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Improving pre-turbine SCR systems in marine two stroke diesel engines using hybrid turbocharging: a numerical study of SCR operation range and system fuel efficiency

Jørgen Bremnes Nielsen[1], Kevin Koosup Yum[2] and Eilif Pedersen[1]

Abstract

In this paper a performance evaluation of a novel system solution combining a hybrid turbocharger and a pre-turbine selective catalytic NO_x reduction system is carried out. Pre-turbine selective catalytic system are used with marine two stroke diesel engines to comply with IMO Tier III. The system solution focuses on expanding the SCR operation range which is limited by fuel sulphur content by increasing exhaust temperature at low engine loads. The extended operation range is to be achieved while minimizing any fuel consumption penalties. Increasing the operation range brings improvements to emission levels during maneuvering operations which are often carried out close to populated areas. It also provides flexibility by enabling emission reduction during slow steaming operations in which mitigating fuel consumption penalties is paramount. In addition to system evaluation in still water conditions additional evaluations have been carried out taking into consideration the effect of waves on the system performance. Investigating the effect of operating in waves bring additional insight that is relevant for predicting performance in operational conditions. Analysis of the system solution found that improvements in SCR operation range can be achieved while also improving fuel consumption. Fuel consumption is significantly improved in the high load range. Effect of realistic operation conditions where found to affect performance, however significant effect are only found for harsh sea states in the load range below the design point.

Keywords

SCR deNOx, Hybrid turbocharger, Marine machinery systems

Introduction

Although shipping is an efficient mode of transport generally using less fuel for a given transport work than other modes of transport, shipping emissions make up a significant fraction of the global CO_2, NO_x, SO_x and particulate matter (PM) emissions[1, 2, 3, 4]. These emissions have a negative impact on the global climate, the environment and the human health [5, 6, 7]. The International Maritime Organization (IMO) is therefore working on reducing both CO_2 intensity and gaseous emissions. Previous efforts to reduce gaseous emissions have often been achieved with a cost of increased fuel consumption and thereby increased CO_2 emissions. With the current focus on reducing both CO_2 and gaseous emissions a more comprehensive approach to improving the marine power plant is required.

Emissions to air that are currently regulated by the IMO are SO_x, NO_x and PM. SO_x and PM is regulated by setting a maximum limits on the amount of sulphur that is allowed in fuels, although exceeding the limit is allowed if the exhaust is cleaned by exhaust gas cleaning system such as a SO_x scrubber. NO_x emissions are regulated by tier based emission limits, where Tier I and II has been met by engine internal measures. However with the introduction of Tier III, engine internal measures are not sufficient and engine manufacturers have to rely on engine external abatement systems. One solution is to use urea based selective catalytic reduction (SCR) NO_x removal. SCR based deNOx is a widely used technique for removal of NO_x which was first introduced on onshore stationary sources like boilers, gas turbines and diesel engines for power generation [8, 9]. In the automotive sector heavy duty diesel engines are currently relying on SCR deNOx to meet NO_x emission limits. SCR systems installations are increasing to meet the Tier III requirements and are common on-board ships that operate in Norwegian NO_x tax area [10].

The use of SCR deNOx systems in combination with a typical marine two stroke engine burning marine high sulphur heavy fuel oil bring challenges. Sulphur can in addition to acting as a catalyst poison, react and form undesirable byproducts [11]. Avoiding formation of byproducts such as ammonia-sulphates requires an SCR operating temperature above a temperature limit given by the fuel sulphur content [12]. This temperature is in the 330

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[2]Sintef Ocean (MARINTEK) AS, Trondheim, Norway

Corresponding author:
Jørgen Bremnes Nielsen, Department of Marine Technology, Norwegian University of Science and Technology, Otto Nielsen vei 10, 7491 TRONDHEIM, Norway
Email: jorgen.b.nielsen@ntnu.no

C° range for typical fuel sulphur concentrations. Marine two stroke after turbine exhaust temperatures are in the range of 230 to 260 C° which are too low for SCR operation with high sulphur fuels. Therefore SCR systems for high sulphur two stroke application are installed before exhaust turbine [13] where temperatures range from 430 C° at max load, to 280 C° at low load and lower at idling and maneuvering speeds. The engine load where the exhaust temperature, despite a pre-turbine installation, drops below SCR operation temperatures depends on the fuel sulphur content, engine efficiency and turbocharger matching. Increasing the SCR operation range depends on rising the exhaust temperature above the operating temperature limit. However, as such temperature increase wastes energy, recovering this energy is necessary to avoid excess increases in fuel consumption. There are several approaches to recover high temperature energy from the exhaust gas stream where the Rankine cycle [14, 15, 16], Kalina cycle [17] and turbo compounding [18] are examples of methods for recovering waste heat.

In this study the use of turbo compounding as a method of achieving increased efficiencies while also increasing the pre-turbine SCR operation range is being evaluated using mathematical modelling and numerical simulation. With the the current compressor and turbine efficiencies, there is a significant potential for exhaust energy recovery [19]. It is therefore suggested to exploit the different operating characteristics of the diesel engine and the turbocharger turbine using turbo compounding to offset the fuel penalty associated with increased exhaust gas temperature. In addition it is suggested to use an auxiliary burner in the exhaust receiver giving additional capabilities to increase the exhaust temperature.

Dynamic models of the engine system is used to evaluate the system performance. The novelty of the study is the use of realistic operation conditions in addition to more common steady state still water evaluations to asses the performance of a suggested system solution. Evaluation of suggested systems or optimization of designs are often focused either on a single load point [20], a couple of loads [21] or an operation profile consisting of series of load points [22]. However a vessel operates in real waves that can change the performance characteristics compared to still water conditions. Evaluation of real operation conditions is achieved by including models for propulsion efficiency, hull motion and waves. Performance indicators used in this paper are specific fuel consumption and SCR inlet temperature.

The paper is structured as following, first a section providing additional problem description and background, followed by a section on description of suggested system layouts and designs. Then follows details on modelling approach and models before the result section, where simulation results of still water and irregular waves scenarios are presented and discussed. Finally the conclusion.

Background

A common marine power plant design for deep sea shipping consists of a slow speed two stroke diesel engine running on heavy fuel oil. The propeller is directly connected to the engine without any gearbox. This design is very efficient reaching peak engine efficiency of approximately 50 %. In addition there are several four stroke auxiliary engines for electric power production. A typical engine system design is based on a design point of 80 % of max continuous engine rating (MCR)

Although the typical design point of 80 % MCR is within the SCR operation range, there are operation scenarios such as slow steaming and operational phases such as manoeuvring in and out of port and hauling between berths that are outside the SCR operation range. Emissions during port maneuvering contribute to local emission levels [23] and being compliant in off design operation such as slow steaming is important to allow for flexibility in operational decisions, hence it is important to enable SCR operation at low load operation.

Increasing the SCR operation range requires controlling the exhaust gas temperature. Controlling the engine air flow is an effective way of achieving this temperature control. In the automotive sector using a variable geometry turbine for air flow control have been used to optimize the engine efficiency and SCR operation [24]. In the marine two stroke sector low load SCR operation has been achieved by controlling air flow using a bypass valve from the scavenge air receiver to the turbine inlet, bypassing the engine and the SCR system [25]. SCR operation down to approximately 25 % load was achieved, however a specific fuel oil consumption (SFOC) penalty was observed.

In this study the use of turbo compounding is to be explored as a method to reduce fuel consumption and increase SCR operation range. There are several approaches to turbo compounding. Energy may be harvested from the turbo charger shaft directly or by a separate power turbine. A separate turbine may be arranged in either series or parallel with the turbo charger turbine. Using a electric generator to harvest energy directly from the turbocharger shaft, also known as hybrid turbocharger (HTC), allows for flexibility in the control of the power production [26, 27]. It also allows for power to be fed to the turbocharger improving transient responses. Electric energy can also be stored in a battery or super capacitors for later use. With the addition of a PTI/PTO solution, electric power from the HTC may also be delivered to the propeller shaft.

Extending the operation range of the SCR system on two stroke engines operating with high sulphur fuels requires changes to the operation and design of the marine power plant. At this level of system complexity and at an exploratory stage of investigation, cost prohibits use of prototype development or testing. A cost effective approach to investigation of marine power systems without the use of prototypes is to use mathematical modelling and numerical simulation.

Mathematical models and numerical simulation have been extensively used to develop SCR catalysts, systems and control designs. Tronconi et al. presented a model for performing unsteady analysis of NO_x reduction including transportation and storing of NO and NH_3 in the catalyst material [28] which is important for understanding performance during transient operation and for control development. McKinley and Alleyne suggested using model predictive control based on numerical models of the SCR system reducing the control development time and the need for control tuning [29].

Turbo compounding have also been investigated using mathematical models. Pasini et al. evaluated different electric turbo compounding layouts on a compression ignition engine using numerical models and simulation [30]. In the work by Frigo et al. the numerical analysis of different electric turbo compounding layouts have been expanded to include the vehicle and the power system responsible for handling the power produced by the electrical generator [31]. Katsanos presented simulation steady state results for a heavy-duty diesel with electrical turbo compounding where the turbocharger model was based on compressor and turbine maps [32].

Investigation of system performance for marine power systems using modelling and simulation have been presented for a variety of different systems. Kyrtatos [33] presented a simulation model for the overall marine propulsion system focusing on the diesel engine control strategy during transient operation. Dimopoulos et al. [34] presented a general purpose process modelling framework for marine energy systems with the focus on optimizing energy efficiency, emissions, safety/reliability and cost. The simulation of a hybrid propulsion system in waves has been carried out by Yum et al. [35].

System Description

In this section three system designs, three turbocharger designs and three hybrid turbocharger operation modes will be presented. These designs and operation modes will be used in the evaluation of the proposed approach to increase SCR operation range. The system designs include a standard diesel engine and turbocharger system setup, where the turbocharger is free spinning, a system setup with SCR, free spinning turbocharger and bypass valve and a system setup with SCR and hybrid turbocharger. The two free spinning system setups are presented in Figure 1 while the hybrid turbocharger system is presented in Figure 2. The three turbocharger designs include the reference turbocharger where the design in matched to the original turbocharger, a hybrid turbocharger design optimized for SCR operation range and a hybrid turbocharger design optimized for reduced fuel consumption. For the hybrid turbocharger system three operation modes are considered: Fuel consumption optimization, SCR operation range optimization and SCR operation range optimization with use of auxiliary burner. For low load engine operation where the exhaust turbine is not able to provide enough power for the compressor to deliver enough air, the reference systems use an auxiliary blower while the hybrid turbocharger system depends on feeding power through the electric motor to drive the compressor removing the need for an auxiliary blower.

The reasoning behind the three turbocharger designs and three hybrid turbocharger operation modes is the geographic application of IMO Tier III NOx regulation and the possibilities of different requirements from ship owners. For some trades high fuel consumption when operating with SCR is acceptable if the savings are large when running without SCR, while the opposite may be true for other trades.

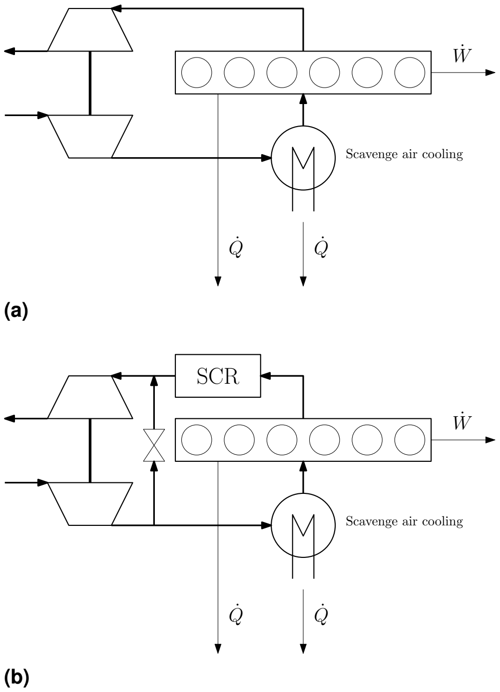


Figure 1. Reference systems. a) Standard diesel engine, b) standard diesel engine with SCR and bypass valve for exhaust temperature control

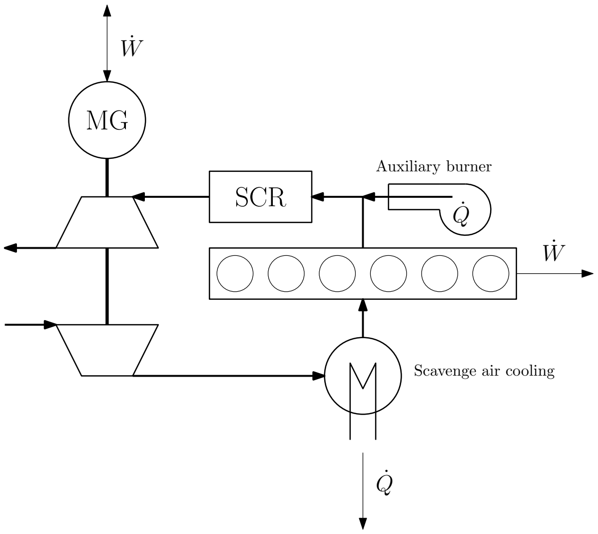


Figure 2. System to be designed and optimized for concept study of combining hybrid turbocharging and pre-turbine SCR systems

Reference and concept systems

The standard diesel engine system and the system with SCR and bypass, see Figure 1, are used as reference systems for the concept system with operation focusing on fuel optimization or SCR operation range optimization respectively. These systems are using the reference turbocharger design. In addition the effect of using optimized turbo charger designs for the hybrid turbocharger is evaluated using the reference turbocharger design in the hybrid turbocharger system, see Figure 2.

The concept systems consists of the hybrid turbocharger system using either the SCR operation range optimization with or without burner operation modes or the fuel

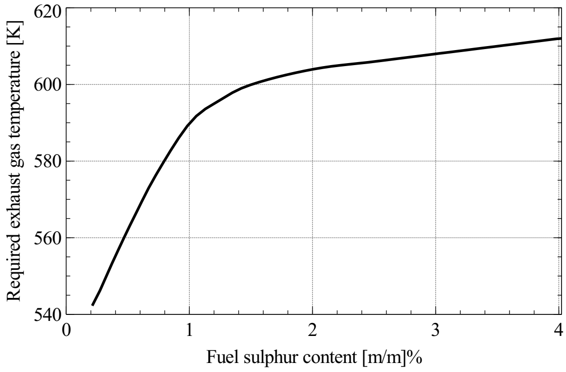


Figure 3. Required exhaust gas temperature at SCR system inlet as function of fuel sulphur content [12]

consumption optimization operation mode. The SCR operation modes are optimized for a exhaust gas temperature of 340 C° which allows for operation with sulphur content up to approximately 3.5 % according to Figure 3.

For easier identification, the turbocharger design for optimized specific fuel oil consumption is designated D-SFOC while the design optimized for SCR operation range is designated D-SCR. The three hybrid turbocharger operation modes are designated as following: optimized specific fuel oil consumption SFOC-O, maximum SCR operation mode SCR-O and maximum SCR operation mode with auxiliary burner in operation SCRB-O. Table 1 summarizes the different system designs, turbocharger designs and operation modes that is to be evaluated.

Hybrid turbocharger design

Total fuel efficiency for a diesel engine with a hybrid turbocharger and auxiliary burner depends both on the engine, compressor and turbine efficiency and amount of fuel burned in the auxiliary burner. For the engine, efficiency increases with excess air ratio as the heat ratio increases. However exhaust energy available for energy harvesting decreases with excess air ratio due to increased boost pressure ratio resulting in reduced compressor polytropic efficiency and increased energy loss in the scavenge air cooler.

Obtaining the maximum efficiency depends on matching both compressor and turbine designs to the efficiency characteristics of the engine. In this study the engine and SCR system design and control is fixed. Design variables that are available for optimization is the hybrid turbocharger and burner control and design of the turbocharger. Determining turbocharger design is simplified by using a initial design method for estimating compressor and turbine performance maps with only limited design parameter inputs. For compressor map estimation the authors have selected to use the method of [36, 37, 38] where both optimum compressor design and resulting compressor map are estimated.

HTC Control strategy

The hybrid turbochargers are controlled based on a table look up approach. Optimum HTC speed which meets the operation temperature requirement is determined based on engine RPM and torque. Break torque on the turborcharger shaft is controlled with a PID controller with HTC speed as measured value and optimum speed from the table look-up as required speed. The optimum HTC speeds take into account the temperature limits of a typical marine SCR system.

SCR deNOx systems for maritime applications use vanadium based catalyst material which has a high resistance against sulphur poisoning. Operation range for vanadium based catalysts are from 250 C° to 450 - 500 C°. The low temperature limit is caused by low reaction rates while the high temperature limit is caused by increased ammonia oxidation rates [39]. In addition there is a upper temperature limit for where thermal aging of the catalyst material increases rapidly. This thermal aging temperature limit depends on catalyst material. Girard [40] found that the maximum temperature for and older type of catalyst is in the range of 530 C°, while [41] found significant loss of $NO_{(}x)$ conversation efficiency at temperatures in the 670 C° range.

Power system model

Two models of the power system and loads have been implemented with ability to evaluate steady state operation and operation in waves. The steady state model is equivalent to a engine test bench setup, while the operation in waves model includes models to take into account the effect of waves on ship motion and speed and its effect on propeller torque which again effects the power system. These two models are presented in Figure 4.

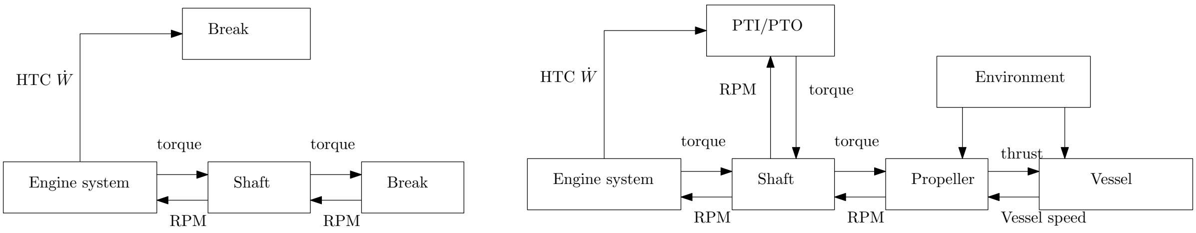
For the steady state model load is included by breaks both on the engine shaft and at the hybrid turbocharger shaft. For the operation in waves model a PTI/PTO system have been included to feed power from the hybrid turbocharger to the propeller shaft.

The diesel engine models used in the this work has been developed by Yum with the aim of being able to simulate time domain responses of the propulsion system, the interactions between propeller and diesel engine and estimate efficiency [42]. Important sub-models for estimating efficiency and transient response are the combustion model and the turbocharger model. A 0D semi-physical approximate model is used for the combustion process and compressor and turbine maps are used for the turbocharger model. The diesel engine model of Yum has been extended with a SCR system model developed by the authors [43]. The SCR system model is based on a constant speed and density flow approximation and an average wall concentration approximation for calculation of reaction rates. For this initial investigation hybrid turbocharging has been implemented by adding additional breaking torque to the turbocharger shaft without any electrical machine dynamics. For this initial study the focus is on the air side and simplifying the electric side is expected to have limited impact on the air side performance estimation, especially in steady state cases. More detailed studies will benefit from a more complete generator model as it allows for investigation of dynamics and optimization of generator size and control.

For operation in waves the model is expanded with a vessel model and a propeller and shaft model. The vessel model includes the effect of waves by estimating added resistance and calculates vessel motion RAOs using one-dimensional vessel representation only considering surge motion. Both

Table 1. System designs and operation modes to be evaluated

		Turbocharger designs		
		Reference	D-SFOC	D-SCR
Reference system designs	Free spinning	×		
	Bypass	×		
Hybrid turbocharger operation modes	SFOC-O	×	×	×
	SCR-O	×	×	×
	SCRB-O	×	×	×



(a) **(b)**

Figure 4. Simulation model setup for steady state a) and unsteady state b)

added resistance and ship motion RAOs have been calculated using ShipX Veres developed by Sintef Ocean (previously MARINTEK). The calculation method uses linear strip theory, utilizing potential theory and pressure integration. Added resistance was calculated for irregular seas for different Hs-Tp and heading combinations using the Pierson Moskowitz wave spectrum with added resistance coefficients using the method by Loukakis and Sclavounos [44]. The propeller model is one-quadrant with thrust and torque coefficient curves obtained using the open source software Openprop. Frictional drag is calculated using Javafoil [45]. Ship motion RAOs are used to calculate stern motion which is used in propeller inflow calculation. Stern motion and propeller inflow affects propeller operation and thereby the propeller torque and thrust. These effects has been calculated according to Taskar et al. [46].

The vessel selected for this study is the academic hull KVLCC2. Wartsila 8RT-FLEX68D was selected for the main engine. Propeller has been adjusted to match the main engine. These choices were made based on the availability of data for validation of the models. Data on hull, propeller and engine is given in Table 2. Table 3 presents the modelling framework of the sub-models used in this concept study.

Results and Discussion

In this work the performance indicators of interest is specific fuel oil consumption and exhaust gas temperature at the SCR system inlet. Calculation of specific fuel oil consumption has been expanded to include energy consumed for blower operation or by the hybrid turbocharger at low engine load. It is assumed that this energy is delivered by auxiliary engines with a specific fuel consumption of 190 [g/kWh]. This fuel consumption is added to the main engine fuel consumption when calculating specific fuel consumption for the main engine.

Hull data	
Length between perpendiculars [m]	320.0
Length at water line [m]	325.5
Breadth at water line [m]	58.0
Depth [m]	30.0
Draft [m]	20.8
Displacement [m^3]	312,622
Block coefficient (CB)	0.8098
Design speed [m/s]	7.97
Propeller geometry	
Diameter [m]	9.86
Number of blades	4
Hub diameter [m]	1.53
Rotational speed [RPM]	95
A_e/A_o	0.431
$(P/D)_{mean}$	0.47
Skew [°]	21.15
Rake [°]	0
Main engine specifications	
Engine model	Wartsila 8RT-FLEX68D
Bore [mm]	680
Stroke [mm]	2720
Rated MCR [kW]	25,040
Speed at rated power [RPM]	95
Mean effective pressure [bar]	20
Number of cylinders	8
Turbocharger	2 x ABB A175-L35
SCR system	
Space velocity [h^{-1}]	13,700
Cell density [1/150 mm]	31
Back pressure at 100 % MCR [kPa]	135
Density catalyst material [kg/m^3]	1200.0
Specific heat capacity [$kJ/kg \cdot K$]	800.0

Table 2. Subsystem parameters and description

Propeller curve results

Reference systems Propeller curve results are based on steady state operation in calm water. Efficiency is evaluated at shaft output for both engine end turbocharger. No electric generator loss has been included.

Specific fuel consumption and exhaust gas temperature for the reference designs are given in Figure 5. The reference

Sub-model	Modelling framework
Diesel engine system	Filling and emptying method 0D phenomenological combustion
Shaft system	Single rigid body
Vessel	1D rigid-body Calm Water Resistance Curve Added Resistance Coefficient
Propeller	Quasi-steady based on propeller curve Mean wake variation model
SCR system	Constant velocity and density Average wall concentration

Table 3. Modelling framework of the sub-models

bypass system shows a higher fuel consumption due to the SCR system induced back pressure. From 25 to 65 % load the bypass system has increased specific fuel oil consumption also due to the bypass valve starting to regulate the exhaust gas temperature. Below 25 % load the valve closes as it is no longer possible to obtain the required exhaust gas temperature and the SCR system is bypassed returning the specific fuel oil consumption to that of the reference standard system. The significant increase in specific fuel consumption for the bypass system in the 25 to 35 % load range is due to the blower being activated. Currently the blower is either on or off resulting in significant losses when blowing air through the bypass valve. An improved blower design or control regime could probably reduce the increase in specific fuel oil consumption between 25 and 35 % load.

Design comparison with SFOC operation Comparison of the all turbocharger designs with SFOC operation is presented in Figure 6. There are only minor differences in specific fuel oil consumption and exhaust temperature between the turbocharger designs with hybrid turbocharging. However compared to the reference design without hybrid turbocharger there is a significant reduction in specific fuel consumption above 50 % load. With a hybrid turbocharger the minimum consumption of the reference non hybrid turbocharger is achieved up to approximately 80 % load giving a larger engine operating range with high efficiency. Below 50 % load there are however no significant differences in specific fuel oil consumption compared to the reference non hybrid turbocharger design. Exhaust temperatures of the SFOC operation mode allows for SCR operation down to between 40 to 50 % load compared to the reference system 65 % load.

Design comparison with SCR operation Comparison of the all turbocharger designs with SCR operation is presented in Figure 7. Using a hybrid turbocharger and the SCRO turbocharger design somewhat extended SCR operation range, however using the bypass arrangement have a larger operation range that both the reference and the SFOCO turbocharger design. Regarding specific fuel consumption hybrid turbocharging have lower specific fuel consumption for the whole SCR operation range with significant lower specific fuel consumption above 50 % engine load compared to the reference bypass design. Using the burner extends SCR operation to the whole engine load range tested, however a significant increase in specific fuel consumption is observed. The increase is highly dependent on turbocharger design. At 10 % engine load the reference design has a 40 % increase in fuel consumption compared with no SCR operation, while the SFOCO has a 35 % increase and the SCRO has a 23 % increase.

The three turbocharger compressor maps with the air flow and pressure ratio for the different operation modes in steady state are presented in Figure 8. It should be noted that SFOC, SCR and SCR-B operation with the reference design leaves a limited surge margin compared to the SFOCO and SCRO compressor design.

Hs	Tp
0	-
4	12
6	14
8	16

Table 4. Hs-Tp combinations investigated for evaluation of specific fuel consumption in waves

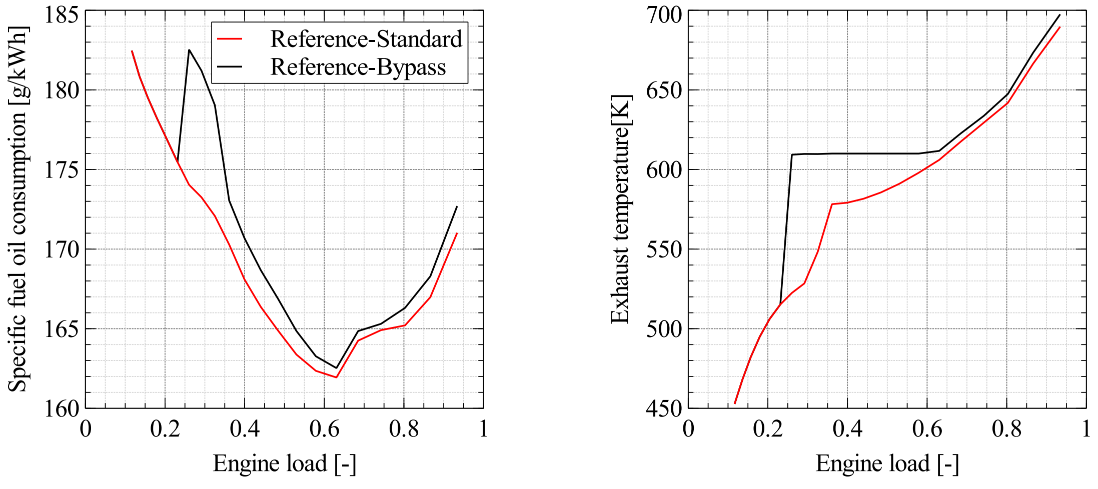
Results for operation in waves

For evaluation of operation in waves it is assumed that all power produced by the hybrid turbocharger is made available as propulsion power through the PTI/PTO. Turbocharger generator and shaft electric motor are assumed to both have an efficiency of 95 %. The irregular sea performance evaluation is based on the sea states given in Table 4.

The procedure for estimating the performance in waves is to select a sea state by selecting a Hs-Tp combination and encounter heading. Required engine power is set and a simulation in run until steady state speed is achieved. Fuel consumption, power and other power system variables are averaged over 100 second operation period after achieving steady state speed.

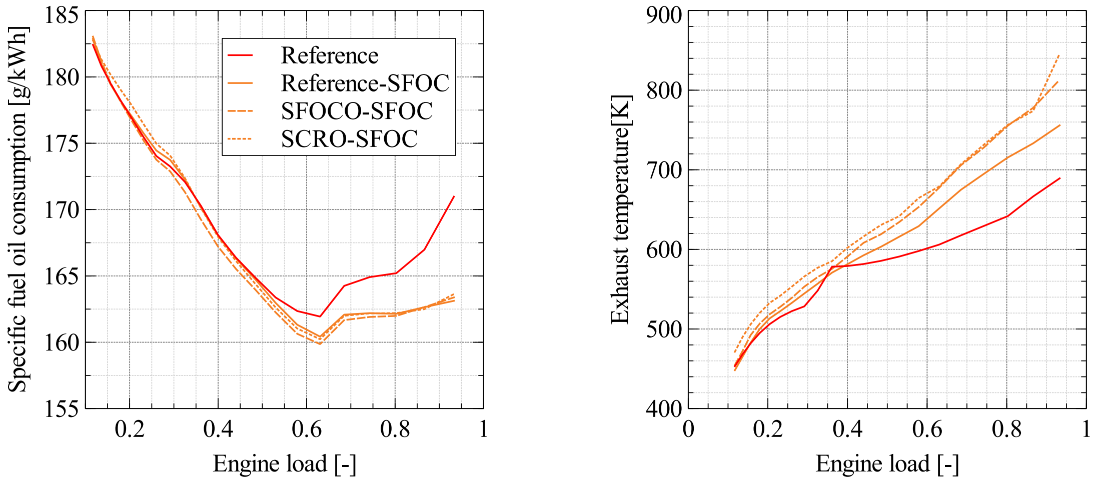
A comparison of the three turbocharger designs with different operation models for three different sea states with different encounter headings are presented in Figure 9. Head waves are defined to be at encounter heading 180° . The engine power range tested is from 10 MW to 25 MW with a total of 11 values. For calm seas, 9a there is as expected no effect of encounter heading. With increasing severity of the sea state, Figure 9b-c encounter heading starts to have an effect and the different designs show slightly different responses.

The results in Figure 9 is useful with respect to showing that there is an effect of sea state on system performance and that the change is performance can be different for different systems. A more detailed comparison of the differences for the system performances in different waves are plotted in Figure 10, where specific fuel consumption are plotted in Figure 10a. In Figure 10b the effect of different sea states on each system is evaluated using the still water curves as references. The observed general effect of waves on the engine specific fuel consumption is reduced efficiency at low load and somewhat increased efficiency at higher load. The Reference Free-spinning design appear to not achieve maximum power at the harsher sea states, while this is not observed for the HTC designs. The effect of the different sea states does also have the same effect on the different systems except for loads above 20 MW where some slight deviations can be observed. The overall effect of waves on the system are limited. One possible reason for the limited impact of waves of waves on performance may be the vessel used in



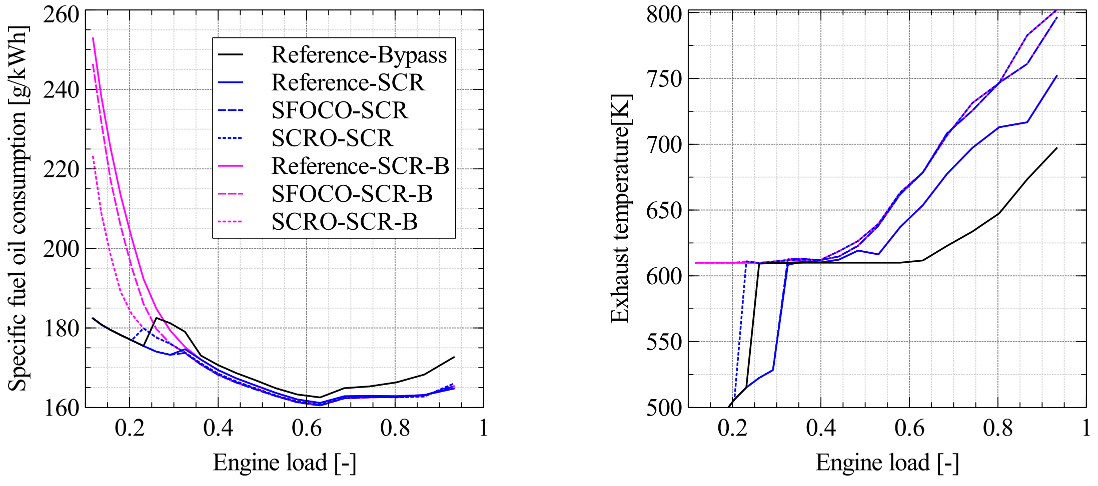
(a) **(b)**

Figure 5. Specific fuel consumption a) and exhaust temperature b) for default design with three different operation modes



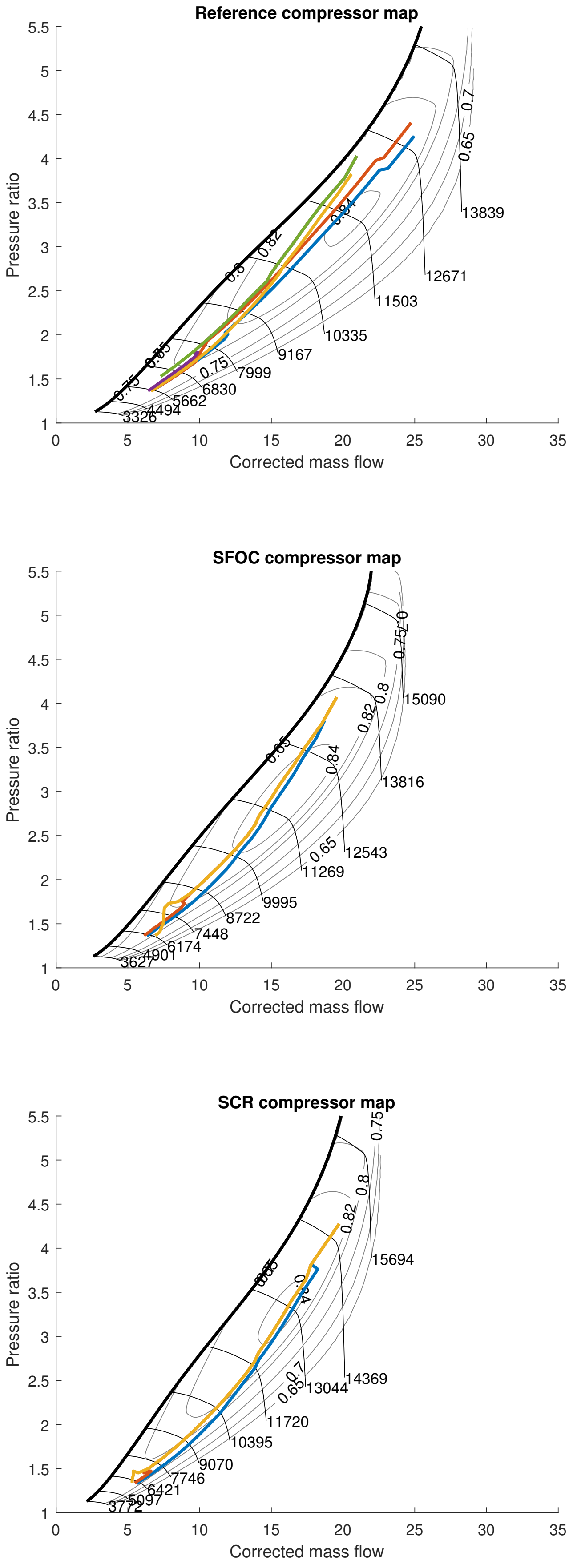
(a) **(b)**

Figure 6. Specific fuel consumption a) and exhaust temperature b) for all designs with SFOC-O operation mode



(a) **(b)**

Figure 7. Specific fuel consumption a) and exhaust temperature b) for all designs with SCR-O operation mode

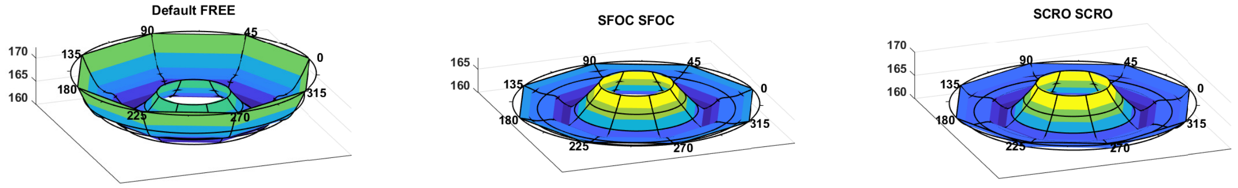


(a)

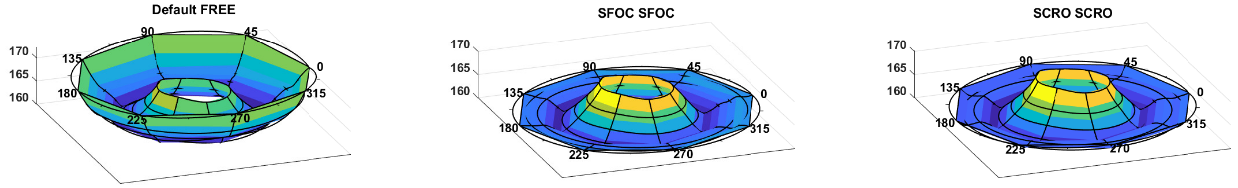
(b)

(c)

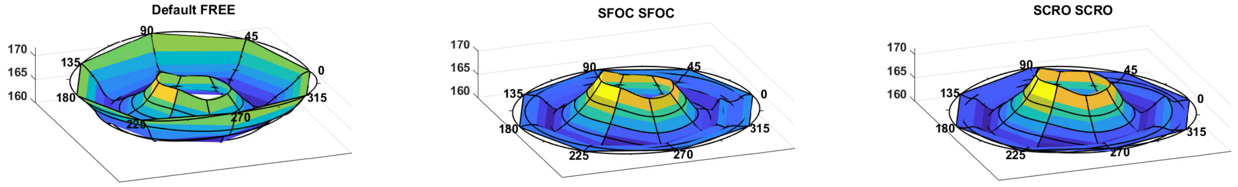
Figure 8. Turbocharger compressor maps a) Reference compressor, b) SFOCO compressor, c) SCRO compressor. Airflow and pressure ratio for the different operation modes are given



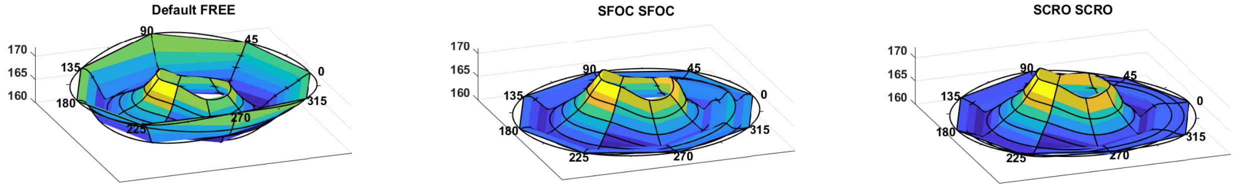
(a) $HS = 0, TP = N/A$



(b) $HS = 4, TP = 12$



(c) $HS = 6, TP = 14$



(d) $HS = 8, TP = 16$

Figure 9. Specific fuel consumption for irregular waves waves with different Hs and Tp values and encounter headings. Engine load is 10 to 25 MW

this case study. It is expected that other ship categories such as high speed container vessels will see a larger impact of waves on the engine and propeller performance.

From these irregular waves system performance evaluation it is possible to obtain data on how much a system performance changes from steady state to more realistic operation. However using this knowledge to estimate the total consumption over an operation for a vessel becomes more challenging. For a steady state performance evaluation an operation profile with steady state loads of different duration could be used to find the total fuel consumption during a whole operation. Using irregular waves increases the challenge of making operation profiles as knowledge of sea states headings and speeds during operation is required to generate input to the simulation.

Conclusion

This preliminary evaluation of a combined SCR and hybrid turbocharger systems have been shown to offer improvements in both SCR system operation range and specific fuel oil consumption compared to system solutions described in the literature. This work highlights the importance of and possibilities in addressing multiple challenges in a single system development. Further possibilities are available in including more comprehensive thermal management improving the utilization of the energy available in a marine power plant.

Using a steady state calm water scenario for system evaluation is a simple and fast method, however more detailed system evaluations should be conducted. Some evaluations in irregular waves were carried out, however only limited conclusions can be drawn from such a small sample. Further work should include a more comprehensive approach to system evaluation in real seaway enabling better understanding of proposed system solutions in real operation.

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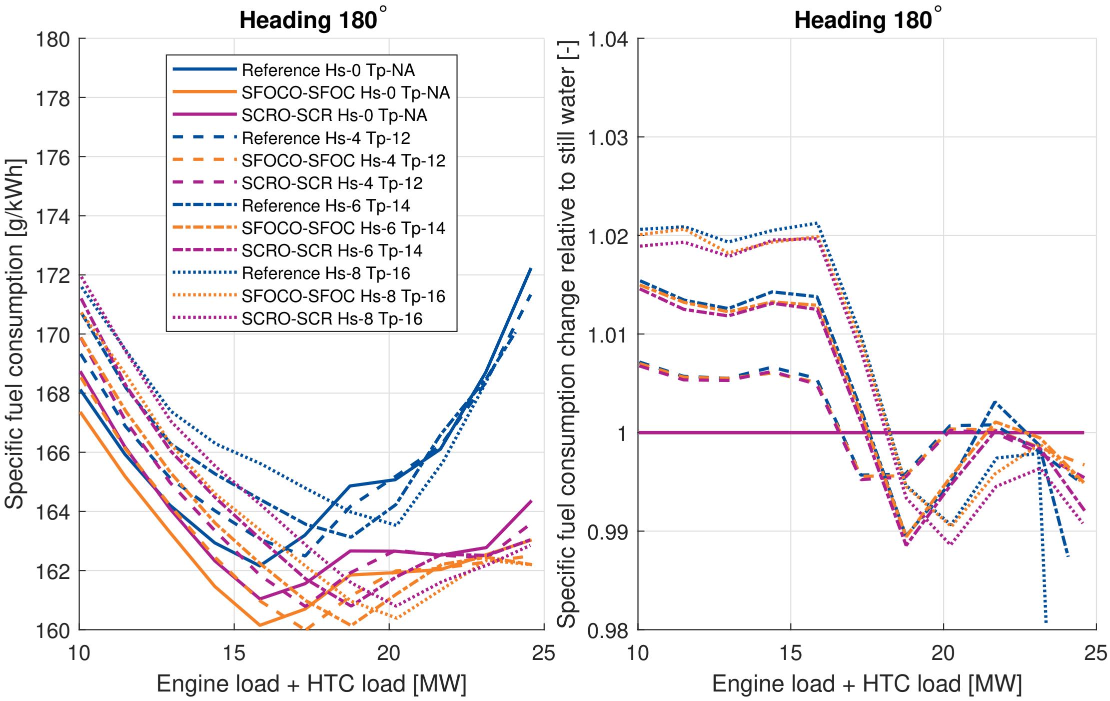

(a) **(b)**

Figure 10. Comparison of different specific fuel consumption curves for different systems operating in three sea states with encounter heading of 180°

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