Optimization of Waste Heat Recovery on Cruise Ships using Dynamic Simulation

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Master’s Thesis in Thermal and Flow Engineering
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ABSTRACT

The shipping industry is currently facing tightening emission regulations and demands for more efficient cruise ships to demand shipyards to find solutions for increased efficiency and lower emissions. Cruise ships still largely use internal combustion engines using marine gas oil as a fuel source. These engines have large heat losses that could be utilized to increase efficiency.

The largest part of the lost energy is in the exhaust gases, these can be recovered by boilers producing steam, the recovery rate in these is limited by the fuel type and exhaust gas temperature. The second large source for waste heat is in high-temperature cooling water unlike the exhaust gas heat recovery, which is widely used on cruise ships there is large amounts of heat in the HT water being unutilized.

The aim of this thesis was to investigate a waste heat recovery system utilizing HT water as its heat source to find both ways to improve the system and possible problems in the current system. The thesis uses a simulation model to investigate the different heat consumers in the system and the possibility to improve the overall heat recovery rate in the system.

The simulation model was built in Apros dynamic simulation software to mimic an actual waste heat recovery system. The simulation model was built based on an existing waste heat recovery system and validated using measurement data from an existing ship. Different alternative configurations were investigated and the simulations showed possibilities to improve the heat recovery rate in different ways. Key words: dynamic simulation, waste heat recovery, cruise ship, energy efficiency, organic rankine cycle, Apros.
## Abbreviations

<table>
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<th>Explanation</th>
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<tr>
<td>AC</td>
<td>Air Condition</td>
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<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>DG</td>
<td>Diesel Generator</td>
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<tr>
<td>ECA</td>
<td>Emission Control Area</td>
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<tr>
<td>EEDI</td>
<td>Energy Efficiency Design Index</td>
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<tr>
<td>EEOI</td>
<td>Energy Efficiency Operational Indicator</td>
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<tr>
<td>EGB</td>
<td>Exhaust Gas Boiler</td>
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<tr>
<td>GT</td>
<td>Gross Tonnage</td>
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<tr>
<td>HFO</td>
<td>Heavy Fuel Oil</td>
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<tr>
<td>HT water</td>
<td>Cooling water from jacket cooling and the High temperature charge air</td>
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<tr>
<td>IMO</td>
<td>International Maritime Organization</td>
</tr>
<tr>
<td>MGO</td>
<td>Marine Gas Oil</td>
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<tr>
<td>NPSH</td>
<td>Net Positive Suction Head</td>
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<tr>
<td>OFB</td>
<td>Oil Fired Boiler</td>
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<tr>
<td>ORC</td>
<td>Organic Rankine Cycle</td>
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<tr>
<td>WHR</td>
<td>Waste Heat Recovery</td>
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1 Introduction

Environmental consciousness is steadily increasing and pressuring the cruise industry. This affects both the cruise lines as well as shipbuilders. Since both customers and regulations are pushing for more environmentally friendly cruises, cruise lines demand the shipyards to build ships with better energy efficiency. Customers want the cruises to be environmentally friendlier to avoid climate anxiety, and cruise lines are starting to market themselves by how sustainable their operation is. Another matter that pressures the cruise lines is tightening pollution regulations from instances such as the International Maritime Organization (IMO) and the European Union (EU).

Today’s cruise ships can be considered as floating cities with entertainment, dining, shopping, and accommodation for up to 9500 passengers (MV Werften, 2020). All these systems together create a complex system with different requirements such as electricity, heat, cooling, and airflow.

Cruise ships still rely mainly on fossil fuels, such as heavy fuel oil (HFO) or marine gas oil (MGO) in internal combustion engines for electricity production. Internal combustion engines have large heat losses, but by utilizing the produced heat in exhaust gases, high temperature (HT), and low temperature (LT) cooling water, the total efficiency can reach over 95% (Rolls Royce, 2017). Cruise ships have significantly lower total efficiency due to limitations in available space and weight. Another limitation is the lack of uses for HT and LT heat.

This thesis focuses on the utilization of HT water in a waste heat recovery (WHR) system and possibilities to expand the use of heat from cooling water. HT water contains large amounts of energy that can be utilized in other parts of the ship, and by using the heat, the cooling water can be directly circulated back to the engine.

1.1 Problem

The heat produced in the engines is utilized in different ways, such as exhaust gas boilers to produce steam from flue gases and a WHR system for HT water. Even though heat is utilized, there are many weaknesses in the system that limit the recovery
rate. Exhaust gases can only be cooled to a certain point before condensation of sulfuric acid occurs. The problem with the WHR system is that it may both produce more heat than is possible to utilize due to consumer design, which can happen during large engine loads, or that the heat production is too low causing a need for auxiliary steam boilers that increases fuel consumption. Low heat production can occur in port when only one engine is running or during maneuvering, when engines run on low load.

1.2 Objective

The objective of this thesis is to find causes of the low recovery rate of heat as well as testing different solutions computationally for the problems on a cruise ship. The aim is to find means to increase the total efficiency for marine power plants and in this way increase the overall energy efficiency of cruise ships. The goal is to find feasible solutions that can be applied to cruise ships, both to new builds and in retrofit projects for ships in use. Different technologies to improve the heat recovery rate as well as modifications to the layout will be investigated to find solutions and then evaluate them to find the best ones.
2 Background

The international shipping industry is constantly growing, currently corresponding for 80% of international trade. The industry also accounts for 3.1% of global greenhouse gas emissions, and with the current growth of the shipping industry, the greenhouse gas emissions can grow by 50-250% by 2050 without regulations (Liikenne- ja viestintäministeriö, 2019, IMO, 2020b). The growing industry gives rise to a need for stricter regulations on pollution to prevent it from growing uncontrollably. The stricter regulations for emissions and efficiency makes it important for the shipping industry to find solutions to cope with these challenges. One way to increase efficiency without increasing emissions is to recover wasted heat in both exhaust gases and cooling water. Cruise ships are mostly powered by internal combustion engines, which have low efficiency and large heat losses if the waste heat is not recovered. There are different waste heat recovery (WHR) systems available to utilize heat losses from engines. Heat in exhaust gases is already widely recovered through exhaust gas boilers (EGB) and their operation is mainly restricted by the dew point of sulfuric acid when using fuels containing sulfur, as well as size limitations. The EGB uses heat from exhaust gases to produce steam that can be used in a steam turbine or in different systems onboard that require steam heating (MAN Diesel & Turbo, 2014). Some of the traditional steam consumers on a cruise ship are laundry and galleys, but steam is also used for machinery components such as AC-reheating, heating of potable water, and HFO tank heating. Another heat source that can be utilized is high-temperature jacket cooling water and high-temperature cooling of the charge-air (HT). This water usually has a temperature between 85°C and 95°C after the engines, and the heat can be utilized by connecting the cooling water circuit to a heat exchanger and heating a secondary WHR circuit that is connected to heat consumers (Meyer Turku, 2020). The HT water is one of the parts that have a large potential for significant efficiency improvements and this is also the main focus of this thesis.
2.1 Waste heat recovery

Waste heat recovery concerns any use of heat produced as either a side product or heat loss from a process. The heat can be recovered from both gas and liquid phases by different heat exchangers. The largest heat loss from an internal combustion engine is in exhaust gases and HT water. There are also some losses in low-temperature charge-air cooling, lubrication oil cooling, and the rest is lost to the surrounding through radiation from surfaces. EGBs can be utilized to recover heat in flue gases to the dew point of sulfuric acid. The dew point varies depending on the sulfur content of the fuel but is usually around 180°C (Mäki-Jouppila, 2020). Another limiting factor for the EGBs is the pressure in the steam system. The steam system is generally designed to eight bar(g) saturated steam with a temperature around 174°C and outlet temperature from the EGB cannot be below that temperature (Mäki-Jouppila, 2020). Additionally, a certain pinch point is used when dimensioning the EGB to keep its physical size within reasonable limits.

Recovering heat from jacket cooling is preferred because if enough heat can be recovered, the cooling water can be directly circulated and used to cool the engine. If the heat recovered is insufficient, it is necessary to feed in more low-temperature cooling water (LT) to achieve sufficient cooling. By utilizing both the heat from exhaust gases and cooling water, the total efficiency of the power plant can be significantly increased; under optimal conditions, land-based power plants can reach efficiencies over 96% (Rolls Royce, 2017). Marine applications usually have a lower total efficiency due to space and heat requirement limitations.

In marine applications, the HT cooling water heat is used to heat different onboard systems while in land-based power plants the heat is mainly used for district heating. Cruise ships utilize the heat in different systems that require external heat sources to function. Some of the heat consumers are engine preheaters, which keep the jacket of engines that are offline sufficiently warm for starting the engine. Another part that uses large amounts of heat is water heating for both potable water and swimming pool heating. Waste heat can also be used to produce water through evaporators or to produce electricity with an Organic Rankine Cycle (ORC).
Waste heat recovery is a subject that is widely discussed in the shipping industry due to stronger regulations such as the IMO Sulphur 2020 that limited the sulfur content in marine fuels to ≤ 0.5% by January 1, 2020 (IMO, 2020c). There are different ways to minimize the sulfur content in fuels, e.g., using further refined fuels or by using LNG; the latter also reduces CO2 emissions by 10%, but LNG has a methane slip that is estimated to be about 30 times more aggressive than CO2 (Berglund, 2019). This directs the shipping industry to focus on reducing fuel consumption and in that way minimizing emissions: this is where WHR comes into the subject because more efficient fuel utilization means lower total fuel consumption.

2.2 Inefficient heat utilization

The current situation is that the total efficiency of the power plant on cruise ships is in the best-case scenario around 60% (Meyer Turku, 2020). This is much lower than a similar power plant onshore. Although marine and land-based power plants cannot be directly compared this shows that there are still possibilities for improvements on cruise ship power plants. There is much to improve in the utilization of HT water. The main restriction being finding suitable consumers that need heat. There are also difficulties due to the varying conditions that cause fluctuations in the available heat; this can cause both excess heat and insufficient heat for all consumers. Insufficient heat means that heat needs to be produced elsewhere e.g. in auxiliary steam boilers, which increase the overall fuel consumption, for heat consumers that are necessary for operation.

2.3 Emission and efficiency regulations

Cruise ships are facing stricter regulations concerning emissions and energy efficiency. Different authorities that regulate both emissions and energy efficiency.

IMO is a specialized agency of the United Nations responsible for setting standards for safety, security, and environmental regulations for international shipping. The IMO was founded in 1948 in Geneva and activated in 1958. Currently, the IMO has 174 member countries with three associate member countries (IMO, 2020). The IMO first
aimed to prevent oil pollution with OILPOL, but this was quickly amended in favor of a more comprehensive convention for preventing all kinds of marine pollution known as MARPOL.

The operation of the cruise line industry is mainly regulated by the IMO where the main regulator is the MARPOL Annex VI, since 1997 has set limitations for air pollution. The main pollutants regulated at the time are nitrous- and sulfur oxides. More recently, there has been further progress with stricter regulations as well as new regulations for greenhouse gas emissions and energy efficiency. There are three different initiatives to limit greenhouse gas emissions: Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP), which both are required, while the Energy Efficiency Operational Indicator (EEOI) is optional (IMO, 2020a). EEDI is the main regulator in the design and construction phase and it is mandatory for all new cruise ships. The EEDI regulates CO\(_2\) emissions per capacity-mile of the ship expressed as

\[
EEDI = \frac{C \cdot P \cdot SFC}{m_{GT} \cdot v_{ref}}
\]

where C is the carbon emission factor [g CO\(_2\) / g fuel], P is power output [kW], SFC is the specific fuel consumption [g/kWh], \(m_{GT}\) and \(v_{ref}\) is the designed speed. The minimum EEDI that is required by IMO is tightened every five years until 2025 so that the CO\(_2\) emission value for 2025 will be reduced by 30 % compared to 2000-2010 (IMO, 2013).

SEEMP is a manual for the operators and ship owners establishing a way to monitor ship efficiency and to operate the ship in an energy-efficient manner. All ships are required to have their own specific SEEMP.

EEOI, in turn, is an index for the design phase. It is based on operational data and is used by ship owners and operators to monitor the ship’s performance and thus to run in a cost-efficient manner, lowering greenhouse gas emissions. It is calculated by

\[
EEOI = \frac{C \cdot SFC}{m_{GT} \cdot D}
\]
where D is the distance traveled. The index is used to promote efficient and low emission shipping as a voluntary measure (IMO, 2009).

In addition to the three energy efficiency initiatives, the IMO also sets regulations for both NO\(x\) and SO\(x\) as well as particle emissions. An example of these restrictions is *Sulphur 2020*, which requires the sulfur content in fuels to be decreased from 3.5 % to 0.5 %. The sulfur content has already been controlled in emission control areas (ECA) and from January 1st, 2020 it is also controlled outside ECAs. Figure 1 shows how the emission restrictions have developed with different regulations. Figure 2 shows the different ECAs and also potential future ECAs (IMO, 2020).

**Figure 1** MARPOL Annex VI restriction levels for SO\(x\) and PM emissions. (Pirttikangas, 2016)
In addition to the regulations from the IMO, the cruise lines set their own requirements for the shipyards that are often stricter than those imposed by the IMO. These requirements are set to achieve different sustainability and emission goals and to minimize the environmental impact. The ship owners also benefit economically from setting efficiency regulations since these can directly have an impact on fuel consumption. Another advantage of emission restrictions is that customers are getting more environmentally conscious, which forces the ship owners to buy better ships with improved technologies.

### 2.4 Auxiliary boilers

Different kinds of heat are required for different purposes on cruise ships. Thermal energy is primarily provided as steam and HT water, mainly produced from waste heat from engines. If the heat recovered from engines is insufficient, an auxiliary boiler is required to produce additional steam to cover the shortage of heat. Even though auxiliary oil-fired boilers (OFB) are required as a back-up, their use should be avoided.
to minimize additional fuel consumption. The goal is to recover enough heat so it is unnecessary to use the OFB, and that all heat come from WHR. It should also be kept in mind that the OFB operation also increases air pollution, so also in this respect a minimal OFB use is preferred.

The auxiliary boilers on a cruise ship account for about 3-5 % of the total fuel consumption. Fuel costs account for around 15 % of the total operating cost for cruise lines, so lowering the auxiliary boiler usage even by 5 % would result in a significant savings for the cruise lines (RCCL, 2018).
3 Combined heat and power plants

Combined heat and power (CHP) plants differ from conventional power plants in that the heat produced at power production is utilized. In conventional combustion power plants, the electricity generation efficiency is 30-50%, which means that large amounts of energy are lost in the form of heat released to the environment (Anonymous, 2007). CHP plants, also known as cogeneration plants, utilize this heat either for heat consumers or for additional electricity production. Utilization of heat can increase the total efficiency significantly and in the best cases even above 96%. (Rolls Royce, 2017) CHP comes in many different sizes with different configurations designed for its specific use, and the heat can be used for a variety of consumers. The size of CHP plants ranges from small plants for individual houses, up to large power plants providing both electricity and district heating for cities. CHP plants have a long history and have been used since the late 19th century. During the 20th century, cogeneration grew and has been used for different applications mainly for electricity and heat for industries. During the late 20th century and early 21st century, CHP plants grew significantly due to their high efficiency and increasing demand for efficiency with regulations (Breeze, 2014). In Figure 3, the prediction for the future is shown that the utilization of cogeneration will grow significantly in the future and become increasingly important.

![Figure 3 Share of CHP of the total electricity production in G8+5 and an estimate for 2030. (Thorin, Sandberg & Yan, 2015)](image-url)
Another reason for turning to cogeneration plants is increasing fuel prices combined with the stagnation of efficiency improvement of conventional power generation. Figure 4 shows a schematic of how a CHP plant can save fuel, showing that the possible fuel saving can be substantial. Utilizing CHP plants minimizes the losses especially in situations when there is a need for heat nearby the power plant. The figure shows that when there is need for both heat and electricity a CHP plant can minimize the losses from electricity production by utilizing waste heat.

Figure 4 Difference in fuel consumption between producing heat and electricity in a CHP plant and two different plants, a) shows a simple steam turbine CHP plant, b) shows two different plants required to produce the same amount of heat and electricity. (Thorin, Sandberg & Yan, 2015)

3.1 Working principle

The basic idea is to produce both electricity and usable heat through a combustion process. CHP plants can work with a range of fuels and systems. The main matter that unites the different systems is a process that produces heat as a side product. The system can either be a combustion process or some other that produces heat, e.g., solar thermal plants and geothermal plants. The combustion power plants can use a variety of fuels ranging from fossil fuels such as oil or coal to biomass or waste (Thorin, Sandberg & Yan, 2015). There are multiple ways to extract heat from the process, extracted e.g., from exhaust gases produced in the combustion process or from the
cooling system. The largest source of heat in combustion plants are exhaust gases. The heat from these gases can be utilized by an exhaust gas boiler to produce steam. The steam can then be used for electricity production and steam heating of other processes. Another heat source is cooling processes, e.g., engine cooling water and charge air-cooling. The heat recovered is divided into three main groups; steam, HT water, and LT water. The steam is usually the largest source of utilizable heat. The steam can be used for a variety of different consumers. HT and LT water from land-based plants are mostly utilized for district heating, while in marine applications both HT and LT water have a variety of uses since there are several heat consumers onboard. The steam produced can be utilized in industrial processes as well as in a steam turbine to produce additional electricity. The HT water can in addition to district heating also be used for electricity production by using an Organic Rankine Cycle unit (Thorin, Sandberg & Yan, 2015).

### 3.2 Marine applications

In marine applications, it is more difficult to utilize as much heat due to size and weight restrictions. Another big restriction is the fuel, which has been HFO for a long time; HFO has a relatively high sulfur content, which restricts the amount of heat that can be recovered from exhaust fumes due to condensation of sulfur oxides, which reacts into sulfuric acid (Merriman, 2020). The sulfuric acid has an aggressive corrosive impact on the steel piping and in the construction of the exhaust gas system.

The largest difference between land-based and marine applications is the use of the produced heat. Marine applications, and especially the cruise lines, have many onboard systems that require heat to operate. Cruise ships are usually equipped with an exhaust gas boiler to produce steam; the steam is used in a variety of systems. The steam produced is used in several machinery systems such as pipe and tank heating, and also for galleys and laundry. Cruise ships also utilize both HT and LT water extracted from engine cooling, HT heat is used as a heat source for systems that require lower value heat such as freshwater production, AC-reheating, and potable water heating, etc (Meyer Turku, 2020). Some of these consumers also have a steam connection as a backup if the HT water is insufficient. Cruise ships are also equipped with auxiliary
boilers to provide steam whenever the steam and HT heat recovered from engines are insufficient.

Figure 5 illustrates the fuel conversion for a marine power plant, showing that over half of the fuel energy is converted to other energy forms than to electricity in the generator (MAN Diesel & Turbo, 2014).

Figure 5 Sankey diagram for fuel consumption in a marine power plant. (MAN Diesel & Turbo, 2014)

Figure 6 shows an example diagram of a marine waste heat recovery system with a dual pressure steam system and a steam turbine for additional electricity production. This system only utilizes the exhaust gas for additional electricity production which still leaves the HT water unutilized (MAN Diesel & Turbo, 2014).
Figure 6 Schematical diagram of a MAN waste heat recovery system. (MAN Diesel & Turbo, 2014)
4 The waste heat recovery circuit

The WHR circuit on the reference ship uses HT cooling water extracted from jacket cooling water and charge air-cooling from the main engines to produce utilisable heat for different consumers. The waste heat recovery circuit works according to the principle to increase the total efficiency of engines together with utilizing waste heat as a heat source for consumers. Many onboard consumers can utilize HT water as a heat source, for example freshwater production and water heating (Meyer Turku, 2020).

The system is divided into two main groups: heat production and heat consumption. The production is mainly heat recovered from main engines; each main engine is equipped with a heat exchanger that extracts HT water from jacket cooling and charge air-cooling (Meyer Turku, 2020). The reference ship of this work is equipped with one circulation pump per main engine controlling the circulation for the whole system. Each engine is also equipped with an engine preheater that utilizes HT water as a heat source (Meyer Turku, 2020).

The efficiency of the system is calculated by comparing the produced heat and the total heat consumption in the WHR circuit. The larger the difference between two the more heat is recovered in the system, i.e., higher efficiency. Currently, the efficiency of the system is low and the return temperature is too high to efficiently cool the engines by the WHR system (Meyer Turku, 2020).

4.1 Heat recovery

The source for the heat in the system is the main engines, and the system is connected to the cooling water circuit through a plate heat exchanger. The heat exchanger is connected to the fresh cooling water circuit to extract heat from the cooling water. Each main engine heat exchanger is equipped with a circulation pump that runs whenever the corresponding engine is running. The pump ensures that the flow
through the heat exchanger and circulation through the whole system are sufficient (Meyer Turku, 2020).

4.2 Preheaters

One of the main consumers that use HT heat from the WHR circuit is the main engine preheaters. The preheaters provide heat to the engine jacket for engines that are not in use: the engines are heated to keep a base temperature in the engine jacket to avoid large temperature increases in the engine when fired up. The engine preheaters are usually a part of the engine itself. The preheaters are used to ensure that the engine jacket has sufficient temperature for firing since heating an engine at 20°C to 60-70°C would take 10-15 hours. The preheaters are equipped with their own pump that is started either when the jacket temperature drops below a certain point or when the corresponding is turned off. The engine preheaters are generally small consumers of heat with a consumption of around 6 kW per cylinder (Wärtsilä, 2019).

4.3 Evaporators

One of the largest consumers of recovered waste heat is freshwater evaporators. Freshwater evaporators use HT heat to evaporate seawater and then condense the vapor to produce fresh water. The freshwater evaporators on the reference ship are of single-stage type, which means there is a single circuit that first evaporates seawater with a heating medium and then condenses the vapor using sea- or cooling water (Meyer Turku, 2020). Figure 7 shows the two circuits included in a single-stage freshwater evaporator with the heating circuit connected to the WHR circuit on the bottom and the condensation stage connected to a seawater cooling circuit. Freshwater evaporators also work under a vacuum to decrease the vaporization temperature for seawater lowering the needed temperature of the heating medium, which in the present case is HT water. The evaporators are equipped with their own circulation pump to ensure sufficient flow through the evaporation part. There are also pumps for seawater, cooling water circulation, and a distillate pump. The cooling circuit uses seawater that absorbs heat from the condenser and is then circulated as feed water to the evaporator (Marineinbox, 2019).
Freshwater evaporators are only used when the ship is at least 20 nautical miles from shore; this is to avoid bacteria and other pollutions from, e.g., factories and sewage, which can be present in seawater closer to shore (Chopra, 2019). These pollutants may foul the inside of the evaporator or pollute the freshwater. The freshwater evaporators are one of the largest consumers of heat in the WHR circuit, requiring around one MW of heat each to produce around 33 m³ per day (Wärtsilä, 2018).

![Working diagram of a single-stage freshwater evaporator.](Marineinbox, 2019)

**Figure 7** Working diagram of a single-stage freshwater evaporator. (Marineinbox, 2019)

### 4.4 AC-Reheating

AC reheating is another important consumer of HT heat. The AC reheating circuit is equipped with two heat exchangers one connected to the WHR circuit and one steam heat exchanger which is used as redundancy for whenever the HT heat is insufficient. The AC-reheating works by heating AC-air that is cooled below the set-point temperature back to the set-point temperature to avoid condensation in the air ducts.
and on other cold surfaces and also to avoid cold spots in air outlets. The reason for first cooling the air below the set-point is to condensate water vapor in the air and then reheating the air to lower the relative humidity in the air. As an example cooling air to about 12°C before reheating to 23°C would result in a relative humidity of 50-60 %.

This is especially important in regions with high temperatures, high humidity since cold air has a lower saturation level than warmer air, and just cooling air causes condensation (Meyer Turku, 2020).

The AC-air is cooled a few degrees below the set-point temperature to saturate the air and condensate water from the air in a controlled environment. The cooled air is then heated to the set-point value with an AC-reheating circuit connected to two heat exchangers; one for the WHR circuit and one for steam heating. The average heat consumption for the AC-reheating is around 300 kW from waste heat and roughly the same from steam heating (Meyer Turku, 2020).

The flow through the WHR heat exchanger is controlled with a three-way valve that controls the temperature in the AC-reheating circuit by bypassing a part of the flow through the heat exchanger. The AC-reheating also continuously uses small amounts of steam heating to maintain a certain flow in the steam pipes and to avoid steam hammers that can occur when there is condensation in steam pipes (EnggCyclopedia, 2012).

### 4.5 Hot potable water

Hot potable water (PW) preheating is another system that can utilize HT heat from the WHR circuit. The potable water heating circuit can utilize both steam and HT water as a heat source depending on heat requirements and availability. The system includes two preheaters with one utilizing steam and one for HT water from the WHR circuit. The WHR circuit heater uses a three-way valve in the WHR circuit to control the bypass of the heat exchanger and controlling the temperature in the hot PW circuit. The hot potable water preheater is the second-largest consumer of waste heat, consuming between 300 kW and 600 kW of heat (Meyer Turku, 2020).
4.6 Reverse Osmosis units

Reverse osmosis (RO) units are utilized on cruise ships to produce potable water from seawater. RO units use pressure to force water through a semi-permeable membrane that stops salt and other impurities. The RO units have two stages of filtration: first, the seawater passes through a sand filter before the reverse osmosis membrane. The first filtration removes impurities to minimize the fouling of the RO membrane (Meyer Turku, 2020). The efficiency of the RO units is affected by the temperature of the seawater, where a higher temperature increases the efficiency of the unit. Figure 8 shows a simple diagram of the working principle of a RO unit. Saltwater is pumped to increase the pressure on the left through a semi-permeable membrane, which removes salt and other contaminants. Freshwater passes through the membrane and is then pumped to freshwater tanks. (Puretec, 2020)

**Figure 8** Simple illustration of the working principle of reverse osmosis. (Puretec, 2020)

Figure 9 shows a more detailed diagram of a RO unit. The feed water is pumped to the RO-unit at high pressure to force a part of the water through the membrane while salt
and other contaminants go into a reject stream containing brine and other contaminants. (Puretec, 2020)

![Diagram](image)

**Figure 9** Detailed drawing of the working of a RO-unit. (Puretec, 2020)

The reverse osmosis units are connected to the WHR circuit by a plate heat exchanger with own circulation pumps. The WHR heater is used to heat the seawater when the temperature drops below 15°C to maintain a certain efficiency of freshwater production (Meyer Turku, 2020). The RO unit heating is mainly used in colder areas because at a certain temperature the energy required to heat the water is higher than the gain inefficiency.

### 4.7 Swimming pool heating

Swimming pools are the last consumer that utilizes waste heat as a heat source on the reference ship. Swimming pool heating is a smaller consumer in the circuit but utilizing HT water as a heat source lowers the need for steam. The swimming-pool heating system consists of a plate heat exchanger and its corresponding circulation pump to ensure sufficient flow through the heat exchanger (Meyer Turku, 2020).

### 4.8 Organic Rankine Cycle

An Organic Rankine Cycle uses excess heat from different processes to produce electricity. ORC units have been used since the 1980s providing a solution for a broad range of systems working in a large range of temperatures and power output (Gas Technology, 2015).

The heat utilized evaporates an organic fluid or refrigerant. Figure 10 shows typical fluids used in ORC units. The gas then passes through a turbine connected to a
generator. The turbine turns the gas from high pressure to a low-pressure gas, which is then condensed (Quoilin et al., 2013).

**Figure 10** $T$–$s$ diagram of water and various typical ORC fluids. (Quoilin et al., 2013)

In marine applications, seawater is used as a cooling medium while in other cases there is a need for some other cooling medium. The liquid is then circulated through a pump back to the evaporator. Figure 11 displays two different possible configurations for ORC units. The organic liquid is used due to its low boiling point making it utilizable to produce electricity from heat sources of lower temperatures. ORC units have a working temperature ranging from 80°C to 300°C. There are extreme cases where a steam Rankine cycle needs temperatures over 400°C to work properly (Quoilin et al., 2013). The working principle behind an ORC is the same as for other Rankine-cycle power plants. The only difference is that the working fluid is an organic fluid instead of water, which is used in traditional power plants. The organic fluid or refrigerant is circulated in a closed loop (CLIMEON, 2019).
ORC units can be utilized in different processes where excess heat is available. The advantage of ORC units is the broad spectrum of temperatures of the heat source that can be utilized, including quite low temperatures (Quoilin et al., 2013).

4.8.1 ORC in WHR applications

Many industries have access to excess heat at relatively low temperatures. Larger industries usually also have an abundance of heat, i.e., more than what is used for district heating, and this heat is usually released to the environment. The lost heat is mostly heat from flue gases and heat from cooling of processes (Quoilin et al., 2013). Utilizing the otherwise lost heat could also have a positive effect on emissions in the exhaust gases, or heat in cooling water that may affect the environment by disturbing the natural equilibrium.

The lost heat from industrial processes can be utilized in an ORC unit to increase the total energy efficiency. The heat consumption for the reference ORC unit varies between 700 kW and 1400 kW. (Climeon, 2017)
5 Data analysis

In this work, a reference ship was used to study the feasibility of the proposed concepts. As a reference, a mid-sized cruise ship equipped with four main engines in the electrical power plant, two larger and two smaller ones with a total power of 48 MW utilizing HFO or MGO as its main fuel (Meyer Turku, 2020).

Based on the collected data, system flaws were found that indicated problems in the energy recovery rate. This was the starting point of the work in the thesis, with the aim to further investigate the problem to find the reason for the low recovery rate. An analysis of the system showed that in conditions when evaporators are in use the water returning seems to collect heat in the circuit. The data available includes temperature measurements between each group of consumers and on both sides of the engine. Other measurements available was water flow rates in the system and some temperature measurements on the receiving sides. There are some deficiencies in the data, mostly due to the lack of actual measurements. The lack of measurements causes problems in detecting inefficiencies as every component does not have its own measurements. Another problem that was revealed was the lack of flow measurements, which means the heat transferred in single heat exchanger cannot be calculated without measurements from the consumer circuit.

Analysis of the system first confirmed the initial hypothesis, i.e., that the AC-reheating circuit is worked in reverse and fed heat to the circuit when evaporators were in use. The problem was further investigated by analyzing both the steam consumption for AC-reheating and the temperature difference of the AC-reheating over the WHR heat exchanger. This analysis showed that the heat exchanger worked according to design and that it was the measurement in the WHR circuit that was faulty. Further investigation revealed that the temperature sensor was misplaced giving misleading information and causing inaccurate calculations of heat consumption in the AC-reheating heat exchanger. The analysis also showed that the steam heat exchanger was used continuously which further lowered the heat consumption from the WHR circuit. The reason for the steam consumption was, as mentioned above, to prevent steam hammers.
A main conclusion that can be drawn from studying data from the reference ship is that the HT heat recovery rate is good whenever only one main engine is running. The system was found to work well under these circumstances. This also indicates that when additional main engines are running the heat production is significantly higher than what the system can consume. The best solution for this would be to find additional consumers for the system, either systems that currently consume steam and could be modified for using HT heat instead, or adding additional heat consumers such as heat pumps or ORC units. The problem with adding heat consumers is that either these need to work properly with fluctuations in the heat available, e.g., by switching them off when there is insufficient heat or they need to work at variable loads. Another possibility is to connect a steam booster to the system, which ensures that enough heat is always available. A steam booster works by adding a heat exchanger that utilizes steam to add extra heat to the WHR circuit. This can work well in situations where heat from steam would otherwise be dumped into the environment. However, problems may occur when there is insufficient steam available. Then an OFB must be used to produce steam, which works against the idea of WHR.
6 Simulation set up

By conducting dynamic process simulation analysis, it is possible to examine the behavior of a system without an actual counterpart. The simulations also give the user the possibility to examine alternative solutions to existing systems without the need to alternate the actual system. The simulations furthermore gives insight into different system components, which can be used to find possible inefficiencies in actual systems. Simulation can be divided into steady-state and dynamic simulations. Dynamic simulation offers variability in the system giving insight into accumulation of mass and energy in the system, which a steady-state model can not provide.

Dynamic simulation models are based on differential equations that are solved numerically. Dynamic simulations have a wide spectrum of uses such as proving the applicability of a concept, developing a system, automation tests, safety tests, and more. (Barton, 1997)

A variety of dynamic simulation tools exist for different uses. A few examples are Aspen plus for the chemical industry and MathWorks Simulink which is a more general simulation tool. (MathWorks, 2020; Aspen Tech, 2020)

6.1 Apros simulation software

Apros is a dynamic simulation tool designed by VTT and Fortum for the thermal power plant market. Although this is the primary focus of Apros, the tool may be used to simulate different power plants and other processes as well. Apros simulation software provides a large library of prebuilt components in addition to providing the user with the possibility to create user-built components. The software has a graphical interface providing an easy to-use- and customer-incorporable model. This gives the user the possibility to integrate own models, making the tool suitable for, e.g., operator training. Figure 12 shows a model process diagram from Apros displaying some of the components of the built-in library. The large library in combination with the possibility to configure the components makes the software viable for many different industrial purposes. The software has advanced dynamic calculators to mimic real components (Tuuri, Paljakka).
Apros software offers users an opportunity to simulate both individual components and larger systems to create an overview of the process conditions. The broad spectrum of components and adaptability gives Apros usability in many fields and applications. Apros 6 thermal was chosen as the simulation tool because of the extensive library for process and automation simulation suitable for marine power plants. (Tuuri, Paljakka)

Apros simulations require component specifications to model the system properly. Specifications for pipe and heat exchanger dimensioning are based on an existing ship and pumps are set-up according to pump curves and specifications. The automation can implement different control loops and strategies, e.g., proportional–integral–derivative (PID) controllers with commonly used parameters.

### 6.2 Components

The components of the simulation model mainly consists of heat exchangers and pipes, and a set of valves that control the flow through the components. The engines are connected to a model of the cooling system from which the heat is extracted. The system also has four circulation pumps but there are also smaller pumps for certain consumers to ensure a desired flow through these units. All pumps were set up by the
head, net positive suction head (NPSH) and efficiency curves to mimic the reality as close as possible.

6.3 Consumers

All the consumers in the simulation model consist of a heat exchanger modeled according to the conditions in the reference ship. The simulation software gives the user the possibility to configure all parts of the heat exchangers to match the specifications from the reference. All consumers also have automation to control both the water flow and the heat transferred. The heat consumption for the different consumers were largely based on assumptions from component specifications and temperature measurements from the system. One exception was the AC-reheating, which had measurements from the heat-receiving circuit from which calculations could be made.

6.4 System configuration

In addition to heat generators and consumers, the system also contains pipes and valves that control the flow of water in the system. All pipes and valves in the simulation were set up according to the specifications of the reference ship to mimic the actual system as well as possible. Still, some simplifications were made. Mainly pressure losses from turns and pipe elevations were disregarded due to lack of data from the reference ship. Other assumptions that were made were system pressure and pressure losses in the components and valves due to the lack of pressure measurements on the reference ship.

6.5 Automation

The heat and water flow for the different components are controlled by an automation system that controls both controller valves and three-way valves, three-way valves are not a part of the Apros so it is made from two control valves automated to work as a three-way valve which can be seen in Figure 13. The controllers are set up according
to set points from the reference ship and specifications by the supplier. PID controllers from the built-in Apros automation library were used. The controller utilizes either a temperature or a flow measurement as input value and controls an actuator connected to either a valve or pump to reach a set-point value. The automation for certain components such as engine heat flow and heat consumption for components were automated using data tables utilizing certain input values based on ship specifications. For instance, engine heat flow uses engine load to calculate waste heat production according to specifications by the manufacturer. The controller can utilize both a set-point set by the user or measurements from the system as a set-point value.

Figure 13 Example of an Apros automation model controlling a three-way valve

6.6 Model set up

The model of the system was created using the built-in graphical user interface. Apros contains a large library of process and automation components that can be easily added to the diagram by the drag-and-drop method. These components then only need to be configured to specifications given by the user, which in the present case were the specifications from the reference ship. The model requires some assumptions to avoid excessive set-up work and long computation time. Creating a connected diagram for all possible components in the real system would make the model too large since this would include an extensive number of different subsystems. To simplify the matter,
some components are only considered to work according to specifications do not take into consideration other circuits they are connected to.

The waste heat recovery circuit model considers one supplier part and three consumer parts. The supplier part consists of one heat exchanger for each main engine and its own circulation pump; these pumps are responsible for the circulation for the whole system. The simulation uses heat data based on engine load and actual measurements. The heat exchangers are plate heat exchangers designed according to engine size. The corresponding pumps are of constant-speed type, designed to run whenever the engine is running.

All piping is dimensioned according to the pertinent values for the reference ship, and all valves are located according to the positions in the actual drawings. Some simplifications are still made mainly in the lengths and elevations of the pipes.

The biggest challenge in building the model is for settings that are manually adjusted in practice, such as control valves. As these settings are done manually on the spot, information about the settings is not available without visiting the ship. Furthermore, due to insufficient measurements on the reference ship, it is challenging to obtain a good overview of the performance of the actual system.

Figure 14 shows a simplified scheme of the WHR circuit showing the different measurements points that are available in the system. The main available measurements in the system is the inlet and outlet temperature from the engines together with the water flow rate in the circuit. There are also a few local temperature measurement onboard for the different consumers in the circuit.
Figure 14 Simplified scheme of the WHR circuit.
7 Model analysis

The study to be presented concerns three different modifications of heat recovery designed to improve the current setup. The idea is to compare data from an actual cruise ship and a validated model to find the best applicable improvements.

The study includes four different test cases, each designed as an alternative configuration to the current layout. The different alternatives are studied as a system: In practice, the feasibility may be constrained due to piping and space limitations on board; such matters are not considered in the simulation. The original plan was to find a solution for the heat transfer from the AC-reheating circuit to the WHR circuit. The revelation of the misplaced measurement lead to a re-focusing of the study, but the initial problem was still examined to determine how the proposed alterations would affect the system. Due to a lack of measurement, the study was also focused in finding problems or inefficiencies in the system. One plausible explanation of the low recovery rate was that heat consumption is not sufficient to recover the available heat. The possible solutions for better utilization of the heat is to either find additional systems that can utilize HT water as a heat source, or to add consumers such as an ORC to produce electricity. Yet another possible solution is to modify the current consumers to utilize more heat.

7.1 Validation model

The validation model uses the configuration of the reference ship and actual cruise data collected from the onboard system. The accuracy of the Apros 6 simulation is validated using data collected from the reference ship. Since the system is based on a reference ship in use, validation can be done to set up a reliable model to find suitable solutions to problems. Although there is limited collected data from certain parts of the ship, the data give a good overview of the system. The limited data however complicates the validation of the operation of certain components and their consumption. Since the measurements are limited, the system is validated on larger entities instead of on the component level. As validation data, a time period over two months was chosen to include variation in loads and ambient conditions to give the
model credibility. The data were collected from the onboard data collection system with a collection interval of one minute.

To validate the model the engine power and information on which consumers were running were used as input data. The validation used a data set of two months to ensure that the system works well under variating circumstances and engine loads.

Figure 5 and Figure 16 show the engine power for the reference data, the figures illustrate that the reference ship works under variating loads during the validation period.

![Engine loads for DG 1 and 2 for the validation data.](image)

**Figure 15** Engine loads for DG 1 and 2 for the validation data.

The validation data also show large variations in engine loads which is due to both variations in route and ambient conditions. Another factor that impacts engine loads is if the ship is at sea or in port. In addition to the engine loads, the running hours for the different heat consumers and ambient conditions, such as seawater and ambient temperature. Holding one-minute average, the validation data has 87 120 data point, which gives a good view of variations in the system.
Figure 16 Engine loads for DG 3 and 4 for the validation data.

The model in Apros was built to describe the WHR circuit on the reference ship. To validate the simulation model, it was run using the operation data as input to simulate the same conditions as the reference ship experienced and the results were compared for validation. To compare the validation and the simulated data, a relative error was used to express the difference between the two

$$\delta = \frac{\Delta x}{x},$$

where \(x\) as the measured output data and \(\Delta x\) the absolute error given by

$$\Delta x = x_{\text{sim}} - x,$$

where \(x_{\text{sim}}\) is the simulated value of the output. To observe the error over a longer time the cumulative relative error

$$\delta_{\text{cum}} = \frac{\sum \Delta x}{\sum x},$$

where the sums are taken over all observations in the validation data. These calculations are used to display how well the simulation model represents the system.

To validate the model, certain critical measurement points where used as “outputs” to demonstrate that the simulated system can mimic the conditions in the reference ship.
The measurement points used to validate the model are the incoming and outgoing temperatures as well as the flow rate of the WHR circuit.

Figure 17 and Figure 18 compares the simulated and observed temperatures. Figure 17 shows that the simulation follows the measurement of the outlet temperature from the engines with a few differences, which are mostly short spikes. The relative error generally falls between -0.05 and 0.05, which means that the model is fairly accurate. Some of the spikes exceed the acceptable range, but these generally occur when the engines are switched on and the simulated temperature drops more than the measured temperature. Figure 18 shows somewhat larger deviations where the simulated temperature is lower than the measured one. A lower return temperature means that the heat consumption is larger in the simulation than in the reference ship. A cause for the variations may also be the lack of measurement on the reference ship that causes uncertainty in the actual consumption of the components, which complicates the comparison.

**Figure 17** Comparison of the outlet temperature from engines to the WHR circuit from the simulation and the validation model and the relative error between validation data and simulation.

The cumulative relative error for the outlet temperature is 2.6 %, which shows that the model works well over a longer period. Similarly, the inlet temperature shows a cumulative relative error of 2.8 %, which is very good considering that the largest problems are individual peaks while the model generally works well.
Figure 18 Comparison of the simulated inlet temperature from engines to the WHR circuit and the validation data and the relative error between validation data and the simulation.

There is a slightly larger deviation between the model and the measurements of the flow rate in the system, which can be seen in Figure 19. The simulated value is slightly lower than the observed value, especially at higher flow rates. Due to this systematic error, the flow rate was investigated further. The analysis revealed that the flow was significantly higher than the design flow rate. The higher flow rate might be caused by a small flow through the engines that are not running. The average relative error for the flow rate was 4.7 % and the cumulative relative error was 2.8 %, which shows that the simulation still represents the system very well.
Figure 19 Comparison between flow rate for the validation data the simulated values and the relative error.

Based on the results of the validation runs, it can be concluded that the simulation model can describe the conditions in the reference ship very well. The largest differences between the simulated and observed variables were short spikes in the flow rate through the system and in the temperatures at engine switches. Except for these, the differences between the simulated and observed variables were generally small.

7.2 Moving the return pipe connection point from the evaporators

The first optimization test alters the configuration of the WHR system to find a more efficient heat utilization while still ensuring sufficient flow for all consumers. Alternating the configuration can increase the available heat for consumers that have larger heat requirements. The idea is to move the return from evaporators and engine preheating returns after the AC reheating to ensure that AC reheating receives sufficient heat so steam use would be unnecessary. Figure 20 shows the suggested alteration to the WHR circuit with the bypass pipe connected to the outlet from evaporators and engine preheating with an additional three-way valve.
The modification was made by adding a three-way valve and an additional pipe that moves the return from evaporators and preheating. The three-way valve that can be controlled by a temperature measurement placed in the return ensures that the water entering the AC reheating has enough heat so that steam heating is not required. Further analysis of the system showed that the temperature measurement for the inlet to the AC-reheating was faulty at the reference ship, causing errors in the measurement data for the AC-reheating circuit.

**Figure 20** The proposed alteration of moving the return point from evaporators and engine preheating.

By bypassing the AC reheating, the system can utilize heat more efficiently by ensuring that the inlet temperature to the AC-reheating heat exchanger is high enough in situations where the heat production is low or where there are large consumptions by evaporators and engine preheating.

Figure 21 illustrates the inlet temperature to the AC reheating before and after the change. This figure shows that moving the return point does not impact the inlet temperature to the AC reheating in situations when the inlet temperature is over 80°C, but in situations when the inlet temperature would drop below 80°C in the current configuration the temperature stayed above 80°C with the modified design. Figure 22
shows that moving the return from evaporators and engine preheating after the AC reheating does not affect the heating of the AC reheating significantly.

**Figure 21** Inlet temperature to the AC-reheating with and without the moving return line connection point.

**Figure 22** Heat consumption for the AC reheating and difference between the moved return and without it.

From this, it can be concluded that moving the return from evaporators and engine preheating returns after the AC reheating can be a viable alternation to the system to increase system efficiency and to ensure that the AC reheating receives enough heat.
to function. Figure 23 also shows that the system experiences an increase in heat utilization by moving the return point.

![Figure 23: Temperature difference over the WHR circuit with and without the AC bypass.](image)

**Figure 23** Temperature difference over the WHR circuit with and without the AC bypass.

### 7.3 Offsetting the AC-reheating design temp

The AC reheating is controlled to a certain set point with a certain amount of heat from waste heat and the rest from steam. The steam heater is constantly used to keep a certain steam flow in the steam pipes to avoid steam hammers. When analyzing the measurement data for the AC reheating system, it was found that the outlet temperature never exceeded 70°C.

The simulation was designed to analyze if the WHR circuit has enough heat to supply the AC reheating without steam heating as this would lower the steam consumption. Steam heating could then be used only as a failsafe for the WHR system.

The modification was implemented by artificially changing the measurement data of the AC reheating by increasing the outlet temperature by 2 °C to consider the steam heating part. The increased temperature will cover the heating that would normally be supplied by steam heating.

Figure 24 shows the heat consumed in the AC-reheating heat exchanger with and without steam heating. By increasing the outlet temperature for the AC reheating, the
heat consumption is increased significantly, which can both be beneficial and harmful to the overall system. By increasing the heat consumption of the AC-reheating, the total heat consumption for the circuit is increased simultaneously increasing the total heat recovery rate. A setback can be that the heat for the end consumers will be insufficient, causing them to require additional steam heating, possibly off-setting the overall benefit.

**Figure 24** Heat consumption for AC-reheating for the original model and the model with steam heating replaced by WHR.

Figure 25 shows that by only utilizing WHR-heating, about 300 kW of steam could be saved. The additional heat consumption also lowers the temperature in the rest of the system. However, the 300 kW increase in heat consumption would not decrease the temperature lower than what is needed for the end consumers. There are some spikes in the data, probably due to temperature spikes in the circuit.
Figure 25 Difference in the heat consumption for the AC-reheating with and without steam.

Figure 26 shows the return temperature for the WHR circuit with and without steam heating for AC reheating. The return temperature is seen to drop by a few degrees when only utilizing waste heat for the AC reheating. By analyzing the return temperature it can be observed that the return temperature seldom drops below 70 °C which is the optimal temperature for cooling the engines. The temperature drop also shows that the additional heat consumption would not lower the inlet temperature for the end line consumers too much. The temperature difference in the WHR circuit, ΔT, is depicted in Figure 27, which shows that the WHR circuit temperature generally drops by about one degree more than with steam heating for the AC reheating. There are some situations when the system shows a lower heat recovery rate, which upon further analysis was found to correspond to situations with low engine loads. The increase in ΔT for the system shows that utilizing only waste heat for the AC reheating
would both increase the waste heat recovery rate while simultaneously decrease steam consumption onboard.

![Figure 26](image1.png)

**Figure 26** Return temperature from the WHR circuit with and without steam heating for AC reheating.

![Figure 27](image2.png)

**Figure 27** Difference in temperature drop of the WHR circuit between with and without steam heating.
7.4 Combination of removed steam heating and changed return from evaporators

A combination of the two options studied above was finally tested to study if the efficiency of the system could be additionally increased. Figure 28 shows that the new system works well in situations when engine loads are high, but whenever the engine loads drop and along with that the available heat, the outlet temperature from the engines drops below the required temperature. From this it can be concluded that revised automation would be needed for situations when the available waste heat drops significantly, e.g., during maneuvering when multiple engines are required for Safe Return to Port (SRtP) reasons and the engines run at low loads. Situations where the engine loads drop below a certain level, the temperature in the WHR system drops and steam heating would be required for multiple consumers. Comparing the temperature drops with engine loads reveals that the system with AC reheating by only waste heat works well at sea, but in port and maneuvering situations the drop in engine load limits the available waste heat.

![Graph showing heat consumption](image)

**Figure 28** Change in the heat consumption for the AC reheating without steam together with the bypass circuit compared to without the bypass.
7.5 Added Organic Rankine Cycle

The largest alteration to the system studied is to add an organic rankine cycle to utilize possible excess heat that would not be utilized normally.

7.5.1 Climeon ORC unit

As an example of an Organic Rankine Cycle unit, a Climeon 150MW was chosen as it is already utilized in marine applications on Viking Grace with promising results (Climeon, 2020b). Another advantage of the Climeon ORC is that it is designed to work at low temperatures in comparison to other units. The proposed design would place the ORC unit in the beginning of the circuit to ensure sufficient heat and water flow. There was also a proposal to implement a steam booster before the ORC unit to ensure enough heat for the unit while also guaranteeing that the rest of the circuit still has enough heat for the other consumers (Meyer Turku, 2020). Figure 29 shows the working principle of the Climeon ORC unit. The working fluid is circulated through two heat exchangers in parallel with a condensation stage in the middle. The hot side uses waste heat to evaporate the organic fluid before it passes through a turbine to produce electricity by a generator. Simultaneously, the other part of the system cools the fluid with an outside cooling medium, such as seawater (CLIMEON, 2019).
Figure 29 Working principle of a Climeon ORC unit. (Climeon, 2020a)

Figure 30 shows efficiency curves for the Climeon ORC unit, which are dependent on both cooling water temperature and hot water temperature. The system efficiency is seen to increase by lowering the cooling water or increasing the HT water temperature. The efficiency curves were calculated for a flow of 40 l/s on both the hot and cold side of the unit; changes in the cold flow would also change the efficiency of the unit (Climeon, 2017).
7.5.2 **ORC simulation**

The WHR circuit with an ORC unit installed in the beginning of the circuit to ensure a temperature as high as possible was simulated. The location of the ORC is critical to ensure the best possible efficiency for the unit. The higher temperature increases both the efficiency and electricity output from the engine. The ORC unit was set up according to specifications provided by Climeon to match the energy consumption and flow rate. The efficiency specifications for the unit were also based on data from Climeon.

The engine loads that were used for the simulations were the same as in the base model to make it possible to compare the simulations. The ORC applied with a flow of 30 $\frac{\text{kg}}{\text{s}}$ of HT water while the heat consumption was controlled according to the inlet temperature to match the efficiency and specific electricity production. The simulation
was done over one month of data with one-minute intervals, i.e., for a total of 43559 data points.

The goal with the configuration is to increase the efficiency of the WHR circuit by increasing the heat recovery rate of the system together with producing additional electricity. Figure 31 shows the difference in the temperature drop in the WHR circuit with and without an ORC unit. As expected, the ORC unit increases the total amount of heat consumed in the system. The return temperature of the system drops by an average of 4°C, which corresponds to a noticeable increase in heat consumption. The higher utilization of heat also means that the return temperature is closer to the aim cooling temperature of the engines, which means that less LT cooling water is needed to cool the engines.

![Graph showing temperature drop](image)

**Figure 31** Difference in the temperature drop between with and without ORC.

Figure 32 shows and the inlet temperature to the ORC unit and how much electricity it produces. As long as the inlet temperature is above 80°C the ORC unit has good efficiency and produces a good amount of electricity. For temperatures below 80°C, the electrical output drastically drops making the use unprofitable since the ORC unit has an own base electrical consumption for circulation pumps.

Although the application of an ORC unit to the WHR circuit has many possible positive advantages, there are a few setbacks that could cause problems. The largest problem is that it would have to be bypassed at low engine loads, e.g., for port
operation, because the available heat would not suffice. Another situation that was further investigated was if the temperature after the unit would be high enough for consumers such as fresh water evaporators and AC reheating, since evaporators are only utilized at sea when engines run at high loads the temperature was found to still be sufficient for these consumers when using the ORC. Some problems were found for times when the ship was in port and at maneuvering situations, when the available heat drops. In these situations the temperature after the ORC decreased significantly, causing a deficit in heat for end-line consumers and the AC reheating unit did not obtain enough heat to function properly.

Figure 32 The electricity produced by the ORC unit and the corresponding inlet temperature.
8 Discussion

This chapter compares how the system works in practice and the simulation results to find the best plausible alterations to the system. The feasibility of the different solutions are compared together with the advantages of the different systems.

The simulation model was first validated using a measurement data from a reference ship. Figure 33 shows the heat recovery rate for the simulation model and the number of main engines producing heat. The measurement data shows that there are large amounts of unutilized HT heat from engine cooling and the waste heat recovery rate is very low at times when there is large amounts of available heat. When comparing the heat recovery rate and the engine loads in Figure 34 it can be seen that the recovery rate drops significantly at lower engine loads. Further investigation shows that the recovery rate is around 90% in best-case scenarios and 60% in worst cases.

Figure 33 Heat recovery rate for the WHR circuit and number of engines running.
Figure 34 Main engine loads in the simulation.

When the engine heat production in Figure 35 is compared with the recovery rate it can be seen that the recovery is better in situations where there is a large amount of available heat than when the heat production is low. The low recovery rate at low engine loads is caused by the low outlet temperature from the engines; hence, there is not enough heat for the consumers and steam is used instead. Another reason for the low recovery rate is that the fresh water evaporators can only be run if the ship is more than 20 nautical miles from shore, and the low recovery rate usually occurs in port or when maneuvering when many engines are run for redundancy reasons. The evaporators are the biggest single heat consumer in the circuit and the use of these are not possible during the times of low recovery rate. Another matter that should be considered is that the recovery rate is relative to the available heat. The actual wasted HT heat is depicted in Figure 36, which shows that the wasted HT heat is between 500 kW and 0 kW. The average wasted heat is around 300 kW, which is a similar quantity as the steam heating requirement for the AC reheating unit. Thus, this was one of the
main investigated alterations to both increase the recovery rate and lower the steam consumption and this way minimize the use of the auxiliary boiler.

**Figure 35** The heat production from engines.

**Figure 36** Amount of wasted HT heat.

The main idea for an alteration came from data analysis that showed that the AC-reheating circuit added additional heat to the WHR circuit instead of consuming it. This problem gave the idea to move the return from engine preheaters and evaporators after the AC-reheating to ensure sufficient inlet temperature to the AC-reheating. Further analysis of both AC-reheating circuit data and 3D drawings of the system showed that the system did not add heat to the system and it was a measurement
problem that caused the faulty data. Analysis of the simulations with the moved return showed that the system alteration did not noticeably affect the system. Although the alteration did not affect the system noticeably, it was investigated to combine the moved return system and simultaneously removing the steam heating from the AC-reheating.

The average fuel consumption for auxiliary boiler is around 45 t/month, i.e., 540 t/a. The average price for HFO is around 350 €/mt and around 600 €/mt for MGO this means that the average cost for the auxiliary boiler is 189 000 € per year if run on HFO and 324 000 € if run on MGO (Ship&bunker, 2020). The prices used were calculated from an average over the last year to take into consideration price fluctuations. By utilizing waste heat instead of steam from auxiliary boilers, a significant amount of fuel can be saved. In addition to fuel savings, this also lowers emissions. The other possible solution to increasing the WHR rate is the utilization of an ORC unit to produce additional electricity and this way lower the engine fuel consumption. The additional electricity produced by an ORC increases the WHR rate significantly, especially at high engine loads where the efficiency of the ORC is high. The biggest difference between the changes is that the modification to the AC-reheating increases the utilization of the current system while the ORC unit increases the total heat consumption of the system. Another change that was investigated is the possibility to only utilize HT water for certain consumers that currently utilize a combination of both steam heating and HT water as a heat source. The WHR circuit currently has an abundance of HT heat, of which a large part is left unutilized especially at high engine loads. The low heat utilization in the current setup also increases pumping of LT cooling water to the engines since the temperature does not reach the necessary temperature.

Figure 37 shows the heat recovery rate for the system when changing the AC reheating set point to cover the steam heating with waste heat. Comparing the recovery rate with the one for the original configuration, a slight increase in heat recovery is observed. Analyzing the temperature before and after the AC reheating, it can be seen that the circuit has sufficient heat for the AC reheating and for consumers after it. Utilizing only waste heat as a heat would lower the steam consumption by around 300 kW, which is a significant amount in situations when an auxiliary boiler is utilized to
produce steam. In other cases, the steam comes from the exhaust gas boiler and does not increase the fuel consumption. The saved fuel would correspond to about 30 kg/h, which is about a third of the average fuel consumption of the auxiliary boilers. However, the solution does not come without its own set of difficulties: steam hammers can occur when steam is exposed to water from condensation on the inside of the pipe causing a sudden drop in pressure that can cause pipes to burst.

Figure 37 Recovery rate with AC-reheating only utilizing HT heat.

Another system alteration investigated was combining the AC-reheating system only utilizing WHR heat and simultaneously moving the return pipe from the evaporators and engine preheating after the AC reheating as seen in Figure 20. This combination ensures that evaporators and engine preheaters would not lower the inlet temperature to the AC reheating in situations when there is little available heat. A combination of the two changes showed an increase in the inlet temperature to the AC reheating whenever the evaporators where in use. The inlet temperature increased on average by 2-4°C ensuring that the inlet temperature always stayed high enough to provide sufficient heat to the system.

The last investigated modification to the WHR system was adding an Organic Rankine Cycle unit to increase heat utilization and electricity output. The advantage of this alternative is mainly the additional electrical output, which can lower the required engine load and thus also the emissions. The ORC unit efficiency depends on the temperatures of the HT water and the cooling water, where a larger difference in
temperature increases the efficiency. The system was tested with three different configurations: two different cooling temperatures, 25°C and 20°C, and regulating the ORC unit to be bypassed if the inlet temperature drops below 75°C. Figure 38 shows the heat recovery rate with an ORC unit operating with a cooling water temperature of 25°C. The heat recovery rate is significantly increased by adding an ORC unit when comparing it to the recovery rate of the current system, from between 60 % and 90 % to an average around 97 %.

![Heat recovery rate with an ORC unit](image)

**Figure 38** Heat recovery rate with an ORC unit.

By adding an ORC unit to the WHR system the waste heat recovery circuit could produce over 500 MWh of additional electricity annually, which could directly lower fuel consumption and emissions. The efficiency of the ORC unit is very dependent on ambient conditions and cruise profile. With cruises in cold waters at high speeds producing the most electricity at the best efficiency. The price of electricity onboard is approximated to around 100 €/MWh, this would result in annual savings of around 50 000 € per year for an ORC unit based on the simulations in chapter 7 depending on the ORC settings (Gustafsson, 2018). The cost for an ORC installation was estimated to roughly 750 000 € giving it a payback time of 15 years with just adding an ORC to the system (Meyer Turku, 2020). The high price of an ORC together with the limited electrical output and long payback time makes the ORC an uneconomic solution if only adding it directly to the system. The efficiency of the ORC could be improved by fitting a steam booster to increase the inlet temperature to the ORC in situations when
the available waste heat is low. The problem with the steam booster is that it would increase steam consumption in situations when it is not available from exhaust gas boilers and auxiliary boilers would be required to produce the necessary steam.

Table 1 and Table 2 show a comparison between the different advantages of the system configurations by comparing the different key performance indicators, the main improvement strived for being increased heat recovery rate. By comparing the different system alterations to the current system, it can be observed that the system has on average over 250 kW of unused heat. The different options studied illustrate that adding an ORC unit increases the heat recovery rate significantly, reaching an average over 99% for a cooling water temperature of 20°C. There is also a significant increase in the heat recovery rate by only utilizing waste heat for AC reheating: this alteration would also be the simplest configuration to the system since it only requires a change of the AC reheating automation. By only utilizing waste heat for the AC-reheating, the heat recovery rate of the system could be increased by 6% while simultaneously decreasing the average steam consumption by 330 kW. Heating the AC reheating with only steam heating would result in fuel savings in situations when auxiliary boilers are required for steam production. On average, around 30 kg/h of fuel could be saved, resulting in annual fuel savings of 86 tons or around 50 000€ if the engines run on MGO. The extra pipes of the system would roughly cost 100 000 €, giving the system a payback time of two years.

Table 1 Comparison of the different systems

<table>
<thead>
<tr>
<th></th>
<th>Current configuration</th>
<th>AC-bypass without steam</th>
<th>AC-reheating without steam</th>
<th>AC-bypass heating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average heat recovery rate [%]</td>
<td>82.8</td>
<td>82.8</td>
<td>88.2</td>
<td>88.6</td>
</tr>
<tr>
<td>Average difference in heat production and consumption [MW]</td>
<td>0.26</td>
<td>0.26</td>
<td>0.22</td>
<td>0.20</td>
</tr>
<tr>
<td>Steam consumption reduction [kW]</td>
<td>0.00</td>
<td>0.00</td>
<td>330</td>
<td>330</td>
</tr>
</tbody>
</table>

**Table 2** Comparison between the different ORC configurations

<table>
<thead>
<tr>
<th></th>
<th>ORC 25°C cooling water</th>
<th>ORC 20°C cooling water</th>
<th>ORC 25°C cooling water over 75°C inlet temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average heat recovery rate [%]</td>
<td>97.0</td>
<td>99.0</td>
<td>97.3</td>
</tr>
<tr>
<td>Average difference in heat production and consumption [MW]</td>
<td>0.073</td>
<td>0.043</td>
<td>0.068</td>
</tr>
<tr>
<td>Average additional electricity production [kW]</td>
<td>59.58</td>
<td>69.98</td>
<td>55.20</td>
</tr>
<tr>
<td>Annual additional electricity production [MW]</td>
<td>520</td>
<td>610</td>
<td>480</td>
</tr>
</tbody>
</table>
9 Conclusion

The increasing demands for energy efficiency from both the International Maritime Organization and cruise lines force shipbuilders to find new solutions for improved energy efficiency. One of the main ways for improving energy efficiency for cruise ships is waste heat recovery from engines. By utilizing waste heat, the total efficiency of the engines can be improved by up to 40% in the best-case scenario.

The thesis study means to improve the efficiency of the current waste heat recovery (WHR) system of the cruise ship. The system was investigated by analyzing operational data from a mid-sized cruise ship and by developing a simulation model in Apros, a dynamic simulation tool. The simulation model was well documented for future analysis for possible new applicable technologies. The simulation model was validated using measurement data from the reference ship. The validation showed that the simulation model was able to describe the operation of the heat recovery with an average relative error below 5%. Since the model showed a good correspondence with the measurements, it was deemed sufficiently accurate for the simulations to be done in the thesis. The simulations showed that on average 250 kW excess heat was available and that the average heat recovery rate was 83%.

The system was first studied for possible flaws in the AC-reheating circuit. The initial analysis indicated that the AC reheating unit seemed to heat the rest of the circuit whenever the evaporators were running. Different possibilities to bypass the AC-reheating system were investigated to find the best way while still utilizing waste heat for AC-reheating. Deeper investigation of the operation of the AC system however showed that the problems were actually caused by an erroneous temperature measurement. This redirected the study toward finding alternative solutions for improving the waste heat recovery rate.

The WHR system simulation model was analyzed to find the causes of the low recovery rate. Deeper analysis showed that the system does not have enough heat consumption since many components still use low amounts of steam even though the HT heat would suffice. Two main solutions investigated was increasing the heat consumption by minimizing steam use and adding an ORC unit for additional heat consumption. The different configurations were investigated by dynamic simulations.
based on the actual system from the reference ship. The simulation model was validated according to measurement data from the reference ship. The validation model showed that the simulation model corresponded to the reference data with an average relative error of under 5%. Since the validation of the model showed good correspondence to the measurement data, it was deemed accurate enough for the simulations for the thesis.

The validation simulations showed an excess of heat with an average of around 250 kW of excess heat and an average heat recovery rate of 83%. The two main solutions investigated for increasing the heat recovery rate investigated were simulated using the validated model to compare the different advantages. By switching, the AC reheating to only utilize waste heat as a heat source it was found that steam consumption could be lowered by around 300 kW. The system showed that adding a bypass from the return from freshwater evaporators and engine preheating to the AC-reheating would ensure that the inlet temperature would always stay over the required temperature. Changing the AC-reheating to only consume waste heat and adding a bypass would increase the average heat recovery rate to 89% while simultaneously lowering steam consumption. Only utilizing waste heat for AC-reheating could save up to 86 mt of fuel annually resulting in annual savings of 50 000 €.

The second main investigated alternation was to add a Climeon ORC unit to utilize excess heat for electricity production. The Climeon ORC unit was added to the simulation as the first consumer in the circuit to ensure that the inlet temperature to be as high as possible. Adding the ORC unit to the system increased the heat recovery rate significantly and reached an average recovery rate of 99% utilizing cooling water with a temperature of 20°C. In addition to the increased recovery rate, average excess heat dropped under 100 kW. The addition of an ORC unit also added an average electricity production between 50 and 70 kW not considering additional energy consumption for the unit itself, which would result in an additional 450-600 MWh annually. The ORC unit could result in annual savings of around 50 000€, with the cost of an ORC with installation this would give a payback time of 15 years which makes it unprofitable with current fuel prices. The ORC unit might be a plausible improvement if the price for the unit drops and fuel prices rise.
The two considered alterations both have their own difficulties when considering implementation on a cruise ship mainly cost from alternating the system and adding additional measurements to the circuit to ensure that every consumer gets sufficient heat. The addition of an ORC unit would also require both space and additional piping and added pump power for cooling water.

The simulations were also only made for a single data set so the result might vary based on different cruise conditions and ambient variables. In reality, several variables are affecting the system including ambient conditions and cruise profiles that were not included in the calculations.

Based on the results of the simulations and knowledge about the WHR system on the reference ship it was demonstrated that there are feasible options for changing the system to increase the heat recovery rate and in this way simultaneously increase the total energy efficiency of the cruise ship. The simulations illustrated two different solutions that could be considered both when a cruise ship is designed and during operation to improve the overall energy efficiency.
10 Optimering av värmeåtervinningen på kryssningsfartyg


Det finns olika lösningar för att förbättra energieffektiviteten och minska utsläppen, bland annat genom nya miljövänligare tekniker och förbättringar av existerande system. Ombord på fartyg finns ett antal olika system för att öka energieffektiviteten och minimera utsläppen. Fartygsmotorer är kraftvärmeverk som genererar både elektricitet och värme i form av ånga och varmvatten. Värmeåtervinningen på fartyg har många även begränsningar som minskar möjligheterna att återvinna spillvärme. Trots dessa begränsningar finns det goda utvecklingsmöjligheter för energieffektivare lösningar.

Spillvärmeåtervinningen kan öka motorernas totala effektivitet från runt 30 % till över 60 %. Spillvärmeåtervinningen består av tre huvudsakliga delar: avgaser, högttemperaturen- och lågtemperaturenvrärme. De största möjligheterna för spillvärmeåtervinning finns i avgaserna samt högtemperatur-värme; avgasvärmen kan återvinnas genom avgaspannor för att producera ånga och högtemperaturvärmen genom värmeväxlare.

Detta arbete koncentreras på högtemperaturvärmen från motorernas insugsluft samt kylvatten från mantelkylningen. Denna värme överförs med hjälp av värmeväxlare till ett separat återvinningssvärmsystem som utnyttjar värmen i diverse komponenter. Så som evaporatorer, återuppvärmning av luftkonditioneringsluft och uppvärmning av dricksvatten, vilka även är de största konsumenterna av högtemperaturvärm. Det
nuvarande systemet har dock brister som gör att värmeåtervinnningen är otillräcklig och därför kommer det här diplomarbetet inriktas på att förbättra systemet för återvunnen värme och på så sätt öka konsumtionen av högtemperaturvärme.

Värmeåtervinnningssystemet studerades både genom att analysera driftsdata från kryssningar och simulerings för att få noggrannare analyser av de olika komponenterna. Driftsdata hämtades från ett medelstort kryssningsfartyg vilket även har använts som referens för simuleringarna.


För att hitta alternativa lösningar till den låga värmeåtervinningsgraden analyseras systemet noggrannare med hjälp av det simuleringsverktyget Apros, som möjliggör dynamisk simuler. Simuleringen valideras först mot driftdata för att verifiera att modellen är giltig. Valideringen visar att modellen fungerar väl och att modellen uppvisade en korrelation på 95 % med mätdata. Eftersom valideringen var framgångsrik, kan simuleringsmodellen användas för att identifiera vilken eller vilka komponenter som utgör begränsningar i systemet. Ett huvudsakligt problem som upptäcktes var att värmeförbrukningen i systemet är för låg vid höga motorbelastningar när det finns stora mängder värme tillgängligt och det finns
överloppsvärme. Andra situationer när återvinningsgraden är låg är när fartygen ligger i hamn och värmekonsumtionen är låg, eftersom flera konsumenter inte används i hamn. Den alternerande värméåtervinningsgraden betyder att lösningen som sökes måste vara robust mot variationer i både temperatur och flöde i systemet.

Den första alternativa lösningen som analyseras är att avlägsna ånguppvärmningen från luftkonditioneringsåteruppvärmning och ersätta den med återvunnen värme från motorerna. Denna lösning ökar värméåtervinningsgraden märkbart samtidigt som den minskar ångförbrukningen, vilket kan minska den årliga bränsleförbrukningen för oljepannorna med 86 ton vilket skulle ge märkbara besparingar för rederiet.

En organisk rankinecykel (ORC) väljs som den andra alternativa lösningen till underskottet av värmekonsumenter av högttemperatursvärme. ORC:n utnyttjar spillvärmen från motorerna för att producera ytterligare elektricitet för fartygets bruk. Problemet med rankinecykeln är att den behöver stora mängder värme, med tillräckligt hög temperatur, för att fungera effektivt. Behovet av värme leder till att placeringen av ORC-systemet är kritiskt. Det höga inloppstemperaturkravet leder till att ORC-enheten leder till att enheten placeras som första konsument i systemet för återvunnen värme. Installationen av en ORC-enhet på 150 kW minskar bränsleförbrukningen eftersom enheten skulle kunna producera runt 500 MW elektricitet årligen, vilket skulle ge besparingar på 50 000 € årligen.

Simuleringarna visar att den låga värméåtervinningsgraden beror på att systemet har för låg värmekonsumtion och inte ett konstruktionsfel, som till en början misstänktes. Genom att endast använda återvunnen värme för återuppvärmningen av luftkonditioneringen, kunde värméåtervinningsgraden ökas och ångkonsumtionen minskas. Denna alteration i systemet skulle inte innebära några extra utgifter vilket gör alterationen länsamt att testa på referensfartyget.

Installationen av en ORC-enhet skulle lösa problemet genom att öka värmekonsumtionen och samtidigt som denna ökar elektricitetsproduktionen. Den optimala värmekonsumtionen skulle fås genom att installera en ORC-enhet innan de övriga värmekonsumenterna, eftersom ORC-enheten kräver den högsta inloppstemperaturen. Trots de många fördelarna med en ORC-enhet är återbetalningstiden runt 15 år vilket gör ORC-enheten ekonomiskt olönsam, om
priserna för enheten minskar samtidigt som bränslekostnaderna stiger kan en ORC-
enhet vara lönsam i framtiden.
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