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Design and modeling of an advanced marine machinery system including waste heat recovery and removal of sulphur oxides

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Abstract:

In order to reduce the formation of acid rain and its harmful effects, stricter legislations on emissions of sulphur oxides from ships applies as of 2015 in emission control areas and globally in 2020 by the international maritime organization (IMO). Consequently, prices on low sulphur fuels are expected to increase drastically compared to those of heavy fuel oil, giving ship owners a strong incentive to find alternative ways of complying with the legislations. In addition, IMO regulations on carbon dioxide emissions and high fuel prices provide incentives for improving the efficiency of the machinery system. The wet sulphuric acid process has shown to be an effective way of removing sulphur oxides from flue gas of land-based coal fired power plants. Moreover, organic Rankine cycles are suitable for heat to power conversion for low temperature heat sources. This paper is aimed at designing and modelling a highly efficient machinery system which includes the removal of exhaust gas sulphur oxides. Numerical simulations are carried out using an open source software developed at Technical University of Denmark called Dynamic Network Analysis (DNA). The machinery system suggested in this paper consists of a two-stroke diesel engine, the wet sulphuric process for sulphur removal and an advanced waste heat recovery system including a conventional steam Rankine cycle and an organic Rankine cycle. The results are compared with those of a state-of-the-art machinery system featuring a two-stroke diesel engine and a conventional waste heat recovery system. The results suggest that an organic Rankine cycle placed after the conventional waste heat recovery system is able to extract the sulphuric acid from the exhaust gas, while at the same time increase power generation from waste heat by 32.9% and the combined cycle thermal efficiency by 2.6%. The findings indicates that the technology has an energetic and environmental potential in marine applications, while still further research and development need to be done before it can be put into operation on ships.

Keywords:

Sulphur Oxides (SO_x), Organic Rankine Cycle, Exhaust gas cleaning, Marine Diesel Engine, Combined cycle

1. Introduction

More than 90% of all global trade is transported by sea summing up to 8.7 billion of loaded tons cargo by 2012 [101]. A great majority of the prime movers for ocean going ships are diesel engines and for large ships almost all are 2-stroke low speed diesel engines. This type of engine has become dominant because of its high efficiency and ability to use cheap heavy fuel oil (HFO). Reduction of the environmental impact and fuel consumption from this type of system is thus an important area, for which to reduce the impact on environment and consumption of resources on a global scale.

Heavy fuel oil is produced at the “bottom-end” of the oil refining process and consists of significant amounts of sulphur, with the world average sulphur content being 2.7 % [104]. The exhaust emission of sulphur oxides (SO_x) formed by combustion of fuels containing sulphur is regulated by the international maritime organization (IMO) through the marine air pollution regulations (MARPOL, Annex VI). Globally the sulphur content in marine fuels was reduced to maximum 3.5% in 2012 and it is being drastically reduced to 0.5 % from 2020. This however is depending on the outcome of a review to be concluded by 2018, where it can be postponed to 2025. Furthermore, the IMO have established emission control areas (ECA) for SO_x , sometimes also referred to as SECA, where stricter legislations apply. SECA includes the North Sea, the Baltic Sea and all sea in a distance of 200 nautical miles from the North American cost line including all coast areas of the United States of America, parts of Canada and the Hawaiian islands. By 1st of January 2014 the United States Caribbean Sea area is expected to enter into effect. For SECA the limits on SO_x are reduced stepwise from the current sulphur content of 1% to 0.1% in 2015 [103]. A graphical overview of the development in legislations on the sulphur content of marine fuels is given in Fig. 1.

If ship owners do not choose to switch between different fuels while entering SECA areas, IMO allows for other ways to comply with the sulphur limits. This is divided into primary, in which the formation of SO_x is avoided, and secondary, in which SO_x is formed but subsequently removed prior to discharge of the exhaust gas. [103].

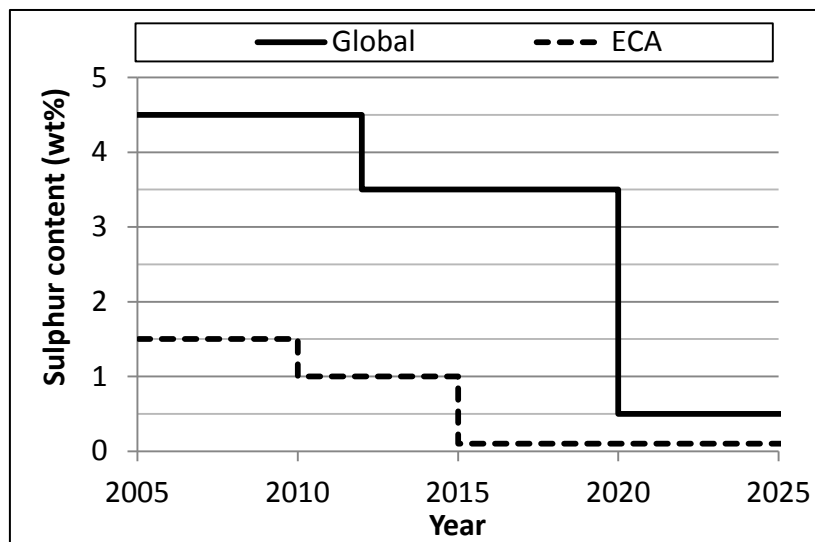


Fig. 1. SO_x limits of fuels for marine transportation globally and in emission control areas (ECA)

In marine transportation the fuel cost is estimated to make up two third of the total freight cost, explaining why fuel efficiency is receiving significant attention within the industry. The current price of distillate fuels is approximately 50% higher than that of HFO [101] and the price difference is expected to increase further as the demand for distillate fuels will increase with legislations on SO_x entering into effect. This trend gives ship owners incentives to find ways of using the cheaper HFO while still complying with legislations on emissions, thus implementing cost-effective exhaust gas after treatment systems is attractive.

Land based power production have for a long time faced legislations on emissions of SO_x , and can be used to find inspiration in the search for effective exhaust gas after treatment systems. Coal fired power plants, which also contains significant amounts of sulphur, have employed Flue Gas Desulphurization (FGD), where an alkaline absorbent, typically limestone, is used to absorb SO_2 under production of gypsum. Salty sea water is considered to be used as absorbent for marine application, commonly referred to as wet scrubbers. A well to wake study by Ma et al. [117] compares green house gas emissions and total energy consumption of different scrubber options as an alternative to switching to low sulphur distillate fuel. The study indicates that it is more attractive to install after treatment systems in form of sea water scrubbers compared to a switch to low sulphur fuels. However, a drawback of the wet scrubbers is that the heat contained in the exhaust gas is wasted and at the same time they use significant amounts of power to pump sea water to the wet scrubber [123].

A method not included in the study by Ma et al. [117] is the wet sulphuric acid (WSA) process, which was introduced and patented by Haldor Topsoe A/S in the late 1980s [110]. The WSA process is a process where a SO_x and water vapor reacts and forms liquid sulphuric acid (H_2SO_4) in high concentrations. The process requires that the exhaust gas is cooled down to a temperature below the dew point of sulphuric acid, while the heat from the process can be used for any suitable purpose.

Over the recent years power production from low temperature heat sources in general has received increasing attention. The organic Rankine cycle (ORC) is considered a promising candidate for this purpose, because the working fluid can be selected to suit relatively low temperature levels [107, 127, 128]. In a review of low grade heat conversion using ORC given by Vélez et al. [107], it is reported that commercial available ORCs exists in the range of 0.2 to 2 MWe. To the knowledge of the authors the first ORC onboard a ship is currently being tested on the new build MV Figaro providing a maximum output power of 0.5 MWe [108].

General studies of ORCs in combination with internal combustion engines [125, 126] exists, whereas a more limited number specifically with marine application exists. A review of waste heat recovery systems on two-stroke internal combustion engines aboard ships is given by Shu et al. [105] and a study by Larsen et al. compares the steam cycle, Kalina cycle and organic Rankine cycle for marine application [124]. The most conventional waste heat recovery system (WHRS) employed today consists of a power turbine expanding part of the exhaust gas to ambient pressure and a steam boiler, which is used in a Rankine cycle for electricity production. Either of the two can be employed alone or in a combination [106]. Common for all WHRS is that the exhaust gas temperature at the outlet of the boiler is kept above 160°C to prevent sulphuric acid corrosion on boiler and piping. This restricts the power production from the WHRS, because more energy could be extracted by further lowering the exhaust gas temperature.

In this paper an exhaust gas after treatment system that integrates the WSA process in to the conventional WHRS is proposed. This is a methodology not found in the present literature. To further increase the energy efficiency of the propulsion system, the heat from the WSA process will be utilized in an organic Rankine cycle, where the extensive work found in literature [125, 126, 124, 107, 127, 128] can be drawn upon. The proposed system will enable ship owners and operators to continue to use the cheaper HFO, while still complying with future legislations on SO_x . The study is performed as case study where a reference plant, case 1, consisting of a 2-stroke marine diesel engine and a state-of-the-art WRHS is compared by means of numerical simulations against the proposed design, case 2.

In the next section the reference plant, case 1, and the proposed plant, case 2, are presented together with the modeling methodology used. The main results are presented in section 3, and the performance of case 1 and 2 are compared. Section 4 contains a discussion of the significance of the results and areas needing further research and development are discussed. Finally section 5 contains the conclusion of the present work.

2. Method

2.1. Case 1 - Reference plant

The propulsion system of the container vessel Alexander Maersk was chosen for the concept study. Alexander Maersk has a container capacity of 1068 twenty-foot equivalent unit (TEU), which makes it a feeder class vessel [122]. Its prime mover is a MAN 7S50MC 2-stroke diesel engine, which has a maximum continuous rating (MCR) of 10,126 kW. The vessel is selected because it is mostly operated in coast-near areas, which makes it more vulnerable to legislations on SO_x. A main engine load of 75% MCR was used with the ambient condition based on the ISO 3046-1:2002(E) and ISO 15550:2002(E) standard and fuel composition as given in Table 1.

Table 1. Ambient conditions and fuel composition

ISO ambient conditions		Fuel Composition [116]	
Barometric pressure	1000 mbar	C	84.47 %wt
Turbocharger air intake temperature	25 °C	H2	11.43 %wt
Charge air coolant temperature	25 °C	O2	1.07 %wt
		N2	0.30 %wt
		S	3.00 %wt
		Lower heating value	42700 kJ/kg
		Specific heat capacity	2.1 kJ/kg-K

Fig. 2a shows a component diagram of the reference plant, which consist of a main engine, turbocharger, exhaust gas turbine, steam boiler with associated steam turbine, condenser and pump, and a generator. Following is a description of the reference plant.

Air is taken into the compressor part of the turbocharger (TCC) and feed to the cylinders of the main engine through a scavenge air receiver. After combustion the exhaust gas goes out to the exhaust gas receiver, from where the exhaust gas flow is split between the turbine part of the turbocharger (TCT) and an exhaust gas turbine, also called power turbine (PT). After the exhaust gas has passed the TCT and the PT the two flows are brought together again and are taken through a series of heat exchangers producing steam for a steam turbine. The steam turbine is connected to the same generator as the power turbine through a reduction gear. Part of the steam produced in the boiler is used for steaming services (SS). Steaming services is among others used to preheat the HFO to a temperature of 120°C, because of its high viscosity, as well as other heating purposes. The feedwater to the steam cycle is preheated by the jacket water from the main engine in the jacket water preheater (JWP) to a temperature of 85°C. The compressed intake air is taken trough two air coolers AC1 and AC2. AC1 is used to preheat the feed water for the steam cycle, while AC2 uses seawater to further cool down the intake air before it enters the scavenge air receiver.

The WHRS is of the configuration proposed by Man Diesel & Turbo with a two-pressure level steam cycle, low pressure being 4.275 bar and the high pressure being 10 bar, while condenser pressure was set to 0.07 bar [106]. Parameters for simulating the main engine is obtained from a computer simulation program, CEAS, provided by manufacturer [120] and a summary of all parameters used to simulate the reference plant is given in Table 2. The combustion in the main engine had an excess air coefficient of 3.08 and the composition of the exhaust gas is as given in Table 3. For the exhaust gas ideal gas properties were assumed.

Table 2. Parameters used to model case 1 – reference plant.

Main Engine and Turbocharger	
Brake Power	7678 kW
Temperature after air cooler	31.4 °C
Scavenge air pressure	3.098 bar
Specific fuel oil consumption (SFOC)	176.68 g/kWh
Exhaust gas temperature (before TCT)	420 °C
Exhaust gas pressure (before TCT)	2.906 bar
Main engine - Jacket water cooling	1074 kW
Main engine - Other heat losses	651 kW
Turbocharger compressor - isentropic efficiency	82.5%
Turbocharger turbine (incl. Mechanical losses) - isentropic efficiency	82.5%
Air intake - pressure loss	90 mmWC
Scavenge air coolers - pressure loss	150 mmWC
Waste heat recovery system	
Power turbine - isentropic efficiency	82.5%
Steam turbine (low pressure part) – isentropic efficiency	78.0%
Steam turbine (high pressure part) – isentropic efficiency	78.0%
Gear (power turbine to steam turbine) – mechanical efficiency	98.0%
Gear (steam turbine to generator) – mechanical efficiency	98.0%
Generator – Electrical efficiency	98.0%
Heat exchangers gas side (all) – pressure drop	12 mbar
Heat exchangers steam side (all) – pressure drop	0 mbar
Feed Water pump – isentropic efficiency	85.0%
Steaming service – Heat load	175 kW
Heat exchangers - Minimum pinch point temperature difference	15 °C

Table 3. Composition of exhaust gas (%mol).

O ₂	13.750
N ₂	75.812
CO ₂	4.703
H ₂ O	4.771
Ar	0.902
SO ₂	0.062

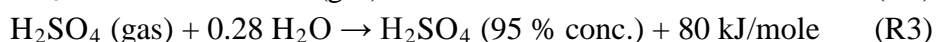
2.2. Simulation software DNA

The main engine and WHRS is modeled in steady state in the numerical simulation software called Dynamic Network Analysis (DNA). DNA is a simulation tool used for energy systems analyses [112, 113]. It is the present result of an ongoing development at the Department of Mechanical Engineering, Technical University of Denmark. In DNA the physical model is formulated by connecting the relevant component models through nodes and by including operating conditions for the complete system. The physical model is converted into a set of mathematical equations to be solved numerically. The mathematical equations include mass and energy conservation for all components and nodes, as well as relations for thermodynamic properties of the fluids involved. In addition, the components include a number of constitutive equations representing their physical properties, e.g. heat transfer coefficients for heat exchangers and isentropic efficiencies for compressors and turbines. The program includes a component library with models for a large number of different components existing within energy systems.

2.3. Formation of sulphuric acid.

The wet sulphuric acid process produces sulphuric acid in high concentrations by cooling down exhaust gas containing water vapor below the dew point of sulphuric acid. The chemical process in the formation of sulphuric acid is here described in order to understand how it can be implemented in to the conventional WHRS of a ship.

The amount of SO_x in the exhaust gas is a simple function of the amount of sulphur in the fuel and cannot be controlled by the combustion process [109]. Most of the SO_x in the exhaust gas is SO_2 and only a small amount is SO_3 . However SO_2 will react with oxygen to form SO_3 in the oxidation process (R1). When sulphur-trioxid is formed it will react with the water vapour in the exhaust gas forming sulphuric acid in a gaseous state (R2) and by further cooling down the exhaust gas sulphuric acid will condense (R3) [114].



The oxidation process (R1) is the rate dependent process, and a catalyst is needed in order for the process to happen within the exhaust gas system [109]. A catalyst for this purpose can be based on vanadium pentoxide (V_2O_5), which operates efficiently down to temperatures of $370 \text{ }^\circ\text{C}$ [118]. The catalyst therefore has to be placed before the turbine part of the turbocharger.

The exhaust gas needs to be taken significantly below the dew point temperature to ensure condensation of sulphuric acid (R3). The condensation temperature depends on the partial pressure of SO_3 and water vapor and can be estimated by the method given by Okkes [111]

$$T_{\text{dew}} = 203.25 + 27.6\log(p_{\text{H}_2\text{O}}) + 10.83\log(p_{\text{SO}_3}) + 1.06(\log(p_{\text{SO}_3})+8)^{2.19} \quad (1)$$

where $p_{\text{H}_2\text{O}}$ and p_{SO_3} are the partial pressures of H_2O and SO_3 in atmosphere respectively. With the exhaust gas composition given in Table 3 and assuming that all SO_2 is converted to SO_3 is the dew point temperature found to be $164.8 \text{ }^\circ\text{C}$.

2.4. Case 2 - Proposed design

The proposed design, which can be seen in Fig. 2b, is similar to the reference plant, but a catalyst is placed between the main engine and turbocharger turbine and a heat exchanger is placed at the outlet of the steam boiler. The extra heat exchanger in the exhaust gas flow termed ORC in Fig. 2b serves the purpose of extracting the sulphuric acid from the exhaust gas and providing heat to an organic Rankine cycle.

The temperature of intake air out of the compressor (TCC) is approx $164 \text{ }^\circ\text{C}$, why this was chosen to be used as a heat reservoir for the ORC as well. In the reference plant the air cooler (AC1) was used to preheat the steam and thus no LP economiser was needed. This is however needed in the proposed design as the feed water is only preheated to $85 \text{ }^\circ\text{C}$ in the jacket water preheater (JWP). Consequently the LP level of the steam boiler was raised from 4.25 to 4.75 bar.

Selection of working fluid for the ORC is a non-trivial task. Apart from matching the thermodynamic properties of the fluid there are concerns about the fluid hazard levels with regards to flammability, toxicity and environmental concerns, mainly global warming potential and ozone depletion potential. Special concerns about hazard levels needs to be taken for marine applications and the IMO SOLAS regulations state that the flash point of a fluid in a machinery space may not be lower than $60 \text{ }^\circ\text{C}$, thus all hydrocarbons are excluded. Quoilin and Lemort [115] suggests R123 and R245fa as working fluids for the temperature ranges considered in this study and a more recent

study by Larsen et al. of working fluids for marine applications suggest R245fa and R236ea as suitable for marine applications. R123 is to be faced out in the recent future and thus it was chosen to use R245fa as working fluid for this study.

All parameters used to model main engine and conventional WHRS is kept the same as in the reference plant. The pump and turbine of the ORC were both given isentropic efficiencies of 80% and no pressure loss were accounted in the heat exchangers on either side. A mechanical efficiency of 98% was introduced between ORC turbine and generator and an electrical efficiency of 98% was assumed for the ORC generator. Pressure drop is not accounted in the catalyst, nor is the heat increase from the chemical reaction (R1) as this is expected to be weighted out with the heat loss from the catalyst (see section 3).

The performance of the ORC was modelled using Engineering Equation Solver © [129] and added to the results of the simulation done in DNA. The ORC performance was validated by comparison to similar studies [126, 127, 128]. A heat temperature diagram of the steam boiler and organic Rankine cycle from case 2 is given in Fig. 3.

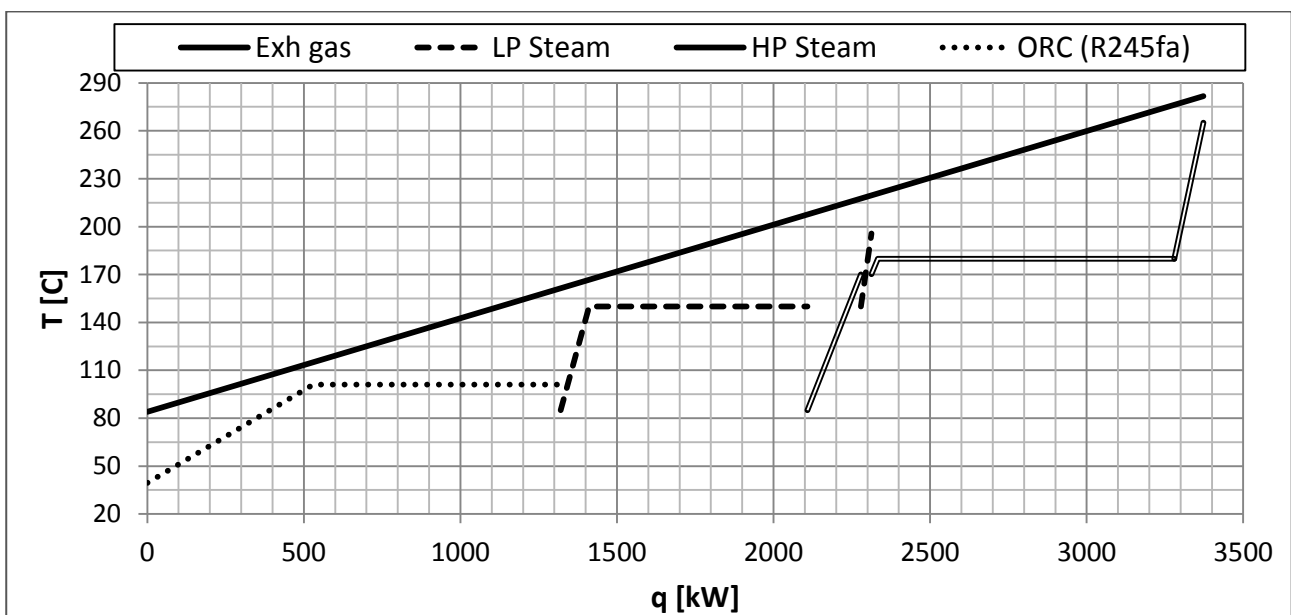


Fig. 3. Heat-temperature diagram of steam boiler and organic Rankine cycle

3. Results

The performance data of the reference plant and the proposed plant is summarised in Table 4. The main engine and turbocharger performance is indifferent in the two cases. The power production from the conventional part of the waste heat recovery system (power turbine and steam turbine) is 7.2% lower in case 2 compared to the reference plant. This is because the power production from the steam turbine is lowered by 48 kW from 466 to 418 kW. In case 2 the electric power production from the ORC is found to be 270.1 kW, which imposes an increase in total waste heat recovery power production of 32.9%. A comparison of the overall thermal efficiency for case 1 and 2 and the total power production from waste heat recovery is given in Fig. 4.

The operation pressure of the organic Rankine cycle was optimised with respect to maximum power output. The pressure was found to be 13 bar, which resulted in the exhaust gas temperature being lowered from 161.7 to 84.0 °C under the constraint of a minimum temperature difference of 15 °C. This is considered sufficiently low for the sulphuric acid to be condensed.

Table 4. Simulation results.

Main Engine and Turbocharger	Case 1	Case 2	
Main engine – brake thermal efficiency	47.72	47.72	%
Main engine – mass flow of air in	15.99	15.99	kg/s
Main engine – mass flow of exhaust gas	16.37	16.37	kg/s
Main engine – excess air coefficient of combustion	3.082	3.082	-
Waste heat recovery system			
Thermal efficiency of combined cycle	51.92	53.29	%
Net power production by WHRS	675	626.7	kW
Net power production by ORC	-	270.1	kW
Exhaust gas outlet temperature	161	84.0	°C

It can be shown that when assuming that all sulphur in the fuel is converted into sulphuric acid the production of sulphuric acid will be given by

$$\dot{m}_{H_2SO_4} = \frac{\dot{m}_{fuel} x_S}{MW_S} MW_{H_2SO_4} \quad (2)$$

The fuel consumption is found to be 1337.4 kg/h and thus the production of sulphuric acid is estimated to be 122.7 kg/h, which is roughly 10% of the fuel consumption.

The heat produced by the chemical reactions from the oxidation of SO₂ (R1) as well as formation (R2) and condensation (R3) of sulphuric acid will be 34.4kW, 34.8kW and 27.8kW respectively. With a heat capacity of the exhaust gas of 1.08kJ/kg-K this will correspond to a temperature rise of the exhaust gas between 1.57 and 1.97 °C. These relatively small temperature increases due to the chemical reactions was neglected in the calculations of case 2 as also heat losses were neglected.

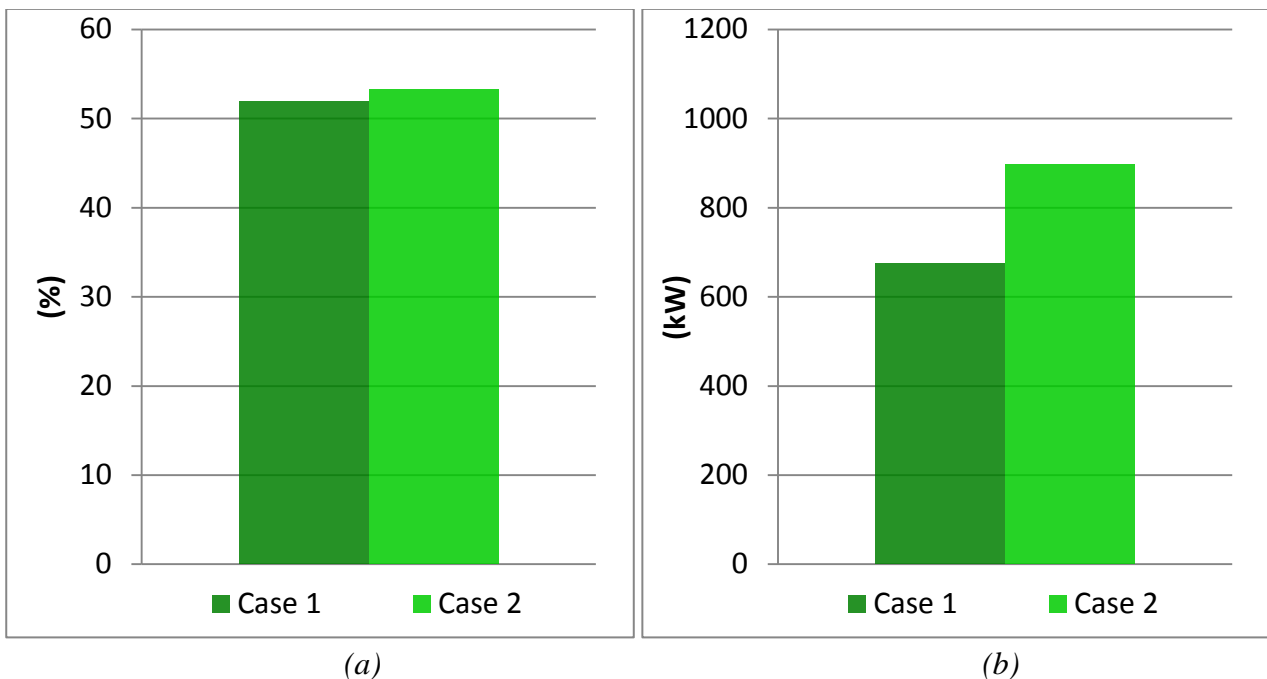


Fig. 4. Comparison between reference and proposed plant: a) thermal efficiency of combined cycle, b) power production by waste heat recovery.

4. Discussion

Considering the 1.37 points increase of the combined cycle system thermal efficiency, it is concluded that the implementation of the wet sulphuric acid process is feasible from an energetic perspective. Furthermore, the implementation enables the ship owner or operator to use the much

cheaper HFO, while still complying with the legislations on SO_x . The results regarding the ORC is very much conceptual and further studies are needed in order to identify the following: 1) the size and practical placement of a catalyst placed before the turbocharger turbine and how effective the conversion of SO_2 to SO_3 may be, 2) will sufficient quantities of sulphuric acid be condensed in the heat exchanger of the ORC and not in other places and 3) how can a system collecting and handling the sulphuric acid be implemented in the ship design.

Regarding point 2) above here, the WSA process is claimed to remove up to 98% of SO_x and the process is operating on land based power plants [114]. Furthermore, a design suitable for marine applications needs to be found. Glass or ceramic materials may be used due to the corrosiveness of the sulphuric acid, but metallic heat exchangers with special coatings could also be an option, as these will have better heat transfer properties and thus smaller dimensions. Polytetrafluoroethylene (PTFE), commonly known as Teflon®, is suggested as well as Tantalum coated heat exchangers might be an option.

Other possible of designs of the WHRS could also be studied, e.g. a system consisting solely of one or more ORC cycles, possibly employing different working fluids or to use dual-pressure ORC. Also there is room for further improvements by reducing the exhaust gas outlet temperature further.

Furthermore part load operation of the system needs to be considered ensuring that the sulphuric acid is condensed and collected under all conditions.

5. Conclusion

The restriction on sulphur content in fuel for ships will be increased drastically in 2015 for operation in special emission control areas, and globally in 2020. Shipowners must comply with these legislations, and therefore it is necessary to find an effective method of reducing emissions of sulphur from ships.

The wet sulphuric acid (WSA) process has shown to be an effective way of removing sulphur oxides from the flue gas of land-based power plants and thus the purpose of this paper has been to show the potential of implementing such technology in ships.

A concept study was carried out with a reference plant being a combined cycle made up of a 2-stroke low speed marine diesel engine and a waste heat recovery system of the configuration proposed by MAN Diesel & Turbo with a dual-pressure steam cycle. A new waste heat recovery systems was proposed, modelled and evaluated against the reference plant at a main engine load of 75 % MCR. The proposed systems has the purpose of extracting the sulphuric acid from the exhaust gas before it is sent to the ambient, while at the same utilize the heat from the exhaust gas in an organic Rankine cycle. It was found that it requires a catalyst as well as a component that takes the temperature of the exhaust gas below the dew point of sulphuric acid, approximately 164 °C, in order for the acid to condense and be extracted. The production of sulphuric acid from combustion of a 3% sulphur HFO was estimated to be 122.7 kg/h, which is equivalent to 9.2% of the fuel consumption.

The proposed plant, case 2, is built up as the reference plant, but with an organic Rankine cycle placed "on top" of the original waste heat recovery system. The heat exchangers of the organic Rankine cycle is placed after the steam boiler, and is the last component the exhaust gas passes through before it is sent to the ambient. The heat exchanger is also the component where the sulphuric acid is condensed and extracted. Furthermore a catalyst is placed before the turbocharger turbine to enhance the oxidation of SO_2 .

By using R245fa as working fluid and a maximum pressure of 13 bar for the ORC, the results suggest that an increase in power output of the WHR system by 32.9% would be obtainable. This corresponds to an increase of the combined cycle efficiency by 2.6%.

These findings indicates that the proposed plant can provide energetic and environmental advantages in marine applications, but further research and development needs to be done before the concept can be applied onboard ships.

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Nomenclature

AC1	Air cooler 1
AC2	Air cooler 2
DNA	Dynamic Network Analysis - computer simulation tool
ECA	Emission control area
ECO	Economiser
EES	Engineering Equation Solver ©
EVA	Evaporator
HFO	Heavy fuel oil
HP	High pressure
IMO	International maritime organisation
JWP	Jacket water preheating
LP	Low pressure
LPV	Low pressure valve
MCR	Maximum continuous rating
NO _x	Nitrogen oxides
PT	Power turbine
SFOC	Specific fuel oil consumption
SH	Superheater
SO _x	Sulphur oxides
SS	Steaming services
ST	Steam turbine
TC	Turbocharger
TCC	Turbocharger compressor
TCT	Turbocharger turbine
WHRS	Waste Heat Recovery System

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