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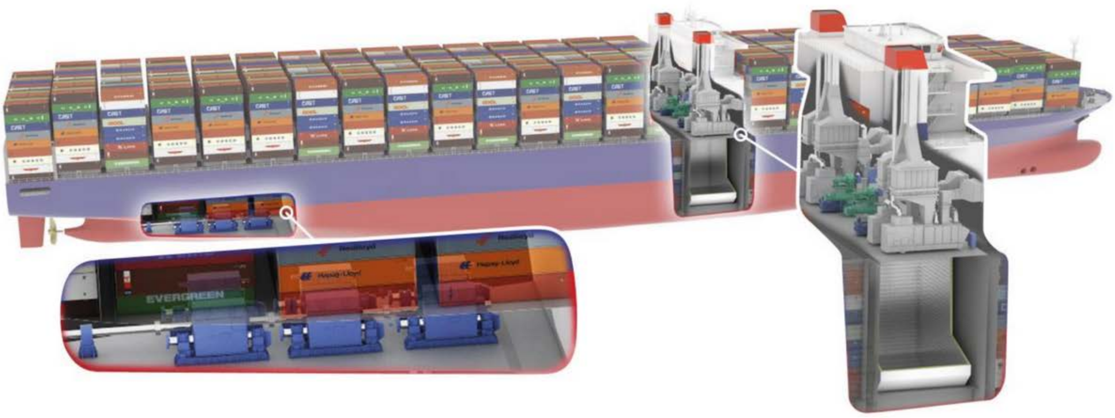

Combined gas- and steam turbine as prime mover in marine applications

Diploma thesis in the Marine Engineering Programme

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Gothenburg, Sweden 2017

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Cover:
Conceptual layout of a container ship with a gas turbine propulsion system in COGES configuration (Siemens Industrial Turbomachinery AB, 2017).

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Abstract

The gas turbines are known to have good efficiency when used in combined cycle configurations and has been used for ship propulsion in different types of vessels; mainly naval vessels, cruise ships and fast ferries. Still, diesel engines are by far the most common type of engines used for ship propulsion today.

Due to some characteristics of the gas turbine, for example the poor efficiency at low loads; not all types of vessels are suitable to use this propulsion system. This study aims to investigates the use of a combined gas- and steam turbine configuration for propulsion and for which types of vessels it would be suitable when considering engine power, emission regulations, trade routes and technical aspects. Since the industry is facing changes due to the upcoming emission regulations in 2020 this study also looks at two different fuels, liquified natural gas (LNG) and marine diesel oil/marine gas oil (MDO/MGO) for gas turbine propulsion in terms of performance, efficiency and environmental impact.

The result is achieved from a combination of scientific articles and an interview performed at Siemens Industrial Turbomachinery AB in Finspång. It reveals that a vessel with a gas turbine as prime mover is most suitable at vessels operating at longer voyages, less time at part-load and as few starts and stops as possible. To increase the efficiency and compete with the diesel engine even at part loads the gas turbine should be in combined gas and steam systems like COGES or COGAS. The fuel most suitable for gas turbine propulsion is natural gas; the difference compared to diesel in terms of efficiency and performance is small but the gaseous fuel is advantageous when looking at specific fuel consumption (SFC), power output and emissions.

Keywords: Gas turbine, steam turbine, COGES, COGAS, Siemens, emissions, efficiency, ship propulsion

Sammanfattning

Gasturbiner är kända för att ha en bra verkningsgrad vid användning i kombinerade konfigurationer och har använts för framdrivning i olika typer av fartyg. Främst inom militären, kryssningsfartyg och snabbgående färjor. Däremot är dieselmotorer överlägset den vanligaste typen av motor som används för framdrivning av fartyg idag.

På grund av vissa egenskaper hos gasturbinen, till exempel den förhållandevis låga verkningsgraden vid låga belastningar är inte alla typer av fartyg lämpliga för denna typ av framdrivningssystem. Denna studies syfte är att undersöka användningen av kombinerad gas- och ångturbinsdrift för framdrivning och för vilka typer av fartyg det skulle vara lämpligt när hänsyn tas till effekt, utsläppsregler, trader och tekniska aspekter. Eftersom industrin står inför förändringar på grund av de kommande utsläppsreglerna år 2020, undersöker denna studie också två olika bränslen, naturgas och marin dieselolja/marin gasolja, för framdrivning med gasturbiner vad gäller prestanda, effektivitet och miljöpåverkan.

Resultatet har tagits fram genom vetenskapliga artiklar och en intervju som genomförts på Siemens Industrial Turbomachinery AB i Finspång. Studien visar att en gasturbin som huvudmotor är lämpligast på fartyg som har långa sjöresor, få start och stop samt lite tid på delbelastning och under manövrering. För att öka effektiviteten och konkurrera med dieselmotorn, även vid lägre belastningar, bör gasturbinen användas i kombinerade gas- och ångsystem som COGES eller COGAS. Bränslet som är mest lämpat för en gasturbins framdrivning är naturgas. Skillnaden jämfört med dieselbränsle när det gäller effektivitet och prestanda är liten men naturgas är fördelaktigt när man tittar på den specifika bränsleförbrukning, effekt och utsläpp.

Nyckelord: Gasturbin, ångturbin, COGES, COGAS, Siemens, utsläpp, effektivitet, fartygs framdrivning,

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Abbreviations

C, Carbon
CO, Carbon Monoxide
CO_2, Carbon Dioxide
COGES, Combined Gas Turbine Electric & Steam
COGAS, Combined Gas Turbine and Steam
ECA, Emission Control Area
H, Hydrogen
HC, Hydro Carbon
H_2O, Water
HFO, Heavy Fuel Oil
IMO, International Maritime Organization
LHV, Lower Heating Value (kJ/kg)
LNG, Liquefied Natural Gas
MDO, Marine Diesel Oil
MGO, Marine Gas Oil
NO_x, Oxides of Nitrogen
PM, Particular matter
SECA, Sulphur Emission Control Area
SFC, Specific Fuel Consumption (g/kWh)
SFOC, Specific Fuel Oil Consumption (g/kWh)
SGFC, Specific Gas Fuel Consumption (g/kWh)
SNGCC, Supercharged Conventional Natural Gas Combined Cycle
SIT AB, Siemens Industrial Turbomachinery AB
SO_x, Oxides of Sulphur
TEU, Twenty-foot equivalent units

1 Introduction

In the shipping industry today, the diesel engine is the most widespread and the most reliable propulsion method for ships in the merchant fleet (Woud & Stapersma, 2008). This is a result of two important aspects, the high relatively efficiency of a diesel engine at various loads and the ability to be powered by heavy fuel oil (HFO), which is relatively cheap compared to distillates and alternative fuels (Haglind, 2008a). The propulsion system is also well proven, the knowledge about the diesel engine technique is immense and the engineers working in this field are well educated for repair, construction and operation of diesel engines. At the same time the engine manufacturers have, for decades, established a vast network of worldwide service, maintenance and accessible spare parts (International Maritime Organization, 2013). All these factors combined, as beneficial as they are for the current operations, are barriers for the necessary conversion towards a more environmental friendly and economically sustainable shipping industry, with alternative propulsion methods and new fuels.

Despite what is stated above, upcoming regulations regarding the emissions from the shipping industry, like IMO Tier III in the revised MARPOL Annex VI regarding NO_x, have increased the pressure on shipping companies and shipyards to find more environmentally friendly solutions for propulsion, operation and maintenance of the vessels. Other international regulations will allow a maximum of 0.5 percent sulphur in the marine fuels worldwide by the year 2020 and is already limiting the fuel sulphur level in the Sulphur Emission Control Area/Emission Control Area (SECA/ECA) to 0.1 percent (IMO, 2013). These regulations in combination with a big technical development (Wik & Niemi, 2016) have made the shipping industry question if the present method with diesel engines and residual fuels like HFO are sustainable from an environmental and economical perspective. The increasing bunker oil price, which between 2001 and 2015 have increased with approximately 450 USD/tonne (Worldscale Association Limited, 2017), can also be a contributing factor to the more sceptical view of the present methods.

In the report *Future ship powering options - exploring alternative methods of ship propulsion,* from the IMO (2013), several conventional propulsion methods and fuels are discussed as future alternatives; including LNG as fuel and gas turbines as propulsion method. LNG as a substitute marine fuel have advantages in terms of the emissions of SO_x, NO_x and CO_2 compared to other fuels as long as the methane slip during combustion is prevented (IMO, 2013). When looking at gas turbines as prime movers, the result has been superior in areas like the navy and aircraft industry and are slowly penetrating some parts of the commercial market, i.e. passenger ships and fast ferries (Elgohary & Seddiek, 2012). To power a larger container-, bulk- or crude oil vessel a suitable gas turbine configuration needs to be a combined gas and steam plant because of the required high efficiency and the benefits regarding emissions which is achieved through higher cycle efficiency (Haglind, 2008a). These combined plants have so far limited use in the shipping industry but is more often used as power supply on shore; however, with the new regulations and the need for alternative propulsion methods it is worth to examine gas turbines in combined cycle as the prime mover for ships in the merchant fleet.

1.1 Purpose

This literature and interview study aims to investigate if combined gas- and steam turbines as prime mover in a ship propulsion system would be a suitable method. To further analyse the possible marine application of gas turbines the study also examines what type of fuel that would be the best option for marine gas turbines. The possibility of compensating for the gas turbines poor efficiency at low/part loads will also be examined and included in the conclusion of the gas turbines potential as prime mover at sea.

1.2 Research questions

The research questions will be discussed and answered separately.

- For what type of vessel would, when considering engine power, emission regulations, trade routes and technical aspects, a combined gas turbine system as prime mover be a suitable alternative?

- How is it possible to compensate for the gas turbines comparatively poor efficiency at low- and part-loads?

- What type of marine fuel would, when considering fuel economy, environmental impact, output power and engine performance, be the best for marine propulsion with gas turbines as prime mover?

1.3 Delimitations

The study will include vessel types in the merchant fleet; crude oil carrier, container ship, bulk carrier, Ro-Ro ships and passenger ships are examples. Only gas turbines for propulsion are analysed, Combined Gas Turbine Electric and Steam (COGES) and Combined Gas Turbine and Steam (COGAS) configurations will be the main focus. When possible vessels are discussed the investment costs are not considered although they are briefly mentioned. Regarding the fuels, only gaseous fuel (LNG) and distillate fuel (Marine Diesel Oil (MDO)/ Marine Gas Oil (MGO)) will be considered.

The gas turbine model SGT-500 is used in the semi-structured interview result to get a fair comparison between fuels – the model is selected because it is today the only Siemens gas turbine which is classified for marine propulsion.

2 Background and Theory

This chapter will present the history and development of gas turbines, both in general and specifically in the shipping industry – to show that the gas turbine is a proven engine and that the technology is well known. The maintenance, working principle and theory of gas turbines and combined gas- and steam turbine systems will also be described to give basic knowledge of the subject. Further, two marine fuels will be introduced and described.

2.1 Gas turbine history

The link between globalization, economic growth and technical development has been investigated and discussed from many different perspectives, including the diesel engines and the gas turbines impact on our society today. These two prime movers have made transportation of raw materials, billions of tons of fuel and an incredible variety of other goods possible and has been one of the most important parts for the globalization and industrialization process during the last century (Smil, 2007). The huge two-stroke diesel engines which powers massive container ships and crude oil carriers, together with the gas turbine that powers big aeroplanes and generates power ashore, had a fundamentally important role for the global economy (Smil, 2007). The idea of gas turbines, as we know them today, was widely introduced during the third decade of the twentieth century with the first successfully prototypes. But the idea of an modern gas turbine engine, which is an internal combustion engine, was born in the last decade of the nineteenth century (Smil, 2007).

When looking at the development of gas turbines, the aeroplane industry has always been at the very front since the aircraft benefits from the large power to weight ratio obtained by the gas turbine engine (Woud & Stapersma, 2008). The gas turbines, or jet engines, were broadly introduced to the shipping industry during World War II when the Navies and shipbuilders noticed how the gas turbine engines, with useful attributes like power-weight, could be converted from the aeroplane industry into the shipping industry. Since the earliest gas turbine engines in airplanes were pure turbojets the need to reduce the shaft speed became essential for the shipping industry to combine the advantages of gas turbine propulsion with the lower working speed needed for the ship's propeller. This was solved with existing transmission technology (Woud & Stapersma, 2008).

The technical advance during World War II led to the first gas turbine driven warship in 1947 (Philips, 2007). The Royal Navy Motor Gun Boat 509 replaced one of its petrol engines with a converted Metropolitan Vickers axial flow aero engine which could produce twice the amount of power from approximately the same weight as the petrol engine. Afterwards, the Royal Navy continued to develop the gas turbine and it could later be used in even larger warships. The first warship with this propulsion system, HSM Ashanti, had one geared steam turbine plus one gas turbine and could cruise at 12 knots using only the steam turbine but could with the gas turbine online reach twice the speed (Philips, 2007). It was possible to run this engine in combined steam and gas turbine (COGAS) arrangements.

A more recent gas turbine application is seen in the cruise ship GTS Millennium, Celebrity Cruises. The ship was built in 2000 and was the first cruise ship with a gas turbine based propulsion plant (Haglind, 2008b). The combined gas- and steam turbine power plant (COGES) consists of two gas turbines with a total output of 50 MW and one steam turbine delivering 9 MW. This was enough to power the ships propulsion and generate sufficient power supply to all onboard consumers (Haglind, 2008b). To maximise the overall efficiency the GTS Millennium only runs on one gas turbine on full power, where the plant efficiency is higher than on part loads (Haglind, 2008a), when in port, during transit or other operations not requiring both gas turbines online. After seven years in operation with the gas- and steam turbine plant a decision was made to install an auxiliary diesel generator. The generator provided 11.6 MW and the idea was to use it to provide the vessel with "base power" for consumers in the hotel and restaurants when the ship is in port.

2.2 Working principle of gas turbines

The main components of a gas turbine are the air compressor, the combustion chamber and the turbine. When looking at the efficiency of a gas turbine the inlet- and outlet ducts are also mentioned as important components (Woud & Stapersma, 2008). In the same way as the diesel engine, the gas turbine converts chemical energy stored in the fuel into mechanical energy on the output shaft. The energy conversion takes place in two main stages. First, the chemical energy is converted to thermal energy in the combustion process where air and fuel is mixed and ignited. Then, the temperature increases when the air-fuel mixture is burning and this thermal energy is converted into mechanical energy when the hot gasses expands and powers the turbine blades (Woud & Stapersma, 2008).

2.2.1 *Main components*

Air compressor:

In an open cycle fresh air enters through the inlet duct continuously and is compressed from atmospheric pressure to the working pressure, 10 – 30 bar (Woud & Stapersma, 2008), by the compressor. The purpose of the compressor is to increase the pressure of the air to make it possible to burn more fuel and in that way, get a higher power output (Nada, 2014).

Combustion chamber:

When the air is compressed to working pressure the air enters the combustion chamber where fuel is added and the air-fuel mixture is ignited by a spark plug or a gas pilot burner and the combustion starts.

The turbine:

The exhaust gases are directed to the turbine side where it pushes the blades which powers the turbine shaft. The turbine side can have more than one stage where the twin-shaft arrangement is the easiest and most simple construction after the single shaft arrangement. The twin-shaft gas turbine consists of one compressor turbine (that powers the compressor) and one power turbine (Woud & Stapersma, 2008) which is either connected via a reduction gear to the propeller shaft or a generator. This depends on the propulsion system layout. The turbine side can have more than two stages but the principle is the same; each stage powers a specific load (a compressor stage or an external load). See chapter 2.3.3 – Twin-shaft.

The ideal simple gas turbine cycle, also named the Brayton cycle, is often used as a reference and/or comparison model when evaluating a real-life GT cycle. When describing an ideal simple GT cycle the following process are assumed (Woud & Stapersma, 2008):

- 1 – 2: Isentropic compression (i.e. constant entropy)
- 2 – 3: Isobaric heat addition (i.e. the pressure is constant)
- 3 – 4: Isentropic expansion
- 4 – 1: Isobaric heat removal

The main differences between the Brayton cycle and the real gas turbine cycle is the losses that occurs during the process. Air friction losses will occur in the compressor, the combustion chamber and the turbine sections; thermal losses occur when heat is transferring to the surrounding environment, mainly from the combustion chamber and the turbine side; there will be combustion losses due to incomplete combustion of the added fuel; and lastly, several mechanical losses in all moving parts like bearings and auxiliary equipment and pressure losses in all ducts will also occur (Woud & Stapersma, 2008).

2.2.2 *Gas turbine efficiency*

The efficiency of a gas turbine is important from various aspects including fuel economy and actual power output. Some parameters affect the efficiency a lot; according to De Sa & Al Zubaidy (2011) there is a difference between the rated power and actual power output for a gas turbine operating at ambient conditions which differs from ISO conditions (a temperature of 20°C and an absolute pressure of 101.325 kPa). Gas turbines have a loss of 0.1 percent in thermal efficiency per degree over ISO standard temperature which also means a loss of 1.47 MW of gross power (De Sa & Al Zubaidy, 2011). The pressure ratio is another parameter which is important for the gas turbine efficiency and a higher pressure ratio will increase the turbine isentropic efficiency and at the same time decrease the compressor isentropic efficiency (De Sa & Al Zubaidy, 2011). The turbine and compressor isentropic efficiencies both starts at 85 % at pressure ratio = 1.0 and for a pressure ratio of 11.0 the turbine efficiency is just below 90 % and the compressor efficiency is close to 80 % (De Sa & Al Zubaidy, 2011).

The real-life gas turbine cycle efficiency can be described as the gross efficiency, a definition used by Siemens Industrial Turbomachinery AB (SIT AB) when presenting their industrial gas turbines (Siemens AG, 2017). On gas turbines ranging from 5 to 53 MW in power output the efficiency is found to be between 31.0 % and 40.3 % for simple cycles (Siemens AG, 2017). The highest gross efficiency, 40.3 %, is received with the model SGT-750 with an output power of 39.8 MW using natural gas as fuel. When looking at the only model classified for marine propulsion, the SGT-500, the gross efficiency is 33.7 % for an output power of 19.1 MW and with the possibility to burn natural gas, distillates and HFO (Siemens AG, 2017). However, a relatively low gas turbine gross efficiency usually generates a higher exhaust temperature which has a higher potential for heat recovery in a subsequent cycle. So, in the end the gas turbine efficiency may not be of crucial importance when used in combined cycles.

2.3 Gas turbine configurations

Exhaust gases from the gas turbine contains thermal energy which can be used for power generation and/or steam production if directed into a waste heat recovery system. This have resulted in different configurations with combined gas and steam turbines to maximise the overall efficiency. There is no difference between the gas turbine side in a COGES/COGAS configuration and a single gas turbine. It consists of a compressor, a combustion chamber and a power turbine connected to a shaft. The turbine can be separated in several stages where the first stage powers the compressor and the other stage is connected to an external load, i.e. the propeller shaft or an electrical generator. Regardless of the type of configuration for exhaust heat recovery the gas turbine(s) can either be connected to the external load, drive the propeller directly or power electrical generator(s). The difference between the configurations is how the exhaust heat is used in the steam turbine. In Table 1 three different configurations are compared where all have different ways to use the waste heat energy.

Table 1. Description of gas turbine configurations

	Gas side, power turbine		Steam side, power turbine		Steam production for consumers**
Configuration	**Mechanical drive**	**Electrical drive**	**Mechanical drive**	**Electrical drive**	
COGES	Yes	Yes	No	Yes	No
COGAS	Yes	Yes	Yes	No	No
COGEN*	Yes	Yes	No	No	Yes

*Note: Mechanical drive means that the power turbine is connected to the external load through a reduction gear. Electrical drive means that the power turbine drives an electrical generator which produces electricity for consumers. (*COGEN is not described in detail in this study. ** the steam produced is used for fresh water generation, reducing NO_x emissions by mixing with inlet air or other general purposes onboard.)*

2.3.1 *Combined gas electric and steam (COGES)*

COGES is a type of propulsion installation where the steam turbines power a set of generators which produces electricity for propulsion or other consumers. Waste heat recovery boilers uses the heat from the gas turbine exhaust to produce superheated steam for the steam turbine side. This raises the thermal efficiency significantly and helps recover the loss of heat of the gas turbine and the results of this is a constant fuel consumption at a wide range of loads (Woodyard & Woodyard, 2009).

This type of installation is used in the Royal Caribbean Cruises' liners, as seen in Figure 1. The vessel has two GE LM2500+ gas turbines and a condensing-extraction steam turbine-generator which together has an output of 59 MW. The steam system results in an increase of total power output because of the steam turbine without increasing the fuel consumption, this raised the thermal efficiency with 15-18 % for the whole cycle compared to only the gas turbines when operating at rated power. Heat recovery steam generators are installed in the exhaust ducts of the gas turbine to produce steam which is supplying auxiliary systems (Woodyard & Woodyard, 2009).

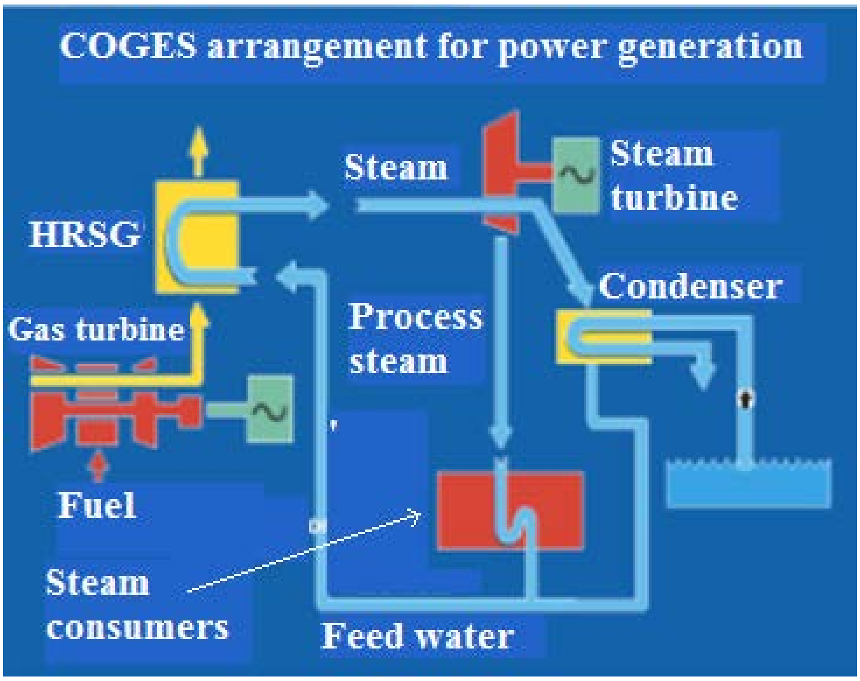


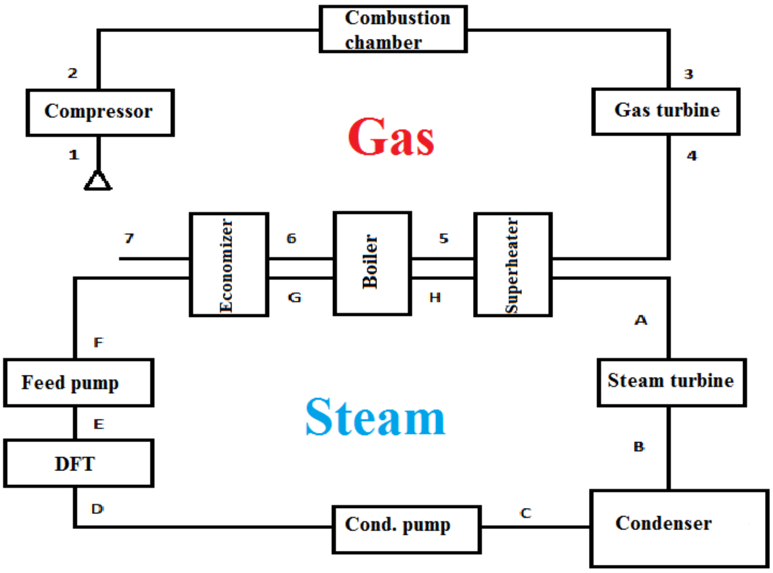
Figure 1. Gas turbine installation in Royal Caribbean Cruises (SIT AB, 2017)

2.3.2 *Combined gas and steam (COGAS)*

A COGAS system is built up by one or more gas turbines and one or multiple steam boilers operating at different pressures. More boiler tube surface will generate a higher overall efficiency but will result in a higher weight and larger space requirement. This can in some cases make configurations with more boilers less suitable for marine applications where space and weight are important factors (Wiggins, 2011).

The steam side often consists of a super-heater, a boiler section and a economizer; in separate compartments or integrated as one unit (Wiggins, 2011). The exhaust gas from the gas turbine enters the first stage of heat exchangers in the steam cycle, the super-heater, and then it is distributed to the boiler and the economizer. The heat exchangers produce steam for the steam power turbine and the layout of the steam side in a COGAS configuration is in many aspects similar to a conventional steam cycle system.

Figure 2 shows a schematic diagram of one type of COGAS configuration. The configuration is a single boiler system with one boiler plus a super-heater and an economizer in different compartments. The steam side also has a deaerating feed tank (DFT) and two pumps.

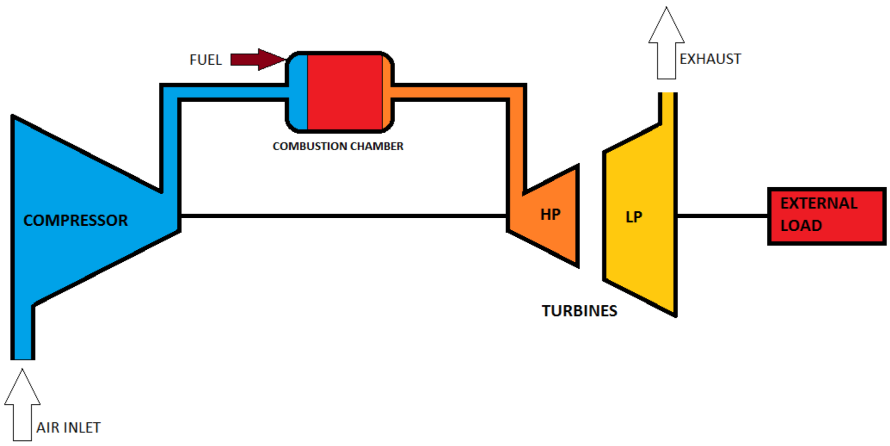


(Packalén, 2017. Authors own figure.)

Figure 2. Schematic diagram of a COGAS configuration

2.3.3 *Twin-shaft*

This configuration is arranged with two separate turbine shafts without mechanical connection. The first turbine stage is called compressor turbine or gas generator turbine and powers the air compressor. The second turbine stage is often called power turbine which is connected to and drives the external load and the fact that it is disconnected from the compressor allows it to rotate at the optimum speed for a given load, thus increasing the overall GT efficiency across different loads. Figure 3 shows a schematic picture of a twin-shaft gas turbine configuration with the high-pressure turbine drives the compressor and the low-pressure turbine powers the load. This arrangement is applicable to all configurations.



(Packalén, 2017. Authors own figure.)

Figure 3. Schematic picture of a twin-shaft gas turbine configuration

2.3.4 *Example: Siemens SGT-500 – marine industrial gas turbine*

This chapter (2.3.4) is based on information received from the interview at SIT AB 2017.

The gas turbine SGT-500 is a light-weight, heavy duty, industrial machine manufactured by SIT AB in Finspång, Sweden. The machine is a three-shaft power turbine with a mechanical output of 18.7 MW and an electrical power output of 18.4 MW. The SGT-500 is designed to burn a wide range of fuels, both liquids and gaseous fuels and can in marine applications drive an electrical generator (at constant speed) or propulsion equipment (at various speed). All main components of the SGT-500s core engine are shown in Figure 4.

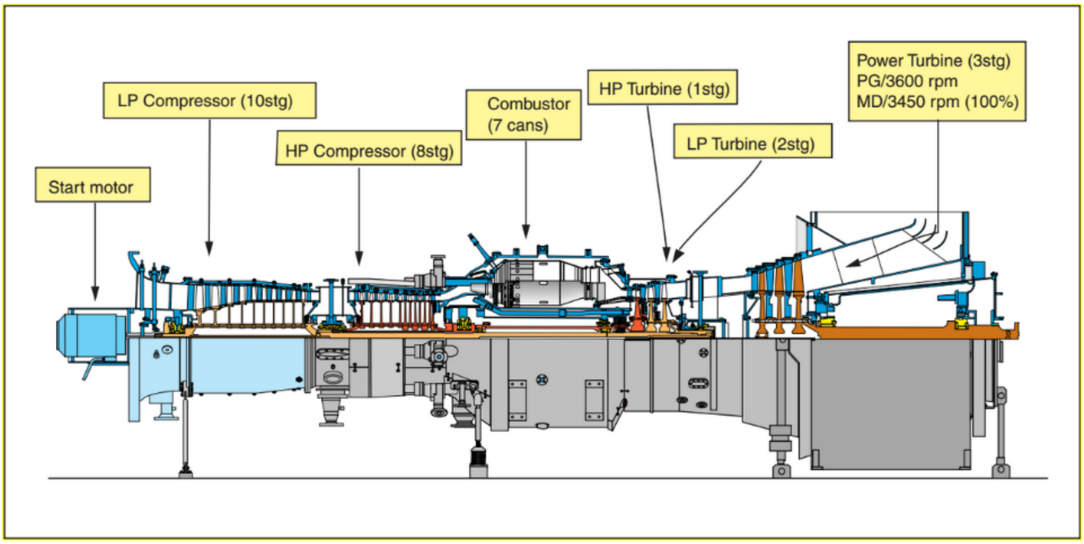


Figure 4. The main components of the SGT-500s core engine (SIT AB, 2017)

The low-pressure compressor (LP Compressor) and the high-pressure compressor (HP Compressor) together with their driving turbines (the HP- and LP – turbine) forms two separate rotor assemblies. Both can operate at different speeds and will automatically match each other after the power demand and ambient condition. The power turbine section is a three-stage axial flow turbine with the shaft connected to the driven equipment via a gearbox. The speed of the power turbine can vary from 1000 to 3450 rpm in mechanical applications and has a constant speed of 3600 rpm for generator drive.

In marine applications and ashore, the need for exhaust heat recovery is solved through the COGES principle, described in chapter 2.4.1, the COGAS principle, described in chapter 2.4.2 or the COGEN principle (see Table 1).

2.4 Maintenance of gas turbines

An important aspect that needs to be considered when choosing a propulsion system is the maintenance, a minimal need of maintenance results in less costs, less downtime and less need for crew and can therefore be a determining factor. Gas turbines used for marine propulsion are based on the same principles as turbines used in aircrafts, however, the conditions are different and therefore adjustments must be made. Gas turbines used for marine propulsion are exposed to different conditions depending on location – examples of these are: air humidity, temperature variation, salinity and sand in the air intake. To minimize and make the maintenance more effective these factors has been analysed by the major marine propulsion manufacturers and strategies have been developed to reduce the damage from these factors (Gîrbă, Pruiu, & Ali, 2014).

Different operators have different strategies of how the maintenance should be carried out. The strategy is not to be decided by the manufacturer, it is the operator who need to plan the maintenance depending on how the plant will be used. It is important to have a good balance in how often the maintenance should be carried out. Too little maintenance will result in breakdowns and thereby huge costs. Too much maintenance on the other hand, will result in an unnecessary cost due to the purchase of spare parts and even more importantly, the idle time. The two most common maintenance strategies are predictive- and preventive maintenance where predictive maintenance means operating without a regular plan for service. The normal costs are 1-2% of the purchase price of the equipment (Soares, 2008). Preventive maintenance means the average lifetime of the components is predicted and is replaced in the end of their lifetime. This method provides optimum safety and prevents unplanned maintenance and stops which can cost the companies a lot of money.

Turbine Washing

No air filter can prevent all dirt, salt and other particles from passing through and dirt sticks to the compressor blades which results in higher turbulence levels, lower compressor outlet pressures and temperatures. Together these factors may cause a power loss up to 4 percent which results in a significant fuel cost increase (Gera, 2010). To prevent this and extend the time between overhaul a turbine washing unit can be installed. Siemens has designed their own; "Advanced compressor cleaning system pro" (ACCSpro). The cleaning can be made either with on-line cleaning or off-line cleaning. On-line cleaning is when the cleaning is carried out while running and off-line cleaning is when it is done when the turbine is standing still. On-line cleaning prevents build-up of dirt and should for this reason preferably be made daily. Off-line cleaning is a more accurate cleaning method which is performed at a lower speed. This should be done every month or at least six times per year (Gera, 2010).

It is important that the gas turbine is designed in a way that makes it is easy to dismantle exposed parts and overhaul them in a quick way. To minimize the maintenance even more it is advantageously if the gas turbine provides inspection access locations. In that way, the first phase maintenance can be made with an endoscope, which is a small camera used to inspect the inside without dismantling which saves a lot of time (Gîrbă et al., 2014).

2.5 Marine fuels – Natural gas and distillate

This chapter will present two fuel types; liquefied natural gas (LNG) and distillates/marine fuel oil. Main characteristics and relevant information will be presented for each fuel type.

2.5.1 *Marine fuel oil (MDO/MGO)*

A wide majority of the larger vessels in the merchant fleet are powered by low-speed, two-stroke diesel engines (Haglind, 2008a) which during many years have been powered with HFO or MDO and other oil products. The oil products used in traditionally marine fuels are primarily divided into two groups; residuals and distillates. With a third subgroup, which basically are a blend of both; the intermediate fuel. Since HFO was introduced during the 1930s, it has been, together with distillates, the only significant energy source for propulsion and power generation onboard ships in the merchant fleet (International Maritime Organization, 2013). In the refinery process four main product categories (refinery gas, liquefied petroleum gas, gasoline and distillates) are separated from each other, and the residuals, due to various boiling points (Kołwzan & Narewski, 2012). Characteristics of the residual fuel is a high viscosity and a relatively high sulphur content.

Distillates are a product of the refinery process, also referred to as distillation process, and is composed of petroleum fractions of crude oil (Kołwzan & Narewski, 2012). The distillates that are used as marine fuels are divided into two sub-groups; MDO and MGO which both have lower sulphur content than HFO and also contains less other contaminations like water and ashes (Haglind, 2008c). Even though MDO and MGO belong to the same fuel group there are some differences; MGO is a lighter distillate than MDO and does not contain any residual components which can be found in the MDO (Haglind, 2008c). One important aspect of a fuel is the lower heating value (LHV) which describes the energy content of the fuel and affect the fuel consumption; according to Burel et al., (2013) marine diesel oil has a LHV of 40.8 MJ/kg which could be compared to LNG with a LHV around 50 MJ/kg. The marine fuels are graded after ISO standards and the distillates are divided into four quality categories; DMA, DMB, DMZ and DMX, based on the characteristics shown in Table 2.

Table 2.Characteristics of four distillates – graded after ISO standards

Requirements for Marine Distillate Fuel					
Characteristics	**Limit**	**Category**			
		DMX	**DMA**	**DMB**	**DMC**
Appearance		Visual		-	-
Density at 15°C, kg/m^3	*Max*	-	890.0	900.0	920.0
Viscosity at 40°C, cSt	*Min* *Max*	1.40 5.50	1.50 6.00	- 11.00	- 14.00
Flash point, °C	*Min*	43	60	60	60
Pourpoint (upper), °C - winter quality - summer quality	 *Max* *Max*	 - -	 -6 0	 0 6	 0 6
Sulphur, %	*Max*	1.0	1.5	2.0	2.0
Cetane number	*Min*	45	40	35	-
Carbon residue, %	*Max*	-	-	0.03	2.50
Ash, %	*Max*	0.01	0.01	0.01	0.05
Sediment, %	*Max*	-	-	0.07	-
Water, %	*Max*	-	-	0.3	0.3
Vanadium, mg/kg	*Max*	-	-	-	100
Aluminium plus silicon, mg/kg	*Max*	-	-	-	25

Note: Values from (JS Oil, n.d.).

Emissions

When burning marine fuel oil, it is unavoidable to produce carbon dioxide (CO_2) and water (H_2O) since all distillate fuels contain both carbon (C) and hydrogen (H) and that the fuel is burned using air. Beyond these two emissions a number of other pollutant are formed; oxides of nitrogen (NO_x), oxides of sulphur (SO_x), hydrocarbons (HC), carbon monoxide (CO) and also particular matter (PM) (Haglind, 2008c).

Since the CO_2 and H_2O emissions always are formed during combustion it is more interesting to examine the amount of emissions and what affects the creation. According to Haglind (2008c) the production of CO_2 is proportional to the to the amount of fuel used in the combustion (about 3.2 ton CO_2 per ton of fuel burned (Woud & Stapersma, 2008)) which leads to the conclusion that the volume of CO_2 produced depends on the engines efficiency and the fuel used. So, if different engine types are compared in consideration of CO_2 emissions, the most essential parameter would be the overall efficiency of the plant (Haglind, 2008c) as well as the fuel type used. The quantity of SO_x emissions, which in most cases is SO_2 with a small amount of SO_3, are determined by the sulphur content in the bunker oil. Therefore, the ongoing debate about sulphur content in marine fuel oil is the most important aspect to reduce SO_x emissions from the shipping industry. NO_x emissions, mostly thermal NO in diesel- and gas turbine engines due to near stoichiometric air-fuel-ratio in the combustion zone (Haglind, 2008c), are formed during combustion when the temperature is high and both nitrogen and oxygen is present. Since nitrogen needs oxygen to form NO and fuel needs oxygen in the combustion these two compete about the oxygen molecules and the amount of NO will be greatest when the fuel side is lean. The thermal NO therefore depends on the temperature and air-fuel ratio for the engine. For NO_x emissions the relationship is; decrease in SFC (and therefore also decrease in CO_2) will generate increasing NO_x emissions (Kim, Kim, & Yoon, 2012). Furthermore, the trade-off between NO_x and SFOC is essential for engine manufacturers and ship owners since a lower SFOC always is economically attractive. PM is another important emission which occurs during combustion of fuel oil. It is a broad name for different emissions including ashes, soot and metal, and strongly depends on the composition and quality of the fuel. Distillate fuels, like MDO and MGO, contains less contamination which will lead to lower PM emissions than residual fuels (Haglind, 2008c). So, regarding PM emissions the fuel type that is used and the quality of it would be the most important aspects.

Table 3 show values of emissions from a low-speed, two-stroke diesel engine on HFO compared to a GT on distillate fuel. It should be taken into consideration that the comparison is not only between different fuels but also different combustion engines.

Table 3. Emission comparison – HFO and distillate

Emission component	El* Diesel (g/kg fuel)	El* GT (g/kg fuel)	Difference, GT compared to Diesel engine (%)
Sulphur oxides (SO_x)	54	7.6	-86
Nitrogen oxides (NO_x)	87	28.6	-67
Particular matter (PM)	7.6	1.1	-85
Carbon monoxide (CO)	7.4	0.14	-98
Hydrocarbons (HC)	2.7	0.05	-98

*Note: Values taken from (Haglind, 2008c). *Emission Indices.*

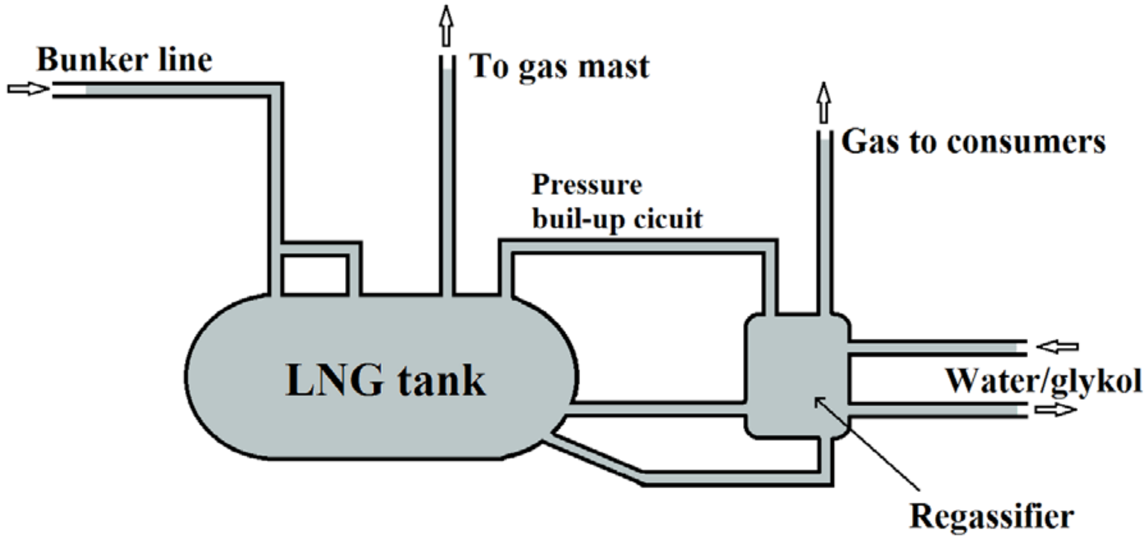
2.5.2 *Liquefied Natural Gas (LNG)*

Natural gas is a gaseous fossil fuel which mainly contains methane. It is found in coal beds and oil fields and it is created in the earth when remains from animals and organics are exposed to heat and pressures over millions of years. The gas is colorless and odorless and contains approximately 50 MJ/kg. Once the natural gas is derived from the underground; water, sand and other compounds must be removed. Some hydrocarbons are removed and can be sold separately (Speight, 2007).

LNG as a marine fuel

LNG is nothing new within the shipping industry; it has been used for propulsion in LNG carriers for over 40 years for both boiler/steam turbine installations and dual fuel engines. These systems has been running for 6 million hours and are now considered reliable (Burel et al., 2013). Today gas handling is limited and to introduce LNG to a larger fleet, bunker stations needs to be installed in ports around the world. To have separate bunker stations for LNG is expensive because it means that ships must go to various locations to bunker fuel and oils which normally is done at the same time. Onboard, LNG is stored in a large cryogenic tank which can sustain pressures from 0.3-10 barg and temperatures reach -162°C. The tanks are double-walled with insulation between the walls. The insulation is very efficient but still the liquid cannot keep the temperature cold by itself (Morsy, Gohary, & Seddiek, 2013).

The regulation for piping arrangement is very strict, no pipes passes through accommodation and control spaces. If a pipe must pass an enclosed space it should be double piping and a gas detector must be installed. The fuel system consists of the storage tank, valves, connections and a vaporizer where the LNG is vaporized to approximately 15°C before injection. The pressure in the tank is used to push the gas and transfer it from the tank, through the vaporizer and in to the engine. The vaporizer also helps keeping the pressure in the tank by reinject the gas into the tank (Morsy et al., 2013).



(Packalén, 2017. Authors own figure.)
Figure 5. Example figure for an LNG tank configuration

All equipment shown in figure 5 are located inside a steel container to prevent any LNG leakage. This container is thermally insulated to prevent that the ships steel is cooled down. The container also has ventilation, gas detection and is A60 fire insulated (Morsy et al., 2013).

Emissions

Compared to other marine fuels natural gas have lower CO_2 emission at a rate of 2.3kg per kg of gas burnt compared to 3.1kg of CO_2 per each kg of MDO burnt (DELTAMARIN LTD., 2001). This equals 0.166 kg CO_2 per kWh for natural gas (LHV = 50,000 kJ/kg) and 0.261 kg CO_2 per kWh for MDO (LHV = 42,800 kJ/kg). The CO_2 is not dependent on the device the fuel is being burnt in. NO_x on the other hand depends on the burn process. A diesel engine in liquid fuel operation have NO_x emissions rates of 13g/kWh while the same fuel in a gas turbine (GT35) has an emission rate of 4.5g/kWh (DELTAMARIN LTD., 2001). If instead burning natural gas in dual fuel diesel engine the emission rate is 1.3g/kWh and a gas turbine operating on natural gas emits 1.0g/kWh (DELTAMARIN LTD., 2001). SO_x are only dependent on the sulphur content of the fuel being burnt and is also the biggest advantage natural gas offers compared to coal or crude oil. SO_x emissions are almost zero for natural gas while HFO emits 4.4g per kWh and MDO 1.3g per kWh (DELTAMARIN LTD., 2001). These are the biggest emissions from the shipping industry and combined with close to zero particular matter (PM) emissions the natural gas is therefore environmentally superior for marine propulsion. Gas engines can suffer a methane slip which means unburned methane leak through the engine which cause an emission 25 times more harmful for the greenhouse effect than CO_2 (Burel et al., 2013). Because of that, the overall environmental impact from production, transportation and using of LNG can be equal to the use of HFO when taking into account the potential methane slip (Brynolf, Fridell, & Andersson, 2014).

2.5.3 *Fuel efficiency calculations*

When comparing fuels with different LHV the result in SFC might be misleading and it is therefore relevant to calculate the overall (primary) energy efficiency for a fair comparison. The efficiency is defined as the engine work output (1 kWh or 3600 kJ) divided by the fuel energy input (Kuiken, 2012).

Lower heating value (LHV) – kJ/kg.
Specific fuel consumption (SFC) – kg/kWh
1 kWh = 3600 kJ

Equation 1

(Kuiken, 2012)

$$LHV\ \left(\frac{kJ}{kg}\right) \times\ SFC\left(\frac{kg}{kWh}\right) = specific\ energy\,\frac{kJ}{kWh}$$

The definition of efficiency is work output/heat input which equals 1/specific energy, where 1 kWh is replaced with 3600 kJ. This leads to the equation:

Equation 2

(Kuiken, 2012)

$$\frac{work\ output}{fuel\ energy\ input} = \frac{3600\ kJ}{specific\ energy} = energy\ efficiency\ (primary\ efficiency)$$

Below is a calculating example:
LHV = 50 000 kJ/kg
SFC = 0.186 kg/kWh

Equation 3

$$Specific\ energy = 50000\,\frac{kJ}{kg} \times\ 0.186\,\frac{kg}{kWh} =\ 9300\ kJ/kWh$$

Since the specific energy is heat in per kWh engine work output, the energy efficiency is calculated with the specific energy 9300 kJ.

Equation 4

$$Energy\ efficiency = \frac{3600\ kJ}{9300\ kJ} = 0.387 = 38.7\ \%$$

3 Method

A combination of a literature review and semi-structured interview have been used in this study to get a view from both a theoretical stand point and from a real-world perspective. Considering the time available and the size of the study these two methods have provided us with enough data and information to answer the research questions.

3.1 Literature review

To answer research question 2 and 3 and provide useful information about question 1 a literature review was conducted. A literature review is a comprehensive survey that focus on a specific field of interest, in this case it was gas turbines and marine fuels, where information is found using bibliographic finding tools both online and in libraries. The literature review did provide us with a huge amount of data and information, mainly from course literature including Chalmers learning platform Ping-Pong and through databases in Chalmers Library´s search engine Summon. Relevant and useful literature for our subject was found using both English and Swedish search words.

The result is presented in running text and with charts, tables and figures as support to give an easier overview and the selection of the documents was made by the authors based on relevance and reliability. The relevance of a document is assessed along how well the content of the document is related to the research questions and if the report/article is “up-to-date” and not older than 15 years (one report is older but considered relevant by the authors). The reliability was considered well enough if the report/article have been reviewed and published in a scientific journal or if the literature is related to course literature.

Search words for results:
Gas turbine, LNG, distillate fuel, gas turbine performance fuel, fuel comparison gas turbine, gas turbine prime mover, increase gas turbine efficiency at part load, gas turbine marine,

Search engines:
Summon, Chalmers Library (Scopus and Web of Science)
Google Scholar

3.2 Semi-structured interview at Siemens Industrial Turbomachinery

The interview was performed by both authors together with two interviewees that was recommended by colleagues at Siemens. The two participants have extensive experience from working in the company within different areas but both are currently working as Senior Product Development Managers in Finspång.

The semi-structured interview at SIT AB in Finspång provided us with information to answer research question 1 and provided essential knowledge for answering research question 2 and 3. During the visit we also received documents and reports from SIT AB which further helped us answering the questions.

To get the most possible information and a greater understanding of the topic a semi-structured interview with open-ended questions was used in combination with a few more specific questions. Open-ended questions give the opportunity to get descriptive answers and a greater understanding of the subject (Denscombe, 2016). When developing the questions, we avoided leading questions, questions with negative or positive association and constructed them as short and concise as possible. For interview questions in Swedish see Appendix 1.

According to Denscombe (2016) an interview should preferably be recorded to get a complete documentation of the interview but we decided to not record the interview for two reasons: the interviewees wished for only notetaking and as we were two interviewers we did have the possibility to split the notetaking and still perform a fluent interview. If an interview is not being taped Denscombe (2016) suggest that notes should be taken during or in direct connection to the interview, which was performed in this interview.

Ethic and anonymity:

According to Denscombe (2016) it is good practice to provide the interviewee with a consent form before the interview and therefore the persons whom will participate in the interview receives a “Participant consent form” for signing. The form states that we have the permission to use all data (notes, pictures and recordings) from the visit in presentations and project publications. The individuals participating in the interview have the opportunity to remain anonymous and will before publication be able to read and comment the documents.

4 Results

The result chapter is divided in two main parts, the first part, 4.1, is the result from the literature review. And the second part, 4.2, is the result from the visit at SIT AB in Finspång.

4.1 Result from literature review

This result chapter will present information received from the scientific articles and journals with relevant data for the research questions. Chapter 4.1.1 will present the literature regarding possible vessels suitable for using gas turbine propulsion. In chapter 4.1.2 the efficiency of gas turbines and gas turbine configurations are evaluated and compared in running text. Chapter 4.1.3 firstly present a numerical comparison of the fuels in Table 5 followed by a summary of each source in running text.

4.1.1 *Vessel types and possible applications*

One advantage with gas turbines is that weight and space requirements are much smaller than with a diesel engine. This space could be used to store more passengers or cargo which suits the most type of vessels. On the other hand, a thing which limits the usage of this installation is the start-up time which for a combined cycle depends on the stand still time due to the necessary heating of the steam turbine. This is because some machinery parts need to be heated before starting to avoid thermal stress on the material. It is, however, possible to keep the steam cycle parts warm by using a supplementary fired heat recovery steam generator (HRSG). The HRSG can also be used in port to provide auxiliary systems with steam (and power). With this type of installation, a wider range of vessels can be suitable to use this type of configurations (Haglind, 2008b).

4.1.2 *Gas turbine efficiency*

Barelli & Ottaviano (2015) present a solution for combined gas turbine plants which could increase the overall efficiency as well as the operational flexibility during part-load operations. The solution is according to the authors a supercharged gas turbine called: supercharged conventional natural gas combined cycle (SNGCC). The SNGCC arrangement has a free compressor stage first in the gas turbine cycle with the purpose to, even during part-loads, provide the main compressor with optimal operational air mass flow and pressure ratio. The result from the paper reveals that the SNGCC “has allowed to reach, during part-load operation, higher efficiency in the compression process, and, consequently, better energy conversion efficiency” according to Barelli & Ottaviano (2015). The study presents a figure with plant efficiency vs. load percentage and the result is presented in Table 4.

Table 4. Plant efficiency result Barelli & Ottaviano (2015)

	Plant arrangement efficiency (%)	
Load percentage (%)	**SNGCC**	**NGCC***
70	51.8	48.7
80	52.8	50.5
90	53.5	52.3
100	54.2	54.2

*Note: *Natural gas combined cycle (NGCC)*

In the study by Haglind (2008a) the two configurations COGAS and COGES are compared in terms of design and efficiency. A COGAS configuration offers a high efficiency at full load operation since the transmission efficiency is high (about 98 – 99 %) and the COGES configuration have slightly lower efficiency since the energy needs to be converted twice; from mechanical to electrical and then back to mechanical. The main advantages of the COGES configuration is the ability to achieve a reasonable performance during part load operations when power units can be shut off when not needed and leave the remaining on nominal loads. This will keep a higher efficiency also at part loads. A last conclusion by the author Haglind (2008a) is that these two systems could be combined to receive an advantageous configuration where the power turbine(s) at the gas side is connected to a reduction gear (mechanical drive) and the power turbine(s) at the steam side to a generator.

In a study by Wan Nik & Sinha (2012) several propulsion arrangements are presented as alternatives on LNG carriers with thermal efficiency, SFC and life cycle cost as main targets for comparison. Gas turbines in combined cycles are described with features like good reliability, compact and light arrangements and a high power to weight ratio. According to the study the main reason that the gas turbines are not found favourable in the shipping industry is the low fuel efficiency. However, the authors Wan Nik & Sinha (2012) believes that combined cycles ashore achieve a "very favourable fuel efficiency often superior to all other prime movers" and that the thermal efficiency is 50 % for a COGES configuration.

The study by Dzida & Olszewski (2011) performed a comparison of combined systems in naval applications; the object was a combined gas and steam cycle compared to a combined low-speed diesel engine and steam cycle. The result showed that a combination plant with gas turbine and steam turbine reached the highest overall efficiency (60 %) even though the simple open gas turbine cycle had the lowest efficiency (33 – 35% on average). A major drawback for the combined gas and steam cycle was the 15 – 20 % drop in relative efficiency when the load changed from 100 % to 50 %. For comparison, the diesel engine efficiency drop was about 1 – 2 % for the same change in load. Two main conclusions by the authors Dzida & Olszewski (2011) are that the use of combined systems is able to increase the output power with 35 – 49 % in a gas turbine system and at the same time reduce SFC with 26 – 36 % for the same configuration.

4.1.3 *Fuel comparison*

Table 5 shows a comparison of natural gas and distillate fuel in gas turbines (all comparison is made during the same ambient conditions and in the same gas turbine) regarding the most important emissions, energy- and cycle efficiency, calorific value and SFC. The table is divided into three sections where each show the values from a specific scientific source.

Table 5. Numerical comparison between diesel and natural gas

Fuel type	Energy efficiency*	Calorific value (kJ/kg)	Emissions (g/kWh)				Cycle Efficiency** (%)	Specific fuel consumption (kg/kWh)	Source
			CO_2	NO_x	SO_2	PM			
Liquid fuel (diesel)	0.3878	42,800	254	0.693	1.791	0.13	0.3798	0.2169	(Morsy et al., 2013)
Gaseous fuel (natural gas)	0.3838	50,000	181.2	0.142	0.001	0.01	0.3788	0.1876	
Liquid fuel (diesel)	0.4005	42,800	NA	NA	NA	NA	0.380	0.21***	(Gohary & Ammar, 2016)
Gaseous fuel (natural gas)	0.4000	50,000	NA	NA	NA	NA	0.379	0.18***	
Liquid fuel (diesel)	0.389	42,800	NA	NA	NA	NA	0.381***	0.216***	(Elgohary & Seddiek, 2012)
Gaseous fuel (natural gas)	0.385	50,000	NA	NA	NA	NA	0.380***	0.187***	

*Note: *Fuel efficiency calculated according to chapter 2.5.3. **Indicates to which extend the added heat is converted to work output. ***Inlet air temperature = 10°C. Which differs from ISO conditions.*

In the study where alternative fuels are compared in marine gas turbines during various ambient conditions (temperatures between 10°C and 45°C) the authors Elgohary & Seddiek (2012) found that the gas turbine performance is almost equal between natural gas and diesel. According to the study four of the most important parameters in the comparison are the cycle efficiency, SFC, exhaust temperature and working ratio. When looking at cycle efficiency, diesel fuel is slightly advantageous at all ambient temperatures, the difference compared to natural gas is constantly around 0.001 percent (Elgohary & Seddiek, 2012). The SFC is found 0.029 kg/kWh lower for the natural gas and the reason is a higher calorific value for the natural gas. The trade-off between SFC and LHV is shown in Table 5 as the primary fuel efficiency where diesel is slightly better (<0.005 % higher efficiency) than natural gas. Regarding exhaust temperatures and work ratio the values are higher for diesel in both cases. The study also provides these key conclusions: one main advantage using gaseous fuels is the 13.5% lower SFC but some modifications may be needed in the gas turbine used in the study to reach the superior performance.

With the upcoming emission regulations as starting point the authors Gohary & Ammar (2016) performed a study where alternative fuels (gaseous fuels) were evaluated and compared to liquid fuels through a thermodynamic analysis. The study shows that natural gas could replace MDO in marine gas turbines due to several aspects where natural gas is advantageous. Since the gaseous fuel delivers satisfactory performance in the gas turbine and is very close to diesel in terms of thermodynamic performance other aspects like emissions become even more relevant. Natural gas delivers lower values of the most important emissions compared to marine diesel and other petroleum fuels which makes it a suitable alternative when the emission regulations enters into force. The study by Gohary & Ammar (2016) show that the cycle efficiency is 0.001 percent better and the energy efficiency is 0.0005 percent better when using diesel instead of natural gas.

Natural gas can successfully be used to replace diesel as fuel in gas turbines. At ISO conditions the efficiency reduction is about 0.25% which makes it a good fuel to use in gas turbines (Morsy et al., 2013). Emissions from gas turbines are generally lower than those from diesel engines, regarding NO_x it is primary due to lower peak flame temperature. Partly from using different fuels and partly because of the different combustion process. The combustion process in a gas turbine is continuous while the combustion process in a diesel engine is intermittent which result in lower HC and CO emissions (Haglind, 2008c).

4.2 Result from semi-structured interview

This result chapter presents the information received from the interview at SIT AB in Finspång. The result is presented in running text with the authors own words strictly based on the notes taken during the interview in combination with the documents we received afterwards. To support the information in the running text tables and figures are used. The result chapter will be divided into three parts where the first part, 4.2.1, is about possible vessels and will support answering research question 1. The second chapter, 4.2.2, discuss gas turbine configurations and will be used to answer question 2 while the last chapter, 4.2.3, will present a fuel comparison for research question 3.

4.2.1 *Vessel types and possible applications*

According to SIT AB the most common vessels to use gas turbines as prime mover are fast ferries and cruise vessels. This is because of the high power-to-weight ratio and the reduction in space needed for machinery which allows more cabins and hotel arrangements on board. Two examples of fast ferries with Siemens gas turbines in the propulsion system are; HSS Stena Carisma and a Buquebus fast ferry (Juan Patricio).

Trade routes:

Since the gas turbine are designed to run continuously without starts and stops and at preferably constant- and high load, vessels with long sea voyages and less time spent in port and during manoeuvring would be most suitable. The runtime is essential for the gas turbine performance and every start and stop is calculated as five equivalent hours which reduce the time between inspections if it occurs often.

Trade routes with variation in climate and ambient conditions is a possible complication since the gas turbine performance is sensitive to the inlet (ambient) temperature. Ashore the gas turbines can be specially adapted for three different climates; arctic, dessert and tropic environment and a vessel which trades the whole globe may face all these climates in periods. Even if the ambient conditions vary, the standard gas turbines can run in all these conditions during a period of time which would make it possible for most types of vessels to neglect the change in weather and climate during a sea voyage.

Required engine power:

A gas turbine in combination with a steam cycle can produce enough power for all kind of vessels in the merchant fleet but the power demand is ship specific and it should therefore be evaluated on a case by case basis when considering propulsion system. In general, a gas turbine configuration in combination with waste heat recovery (i.e. COGES/COGAS) produces enough power to drive even the largest crude oil carriers and container ships with installed power on just under 100 MW. Siemens have used a 20.000 TEU container vessel with a total power output of 90 MW as a reference ship when calculating the power demand during sea voyages, manoeuvring, berth and channel operations. Figure 6 shows the total electrical power required during a voyage China – Europe – China, on a running time axis.

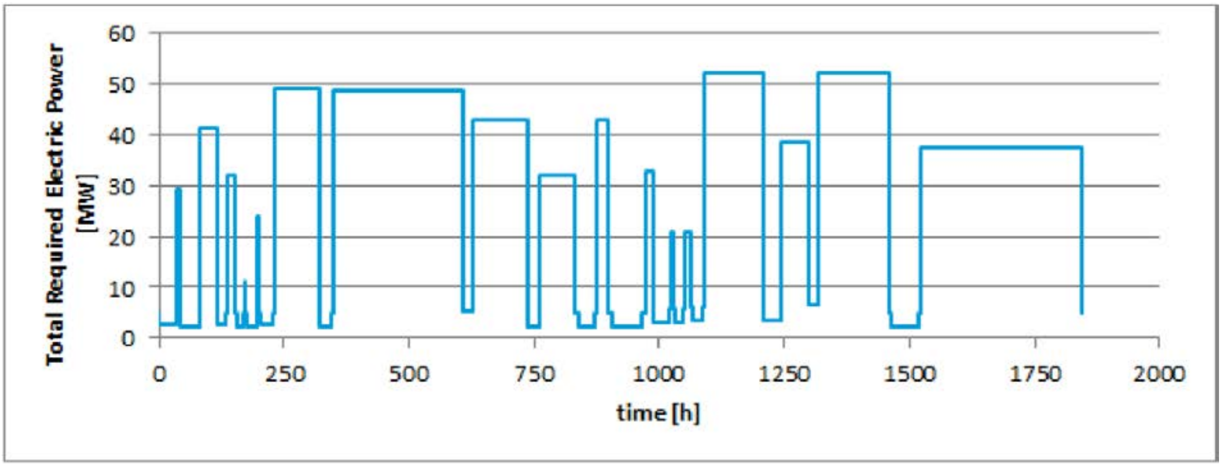


Figure 6. Graph of "total electrical power required" – container vessel one voyage

As seen in Figure 6 the power demand is between 25 – 50 MW most of the time which can be generated by a 2 × 1 COGES system (two GT plus one steam turbine). Figure 6 also shows that the load changes unfavourable for the gas turbine but the time on part loads are at a minimum which is beneficial for the gas turbines.

New buildings or existing vessels:

The economical aspect when consider installation costs makes it hard for gas turbine manufacturers to penetrate the existing market and compete with the diesel engines that are already installed and in operation. The economical challenge is not only for the ship owners who is not interested in changing the propulsion system on the existing fleet. It is also a challenge for the gas turbine manufacturers who needs to get the machine and systems classified by classification societies. If the interest from the shipping industry would increase, SIT AB have the ability to classify more gas turbines which today produces an efficiency above 57% in the power range of 70-80MW. All these aspects together make it more suitable to install gas turbine propulsion on new buildings.

4.2.2 *Gas turbine configurations and advantages*

A normal two-stroke diesel engine has an efficiency of 46-48% and a COGES installation an efficiency of 55-60% according to Siemens.

Siemens article "GT 35 Big Cruise Vessel Study" contains an example of a COGES installation. The installation has 3 x GT35 turbines installed with an output of 3 x 15.4 MW at 25°C and a steam turbine with an output of 10 MW with extraction at 8 bar and 2 bar. This installation can be seen in figure 7. It would have 3 exhaust gas heat recovery steam boilers which delivers 3 x 30 t/h and one oil fired boiler deliver 3 t/h at 8 bar. The propulsion motors would consist of 3 x 14 MW variable speed controlled electric propulsion motors in pods.

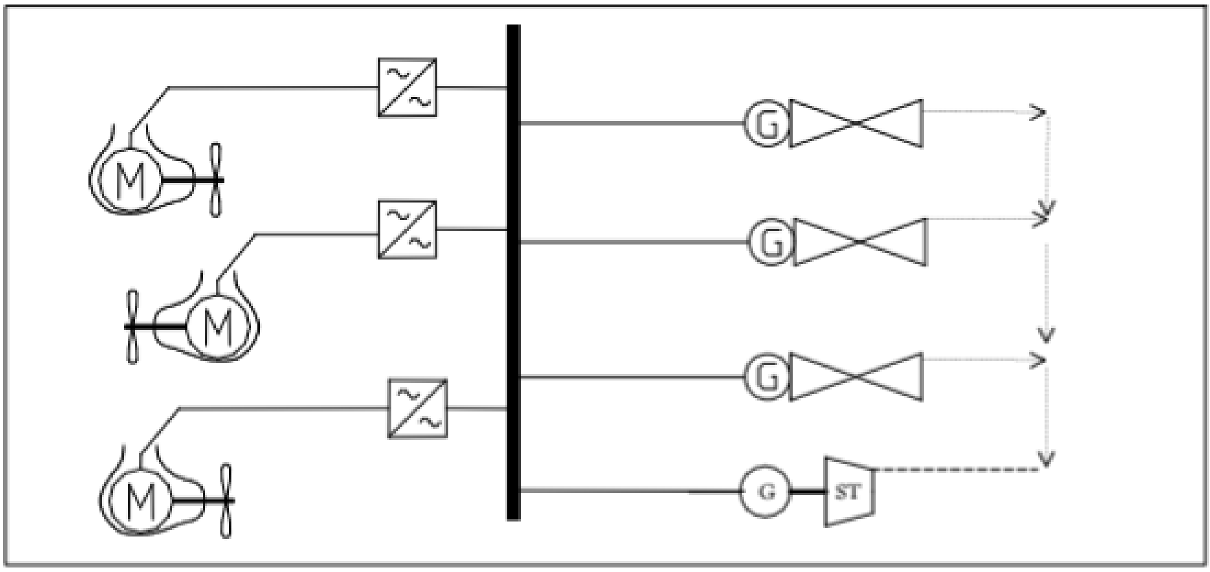


Figure 7. COGES installation on big cruise vessel

With this machine arrangement, the vessel could save 8100 m^3 of space compared to a diesel electrical machinery and a lot of rearrangement could be done. This would result in 66 new passenger cabins which can lead to more income. The weight saving with this machinery change would be 1440 tonnes. And further, the weight and cost difference from external systems is showed in Table 6.

Table 6. Weight and cost of piping for COGES and COGAS configurations

Weight of piping				
System	**COGES**		**COGAS**	
	Weight (t)	**Cost ($)**	**Weight (t)**	**Cost ($)**
Fuel oil filling and transfer system *Black steel pipes*	34.5	366,177	73.7	463,748
Fuel oil feeding system *Black steel pipes* *Stainless steel pipes*	0.7	20,142	4.4	46,693
Lubricant oil system *Black steel*	0.2	2,122	23.6	250,445
Fresh water cooling system *Black steel*	16.9	179,344	112.7	1,195,981
Sea water cooling system *Cunifer*	38.4	1,328,626	96.8	3,349,244
Combustion air system *Galvanized duct*	19.4	210,424	35.5	385,055
Exhaust gas piping *Black steel*	55.4	587,909	67.9	720,560
Steam/Feed water system *Black steel*	25.9	274,853	20.2	214,364
Heating coil in tanks *Black steel*	3.2	33,959	9.7	102,937
Steam pipes for separators and booster units *Black steel*	0.6	6,367	2.4	25,469
Starting air system *Black steel*		0	2.0	21,244
Total weight and cost of auxiliary piping system	**195.2**	**3,009,863**	**416.9**	**6,754,496**

Maintenance:

Normal maintenance consists of weekly routines and inspect of filters and monthly overhaul of auxiliary systems but the maintenance was reduced when using a maintenance program consisting of various levels of maintenance (A-D) which is performed yearly. In table 7, the parts overhauled in every level can be seen.

Table 7. Siemens maintenance program

	LEVEL A	LEVEL B	LEVEL C	LEVEL D
Inspection	GT blading Combustor (Borescope) Couplings and gears Auxiliaries Running check	GT blading Fuel injectors Combustor Gas collector Couplings and gears Auxiliaries Running check	NDT test of GT Blading and discs Spray test of liquid Fuel injector Combustor Gas collector	NDT test of GT Blading and discs Spray test of liquid Fuel injector Combustor Gas collector Couplings and gears Auxiliaries Bearings Running check
Replacement or refurbishment as required			**REPLACEMENT** Relative Bearings	**REPLACEMENT** Gas collector Flame tubes LP turbine rotor Disc stage 1 Relative Bearings HP turbine rotor Disc with blades
Verification	Control system and instruments	Control system and instruments	Control system and instruments	Control system and instruments

The fuel is also an important parameter for the maintenance and the inspection needed for the gas turbine. The running hours between each planned inspection is 10.000 hours measured in "equivalent hours" where:

Every start/stop = 5 equivalent hours.

1 hour running on distillate fuel = 1.5 equivalent hours.

1 hour running on gaseous fuel = 1 equivalent hour.

The maintenance cost is approximately 3 dollars per MWh during "normal operation" i.e. optimum load with gaseous fuel.

4.2.3 *Fuel comparison*

The technical development around gas turbines is directed towards gaseous fuels and therefore the performance is better when gas turbines run on gas instead of liquid distillates. However, it is still necessary for gas turbines to be able to burn liquid fuels like HFO and different distillates to compete with diesel engines on the marine market.

Power output and fuel consumption:

Comparison have been made between liquid and gaseous fuels in the gas turbine model SGT-500 from SIT AB. The result show output power, fuel consumption, exhaust gas temperature and the primary efficiency for both fuel types during variable and constant speed operations. Table 8 - 11 shows the numerical result (values from *Siemens Project guide SGT-500*). Tables 8 and 9 show the values when liquid fuel is used and tables 10 and 11 show the values when gaseous fuel is used. In table 8 - 11 the overall (primary) energy efficiency for the fuel is calculated according to chapter 2.5.3.

Table 8. Values for liquid fuel, various speed operation

Variable speed operation with liquid fuels. LHV = 42,700 kJ/kg				
Inlet temperature (°C)	Output power* (kW)	Exhaust temperature (°C)	SFOC (kg/kWh)	Primary fuel efficiency (%)
15	18,700	390	0.256	32.93

*Note: *Maximum continuous rating (MCR), power at power turbine shaft flange, no pressure losses in inlet-/outlet duct, reference conditions per ISO 3977 (15°C, 60 % relative humidity and sea level elevation).*

Table 9. Values for liquid fuel, constant speed operation

Constant speed operation with liquid fuels. LHV = 42,700 kJ/kg				
Inlet temperature (°C)	Output power** (kW)	Exhaust temperature (°C)	SFOC (kg/kWh)	Primary fuel efficiency (%)
15	18,400	388	0.261	32.30

*Note: **Electric power output corresponding turbine NCR valid for power turbine speed 3600 rpm, no pressure losses in inlet-/outlet duct, reference conditions per ISO 3977.*

Table 10. Values for gaseous fuel, various speed operation

Variable speed operation with gaseous fuels. LHV = 46,798 kJ/kg				
Inlet temperature (°C)	Output power* (kW)	Exhaust temperature (°C)	SGFC (kg/kWh)	Primary fuel efficiency (%)
15	19,300	388	0.231	33.30

*Note: *Nominal continuous rating (NCR), power at power turbine shaft flange, no pressure losses in inlet-/outlet duct, reference conditions per ISO 3977.*

Table 11. Values for gaseous fuel, constant speed operation

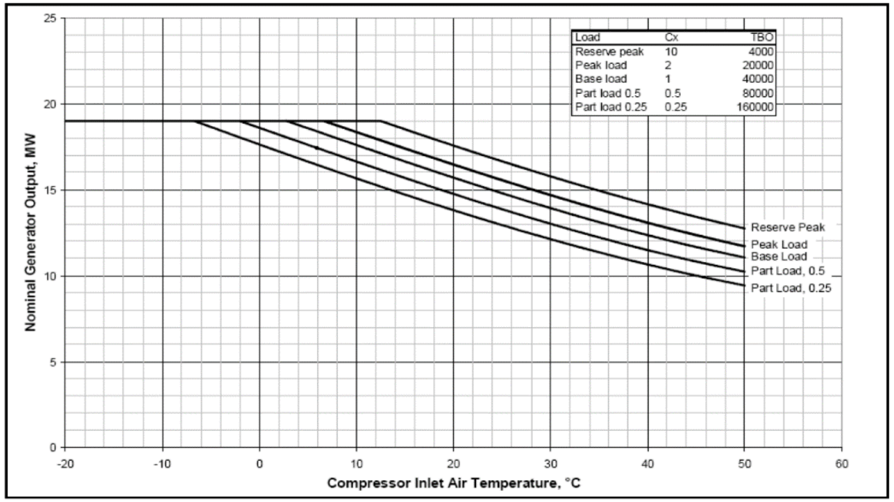
Constant speed operation with gaseous fuels. LHV = 46,798 kJ/kg				
Inlet temperature (°C)	Output power** (kW)	Exhaust temperature (°C)	SGFC (kg/kWh)	Primary fuel efficiency (%)
15	18,900	385	0.236	32.60

*Note: ** Electric power output corresponding turbine NCR, no pressure losses in inlet-/outlet duct, reference conditions per ISO 3977.*

Table 8 - 11 show that gaseous fuels generate 500 – 600 kW higher power output than liquid fuels during equivalent operation and the same ambient condition, which is an increase of 2.7 - 3.2 %. Gaseous fuel also has 0.025 kg/kWh lower specific fuel consumption than liquid fuel. When comparing fuel consumption, it is also worth mentioning that the LHV is higher in gaseous fuels and the fuel overall energy efficiency is shown 0.30 – 0.37 % better.

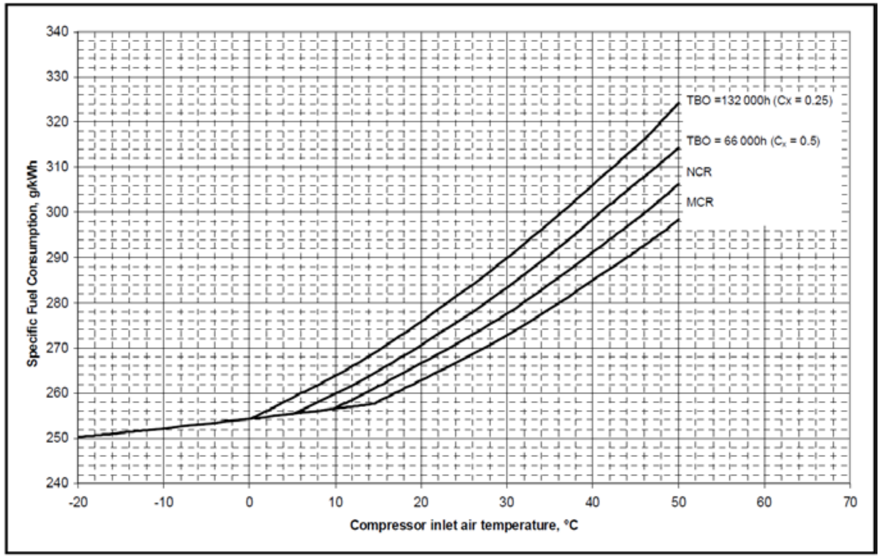
To further show the comparison between liquid and gaseous fuels regarding power output and SFC during nominal performance at constant speed (i.e. electrical generator drive) test values are shown in Figure 8 - 11. In Figure 8 and 10 the actual power output for different load operations are shown as functions of the compressor inlet temperature. When looking at Figure 9 and 11 the graphs describe the SFC at different load conditions as a function of the compressor inlet temperature.

Constant speed with liquid fuel (Figure 8 and 9):



Power output for electrical generator drive.

Figure 8. Graph over power output for electrical generator drive – liquid fuel



SFC versus compressor inlet air temperature for generator drive.

Figure 9. Graph over SFC for electrical generator drive – liquid fuel

Constant speed with gaseous fuel (Figure 10 and 11):

Power output for electrical generator drive

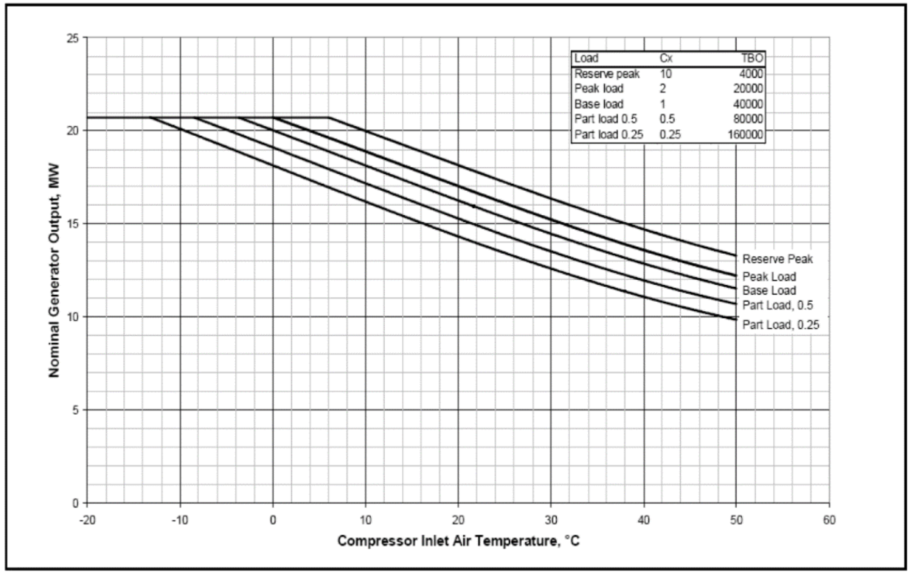


Figure 10. Graph over power output for electrical generator drive – gaseous fuel

SFC versus compressor inlet air temperature for generator drive.

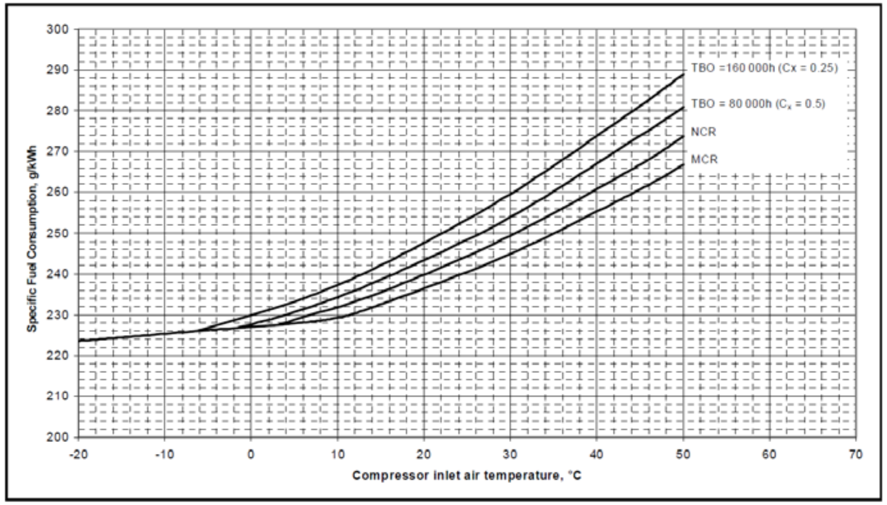


Figure 11. Graph over SFC for electrical generator drive – gaseous fuel

Figure 8 and 10 shows that the generator power output is higher when using gaseous fuels compared to liquid fuels during variation in inlet temperature and during peak load, base load and different part loads. The biggest difference in output power (ca 2 MW or 10 %) between the two fuels is for compressor inlet temperatures between -20°C and 6°C. Thereafter the difference is below 1 MW.

5 Discussion

The discussion chapter is divided into four parts where the first three parts are regarding each of the research questions and in chapter 5.4 the authors discuss the method, validity and reliability of this study.

5.1 Vessel types and possible applications

Gas turbine systems has showed to save a lot of space and weight compared to a diesel engine installation. This probably benefits all types of vessels because the space and weight saved can be used to carry more cargo, bunker or passengers. Considering power demand, a gas turbine in combination with a steam cycle can produce enough power to provide any vessel in the merchant fleet with the sufficient power for propulsion. The maintenance of the gas turbine had showed to be very low compared to a two-stroke diesel and the yearly bigger maintenance could probably be planned to be carried out during dry dock or longer stops - this makes the gas turbine propulsion system suitable for all types of vessels. The conclusion that the application is suitable for all vessel types should be further discussed in terms of the operating profile of a vessel where load- and speed profile are important aspects due to the gas turbine performance.

Gas turbine propulsion has mostly been used on cruise vessels and fast ferries due to the power-weight ratio and the space reductions being particularly useful here. Gas turbines however, are designed to run continuously at a high load with few stops and when considering the trade routes of this type of vessels they normally have a lot of stops and manoeuvring which means lower speeds and a lot of start and stop of the gas turbine. Gas turbines are therefore much more suitable on ships with longer voyages, for example large ocean going vessels. These vessels could use a COGAS installation which has a transmission efficiency of 98-99%. Thus, a COGES installation could be one way to overcome the problem with cruise vessels and fast ferries by having one of the turbines shut off and only using one turbine, running on full load while manoeuvring, and only use the other one when full speed is required. This should also be possible with a COGAS configuration as long as the gearbox allows it. The fact that gas turbines efficiency is very good on LNG makes it great for vessels that need to operate in ECA/SECA areas or carries LNG as cargo.

As the gas turbines installed ashore can be adapted to three different weather conditions to get an optimal load and a ship which operates worldwide can face a lot of different conditions regarding the weather it may have to operate at non-optimal conditions. However, the standard gas turbine can operate in all these conditions which makes it possible for the most vessels to use gas turbine propulsion regarding this matter. Even though it is possible to operate the standard gas turbine in all conditions it could be a significant drawback since the power output decreases when the compressor inlet temperature increases. This leads to the conclusion that a gas turbine driven vessel could operate worldwide but should preferably be used in areas where the conditions are more alike.

5.2 Gas turbine efficiency

A gas turbine has a gross efficiency of 31-40 percent and according to Siemens a normal diesel engine has an efficiency of 46-48 percent. A COGES installation has an efficiency of 55-60 percent and therefore, it makes it obvious to run the gas turbine in a combined system when used for propulsion. The barrier is that the gas turbine needs to operate at a high load to achieve this efficiency, when operating on part-loads the efficiency is much lower than the diesel engine. But the result shows at least two ways to overcome this problem. One way is to only run one gas turbine at full load and have the other one stopped while manoeuvring and only start the other when full speed is required. The other way is to use the SNGCC system which is a supercharged gas turbine which has shown to increase the performance at part-loads. On vessels which does not need to manoeuvre a lot the COGAS system could benefit due to its transmission efficiency of 98-99 percent

5.3 Fuel comparison

The results from the literature review showed numerical values from three sources in table 5, where all agreed that the cycle efficiency where slightly higher with diesel fuel. The table 5 also showed that the fuel consumption and emissions where lower for the natural gas which Morsy et al., (2013), Gohary & Ammar (2016) and Elgohary & Seddiek (2012) all agreed on. The relationship between SFC and emissions is not surprising and the fact that lower SFC generates less emissions is also consistent with table 3 in the theory chapter which further supports the argument that natural gas is more environmentally friendly than liquid fuel when used in gas turbines. Regarding the energy efficiency Morsy et al., (2013), Gohary & Ammar (2016) and Elgohary & Seddiek (2012) all had minimal differences between the fuel types in favour for diesel fuel. The difference is less than 0.01 percent in all three cases and should be argued as equal due to some potential margin of error in the study results. The fact that the cycle efficiency and the primary fuel efficiency is found close to equal in the literature review and that the emissions from natural gas is showed lower in table 5 and argued to be lower by Gohary & Ammar (2016) one can assume that natural gas would be preferable as primary fuel when looking at efficiency and emissions.

In three different studies by Morsy et al., (2013), Gohary & Ammar (2016) and Elgohary & Seddiek (2012) the gas turbine performance where found comparable and even advantageous when gaseous fuels where used in comparison with diesel fuel. The thermodynamically performance is by Gohary & Ammar (2016) argued to be close to equal for the fuels with a slight advantage for natural gas.

The interview result from SIT AB had both real numerical values of fuel comparison in the gas turbine model SGT-500 and the knowledge from development and operation of gas turbines ashore and at sea. A main conclusion from the interview was the fact that the gas turbines are developed more and more into running entirely on gaseous fuels and the only thing that slows the conversion phase down is that the industries (including the shipping industry) still wants to run the gas turbine on diesel and in some cases HFO. The reason is argued to be mainly economically but to some extend a conservative thinking. The comparison between a liquid fuel with LHV = 42,700 kJ/kg and the gaseous fuel with LHV = 46,798 kJ/kg is shown in table 8 – 11. For equivalent operations, the liquefied fuel shows a higher output power, higher exhaust temperature, lower SFC and better primary fuel efficiency. All these values are supporting the argumentation that todays´ gas turbines should run on gaseous fuels (natural gas) from a technical and economically perspective. In figure 10 – 13 the arguments for gaseous fuels are further strengthened since the figures show SFC and output power are better for gaseous fuels at various inlet air temperatures and different load conditions.

When taking both the literature review and the semi-structured interview into account the two results are supporting each other's argumentation in terms of SFC where gaseous fuel is said to be better (i.e. lower SFC). Even though the SFC is argued to be lower with gaseous fuels in both result parts the result from the interview and from the literature differs when it comes to primary fuel efficiency. Table 5 shows that diesel is said to have a higher primary fuel efficiency than natural gas and in table 8 – 11 it is found that gaseous fuel should have a better fuel efficiency than diesel. This difference is marginal and the fact that the company SIT AB argues that gaseous fuel is better can possibly be biased in commercial purpose. But it could also be due to the fact that the company should have better testing facilities and knowledge and that gaseous fuel in reality has a higher fuel efficiency.

5.4 Method discussion

The method choice was a combination of a literature review and a semi-structured interview. The literature review was selected due to the authors vague knowledge of the subject in the beginning of the study, it was also considered to be a suitable method to increase the knowledge and at the same time collect necessary information to answer the research questions. A literature review can be a great method if there is a lot of information and the available information is up to date. In our case, it would have been beneficial to first investigate the possibility to find enough relevant information before starting since we had some difficulties answer the questions using solely literature.

The choice to combine the literature review with an interview was taken early in the process to fill out some gaps of information that we noticed in the literature that we found. The two methods also complement each other and giving both a theoretically perspective as well as practical and real-life information. The interview was planned and conducted as a semi-structured interview which means that the questions is open-ended to give the interviewee the opportunity to give descriptive answers and us the ability to come up with questions during the interview and at the same time have a template as base structure. Other possible alternatives for an interview could have been a structured or an unstructured interview which both have strengths and weaknesses, just like a semi-structured interview. If we had interviewed more than one company a structured interview might have been better to have the ability to compare answers like in a quantitative study. An unstructured interview could have resulted in a lot of information and but since we only got one opportunity we tried to make sure we could get the most relevant information. With this in mind, we still think that a semi-structured interview was appropriate for this subject and for the time available.

The choice to not record the interview is likely to have an immense impact on the result in chapter 4.2 since we had to use only notes and memories from the visit to present the result. For the study, it would have been better to record the interview and in that way, have the possibility to get exact comments and be able to discuss some parts of the interview after listening again, but the barrier for this was the two interviewees will, which should be respected.

5.4.1 *Reliability and validity*

Validity means here to what extend the study succeeded to address the research questions and how well the answers is connected to the questions. With a combination of a literature review and an interview the validity of the study should be considered good since we both have reviewed and published scientific articles in combination with input from a major company in the field.

The reliability of this study is fairly good since the result is similar from both the interview and the literature review. To further increase the reliability of the study more than one company should have been interviewed because of the possibility of the company to have been biased. To include other major companies with gas turbines in marine applications would have generated a wider perspective and a greater number of values to support or contradicts our result. The reliability would also be better if more literature were available that supported our conclusions and result.

6 Conclusions

The most common vessel types using gas turbine propulsion today (cruise vessels and fast ferries) are not the ones benefitting the most. Instead, the result shows that the ships most suitable for combined gas turbine and steam turbine propulsion is vessels operating at longer voyages with less manoeuvring due to the design of the gas turbine, which optimal operation is to work on full load with few stops. The study also present that all vessels, regardless of required engine power, successfully can use gas turbines as prime mover. This kind of vessel could benefit the COGAS system which has a transmission efficiency of 98-99 percent.

The poor efficiency of a gas turbine running on part-load can be solved by using a COGES or COGAS system and have one turbine off-line while running on part-load. Another way is by using the supercharged turbine (SNGCC) which has a free compressor stage in the beginning of the gas turbine cycle which provides the main compressor with optimal operational air mass flow and pressure ratio even during part-loads. The COGES configuration offer a high flexibility since the output energy is addressed as electrical power while the COGAS configuration offers a slightly higher efficiency due to the energy conversion in fewer steps.

Regarding gas turbine fuel this study focused on liquid fuel (diesel) and gaseous fuel (natural gas). The results show that gaseous fuel is close to equal with the liquid fuel regarding performance and fuel efficiency and advantageous in terms of emissions and power output. Combined these results proves that gaseous fuel is the best for marine propulsion with gas turbines as prime mover.

6.1 Suggestions on future work

Since this study is a relatively broad the need of further investigation regarding gas turbines as prime mover on vessels in the merchant fleet is necessary if the goal is to replace the diesel engine. Subjects that might be of interest are:

- Investment and operational cost for gas turbines compared to diesel engines.
- A comprehensive analyse of gas turbine performance at low- and part loads in marine applications, preferable in comparison with the diesel engine.
- Since there are several other ways of increasing the gas turbine simple cycle efficiency than this report covers it would be of interest to investigate how well these work onboard ships.

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Appendix

Appendix 1 – the interview questions in Swedish from the visit at SIT AB in Finspång, Sweden.

Siemens Finspång 13/3 – intervjufrågor

SIEMENS MARINA GASTURBINER

1. Vilka av era gasturbiner har använts för framdrift av fartyg?
2. Vilka typer av fartyg har haft gasturbindrift och varför just dessa?
3. Hur har konfigurationen sett ut? (Gasturbin elektriskt, direktdrivet etc.)
4. Vilken typ av bränsle har använts?
5. Vilka utmaningar har varit störst?

UTVECKLING AV MARINA SYSTEM

1. Har Siemens intresse av att ta sig in på den marina marknaden mer?
2. Om ja, vilka hinder/barriärer finns och hur kommer ni förbi dem?
3. Varför har inte tidigare satsningar fortsatt?
4. Skiljer sig installationskostnader åt beroende på bränsle?
5. Bedriver Siemens någon form av forskning/utveckling angående marina framdrivningssystem? Om ja, hur ser det ut?

GASTURBINER TEORI

1. Hur klarar gasturbiner miljön ombord på fartyg? (luftfuktighet, salthalt, vibrationer etc.)
2. Vilka typer av underhåll är essentiella? (Turbin washing)
3. Kan alla typer av underhåll göras ombord?
4. Vilka faktorer påverkar valet av bränslen?
5. Är det tekniska aspekter som också spelar roll i val av bränsle?
6. Hur kan man kompensera för en dålig verkningsgrad på låg last?