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Analysis of the influence of the engine, propeller and auxiliary generation interaction on the energy efficiency of controllable pitch propeller ships

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Abstract: In a context of increasing requirements for energy efficiency, this paper aims at improving the understanding on the interaction between engine, propeller, and auxiliary heat and power generation in the particular case of controllable pitch propeller (CPP) ships. The case study of a CPP propelled chemical tanker is used to analyze the application of the proposed approach. The performance of the ship's standard arrangement using a shaft generator for the fulfillment of auxiliary power demand is compared to the operational alternative of using auxiliary engines, and with the possibilities for retrofitting with frequency converters and waste heat recovery systems. The influence of control systems parameters and of sea state are also analyzed and compared. The results show a large possibility for improvements, both via operational optimization (up to 8.3% increased energy efficiency) and via different types of retrofitting (with increased efficiencies of up to 11.4% for frequency converters, and 16.5% for WHR systems). The influence of a broad operational envelope brings even larger improvements to the efficiency of the energy system at low speeds. The results of the paper provide useful information about the influence of different technologies for auxiliary power generation on the efficiency of CPP propelled vessels.

Keywords: propulsion system, energy efficiency, shipping, CPP, modelling
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1 Introduction

1.1 Background

In recent times two main factors have exerted a strong influence on the development and the use of fossil-fueled energy systems and, in particular, of internal combustion engines. On the one hand, the awareness is growing about human contribution to climate changes in terms of greenhouse gases emissions (Houghton, et al. 1990). On the other hand, the fuel market is experiencing a new, large increase in demand, mainly triggered by developing countries' growing economies, that is not matched by a proportionate increase in resources availability (Bentley 2002). The joint influence of these two elements has brought a new, rising interest in technologies for reducing engine fuel consumption.

One of the directions researchers have started to look at is a better understanding of the connections that can be found in complex energy systems. In this kind of structures a simple component-by-component optimization could be inefficient and even lead to the undesired phenomenon of sub-optimization. However, the many possible configurations that each energy system could take do not allow a simple, straight-forward experimentation which is expensive and time consuming. For this reason, the analysis and optimization of energy systems is subject to the use of accurate predictive mathematical models.

1.2 Previous work

Even though the extent of research in energy system modelling in shipping is not as wide as what available for other industrial sectors, extensive research has been published focusing on the main propulsion systems: Schulten and Stapersma (2007) presented an analysis of the uncertainty in relation to the validity of a ship's model as a complex system; Grimmelius, et al. (2007,2010) proposed a useful modeling methodology and a complete verification, calibration and validation,of a ship propulsion system; Campora and Figari (2003) proposed a similar analysis making use of models with higher mechanistic content and providing validation of the system transient behavior; Dimopoulos, et al. (2010,2011); proposed a thermo-economical optimization of a waste heat recovery (WHR) plant for a containership. Theotokatos (2007, Theotokatos and Tzelepis, 2013) presented a simplified modeling approach for the overall ship propulsion system model, both in steady-state and in transient operations and its application to mapping ship energy and environmental performance.

Most of the work previously mentioned focused on the most typical propulsion system configuration, i.e. a large two-stroke engine coupled with a fixed pitch propeller (FPP). This configuration is very common and therefore very

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relevant to study. The utilization of four-stroke engines, in combination with a controllable pitch propeller (CPP) and with a shaft generator (SG) for the generation of auxiliary power, generates additional complexity in the analysis. However, only the work from Tian, et al. (2012) exists to the knowledge of the authors, which however does not consider auxiliary power generation. Even though CPP propeller ships represent a lower share of global fleet tonnage, they are particularly relevant for some specific sectors, e.g. RoRo vessels and cargo ships operating on short routes.

1.3 Aim

The aim of this paper is to provide an analysis of the performance of the combined propulsion-electric generation system for a CPP propelled ship. The objective is to provide useful information about the influence of the choice of the auxiliary power generation system on the energy efficiency of the whole system under different conditions of ship resistance and engine operating envelop. The methodology here presented can be applied in the evaluation of different alternatives both in operational, retrofitting, and design phases.

2 Study cases and scenarios

As the aim of the paper is to study the influence of different arrangements for onboard energy generation, this has to be tested on a specific system, i.e. for a given power and size, In this study, a case study ship is used for the evaluation, and described in Section 2.1.

Four different arrangements are compared, based on the choice of the auxiliary generation system:

- Fixed speed shaft generator (SG)
- Auxiliary engines (AE)
- Shaft generator with frequency converter (SG-FC)
- Waste heat recovery system (WHR)

The comparison of the different systems was performed on the case study ship in calm water conditions. In addition, the influence of added resistance and type and shape of engine operating envelope were also taken into account, as detailed respectively in Sections 2.3 and 2.4.

2.1 Description of the case study

In order to demonstrate the applicability of the proposed methodology, operational data from a real ship is used in this study. The selected ship is a Panamax chemical / product tanker. Relevant ship features are provided in Table 1, while Figure 1a conceptually represents the ship energy systems.

The ship is propelled by two 4-stroke Diesel engines rated 3840 kW each. The two engine shafts are connected to a common gearbox (GB). One of the gears reduces the rotational speed from 600 rpm to 105.7 rpm, the design speed for the controllable pitch propeller (CPP). Another shaft connects the gearbox to the electric generator (SG) which provides electric power at 60 Hz to the ship. Additionally, two auxiliary engines rated 682 kW each can provide electric power when the main engines are not in operation, or in case of SG failure. Auxiliary heat needs are fulfilled by the exhaust gas economizers (EGE) or by auxiliary boilers (AB) when the main engines are not running or when heat demand is higher than what provided by the EGEs.

Table 2 Case study ship main features

Ship feature	*Value*	*Unit*
Deadweight	47 000	ton
Installed power (Main Engines)	7 680	kW
Installed power (Auxiliary Engines)	1 364	kW
Shaft generator design power	3 200	kW
Design speed	15	kn

The propulsive power is considered a function of ship speed and propeller speed, whose modeling is detailed in Section 3.2. Available measurements for the case study ship showed that auxiliary electric power is almost constant over time, and can be assumed as constant for the purpose of this study. After an analysis of the ship operational data, it was found that auxiliary power demand is equal or lower than 364 kW for 80% of the time spent at sea. This value was therefore considered as the approximation for the auxiliary power demand. A similar analysis for the heat demand led to an approximated value of 300 kW that has to be generated using the EGEs and is therefore not available for possible WHR systems.

2.2 Alternative energy system arrangements

Four alternative arrangements were tested and compared in this study, which are described in sections 2.1.1 to 2.1.4. It should be noted that cases SG and AE refer to possible operational configurations of the system already in place, while cases SG-FC and WHR refer to possibilities for retrofitting. All cases are compared in terms of the ship specific fuel consumption (SSFC) defined as the amount of fuel required by the ship to sail over one nautical mile.

2.2.1 SG case: Shaft generator at constant speed

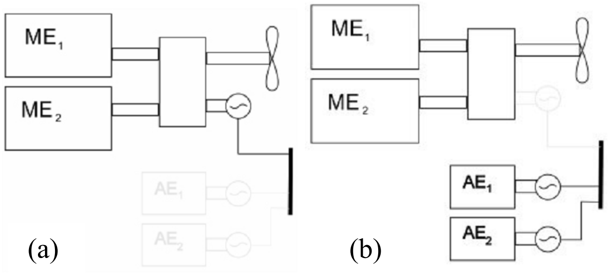
The SG case corresponds to the arrangement employed on the case study ship in most of its sea passages, and is conceptually described in Figure 1a. Both the main engines and the propeller are operated at constant speed to allow the SG to generate electricity with a constant frequency. For the SG case, the SSFC is calculated according to Equation 1.

$$SSFC_{SG} = v_s^{-1}\left[bsfc_{ME}\left(\frac{P_{prop,\mathrm{FS}}}{\eta_{GB}\eta_S} + \frac{P_{el}}{\eta_{GB}\eta_{SG}} \right) \right] \qquad (1)$$

where the variables $bsfc$, v_s, P_{el} and $P_{prop,FS}$ respectively represent engine breake specific fuel consumption, ship speed, auxiliary electric power demand and propulsion power demand with fixed engine speed; the subscripts ME, *GB* and *S* respectively represent the main engines, the gearbox and the shaft.

2.2.2 AE case: Auxiliary engines

The AE case corresponds to the arrangement normally employed on the case study ship when the shaft generators are out of order, and is conceptually described in Figure 2b. This configuration allows the main engines and propeller to be operated at variable speed, in accordance to the limits imposed by the operating envelope of the main engines.



(a) Case SG
(b) Case AE

Fig.1 Conceptual representation of alternative propulsion systems, Case SG and AE

For Case 2, the SSFC is calculated according to Equation 2.

$$SSFC_{SG-FC} = v_s^{-1}\left[bsfc_{ME}\frac{P_{prop,\mathrm{VS}}}{\eta_{GB}\eta_S} + bsfc_{AE}\frac{P_{el}}{\eta_{AG}} \right] \qquad (2)$$

2.2.3 SG-FC case: Shaft generator with frequency converter

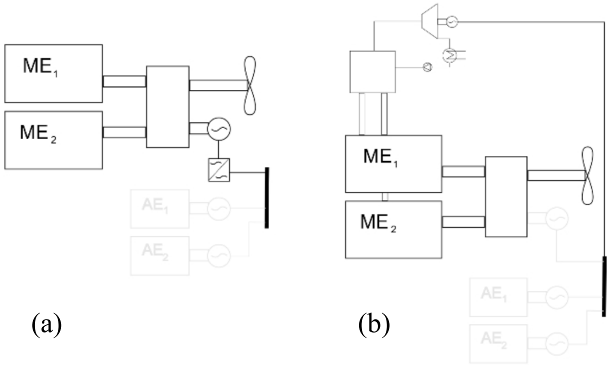
Case 3 corresponds to the arrangement in which the shaft generator has been retrofitted with a frequency converter. This case is conceptually identical to Case 1 except that the engines and propeller can be operated at variable speed, since the frequency of the electricity is kept constant by the frequency converter. For Case 3, the SSFC is calculated according to Equation 1, where the propulsion power is updated to account for variable engine speed operations and the efficiency of the frequency converter is also taken into account, as shown in Equation 3.

$$SSFC_{SG-FC} = v_s^{-1} bsfc_{ME}\left[\frac{P_{prop,\mathrm{VS}}}{\eta_{GB}\eta_S} + \frac{P_{el}}{\eta_{SG}\eta_{FC}} \right] \qquad (3)$$

2.2.4 WHR case: waste heat recovery

The WHR case corresponds to the arrangement in which a WHR system has been installed on the exhaust line of the main engines in order to generate auxiliary power. This allows generating auxiliary power without any additional fuel input, and operating engines and propeller at variable speed at the same time. For the WHR case, the SSFC is calculated according to Equation 4.

$$SSFC_{WHR} = v_s^{-1}\left[bsfc_{ME}\frac{P_{prop,\mathrm{VS}}}{\eta_{GB}\eta_S} \right] \qquad (4)$$



(a) Case SG-FC
(b) Case WHR

Fig.2 Conceptual representation of alternative propulsion systems, Case SG-FC and WHR

2.3 Influence of added resistance

The balance and coupling between engine and propeller is strongly connected to the ship resistance. Ship resistance dependence on ship speed is accounted for in the correlations described in section 3.2. However, ship resistance is influenced by a large number of other factors, such as draft, weather, water depth, fouling, etc.

A detailed modeling of those phenomena is considered to be beyond the scope of this study. However, a simplified analysis of the influence of added resistance on engine-propeller interaction was performed. Two separate scenarios are therefore employed in the evaluation and comparison of the 4 alternative arrangements:

- 0% added resistance
- 15% added resistance

For both cases, data provided by the manufacturer as described in section 3.2 was used for the modeling of propulsion power demand.

2.4 Influence of engine operating envelope

The operating envelope defines the possible range of operating points of an engine in terms of shaft speed and power. Maximum speed and power are limited by considerations in engine loading and inertias. Below these values, engine power is limited for each speed value by considerations of excessive thermal loading of the engine and of insufficient combustion air.

The engine employed in this study is a MaK 8M32C, for which the operating envelope (E1) is available from technical documentation (MaK). However, the shape and size of the operating envelope largely depends on a number of parameters connected to engine design and to the choice of the turbocharger. In this study, we also wanted to investigate the influence of having a larger operating envelope for the engine. A broader envelope (E2), as described in (MAN), was therefore also considered in this study. Figure 3 presents a representation of both envelopes.

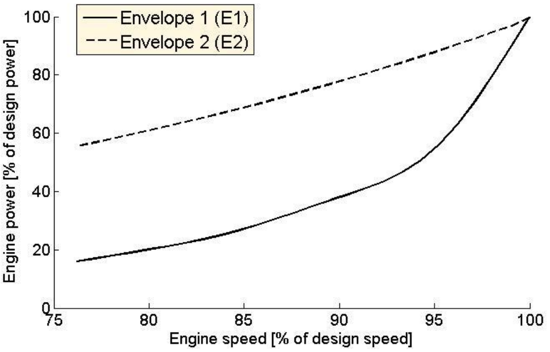


Fig. 3 Comparison of the alternative operating envelopes employed in the study

3 Energy system modelling

In order to simulate the behavior of the energy system for different ship operational conditions the different parts of the system were modelled. The different assumptions and hypothesis employed in component modelling are therefore described in the following sections.

3.1 Main engine

The engine model employed for this study is an adaptation of the model presented by Scappin, et al. (2012). The model is a zero-dimensional crank-angle model, were engine evolution is modeled throughout five main phases: compression, injection, combustion, expansion, and post-exhaust valve opening (EVO) blowdown. Each phase is modeled using a set of differential equations.

A set of case-dependent parameters employed by the model needs to be defined. This involves engine geometrical parameters (number of cylinders, cylinder bore and stroke) and calibration parameters. The model is calibrated on four operational points resulting from engine shop tests for the determination of unknown parameters, i.e. injection timing, combustion duration, and cylinder wall temperature.

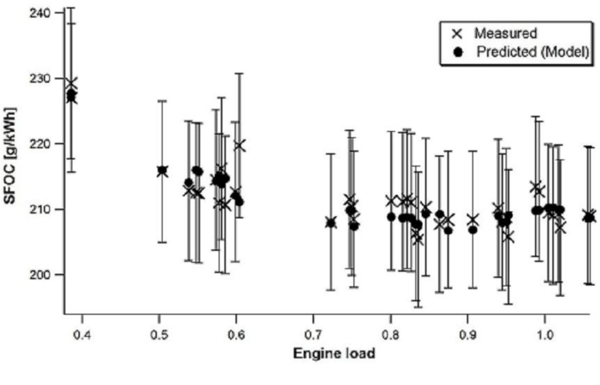


Figure 4: Engine model validation, predicted versus measured specific fuel oil consumption

A more detailed description of model equations is available in the work of Scappin, et al. (2012). Modifications to the model included an approximated modeling of the gas exchange phase and the utilization of the real gas equation. The engine model was validated versus the measurements performed on the case study ship and its sister ships during sea trials. Figure 4 shows the very good agreement between measured and predicted engine performance.

3.2 Propeller

Curves for propeller power demand as a function of ship speed, propeller pitch and propeller rotational speed were provided by the propeller manufacturer. Starting from the interpolation of the curves it was possible to approximate the required propulsive power for each condition of ship and propeller speed, in the form expressed in Equation 5:

$$P_{prop} = c_0(v_s) + c_1(v_s)\,n_{prop} + c_2(v_s)\,n_{prop}^2 \tag{5}$$

where:

$$c_i(v_s) = c_{i,0} + c_{i,1}v_s + c_{i,2}v_s^2 \tag{6}$$

where P_{prop}, v_s and n_{prop} respectively represent the propulsive power demand, the ship speed and the propeller speed.

The result of the regression is showed in Figure 5. An analogous diagram for an increased resistance of 15% was used in order to estimate the effect of added resistance on the performance of the energy system.

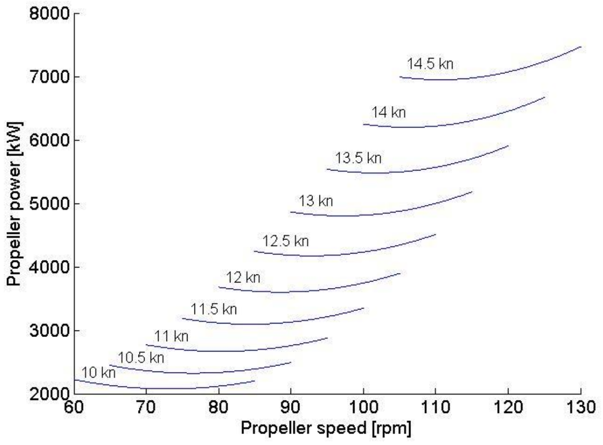


Figure 5: Propeller curves, regression of data provided by the propeller manufacturer

3.3 Auxiliary generation systems

3.3.1 Shaft generator

The SG installed onboard is a synchronous generator with a design efficiency of 95%. Electrical generators are known to be very efficient even at off-design conditions. However, in this specific case, the SG is designed for full operations of cargo pumps, which makes it operated at an average load of 11% during sea passages. In this condition it is not possible to ignore SG efficiency dependence on load. This was modelled using a polynomial regression of typical generators behavior as reported in (McCarthy, et al. 1990). This gives a SG efficiency of approximately 89%.

3.3.2 Auxiliary engines

As rather limited information was available concerning the auxiliary engines, the modelling of this component has been simplified to a numerical regression. In particular, the efficiency of the auxiliary engines is accounted as a second degree polynomial function of engine load based on the data available from engine manufacturer, corrected for non-ISO conditions.

3.3.3 Waste Heat Recovery system

Case 4 corresponds to the utilization of a WHR for the generation of auxiliary power. The performance of WHR systems based on marine engines is largely discussed in literature (see, among others, Dimopoulos, et al. (2011), Dimopoulos and Kakalis (2010), Larsen, et al. (2013), and Theotokatos and Livanos (2013)). The design and modeling of a WHR system is therefore beyond the scope of this work. However, in order to take the possibility of WHR into account, we decided to estimate the WHR potential from the exhaust gas of the main engines in terms of its exergy content; the use of exergy is preferred as it is a better measure of approach to ideality and it accounts both for energy quantity and quality (Dincer and Rosen 2013). The exergy flow in the exhaust gas of the main engines is calculated according to Equation 7.

$$E\dot{X}_{eg} = \dot{m}_{eg}[(h_{eg,\mathrm{aTC}} - h_{eg,150}) - T_0(s_{eg,\mathrm{aTC}} - s_{eg,150})] \quad (7)$$

where h and s respectively represent specific enthalpy and entropy, and the subscripts *eg, aTC* and *150* respectively represent the exhaust gas, the properties of the exhaust gas after the Turbocharger and at 150$^{\mathrm{O}}$C, which is the minimum exhaust temperature to avoid sulfuric acid condensation in the boilers. The feasibility of the WHR case is evaluated in terms of the minimum required exergy efficiency of the WHR system to alone provide the auxiliary power demand, as expressed in Equation 8:

$$\eta_{ex,req} = \frac{P_{el}}{E\dot{X}_{eg,av}} \quad (8)$$

where the $EX_{eg,av}$ is calculated from EX_{eg} accounting for the required power for auxiliary heat generation.

3.4 Other components

As described in Equations 1-3, other values needed to be assumed estimated for the calculation of ship SSFC for all the alternative cases. Gearbox efficiency (η_{GB}) was assumed equal to 98.7% based on technical documentation; shaft efficiency (η_S) was assumed equal to 99% based on (Shi, et al. 2010); The efficiency of the frequency converter (η_{FC}) was approximated at 95%, based on a conservative estimation of the values proposed by Ådanes (2003); the efficiency of the generators placed on the auxiliary engines was assumed equal to 95% based on Ådanes (2003).

4 Results

The resulting SSFC as a function of ship speed for the four alternative arrangements are shown in Figures 6 to 9.

4.1 Calm water resistance with original envelope

Figure 6 presents the results of the simulation in the case of the original MaK operating envelope and calm sea (no added resistance). This condition is seldom encountered in real operations, as seas are not often completely calm, and fouling and other phenomena normally increase ship resistance. However, looking at these "ideal" results constitutes a useful baseline condition to compare with other simulations and is often used in the estimation of reference conditions for ship design.

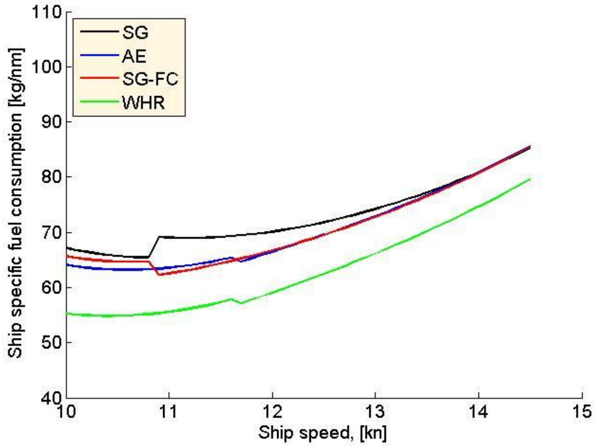


Figure 6: Baseline SSFC for the four alternative arrangements

Figure 6 allows observing the influence of the increase of propeller efficiency at lower propeller speed. For low ship speeds, the SSFC reduction is limited by the operating envelope that allows reducing the propeller speed only to a minimum of 97% of the nominal value. This reduction is however sufficient to overcome the additional fuel consumption for auxiliary power generation, related to the use of the auxiliary engines instead of the shaft generator. When increasing the speed, the correspondent increase in propulsive power demand requires clutching in the second engine. At this point, operations at low engine load allow a larger reduction of engine speed. After this minimum, the point of maximum propeller efficiency moves towards higher propeller speed, until benefits of running at variable speed become negligible at around 14 kn. Results for the use of a frequency controlled shaft generator (SG-FC) are quite similar to those for the AE case; for ship speed lower than 10.8 kn the SSFC is higher as a consequence of the higher engine load, hence the limitations on propeller speed. From the moment when operations on two engines are allowed the performance of the SG-FC case are comparable with those of the AE case.

The WHR combines the optimal propeller operations with fuel-free auxiliary power generation, leading to the lowest values of SSFC for almost all speeds. However, this can be considered feasible only for ship speeds above 11.2 kn: in fact, when only one engine is running, the required exergy efficiency of the WHR system would be of 60-62%, which corresponds to a very efficient system. When two engines are running, instead, the required exergy efficiency drops at 29-36% values, which can be reached with a common single-pressure steam cycle (Theotokatos and Livanos 2013).

4.2 Influence of the added resistance

The results from the simulation accounting for a 15% added resistance are shown in Figure 7. As expected, the maximum reduction in SSFC for variable propeller speed operations can be observed at lower speed (between 10.9 kn and 11.4 kn depending on the auxiliary generation system employed), while the SG case becomes the most efficient of the first three arrangements at 13 kn. On the other hand, the benefits connected to the retrofitting of a WHR system would be reachable at lower speed, since it would be less likely to operate on one engine only.

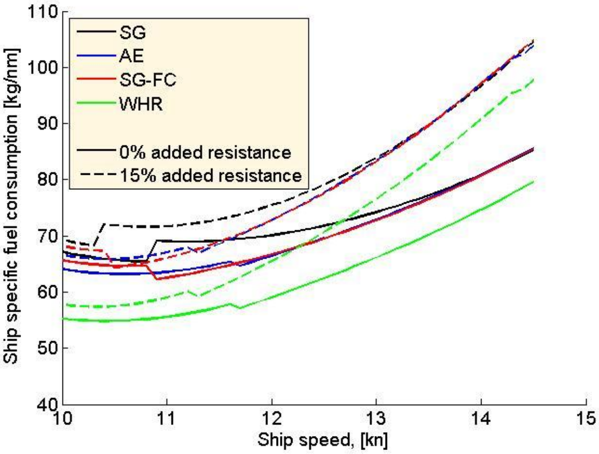


Figure 7: Influence of the 15% added resistance on the SSFC of the four alternative arrangements

4.3 Influence of the operating envelope

The results presented so far suggested that reducing the propeller speed leads to an increase of ship energy efficiency. However, these benefits are limited by a rather small operating envelope for the engine installed on board the case study ship. The simulations were therefore extended to the case of a broader operating envelope (E2) in order to test the expected improvements on ship energy efficiency.

Figure 8 represents the results for the SSFC of the ship in the 4 arrangements when the "enlarged" operating envelope (E2) is used, in calm seas. The results indicate that when the ship is operating at speeds below 13.5 kn the possibility to operate in a wider range of engine (and, hence, propeller) speed can generate larger benefits in terms of fuel economy. As an additional comment to Figure 8, it can be noticed that when the operating envelope is enlarged, the AE case becomes more convenient than the SG-FC case for speed between 10 and 11.4 kn. In this condition, the improvements in propulsive efficiency connected to the possibility of operating at lower speed are higher, and in the SG-FC the limit is set by the higher load of the main engine(s).

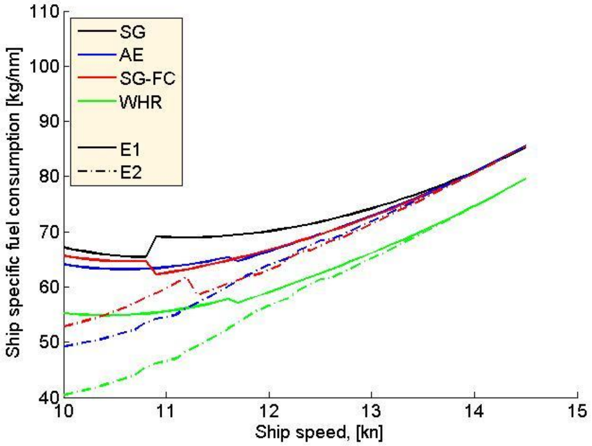


Figure 8: Influence of the size of the operating envelope on the SSFC of the four alternative arrangements, 0% added resistance

Figure 9 further clarifies the role of an enlarged operating envelope for higher propulsive efficiency. In particular, having a broader operational profile allows keeping the propeller speed closer to the optimal value over a broader range of operations when compared with a smaller envelope.

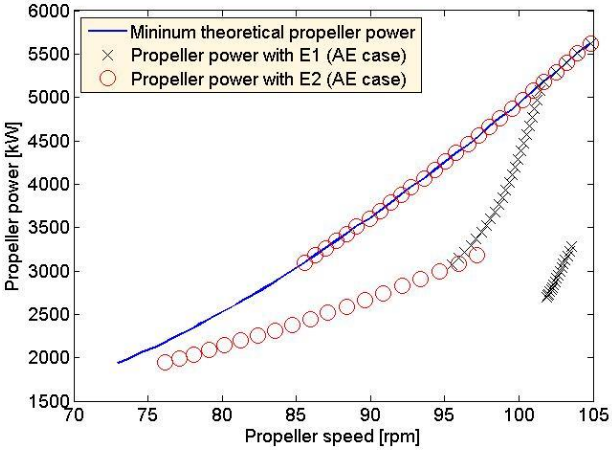


Figure 9: Propulsion power demand versus propeller speed; minimum demand and optimal values for the AE case with E1 and E2 operating envelopes

Table 2 summarizes the decrease in SSFC for the 3 “non-standard” arrangements compared to the standard (SG) case, in the 15% added resistance scenario for E1 and E2 operating envelopes. Apart from the WHR case, savings of up to respectively 8.3% and 10.5% for the AE and FC-SG cases can be reached with the “E1” operating envelope; in the “E2” condition instead the savings increase up to respectively 24.6% and 16.7% instead.

Savings related to the installation of a WHR system are the highest in all cases, and remain valid for higher loads. It should be noted that for the values corresponding to operations with one engine (underlined values in Table 2) it would be more realistic to assume the AE value instead, since under these conditions the exergy efficiency required by the WHR system to generate all auxiliary power would be higher than what ca be expected for a reasonably simple system.

Table 2 Relative reduction in SSFC for the AE, SG-FC and WHR cases versus the SG case for 15% added resistance

Speed	E1 [% saving vs SG]			E2 [% saving vs SG]		
[kn]	AE	SG-FC	WHR	AE	SG-FC	WHR
10.0	-3.9	-1.6	-16.6	-24.6	-16.7	-37.3
10.5	-8.3	-10.5	-20.0	-23.1	-15.6	-34.8
11.0	-6.5	-7.8	-17.6	-17.1	-15.8	-28.2
11.5	-6.0	-5.4	-16.5	-10.0	-11.3	-20.9
12.0	-3.5	-3.5	-13.2	-5.9	-6.1	-15.6
12.5	-1.8	-1.9	-10.7	-3.4	-4.0	-12.3
13.0	-0.6	-0.8	-8.7	-1.3	-1.7	-9.3
13.5	0.0	-0.1	-7.2	0.0	-0.2	-7.3
14.0	0.4	0.4	-6.1	0.4	0.4	-6.1
14.5	0.7	0.7	-5.5	0.7	0.7	-5.5

5 Discussion

Here the relevance and the implications of the results (Section 5.1) and the influence of modeling assumptions on the validity of the results (Section 5.2) are discussed.

5.1 Results discussion

The results presented in Section 4 suggest that there are opportunities for improving ship energy efficiency. Both the case at 0% and 15% added resistance were analyzed, where the former allowed a better identification of the behavior of the different arrangements. However, the condition of 15% added resistance is much closer to expected real operations than the case with calm water resistance. As an indicative estimation, at a significant wave height of 2 m the added resistance for the selected ship, calculated according to ITTC recommended practice (ITTC 2005), would be 17%.

The results presented in Section 4 suggest that operations at variable propeller speed (AE and SG-FC settings) lead to reasonable improvements for ship speeds lower than 11.5 kn. Operations in AE mode or the retrofitting of a frequency converter could therefore be considered as viable options with respect to the expected operating speed of the vessel.

The analysis of Figures 9 and 10 indicates that the operating envelope of the engine also plays an important role in the efficiency of the vessel when high speed flexibility is required. This can be particularly observed in the AE case. This consideration can be of relevance both in the design phase, where the selection of an engine with a broader operating envelope could be prioritized despite of a hypothetical lower design efficiency; and in the retrofitting of means for the enlargement of the operating envelope, such as sequential turbocharging or exhaust blow-by.

The installation of a WHR device can result in very large savings, while allowing higher speeds. Savings of more than 10% compared to the currently installed arrangement can be expected for ship speed up to 12.5 kn. On the other hand, however, WHR installation is not profitable when very low speed operations are expected, since standard WHR systems would be unable to generate the required auxiliary power when only one engine is running.

The results obtained though the simulations as described in the previous sections of the work only relate to quantitative estimations of fuel demand for given operational settings. For a complete evaluation of the feasibility of the proposed arrangements, these results should be integrated with considerations related to other practical aspects which have a key importance for such decisions. From an economic perspective, only fuel costs can easily be derived from the proposed work, and capital costs for the “SG-FC” and “WHR” case should be estimated to evaluate economic indexes such as the payback time or the return of investment. Additionally, issues connected to maintenance (AEs and WHR systems require more maintenance than SGs) and control (WHR systems require additional complexity in the control systems) should also be taken into account.

5.2 Model assumptions

The method employed, and in particular the modeling choices, have an influence on the results and should therefore be discussed here.

The engine employed in this study has been designed and tested for operations at constant speed. For this reason, there is no data point available for the calibration and validation of the model for engine speed at off-design conditions. All the results presented in the study are, hence, more reliable for engine speeds closer to the design point. However, given the high mechanistic nature of the model, it is reasonable to expect better extrapolation performance compared to empirical models (Duarte, et al. 2004).

For the WHR case, it was decided to estimate the required exergy efficiency for the recovery system based on the recovery potential from the exhaust gas. This is considered to be a reliable approximation, given the amount of effort required by the design and optimization of WHR systems. However, the performance of the WHR case should be verified once a WHR design has been selected for a more accurate estimation of the savings and of the required complexity of the required technology. On the other hand, the possibility of recovering energy from the cooling systems, often discussed in literature (e.g. by Dimopoulos, et al. (2011)) was not considered in this study.

6 Conclusions

This paper presented the modeling and analysis of the energy performance of different arrangements for a CPP propeller ship. Four alternative arrangements, distinguished by the means employed for auxiliary power generation, were modelled and compared.

The results show that the utilization of devices for auxiliary power generation which allow a free variation of the propeller speed (i.e. auxiliary engines and shaft generator in combination with a frequency converter) can lead to a very relevant improvement in the energy efficiency of the system (respectively a maximum improvement of 8.3% and 11.4% can be achieved) when the sailing speed of the vessel is lower than the design speed. The installation of a WHR system, even though connected to a significant capital investment, can bring even higher efficiency (improvement up to 16.5%).

The effect of broadening the operating envelope of the engine was also analyzed; for larger envelopes savings can be further improved, as this makes it possible to operate the engines and the propeller at even lower speed. This improvement is higher for low values of propulsive power, i.e. low ship speed and small added resistance.

This paper sheds some light on the operations of CPP propelled ships, showing that their efficiency can be highly improved if correctly operated. As a consequence of such a strong interaction between parts of the system, an improved systems thinking would be very beneficial if employed both in ship operations, retrofitting, and design.

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