Assessment of a Marine Gas Turbine Installation on a Liquefied Natural Gas Carrier

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Abstract. A prototype integrated marine simulation environment, ''POSEIDON'', has been developed. It encompasses the numerical model of a ship, coupled to a gas turbine propulsion system and can be used for a wide range of ship type simulation with the ability to program journey scenarios under diverse geographical and resistance conditions (weather and hull fouling), while the engine operational parameters are recorded for assessing engine performance.

In the present paper, the performance of a Liquified Natural Gas carrier, powered by two 25MW marine gas turbines, has been assessed for several trip scenarios. The vessel travels from Algiers to Southampton and is subject to varying ambient weather conditions, whose effect on ship and engine performance is evaluated. Moreover, extra scenarios include various hull fouling levels in order to assess the performance degradation due to increased hull resistance. As a result the off-design performance of a marine gas turbine has been assessed, in a systemic approach.

Keywords: marine gas turbine performance, ship performance model, LNG carrier.

INTRODUCTION

Investigation of the off-design performance of marine gas turbines is vital in order to predict the suitability of a prime-mover on a specific operational profile of a chosen ship type. A proposed method of off-design performance investigation is the simulation of the prime-mover in a virtual environment that can approach the engine's actual operating conditions in the open sea and consequently in a more accurate technical analysis of the prime mover.

The gas turbine is a prime mover that has not been broadly utilized in marine applications, especially in the category of civil, low speed vessels. A significant reason can be traced at its relatively lower thermal efficiency [1], compared to low speed Diesels that is not compensated by its superior power-to-volume and power-to-weight characteristics [1]. However, when extra design conditions, and external constraints come to force, the gas turbine becomes a possible candidate.

One application of particular interest is the Liquified Natural Gas carrier. The main reason is that the gas turbine is a power generator that can easily adapt to several types of fuel. As a result, it can operate with boil-off fuel, which can be mixed with the main fuel that can be natural gas. Additionally, a gas turbine offers several benefits to full electric configurations, due to its coupling to electric generators [2].

Gas turbine performance performance calculation methods are well established in existing literature such as [3] and [4]. However, most of studies regard the prime mover as isolated equipment, separated from its operating environment. This study comes to fill this gap, following a systems-of-systems approach, where the gas turbine is modeled as part of a system; i.e. the marine vessel. As a result, the off-design behaviour of the prime mover is predicted in close couple to the performance of the ship.

MODEL DESCRIPTION

Investigation of the off-design performance assessment of complex ship propulsion systems is vital in order to predict the suitability of the chosen prime-mover on the specific operational profile of the chosen ship type. A proposed method of off-design performance investigation is the simulation of the prime-mover in a virtual integrated environment (Figure 1) that can approach the prime-mover's actual operating conditions in the open sea. Such an environment has been developed in Cranfield University, under the name "POSEIDON". "POSEIDON" can be used for a wide range of ship type simulation using either electrical or mechanical propulsion systems, and is provided with the ability to program journey scenarios not only in ideal but also in increased resistance conditions, such as weather or hull fouling, by the implementation of relevant modules, as seen in Figure 1.

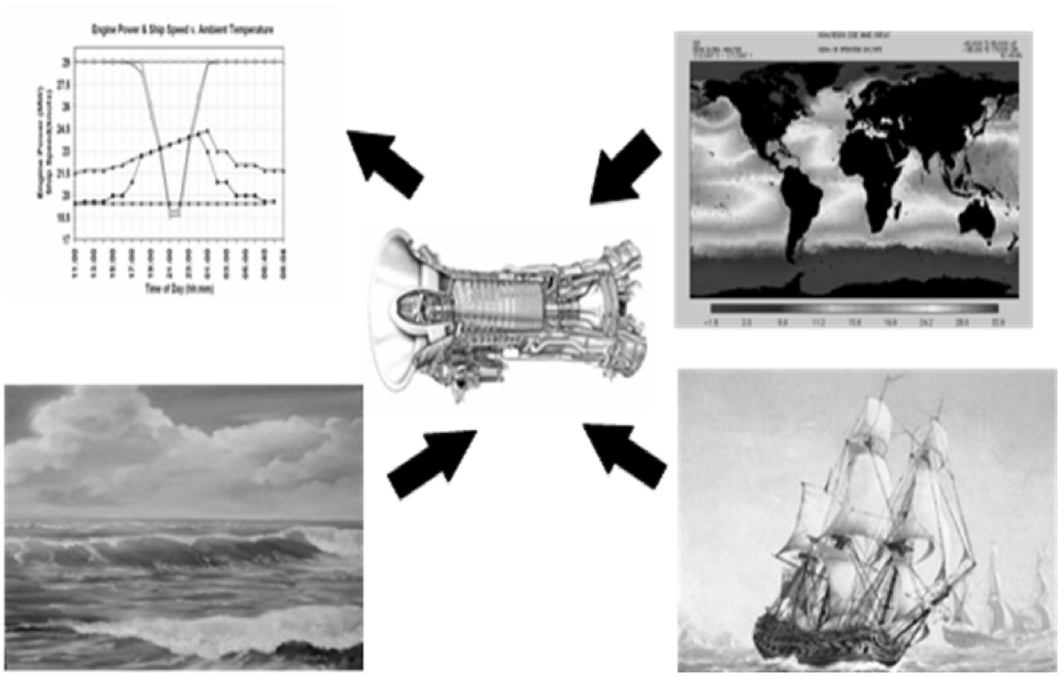


FIGURE 1. Virtual integrated marine environment.

The prototype integrated marine simulation environment tool is constituted by six modules; a ship model, a propeller model, a gas turbine model, a weather model, hull fouling model and a journey model, further discussed below.

Ship Model

A statistical method [5], [6] is used to estimate the power requirements of the ship type to be used as a platform for any propulsion system. The chosen statistical method is capable of simulating full-displacement and semi-displacement vessels, under trial conditions [5], while the propulsion factors are calculated according to [6] for one or two propeller units. The current adopted statistical method simulates several types of existing monohull vessels, with a valid range discussed in [7].

The ship type that is chosen in the present work as engine platform a Liquified Natural Gas Carrier monohull [8] with the main characteristics shown in Table 1, while integrated full electric propulsion (IFEP) approach is implemented. The prime movers are chosen to be two identical gas turbines, sharing equally the propulsion load, each one driving an electrical generator, which are responsible only for the prolusion of the vessel, and is assumed that they transfer power to two podded drives. The transmission efficiency from the prime movers to the propellers is estimated at 95% and has been kept constant throughout the journey, as the propulsion system is expected to operate at high power settings.

TABLE (1): Main design parameters of vessel.

Main parameters	Nomenclature	Values
Length at water level [m]	L_{WL}	266.0
Maximum beam [m]	B	42.6
Average design draft	T	11.3
Block coefficient	C_B	0.7493
Mid ship coefficient	C_M	0.9857
Water plane coefficient	C_{WP}	0.7848
Service speed [knots]	V_S	19.5
Froude number	F_n	0.1964
Displacement [ton]	Δ	965604.88
Wetted surface [m^2]	S	13831.0
Lambda	λ	0.93

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, [9]. The propeller model is also complemented by the calculation of water-jet open water characteristics, [10]. In order to be able to obtain the open water efficiency at any required off-design conditions an iterative method [11] has been applied, using the advance ratio as variable.

The propellers that are installed on the pods of the marine vessel that is used in the journey scenarios are assumed to be two fixed-pitch propellers (FPP) and their main design-point parameters at service speed are shown in Table 2.

TABLE (2). Design parameters of vessel's propeller

Propeller parameters	Values
Propeller diameter, D_p	8.5m
Expanded area ratio, A_E/A_O	0.7674
Pitch ratio	0.8895
Propeller rotational speed	76 rpm
Open water efficiency	0.663

Gas Turbine Model

The performance of the power generation system is predicted using 'Turbomatch'. 'Turbomatch'[12] is a 0-D gas turbine performance code, with the capability of design point and off design calculations, under development in Cranfield University, since 1967 [13]. At design point mode, 'Turbomatch' provides engine performance and size data, while at off-design mode, engine performance is predicted for varying throttle setting (rotational speed, combustor exist temperature, or fuel flow). Of particular interest, is the working principle of Turbomatch's thermodynamic off design calculation being based on mass and energy balance, carried out through an iterative method, based on component maps. These generic, experimentally derived maps are scaled to match the design point of a particular engine before an off-design calculation is performed. The choice of using such maps came as a result of the structure of this code. 'Turbomatch' comprises several pre-programmed modules, known as Bricks. Most Bricks correspond to models of individual gas turbine components, such as compressors, burners, turbines, mixers, nozzles, heat exchangers, splitters and power turbines. As a result, its modularity –supported by the implementation of generic component maps – enables the detailed design of any modern and aero engine. 'Turbomatch' has been validated against commercially sensitive data and further details can be found in [14], [15] and [16], while the working design point and off-design calculations in 'Turbomatch' are fully described in [4] and [12].

In the present study, a Brayton cycle gas turbine has been modeled using "Turbomatch". In order to assess the overall performance of the engine, a systemic approach has been followed, installing the prime mover on a LNG carrier platform using "POSEIDON", as previously discussed.

The two marine gas turbines are rated at 25MW and their design parameters are included in Table 3. They are 2-spool with a free power turbine, allowing for improved performance at part load.

TABLE (3). Design parameters of the gas turbine.

Parameters	Values	Units
Power turbine rating, P_{PT}	25	MW
Turbine entry temperature	1500	K
Compressor Pressure Ratio	19.25	-
Intake mass flow	72.5	Kg/s
Exhaust mass flow	74.05	Kg/s
Exhaust gas temperature	805	K
Thermal efficiency	37.57	%
Specific fuel consumption	222.8	g/KWh
HPT blade height	13.3	cm
Mid blade to mid shaft	67.2	cm

The operational behaviour of the gas turbine is illustrated in Figures 2 and 3, where its off-design performance is presented. The operating line of the engine, in Fig. 2a, is created by varying engine power setting. The throttling of the engine is controlled by varying the turbine entry temperature (TET), as shown in Fig. 2b.

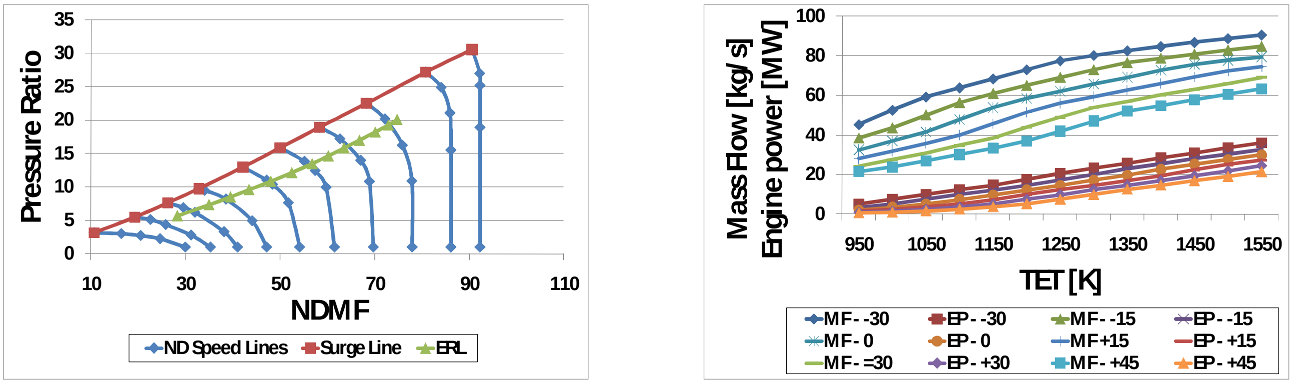


FIGURE 2. (A) Gas turbine performance characteristics. **(B)** Effect of changes in the ambient conditions over the Gas turbine power output and mass flow

The decrease of TET has an adverse effect on both engine mass flow and power, illustrated in Fig. 2, as low energy at the combustor exit, drives the power-balance between turbine and compressor to lower levels, thus lower pressure ratio, rotational speed and non dimensional mass flow (NDMF). The resulting operating line, plotted on the compressor map, lies almost parallel to the compressor surge line, proving that the compressor is safe from surge under most off design conditions.

The performance effect of engine power setting, as represented by turbine entry temperature is depicted in Fig.3, where fuel flow, specific fuel consumption and thermal efficiency have been plot for various ambient temperature and TET levels. The decrease of TET, has a consistent degrading effect on fuel flow which is mainly driven by both the decrease of fuel to air ratio, and compressor mass flow.

In Figs. 2 and 3 is also shown the effect of ambient temperature on engine performance, with temperature varying from -30^{o}C to +45^{o}C. It becomes apparent that increasing ambient temperature has an adverse effect on performance; i.e. lower power output, higher specific fuel consumption, lower efficiency, lower mass flow. This comes as a result of the duofold effect of high ambient temperature, firstly on the engine temperature ratio defined as the ratio of maximum and minimum cycle temperatures, and secondly on the density of the air entering the compressor, reducing the mass flow of air ingested.

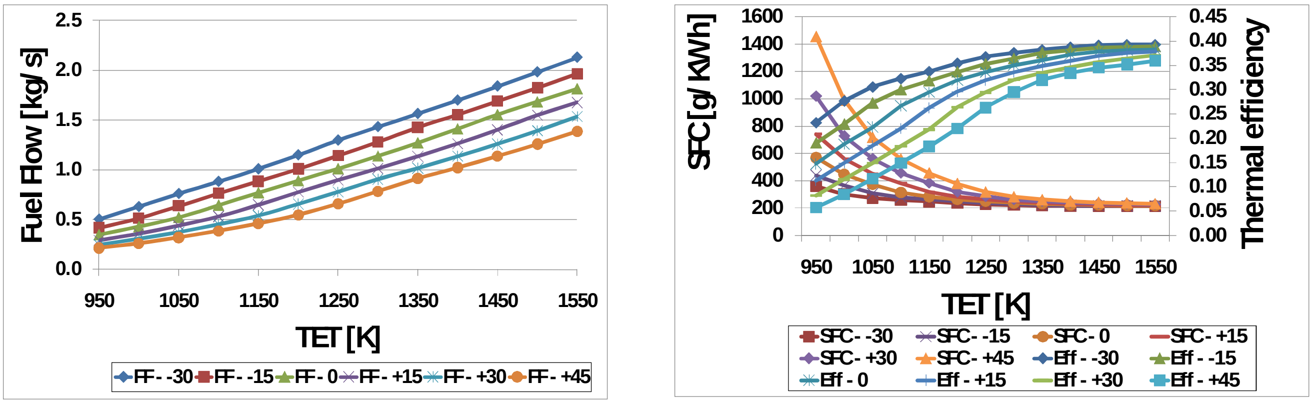


FIGURE 3. Effect of changes in ambient conditions over: **(A)** The fuel flow and **(B)** The efficiency and SFC of the gas turbine when considering a wide range of ambient temperature regimes

Weather and Hull Fouling Model

The weather model that is incorporated within the "POSEIDON" simulation tool is comprised by two modules: a sea-wave module, [17] and a wind module, [18]. 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 journey, 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, described in [19], 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.

Journey Model

The journey model handles the journey 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, and calculates the total journey time and the total fuel consumption of the engines. It should be noted though, that the journey focuses on cruise, so port time and maneuvering is not taken into consideration.

CASE DESCRIPTION

This paper presents the utilisation of 'POSEIDON' tool on a Liquefied Natural Gas (LNG) carrier powered by two 25MW marine gas turbines, part of an integrated full electric propulsion system. Outcome of the study is the assessment of the ship and engine performance, under several journey scenarios. The base to all scenarios is a ~1600nm journey from Algiers to Southampton, with details shown in Table 4. During its journey, the vessel is subject to varying ambient weather conditions; i.e. ambient temperature and sea state, shown in Fig.4. These variations come as results of the route, as the vessels passes through several parallels. As a result, ambient temperature is calculated as a function of geographical position, season and time of day, while sea-state has been assumed as a function of geographical position and annual season. These information are based on MET office data, for given regions and annual seasons, as shown in Table 4 and Fig.4.

Several journey scenarios have been investigated. These include several weather conditions for various annual seasons, In further detail, trips for Winter, Spring and Summer have been calculated, for both ideal (IWC) and adverse weather conditions (AWC), represented as variable sea state profile, in order to introduce a level of realism in the calculation. Furthermore, four hull fouling levels, starting with clear hull (CSHS) and increasing for three fouling levels (SHSD1=120μm, SHSD2=240 μm and SHSD3=300μm) have been taken into account. Their adverse effect on engine and ship performance is plotted and analysed in the following sections.

The journey distance for all scenarios is 1619 nautical miles and under permissible conditions the vessel travels constantly at speed of 19.5knots. Under increased resistance conditions the prime movers are allowed to increase their output power until maximum TET is reached. The target in all cases is to maintain the speed of the vessel speed, or the maximum permissible speed. Each journey is split into one hour segments and calculations of the system's parameters are carried out for each time segment until the end of each journey.

TABLE 4. Journey profile of vessel

Sea port	Journey(nm)	Duration(hrs)	Max temp	Min temp	Max temp	Min temp	Max temp	Min temp
Algiers-Malaga	366	19	17	7	24	12	33	20
Malaga-Porto	509	26	14	5	22	10	28	15
Porto-Brest	499	26	13	4	19	9	25	13
Brest-Southampton	245	12	7	2	17	7	22	11
TOTAL	**1619**	**83**						

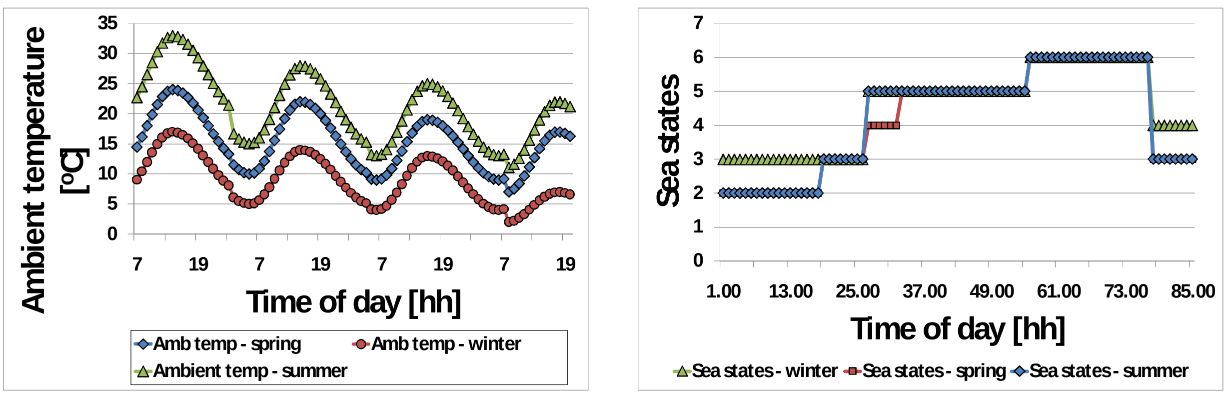


FIGURE 4(A). Ambient temperature profile and **(B)** Sea state profile along the trade of the LNG Carrier from Algiers to Southampton in winter spring and summer seasons

Figure 4 shows the variation of ambient temperature and sea state for the three season scenarios. In this figure, the effect of geographic position is clearly depicted, where maximum day temperature that appears at ~14:00 reduces, as a result of the vessel travelling north. Moreover, minimum temperatures are experienced during the winter season. On the other hand, sea-state starts at 2 in he Beaufort scale, during the Algiers-Malaga part, increases to 3 from Malaga to Porto, to 5 during the Porto-Brest leg and to a maximum of 7 for most of the Brest-Southampton leg.

The major results of the analysis are presented in Figs. 5 to 12, which show the variation of vessel and engine performance during all journey scenarios. This includes, engine power, ship speed, fuel flow and turbine entry temperature. Moreover, total results are plotted for the assessment of the effect of various journey scenarios on total fuel consumed during the chosen trip.

Gas Turbine Power Output

Power output from each gas turbine has been calculated for the duration of every journey and is plotted in Figs. 4 and 5. Engine power is derived from break power propelling the ship, less the transmission losses. As seen in Fig.4a for ideal weather conditions, and clean hull, power output remains constant during the summer journey, and shows a minor fluctuation for spring and winter. However, in general terms, it is considered as constant, as the prime mover is able to cover the power requirement in order to maintain cruise speed. This is not the case, though when the vessel travels under adverse weather condition, in addition to 120μm of hull roughness.

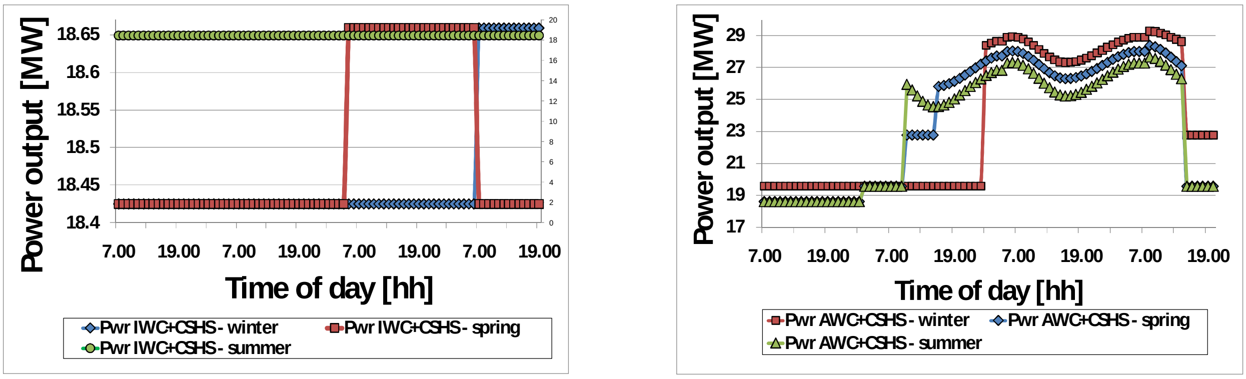


FIGURE 4. Engine power output variation in **(A)** IWC and **(B)** AWC with a CSHS

It becomes apparent in Fig.4b that after the first third of the journey, the engine reaches its limits at maximum allowed operating turbine entry temperature, in an attempt to maintain cruise speed, under adverse conditions. After this point power output fluctuates. This fluctuation is a function of ambient temperature. As a result, during summer, where higher ambient temperature is experienced, power output ranges between 24MW and 27MW, while during the winter journey, power fluctuates between 27.5MW and 29MW, as the low ambient temperature acts in favour of total power.

Further increase of hull fouling, has a direct impact on brake power of the vessel and the part of the journey during which power demand is constant and completely covered by the prime mover is limited. It can be observed in Fig.5a that for 120μm of hull roughness, less than a third of the trip is performed at constant power, during the winter and spring scenarios. On the other hand, during summer, where ambient temperature is higher, engine power output fluctuates as a function of ambient temperature during the whole journey. The same attribute is shown in Fig. 5b for higher hull fouling, and all annual seasons.

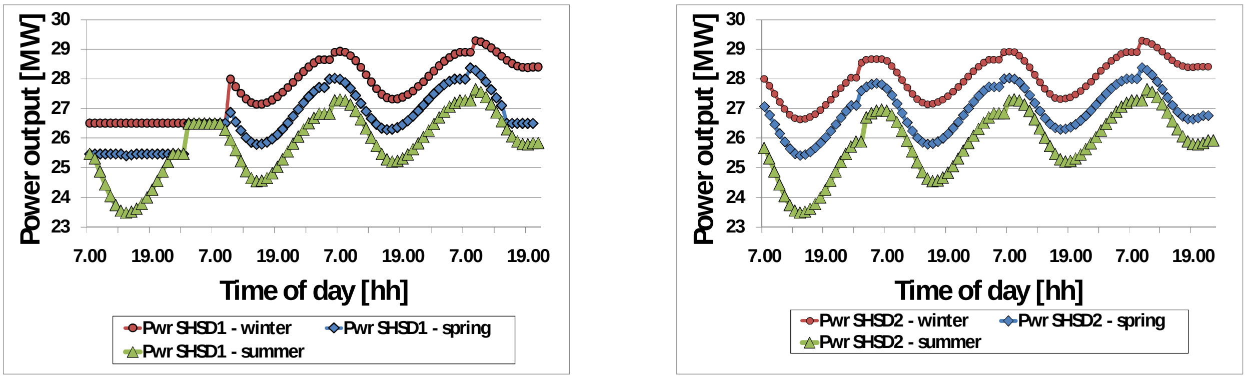


FIGURE 5. Engine power output variation in AWC with **(A)** 120μ and **(B)** 240μ of SHSD

Vessel Cruise Speed

One of the features of 'POSEIDON' is its ability to predict maximum attainable ship speed, for every timestep, by evaluating the balance between power requirement and available power. As a result, for adverse conditions that increase brake power, the vessel is forced to slow down and operate at speed that is in agreement with available power.

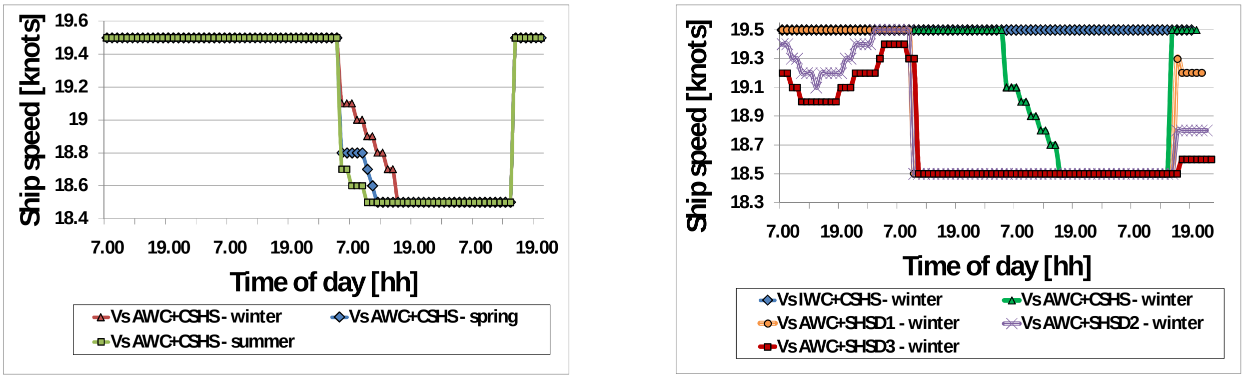
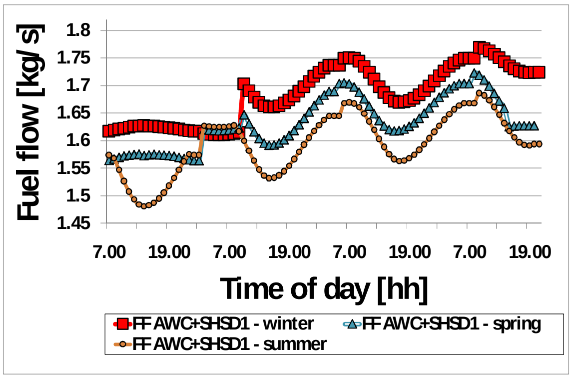
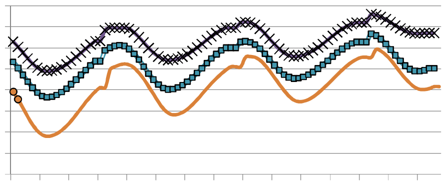


FIGURE 6: Ship speed variation under **(A)** Different weather and SHSDs in winter season only **(B)** AWC with a CSHS in winter, spring and summer seasons

As it is expected and shown in Fig.6b, for ideal weather conditions, the vessel is able to maintain its original speed for the duration of the journey. However, the application of high sea-state has an adverse effect, shown in Fig.6a for all seasons. Even though, the ship travels at constant speed for the first 24 hours, it gradually decelerates, when beaufort levels are in excess of 5. It is worth noting that deceleration is more steep for the case of summer, due to the effect of higher ambient temperature. Furthermore, when hull fouling is added to adverse weather conditions, the increase brake power leads the prime mover to its limits since the beginning of the trip. As a result, the vessel speed fluctuates between 19.5 and 19 knots during the first 12 hours, in accordance to the fluctuation of engine power, as shown in Fig.6b. After the first 24 hours, though, cruise speed falls further as a result of the increase of sea-state,

constant power, (Fig.5), fuel flow (Fig.9) follows ambient temperature fluctuation, while for varying power, fuel flow follows engine power curve.





In a similar manner to fuel flow variation, TET fluctuates with time and ambient temperature, for journeys that include ideal weather and clean hull conditions. The reason is that in such scenarios the gas turbine maintains constant power, thus constant engine temperature ratio, (Fig.10a). The application of adverse weather, brings the engine to its limit for the two thirds of the journey, as previously discussed. This is clearly depicted in Fig.10b, where maximum limit of 1550K is maintained during this part of the journey. It should be noted that maximum TET is in accordance to material limitations and blade cooling technology on the high pressure turbine rotor and nozzle guide vanes.

A similar attribute appears in Fig.11 where the effect of adverse weather and fouled hull for different seasons on TET is shown. A close comparison with Fig.5a reveals that for the first third of the journey, turbine entry temperature fluctuates, following the fluctuation of ambient temperature, but only for the winter and spring seasons. During the summer journey, where inlet temperature is even higher, TET reaches a maximum value, thus power fluctuates, falling with increasing ambient temperature. This relationship between power, ambient temperature and TET is apparent in the rest part of the journeys, where the engine operates at its limit (maximum TET) and power production is directly affected by ambient temperature.

CONCLUSIONS

The 'POSEIDON' code is a tool for assessing the performance of a marine gas turbine, as a part of a system, in a virtual environment. As a result, the off-design performance of the engine is predicted in relation to ambient conditions and journey requirements, contributing to an apprehensive preliminary gas turbine performance estimation. As a result, conclusions, regarding the total effect on fuel consumption of any journey scenario can be derived, as shown in Fig.12.

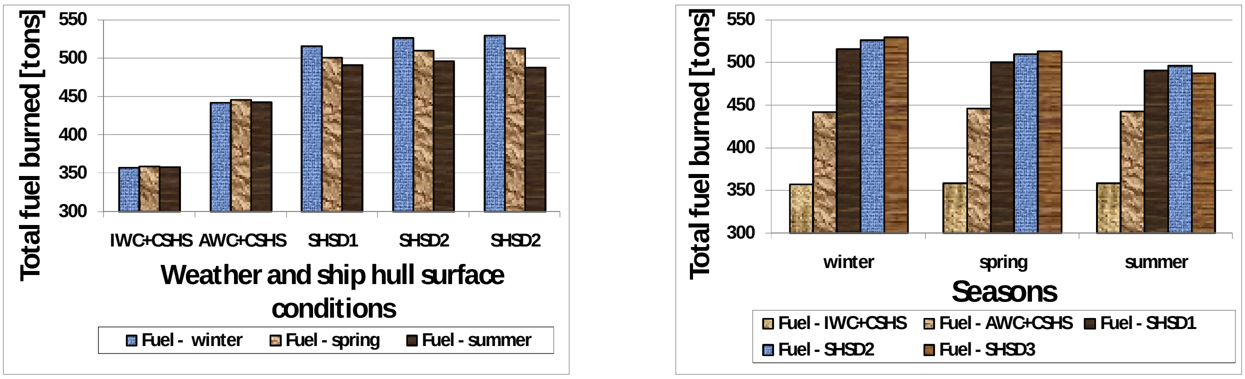


FIGURE 12. Comparison of the quantity of fuel burned per voyage under the effect of **(A)** Weather and ship hull fouling conditions. **(B)** Climatic conditions in winter, spring and summer seasons

Figure 12 illustrates the overall results for all journeys calculated in the present paper. The effect of season, weather and hull condition is therefore clearly depicted through the amount of total journey fuel consumed.

As expected, an LNG carrier traveling from Algiers to Southampton is predicted to consume minimum amount of fuel when exposed to ideal calm weather, and operates with a clean hull. Moreover, under these ideal conditions, the effect of ambient temperature can be noticed, that leads to slightly higher fuel consumption during the summer season. This effect though, becomes obsolete when adverse weather and hull fouling is taken into account. In Fig.12 it becomes apparent that hull fouling can have a significant effect on the operating costs of the prime mover, showing a ~15% increase in fuel consumption, even for hull roughness as low as 120μm. Moreover, it is shown that further increase of hull roughness does not have a linear impact on fuel consumption, highlighting the need for clean hull.

The effect of weather can be assumed as an uncertainty parameter that appears to have a contribution to total fuel consumption. As shown in Fig.12 a vessel traveling under adverse weather profile, can consume ~20% more fuel, compared to ideal weather conditions. Evidently, journey prediction results should be approached with a conscious mind of the uncertainties that could apply in a real life scenario. Nevertheless, studies as the present, highlight the sensitivity of prime mover performance to external conditions and can be utilized for quantitative assessment and preliminary design of marine gas turbines.

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