H_8) and nitrogen (N_2). Usually, a small amount (0 to 1.5%) of other hydrocarbons is present in the LNG. For ease of calculation, it is assumed that the only components available in the LNG are methane, ethane, propane and nitrogen.

The engine characteristics supplied by the engine manufacturer are based on LNG with a lower heating value (LHV) of 49,620 kJ/kg (see Appendix B). For the sake of consistency, the same LHV is used to determine the LNG composition with which the flue gas composition is calculated.

With the abovementioned assumptions, the LNG is determined to be composed of 92% methane, 5% ethane, 2% propane and 1% nitrogen. These are molar percentages. Using this LNG composition and assuming low-sulfur marine gasoil (MGO, ISO-F-MDA) as pilot fuel, the flue gas composition is calculated, assuming full combustion of the LNG. Only the main constituents are calculated; any contaminants present in the combustion air, for example, are neglected. The resulting flue gas composition is shown in Table 3.1.

	share (molar)	mol/h	kg/h
N2	74,0%	4,36E+05	12219
O2	9,9%	5,83E+04	1866
Ar	0,9%	5,59E+03	223
CO2	4,8%	2,85E+04	1254
H2O	10,4%	6,12E+04	1103
Total	**100,0%**	**5,90E+05**	**16666**

TABLE 3.1 EXHAUST GAS COMPOSITION AT 100% MCR

NO_x emissions from the engine are not easily calculated without detailed knowledge of the combustion process and temperatures inside the engine. These emissions are however known to be very low for LNG fueled engines. The engine manufacturer does not give any exact numbers, but states that in gas mode, the engine complies with the IMO tier 3 NO_x emission standard, which is defined as:

$NO_x = 9 \cdot rpm^{-0.2} = 9 \cdot 750^{-0.2} = 2.4\ g/kWh$ (Wärtsilä, 2016, pp. 13-3 to 13-4).

At 100% MCR the exhaust gas flow is 4.6 kg/s or $\frac{4.6\frac{kg}{s}\cdot 3600\ s}{3000\ kW} \sim 5.5\frac{kg}{kWh}$. This means that NO_x emissions are less than 0.04% by mass.

Sulfuric emissions are negligible, as LNG contains no sulfur and low sulfur MGO is used as a pilot fuel.

3.2 SYSTEM DESIGN

Before giving a description of the capture system that is designed in section 3.2.2, the philosophy upon which this design is based is shortly elaborated on in section 3.2.1. In section 3.3 the performance of the system is discussed, based on heat balances. The system process is modeled by Juliana Monteiro from TNO, using commercial software (Aspen Plus®)

3.2.1 DESIGN PHILOSOPHY

The general philosophy applied in the design of the carbon capture system is that it is as simple and straightforward as possible. Only standard commercially available equipment is used.

Furthermore, there are two principles the design is based upon:

- To model the capture system, it is assumed that the solvent used in the capture process is an aqueous solution of 30 wt% MEA. Although more effective solvents are available and being developed, A MEA solution is the most conventional solvent. Using MEA as solvent allows for comparison with a lot of existing literature focused on carbon capture.
- The heat required for the capture process is extracted solely from the exhaust gas. In other words: no external heat is produced to be added to the capture process. Analogously, the cold required for liquefaction of the captured CO_2 is supplied by the LNG is evaporated. This eliminates the need for a refrigeration process.

This last principle is important: By not adding external heat to the process and not having a refrigeration process the amount of energy used for carbon capture is significantly decreased. Because of this heat integration, however, the capture rate of the system is determined by the amount of heat and cold available in the exhaust gas and in the LNG, respectively.

3.2.2 System description

First, a general description of the capture system is given in section 3.2.2.1. After that the system components are summed up in section 3.2.2.2.

3.2.2.1 General description

The capture system design, based on the principles explained in section 3.2.1, is schematically shown in Figure 3.1.

LNG from the fuel tank is vaporized and then enters the engine, where it is combusted. Upon leaving the engine, the exhaust gases pass through a heat exchanger (reboiler), thereby heating the amine solution. The exhaust gases are then cooled further using seawater[1] in a direct-contact cooler, after which they are fed to the absorber column at low temperature. In the absorber column the CO_2 is absorbed by the MEA solution. The cleaned exhaust gases are then released to the atmosphere.

The low-temperature, CO_2-rich amine solution from the absorber column is moved to the stripper column, passing through a heat exchanger (Lean-RichHX) in which the CO_2-rich amine is heated to around 100°C. Any extra heat required in the stripper is provided for by circulating the amine through the reboiler (thereby cooling the exhaust gases). The high temperature in the stripper column causes the amine solution to release its CO_2, resulting in a near-pure CO_2 stream from the stripper column. The CO_2-lean amine solution is then circulated back to the absorber column, again passing through the lean-rich heat exchanger.

The CO_2 from the stripper column is compressed to 20-22 bar in two stages. After this, it passes through a seawater-fed direct-contact cooler and a dryer, to remove excess moisture from the CO_2. The CO_2 is then liquefied by further cooling it in the LNG vaporizer. Finally, the liquefied CO_2 is stored in pressure vessels at around 22 bar.

Thus, the LNG vaporizer is at the same time the CO_2 cooler. However, a separate vaporizer is still required for when not enough heat is available in the captured CO_2. This could for instance occur when the engine is starting up.

[1] For the system model, a seawater temperature of 20°C is assumed. This corresponds approximately with the maximum temperature of the North Sea during summer.

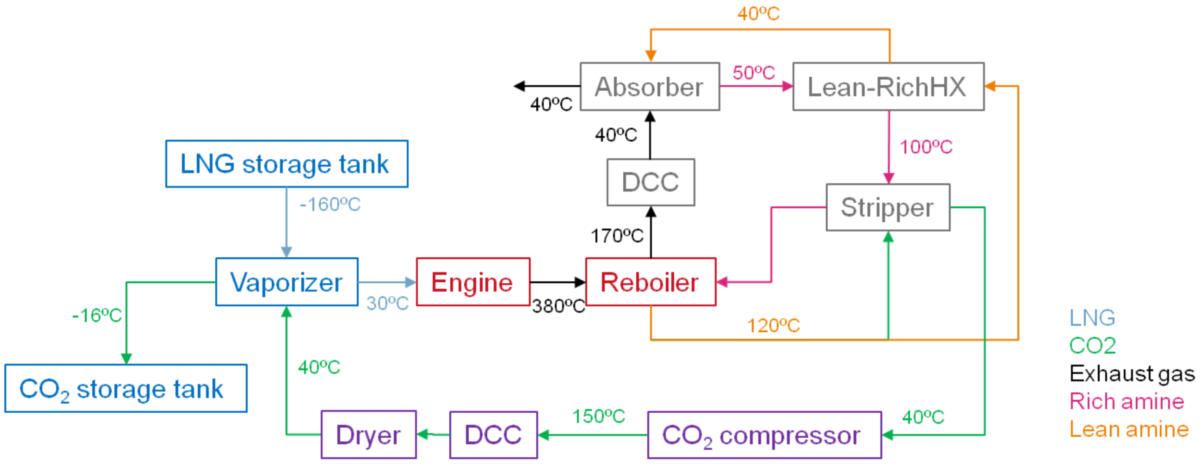


FIGURE 3.1 SCHEMATIC REPRESENTATION OF THE CAPTURE SYSTEM (MONTEIRO ET AL.,2017)

3.2.2.2 Sizing and costing

The components that make up the capture system are shown in Table 3.2. Some components have a considerable length. These components must be mounted vertically, it is impossible to mount them in a horizontal position. The stripper, measuring 14 m in height, is the highest component. Other components require a length of up to 6 meters to install. These components, except for the reboiler, can however also be mounted vertically, which will give some flexibility designing the ship.

Component	Type	Dimensions	Weight (ton)	Cost (kEUR)
Absorber	Packed Column	H = 10 m D = 1.5 m	4.8	89
Stripper condenser	Shell and tube	L = 6 m D = 0.2 m	0.6	11.5
Condensate separator	Vessel	H = 2.6 m D = 1 m	1.1	17
Lean-rich heat exchanger	Shell and tube	L = 6 m D = 1.15 m	17.1	111.7
Lean cooler	Shell and tube	L = 6 m D = 0.25 m	0.94	13.3
Lean pump	Centrifugal pump	?	0.19	7.3
Rich pump	Centrifugal pump	?	0.23	8.3
Stripper	Packed Column	H = 14 m D = 0.76 m	6	74
Reboiler	Shell and tube	L = 4 m D = 0.35 m	0.8	15.2

TABLE 3.2 CAPTURE SYSTEM COMPONENTS AND THEIR DIMENSIONS, WEIGHTS AND PURCHASE COSTS (MONTEIRO, VAN DEN AKKER, VREDEVELDT, VAN OS, & GOETHEER, 2017)

In Table 3.3 the components required for exhaust gas cooling and LNG vaporization are listed. The quench tower is the direct contact cooler used to cool the exhaust gases before they enter the absorption column. It must be mounted vertically, requiring nearly 14 meters in height. A blower is added to compensate for the pressure drop over the quench tower and the absorber column.

The LNG is vaporized with the captured CO_2 in a kettle reboiler. This will have to be located near the LNG tanks in order to keep the cryogenic lines as short as possible.

Component	Type	Dimensions	Weight (ton)	Cost (kEUR)
Quench	Packed tower	H = 13.9 m D = 2.29 m	14.2	193.9
Blower	Fan propeller	? (26.6 kW)	?	2.2
Vaporizer	Kettle reboiler	L = 4 m	0.87	15.7

TABLE 3.3 COMPONENTS REQUIRED FOR EXHAUST GAS COOLING AND LNG VAPORIZER

The main components used to compress and cool the captured CO_2 are listed in Table 3.4. The heat exchanger cooling the CO_2 from ambient temperature to -16°C/-20°C is excluded from this table, as it is already included in Table 3.3 as the LNG vaporizer. There are several options when it comes to CO_2 compression; centrifugal compressors have a low weight, but require slightly more volume and are more expensive than reciprocating compressors. For the direct contact coolers a similar choice can be made: packed columns have smaller dimensions than trayed columns, but are slightly heavier and more expensive.

For this thesis, the choice is made to go use the equipment with the highest weight, so reciprocating compressors and packed columns are used. This way, the estimation for the equipment weight is kept conservative.

Component	Type	Dimensions	Weight (ton)	Cost (kEUR)
Compressor #1	Centrifugal	Casing: H = 0.92m W = 9.5m L = 1.63	4.4	700
	Reciprocating	Casing: H = 0.76m W = 1.14m L = 7.01	8.5	480
Compressor #2	Centrifugal	Casing: H = 0.92m W = 9.5m L = 1.63	4.4	805
	Reciprocating	Casing: H = 0.76m W = 1.14m L = 7.01	6.8	450
DCC1	Packed column	D = 0.45 m H = 3.5 m	1.4	22.6
	Trayed column	D = 0.45 m H = 5.1 m	1.1	19.8
DCC2	Packed column	D = 0.45 m H = 3.5 m	1.4	22.6
	Trayed column	D = 0.45 m H = 5.1 m	1.1	19.8

TABLE 3.4 COMPONENTS REQUIRED FOR CO_2 COMPRESSION AND COOLING

The total weight of all main components amounts up to 64.9 tonnes. What is not yet included in this weight estimation are the fluids that are present in the system when it's operating. These are the amine solution and the seawater used in the direct contact coolers. Together, these weights are estimated to be 15 tonnes.

Also not included in the tables are the tanks used for CO_2 storage. The exact size and shape of these storage tanks are dependent on the ship design. It is however possible to estimate the weight of the tanks, based on the working pressure of the storage tanks. The maximum allowed working pressure (MAWP) is estimated to be 22 bar (atmospheric). The empty weight of the tanks depends strongly on the tank capacity; a tank with a capacity of 3 tonnes CO_2 has an empty weight of around 80% of its capacity, whereas a 60-tonne capacity tank has an empty weight corresponding to 41% of its capacity. As an initial estimation for the ship design, an empty weight of 50% of the tank capacity is assumed.

3.3 SYSTEM PERFORMANCE

There are a number of aspects to the performance of the system. An important one is the capture rate that can be attained. This is discussed in section 3.3.1. As explained earlier, the system is designed such that all heating and cooling is done using available heat sources and sinks, so that no extra energy is required for the purpose of heating or cooling. However, the system does require some electric power. This is discussed in section 3.3.2. Other aspects of the system performance, such as the CO_2 emission that is avoided by the application of onboard carbon capture, depends on more than the system alone. The ship design and operational profile, for example, play a role in this. Hence, this part of the system performance is elaborated on later in this thesis.

3.3.1 ATTAINED CAPTURE RATE

The capture rate that can be attained by the system depends strongly on the available heat in the exhaust gas (the heat source for heating of the amine solution) and the available cold in the vaporizing LNG (the heat sink for CO_2 liquefaction). The system is dimensioned to be able to deal with full engine load. In section 3.3.1.1 this full load situation is elaborated on. Lower engine loads are discussed in section 3.3.1.2.

3.3.1.1 FULL ENGINE LOAD

At 100% MCR, exhaust gases leave the engine's turbocharger at 381°C (Wärtsilä, 2016). The amine solution is heated to around 120°C. With a comfortable ΔT between amine and exhaust gas of 10°C, the minimum exhaust gas temperature after the heat exchanger is 130°C. The difference between gas inlet and outlet temperatures thus becomes:

$$\Delta T = 381°C - 130°C = 251°C$$

With an exhaust gas flow of 16666 kg per hour (Table 3.1) or 4.63 kg/s and a heat capacity of 1 kJ/kgK, the available reboiler heat duty becomes:

$$4.62 \frac{kg}{s} \cdot 1 \frac{kJ}{kgK} \cdot 251°C \cong 1160\ kW$$

As illustrated in Figure 2.1 simulations show that the available heat is sufficient for a capture rate of 94%. However, a slightly lower capture rate of 90% is assumed, to allow for some tolerance in the available heat.

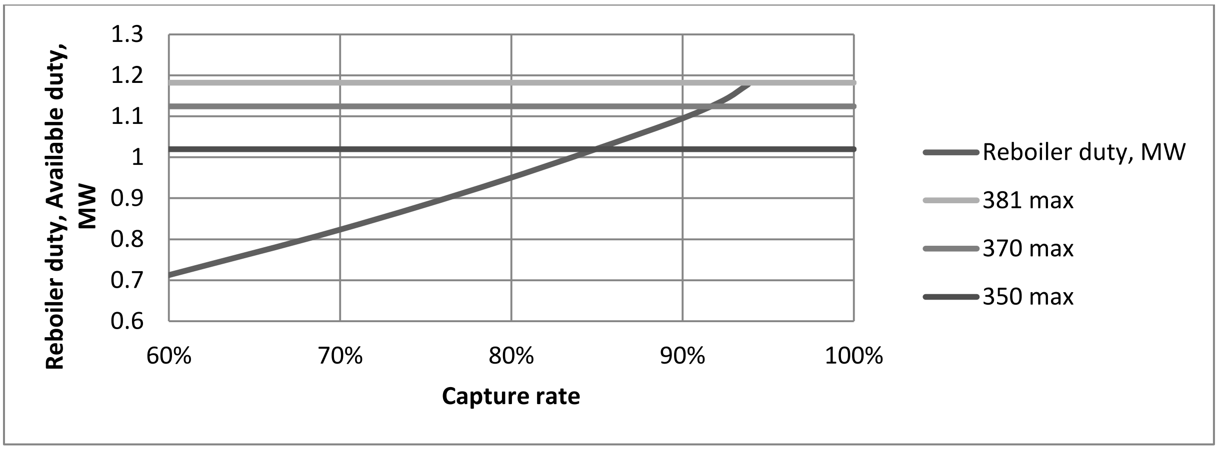


FIGURE 3.2 REBOILER DUTY AGAINST CAPTURE RATE AND AVAILABLE DUTY FOR THREE DIFFERENT EXHAUST GAS TEMPERATURES (MONTEIRO ET AL.,2017)

The LNG vaporizer acts as a heat sink for liquefying the CO_2. The amount of LNG vaporized determines the capacity of the heat sink. At a 90% capture rate, the heat sink has sufficient capacity to cool the CO_2 from 40°C to -16°C, which is the saturation temperature at 22 bar. This is illustrated in Figure 3.3. In this figure, the CO_2 enters the vaporizer on the left and is then liquefied. LNG flows in the opposite direction, entering on the right of the figure, vaporizing and exiting as a gas on the left of the figure. The minimum temperature difference ΔT between CO_2 and LNG is 11°C and occurs at the point where CO_2 enters the heat exchanger at 40°C and the LNG exits at 29°C. It is possible to design the system for a smaller ΔT, so there is some tolerance regarding the maximum amount of heat that can be extracted from the CO_2 in order to liquefy it. Concluding from these figures, the capacities of the available heat source and heat sink are sufficient for a capture rate of 90%.

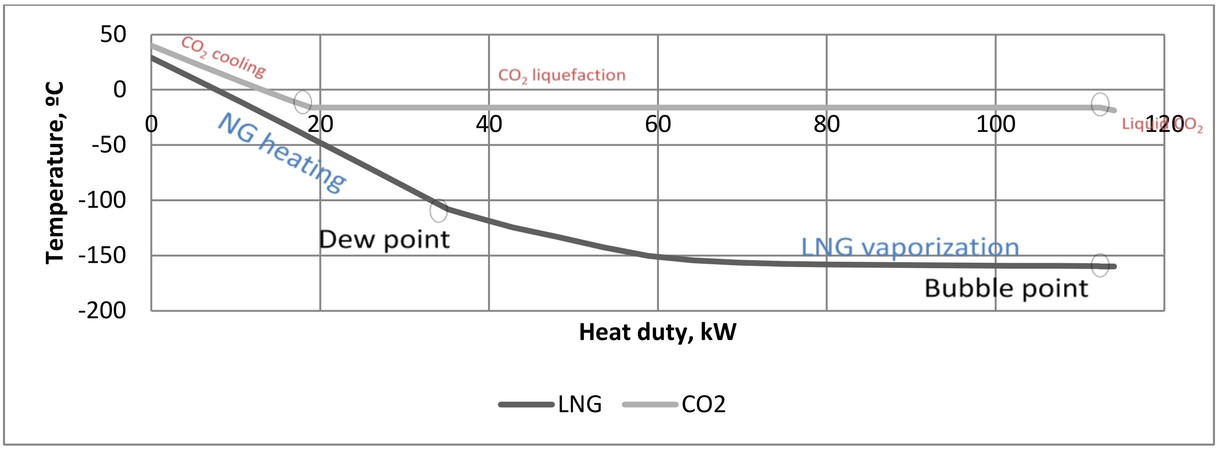


FIGURE 3.3 TEMPERATURES IN THE LNG VAPORIZER. CO_2 ENTERS THE VAPORIZER ON THE LEFT AND EXITS ON THE RIGHT. (MONTEIRO ET AL.,2017)

3.3.1.2 LOWER ENGINE LOADS

At full engine load, there is enough heat available for a capture rate of over 90%. At lower engine loads, however, the heat balance changes because the engine efficiency changes with engine loading. Moreover, the exhaust gas composition changes with engine loading as well. For this reason, the exhaust gas composition and heat balances are also evaluated at lower engine loads, namely 75% MCR and 50% MCR. The results are shown in Table 3.5. The full calculation sheets can be found in Appendix A.

The results show that at lower loads, relatively more heat is available for the capture process. This can be explained by the fact that engine efficiency decreases with decreasing engine loading. Hence, more heat is produced per kW output from the engine.

With decreasing engine loading the concentration of CO_2 in the exhaust gas also decreases. This has to do with the fact that relative decrease in exhaust gas flow is smaller than the decrease in power; at 75% MCR, the exhaust gas flow is 82% of the flow at full load. At 50% MCR, the flow is 67% of the flow at full load. This causes the CO_2 in the exhaust gas stream to be diluted.

In general, a lower CO_2 concentration in the exhaust gas means that more energy is required for the separation of the CO_2 from the rest of the exhaust gas. In this case, this extra heat is available: at 75% MCR, the amount of heat available per kg CO_2 is 14% higher than at 100% MCR. At 50% the relative increase in available heat is 28% compared to 100% MCR. Combined with the fact that at 100% MCR a significant amount of surplus heat is available already (section 3.3.1.1), the amount of heat available at lower engine loads is estimated to be sufficient for a 90% capture rate.

As can be seen in Table 3.5 the amount of LNG vaporized per kg CO_2 liquefied decreases slightly with decreasing engine load. At 50% MCR, the amount of LNG vaporized per kg CO_2 liquefied is 1% lower than in the full load situation. As explained in section 3.3.1.1, there is some tolerance in the heat extractable from the CO_2. Hence, the 1% decrease LNG available for vaporization is considered to be negligible.

MCR	100%	75%	50%
Exhaust gas flow (kg/h)	16666	13691	11168
CO2 production (kg/h)	1254	990	724
CO2 concentration in exhaust gas (molar)	4.8%	4.6%	4.2%
Available heat in exhaust gas (kW)	1035	931	763
Heat available per kg exhaust gas (kWh/kg)	0.062	0.068	0.068
Heat available per kg CO2 produced (kWh/kg)	0.83	0.94	1.05
Heat available per kg CO2 captured at 90% capture rate (kWh/kg)	0.92	1.05	1.17
LNG vaporized per kg CO2 liquefied at 90% capture rate (kg)	0.396	0.394	0.391

TABLE 3.5 EXHAUST GAS COMPOSITION AND HEAT AVAILABLE FOR CO_2 CAPTURE AT ENGINE LOADS OF 100%, 75%, AND 50% OF MCR

3.3.2 ELECTRIC POWER REQUIREMENT

Because of the heat integration of the capture process, no external energy is required for heating or cooling. However, the process does require some electric power. The two major consumers are the blower in the exhaust, necessary to compensate for the pressure drop in the DCC and the absorption column, and the compressors needed for CO_2 liquefaction. Simulations show that 26.6 kW is required for the exhaust blower.

To estimate the compressor power, it is assumed that the compressors have 90% efficiency. The CO_2 is compressed in two stages from 2 bar to 22 bar. The total enthalpy difference over both compressors is around 185 kJ/kg (Figure 3.4). With a capture rate of 90%, 1129 kg CO_2 is liquefied per hour. The required compressor power is then:

$$P_{comp.} = \frac{1}{\eta} \cdot flow_{CO2} \cdot \Delta_{enthalpy} = \frac{1}{\eta} \cdot \frac{1129 \frac{kg}{h}}{3600} \cdot 185 \frac{kJ}{s} \cong 65\ kW$$

All other power consumers (mainly pumps) in the system are assumed not to exceed 30 kW in total. The total electric power requirement is then:

$$P_{el} = P_{blower} + P_{comp.} + P_{rest} = 26.6 + 65 + 30 = 121.6\ kW$$

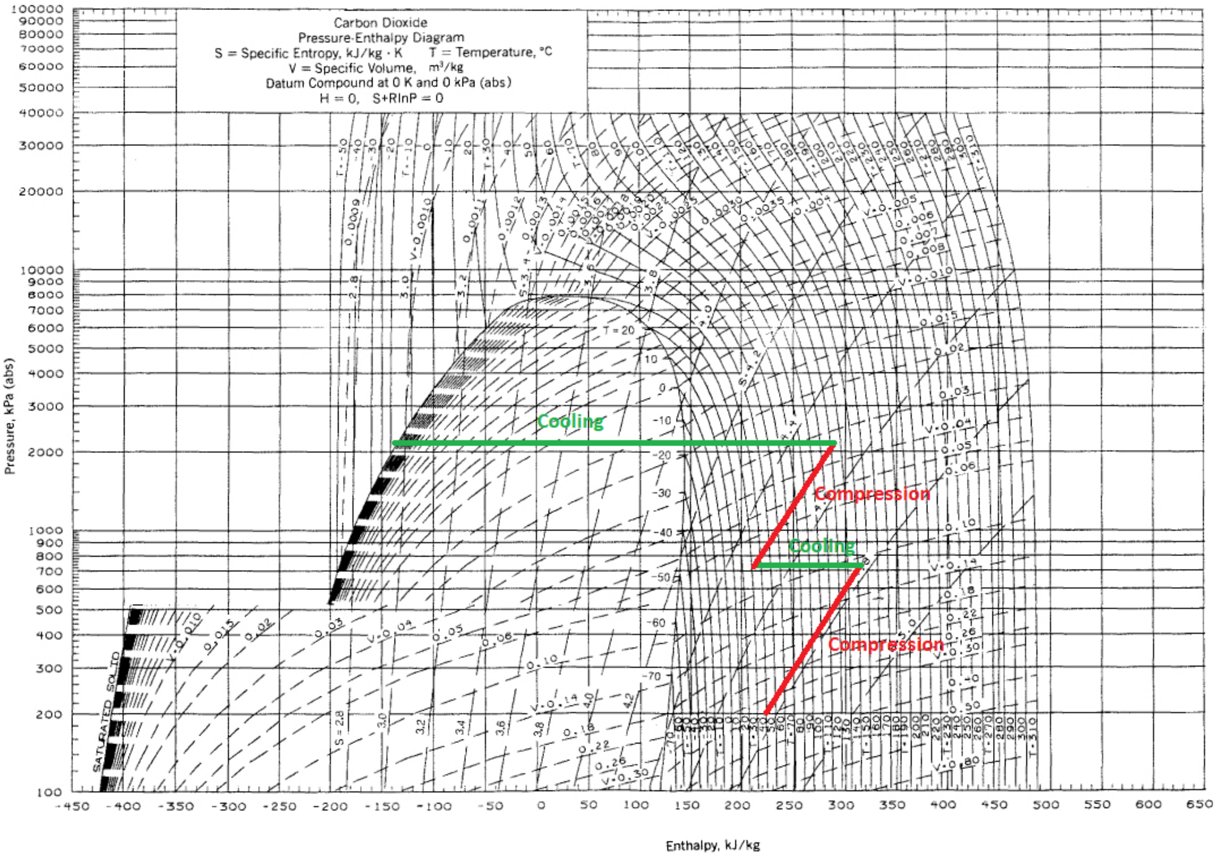


FIGURE 3.4 CO_2 PRESSURE-ENTHALPY DIAGRAM SHOWING TWO-STAGE COMPRESSION

4 SHIP DESIGN

With the reference vessel mentioned in chapter 3 as starting point, a concept design is developed. In section 4.1 the reference vessel is described in further detail, followed by a description of its operational profile in section 4.2. The principles on which this new concept design is based are explained in section 4.3. In section 4.4 the resulting design is described.

4.1 REFERENCE VESSEL DETAILS

As mentioned earlier, the reference vessel is an 8000 DWT general cargo vessel, supplied by Conoship. Its main particulars are listed in Table 4.1. When it comes to LNG fueled vessels, there is some debate concerning the placement of the fuel tanks. For this thesis, it is assumed that the fuel tanks are located between the engine room bulkhead and the hold, as shown in Figure 4.1. Another option would be to place the fuel tank in the front of the ship, but combining this with the capture system would be very impractical, because the cold from the LNG is needed for CO_2 cooling, resulting in very long cryogenic lines. As prescribed in the IMO's IGF Code (IMO, 2015), the distance between the fuel tanks and the ship side is B/5.

The vessel has two holds. Both holds are 13.5 meters wide and 9.6 meters in height. The aft hold has a length of 34.0 meters and the forward hold is 43.6 meters long.

The vessel is designed for the possibility to be built at one of the shipyards located on the canal Winschoterdiep near Groningen, the Netherlands. Because of the dimensions of the bridges on that canal, the beam of the ship is limited to 16 meters.

L_{oa}	119.4 m
L_{wl}	118.5 m
B	16 m
D	9.9 m
T	7.3 m
DWT	8000 tonnes
Design speed	13 knots
Main engine	3000 kW
LNG capacity	300 m^3, 135 tonnes

TABLE 4.1 MAIN PARTICULARS OF THE REFERENCE VESSEL

4.2 OPERATIONAL PROFILE

To be able to assess the (physical and economic) performance of the system on board, it is necessary to determine an operational profile. The operational profile is based on a study using AIS data of general cargo vessels that have a similar size as the benchmark design (Wigforss, 2012). The ship is assumed to be underway using its engine for 57% of the time. The remaining 43% the ship is assumed to be either in port or at anchor. The capture system is only used when the vessel is underway. While underway, the power produced by the engine is assumed to be more or less constant at around 85% MCR. The reason for choosing 85% MCR is that fuel consumption data is provided by the engine manufacturer at this load. Moreover, it corresponds with the power required for propulsion (76%-78% MCR, see section 4.4.4) plus a 7% allowance for electrical power.

Fuel consumption of the benchmark vessel when docked or anchored is assumed to be 4% of the consumption at design speed (Wigforss, 2012). For the concept vessel, the consumption when docked or anchored is assumed to be the same as for the benchmark vessel. As already mentioned none of the CO_2 produced when in port or at anchor is captured.

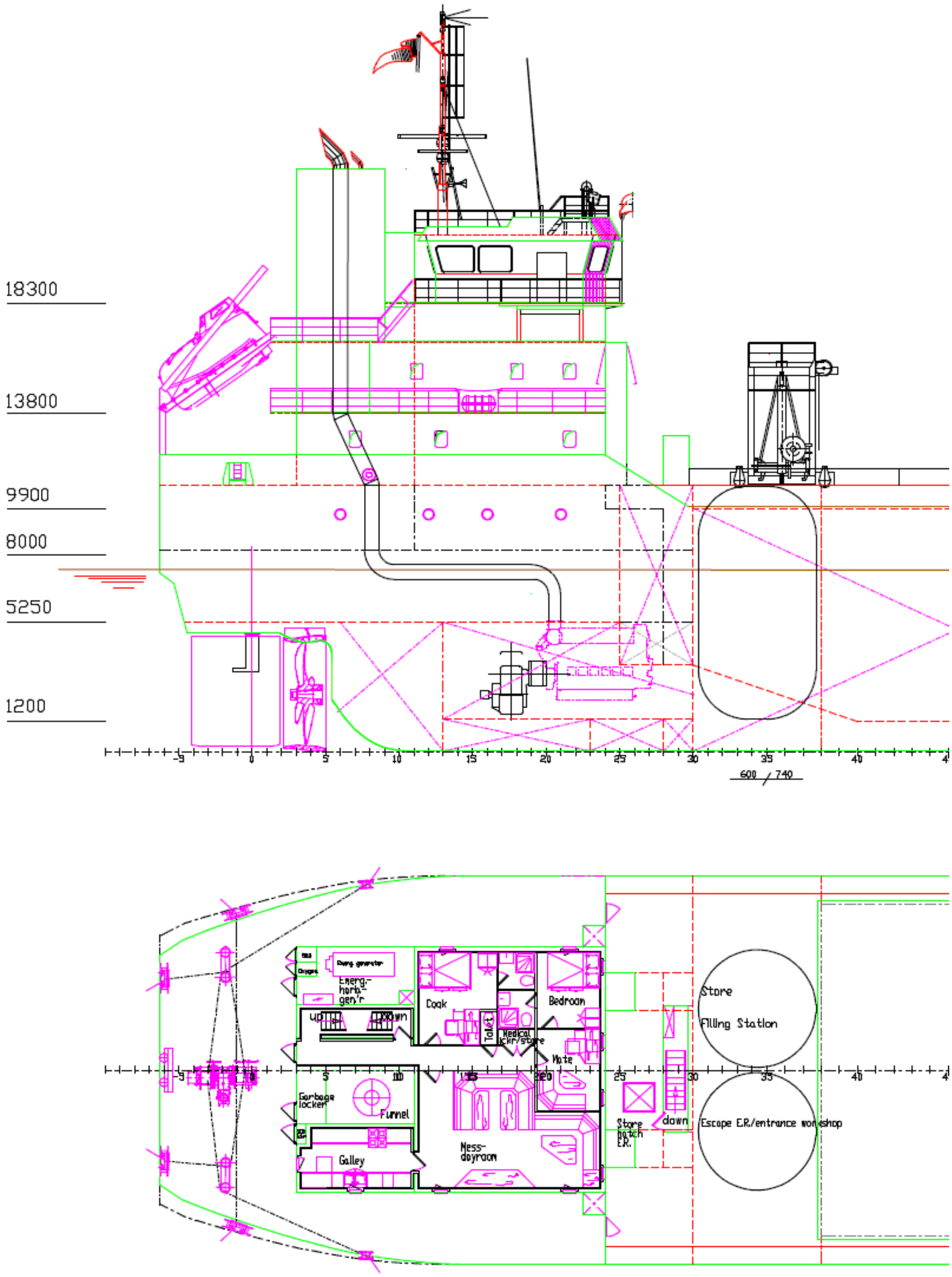


FIGURE 4.1 PART OF THE REFERENCE VESSEL'S GENERAL ARRANGEMENT, SHOWING THE LOCATION OF THE FUEL TANKS AND THE EXHAUST PIPE

4.3 Design principles

In adapting the reference design to accommodate the capture system, one general principle is applied, to allow for fair comparison:

The transport capacities of the reference design and the new concept design must be equal.

This principle has a number of consequences, which are discussed in this section. First, some attention is given to the question whether the design is deadweight critical or volume critical and how this is dealt with in new concept design. Next the hold and deck dimensions are briefly discussed in section 4.3.2. In section 4.3.3 the ship's deadweight capacity is discussed, after which the ship stability is elaborated on in section 4.3.4.

4.3.1 Deadweight versus volume

Whether a ship is deadweight critical or volume critical depends on what is the limiting factor in its cargo capacity: if a ship has excess cargo space available after it has been loaded to its deadweight capacity, weight is the limiting factor, so the vessel is called deadweight critical. If on the other hand a ship's holds are fully filled while its maximum draft is not attained, the vessel is called volume critical because the ship's volume is the limiting factor.

General cargo ships cannot simply be classified as either deadweight critical or volume critical, because they are designed to transport different types of cargo: when a ship is loaded with heavy steel coils, the weight of these coils will be the limiting factor when it comes to cargo capacity, so the ship is deadweight critical. When on the other hand the ship is loaded with windmill blades, it is more likely that volume is the limiting factor. Whether the ship is deadweight critical or volume critical thus depends on the specific weight of the cargo.

For a fair comparison between benchmark and concept, both deadweight and volume are important. To achieve a balance between both quantities, the ship's holds are assumed to be completely filled with grain with a density of 0.78 tonne/m3. Grain is a common cargo type and its density is close to the cargo density at which volume and deadweight are balanced against each other. To reach its full deadweight capacity, another 518 tonnes of ballast is required. This situation in which the holds are completely filled and the ship is ballasted to its design waterline is used to judge the stability of both benchmark and concept design.

4.3.2 Hold and deck dimensions

To make sure that the cargo capacity of the ship remains equal, the hold dimensions will not be changed. As the hold dimensions remain exactly the same, the grain capacity remains equal as well. The length of the deck will, in principle, be kept equal as well. However, if the deck length turns out to be greater than that of the reference vessel, this is acceptable. A smaller deck length is not accepted.

4.3.3 Deadweight

The concept design will have a deadweight cargo capacity of 8000 tonnes, equal to the reference design. This means that if the ship's lightweight increases because of the extra equipment on board, this will have to be compensated for by means of increased displacement. This increased displacement cannot be achieved by means of a larger beam, because of the 16-meter beam limit mentioned in section 4.1. Hence, the displacement will have to be found in either an increased length or an increased draught.

With regard to the deadweight it is interesting to note that a ship with onboard CCS behaves differently than ships without CCS; a conventional ship is at its maximum displacement is when it is fully loaded and stocked with consumables, including fuel. The displacement decreases during the voyage, as fuel is consumed. A ship that is equipped with CCS, however, will capture CO_2 from the exhaust gases and store it onboard. This compensates for the reducing displacement that results from the fuel consumption. In fact, the displacement will increase during the voyage because of the CO_2 captured on board, as the following calculation shows:

The Wärtsilä 6L34DF consumes 452 kg of fuel per hour (447 kg/h of LNG, the rest is pilot fuel, see Appendix A). This results in CO_2 emissions of 1254 kg/h. At a 90% capture rate, 1129 kg/h of CO_2 is liquefied and stored on board. In other words, the ship's displacement increases with:

$$\dot{\nabla} = 1129 - 452 = 677 \frac{kg}{h}$$

For a one-week trip (at full power) this would mean a displacement increase of 114 tonnes.

Because the displacement of the ship is larger at the end of the voyage than on departure, the deadweight of the concept design must also be based on this increased displacement. In other words: the deadweight is calculated based on the loaded displacement *on arrival* instead of the loaded displacement *on departure*. The ship has a fuel capacity of 135 tonnes LNG. Not all of this LNG can be consumed, as a small amount of LNG is required to be in the tanks to prevent them from warming up. It is assumed that at maximum 90%, or 121.5 tonnes of LNG is consumed on arrival, along with a corresponding 1.6 tonnes of pilot fuel. With a capture rate of 90%, the ship's CO_2 tanks are then filled with 307 tonnes of CO_2, so the displacement has increased with:

$$\Delta\nabla = CO_2\ stored - fuel\ consumed = 307 - (121.5 + 1.6) = 183.9\ tonnes$$

For deadweight calculations on the concept design, the LNG tanks are assumed to be empty (meaning filled to 10% of their total capacity), whilst the CO_2 tanks are full. All other consumables are assumed full as well.

4.3.4 Stability

Equal cargo capacities also mean equal stability in loaded condition. Ship stability can be defined in a number of ways. With respect to transverse stability, for this thesis, it is defined as the metacentric height (GM). The concept design will have the same GM in loaded condition as the reference vessel. A slightly higher GM (resulting in a higher stability) is acceptable, a lower GM is not. Damage stability is not specifically investigated in this thesis. Although damage stability is an important factor in ship design, for the purposes of this thesis it is assumed that if the ship's GM is kept equal, the damage stability of the concept design is as good as that of the benchmark design. This is based on the assumption that the ship's main particulars are not changed drastically. In section 4.4.4 the damage stability of the concept design is briefly discussed.

When it comes to longitudinal stability, the main issue is the trim of the ship. Like the reference vessel, the vessel should be trimmed horizontally at full load. This will not be achieved by manipulating the shape of the ship's stem and stern, because this could have a big impact on the ship's resistance. As it is not within the scope of this thesis to engage in computational fluid dynamics, the choice is made not to alter the shape of the stem and the stern. Hence, the focus will be on weight distribution when it comes to trimming the ship. This can be done either by placement of the system components or by ballasting, or a combination of both.

As with the deadweight calculations, the CO_2 stored onboard has to be taken into account in the stability calculations; CO_2 stored above the ship's center of gravity will result in the ship becoming less stable during the voyage. As the ship's GM is to remain equal, the placing of the tanks is very important. Preferably, the ship's GM on arrival is not higher than it was on departure. This would reduce the room for error in stability calculations by the crew. For the purpose of this thesis, however, this is not an essential requirement as it does not influence the cargo capacity itself.

4.3.5 Ship speed

As all cargo capacities of the concept design are kept equal to the reference design, the ship's speed must also remain equal, because the design principle is that the transport capacity is not changed. As is shown later in this thesis, the installed main engine is able to deliver the required power for this; although the ship's displacement and wetted area are increased because of the extra equipment (resulting in a higher resistance), the length of the concept design will be consequently larger as well, decreasing the Froude number and with it the wave-making resistance. It is estimated that the required propulsion power is not increased enough to justify a more powerful main engine. Calculations supporting this assumption can be found in section 4.4.4.

4.4 The design

Based on the design principles explained in section 4.3, a concept design is produced. The goal of this concept design is to provide a basis for comparison of a ship with provisions for onboard carbon capture with a ship that doesn't have those provisions. It is very likely that a more optimal design can be produced, as some of the constraints discussed in the previous section might not be relevant for a shipping company in need of a new vessel. However, the goal of this thesis is not to optimize the ship design, but to assess the feasibility of a novel concept. For this, comparability to the reference design is important. Hence, the constraints formulated in section 4.3 are adhered to strictly.

The concept design focuses on a number of specific subjects. First, the required equipment must be efficiently placed onboard the ship. As a result of its dimensions, much of the capture equipment is placed in the engine casing and funnel. With placing the equipment comes a redesign of the accommodation. This is explained in section 4.4.1. The second main design issue is the placement of the CO_2 storage tanks, described in section 4.4.2. Third, an analysis of the ship's weights and hydrostatics is discussed in section 4.4.3. Last, differences in ship resistance and propulsion power are discussed in section 4.4.4.

4.4.1 Placing the capture equipment

As already mentioned in section 3.2.2, some of the equipment components are columns that require a considerable height. The two highest components are the stripper column and the exhaust gas cooler, both requiring about 14 meters in height. The obvious location on the ship with an available height like that is behind the accommodation, in the engine casing and funnel. Moreover, it is desirable to place the exhaust gas cooler close to the engine's exhaust, as they must be routed from the engine to the cooler. Consequently, the engine casing and funnel seem to be the most suitable place for the exhaust gas cooler. Most of the other capture equipment is also placed in the funnel to keep piping length to a minimum. In the resulting design, all components required for the capture process (these are all components listed in Table 3.2 and Table 3.3) are placed vertically in the funnel and engine casing, except for the reboiler that provides the heat for the stripper; that is placed in the horizontal part of the exhaust pipe after the engine, as can be seen in Figure 4.3. Some space is required between the main components to allow for inspection, maintenance and repairs. As a result of this, the funnel size is increased considerably. Figure 4.2 shows an impression of the new situation. A plan view of the funnel is shown in figure 4.4.

The equipment needed for CO_2 compression (listed in Table 3.4) is placed near the engine room, in an enclosed space. The enclosed space is necessary to prevent CO_2 from spreading over the ship in case of leakage, expelling the available oxygen. The compressed CO_2 is cooled by the LNG coming from the fuel tanks, so a location close to the fuel tank is preferred. Hence, the compression space is located below main deck, behind the LNG tanks. Access from open deck is provided for by means of stairs to main deck. Figure 4.6 shows the location of the CO_2 compression room.

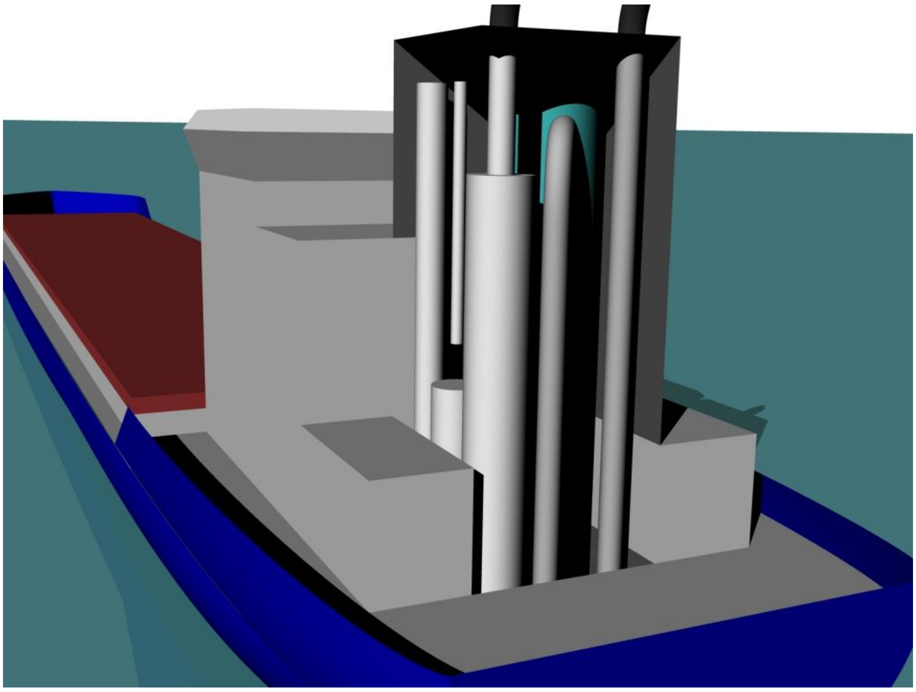


FIGURE 4.2 IMPRESSION OF THE CONCEPT DESIGN WITH THE CAPTURE EQUIPMENT LOCATED IN THE ENGINE CASING AND FUNNEL. VISIBLE ARE THE MAIN COMPONENTS OF THE SYSTEM, WITHOUT PIPING.

4.4.1.1 ACCOMMODATION REDESIGN

Increasing the engine casing and funnel is at the expense of some accommodation volume, which is compensated for by increasing the length of the accommodation by three meters. This is possible without losing deck length, because the hull itself is also lengthened, as will be explained in section 4.4.3. Figure 4.4 shows the redesign of the accommodation on main deck. In order to make room for the enlarged engine casing and funnel, the staircase and the galley are moved. The forward façade of the deck house is moved forward 3 meters. On the captain's deck (figure 4.5), the staircase is also moved to its new location.

4.4.1.2 WEIGHTS

Another consequence of placing most of the capture equipment in the funnel is that the ship's center of gravity rises: the weights of all components in the casing and funnel add up to over 45 tonnes, with a vertical center of gravity at 15.5 meters. This will have to be compensated for in order to keep the metacentric height equal to that of the reference design. A summary of the component weights and their locations is shown in Table 4.2. These data are used in section 4.4.3 where the weights and hydrostatics of the vessel are discussed.

Location	Weight (tonne)	VCG (m)	LCG (m)
Funnel	45.2	15.5	4
Engine room	18.9	6.7	18.6
Near LNG tanks	0.87	2.95	22.3
Total	**64.9**	**12.77**	**8.50**

TABLE 4.2 SUMMARY OF COMPONENT WEIGHTS AND THEIR LOCATIONS

As mentioned earlier, the reboiler that is used for heating the amine in the stripper column is placed horizontally in the exhaust, between the engine and the exhaust gas cooler. This can be seen in figure 4.3.

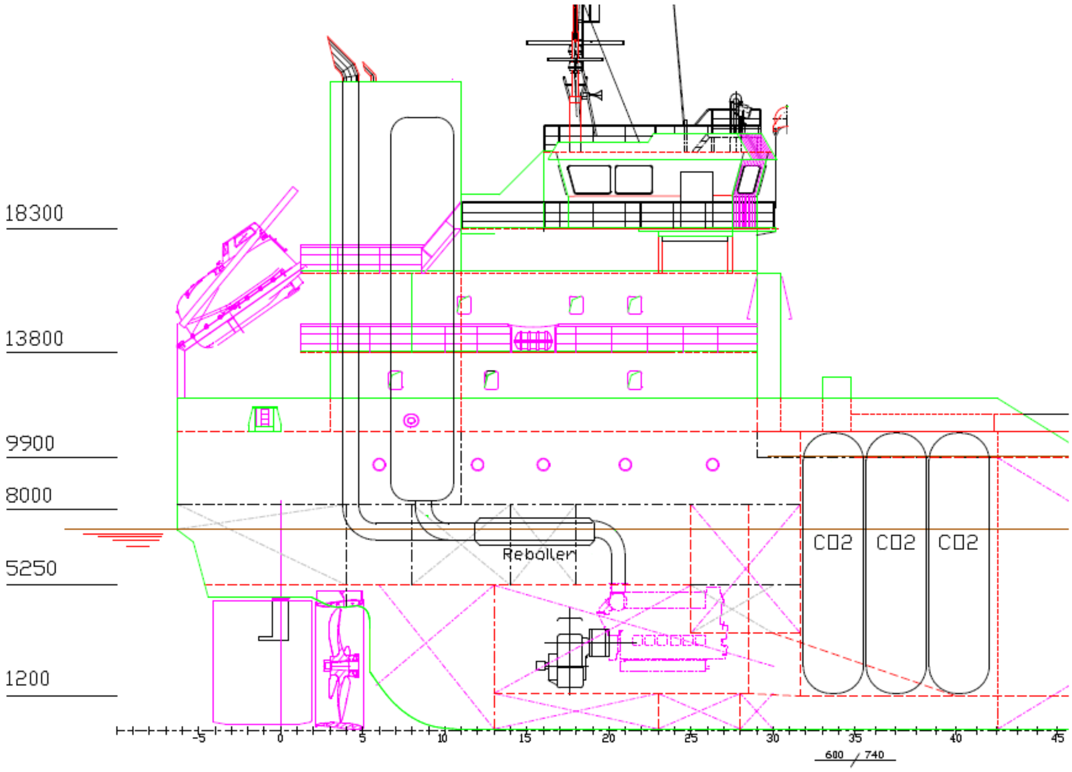


FIGURE 4.3 AFT PART OF THE CONCEPT DESIGN, SHOWING THE LOCATION OF THE REBOILER IN THE ENGINE ROOM. ALSO VISIBLE ARE THE EXHAUST GAS COOLER IN THE FUNNEL AND. AFT CO_2 STORAGE TANKS, LOCATED BETWEEN THE LNG TANK AND THE SHIP SIDE. THE ACCOMMODATION HAS INCREASED 3M IN LENGTH (COMPARE FIGURE 4.1)

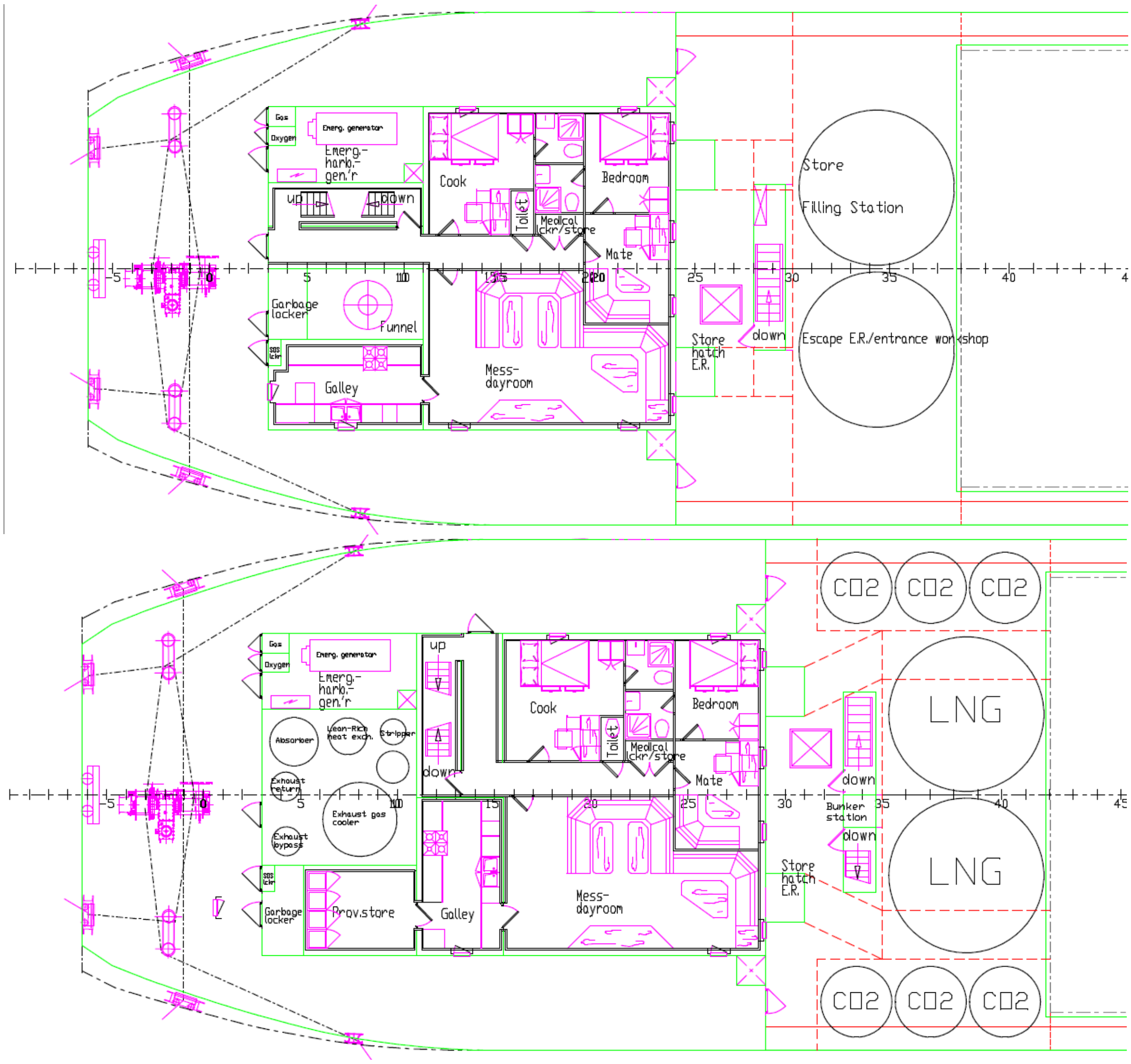


FIGURE 4.4 PART OF THE GENERAL ARRANGEMENT. MAIN DECK, AFT. TOP IS THE BENCHMARK DESIGN, BELOW IS THE CONCEPT DESIGN WITH THE CAPTURE EQUIPMENT IN THE FUNNEL. LNG TANKS AND FRONT OF ACCOMMODATION ARE MOVED FORWARD 3 METERS. BEHIND THE LNG TANKS, AN EXTRA STAIRCASE IS PLACED, LEADING TO THE CO_2 COMPRESSION ROOM.

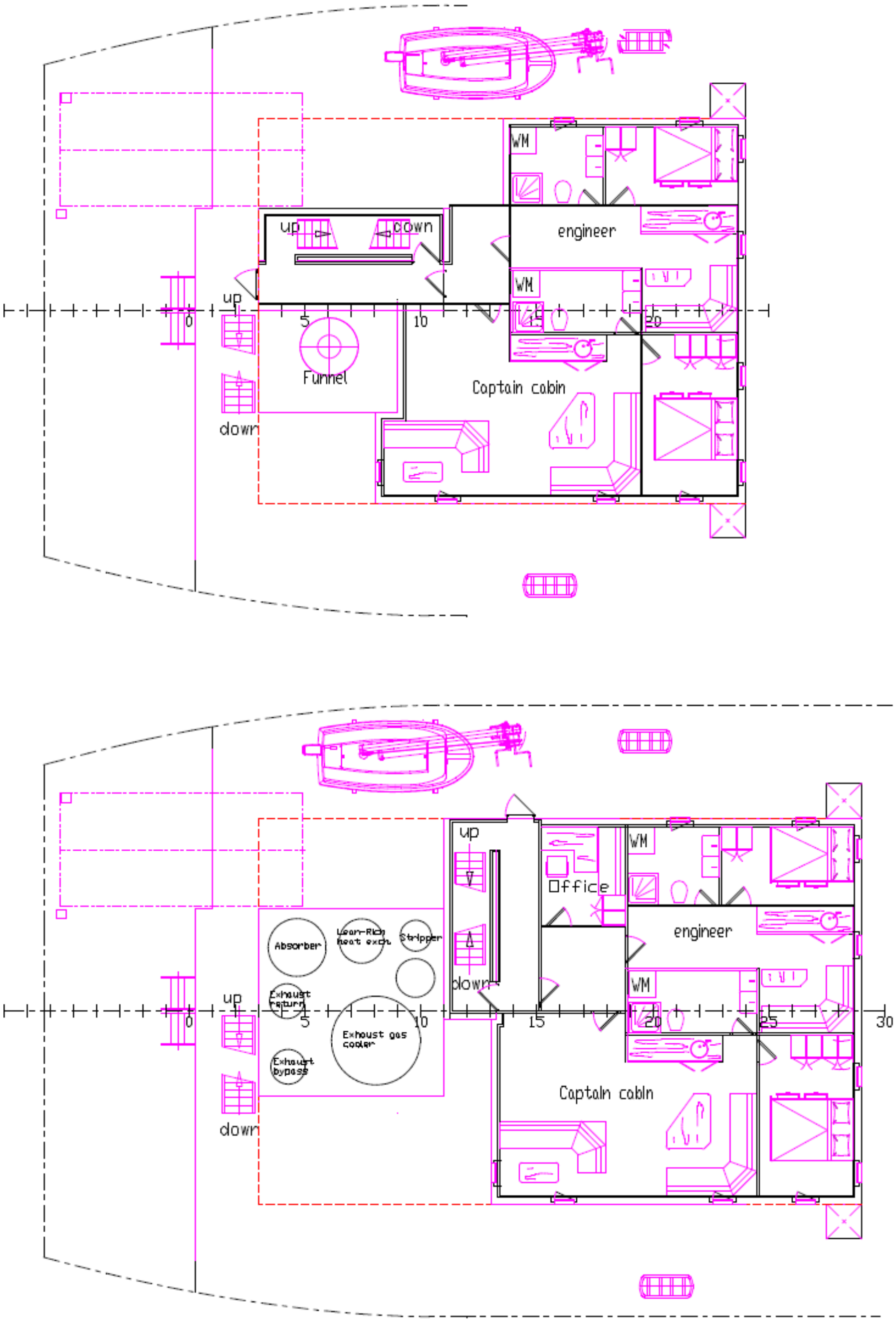


FIGURE 4.5 PART OF THE GENERAL ARRANGEMENT. CAPTAIN'S DECK. TOP IS THE BENCHMARK DESIGN, BELOW IS THE CONCEPT DESIGN. AGAIN, THE STAIRCASE IS MOVED TO MAKE ROOM FOR THE FUNNEL.

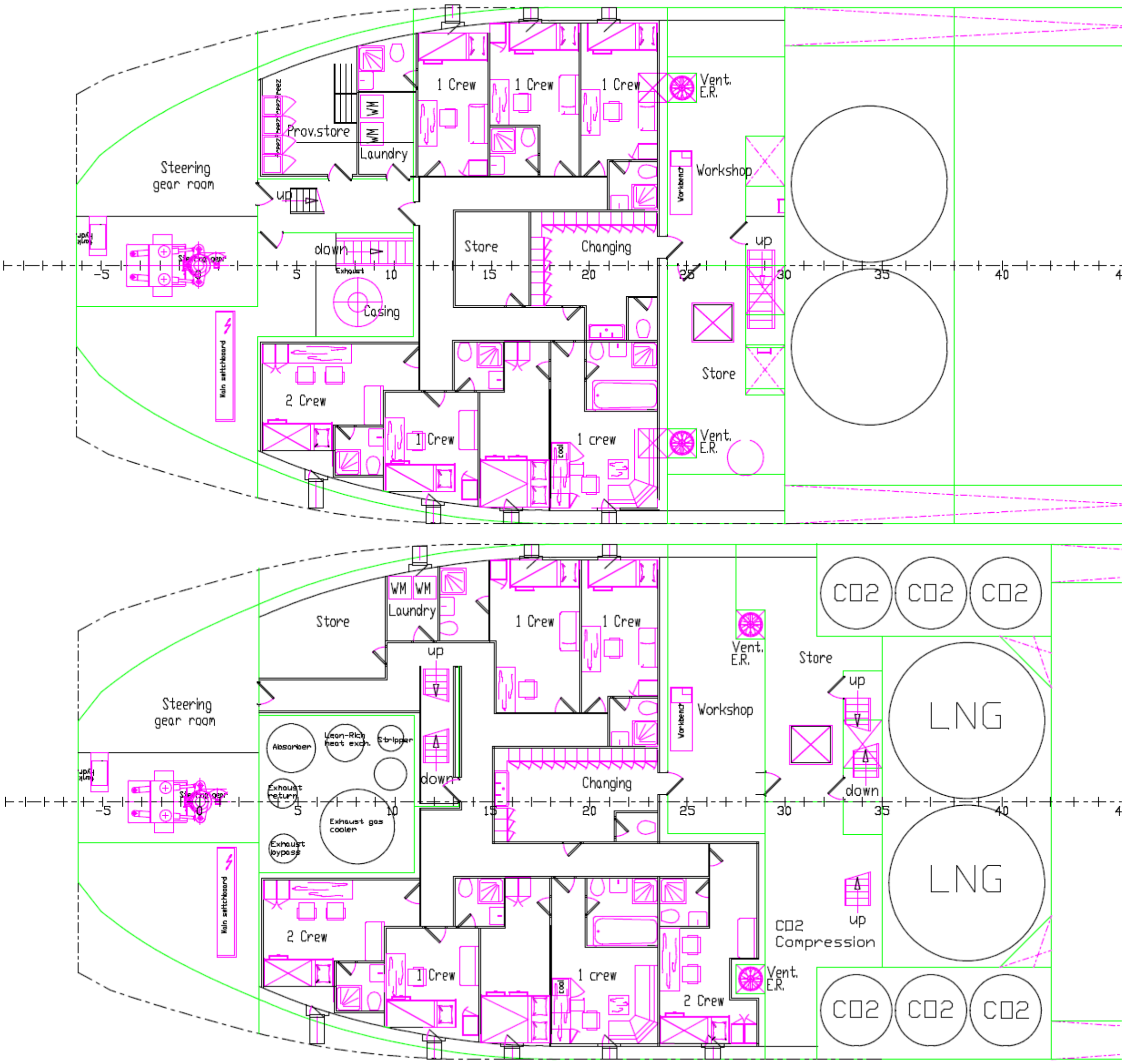


FIGURE 4.6 PART OF THE GENERAL ARRANGEMENT. TWEENDECK, 8M. TOP IS THE BENCHMARK, BELOW IS THE CONCEPT. THE ACCOMMODATION IS SLIGHTLY ADAPTED. THE LNG TANKS ARE MOVED 3 METERS FORWARD. BEHIND THE LNG TANKS ON THE STARBOARD SIDE IS THE CO_2 COMPRESSION ROOM WITH DIRECT ACCESS TO OPEN DECK (MAIN DECK).

4.4.2 PLACING THE CO_2 STORAGE TANKS

In determining the location of the CO_2 storage tanks, the first task is to determine the required amount of storage space. The ship has a fuel capacity of 135 tonne LNG. The LNG tanks are never completely emptied, as that would result in heating of the fuel tanks and consequently in the need for precooling the tanks again before bunkering. Instead, a small amount of LNG always remains in the tank. Assuming that a maximum of 90% of the fuel is consumed on arrival in port, a corresponding amount of 300.6 tonnes CO_2 must be stored onboard. As the density of liquid CO_2 is 1.02 tonne/m^3, the total required tank volume is 294 m^3.

To keep the trim angle that results from adding 300 tonnes of CO_2 during the voyage to a minimum, the center of gravity of the stored CO_2 should be not too far from the ship's longitudinal center of buoyancy (LCB). That is why most of the CO_2 is stored in the cofferdam between the two holds. The length of the cofferdam is increased with 4 frame distances (2.96 m) to 3.7 m. This gives room for four CO_2 storage tanks of 3.2 m in diameter and 9.5 m in height. Figure 4.7 shows the tanks placed in the cofferdam between holds.

To estimate the capacity of these tanks, they can be represented as cylinders with a half-sphere on each end. The height of the cylinders is then determined by the total height of the tanks and the radius of the sphere:

$$H_{cyl} = H_{tank} - 2 \cdot R_{spere} = 9.5m - 3.2m = 6.3m$$

The volume of the tanks can then be calculated based on the inner radius of the cylinders and spere. Assuming an insulation layer (including steel walls) of 25 cm[2], the inner radius of both the cylinder and the sphere is thus:

$$R_{in} = 1.6m - 0.25m = 1.35m$$

The volume of the tanks is the sum of the cylinder volume and the volume of the two half-spheres:

$$V_{tank} = V_{cyl} + V_{sphere} = H_{cyl} \cdot \pi R_{in}^2 + \frac{4}{3}\pi R_{in}^3 = 49.2\ m^3$$

With a CO_2 density of 1.022 tonne/m^3, the gross capacity per tank is 50.3 tonnes. Assuming a 95% filling ratio, the net capacity then becomes 47.8 tonnes. Together, the four tanks have a capacity of 191.2 tonnes.

In addition to these midship tanks, the remainder of the CO_2 is stored next to the LNG tanks; as already mentioned in section 4.1, the LNG tanks are placed a distance B/5 from the ship side. This room is now utilized for CO_2 storage. A total of 6 storage tanks are placed in the double hull next to the fuel tanks (see 4.7, as well as figures 4.3 and 4.4). The tanks have a diameter of 2.2 meters. Their height is 9.5 meters, similar to the midship tanks. With these tanks, another 112 tonnes of net storage capacity is added to the ship (calculated analogously to the midship tanks).

In total, the concept design has a net CO_2 storage capacity of 303 tonnes.

[2] The insulation thickness is arrived at by applying the mentioned calculation method to commercially available standard tanks with a known capacity (Linde tanks)

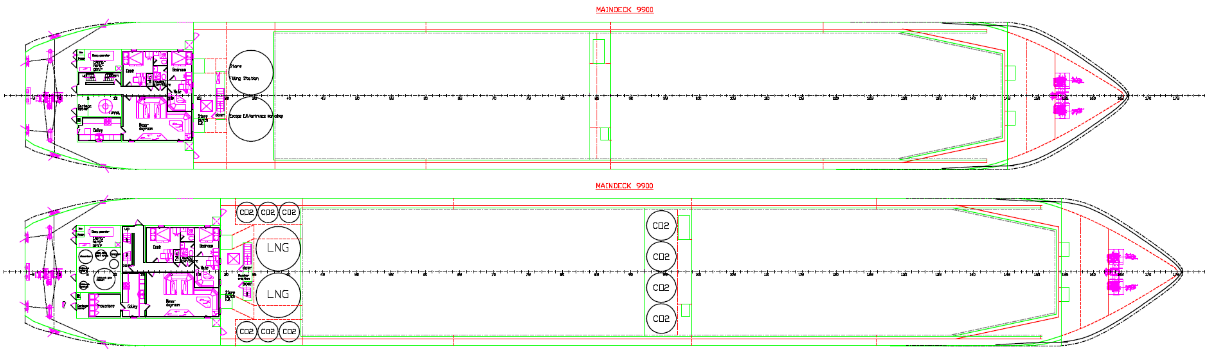


FIGURE 4.7 PART OF THE GENERAL ARRANGEMENT. MAIN DECK. TOP IS THE BENCHMARK DESIGN, BELOW IS THE CONCEPT DESIGN. CLEARLY VISIBLE IS THAT THE CONCEPT IS LONGER THAN THE BENCHMARK. ALSO SHOWN ARE THE CO_2 TANKS IN THE COFFERDAM BETWEEN HOLDS AND NEXT TO THE LNG TANKS. AN ENLARGED VERSION OF THIS FIGURE CAN BE FOUND IN APPENDIX D.

4.4.3 WEIGHTS AND HYDROSTATICS

Adding all weights of the capture system, plus the captured CO_2, but minus the consumed LNG, yields the minimum displacement that must be added to compensate for the lost deadweight capacity:

Capture equipment	65
Capture system fluids	15
CO2 tanks	146
CO2	316
LNG	-122
Total	**420**

TABLE 4.3 CAPTURE SYSTEM WEIGHTS ADDED, INCLUDING CO_2 AND LNG

To compensate for 420 tonnes of added weight would require the midship to be lengthened by 3.6 meters. However, lengthening the vessel also results in an increased weight of the ship's steel hull. Moreover, lengthening the parallel midship section of the vessel causes the vertical center of buoyancy (VCB) to be increased, if only slightly. The metacentric height consequently decreases slightly.

In addition, some of the weight added to the ship is placed quite high in the ship (specifically the 45 tonnes of equipment in the funnel). This causes the vessel's vertical centre of gravity (VCG) to increase. To compensate for this, ballast can be added in the double bottom tanks. This in turn increases the vessel's displacement. The increased displacement then requires the main dimensions to be altered again. This is an iterative process that is gone through a number of times before a satisfactory solution is found.

Ship Loading condition	Benchmark Homogeneous departure				Concept Homogeneous arrival			
	S.W.	Weight	VCG	LCG	S.W.	Weight	VCG	LCG
Lightship		2827.1	7.31	50.91		3207	7.35	52.59
Steel hull		1804	7.25	55		1932.4	7.25	57.91
Outfitting		732.8	7.25	55		769.9	7.25	57.91
Machinery		222.8	8.4	13.5		222.8	8.4	13.5
LNG tanks		67.5	6.05	20.6		67.5	6.05	23.6
CO2 tanks aft						58.5	5.6	23.60
CO2 tanks midship						90.585	6.05	65.00
Capture equipment						64.9	12.77	4.00
Cargo		7641	5.97	61.48		7641	5.97	65.99
Aft hold	0.78	3745	5.98	41.72	0.78	3745.0	5.98	44.72
Forward hold	0.78	3896	5.97	80.48	0.78	3896.4	5.97	86.44
LNG	0.45	135	6.05	20.60	0.45	13.5	1.78	22.08
MGO	0.85	67.2	6.48	16.64	0.85	67.2	6.48	16.64
Fresh water	1	133.5	7.46	2.10	1	133.5	7.46	2.10
Capture system fluids						15.0	10.00	6.00
Miscelaneous		63.6	4.69	12.15		63.6	4.69	12.15
CO2						318.3	5.88	49.78
CO2 aft						117.0	5.6	23.60
CO2 midship						201.3	6.05	65.00
Ballast		518	0.6	58		619	0.6	51.5
Total		**11386**	**6.075**	**56.98**		**12078**	**6.074**	**59.88**
Difference with benchmark						**692**	**-0.001**	**2.90**
DWT		**8559**				**8872**		
LCG (m from midship)				**-0.37**				**-0.37**

TABLE 4.4 HYDROSTATICS OF THE BENCHMARK DESIGN IN DEPARTURE CONDITION AND OF THE CONCEPT DESIGN IN ARRIVAL CONDITION

As already explained in section 4.3.1, in order to be able to compare the designs to each other, the reference design is assumed to have its holds fully loaded with grain, at a density of 0.78 tonne/m^3. The vessel is then trimmed to its design waterline using ballast water in the double bottom tanks. This way, maximum stability is achieved. The concept design is then compared to this benchmark. The reference design has a metacentric height of:

$$GM = KM - KG = 6.736 - 6.013 = 0.723\ m$$

In the resulting concept design, the ship is lengthened by 5.82 meters. As a result of this, KM is lowered by 8 mm. The ship's VCG will have to be lowered an extra 8 mm to keep GM equal. This is of course on top of the ballast that is needed to compensate for the equipment that is placed in the funnel.

When the concept design is ballasted to its design waterline, it carries 158 tons more ballast than the benchmark design. If all this ballast is located in the double bottom tank, the center of gravity is 2.6 centimeters lower than that of the benchmark design, resulting in a slightly higher value for GM:

$$GM = KM - KG = 6.728 - 5.987 = 0.741\ m$$

Thus, the stability design criterion is satisfied. The hydrostatics of both the benchmark design and the concept design are shown in Table 4.5. Damage stability was not explicitly addressed in this work, but in section 4.4.4 it is shortly discussed.

Hydrostatics	**Benchmark**	**Concept**	**Difference**	**Unit**
Waterplane area	1677.11	1769.939	92.83	m^2
Centre of flotation	53.34			m
Mom. Of inertia long.	1595503			m^4
Mom. Of inertia tran.	32395	34363	1968	m^4
Ton/cm immersion	17.28	18.14	0.86	tonne
Volume	11053.42	11728.36	674.94	m^3
Volume & appendages	11108.68	11783.62	674.94	m^3
Displacement	11386.4	12078.21	691.81	tonne
Vert. Centre of buoyancy	3.806	3.798	-0.008	m
Long. Centre buoyancy	56.978	59.880	2.90	m
Trans. Centre of buoyancy	0	0	0.00	m
KM transverse	6.736	6.728	-0.008	m
KM longitudinal	148.15			m
Mom change trim 1 cm	141.86			kNm
Wetted surface	3092	3264.805	172.81	m^2
Block coefficient	0.8276	0.836	0.01	
Hor. Prism. Coef	0.831	0.843	0.01	
Vert. Prism. Coef	0.9028			
Midship coefficient	0.9960	0.9960	0.0000	
Waterplane coef.	0.9167	0.9207	0.0040	
Waterplane coef. Fore	0.8448	0.8523	0.0075	
Waterplane coef. Aft	0.9886	0.9892	0.0006	

TABLE 4.5 HYDROSTATICS OF THE BENCHMARK DESIGN AND THE CONCEPT DESIGN

4.4.4 DAMAGE STABILITY

No damage stability calculations are performed on the concept design, as it is outside the scope of this work. However, some notes are in order as to why the assumption is made that the concept design is expected to comply with damage stability criteria, given that the benchmark design satisfies the same criteria.

The main particulars are not drastically changed. Draught, depth and breadth have remained the same. Only length has increased by 5.82 meters. The volume that was gained with the increased length has been mostly used for the placement of CO_2 storage tanks (fig. 4.7). These CO_2 tanks fill a large portion of the compartment they are placed in, reducing the permeability of the compartment. This should provide for increased damage stability.

For instance, the cofferdam between the holds was increased in length by 2.82 meters, increasing its volume with 362m^3 to 457m^3. The storage tanks however take up a volume of at least 287m^3, reducing the permeability of the compartment form 0.95 to around 0.37 or less. A similar calculation can be done for the space between the LNG tanks and the ship side, which in the concept design is filled with CO_2 storage tanks.

Additionally, it could be argued that because of the 'wall' of tanks placed in the side of the ship increases the crashworthiness of the vessel at that point.

For the above reasons, for the purpose of this thesis, it is assumed that the damage stability of the concept design is as good as or better than the damage stability of the benchmark design.

4.4.5 RESISTANCE AND POWER

Because of the increased displacement, it is expected that the ship's resistance is slightly increased compared to the benchmark. However, because the ship's length has increased, its Froude number has decreased. Thus, the increase in ship resistance is very small. A Holtrop-Mennen estimation has been done for both vessels using Maxsurf Resistance software. The input data and full results can be found in 0. No appendages have been taken into account, as these are assumed to be equal for both ships. The results of the analysis show that the required propulsion power is only slightly higher for the concept design compared to the benchmark (Figure 2.1). At the design speed of 13 knots the propulsion power delivered by the engine is estimated to be 2348 kW (78% of the engine's rated power), which is an increase of approximately 58 kW compared to the benchmark. This is less than 2% of the engine's rated power.

As explained in section 3.3.2, the electric power demand of the capture system itself is estimated at 121.6 kW. The total power requirement of the system, including the extra propulsion power, thus amounts to 180 kW. This is 6% of the engine's rated power. As the maximum power required for propulsion is 78% of the rated power, it is assumed that the 3000 kW engine is able to deliver the extra 6% required for carbon capture.

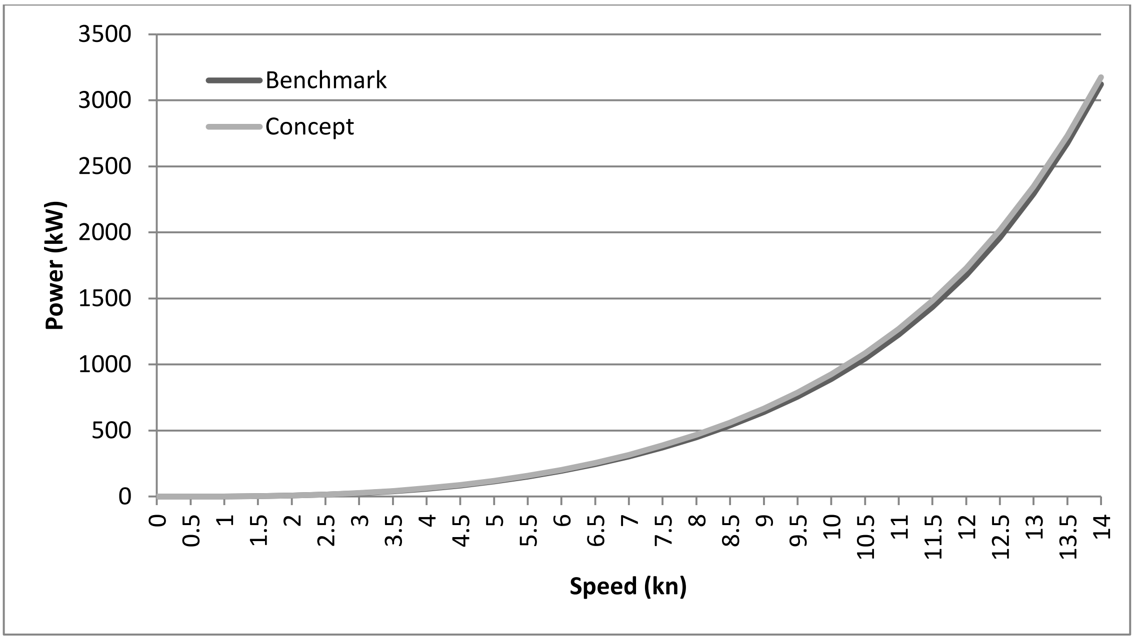


FIGURE 4.8 RESULTS FROM THE HOLTROP-MENNEN POWER PREDICTION

5 ECONOMIC ANALYSIS

To evaluate the economic feasibility of carbon capture onboard LNG fueled ships, the costs and benefits of the system are evaluated. The costs are discussed first in section 5.1. Next, in section 5.2 the potential financial benefits of onboard carbon capture are discussed. In section 5.3 these costs and benefits are analyzed and the net cost of onboard carbon capture is calculated for a base case scenario. Last, a sensitivity analysis is performed to find out which are the most important factors influencing the net cost of onboard carbon capture. The sensitivity analysis will also show under what circumstances onboard carbon capture can be cost neutral or even profitable.

5.1 COSTS

The cost of onboard carbon capture is a sum of a number of individual costs, which are discussed in this section, starting with the capital cost in section 5.1.1. Second, the operational costs are discussed in section 5.1.2.

5.1.1 CAPITAL COST

The capital cost of onboard carbon capture can be split in two parts. The first part is the cost of the system itself, along with the costs of installation and all supporting systems. This is discussed in section 5.1.1.1. The second part, discussed in section 5.1.1.2, is the increased newbuild cost of the ship itself, as it is larger than a conventional ship that has an equal deadweight (the benchmark ship). As explained in next two paragraphs, the total capital amounts to 4.79 million euro.

5.1.1.1 CAPTURE SYSTEM COST

The approach followed to arrive at an estimation for the capital cost of the capture plant is derived from the work of Sanchez Fernandez (Sanchez Fernandez, 2013), which in turn is based on the European Best Practice Guidelines for Assessment of CO_2 Capture Technology (EBTF, 2011). The total capital investment in those works uses the equipment cost as the starting point to calculate the total capital cost of the capture system. A number of cost items is defined and costed as a percentage of the total equipment cost, to derive at a Total Direct Plant Cost (TDPC). This TDPC is in turn used as the starting point to base the indirect plant cost (TIPC) on. The total capital cost is then the sum of TDPC and TIPC. In Sanchez Fernandez' work, costs are taken into account for civil works and buildings. For onboard carbon capture, this is not relevant. Instead, the increased newbuild cost of the ship (excluding capture equipment) is estimated, which is discussed in section 5.1.1.2.

The estimated equipment cost of the system is the sum of the components listed in section 3.2.2.2 and the estimated cost of the CO_2 tanks. The total equipment cost amounts to around €1,800,000 (Table 5.1). With a cost of €930,000 the most expensive part of the equipment by far are the compressors used for CO_2 liquefaction (Table 3.4).

Table 5.2 shows that the estimated capital cost of the onboard capture system is around 4.5M€.

Component	Price (k€)
Capture equipment	1534.3
CO2 tanks mid	160
CO2 tanks aft	100
Total	1794.3

TABLE 5.1 ESTIMATED PRICE OF CAPTURE PLANT COMPONENTS

Direct costs	% of Total Equipment Cost		€
	Sanchez Fernandez	this work	this work
TEC	100.0%	100.0%	1,814,300
Erection costs	50.0%	50.0%	907,150
Instrumentation and Controls	9.0%	9.0%	163,287
Piping	20.0%	20.0%	362,860
Electrical equipment and materials	12.0%	12.0%	217,716
Civil works	11.0%	0.0%	-
Solvent inventory	8.5%	8.5%	154,216
Total Direct Plant Costs (TDPC)	210.5%	199.5%	3,619,529
Indirect costs	% of Total Direct Plant Costs		€
	Sanchez Fernandez	this work	this work
Yard improvements	1.5%	1.5%	54,293
Service facilities	2.0%	2.0%	72,391
Engineering and supervision	6.5%	6.5%	235,269
Buildings	4.0%	0.0%	-
Ship build costs	n.a.	n.a.	496,040
Total Indirect Plant Costs (TIPC)	14.0%	10.0%	857,992
Total plant capital cost			**4,477,521**

TABLE 5.2 CALCULATION OF THE CAPITAL COST FOR THE CAPTURE SYSTEM, COMPARED WITH SANCHEZ FERNANDEZ' WORK (SANCHEZ FERNANDEZ, 2013). IN THIS WORK, CIVIL WORKS AND BUILDINGS ARE EXCLUDED FROM THE CAPITAL COST.

5.1.1.2 INCREASED NEWBUILD COST

The increased build cost of the ship itself is estimated using the work of Aalbers (Aalbers, 200x). In this work, a number of cost functions are derived for a ship's systems by means of a statistical analysis of 30 vessels. The assumed to have the form $C = c \cdot a \cdot W^b$, where C is either the material cost or the number of man hours, c is a factor to account for local conditions which is assumed 1 for the purpose of this thesis, and W is a relevant weight or size parameter.

The derived cost functions, along with the relevan parameters, are shown in table Table 5.3. Using these functions, an estimation is done for the newbuild cost of both the benchmark vessel and the concept vessel (excluding capture system). The difference between these two newbuild cost is then the extra cost that can be associated with onboard carbon capture. The parameters used as input for the cost functions are shown in Table 5.4. For the lightship weight Wsm, the method proposed by Watson is used, which makes use of the old Lloyd's equipment numeral (Watson, 1998, p. 82).

The resulting costs can be found in Table 5.5. The cost difference between the vessels is around €500.000. Adding this to the capital cost for the plant, the total capital cost for onboard carbon capture is 4.79 million euro. Assuming a linear depreciation of 25 years, the yearly capital cost then becomes:

$$\frac{4.97M€}{25\ years} = €198.942$$

	parameter	Materials		Man hours	
		a_m	b_m	a_h	b_h
General & engineering	Wsm	2500	0.72	27	0.9
Hull & conservation	W_steel, LBD, Cb	950	1.00	Kerlen	
Equipment	W_equip, L(B+D)	7500	0.80	8.5	0.86
Accommodation	Area_acc	750	1.00	250	0.55
Electrical systems	P_gen	9250	0.62	20	0.55
Propulsion & power system	P_b, nr_p_b	2050	0.84	6	0.75
Systems for propulsion & power	P_b, nr_p_b	1500	0.70	35	0.7
Bilge, Ballast, Sanitary	hullnr	150	0.93	2.75	1

TABLE 5.3 COST FUNCTIONS (AALBERS, 200X)

parameter	**Benchmark**		**Concept**	
Wsm	2760	tonne	2925	tonne
W_steel	1804	tonne	1932	tonne
LBD	18112		19031	
Cb	0.828		0.836	
W_equip	732.8		769.9	
Area_acc	428		443	
P_gen	750	kW	750	kW
P_b	3000	kW	3000	kW
nr_p_b	1		1	
hullnr (L(B+D))	2965		3115	

TABLE 5.4 PARAMETERS USED AS INPUT FOR THE COST FUNCTIONS

	Benchmark		**Concept excl. CCS plant**	
System	Material ($)	Manhours	Material ($)	Manhours
General & engineering	750,497	33,738	782,639	35,554
Hull & conservation	1,713,800	59,909	1,835,780	63,640
Equipment	1,469,094	8,229	1,528,300	8,587
Accommodation	321,000	7,002	332,250	7,136
Electrical systems	560,634	763	560,634	763
Propulsion & power system	1,708,188	2,432	1,708,188	2,432
Systems for propulsion & power	407,452	9,507	407,452	9,507
Bilge, Ballast, Sanitary	254,140	8,154	266,112	8,567
manhour cost (€)		45.00		45.00
conversion €/$	1.15		1.15	
Total material (€)	6,247,658		6,453,353	
Total labor cost (€)		5,838,060		6,128,405
Total cost	**12,085,718**		**12,581,757**	
Difference			**496,040**	

TABLE 5.5 NEWBUILD COST ESTIMATION OF THE BENCHMARK VESSEL AND THE CONCEPT DESIGN

5.1.2 Operational costs

The operational costs of onboard carbon capture are broken down into four components. First, there are the fuel costs associated with both the electric power requirement of the system itself and the extra power demand due to the increased ship resistance. These are discussed in sections 5.1.2.1 and 5.1.2.2, respectively. Then there are the maintenance costs of the system in section 5.1.2.3. Last, the extra port fees due to the increased Gross Tonnage (GT) of the vessel are discussed in section 5.1.2.4. Summing all operational costs discussed in this section, a total yearly operational cost for onboard carbon capture of €100,104 is arrived upon.

5.1.2.1 System power demand

As explained in section 3.3.2 the electric power demand of the capture system amounts to 121.6 kW. In order to estimate the associated fuel costs, a fuel price of €610 per ton (Danish Maritime Authority, 2012) and an LNG consumption (at 85% MCR) of 151 g/kWh (Wärtsilä, 2016) are assumed. When the ship is at sea using its engine for 57% of the time, the yearly costs then amount to:

$$57\% \cdot 0.151 \frac{kg}{kWh} \cdot 121.6\ kW \cdot 610€ \cdot 24 \cdot 365 = €55{,}765$$

5.1.2.2 Increased propulsion power

As described in section 4.4.4 the ship propulsion power is expected to increase with approximately 58 kW at its design speed. Using the same assumptions for operating profile, and fuel price as in section 5.1.2.1, the yearly costs due to the increased propulsion power become:

$$57\% \cdot 0.151 \frac{kg}{kWh} \cdot 58\ kW \cdot 610€ \cdot 24 \cdot 365 = €26{,}394$$

5.1.2.3 Maintenance

The capture system is designed to be as simple as possible. It is expected that there is no need for an extra engineer onboard. The system is expected to be quite low in maintenance, but there are some pumps and compressors that require maintenance. The yearly maintenance costs are estimated to be €15,000, which is in the same order of magnitude as the maintenance costs for the main engine.

5.1.2.4 Gross tonnage cost

Because the concept design has a larger volume than the reference vessel, its GT is higher. As port fees are usually based on the ship's GT, these will be higher for the concept design as well.

GT is calculated according to the International Convention on Tonnage Measurement of Ships:

$$GT = K \cdot V$$

Where V is the volume of all enclosed spaces on the ship and K is defined as follows:

$$K = 0.2 + 0.02 \cdot \log_{10}(V)$$

The original ship has an approximate volume of 25,000 m^3, resulting in a GT of 5720. The concept design is 5.82 meters longer, resulting in an extra volume of:

$$5.82 \cdot 16 \cdot 9.9 \cong 922$$

In addition, the superstructure has been increased: the bottom two floors are 3 meters longer than those of the benchmark design. This results in another increase in volume:

$$2 \cdot 10 \cdot 3 \cdot 2.9 = 174$$

So, the resulting volume is 21096 m^3. The GT then becomes 6044. The difference in GT with the benchmark vessel is: $6044 - 5720 = 324$.

To estimate the cost associated with this, the tariffs of the Port of Rotterdam are used (Port of Rotterdam, 2017). For the calculation, the ship is considered to be a 'General cargo ship not in Scheduled Service", for which the GT tariff is €0.303. With 30 port calls per year, the extra cost associated with increased GT then becomes:

$$\Delta GT \cdot tariff \cdot port\ calls = 324 \cdot 0.303 \cdot 30 = €2945$$

For the purpose of this thesis it is assumed that the port fees increase with the increased volume that is required for the carbon capture plant. It is however conceivable that the opposite is true; It is very well possible that if onboard carbon capture is actually applied in the future, the port fees for ships with onboard carbon capture are lowered as a means of stimulating 'green shipping'. The Port of Rotterdam, for instance, applies such a discount for ships that use LNG as a fuel (Port of Rotterdam, 2017).

5.2 BENEFITS

Aside from an increase in costs, there might also be financial benefits to onboard carbon capture. First, it is possible to sell the captured CO_2 to users, such as Dutch greenhouses or the food industry. These benefits are explained in section 5.2.1. Also, it is conceivable that in the future a price tag is put on the emission of CO_2, for example by means of taxes or emissions rights trading. Because this would decrease the relative cost of onboard carbon capture, it is discussed in section 5.2.2, even though literally it would mean a cost increase for ships without onboard carbon capture instead of increased benefits for ships with onboard carbon capture.

5.2.1 SALE OF CO_2

The CO_2 captured and stored onboard is of high purity (over 99%). This makes that it can be sold to industries demanding high-grade CO_2. The Dutch greenhouse sector for example could directly use the CO_2, without any treatment. An additional benefit is that there already is a CO_2 pipeline from the Port of Rotterdam to the greenhouses in the 'Westland' (the OCAP pipeline). For the food industry it might be necessary to slightly upgrade the purity.

CO_2 is delivered to the greenhouses through the OCAP pipeline at a price of €50 to €80 per tonne (Mikunda et al., 2015, p. 25). For the base case scenario, it is assumed that the CO_2 captured onboard can sold at €50. Costs for offloading and transport are assumed to be €10 per tonne, leaving a net income of €40 per tonne CO_2.

With the ship at sea for 57% of the time, sailing at 85% of the MCR, the amount of CO_2 captured per year is 5322 tonnes. This would yield a yearly income of €212,880.

5.2.2 CO_2 EMISSION COSTS

The possibility should be taken into account that in the future a price will be put on the emission of CO_2 from international shipping. This could be by means of taxation or an emissions trading scheme (ETS). If this would be the case, onboard carbon capture would become more attractive for shipping companies. At the moment, however, international shipping is excluded from any policy measures putting a price on the emission of greenhouse gases. Hence, the base case scenario assumes that CO_2 can be emitted free of charge.

5.3 BASE CASE SCENARIO

An economic analysis is done of the base case scenario, which is based on the assumptions discussed in sections 5.1 and 5.2. The main figures for the economic analysis are summarized in Table 5.6. Using these data the cost of onboard carbon capture is calculated and expressed in a cost per ton CO_2 avoided. The amount CO_2 avoided is not exactly the same as the amount of CO_2 captured. This has to do with the fact that the capture of

CO_2 requires some energy. This energy is provided for by the main engine, which in turn emits some extra CO_2. On land based systems the discrepancy between CO_2 avoided and CO_2 captured can be sizeable. However, because of the heat integration of the onboard capture system, in our case the difference is quite small: the estimated yearly amount of CO_2 captured is 5128 tonnes, whereas the amount of CO_2 avoided is 4752 tonnes. This is a difference of less than 1%.

With the assumptions from section 5.1 and 5.2, summarized in Table 5.6, the net cost per tonne CO_2 avoided amounts to €34.71.

Capital investment	€ 4,973,560	
Depreciation period	25	years
LNG bunker price	€ 610	per tonne
Maintenance	€ 15,000	per year
CO2 sale income	€ 40	per tonne
CO2 emission cost	€ -	per tonne

TABLE 5.6 SUMMARY OF THE ASSUMPTIONS MADE FOR THE ECONOMIC ANALYSIS OF ONBOARD CARBON CAPTURE

5.4 SENSITIVITY ANALYSIS

The base case scenario shows an estimated cost of €19.76 per tonne CO_2 avoided. There is however some uncertainty in the assumptions made to arrive at this cost. Hence, a sensitivity analysis is performed. By means of on-at-a-time variation the significance of the cost influencing factors is assessed.

5.4.1 PARAMETERS

The sensitivity analysis will show a number of things:

The robustness of the estimation: how much does changing the input variables change the outcome of the calculation?

The significance of the different cost influencing factors: which specific input variables contribute most to the net cost of carbon capture? The answer to this question will help to determine the areas to focus on when aiming to reduce costs.

Five variables are varied: capital investment, LNG price, maintenance costs, income from CO_2 sales and costs of CO_2 emissions. The input values for the sensitivity analysis are summarized in Table 5.7.

	low	medium	high
Capital investment (total)	€ 2,486,780	**€ 4,973,560**	€ 7,460,340
LNG bunker price (per tonne)	€ 485.00	**€ 610.00**	€ 740.00
Maintenance (per year)	€ 7,500.00	**€ 15,000.00**	€ 22,500.00
CO2 sale income (per tonne)	€ -10.00	**€ 40.00**	€ 70.00
CO2 emission cost (per tonne)	**€ -**	€ 20.00	€ 40.00

TABLE 5.7 INPUT VALUES FOR THE SENSITIVITY ANALYSIS. THE BASE CASE SCENARIO IS DISPLAYED IN BOLD.

The capital investment and the maintenance costs are varied between 50% and 150% of the base case scenario. There is a high degree of uncertainty regarding these variables, so a broad range is taken. The LNG bunker prices are varied between €485 per tonne and €740 per tonne (Danish Maritime Authority, 2012).

For the income from CO_2 sales, the minimum is assumed to be €-10 per tonne. This represents the situation that no revenue is generated at all from selling the CO_2 and €10 per tonne CO_2 is payed for CO_2 disposal. The maximum income is taken as €70, based on a revenue of €80 per tonne and a logistics cost of €10 per tonne. The cost of CO_2 emissions is varied from €0 to €40, which is equal to a conservative estimate of the social cost of CO_2 emissions(Cost of Carbon Project, 2015).

5.4.2 Results

The results of the sensitivity analysis are shown in table Table 5.8. It can be seen that variation in LNG price and maintenance costs have a relatively small influence on the net cost of carbon capture. The capital investment, on the other hand, is a very important cost item.

Both the income from selling the captured CO_2 and setting a price on emission of CO_2 significantly influence the net cost of onboard CO_2 capture. If it is assumed that no revenue generated with CO_2 sales (and the €10 cost for disposing of the CO_2 remains), the cost per tonne CO_2 avoided rises to €73.62. This can be seen as the gross cost of CO_2 avoided. Of this €73.62, €51.86 or 57% is due to the capital investment. Hence, the capital investment is the most important parameter influencing the gross cost of CO_2 avoided. If a revenue of €80 per tonne CO_2 can be achieved, onboard carbon capture can be profitable.

If a price of €40 per tonne is set on the emission of CO_2, onboard carbon capture is estimated to be profitable with a profit of €20 per tonne CO_2 avoided. The price at which onboard carbon capture becomes cost neutral is approximately €20 per tonne.

Overall, onboard carbon capture appears to be quite cost effective. Under the right circumstances, it could even be profitable. There is however a fair amount of uncertainty, mainly due to uncertainty in CO_2 prices (both income from sales and price for emission) and the required capital investment.

	low		medium		high	
Capital investment	€	-1.17	**€**	**19.76**	€	40.69
LNG bunker price	€	16.22	**€**	**19.76**	€	23.45
Maintenance	€	18.18	**€**	**19.76**	€	21.34
CO2 sale income	€	73.72	**€**	**19.76**	€	-12.61
CO2 emission cost	**€**	**19.76**	€	-0.24	€	-20.24

TABLE 5.8 RESULTS OF THE SENSITIVITY ANALYSIS. SHOWN IS THE COST PER TONNE CO_2 AVOIDED. THE BASE CASE SCENARIO IS DISPLAYED IN BOLD.

6 CONCLUSIONS AND RECOMMENDATIONS

The goal of this thesis was to investigate the feasibility of carbon capture onboard LNG-fueled ships. The approach adopted in achieving this goal was to adapt an existing ship design so that a carbon capture system was fitted onboard. This design was then analyzed. In section 6.2 the research questions formulated in the introduction of this thesis are answered to the extent possible. Of course, before these conclusions are drawn the results of this study are discussed in section 6.1. A number of recommendations are given in section 6.3.

6.1 DISCUSSION

The results of this study show that the gross cost of carbon capture onboard LNG fueled vessels (so assuming no income for CO_2 sales and no pricing of CO_2 emissions) is estimated to be around €74 per tonne CO_2 avoided. To put this in perspective, the cost of CO_2 avoided for gas powered power plants on land using a similar MEA based capture system is estimated to be around €50 per tonne (Sanchez Fernandez, 2013). There are several reasons for this difference. Where power plants are operational nearly fulltime, ships spend a lot of time in port or at anchor, with the main engine idling or shut down. At these moments, no CO_2 is captured, so the utilization factor of the capture plant decreases. Because the capital investment is the most important parameter influencing the gross cost of CO_2 avoided, a low utilization factor has a major impact on this cost. Another difference between onboard carbon capture and carbon capture on land is the fact that ships need a relatively large amount of (expensive) storage capacity to store the captured CO_2 onboard.

Regarding the capital investment: the estimation done in this study is quite rough. Because of its importance for the cost of CO_2 capture, this rough estimate introduces a great deal of uncertainty in the results of this study. It is however hard to provide a more exact estimation, as there is not much experience with with fitting carbon capture plants onboard ships.

As the quality of the captured CO_2 is high, it is assumed that it can be sold for €50 per tonne, reducing the net cost of carbon capture to around €20 per tonne CO_2 avoided. There is however a catch to this: it is expected that carbon capture will be applied more in the future. If this is the case, the CO_2 market could be flooded with captured CO_2, lowering the price. The assumption that a revenue of €50 per tonne can be achieved is a valid assumption for the near future, but might not hold in the long run. However, for the time being it is reasonable to assume an income from the captured CO_2, as no large scale carbon capture projects are expected to go into operation in the Netherlands in the near future. Moreover, if onboard carbon capture takes off, the capital investment might decrease because of the production volume, possibly compensating for the reduced CO_2 sales income.

The net cost of onboard carbon capture can be influenced by climate policy; if a price of €20 would be set on emission of CO_2, carbon capture could be cost neutral. Another alternative for policy makers is to oblige ships to reduce their CO_2 emissions, much like Sulfuric and NO_x emissions are already being restricted. In that case, carbon capture would be an attractive method of complying with these new regulations.

The capture plant that was designed in light of this study is a relatively simple system. If a capture plant is to be fitted onboard a vessel, the system design could be tailored to the needs for that particular vessel. The system could for example be adapted such that it is capable of handling very low engine outputs as well. Another item is uncertainty about the actual efficiency of the capture system on a moving ship; all capture plants that have been built so far are land based, and thus not subjected to rolling, pitching, heaving, et cetera. Solutions could however be provided for this potential problem.

The goal of this study was to investigate the feasibility of carbon capture onboard LNG fueled vessels. The approach followed to this end was to take an existing design for a general cargo vessel and adapting that to accommodate a capture plant and CO_2 storage capacity. This means that the feasibility has only been investigated for one specific ship type. Moreover, this specific ship type, which is usually deployed in tramp service, might not be the most obvious ship type to start with when applying carbon capture to ships. It might for example be easier to start with a ship that is on a fixed route, so that the CO_2 handling logistics can be taken care of in the ports frequented by the ship. Also, it might be that the first capture plants will not be applied on cargo vessels, for which volume- and DWT efficiency are very important. Rather, passenger vessels could be a more obvious choice, as passengers might be happy to pay a little extra for going on a cruise or trip that is nearly CO_2 neutral. Other ship types that could benefit from onboard carbon capture are vessels that have a relatively high speed. At the moment, some of these ships (e.g. RoRo/RoPax vessels) can be limited in their service speed because of the Energy Efficiency Design Index (EEDI) regulations, which set a limit to the ship's CO_2 emissions based on the vessel's transport work. With onboard carbon capture, CO_2 emissions could be reduced without having to reduce the service speed. The way the EEDI is calculated would have to be updated for this purpose, as the current formulation does not account for the possibility of onboard carbon capture.

Taking into account these considerations, the author believes that this study can be of value for other ship types than 8000 DWT general cargo vessels. The specific ship design used in the study served mainly to give an indication of the necessary modifications to the ship to accommodate a carbon capture plant. For other ship types these modifications will be essentially the same: there is a volume requirement, a tonnage requirement, a power requirement, and the stability of the ship should not be compromised. This study is not a full business case for one specific ship type: it takes into account only the costs associated with the capture plant. This way, it can be extrapolated to apply to other ship types with relative ease.

6.2 Conclusions

In the introduction of this thesis, four research questions were formulated that should help in investigating the feasibility of carbon capture onboard LNG fueled vessels. These four questions are stated again below, and subsequently answered to the extent possible.

- Is carbon capture and intermediate storage onboard LNG-fueled vessels technically feasible?
- What would be the main design consequences of implementing onboard carbon capture and intermediate storage?
- To what extent can CO_2 emissions be reduced by implementing onboard carbon capture and storage?
- When is onboard carbon capture and intermediate storage economically feasible?

Calculations at TNO, combined with a ship design accommodating an onboard capture plant have shown that it is technically feasible to apply carbon capture and intermediate storage onboard LNG fueled vessels. Integration of the heat from the engine's exhaust gases and of the cold from the cryogenic LNG makes that no external heat is required for the capture process, reducing the power demand of the process. The system designed is simple and the exact implementation, if applied to actual ships, could vary, but it is certainly possible to fit such a system onboard a ship. In this thesis a general cargo vessel was used as an example, but there is no reason to assume that a similar system could not be applied to other ship types.

The main design consequences are that the capture plant and the captured CO_2 have a significant weight. Also, volume must be found onboard to fit the plant and storage tanks. In this case the result is a longer ship with an increased displacement. Important to take into is that, contrary to conventional ships, the displacement of the ship increases during its voyage due to the CO_2 that is stored onboard. Hence, the condition with the largest displacement is the arrival condition of the ship, instead of the departure condition.

According to calculations at TNO a capture rate of 90% can be achieved. The capture process requires little external power, so there is only a small amount of extra CO_2 emitted to provide for this power. The yearly amount of CO_2 emitted by the concept design is estimated to be 730 tonnes. This includes 160 tonnes of CO_2 emissions of the ship when it is in port and at anchor, when no CO_2 is captured. The amount of CO_2 emitted on the reference design is 5483 tonnes per year. This makes that the amount of CO_2 avoided is 4752 tonnes per year. This is an emission reduction of 87% compared to the reference ship.

Regarding the economic feasibility, there is some uncertainty, mainly because of uncertainty about the capital costs and about the cost of CO_2 (both the CO_2 trade price and the cost of CO_2 emissions). Gross cost per ton CO_2 avoided is estimated to be around €74, whereas the net costs are less than €20. This is slightly more than land based carbon capture projects, but in the same order of magnitude. Setting a price on the emission of CO_2 could make onboard carbon capture profitable; a price of €20 per ton CO_2 emitted could make it cost neutral.

Concluding: carbon capture onboard LNG fueled vessels is technically feasible and could drastically reduce CO_2 emissions from international shipping. Its economic feasibility depends mainly on the capital investment required for the capture plant, as well as policy measures to reduce CO_2 emissions from shipping. It is a promising solution for the shipping industry, as CO_2 emissions from shipping will have to be reduced in the future.

6.3 RECOMMENDATIONS

This thesis shows that fitting a carbon capture plant onboard a ship is technically feasible, and could be economically feasible. However, there are some questions regarding both the technical aspects and the economic aspects that could do with further investigation.

Regarding the technical aspects; there are some factors that might influence the performance of an onboard carbon capture plant that have not been addressed in this thesis. What, for example, is the influence of ship movements on the efficiency of the system? Is the capture rate compromised when the ship is rolling, pitching, heaving and surging in heavy seas? And what about a static heeling angle? Should the design of the absorber column be different from absorber columns on land for optimal performance?

In thesis it is assumed that the solvent used for the capture process is an MEA solution. This is a conventional solvent, but is in some respects not ideal for the onboard capture system; it is quite sensitive to heat degradation and the capture process takes place at low pressures, which means that a lot of compression is required for liquefaction of the captured CO_2. Other solvents exist and might me more suitable for onboard use. This should be investigated.

Also interesting to investigate is the possibility of capturing the CO_2 produced by the ship's auxiliary engines when the ship is at anchor or in port. The power of these auxiliary systems is so low that the capture plant described in this thesis cannot be used. Is there a way to make carbon capture possible at low power? Or will the system then become too complicated and expensive? This issue is worth looking into.

Regarding the economic feasibility; capital costs are the most important factor influencing the total cost of onboard carbon capture. For now, the cost estimations are quite uncertain. Reducing this uncertainty should be high on the list of priorities for anyone looking to make onboard carbon capture a reality. This could be accomplished by means of an in-depth analysis of the building process of such a system; the approach used in this thesis is quite high-level. Perhaps experience from land based chemical industries could be used, as well as experience gained from floating chemical plants, such as FPSO's. When looking to reduce the costs associated with onboard carbon capture, the first thing to look at is the compressors required for CO_2 liquefaction. These compressors are quite expensive and a way should be found to reduce the required compression ratio, thereby reducing the capital cost of the compressors.

In order for onboard carbon capture to be successfully applied, it is necessary to think about what to do with the CO_2 once it's been captured and stored onboard. In this thesis, some concepts have been briefly explored, but this could, and should, be investigated more thoroughly.

Lastly, it is recommended that more concept designs are developed for ships with onboard carbon capture. One could think of other ship types, such as RoRo/RoPax vessels, but also different concepts of bunkering and CO_2 storage. For example, the possibility could be explored of storing CO_2 in the same tanks as where the LNG is stored in. This would pose quite some technical challenges, but is worth investigating as the required tank volume would be significantly reduced, thereby possibly reducing the cost of onboard carbon capture. Another concept that could be explored is that of containerized fuel tanks and CO_2 storage tanks. This way, a lot of flexibility could be gained, as the volume of the fuel- and storage tanks could be adjusted to each voyage. Bunkering operations would be reduced to loading some containers onboard. Filling of the tanks could be done on land, in a controlled environment, reducing the risk of accidents during bunkering.

Undoubtedly, there are many more issues worth investigating when it comes to onboard carbon capture. The most important recommendation, however, is to keep pushing technologies that can make shipping more sustainable. This slow moving industry needs it.

APPENDICES

APPENDIX A. CALCULATION OF FLUE GAS COMPOSITION

Engine data sheet can be found in Appendix B

Engine type		**Wärtsilä 6L34DF**	
Power	3000	kW	From data sheet
Gas consumption	7387	kJ/kWh	From data sheet
	447	kg/h	
Gas lower calorific value	49620	kJ/kg	From data sheet
Fuel oil consumption	1,9	g/kWh	From data sheet
	5,7	kg/h	
	42700	kJ/kg	From data sheet
Air consumption	4,5	kg/s	From data sheet
	16200	kg/h	
CO_2 emission	2,81E+04	mol/h	
	1238	kg/h	

Intake air composition

	share (molar)	molar mass (g/mol)	intake (mol/h)	intake (kg/h)
Air (total)	**100%**	**28,98**	**5,59E+05**	**16200**
N2	78%	28,02	4,36E+05	12219
O2	21%	32,00	1,17E+05	3757
Argon	1%	39,95	5,59E+03	223

Flue gas composition

	share (molar)	mol/h	kg/h
N2	74,1%	4,36E+05	12219
O2	10,2%	6,00E+04	1920
Ar	0,9%	5,59E+03	223
CO2	4,8%	2,81E+04	1238
H2O	9,9%	5,85E+04	1055
Total	**100,0%**	**5,89E+05**	**16656**

Gas	Methane CH4	Ethane C2H6	Propane C3H8	Nitrogen N2	**Total**	**Average**
molar %	92,00%	5,00%	1,99%	1,01%	**100,00%**	
molar mass (g)	16,04	30,07	44,09	28,01		**16,71**
mole/kg LNG	57,36	1,66	0,45	0,36	**59,83**	
mass %	95,86%	2,78%	0,75%	0,60%	**100,00%**	
LHV (kJ/kg)	50020	47480	46360	0		**49620**
consumption (mole/h)	25616	743	201	161	**26722**	
consumption (kg/h)	410,9	22,3	8,9	4,5	**446,6**	
CO2 emission (mole/h)	25616	1485	604	0	**27706**	
CO2 emission (kg/h)	1127	65	27	0	**1219**	

Pilot fuel Marine Gas Oil (MGO) / no.2 oil / bunker A			
consumption	5,70	kg/h	
	6,40	L/h	Density 0,89 kg/L from ISO standard for bunker A fuel oil
emission factor	2,88	kg/L	From co2emissiefactoren.nl
CO2 Emission	18,44	kg/h	
	419,11	mole/h	
H2O Emission	440,06	mole/h	

Volumes			
LNG density (in tank)	0,45	tonne/m3	From LNG Density Calculator
LNG consumption	0,992	m3/h	
CO2 capture rate	85%		
CO2 density (16 bar)	1,06	tonne/m3	From Mollier diagram
CO2 production	0,993	m3/h	

Heat balance			
Engine efficiency	48,19%		
Jacket water, HT	372	kW	
Charge air, HT	601	kW	
Charge air, LT	171	kW	
Lubricating oil, LT	260	kW	
Radiation	120	kW	
Exhaust gas (1)	1701	kW	Heat generated minus heat losses listed above
Exhaust gas (2)	1661	kW	Exhaust gas 4.6 kg per second at ΔT=361°C and 1kJ/kgK

APPENDIX B. MAIN ENGINE TECHNICAL DATA

From (Wärtsilä, 2016)

Wärtsilä 6L34DF		AUX		AUX		DE		DE		ME		ME	
		Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode
Cylinder output	**kW**	**480**		**500**		**480**		**500**		**500**		**500**	
Engine speed	rpm	720		750		720		750		750		750	
Engine output	kW	2880		3000		2880		3000		3000		3000	
Mean effective pressure	MPa	2.2		2.2		2.2		2.2		2.2		2.2	
Speed mode		Constant		Constant		Constant		Constant		Constant		Variable	
IMO compliance		Tier 3	Tier 2	Tier 3	Tier 2	Tier 3	Tier 2	Tier 3	Tier 2	Tier 3	Tier 2	Tier 3	Tier 2
Combustion air system (Note 1)													
Flow at 100% load	kg/s	4.5	5.4	4.5	5.4	4.5	5.4	4.5	5.4	4.5	5.4	4.5	5.5
Temperature at turbocharger in-take, max.	°C	45		45		45		45		45		45	
Temperature after air cooler (TE 601), load > 70%	°C	45	-	45	-	45	-	45	-	45	-	45	-
Temperature after air cooler (TE 601), load 30...70%	°C	55	-	55	-	55	-	55	-	55	-	55	-
Temperature after air cooler (TE 601)	°C	-	50	-	50	-	50	-	50	-	50	-	50
Exhaust gas system (Note 2)													
Flow at 100% load	kg/s	4.6	5.5	4.6	5.5	4.6	5.5	4.6	5.5	4.6	5.5	4.6	5.6
Flow at 75% load	kg/s	3.8	4.4	3.8	4.4	3.8	4.4	3.8	4.4	3.8	4.4	3.7	4.3
Flow at 50% load	kg/s	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.0	3.1
Temperature after turbocharger at 100% load (TE 517)	°C	362	355	381	381	362	346	381	370	381	370	381	361
Temperature after turbocharger at 75% load (TE 517)	°C	383	327	401	349	383	318	401	340	401	340	386	348
Temperature after turbocharger at 50% load (TE 517)	°C	386	350	402	371	386	346	402	366	402	366	340	333
Backpressure, max.	kPa	4		4		4		4		4		4	
Calculated exhaust diameter for 35 m/s	mm	545	596	553	608	545	591	553	603	553	603	553	605
Heat balance at 100% load (Note 3)													
Jacket water, HT-circuit	kW	357	410	372	430	357	406	372	425	372	425	372	443
Charge air, HT-circuit	kW	601	933	601	933	601	933	601	933	601	933	601	966
Charge air, LT-circuit	kW	171	179	171	179	171	179	171	179	171	179	171	184
Lubricating oil, LT-circuit	kW	250	252	259	264	250	250	260	261	260	261	260	281
Radiation	kW	115	117	120	123	115	116	120	121	120	121	120	123
Fuel consumption (Note 4)													
Total energy consumption at 100% load	kJ/kWh	7470	-	7470	-	7470	-	7470	-	7470	-	7470	-
Total energy consumption at 85% load	kJ/kWh	7620	-	7620	-	7620	-	7620	-	7620	-	7570	-

Wärtsilä 6L34DF		AUX		AUX		DE		DE		ME		ME	
		Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode
Cylinder output	**kW**	**480**		**500**		**480**		**500**		**500**		**500**	
Total energy consumption at 75% load	kJ/kWh	7850	-	7850	-	7850	-	7850	-	7850	-	7590	-
Total energy consumption at 50% load	kJ/kWh	8600	-	8600	-	8600	-	8600	-	8600	-	7790	-
Fuel gas consumption at 100% load	kJ/kWh	7387	-	7387	-	7387	-	7387	-	7387	-	7387	-
Fuel gas consumption at 85% load	kJ/kWh	7527	-	7527	-	7527	-	7527	-	7527	-	7471	-
Fuel gas consumption at 75% load	kJ/kWh	7743	-	7743	-	7743	-	7743	-	7743	-	7478	-
Fuel gas consumption at 50% load	kJ/kWh	8435	-	8435	-	8435	-	8435	-	8435	-	7643	-
Fuel oil consumption at 100% load	g/kWh	1.9	191	1.9	192	1.9	189	1.9	190	1.9	190	1.9	190
Fuel oil consumption at 85% load	g/kWh	2.2	188	2.2	189	2.2	186	2.2	187	2.2	187	2.2	186
Fuel oil consumption at 75% load	g/kWh	2.5	188	2.5	189	2.5	186	2.5	187	2.5	187	2.5	184
Fuel oil consumption 50% load	g/kWh	3.8	194	3.8	195	3.8	194	3.8	195	3.8	195	3.4	183
Fuel gas system (Note 5)													
Gas pressure at engine inlet, min (PT901)	kPa (a)	535	-	535	-	535	-	535	-	535	-	535	-
Gas pressure to Gas Valve Unit, min	kPa (a)	655	-	655	-	655	-	655	-	655	-	655	-
Gas temperature before Gas Valve Unit	°C	0...60	-	0...60	-	0...60	-	0...60	-	0...60	-	0...60	-
Fuel oil system													
Pressure before injection pumps (PT 101)	kPa	700±50		700±50		700±50		700±50		700±50		700±50	
Fuel oil flow to engine, approx	m³/h	3.1		3.2		3.1		3.2		3.2		3.2	
HFO viscosity before the engine	cSt	-	16...24	-	16...24	-	16...24	-	16...24	-	16...24	-	16...24
Max. HFO temperature before engine (TE 101)	°C	-	140	-	140	-	140	-	140	-	140	-	140
MDF viscosity, min.	cSt	2.0		2.0		2.0		2.0		2.0		2.0	
Max. MDF temperature before engine (TE 101)	°C	45		45		45		45		45		45	
Leak fuel quantity (HFO), clean fuel at 100% load	kg/h		2.2		2.3		2.2		2.3		2.3		2.4
Leak fuel quantity (MDF), clean fuel at 100% load	kg/h	5.6	11.1	5.8	11.6	5.6	11.1	5.8	11.6	5.8	11.6	5.9	11.8
Pilot fuel (MDF) viscosity before the engine	cSt	2...11		2...11		2...11		2...11		2...11		2...11	
Pilot fuel pressure at engine inlet (PT 112)	kPa (a)	550...750		550...750		550...750		550...750		550...750		550...750	
Pilot fuel pressure drop after engine, max	kPa	150		150		150		150		150		150	
Pilot fuel return flow at 100% load	kg/h	590		590		590		590		590		590	
Lubricating oil system													
Pressure before bearings, nom. (PT 201)	kPa	500		500		500		500		500		500	
Suction ability, including pipe loss, max.	kPa	30		30		30		30		30		30	
Priming pressure, nom. (PT 201)	kPa	50		50		50		50		50		50	

Wärtsilä 6L34DF		AUX		AUX		DE		DE		ME		ME	
		Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode
Cylinder output	**kW**	**480**		**500**		**480**		**500**		**500**		**500**	
Suction ability priming pump, including pipe loss, max.	kPa	30		30		30		30		30		30	
Temperature before bearings, nom. (TE 201)	°C	63		63		63		63		63		63	
Temperature after engine, approx.	°C	78		78		78		78		78		78	
Pump capacity (main), engine driven	m^3/h	78		81		78		81		81		81	
Pump capacity (main), electrically driven	m^3/h	67		70		67		70		70		70	
Priming pump capacity (50/60Hz)	m^3/h	15.0 / 18.0		15.0 / 18.0		15.0 / 18.0		15.0 / 18.0		15.0 / 18.0		15.0 / 18.0	
Oil volume, wet sump, nom.	m^3	1.6		1.6		1.6		1.6		1.6		1.6	
Oil volume in separate system oil tank	m^3	3		3		3		3		3		3	
Oil consumption at 100% load, approx.	g/kWh	0.4		0.4		0.4		0.4		0.4		0.4	
Crankcase ventilation flow rate at full load	l/min	840		840		840		840		840		840	
Crankcase ventilation backpressure, max.	kPa	0.3		0.3		0.3		0.3		0.3		0.3	
Oil volume in turning device	l	...		...		...		...		...		...	
Oil volume in speed governor	l	1.4...2.2		1.4...2.2		1.4...2.2		1.4...2.2		1.4...2.2		1.4...2.2	
HT cooling water system													
Pressure at engine, after pump, nom. (PT 401)	kPa	250 + static		250 + static		250 + static		250 + static		250 + static		250 + static	
Pressure at engine, after pump, max. (PT 401)	kPa	530		530		530		530		530		530	
Temperature before cylinders, approx. (TE 401)	°C	85		85		85		85		85		85	
Temperature after engine, nom.	°C	96		96		96		96		96		96	
Capacity of engine driven pump, nom.	m^3/h	60		60		60		60		60		60	
Pressure drop over engine, total	kPa	100		100		100		100		100		100	
Pressure drop in external system, max.	kPa	100		100		100		100		100		100	
Pressure from expansion tank	kPa	70...150		70...150		70...150		70...150		70...150		70...150	
Water volume in engine	m^3	0.41		0.41		0.41		0.41		0.41		0.41	
Delivery head of stand-by pump	kPa	250		250		250		250		250		250	
LT cooling water system													
Pressure at engine, after pump, nom. (PT 471)	kPa	250+ static		250+ static		250+ static		250+ static		250+ static		250+ static	
Pressure at engine, after pump, max. (PT 471)	kPa	530		530		530		530		530		530	
Temperature before engine, max. (TE 471)	°C	38		38		38		38		38		38	
Temperature before engine, min. (TE 471)	°C	25		25		25		25		25		25	
Capacity of engine driven pump, nom.	m^3/h	60		60		60		60		60		60	
Pressure drop over charge air cooler	kPa	35		35		35		35		35		35	
Pressure drop in external system, max.	kPa	100		100		100		100		100		100	

Wärtsilä 6L34DF		AUX		AUX		DE		DE		ME		ME	
		Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode
Cylinder output	**kW**	**480**		**500**		**480**		**500**		**500**		**500**	
Pressure from expansion tank	kPa	70...150		70...150		70...150		70...150		70...150		70...150	
Delivery head of stand-by pump	kPa	250		250		250		250		250		250	
Starting air system (Note 6)													
Pressure, nom.	kPa	3000		3000		3000		3000		3000		3000	
Pressure, max.	kPa	3000		3000		3000		3000		3000		3000	
Pressure at engine during start, min. (alarm) (20°C)	kPa	1500		1500		1500		1500		1500		1500	
Low pressure limit in starting air receiver	kPa	1600		1600		1600		1600		1600		1600	
Starting air consumption, start (successful)	Nm^3	4.7		4.7		4.7		4.7		4.7		4.7	
Consumption per start (with slowturn)	Nm^3	6.1		6.1		6.1		6.1		6.1		6.1	

Notes:

Note 1 At ISO 15550 conditions (ambient air temperature 25°C, LT-water 25°C) and 100% load. Flow tolerance 5%.

Note 2 At ISO 15550 conditions (ambient air temperature 25°C, LT-water 25°C). Flow tolerance 5% and temperature tolerance 10°C in gas mode operation. Flow tolerance 8% and temperature tolerance 15°C in diesel mode operation.

Note 3 At 100% output and nominal speed. The figures are valid for ambient conditions according to ISO 15550 except for LT-water temperature, which is corresponding to charge air receiver temperature 45°C in gas operation. With engine driven water and lubricating oil pumps. Tolerance for cooling water heat 10%, tolerance for radiation heat 30%. Fouling factors and a margin to be taken into account when dimensioning heat exchangers.

Note 4 At ambient conditions according to ISO 15550 and receiver temperature 45 °C. Lower calorific value 42 700 kJ/kg for pilot fuel and 49 620 kJ/kg for gas fuel. With engine driven pumps (two cooling water pumps, one lubricating oil pump and pilot fuel pump). Tolerance 5%.

Note 5 Fuel gas pressure given at LHV ≥ 36MJ/m³N. Required fuel gas pressure depends on fuel gas LHV and need to be increased for lower LHV's. Pressure drop in external fuel gas system to be considered. See chapter Fuel system for further information.

Note 6 Minimum pressure for slow turning is 1800kPa.

ME = Engine driving propeller, variable speed

AE = Auxiliary engine driving generator

DE = Diesel-Electric engine driving generator

Subject to revision without notice.

APPENDIX C. Power PREDICTION

Maxsurf Resistance software was used for the power prediction

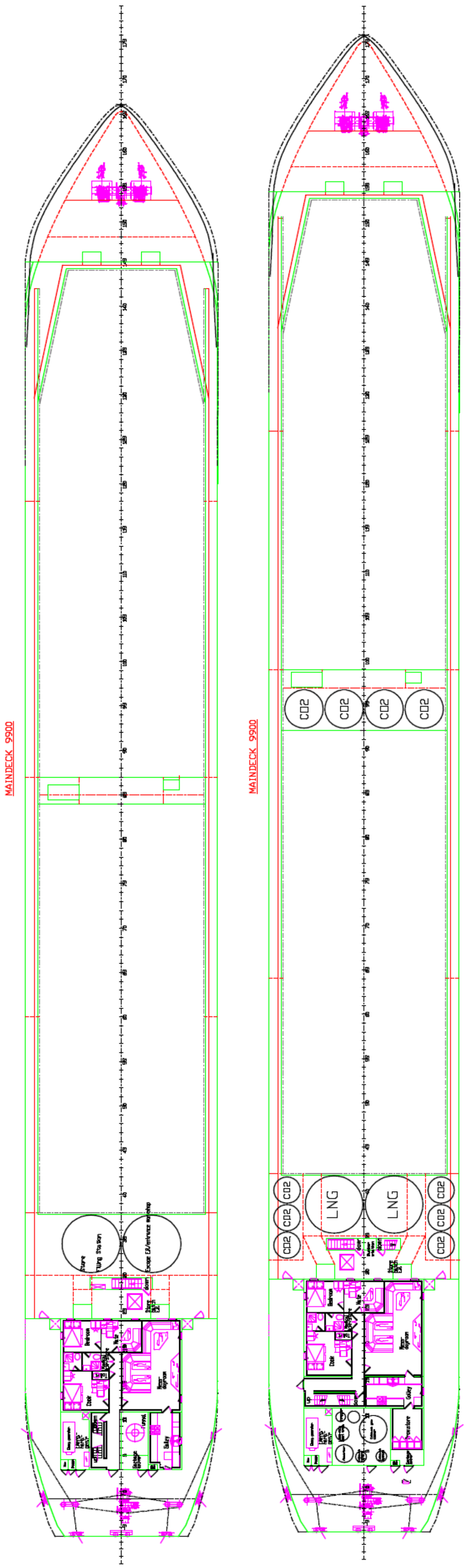
C.1 Input data

	Benchmark			Concept		
Item	**value**	**unit**	**Holtrop**	**value**	**unit**	**Holtrop**
LWL	118.5	m	118.5	124.32	m	124.32
Beam	15.95	m	15.95	15.95	m	15.95
Draft	7.3	m	7.3	7.3	m	7.3
Displaced volume	11053.42	m^3	11053.42	11728.36	m^3	11728.36
Wetted area	3092	m^2	3092	3264.8	m^2	3264.8
Prismatic coeff. (Cp)	0.804		0.804	0.813		0.813
Waterpl. area coeff. (Cwp)	0.917		0.917	0.921		0.921
1/2 angle of entrance	27	deg.	27	27	deg.	27
LCG from midships(+ve for'd)	1.5	m	1.5	1.48	m	1.48
Transom area	0.3	m^2	0.3	0.3	m^2	0.3
Transom wl beam	3	m	--	3	m	--
Transom draft	0.15	m	--	0.15	m	--
Max sectional area	116.017	m^2	--	116.039	m^2	--
Bulb transverse area	0	m^2	0	0	m^2	0
Bulb height from keel	0	m	0	0	m	0
Draft at FP	7.3	m	7.3	7.3	m	7.3
Deadrise at 50% LWL	0	deg.	--	0	deg.	--
Hard chine or Round bilge	Round bilge		--	Round bilge		--
Frontal Area	0	m^2		0	m^2	
Headwind	0	kn		0	kn	
Drag Coefficient	0			0		
Air density	0.001	tonne/m^3		0.001	tonne/m^3	
Appendage Area	0	m^2		0	m^2	
Nominal App. length	0	m		0	m	
Appendage Factor	1			1		
Correlation allow.	0.0004			0.0004		Calculated by method
Kinematic viscosity	1.19E-06	m^2/s		1.19E-06	m^2/s	
Water Density	1.025	tonne/m^3		1.025	tonne/m^3	

C.2 Results

Benchmark						Concept					
Speed (kn)	Froude Nr. LWL	Froude nr. Volume	Holtrop resistance (kN)	Holtrop power (kW)	Engine power (kW)	Speed (kn)	Froude Nr. LWL	Froude nr. Volume	Holtrop resistanc e (kN)	Holtrop power (kW)	Engine power (kW)
0	0	0	--	--	0	0	0	0	--	--	0
0.5	0.008	0.017	0.4	0.1	0.2	0.5	0.007	0.017	0.4	0.104	0.2
1	0.015	0.035	1.4	0.726	1.1	1	0.015	0.034	1.5	0.758	1.2
1.5	0.023	0.052	3	2.327	3.6	1.5	0.022	0.052	3.1	2.429	3.7
2	0.03	0.07	5.2	5.32	8.2	2	0.029	0.069	5.4	5.555	8.5
2.5	0.038	0.087	7.9	10.108	15.6	2.5	0.037	0.086	8.2	10.555	16.2
3	0.045	0.104	11.1	17.082	26.3	3	0.044	0.103	11.6	17.838	27.4
3.5	0.053	0.122	14.8	26.623	41.0	3.5	0.052	0.121	15.4	27.803	42.8
4	0.06	0.139	19	39.105	60.2	4	0.059	0.138	19.8	40.84	62.8
4.5	0.068	0.157	23.7	54.917	84.5	4.5	0.066	0.155	24.8	57.356	88.2
5	0.075	0.174	28.9	74.447	114.5	5	0.074	0.172	30.2	77.754	119.6
5.5	0.083	0.191	34.7	98.05	150.8	5.5	0.081	0.19	36.2	102.407	157.5
6	0.091	0.209	40.9	126.103	194.0	6	0.088	0.207	42.7	131.707	202.6
6.5	0.098	0.226	47.6	159.006	244.6	6.5	0.096	0.224	49.7	166.069	255.5
7	0.106	0.244	54.8	197.2	303.4	7	0.103	0.241	57.2	205.952	316.8
7.5	0.113	0.261	62.5	241.211	371.1	7.5	0.111	0.258	65.3	251.891	387.5
8	0.121	0.278	70.9	291.686	448.7	8	0.118	0.276	74	304.541	468.5
8.5	0.128	0.296	79.9	349.452	537.6	8.5	0.125	0.293	83.4	364.728	561.1
9	0.136	0.313	89.8	415.574	639.3	9	0.133	0.31	93.6	433.5	666.9
9.5	0.143	0.331	100.5	491.405	756.0	9.5	0.14	0.327	104.8	512.177	788.0
10	0.151	0.348	112.5	578.642	890.2	10	0.147	0.345	117.1	602.401	926.8
10.5	0.158	0.365	125.8	679.37	1045.2	10.5	0.155	0.362	130.7	706.171	1086.4
11	0.166	0.383	140.7	796.093	1224.8	11	0.162	0.379	145.9	825.874	1270.6
11.5	0.174	0.4	157.5	931.756	1433.5	11.5	0.169	0.396	163	964.299	1483.5
12	0.181	0.418	176.5	1089.765	1676.6	12	0.177	0.414	182.2	1124.647	1730.2
12.5	0.189	0.435	198.1	1273.928	1959.9	12.5	0.184	0.431	203.8	1310.548	2016.2
13	0.196	0.452	222.6	1488.471	2290.0	13	0.192	0.448	228.2	1525.88	2347.5
13.5	0.204	0.47	250.4	1738.778	2675.0	13.5	0.199	0.465	255.6	1775.212	2731.1
14	0.211	0.487	281.8	2029.231	3121.9	14	0.206	0.483	286.6	2064.019	3175.4
14.5	0.219	0.505	316.6	2361.857	3633.6	14.5	0.214	0.5	321.1	2395.284	3685.1
15	0.226	0.522	355.7	2745.098	4223.2	15	0.221	0.517	359.1	2771.204	4263.4

APPENDIX D. GENERAL ARRANGEMENT: PLAN VIEW AT MAIN DECK



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