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Analysis of engine tuning for optimum waste heat recovery power

Diploma thesis in the Marine Engineering Programme

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Abstract

A marine diesel engine have an efficiency of 50%, the other 50% can be parted in two, where 25% are heat which is cooled away in the cooling systems and 25% is waste heat in exhaust gases. The waste heat have potential to be useful by converting it to electricity where the gained electricity can be used for propulsion via electric shaft motor.

This reports data are received from questionnaires handed out to engine manufacturers and personnel on board ships, and MATLAB simulations. The data proves that combining an Organic Rankine Cycle (ORC) system with a 2-stroke marine diesel engine can improve a ships specific fuel consumption without increasing ships emissions.

Simulations were done in order to find an optimal way of tuning for increased combined cycle engine efficiency. Before running the simulation material the environmental limitations needed to be considered whit regard to increased temperature, the engine is under more stress from higher exhaust and cooling water temperature. Mechanical limits needs to be accounted for as well, in particular on the fuel nozzles, pistons and piston rings. These limitations have been examined and compared to adjust the appropriate limits for the calculations.

The results of this report show a way to reach optimum tuning for a combined cycle engine. For example does this result prove that by using an Organic Rankine Cycle can the Specific Fuel Oil Consumption be decreased by 12g/kWh. With live operating ships and personnel's input the report gives an idea for changes that can be made in order to improve fuel consumption, for new builds and current vessels.

Keywords:
Diesel, Limitations, Marine, Optimize, ORC, Tuning, Two stroke, WHR

Sammanfattning

En marin dieselmotor har en effektivitet på 50%, de andra 50% kan delas i två, där 25% är värme som kyls bort i kylsystemen och 25% är spillvärme i avgaserna. Spillvärmen har potential att vara till nytta genom att omvandla den värmen till elektricitet där man sedan kan använda elektriciteten för framdrivning via en elektrisk axelmotor.

Rapportens data har samlats in via frågeformulär som har delats ut till motortillverkare, personal ombord på fartyg och via MATLAB simuleringar. Data bevisar att kombinera en Organic Rankine Cycle (ORC) system med en 2-takts marindieselmotor kan förbättra ett fartyg specifika bränsleförbrukning utan att öka fartygens utsläpp.

Simuleringar gjordes för att hitta ett optimalt sätt öka den kombinerade cykelns verkningsgrad. Innan simuleringen kördes togs det hänsyn till de miljömässiga begränsningar som finns samt att en till ökad temperatur ger motorn mer stress från högre avgas och kylvattentemperatur. Mekaniska gränser måste samt ta till hänsyn, i synnerhet på bränslemunstyckena, kolvar och kolvringar. Dessa begränsningar har undersökts och jämförts att ändra de lämpliga parametrarna för beräkningarna.

Resultaten i denna rapport visar ett sätt att nå optimal optimering för en kombinerad cykel-motor. Till exempel visar resultatet att genom att använda en Organic Rankine Cycle kan den specifika bränsleoljeförbrukning minskas genom 12g/kWh. Med fartyg i drift och personalens egna kommentarer ger rapporten en uppfattning om förändringar som kan göras för att förbättra bränsleförbrukningen, för nybyggnationer och nuvarande fartyg.

Nyckelord:
Begränsningar, Diesel, Mappning, Marin, ORC, Optimering, Tvåtakt, WHR

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List of abbreviations

CCE – Combine Cycle Engine
CCSFOC – Combine Cycle Specific Fuel Oil Consumption
deltaT – Difference in temperature (T_1-T_2)
EEDI – Efficiency Design Index
g/kWh – gram per kilo Watt hour
HT – High Temperature
HTFW – High Temperature Fresh Water
IMO – International Maritime Organization
kW – kilo Watt
MARPOL – International Convention for the Prevention of Pollution from Ships
ME – Main Engine
ORC – Organic Rankine Cycle
RoRo – Roll on Roll off
SFOC – Specific Fuel Oil Consumption
T – Temperature
WHR – Waste Heat Recovery

1 Introduction

Today the shipping industry strives for an improved environmental policy due to mandatory regulations from the International Maritime Organization (IMO) such as the Energy Efficiency Design Index (EEDI) that was made mandatory for new ships in 2011. A good way to reduce the effect from ships is to reduce its fuel consumption, doing so reduces all emissions. One way to do that is to optimize the ship propulsion efficiency rather than focusing on single components. Organic Rankine Cycle (ORC) is a Waste Heat Recovery (WHR) system that can improve the propulsion efficiency without the risk of increasing a ships emissions (Tian, Zhang, & Roskilly, 2014)

This thesis will investigate the possibility of tuning a marine diesel engine for the optimal amounts and temperatures of waste heat sources needed for a WHR system and to see how much it could improve a ships fuel consumption. Doing so will hopefully increase the power outtake and efficiency in a combined cycle engine, consisting of a conventional 2-stroke marine diesel engine and an Organic Rankine Cycle (ORC) Waste Heat Recovery (WHR) system. Figure 1 describes that engine tuning that result in higher engine Specific Fuel Oil Consumption (SFOC) can result in an increase of the propulsion system's total efficiency by increasing the heat recovery to electrical power and thereby lowering the ships total SFOC (Larsen, Pierobon, Baldi, Haglind, & Ivarsson, 2015).

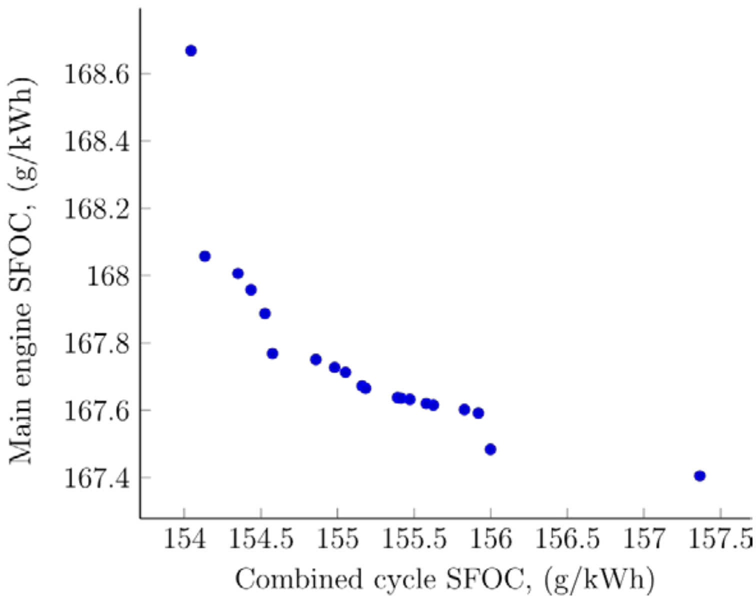

Figure 1 SFOC Main engine and combined cycle with OCR , (Larsen et al, 2015) by permission

1.1 Purpose

To find out the optimum amount and temperatures of heat that is possible to recover from a two-stroke marine diesel engine through engine tuning, convert the heat to electrical power and see how much a Combined Cycle Engine (CCE) can reduce a ships Specific Fuel Oil Consumption (SFOC).

1.2 Questions

1. What sets the limits for engine tuning of a 2-stroke marine diesel?

2. What possible ways there are to tune a 2-stroke diesel engine during continuous operation for a Combined Cycle Engine?

3. How much can a ship's Specific Fuel Oil Consumption (SFOC) be lowered by adding an ORC system?

1.3 Delimitations

The interviews will be limited to chief engineers, 2:nd/3:rd engineers and personnel employed at Scandinavian shipping companies and engine manufacturers. The engines we aim to research are two-stroke engines with electronic controls that will make the tuning possible. This report is not aimed to be a literature research article, that’s why there is not a lot of references to articles or a deeper research in beforehand. The report is anchored to real numbers and variables from live engines operating in ships. The mathematical modelling is limited looking at energy and mass balances for the system.

2 Background and/or Theory

The background section first explains the losses that are available for power recovery in Figure 2 to fully understand which losses that are available for power recovery. Figure 3 shows how an ORC system is laid out, it explains what kind of WHR the ORC is. Earlier experiments are shortly summarized too explain how effective the integration of an ORC can be. Equation 1 is a heat balance equation, it simply describes the parameters that can be changed with engine tuning. The different parameters in Equation 1 that can be changed via engine tuning are investigated in detail since this report aims at finding out the possible adjustments of parameters for power recovery. General limitations are described shortly in the background since they are a vital part of the report. The limitations are investigated with questionnaire and are therefore more deeply explained in results part.

2.1 Main Engine energy balance input/output

The energy from the fuel in a main engine (ME) that is not turned into efficient work becomes heat around 50%, the waste heat is in the exhaust gases are about 25% of that (Kuiken, 2012). If a waste heat recovery (WHR) system is installed the temperature from exhaust gases and jacket water can be useful for power generation.

Figure 2 describes the amounts of heat loss that could be used for a WHR system. In the reference case used for calculations are there 250°C in the exhaust system however before the exhaust turbine can the temperature be around 500°C. Prior to the air cooler are the temperature at 170°C and afterward is the temperature cooled down to 50°C. Jacket water cooler is used to lower the HTFW temperature from the main engines 80°C to 72°C. The lube oil cooler lowers the lube oil from 65°C to 48°C. About 1% is heat radiation from the engine.

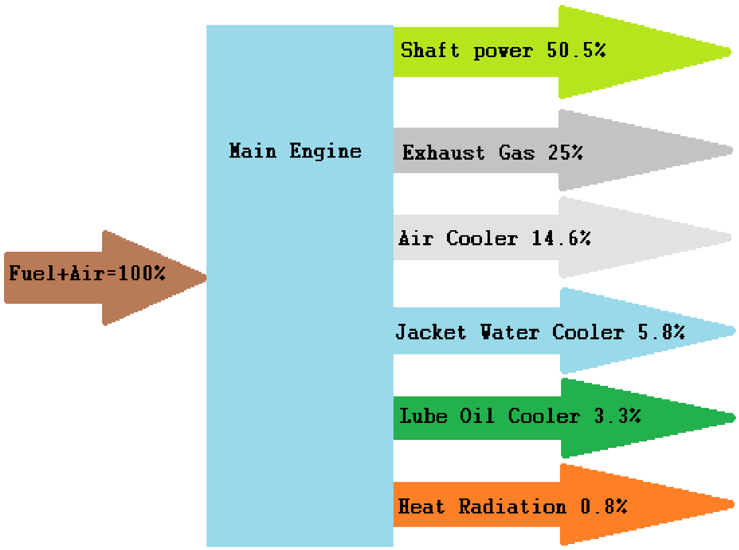

Figure 2 Engine input/output

2.2 Waste heat recovery

2.2.1 Organic Rankine Cycle (ORC)

The ORC is a type of WHR. It operates similar to an exhaust gas boiler, but uses an organic fluid instead of water to utilize the heat more efficiently at varying temperatures. With an ORC it is possible to choose different fluids based on the heat source inlet temperature. That makes the ORC more efficient as a WHR-system for low-temperature heat recovery. With increased heat source inlet temp the thermal efficiency will be higher (Larsen, Pierobon, Wronski, & Haglind, 2014).

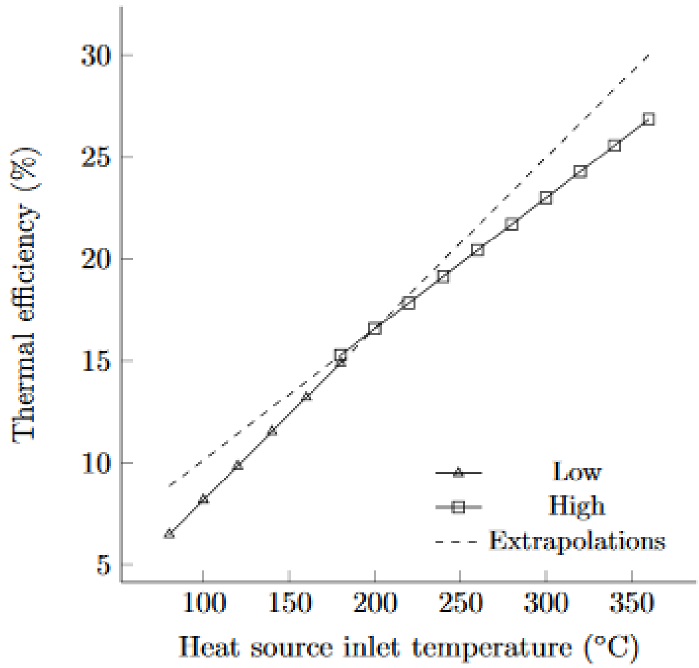

Figure 3 ORC thermal efficiency compared to Heat source inlet temperature (Larsen et al, 2014) by permission

The ORC works in stages, first a pump increases the pressure. The fluid is then preheated by a fluid, ex thermal oil, which is heated by a heat source. A heat source can be ME's exhaust gases, High Temperature Fresh Water (HTFW), lubricating oil or with a regenerator that uses the heat from the vapour after the expansion. After being preheated the fluid is evaporated then finally it is superheated. The high pressured superheated vapour is led in to a turbine that expands the vapour. When the vapour expands and drops in pressure the turbine rotates and drives an electrical generator that produce electricity. After the turbine the vapour goes through the regenerator, then to the condenser where it becomes a liquid again and the process starts over (Teng, Regner, & Cowland, 2007). A sketch of an ORC layout is shown in Figure 4 below.

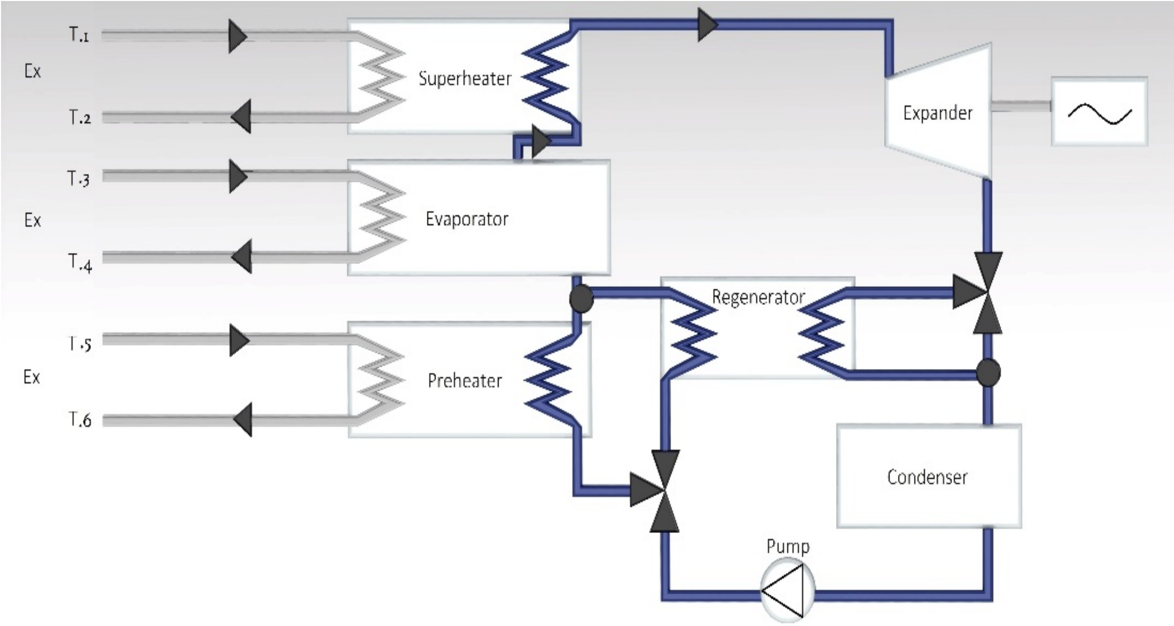

Figure 4 ORC system, Authors own image

2.2.2 Integration of WHR

Using an organic fluid instead of water is preferred for turbine operation to avoid mechanical damage due to saturated steam in expander. Organic fluids in low temperature WHR systems avoids the risk of steam saturating early (Tian, Zhang, & Roskilly, 2014). When operating in warm climates there is some wasted heat, for example dumping steam from the exhaust gas boiler that is only used for heating bunker, according to 3rd engineer, Wallenius. With an integration of a WHR system like the ORC, the steam could be used for heating of the ORC.

2.2.3 Researched experiments

2.2.3.1 ORC truck installation

An ORC installed in a truck with a small six cylinder four stroke engine have been proved that the SFOC can be improved up to 10.2% at 25% load and 8.5% at 100% load (Katsanos, Hountalas, & Pariotis, 2012). The difference between 10.2% and 8.5% is because the medium R245ca that is used in this system are made for a low temperature.

2.2.3.2 Wallenius marine and OPCON

Wallenius and OPCON installed 2011 an ORC system on the vehicle carrier "FIGARO". One important component of the installation is the turbine expander. The turbine can deliver electricity up to 500kW. They expect to see a fuel saving of 4-6%, OPCON says 4-10% is possible depending on the different setups on different ships. OPCON's equipment can be installed both on new builds and for retrofitting.
(Siuru, 2013).

2.2.3.3 Sulzer RTA96-C

This is an example of a large 2-stroke engine that is fitted in Emma Maersk. The efficiency is today at the propeller shaft is 49.3%. The total propulsion efficiency would be better if an ORC would be installed the ship. With the ORC the shaft power would be less at 49%. The efficiency will be lower when you tune the engine to get more heat from the combustion. The overall efficiency with a turbine generator that takes a lot of heat from the exhaust gases and convert it to electricity that will be used for propulsion with an output at 5.9% of total fuel inlet. Total efficiency of the ship would be at 54.9%.
(Shu & Liang, 2012)

Table 1 Sulzer RTA96-C

Outputs	**Energy of 100% fuel/air mixture**
Shaft power output	49%
Electrical power output	5.9%
Condenser	8.6%
Exhaust gas	12.6%
Air cooler	12.9%
HTFW	6.2%
Lube oil	4.2%
Radiation	0.6%

2.3 Engine tuning

This section describes the different types of engine tuning that later will be used for the calculations of optimum heat recovery.

Engine tuning is a way of adjusting the engine in order to improve efficiency. To tune the engine some parameters can be changed such as the injection timing and the amount of fuel. The heat balance equation, Equation 1, below show how changing of the parameters affects the others.

$$mFuel * LHVFuel + mAir * hAir + mFuel * cpFuel * TFuel$$
$$=$$
$$Power + Qscav + Qhtfw + Qlo + Qradiation + mExh * cpExh * TExh$$

Equation 1 Engine energy input = power and losses output

mFuel = mass fuel, kg/s
LHVFuel = Latent Heat Value fuel, kJ/kg
mAir = mass air, kg/s
hAir = Enthalpy air, kJ/kg*°C
cpFuel = specific heat capacity fuel, kJ/kg*°C
TFuel = temperature fuel °C
Q = losses, kiloWatt
scav = scavenging air
lo = lube oil
Exh = Exhaust

2.3.1 Parameters

2.3.1.1 Air flow

Adjusting the air flow to change the temperature and pressure of the scavenging air will have an effect on the combustion, the engine needs a certain amount of air to operate properly. The air flow is dependent on the turbocharger and the exhaust gas as Figure 5 below shows. Tuning that leads to lower or higher exhaust temperature and pressure will affect the air flow and vice versa. According to engine manufacturers with their new engines it is possible to reduce the scavenge air pressure by cutting out one of the turbos in a two stage turbo system, this would reduce the amount of excess air during combustion and thereby increasing the exhaust gas temperature. Teachers at Chalmers mentions that to achieve high temperatures for an ORC Heat source the exhaust turbine can be bypassed. An amount of exhaust gas at around 450-500°C could be used to heat thermal oil. That would mean energy that usually goes through the turbo charger would be used, this lowers the effect from the turbine and would affect the scavenge air. There are possibilities with new turbochargers to adjust the blades inside the turbine. Varying different angles and the blade area changes the flow and pressure of the scavenge air. This is an option for 2-stroke engines that has scavenging air ports which are difficult to adjust.

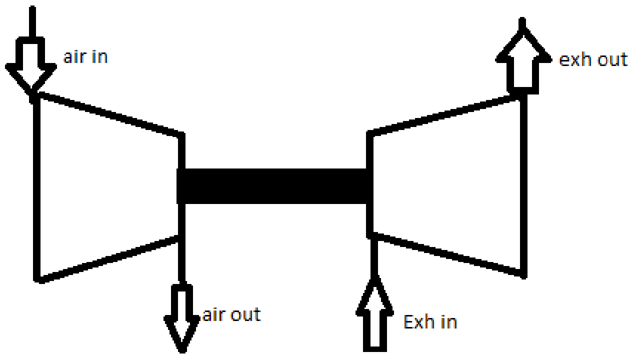

Figure 5 Description of turbocharger, Authors own image

2.3.1.2 Injection timing and fuel flow

Adjusting the injection timing could be used for tuning of fuel flow. When increasing the fuel flow the air flow has to be considered to maintain a correct fuel and air mixture. A proper mixture is important to maintain an efficient combustion. Newer ships have computer adjustable fuel valve timing. Tuning for higher exhaust temp can be achieved by delaying the fuel injection, but doing so requires more fuel to maintain the power outtake since the combustion will be less efficient. Electrically controlled fuel injection enables adjustment of the combustion process such as fuel amount and valve timing. This is possible with modern common rail as they use on Wallenius Figaro with an engine from MAN B&W. Parameters as peak pressure, compression pressure and mean pressure can be adjusted with common rail, but the engines are optimized for high efficiency at different loads for a reduced fuel consumption and minimum impact on the environment. According to a chief engineer the fuel cost is one of the largest cost when running a ship.

2.3.1.3 Cooling water

Adjusting the HTFW temperature regulator set points can be done to achieve higher HTFW temperatures. Then the engines HTFW cooled systems will increase in temperature and the extra heat in both the HTFW and lubricating oil could be used as a heat source for an ORC system.

2.3.1.4 Exhaust valve

There is a possibility with new engines according to engine manufacturer MAN to install an electronically/pneumatically adjustable exhaust valve that enables opening of the valve earlier (MAN Diesel & Turbo, 2012). Exhaust valve opening early results in an increased exhaust gas temperature, but according to teacher Larsen it is limited by the need to scavenge the cylinder properly after combustion. The efficiency of the engine will be lowered and more fuel will be needed to maintain the same amount of power outtake. Adjusting the valve is also possible on older engines, but it requires a mechanical adjustment of the valve timing by reconfiguring camshaft, says a first engineer, Donsötank.

2.4 Ship limitations

This section describe material and mechanical limitations, the limitations will be a restriction for the calculations.

2.4.1 High temperature corrosion

It is well known that if the temperature in the combustion is too high, a risk of high temperature corrosion may occur. That can lead to vanadium and sodium fouling of turbocharger, and eventually it might damage the turbine.

2.4.2 Low temperature corrosion

The economizer on a ship has a limited temperature range. It is well known that the exhaust gas temperature gets below the dew point of sulphuric acid (160°C) deposition of corrosive sulfuric acid can occur.

2.4.3 Mechanical limitations

The peak pressure in the engine should not be raised too much because the piston rings are vulnerable and already working in a harsh environment. Increased pressure might induce extra wear and cause physical damage to cylinder liner and possibly lead to further damage on main engine

2.5 Environmental limitations

2.5.1 NOx

Tuning the engine for extra heat via the combustion could result in an environmental limitation. Too high combustion temperature and pressure will cause NOx emissions, this is regulated by IMO. Using engine tuning, adjusting valve timing and injection timing, for reduction of NOx normally increases the engine SFOC. By lowering the top pressure and maximum combustion temperature, NO_x will reduce and the waste heat will increase that can be used (Larsen, Pierobon, Baldi, Haglind, & Ivarsson, 2015).

2.5.2 CO_2

CO_2 is directly connected to the amount of fuel the engine uses, CO_2 is a Green House Gas that is regulated by the mandatory EEDI directives from IMO. Tuning that causes slightly higher ME SFOC can reduce the combined cycle engine's SFOC. The extra waste heat is used for increased power outtake of the ORC, therefore a CCE would reduce the ships CO_2/kWh. (Larsen, Pierobon, Baldi, Haglind, & Ivarsson, 2015)

2.5.3 Energy efficiency design index (EEDI)

The EEDI is a technical measure that aims at newer ships ability to utilize their energy input more efficiently. The EEDI set limits for different types of newly built ships, tonne CO_2 per ton nautical mile for different ship types. It regulates how much fuel that is allowed to use per mile travelled with cargo (International maritime organisation, 2016).

The EEDI will be improved by adding a WHR since there is a more efficient power output on the shaft that propels the ship and more mileage will be gained per gram fuel. Less g/kWh → Less CO_2/kWh → Less CO_2/ton nm.

3 Method

Research questions were based on a project from Ulrik Larsen, a teacher at Chalmers University, as a pre-study in a larger project with DTU, Maersk and MAN Diesel & Turbo. Larsen wanted to know more about the physical limitations to engine tuning and how it could be used to maximize an ORC-system on a merchant vessel. To acquire real data a questionnaire was sent out via email to shipping companies and engine manufacturers. The different answers were analysed and composed into different types of physical limitations and variables such as temperatures was put into tables to be compared and used later in simulations.

3.1 Data collecting

A questionnaire was handed out to engineers that work with engines and engine tuning, professors in relevant subjects and companies. The questionnaire asks questions in order to find out the facts about engine tuning and waste heat recovery, real numbers and tuning possibilities from live ships and relevant sources. Contact was made via email and telephone with shipping companies, professors and engine manufacturers. The questionnaire was sent out and filled in digitally, the data collected was analyzed, compared with each other and conclusions derived.

Multiple sources were contacted, two of the biggest Swedish shipping companies that has 2-stroke engines onboard, two of the largest Scandinavian engine manufacturers and several engineers in the field of work.
Questionnaire can be found in appendices.

Table 2 Response data

Questioned	Response
Donsötank crew	Fast and good response, referred limitations to MAN
ACL crew	Fast and very well formed answers with arguments
Wallenius Crew	Fast and very well formed answers with arguments
Wallenius	Good communication but response not within deadline
Stena Nautica	Fast but limited response due to lack of time.
Wärtsilä	No response on questionnaire
MAN	No Response on questionnaire, referred to website
Teacher Larsen	Good and fast response

3.2 Literature search

The background data was collected using Chalmers library online search engine. There was a limit to what could be found about combined cycle engines in marine applications, but experienced professors at Chalmers were asked and they delivered some relevant articles. A lot of the background needed to explain the report to the reader comes from the course materials that we, the authors, has studied over the years at Chalmers marine engineering program.

3.3 ORC estimations

The equations below are results of hundreds of calculations tested on linear models that matches previous research, to predict maximum ORC efficiency. Larsen U, Pierobon L, Wronski J and Hagling F published these calculations for combined cycle engine system in an article named *Multiple regression models for the prediction of the maximum obtainable thermal efficiency of organic Rankine cycles*. (Larsen, Pierobon, Wronski, & Haglind, 2014).

$$effORC = -16.32 + 0.08402 * Tin + 0.08349 * Tout + 0.1583 * TurbineEff$$

Equation 2 ORC efficiency low temperature

$$effORC = -12.76 + 0.06428 * Tin + 0.05897 * Tout + 0.2576 * TurbineEff - 0.127 * Tc - 0.1556 * dTpp$$

Equation 3 ORC efficiency high temperature

effORC = thermal efficiency of ORC, %
Tin= ORC inlet temperature, °C
Tout = ORC outlet Temperature, °C
TurbineEff = Thermal efficiency of Turbine(Expander), %
Tc= Condensing temperature, °C
dTpp= Delta temperature (Tin-Tout) of heat exchanger pinch point °C

3.4 Reference case

A reference case was made with the data collected, the data supplied the limitations of the engine and all simulations were done within the analyzed range. Multiple simulations were done with varying of input values in MATLAB with equations from (Larsen, Pierobon, Wronski, & Haglind, 2014) and with personal assistance from Ulrik Larsen. The calculations were done within consideration to the limitations given by the experienced personnel, the limitations that was used in the calculations are shown in

Table **3**. The heat balance equation was calibrated by adjusting the SFOC, within the given range from questioner, and the mass of air (kg/s) to match 50% ME efficiency and the losses to match a Sankey diagram from (Kuiken, 2012). Some assumptions had to be made since not all data to run the equations was given by the questionnaire, these assumptions were made when developing the code with Ulrik Larsen. The simulation results are presented in tables to clearly show what was changed and what is gained or lost.

4 Results

This section first explains the differences in values received via the questionnaire from ships and their limitations. Which is needed to understand the limits for running the calculations. The reference case is at the top of every table with or without an ORC to make it easier to follow the effect of an ORC. The results with different ORC's, low temperature and high temperature ORC, are presented in tables with an analysis to give a short but clear view of what the ORC can achieve.

4.1 Differences in variables between ships

It was found that the 2-strokes engines investigated in this report operated at similar temperatures and pressures. The most important thing separating the engines was that the smaller 2-strokes did have higher SFOC-range.

4.2 Engine & Tuning Limitations

On Atlantic Compass that is a large container ship with Roll on Roll off (RoRo) possibilities that is 298 meter. The engine is a Götaverken B&W 6L90 GB 2-stroke. It was found that too high scavenge air pressure causes the turbocharger to surge when running. Surge appear when the turbo charger does not build up the pressure as the pressure is after the charger. They have installed dumping valves to reduce the scavenge air pressure.

There was also a change of material in exhaust valve spindle to handle higher exhaust gas temperature. With the new material, it can tolerate 500°Celsius compared to the old material that had a limit of 450°Celsius.

According to a first engineer they keep the operating temp of HTFW slightly below the recommended maximum temperatures, from engine manufacturer MAN, for continuous running. It is important that the difference in HTFW inlet and outlet temperature is kept in balance, too big of a difference may cause damage to the cylinder liner, according to a chief engineer. The older ships does not have the same tuning possibilities as the newer ones, but it is still possible to do manual and mechanical tuning on some parameters. Such as adjusting the camshaft, temperature regulator and increasing fuel.

Table 3 shows a summary of the ships engines and limitations found through our survey.

Table 3 Ships Limitations

Limitations/ Ship Name	Engine	GRT	Scavenging Air	Lube oil °Celsius	HTFW °Celsius	Exhaust °Celsius
Atlantic Compass	6L90 GB	57 255	1.9bar	65	85	500
Figaro	8S60ME	74 258	2.6bar	85	95	510
Solero	8S35ME-B	13 472	1.9bar		92	445
Stena Nautica	2x 8L45GB	11 602	1.7bar	55	90	450

4.3 Calculations

Below follows the results of the calculations that were run in MATLAB.

4.3.1 Reference/normal

The reference case in Table 4 sets the base for the rest of the calculations. It is made up with values from the questionnaire and an input/output energy balance (Kuiken, 2012).

LHV= 42200 kJ/kg
Qrad = 1-2%
cpExh = 1.04 kJ/Kg*K
cpair = 1.0 kJ/Kg*K
orcEff = 80%

Table 4 Reference/normal

SFOC g/kWh	Power kW	Eff %	Qscav kW	Qhtfw kW	Qlo kW	Qradiation kW	Qexh kW
168	18400	49.63	4368	2170	1400	184	10752

This reference is normal before tuning and using an ORC for optimizing combined cycle. Normal consumption without any ORC is 74.2ton/24h

4.3.2 Reference with ORC using HTFW as heat source

Table 5 presents the data of the case with an ORC on the HTFW.

Table 5 ORC using HTFW

SFOC g/kWh	Power kW	Eff %	ORC Power kW	CC Eff %	CC SFOC g/kWh
168	18400	49.63	197	50.16	166.2

It clearly shows in Table 5 that using a combined cycle reduces the amount of SFOC (g/kWh). A total reduction by 0.8Ton/24h.

4.3.3 Reference with ORC using exhaust gas as heat source

Table 6 presents the data of the case with an ORC that uses the exhaust gas as a heat source.

Table 6 ORC using exhaust gas

SFOC g/kWh	Power kW	Eff %	ORCpower kW	CCEff %	CC SFOC g/kWh
168	18400	49.63	1420	53.46	156

Table 6 shows that a CCE with a high temp ORC reduces the amount of SFOC by 10 g/kWh more than a low temperature. The power output is 7.2 times greater than a low temperature ORC. The CCE with high temperature ORC saves 5.3Ton/24h.

ORC exhaust gas tuning with adjusting scavenge air mass flow

Table 7 presents data from calculations of case with scavenge air tuning.

Table 7 ORC exhaust tuning

mAir kg/s	SFOC g/kWh	Power kW	Eff %	ORCpower kW	CCEff %	CC SFOC g/kWh	T_exhout °Celsius
33.6	168	18400	49.63	1421	53.46	156	300
32	168	18400	49.68	1635	54.10	154.3	319
31	168	18400	49.72	1778	54.52	153.2	333
30	168	18400	49.75	1929	54.96	152.1	346
29	168	18400	49.78	2089	55.43	150.9	361

Table 7 shows that lowering the amount of air increases the ME Exhaust temperature. This results in better combined cycle efficiency. It should decrease ME efficiency but in this case there is a lot of excess air, in accordance with example (Kuiken, 2012). Calculations are based on (Larsen, Pierobon, Wronski, & Haglind, 2014) and in that article they say that high temperature ORC can´t have an input of more than 360°Celsius. With tuning of scavenging air it is possible to reduce the SFOC with 17.1g/kWh.

4.3.4 ORC HTFW water tuning

Simulating adjustment of the temperature regulator to achieve higher HT temperature for the ORC by setting the max temperature at 90°C. This value comes from data in questionnaire, we did this constant deltaT because a chief engineer sad that the temperature difference shouldn’t be too high in ME. Higher difference in T may cause cylinder liner to crack.

4.3.4.1 HTFW TUNING constant deltaT

Table 8 HTFW tuning deltaT

SFOC G/kWh	ME HT in °C	ME HT out °C	Power kW	Eff %	ORC Power kW	CC Eff %	CC SFOC g/kWh
168	72	80	18400	49.63	197	50.16	166.2
168	82	90	18400	49.63	234	50.26	165.9

With a higher temperature, but the same deltaT we achieved a more efficient power output as shown in Table 8.

4.3.4.2 HTFW Tuning change in outlet/inlet temp.

Table 9 presents the case of tuning for an increase in ME HTFW inlet, 87°C inlet is the max according to the data collected.

Table 9 HTFW tuning outlet/inlet

SFOC g/kWh	MEHT in °C	MEHT out °C	Power kW	Eff %	ORC Power kW	CC Eff %	CC SFOC g/kWh
168	72	80	18400	49.63	197	51.32	166.2
168	72	90	18400	49.63	216	50.21	166.1
168	76	90	18400	49.63	223	50.23	166
168	80	90	18400	49.63	229	50.25	165.9
168	84	90	18400	49.63	237	50.27	165.9
168	87	90	18400	49.63	243	50.28	165.8

Table 9 and Table 8 shows that the SFOC does not need to be changed when using a low temperature ORC, but there is an increase in the ORC power. It is clear that tuning for an increased inlet temperature can result in a higher power output, and it is more efficient to lower the deltaT.

4.3.5 ORC higher exhaust temperature.

Table 10 Higher exhaust temp

T Exh °Celsius	SFOC g/kWh	Power kW	Eff %	ORCpower kW	CCEff %	CCSFOC g/kWh	Delta SFOC.(g)
300	168	18400	49.63	1421	53.46	156	12
310	171	18400	48.6	1596	52.99	157.4	13.6
320	174	18400	47.92	1782	52.56	158.6	15.4
340	180	18400	46.32	2186	51.82	160.9	19.1
360	186	18400	44.83	2633	51.24	162.7	23.3

Table 10 shows how a high temp ORC can reduce the ships SFOC by using the waste heat from the engine exhaust gas. When tuning for more heat in the exhaust the SFOC for ME increases to maintain the same power with less efficiency. In this simulation the mass of the air is calibrated to be 39 times the mass of the fuel according to our balance that was made (Kuiken, 2012). By increasing the temp in the exhaust by example injection timing or opening the exhaust valve earlier, to maximum (360°C) the ME SFOC is increased by 18g/kWh. The combined cycle reduces SFOC by 23.3 g/kWh. A total of 5,3g/kWh less in ships total SFOC compared with the reference at 168 g/kWh. Analysis of the tables says that it is better to install the ORC and use it in normal running mode.

4.3.6 Tuning experiment Increased SFOC and less air/fuel ratio.

Table 11 experiment air/fuel ratio

T Exh °C	SFOC g/kWh	mAir kg/s	Power kW	Eff %	ORCpower kW	CCEff %	CC SFOC g/kWh
300	168	33.6	18400	49.63	1421	53.46	156
360	173	31.4	18400	48.3	2219	54.12	154.4
360	178	33.6	18400	46.9	2382	52.97	157.6

Table 11 shows an attempt to find a more optimal solution with two types of tuning; the exhaust gas temperature is increased by higher ME SFOC while the mass Air is reduced. This was done by the usage of the high temperature system, since the analysis of the tables shows that the high temperature is the most efficient. An analysis of the result implies that tuning for an increased SFOC is not the optimum choice furthermore does it indicate that reducing the amount of air affects the CCSFOC in the best way since reduction of air and constant SFOC slightly increases the ME efficiency in this case which are visualized in table 11.

5 Discussion

5.1 Result discussion

5.1.1 Tuning possibilities and limitations.

Most of the tuning that was mentioned in the background of the report was confirmed via engine manufacturers and teachers. However the ships that answered our questionnaire does not have all the modern possibilities, such as electronical controlled exhaust valves, two stage turbo or variable turbine area.

The limitations varied some between the ships and some officers had a difference of opinion about the limits of HTFW temperatures. On some ships the personnel onboard had the high level limits set to lower values then the limits recommended by engine manufacturer.

We chose not to calculate an ORC based on the lube oil because the HTFW has a higher temperature and have more energy to use.

5.1.2 Calculations

From our simulations it clearly shows that the high temp ORC is the most efficient, as was stated in the article (Larsen, Pierobon, Wronski, & Haglind, 2014). Our result show that the best way for tuning a combined cycle engine is to reduce the amount of air to increase the exhaust gas temperature. One possible drawback of doing so is that the combustion may not be optimal with less air, there will be black smoke and lower efficiency. This reduces the CCSFOC by 17,1g/kWh compared to the amount SFOC reduction by tuning the valve timing. The valve timing only saves 5.3 g/kWh with exhaust gas at 360°Celsius, but it delivers around 550kW more power. We think that it also might be preferable to tune with reduced mass air since it doesn't affect the ME SFOC, but as we mentioned in the background it is hard to tune a 2-stroke marine diesel engine due to the fixed scavenging air ports. This might not be an option for retrofitting an ORC but with future new builds it may be a good choice for improved CCSFOC.

The low temperature ORC is not as efficient as the high temperature, but it still delivers 220-240kW depending on the choice of tuning. The Tuning with constant deltaT on the HTFW is not as good as the tuning where deltaT is decreased. According to our research the efficiency increases when deltaT decreases, also a high deltaT may cause structural damage. We wonder however if it is possible to have 87°Celsius inlet temperature and 90°out. Our calculations can't control this, it might be possible with an increase of HTFW flow but then there might be some physical limitations, such as piping and pumps not being able to supply. However it is quite simple to adjust the temperature regulator on the HTFW compared to high temp ORC tuning.

5.2 Method discussion.

5.2.1 Method

This method was helpful due to the lack of material written about engine tuning and its limitations, concerning marine heavy duty two-stroke diesel engines. Quantitative results via a questionnaire is useful for getting an average of input/output data from different ships and engines (Denscombe, 2009). Varying numbers helps to calculate and to investigate this reports thesis. By using engineers on board ships it is possible to get an input from people with different amount of experience and what limits experienced officers set for their machinery. It would've been very interesting to have done the questionnaire onboard the ships too also get the personal response directly from the engineers, maybe interviews with both quantitative and qualitative results would've been a good method. All though that might have been difficult, it was quite hard to get response from the ships.

5.2.2 Calculation

The calculations in MATLAB that were made are very simple due to the simplified method of modelling. The calculations are made so when we change one input data not all of the data changes like it does in practice, but it is still checked for accuracy with the heat balance. In spite of the simplified method we got data that is trustful and usable in this thesis to get a view of the fact that we can reduce SFOC. The calculations about low temp ORC is reliable because it does not affect the main engines exhaust gas temperature or mass air, only the energy in the jacket water. The values of the jacket water is set in the calculations, deltaT is fixed in the engine to see if what gets most efficient compared to a larger temperature difference. We think that our results can be applied to most vessels, with 2-stroke, since the data that we collected and used for calculations didn't vary that much.

6 Conclusions

6.1 Answers to research questions

The limits for engine tuning are set by multiple factors. The physical limitations are the temperatures of different fluids and gases that are mostly the same for different engines. Mechanical limitations are more specific, older ships does not have the same tuning possibilities as newer ships and engines. Then there are the difference in people. Some ships that answered the questionnaire had different set values then what was recommended by engine manufacturer, lower max values then the recommended maximum.

We found that using a high temp ORC at 360 Celsius with tuning for reduced air lowers a ships SFOC up to 17,1g/kWh, but this might be hard to achieve on older ships.

- Adding an ORC that uses HTFW as heat source lowers the SFOC by 1.8g/kWh. Tuning for an increase in HTFW inlet temperature from 72°C to 87°C reduce SFOC by 2.2g/kWh.
- Adding an ORC that uses the exhaust gas as a heat source lowers the SFOC by 12g/kWh. Tuning for an increase in exhaust gas outlet via less excess scavenging air temperature reduce SFOC by 17.1g/kWh

6.2 Further studies

The authors recommend further development of the MATLAB code. A more complex code that intertwines more between the different equations, thus making the parameters affect one another further. It would also be very interesting to take this thesis into the real world and do a field study on Wallenius Figaro. A field study on a real ship could give some verification of the results.

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Appendix 1 – Questionnaire

Motive:
We aim to find out what the material and environmental limits there is to engine tuning for extra heat recovery.

Name (optional):
Age (optional):
Rank and position:
Name of vessel and machinery:

1. What engine parameters could be changed to achieve more heat at normal running conditions (Air flow, fuel flow, valve timing, injection timing, etc)?

2. What sets the limits for engine tuning? Adjustable parameters, environmental, material and physical (Specifically on this machinery)

3. What is the normal HTFW outlet temp and the max temp for continuous running? Limitations for high/low temp?

4. What is the main engine lube oil inlet/outlet temp? Limitations for high/low temp?

5. What is the scavenge air inlet temp and pressure? Limitations for high/low temp?

6. What is the exhaust gas temp before and after the turbo charger and the max temp for continuous running? Limitations for high/low temp?

7. What is the engine SFOC (g/kWh)?

8. What is your propulsion layout? (Main Engine, gearbox, shaft generator)

9. Where else is there big heat losses that possible could be recovered? For example steam system.

Comments, thoughts, ideas.

Appendix 2 - MATLAB

High Temperature OCR Case

```
function [ output_args ] = energibalance( input_args )
%ENERGIBALANCE Summary of this function goes here
%   Detailed explanation goes here


%temperaturer i Celcius, m in kg/s


% as a first step we calibrate the reference model to fit known data



%adjusted from observed data (ship: ACL) to get 50% fuel efficiency
SFOC = 0.168; %kg/kWh



LHV = 42200; %kJ/kg

T_loIn = 45;
T_loOut = 55;
T_scavAirIn = 25;

%calibrated
T_exhOut = 300;
T_HTIn = 72;
T_HTOut = 80;
T_HFO = 130;

Power = 18400;

cpWater = 4.19;
cpFuel = 1.8;
cpAir = 1.0;
cpExh = 1.04;
cpLO = 1.97;

mFuel = (SFOC/3600) * Power



mAir= 34*mFuel

mExh = mFuel+mAir;

inputFuel = mFuel*LHV
inputAir = mAir*cpAir*(T_scavAirIn)
inputFuelOil = mFuel*cpFuel*T_HFO

eff = Power/(inputFuel+inputAir)

inputEnergy = inputFuel + inputAir + inputFuelOil
```

```
%input      =      mFuel*LHV      +      mAir*cpAir*(T_scavAirIn+273.15)      *
mFuel*cpFuel*(T_HFO+273.15) %kW

Qscav = mAir*cpAir*(170-40)
QHT = 3100/26275 * Power

mHT = QHT/(cpWater*(T_HTOut-T_HTIn))

QLO = 2000/26275 * Power
QRad = 0.01* Power
Qexh = mExh*cpExh*(T_exhOut)

f_Qscav = Qscav/inputFuel
f_QHT = QHT/inputFuel
f_QLO = QLO/inputFuel
f_Qexh = (Qexh-inputAir)/inputFuel
f_power = Power/inputFuel
f_QRad = QRad/inputFuel

% f_Qscav = Qscav/inputEnergy
% f_QHT = QHT/inputEnergy
% f_QLO = QLO/inputEnergy
% f_Qexh = Qexh/inputEnergy
% f_QRad = QRad/inputEnergy
% f_power = Power/inputEnergy

checkSum = f_Qscav + f_QHT + f_QLO + f_Qexh +f_power + f_QRad

output = Power + QHT + Qscav + QLO + QRad + Qexh

balance = inputFuel + inputAir + inputFuelOil - (Power + QHT + Qscav + QLO +
QRad + Qexh)

%tuning
Qexh  =  inputFuel  +  inputAir  +  inputFuelOil  -  Power  -  Qscav  -  QLO  -  QRad  -
QHT

T_exhFunnel = 180;



T_exhOut = Qexh/(mExh*cpExh)


effORCTurbine = 80;

EffORCHT = ORCHighT( T_exhOut, T_exhFunnel, effORCTurbine )/100

PowerORC = EffORCHT*mExh*cpExh*(T_exhOut-T_exhFunnel)

effCC = (PowerORC+Power)/(inputFuel+inputAir)

CCSFOC = (mFuel*3600)/(Power+PowerORC)
```

Low Temperature OCR Case

```
function [ output_args ] = energibalance( input_args )
```

```
%ENERGIBALANCE Summary of this function goes here
%   Detailed explanation goes here


%temperaturer i Celcius, m in kg/s


% as a first step we calibrate the reference model to fit known data



%adjusted from observed data (ship: ACL) to get 50% fuel efficiency
SFOC = 0.168; %kg/kWh



LHV = 42200; %kJ/kg

T_loIn = 45;
T_loOut = 55;
T_scavAirIn = 25;

%calibrated
T_exhOut = 300;
T_HTIn = 87;
T_HTOut = 90;
T_HFO = 130;

Power = 18400;

cpWater = 4.19;
cpFuel = 1.8;
cpAir = 1.0;
cpExh = 1.04;
cpLO = 1.97;

mFuel = SFOC/3600 * Power



mAir = 39.132*mFuel

mExh = mFuel+mAir;

inputFuel = mFuel*LHV
inputAir = mAir*cpAir*(T_scavAirIn)
inputFuelOil = mFuel*cpFuel*(T_HFO)

eff = Power/(inputFuel+inputAir)

inputEnergy = inputFuel + inputAir + inputFuelOil

%input     =     mFuel*LHV     +     mAir*cpAir*(T_scavAirIn+273.15)     *
mFuel*cpFuel*(T_HFO+273.15) %kW

Qscav = mAir*cpAir*(170-40)
```

```
QHT = 3100/26275 * Power

mHT = QHT/(cpWater*(T_HTOut-T_HTIn))

QLO = 2000/26275 * Power
QRad = 0.01* Power
Qexh = mExh*cpExh*(T_exhOut)

f_Qscav = Qscav/inputFuel
f_QHT = QHT/inputFuel
f_QLO = QLO/inputFuel
f_Qexh = (Qexh-inputAir)/inputFuel
f_power = Power/inputFuel
f_QRad = QRad/inputFuel

% f_Qscav = Qscav/inputEnergy
% f_QHT = QHT/inputEnergy
% f_QLO = QLO/inputEnergy
% f_Qexh = Qexh/inputEnergy
% f_QRad = QRad/inputEnergy
% f_power = Power/inputEnergy

checkSum = f_Qscav + f_QHT + f_QLO + f_Qexh +f_power + f_QRad

output = Power + QHT + Qscav + QLO + QRad + Qexh

balance = inputFuel + inputAir + inputFuelOil - (Power + QHT + Qscav + QLO +
QRad + Qexh)

%tuning
QHT = inputFuel + inputAir + inputFuelOil - Power - Qscav - QLO - QRad - Qexh

T_HTOut = (T_HTIn+273.15) + QHT/(mHT*cpWater) - 273.15


effORCTurbine = 80;

EffORCHT = ORCLowT( T_HTOut, T_HTIn, effORCTurbine )/100

PowerORC = EffORCHT*QHT

effCC = (PowerORC+Power)/(inputFuel+inputAir)

CCSFOC = (mFuel*3600)/(Power+PowerORC)
```

EnergyBalance

```
function [ output_args ] = energibalance( input_args )
%ENERGIBALANCE Summary of this function goes here
%   Detailed explanation goes here


%temperaturer i Celcius


% as a first step we calibrate the reference model to fit known data

LHV = 42200; %kJ/kg

%adjusted from observed data (ship: ACL) to get 50% fuel efficiency
SFOC = 0.168; %kg/kWh



T_loIn = 45;
T_loOut = 55;
T_scavAirIn = 25;

%calibrated
T_exhOut = 300;
T_HTIn = 72;
T_HTOut = 80;
T_HFO = 130;

Power = 18400;

cpWater = 4.19;
cpFuel = 1.8;
cpAir = 1.0;
cpExh = 1.04;
cpLO = 1.97;

mFuel = SFOC/3600 * Power



mAir = 39.132* mFuel

mExh = mFuel+mAir;

inputFuel = mFuel*LHV
inputAir = mAir*cpAir*T_scavAirIn
inputFuelOil = mFuel*cpFuel*(T_HFO)

eff = Power/(inputFuel+inputAir)

inputEnergy = inputFuel + inputAir + inputFuelOil

%input = mFuel*LHV + mAir*cpAir*(T_scavAirIn+273.15) * mFuel*cpFuel*(T_HFO+273.15) %kW

Qscav = mAir*cpAir*(170-40)
```

```
QHT = 3100/26275 * Power
QLO = 2000/26275 * Power
QRad = 0.01* Power
Qexh = mExh*cpExh*T_exhOut

% f_Qscav = Qscav/inputFuel
% f_QHT = QHT/inputFuel
% f_QLO = QLO/inputFuel
% f_Qexh = Qexh/inputFuel
% f_power = Power/inputFuel

f_Qscav = Qscav/inputEnergy
f_QHT = QHT/inputEnergy
f_QLO = QLO/inputEnergy
f_Qexh = Qexh/inputEnergy
f_QRad = QRad/inputEnergy
f_power = Power/inputEnergy

checkSum = f_Qscav + f_QHT + f_QLO + f_Qexh +f_power + f_QRad

output = Power + QHT + Qscav + QLO + QRad + Qexh



balance = inputFuel + inputAir + inputFuelOil - (Power + QHT + Qscav + QLO + 
QRad + Qexh)
```

ORC high temp calculation

```
function [ effORC ] = ORCHighT( Tin,Tout,TurbineEff )
%ORCLOWT Summary of this function goes here
%
http://orbit.dtu.dk/files/60269478/Multiple_regression_models_postprint.pdf
% EQ. 4

dTpp=10;
Tc=25;

effORC = -12.76 + 0.06428*Tin + 0.05897*Tout + 0.2576*TurbineEff - 0.127*Tc 
- 0.1556*dTpp;
```

ORC low temp calculation

```
function [ effORC ] = ORCLowT( Tin,Tout,TurbineEff )
%ORCLOWT Summary of this function goes here
%
http://orbit.dtu.dk/files/60269478/Multiple_regression_models_postprint.pdf
% EQ. 2

effORC = -16.32 + 0.08402*Tin + 0.08349*Tout + 0.1583*TurbineEff;
```