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MARINE GAS TURBINE PERFORMANCE MODEL FOR MORE ELECTRIC SHIPS

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ABSTRACT

This paper presents the benefits of the more electric vessels powered by hybrid engines and investigates the suitability of a particular prime-mover for a specific ship type using a simulation environment which can approach the actual operating conditions.

The performance of a mega yacht (70m), powered by two 4.5MW recuperated gas turbines is examined in different voyage scenarios. The analysis is accomplished for a variety of weather and hull fouling conditions using a marine gas turbine performance software which is constituted by six modules based on analytical methods.

In the present study, the marine simulation model is used to predict the fuel consumption and emission levels for various conditions of sea state, ambient and sea temperatures and hull fouling profiles. In addition, using the aforementioned parameters, the variation of engine and propeller efficiency can be estimated. Finally, the software is coupled to a creep life prediction tool, able to calculate the consumption of creep life of the high pressure turbine blading for the predefined missions.

The results of the performance analysis show that a mega yacht powered by gas turbines can have comparable fuel consumption with the same vessel powered by high speed Diesel engines in the range of 10MW. In such Integrated Full Electric Propulsion (IFEP) environment the gas turbine provides a comprehensive candidate as a prime mover, mainly due to its compactness being highly valued in such application and its eco-friendly operation.

The simulation of different voyage cases shows that cleaning the hull of the vessel, the fuel consumption reduces up to 16%. The benefit of the clean hull becomes even greater when adverse weather condition is considered. Additionally, the specific mega yacht when powered by two 4.2MW Diesel engines has a cruising speed of 15 knots with an average fuel consumption of 10.5 [tonne/day]. The same ship powered by two 4.5MW gas turbines has a cruising speed of 22 knots which means that a journey can be completed 31.8% faster, which reduces impressively the total steaming time. However the gas turbine powered yacht consumes 9 [tonne/day] more fuel. Considering the above, Gas Turbine looks to be the only solution which fulfills the next generation sophisticated high powered ship engine requirements.

NOMENCLATURE

K_s	Shroud parameter	[m]
LMP	Larson-Miller parameter	[-]
N	Design point rotational speed	[rpm]
N_{od}	Off-design rotational speed	[rpm]
OWE	Open water efficiency	[-]
PB	Brake power	[W]
PD	Delivered power	[W]
PR	Pressure ratio	[-]
SFC	Specific fuel consumption	[kg/(N·s)]
S_v	Voyage distance	[nm]
T_{amb}	Ambient temperature	[K]
T_b	Blade temperature	[K]
T_c	Blade cooling air temperature	[K]
TET	Turbine entry temperature	[K]
ff	Fuel flow	[kg/s]
h_b	Height of blade	[m]
k_h	Average hull roughness amplitude	[nm]
r_{mb}	From mid-shaft to mid-blade	[m]
t_f	Blade's time to failure	[h]
t_T	Voyage time	[h]

Greek

η_{th}	Thermal efficiency	[-]
ρ_b	Blade's material density	[kg/m^3]
σ_{cf}	Blade's centrifugal stress	[MPa]

Abbreviations

IFEP	Integrated full electric propulsion
FPP	Fixed-pitch propeller

INTRODUCTION

In recent years, the maritime industry has been focused on the reduction in exhaust emissions and fuel consumption. The implementation of a gas turbine power plant has been proven to be the appropriate option for the propulsion system of an eco-friendly vessel with large energy demands.

The main asset of a gas turbine is the large power density, which means a small and light engine is able to produce considerable amount of power, offering weight and space savings [1-3]. In this respect, vessels powered by gas turbines achieve high speeds and have excellent maneuverability [2]. Table 1 presents indicative values of specific power densities.

	Gas Turbine Engines	Low-Speed Diesel Engines
Specific Power Density [MW/tonne]	10	0.125

Table 1: Indicative Specific Power Density

Lower exhaust emissions due to better combustion process and higher quality fuels is an important advantage, considering that stricter measures and regulations are continuously imposed worldwide for the avoidance of environmental pollution [1,4,5]. The estimated reduction in PM (particulate matters) could reach 75%. Additionally, the noise and vibration pollution levels produced by this engine are low, improving the onboard living conditions.

Criteria	Diesel Engines	Gas Turbines
Weight and size		✓
Initial costs	✓	
Maintenance costs	✓	
Fuel consumption	✓	
Heavy fuel oil capability	✓	
Part-load operation	✓	
Transient response	✓	
Structure-borne noise		✓
Air-borne noise		✓
Lubrication oil consumption		✓
NOx emission		✓
SOx emission		✓
CO_2 emission	✓	
Ambient conditions	✓	
Workload for crew		✓

Table 2:Comparison of Gas Turbine and Diesel Engine characteristics

Hybrid configurations appear as a viable means of exploiting the benefits of gas turbines limiting any fuel consumption penalties [6,7]. The hybrid engines that concentrate most advantages are the *CODOG (combined diesel or gas turbine)* and *CODAG (combined diesel and gas turbine)*, that combine Diesel and gas turbine engines integrated in more electric power plants, while the *COGES (combined gas turbine, electric and steam turbine)* features a combination of gas turbine and steam turbine integrated in more electric architecture. The *COGOG (combined gas turbine or gas turbine)* and the *COGAG (combined gas turbine or gas turbine)* integrated on more electric architecture are another two alternative configurations.

The CODOG engine, combining Diesel engine's and gas turbine's advantages, offers low initial installing cost, low operational cost, large amount of power and reliability. This configuration can also be integrated in more electric architecture improving its efficiency. The COGES is characterized by even lower operational cost, due to the steam turbine, but there is a risk factor by using an innovative technology.

The success of a hybrid engine depends largely on the performance of the control system which manages the engines of the ship [8]. Depending on the energy demands and the operational profile of the vessel, the system uses different number of engines and in different combination in each voyage case, in order to achieve optimum power generation and fuel consumption.

The concept for a power system that satisfies both propulsion needs and shipboard electrical distribution demands (hotel and auxiliary devices) maximizes the advantages of a gas turbine marine power plant. The more electric architecture is based on the generation of electric energy instead of mechanical energy by the prime movers, which can be both diesel engines and gas turbines.

The marine gas turbines offer advantages to specific ships categories such as cruise ships, fast ferries, mega yachts and naval vessels. Nevertheless, fuel consumption is severely affected by low power operation. It has been estimated that a prime mover operates under load less than *60%* of full power for more than *90%* of its operational life. The part-load operation of marine gas turbines increases further the fuel consumption in a direct shaft configuration. However, such condition can be mitigated by using more electric architectures, where the marine gas turbine is operated at design point for most of its operating envelope [9]. As a result the engine's efficiency increases with subsequent limitation of losses and fuel consumption, while maintenance cost decreases as less damages occurs.

The Integrated Full Electric Propulsion (IFEP) permits the installation of both propellers and engines of a ship to optimal position according to a variety of parameters [7]. This is possible because the main engines are not connected with the propellers via shafts but they are electrically connected. The installation of the engine far from the bottom of the hull decreases vibration, facilitates access for maintenance, less space is occupied and inlet and exhaust ducting designs can be optimized with subsequent benefit on gas turbine eficiency by reducing choking effect and the pressure drop. The use of more, smaller in size propellers enables their distribution on the ship's hull, in such a way as that optimum result in relation with maximum speed and maneuverability is delivered.

The substitution of the hydraulic and pneumatic systems for electric ones is also proposed, because hydraulic systems are prone to damages and hydraulic oils are extremely flammable, while pneumatic systems are heavy and consume a lot of space. The electric systems of a vessel enable the installation of an electronic control system. Fast detection of potential damages facilitates and accelerates the repair, reducing the maintenance costs. An electric vessel has no need for large gear boxes because the propellers are electric powered and are supplied with the appropriate amount of power every moment. Considering that an electric motor has a very good efficiency (91% including all losses), this electric installation reduces significantly total transmission losses [10].

The installation of marine gas turbines integrated in an electric architecture is presented as the appropriate power plant for a next generation mega yacht, characterized by large electric energy demands and environmentally-friendly design. By using this arrangement, the vessel achieves high speeds, its light engines have a wide operating range and increased power is combined with low fuel consumption. Additionally, the engine room consumes less space, maintenance costs and workload are decreased and improved living conditions can be achieved due to low vibration and noise levels.

MODEL DESCRIPTION

Investigation of the off-design performance of complex ship propulsion systems is vital in order to predict the suitability of a chosen prime-mover on a specific operational profile. A proposed method of off-design performance investigation is the simulation of the prime-mover in a virtual integrated environment that can approach the prime-mover's actual operating conditions in the open sea. The software can be used for a wide range of ship types simulation using either electrical or mechanical propulsion systems, and is provided with the ability to program voyage scenarios not only in ideal but also in increased resistance conditions, such as adverse weather or hull fouling.

Ship Model

A statistical method [11] is used to estimate the power requirements of the ship type. This statistical method is capable of simulating full-displacement and semi-displacement vessels, under trial conditions. The propulsion factors are calculated for one or two propeller units. The current adopted statistical method simulates several types of existing monohull vessels, with a valid range.

The simulated vessel of the current investigation is a monohull Mega Yacht (70m) with integrated full electric propulsion (IFEP). The prime movers are two identical 4.5MW recuperated gas turbines, which share equally the propulsion load. Each engine drives an electrical generator, which is responsible only for the propulsion of the vessel, and is assumed that the power is transferred to two podded drives. The transmission efficiency from the prime movers to the propellers is estimated at 95%. The main characteristics are shown in Table 3.

Length at water level, L_{WL} (m)	65.0
Maximum beam, B (m)	12.0
Average design draft, T (m)	3.50
Block coefficient, C_b	0.55
Midship coefficient, C_m	0.93
Prismatic coefficient, C_p	0.59
Water plane coefficient, C_{wp}	0.69
Cruise, V_s (knots)	22.0
Boost speed, V_s (knots)	27.0
Frontal area (m^2)	240.0
Displacement, Δ (mtons)	630.0
Wetted surface, S_w (m^2)	1200.0

Table 3: Main parameters of the Mega Yacht

Propeller Model

The method that is used to simulate the design-point open water characteristics of the propellers is based on the open water characteristics of the Wageningen B-series propellers, [12]. In order to be able to obtain the open water efficiency at any required off-design conditions an iterative method [13] has been applied, using the advance ratio as variable.

The propellers, installed on the pods of the mega yacht, are assumed to be two fixed-pitch propellers (FPP) and their main design-point parameters at service speed are shown in Table 4.

Propeller diameter, D_p (m)	3.80
Pitch diameter ratio, P/D_p	1.25
Expanded area ratio, A_E/A_o	0.76
Propeller rotational speed N_{prop} Cruise/Boost (rpm)	71.0/183.0
Number of propellers	2
Number of blades, N_{blades}	5
Open water efficiency, η_o (Cruise/Boost)	0.706/0.713

Table 4: Main parameters of the propellers

Gas Turbine Model

The performance of the ship's power plant is predicted using an one-dimensional gas turbine performance code, with the capability of design point and off-design calculations [14]. The working principle of this model, which called "Turbomatch", is based on mass and energy balance, carried out through an iterative method, based on component maps. It has been validated against commercially sensitive data and further details can be found in [15]. The throttling of the engine is controlled by varying the TET, while the effect of ambient temperature is included as well.

In the present study, a recuperated gas turbine has been modeled and a heat exchanger has been utilized in order to improve the overall performance, transferring heat from the exhaust gas to the combustor inlet. As a result the total enthalpy rise due to combustion reduces, with an effect on the thermal efficiency. In order to assess the overall performance benefits a systemic approach has been followed, installing the recuperated cycle on a mega yacht platform using the integrated ship model. The design parameters of the two gas turbines are included in Table 5. The configurations of the engines are 1-spool with a free power turbine, allowing for improved performance at part load. The recuperated cycle exhibits higher thermal efficiency but decreased specific power, due to the heat recovery (recuperation). This condition that is apparent in the design point data in Table 5 has a direct impact on the engine mass flow, leading to more compact gas turbine, something that tends to partially mitigate the extra weight due to the heat exchanger.

Power turbine rating, P_{PT} (MW)	4.5
Turbine entry temperature, TET (K)	1600
Compression pressure ratio, PR_c	18.0
Intake mass flow W_{in} (kg/s)	12.74
Exhaust mass flow, W_{out}	13.03
Exhaust gas temperature, T_{exh} (K)	810.8
Recuperator effectiveness, ε_{rec}	0.75
Thermal efficiency, η_{th}	0.37
Specific fuel consumption, SFC (g/kWh)	62.52
Specific thrust, Sp.T (MJ/kg)	0.353

Table 5: Design point main parameters of the marine GT at ISA

Weather and Hull Fouling Model

The weather model is comprised by two modules: a sea-wave module, [16] and a wind module, [17]. The input variables are, the ambient temperature of the air and sea, sea state, and wind speed. All input variables can change value as required by the simulated voyage, with the ambient temperature of air and sea being independent variables and on the other hand wind speed being depended on the chosen sea state. Both sea-waves and wind act, at this prototype stage of the method, in all cases in a head direction towards the vessel's bow.

The hull fouling model [18] uses as variable the mean hull roughness amplitude and as an average it increases hull resistance by approximately 2% for every 30μm of mean additional roughness amplitude.

Voyage Model

The voyage model handles the voyage distance, the time intervals that ambient conditions change, the ambient temperature of air and sea at the specified time intervals, as also the speed of the vessel. Considering these variables, it calculates the total voyage time and the total fuel consumption of the engines. Furthermore in the case of a multi-engine vessel, the number of prime movers that are engaged in each time interval is calculated, according to the power requirement.

The calculation of air ambient temperature T_{amb} profile that is applied to all case studies is based on the method proposed in [19]. The input data to the model are summarized in Table 6, based on information derived from [20].

Parameter / Day	Hot	Normal	Cold
Minimum day temperature, T_{min} (°C)	30.5	10.0	-5.0
Maximum day temperature, T_{min} (°C)	45.0	25.0	8.0
Sunrise time of day, t_d (hh:mm)	06:00	06:00	06:00
Peak day temperature, t_P (hh:mm)	14:00	14:00	14:00
Voyage start time, t_{start} (hh:mm)	07:00	07:00	07:00

Table 6: Air ambient conditions input data

Emission Prediction Model

The major engine exhaust emissions (NOx, CO, CO2, UHC) have been calculated using a prediction tool. The model is based on the semi-empirical model from Lefebvre [21]. It simulates a single annular combustor and incorporates a technology factor in order to provide the ability to calibrate the quantities of exhaust emissions to standard technological levels. The design-point exhaust emissions rates were mostly modeled from published information on already in production and measured dry-low emissions combustors [22].

Turbine Blade Creep Life Model

The task of the turbine blade creep life model is to predict blade life consumption of the high pressure turbine rotor. The model is able to quantify the blade's creep life consumption during a scheduled voyage that the gas turbine is requested to operate.

To calculate the temperature of an air cooled blade, it was assumed that the overall blade cooling effectiveness remains constant at all gas turbine off-design conditions, the gas temperature is the same as the turbine entry temperature and the compressor derived blade cooling air temperature is the same as the compressor outlet temperature.

The direct inputs that the model requires by the user before any scheduled mission are the blade's design parameters: the shroud parameter K_s, the height of blade h_b, the design point rotational speed of the turbine's shaft N, the distance from mid-shaft to mid-blade r_{mb} and the blade's material density ρ_b. The variable parameters that define the blade's life fraction t_f (blade cooling air temperature T_c, turbine shaft off-design rotational speed N_{od} and gas temperature T_g) are obtained from the gas turbine performance model.

The output parameters are (at every time interval): the blade's time to failure t_f, and the turbine blade temperature T_b. In addition to the variation of blade time to failure estimation at each time interval the total life consumption for a given voyage is of particular interest. In order to calculate the cumulative creep life consumption of the hot section rotor blade after a voyage at t_j, the linear damage summation law or Miner's law was implemented.

The method includes several steps starting with the calculation of the gas path geometry [23]. In a further step, the centrifugal stresses are calculated, using input from the gas turbine performance code. Finally, the blade's creep life fraction t_f is calculated at a specific gas turbine off-design condition according to the Larson-Miller criterion.

$$t_f = 10^{\frac{LMP}{T_b}-20} \qquad (1)$$

The predominant stress on the blade is of centrifugal nature, while the shape of the blade is simplified to rectangular and one blade represents the creep life of all the blades of the turbine stage. The centrifugal stress σ_{cfd} on the blade at turbine design point can be defined as :

$$\sigma_{cfd} = \rho_b \times K_s \times h_b \times \left(\frac{2\pi N}{60}\right)^2 \times r_{mb} \qquad (2)$$

In order to calculate the centrifugal stress σ_{cfo} on the blade of any turbine off-design point :

$$\sigma_{cfo} = \sigma_{cdf} \times \left(\frac{N_{od}}{N}\right)^2 \qquad (3)$$

CASE DESCRIPTION

At ideal weather conditions the yacht uses a single prime mover at low speed mode (10 knots), and both prime movers at cruise mode (20 knots) and boost mode (27 knots).

In the case that scheduled steaming time is prolonged due to adverse weather conditions or high hull roughness amplitude due to fouling, the ship is programmed to travel at cruise speed for the remaining of the voyage. The maximum turbine temperature (*TET*) that the gas turbine prime movers are allowed to operate up to in all scheduled voyages of the case studies of this project is set to 1700 K.

Mega Yacht Features

The vessel has bulbous bow and a transom stern design has been adopted due to the azimuth thrusters. For good stability the yacht incorporates a pair of anti-vortex stabilizer fins positioned mid-ship in order the effect of waves to be reduced in adverse weather conditions A bow thruster is installed for docking manoeuvring.

Voyage Schedule

The trip time and distance that were chosen, are considered as realistic for a mega yacht at ideal weather conditions and clean hull (k_h=120μm), while simulation time was kept at reasonable amounts. No port manoeuvring and entering/exiting port procedure is included in the case studies of this project.

The mega yacht is simulated for five hull fouling progression profiles, three sea-state profiles and three air ambient temperature profiles in any possible combination of the above parameters during the two voyage cases.

The marine performance prediction software provides assessment about the ship's power demands, gas turbine performance (TET, PR, mass flow, etc), fuel consumption, emission levels, propeller efficiency, voyage time and ship's speed variation during the voyage.

Air Ambient Temperature Profiles and Sea-State Profiles

Three different air ambient temperature profiles and three different sea-state profiles are used in order to cover all the potential conditions that a yacht may face. Sea-water ambient temperature T_{sea} is assumed to be constant during the duration of all the scheduled voyages at 15 ^{o}C, while ambient air temperature profiles are presented in Figure 1.

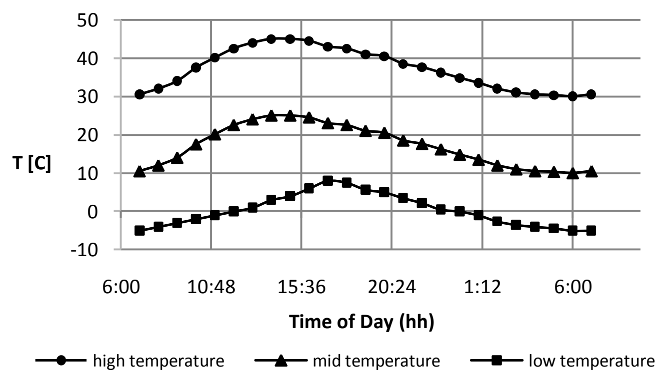

Figure 1: Air ambient temperature profiles

The first two weather profiles simulate a voyage of constant sea-state 2 and 5 in the Beaufort scale respectively. The third weather profile contains a variable sea-state profile where all sea-state conditions are included from 0 to 8. In the case that there is a trip time prolongation (t_{T+a}) all remaining time intervals assume in ideal weather conditions.

The variable weather profile is presented in Figure 2.

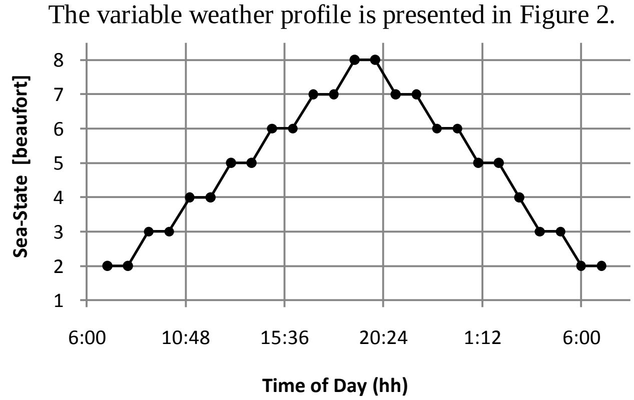

Figure 2: Adverse weather condition profile (AWC)

Hull Fouling Progression

The hull of all the simulated marine vessel is assumed that is coated with a hydrid TBT self polishing anti-fouling system, which a balanced mixture of SPC (Self Polishing Copolymer) and CDP (Controlled Depletion Polymer). The average annual increase in hull roughness amplitude due to fouling when a hydrid TBT self polishing antifouling system is used is 30μm. For SPC and CDP anti-fouling systems the average annual increase in hull roughness amplitude due to fouling is 20μm and 40μm respectively, and the cost of an anti-fouling system is proportional to its performance.

Table 7 presents the average annual increase in hull roughness amplitude (bottom and sides) due to fouling.

Year	k_h (μm)
f1	120
f2	150
f3	180
f4	210
f5	240

Table 7: Average annual increase in hull roughness amplitude

FIRST CASE – SPEED VARIATION

The voyage distance S_v is 300 [nm] and the voyage schedule time t_T directly depends on the vessel's speed. In every voyage case the speed is kept constant. The simulation is accomplished for a speed range from 10 knots to 27 knots with 2 knots step.

Figure 3 : Fuel flow variation – Ship speed (2 beaufort and mid-temperature profile)

The Figure 3 shows the variation of the fuel flow in term of the ship speed and two different hull fouling conditions.

Increase in the hull fouling causes considerable increase in hull resistance, which means more fuel needs to be added in order to maintain the required power output. Particularly, changing the hull fouling from 120[nm] to 240[nm], the fuel consumption increases about 14.5% .

Up to 22 knots, the fuel consumption increases in high rate making the operation of the GT powered vessel affordable only for booster operation, in such a high speeds.

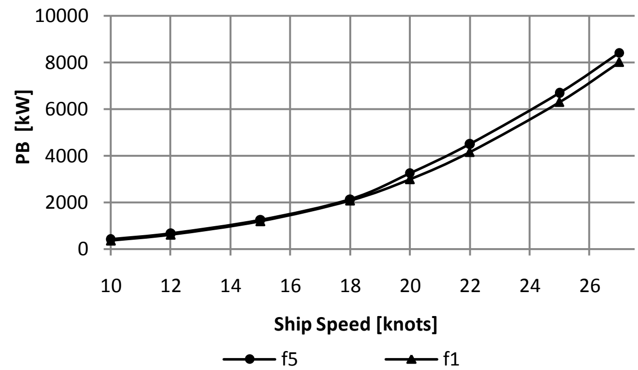

Figure 4: Brake power variation – Ship speed (2 beaufort and mid-temperature profile)

Figure 4 shows the variation of brake power in relation to ship speed and two different hull fouling conditions.

For speed higher than 18 knots, increase in hull fouling causes considerable increase in hull resistance, which means need for extra power. Particularly, changing the hull fouling from 120[nm] to 240[nm], there is 7.5% increase in brake power demand.

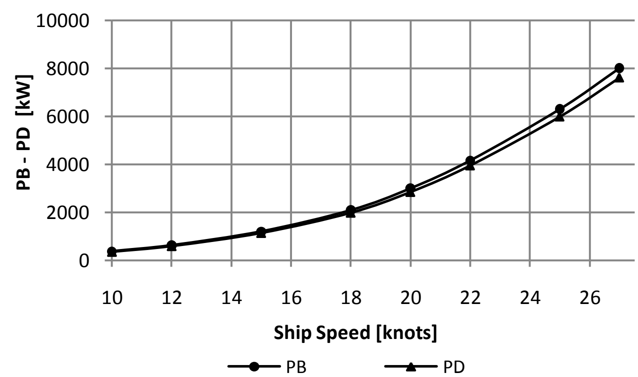

Figure 5: Brake power and delivered power variation – Ship speed (2 beaufort, mid-temperature profile and f1-hull fouling)

Figure 5 shows the power in terms of the ship speed.

The difference between the brake power and delivered power gives the mechanical and electric losses during the transmission. As the vessel speed increases the losses also increase, reaching the maximum value of 5% losses at speed of 27 knots.

The Figure 6 shows the variation of thermal efficiency as function of ship speed and air ambient temperature.

As the air ambient temperature increases, the prime mover is required to maintain the same power output which means that air density decreases. As a consequence, the entropy of air increases, total compression work increases, total compression pressure ratio decreases as well as intake mass flow. Considering the above, more fuel needs to be added, which results in higher turbine entry temperature and a drop in the thermal efficiency as shown in Figure 6.

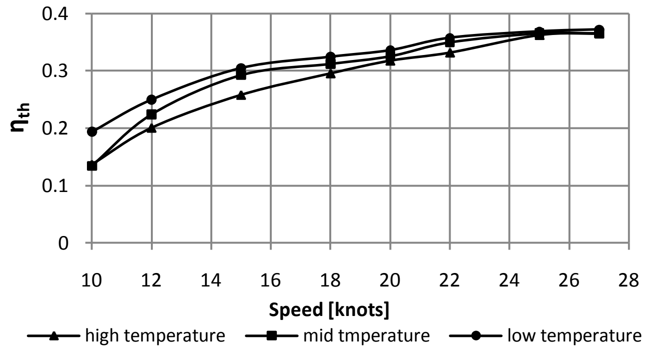

Figure 6: Thermal efficiency variation – Ship speed (2 beaufort and f1-hull fouling)

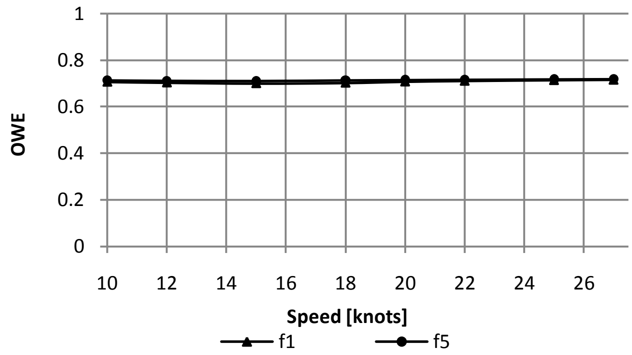

Figure 8 : Open water efficiency variation – Ship speed (2 beaufort and mid-temperature profile)

At low speeds, the gas turbines of the vessel present 15.4% better efficiency operating at a cold day in comparison to a hot day. However, the above benefit reduces as the ship speed increases.

Increasing ship speed, thermal efficiency also increases due high thermal efficiency of the gas turbine when operating at design point, close to maximum power settings.

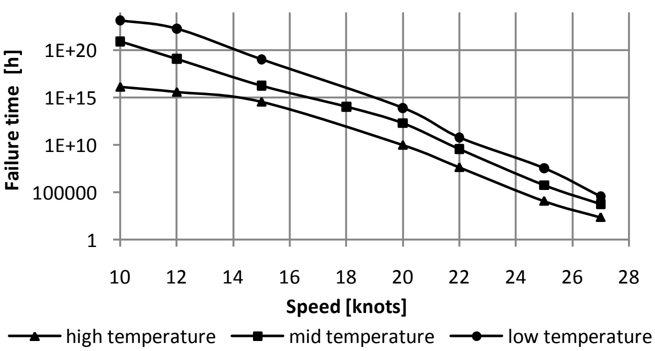

Figure 7: Turbine creep life (failure time) – Ship speed (2 beaufort and f1-hull fouling)

Figure 7 shows the variation of engine failure time due to creep of the gas turbine's hot section rotor blades in relation to ship speed and air ambient temperature.

The effects of high air ambient temperature on the gas turbine hot section rotor blade time to failure is that the compressor outlet temperature and relative rotational speed increases, driving the turbine entry temperature to higher values, with a direct impact on blade time to failure and consequently an increase in gas turbine maintenance cost.

At speeds less than 20 knots, the expected useful life of turbine blades, which are the most sensitive components of a gas turbine engine, is very high making the use of this kind of engine economically feasible, as shown in Figure 7. This is important for a mega yacht as there is no need for often onboard service, reducing the maintenance cost and the crew's workload.

Figure 8 shows the variation of open water efficiency of the propeller in terms of ship speed and hull fouling.

There is a slight change in open water efficiency as the speed increases but is less than 2% and without a specific trend. As a result, it does not considerably depend on ship speed. Additionally, neither an increase in hull fouling affects the propeller efficiency. However, as the shaft speed increases, the OWE also improves a little.

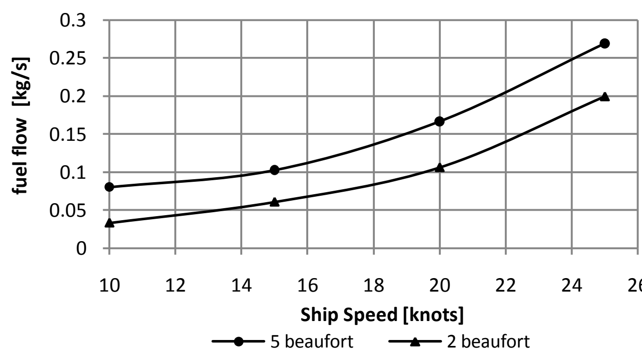

Figure 9 : Fuel flow variation – Weather conditions (mid-temperature profile and f1-hull fouling)

Figure 9 shows the difference between fuel flow at 2 Beaufort weather conditions and at 5 Beaufort weather conditions.

The vessel consumes 36.5% more fuel when it sails under adverse weather conditions. The fuel consumption increases almost with the same rate at every speed.

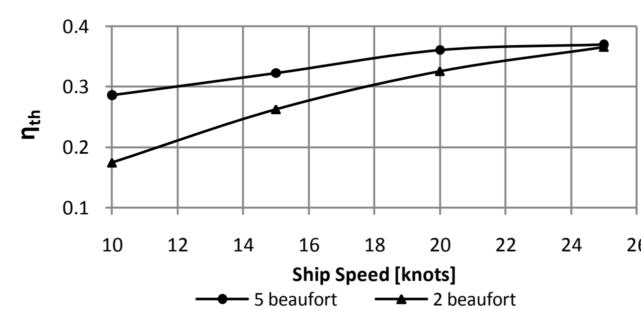

Figure 10: Thermal efficiency variation – Weather conditions (mid-temperature profile and f1-hull fouling)

Figure 10 shows the difference between the thermal efficiency at 2 Beaufort weather conditions and at 5 Beaufort weather conditions.

According to Figure 10, when the vessel sails in adverse weather conditions, its thermal efficiency is higher. The engine needs more power to maintain ship's speed when the weather conditions change from 2 to 5 Beaufort, which means that the engine operates more close to the design point for the whole speed range. As the speed increases the difference between the efficiency at 2 Beaufort and 5 Beaufort reduces because the engine tends to the design point in both cases. The two curves reach exactly at the same thermal efficiency (best efficiency) because this is the point of maximum power.

Figure 11: Turbine creep life variation – Weather conditions (mid-temperature profile and f1-hull fouling)

Figure 11 shows the difference between failure time of the engine due to the creep at 2 Beaufort weather conditions and at 5 Beaufort weather conditions.

In rough sea conditions, the vessel requires more power to maintain its scheduled speed. This results in higher turbine temperatures, which means more intensive creep. As a result the hot section rotor blade life to failure decreases, nevertheless it remains in viable level, proving the use of a gas turbine engine beneficial even in these severe conditions.

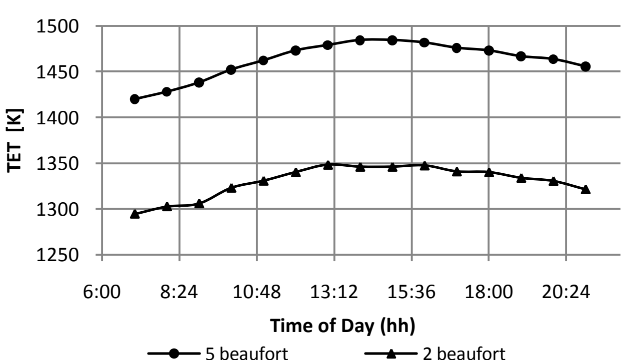

Figure 12: Turbine entry temperature variation – Weather conditions (mid-temperature profile, f1-hull fouling and 20 knots)

Figure 12 shows the difference between turbine entry temperature (TET) at 2 beaufort weather conditions and at 5 beaufort weather conditions. Every one hour the air ambient temperature changes in accordance with the temperature profiles that have already presented.

When the hydrodynamic resistance of the vessel at a certain speed is greater than the maximum available output power produced by the installed power plant, due to increased sea-state numbers and/or hull fouling progression, then the operating turbine entry temperature of the engaged prime movers peaks at the maximum input value of 1700 K which stops to be a variable performance factor and the maximum prime mover power output depends on the variation of the air ambient temperature with time of day. Consequently the vessel is not able to produce more power and it cannot maintain the scheduled speed. As air ambient temperature decreases maximum power output increases, due to increased intake mass flow rate, total compression ratio and as a result increased fuel flow rate (see Figure 12 and 18).

The Figure 12 presents the TET profile when the vessel sail at a speed of 20 knots, therefore the TET does not peak it maximum value of 1700 [K] and the vessel is able to maintain its scheduled speed.

Emissions

The figures (13-16) show the distribution of UHC, CO_2, CO, NO_X exhaust emissions in terms of the turbine entry temperature and the air ambient temperature.

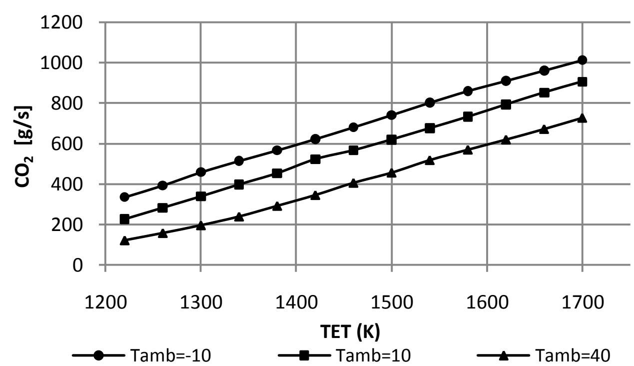

Figure 13: CO_2 exhaust emissions variation – TET (2 beaufort and f1-hull fouling)

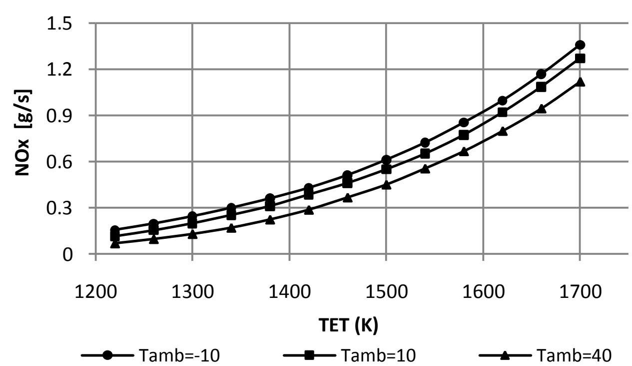

Figure 14: NO_X exhaust emissions variation – TET (2 beaufort and f1-hull fouling)

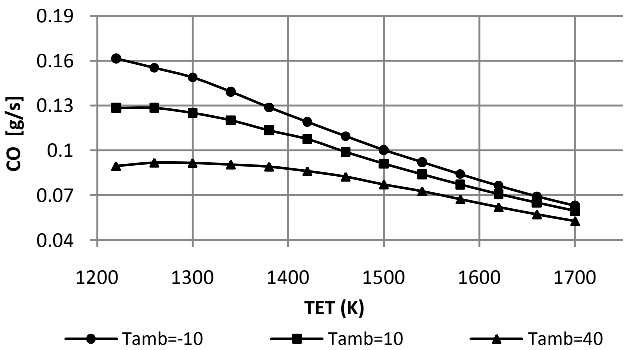

Figure 15: CO exhaust emissions variation – TET (2 beaufort and f1-hull fouling)

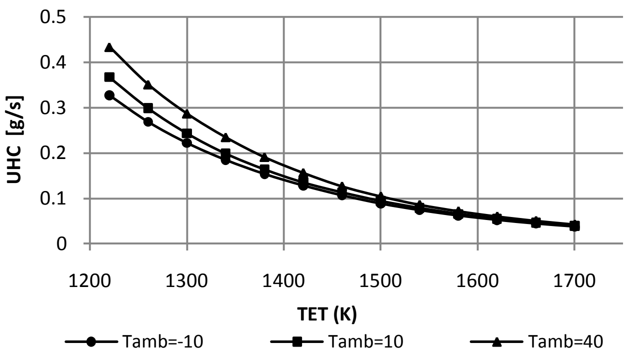

Figure 16: UHC exhaust emissions variation – TET (2 beaufort and f1-hull fouling)

Increasing the fuel flow, the turbine entry temperature rises, but the exhaust emission rates of *CO* and *UHC* decrease (see Figures 15 and 16) because of more efficient combustion process. The NO_x exhaust emissions rates increase, as they are strongly affected by TET (Figure 14). The production of CO_2 solely depends on fuel flow rate and is directly proportional to it (see Figure 13).

Increase in the sea-state numbers or hull fouling result in higher power requirements. This means that NO_x and CO_2 exhaust emissions rate increase and *CO* and *UHC* emissions rate decrease.

SECOND CASE – 24h VOYAGE

Trip distance S_v which directly depends on the vessel's speed profile is 530 [nm] and the trip schedule time t_T is set to 24 hours for all schedule voyages. The speed varies according to the weather and hull conditions.

Figures (17 to 19) show the variation of ship speed, brake power and propeller efficiency through a day trip for different hull fouling and sea-state profiles. Every one hour the air ambient temperature changes in accordance with the mid-temperature profile. Additionally, every one hour the weather conditions change in accordance with the variable sea-state profile (AWC) as well as one more sea-state profile of constant weather conditions 2 in the beaufort scale is used. The voyage starts at 7:00 and it is completed the next day at 7:00 (530 [nm] in 24 hours).

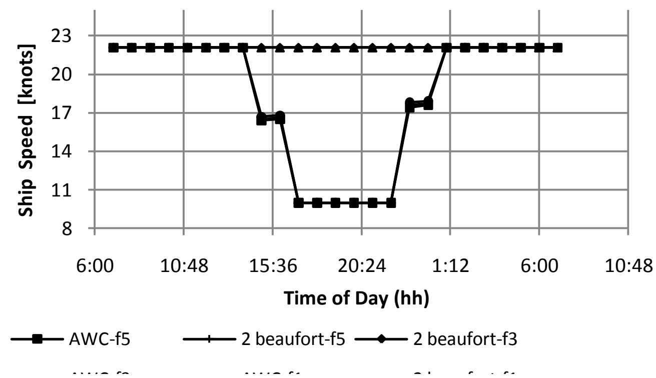

Figure 17: Ship speed variation

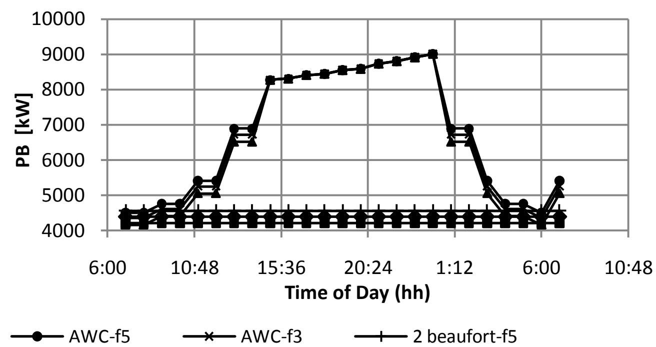

Figure 18: Brake power variation

Due to increased sea-state numbers, the speed of the vessel reduces (Figure 17) because the operating turbine entry temperature of the engaged prime movers peaks at the maximum input value of 1700 K. Consequently the vessel is not able to produce more power and it cannot maintain the scheduled speed (Figure 18). As air ambient temperature decreases maximum power output increases, due to increased intake mass flow rate, total compression ratio and as a result increased fuel flow rate (Figures 12 and 18). The reduced speed leads to the prolongation of the voyage in adverse weather conditions.

The efficiency of the propeller drops considerably in rough sea conditions. According to Figure 19, drop up to 45% is estimated.

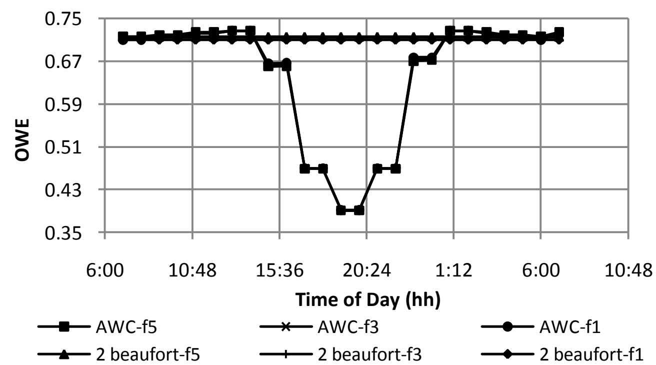

Figure 19: Open water efficiency variation

CONCLUSIONS

A complete investigation has been conducted in order to be examined the applicability of marine gas turbine as prime mover of the future environmentally friendly, large energy demand vessel. The advantages of the gas turbine as prime mover and the benefits of the more electric architecture have been assessed. In this direction, a mega yacht (70m), powered by two 4.5MW recuperated gas turbines, has been simulated for various voyage scenarios using a performance prediction model.

The simulation of different voyage cases shows that cleaning the hull of the vessel, the yacht requires on average 7.5% less power to maintain the scheduled speed, reducing the fuel consumption up to 16%. The benefit of the clean hull becomes even greater when adverse weather conditions are considered.

The effects of the weather conditions on the performance parameters are also examined in this paper. Sailing during a cold day at low speeds (lower than 18 knots), the thermal efficiency is improved by 15.4%. Above this speed, the thermal efficiency is always high as the engine operates close to the design point. Moreover, the vessel consumes 36.5% more fuel when it sails in adverse weather conditions.

Increase in the sea-state numbers or hull fouling result in higher power requirements. This means that NO_x and CO_2 exhaust emissions rate increase and *CO* and *UHC* emissions rate decrease. The emission levels of the gas turbine powered yacht satisfy the international exhaust emission limits and are much better than the emission levels of the specific yacht when powered by Diesel engines, as shown in Figure 20 [24].

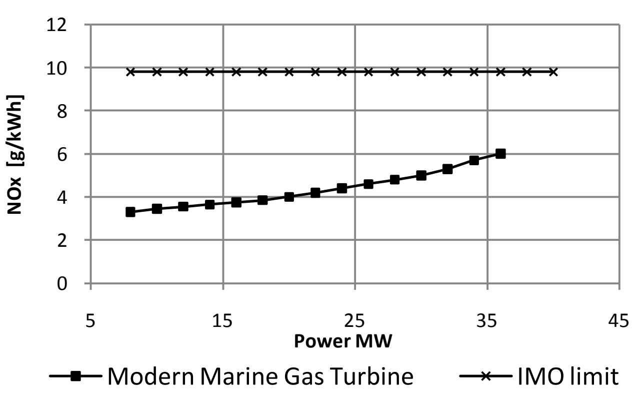

Figure 20: NOx exhaust emissions for distillate fuel

As far as the mechanical and electric losses during the transmission is concerned, they are about 2% at the cruising speed of 20 knots, whereas they reach the maximum value of 5% at speed of 27 knots.

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