

Research paper

Techno-environmental assessment of a hydrogen-fuelled combined-cycle gas turbine for a liquid hydrogen tanker

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ARTICLE INFO

Article history:

Received 4 May 2022

Received in revised form 31 July 2022

Accepted 14 August 2022

Available online xxxx

Keywords:

Liquid hydrogen tanker

Engine thermal efficiency

Combined-cycle gas turbine

NOx emissions

Hydrogen-fuelled engine

LH2 tanker mission

ABSTRACT

The purpose of this study was a techno-environmental assessment analysis for a 280,000 m³ liquid hydrogen (LH2) tanker powered by a hydrogen-fuelled combined-cycle gas turbine (COGAS) as the prime mover. This study utilised established and reliable methods to simulate the LH2 tanker in different journeys and conditions for analysing the advantages of the hydrogen-fuelled COGAS in terms of performance and emission reduction. The assessment was based on engine behaviour on different journeys under cargo loaded and unloaded conditions, with a normal and a 6% degraded engine, and under various ambient conditions. According to the results, the single-pressure hydrogen-fuelled COGAS reached a maximum overall thermal efficiency of 55.5% in winter under unloaded and normal engine conditions at a ship speed of 18 knots during the journey from Marseille to Algeria. From an environmental perspective, the maximum NOx emission of the COGAS was 3.5 kg/h during the journey from Tangier to Southampton in summer with a 6% degraded engine under the loaded condition at a ship speed of 18 knots. The results of the techno-environmental assessment indicated that the LH2 tanker powered by the hydrogen-fuelled COGAS could successfully achieve high efficiency and low emission targets in off-design conditions. The outcome of this study will lead to a future investigation of the LH2 tankers operation economic aspects.

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1. Introduction

Global sustainability requires urgent action to tackle climate change and global warming. Accordingly, world leaders at the UN climate change conference (COP26) in Glasgow took action to apply the 2015 Paris climate change agreement for overcoming the negative impact of climate change and limiting the global temperature increase to approximately 1.5 °C (COP26, 2021). In the same direction, the International Maritime Organisation (IMO) aims to reduce 50% of greenhouse gas emissions from global shipping by 2050 compared to 2008 (IMO, 2018). Regarding the environment, maritime transportation and shipping sectors are responsible for approximately 3% of the CO₂ emissions globally (Tillig and Ringsberg, 2020). Moreover, several studies have shown that the continually growing CO₂, CO, and NO_x emissions from shipping are expected to play a crucial role in IMO regulations in future (Skjolsvik et al., 2000; Buhaug et al., 2009).

Additionally, the IMO applied the energy efficiency design index, a design instrument for reducing the emissions from newly

constructed ships. The IMO also increased the strictness of the regulations on the NO_x and SO_x emissions from vessels and designated emission control areas, such as the Baltic and North seas (Van Hoecke et al., 2021). In 2019, the United Kingdom was one of the countries that took action in this regard by publishing the UK Clean Maritime Plan to achieve zero-emission shipping by 2025. The plan indicated that the use of hydrogen fuel in vessel propulsion systems can play a significant role in the global transition to zero-emission shipping and transportation in the maritime sector (UK Department for Transport, 2019).

Consequently, employing clean hydrogen can be a promising solution for global decarbonisation and climate change mitigation (Alkhaledi et al., 2021). In actuality, the expectation indicates that hydrogen fuel has considerable potential to decarbonise the maritime sector if used in thermal engines by utilising the green hydrogen produced from renewable energy sources through electrolysis. Furthermore, hydrogen removes unburnt hydrocarbons, aromatic compounds, sulphur oxides, soot, and smoke as harmful emissions (Alkhaledi et al., 2022). The use of hydrogen as an energy storage mechanism is considered particularly useful in the context of electricity generated from sources where a significant mismatch between supply and demand is present; these include wind, solar, and nuclear sources, which could be used to electrolyse seawater rather than fresh water, which is scarce in

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Abbreviations

COGAS	Combined-cycle gas turbine
LH2	Liquid hydrogen
IMO	International Maritime Organisation
3D	Three-dimensional
NO _x	Nitrogen oxide
CO ₂	Carbon Dioxide
CO	Carbon monoxide
SO _x	Sulphur oxide

Units

Tonnes	Total displacement
m	Lightweight, Deadweight, LOA, Length between perpendiculars, Length on the waterline, Extreme breadth, Depth, Draught, Propeller diameter
m ²	Wetted surface area
knots	Vessel speed
MW	Output power of combined-cycle gas and steam, Output power, Steam turbine output power, Pump work
K	Ambient temperature, Exhaust gas temperature, Turbine inlet temperature;
kPa	Ambient pressure
kg/kWh	Specific fuel consumption
kg/s	Exhaust gas mass flow rate, Fuel flow rate, Steam mass flow rate
%	Thermal efficiency, Open-water efficiency
°C	Superheated steam temperature, Pinch point temperature difference, Approach points temperature difference, Feed water temperature
bar	Steam pressure, Condenser pressure
rpm	Propeller rotational speed
g/kWh	Emission factor
ppm	Concentration of gaseous species
m ³ /h	Engine exhaust flow rate
J/(mol K)	Ideal gas constant
kW	Engine power

many regions. Hydrogen can also be used with a thermal engine for waste heat recovery, such as a combined-cycle gas turbine (COGAS), to achieve a higher thermal efficiency and lower emissions compared to those achieved using conventional internal combustion engines (Alkhaledi et al., 2022).

The combined cycle fuelled by hydrogen could be a successful alternative for ship propulsion systems to achieve almost zero-emission targets in the maritime sector. In this regard, the key issues that necessitate a techno- environmental examination of the combined cycle fuelled by hydrogen as a prime mover of liquefied hydrogen tankers (Alkhaledi et al., 2022) through different mission assessments in terms of the performance and environmental impact represent an essential stage in achieving the reliability of the combined cycle gas turbine fuelled by hydrogen as a propulsion system of liquefied hydrogen carrier ships in the design implementation stages of these tankers in the future.

However, interesting, exciting studies presented organic Rankine cycle, fuel cells, nuclear energy, batteries, superconducting

motors, renewable energy, and hybrid propulsion as future marine propulsion technology with low fuel consumption and emission reduction solutions (Parker, 2013). Benvenuto et al. provided vital fundamental information for evaluating the performance of marine COGAS propulsion systems using a single- and dual-pressure heat recovery steam generator without using LH2 fuel (Benvenuto et al., 2012, 2014). McKinlay et al. evaluated several viable options to achieve ships zero-emission target by 2025, using three promising alternative fuels on board large-scale international vessels; hydrogens, ammonia and methanol. This is essentially owing to fuel's possibility to generate emission-free electricity using fuel cells (McKinlay et al., 2021). Yan et al. studied the design optimisation of a cruise ship energy system using a multi-objective mathematical programming model that considered the technical, environmental, and economic aspects of ship function (Yan et al., 2019). Ahn et al. evaluated a four propulsion system options for a hydrogen tanker in terms of their economic, technological, and environmental feasibilities by considering factors such as lifecycle cost analysis (Ahn et al., 2017). Doulgeris et al. developed a Techno-economic, Environmental and Risk Analysis (TERA) computational method for marine propulsion systems. The method includes several numerical models to simulate the life cycle operation of marine gas turbines as a propulsion system for marine vessels in different journeys and conditions (Doulgeris et al., 2012). Talluri et al. applied a Techno-economic, Environmental and Risk Assessment (TERA) method to evaluate the performance and economic benefits of a 4.5 MW simple cycle, twin-shaft marine gas turbine fuelled by natural gas and twin-diesel engines, each of 3 MW rating, operating on marine diesel oil as ship power plants in conjunction with three Flettner towers as assistance propulsion system (Talluri et al., 2018).

To the best of the authors' knowledge, the techno-environmental evaluation of hydrogen-fuelled combined cycle gas turbines in different journeys and conditions for marine applications to support the acceleration of manufacturing and utilising the liquefied hydrogen tankers has not yet been investigated. Therefore, this study makes a novel contribution by employing and examining a combined cycle gas turbine fuelled by hydrogen as an alternative efficient prime mover for a new design of hydrogen carrier ships in different journeys and ambient conditions to achieve an almost zero-emission target for the maritime transportation sector.

This study aimed to assess the missions of a novel improved hydrogen tanker powered by hydrogen-fuelled COGASs using the techno-environmental analysis method in off-design conditions in terms of the performance and environmental impact; for this purpose, the authors used state-of-the-art design and analysis methods as a feasible and sustainable approach to the large-scale investigation. This assessment is a very important stage and one of the research and development stages for implementing liquefied hydrogen tankers as a new design in the future.

2. Methods

An established methodology was developed to improve the novel design of the LH2 tanker with a total capacity of 280,000 m³ of LH2, which was designed in a previous study (Alkhaledi et al., 2021). In addition, the methodology was analytically extended to assess the performance and emission for the improved design of the LH2 tanker using a techno-environmental assessment framework by applying a computational method for marine propulsion systems (Doulgeris et al., 2012). Developing the utilised method in this research could facilitate the design of a COGAS power plant fuelled by hydrogen as a prime mover to optimally reduce the fuel consumption and emissions of LH2 tankers. This improved design

was performed using the in-house TURBOMATCH gas turbine performance code (MacMillan, 1974), MATLAB (Mathworks, 2020), and SOLIDWORKS software to design and simulate an LH2 tanker powered by a COGAS within POSEIDON, a ship-wide in-house simulation software of Cranfield University. This approach evaluates proposed systems using the COGAS engine thermodynamic and environmental performance models. This study employed the hydrogen-fuelled COGAS as a prime mover to achieve the off-design requirements from geographic location and ambient conditions for LH2 tankers in different journeys. In addition, the assessment considered the influence of the cargo weight, which was approximately 20,000 tonnes (Alkhaledi et al., 2021), and an engine degradation of 6% (Alkhaledi et al., 2022). Further, the analysis provided a techno-environmental method for evaluating the ability of a proposed LH2 tanker to satisfy the zero-emission target with an efficient power system.

2.1. Overall improved design philosophy

The overall design philosophy of the LH2 tanker has been presented in a previous study (Alkhaledi et al., 2021). In the present study, only a few modifications were implemented to improve the previous design of the LH2 tanker; these modifications concerned adding new design elements represented by the LH2 tank pumps, ship anchors, storage facilities, and crew service tunnel. The updated design of the LH2 tanker is expected to improve applicability in the manufacturing sector.

2.2. Description of techno-environmental modelling modules

2.2.1. Ship module

An improved design of the LH2 tanker named JAMILA was simulated in this study, as described in Section 2.1. The LH2 tanker evaluated in this research was 370 m long, 75 m wide, and had draughts of 9.263 and 10.012 m under the unloaded and fully loaded conditions, respectively. The full-load displacement was 230,000 tonnes for the transportation of 20,000 tonnes of LH2. Furthermore, the Lightweight of the ship was 208,000 tonnes which represents; the LH2 ship cargo tanks, fuel tank, engine, hull structure, Deck gear, anchor, cables, pipes and LH2 tanks accessories and equipment weights, and the ship's Deadweight was 22,000 which represents; the cargo, accommodation, crew, and fuel weights (Alkhaledi et al., 2021). The specifications of the LH2 tanker are highly unusual compared with other traditional tankers designs because the Deadweight is 22000 tonnes which is very light compared with the ship's immense size. This is the result of the very low density and a substantial volume of hydrogen as a cargo. However, increasing the ship's Lightweight in the ship design stage to 208,000 tonnes directly supported the ship stability requirements based on the 2008 IMO Intact Stability Code (ISC) (Alkhaledi et al., 2021; IMO, 2008).

Moreover, the vessel used a single-pressure COGAS as the prime mover with an output power of approximately 50 MW (Alkhaledi et al., 2021). The specifications of the LH2 tanker are listed in Table 1. To achieve adequate simulation accuracy, the authors assumed that the ship maintained a maximum operating speed of 18 knots during all journeys.

2.2.2. COGAS and propeller module

The primary propulsion system of the ship was designed to be a 50-MW combined-cycle gas and steam turbine (Alkhaledi et al., 2022). The performance of the power plant was analysed using an in-house gas turbine performance software (MacMillan, 1974) with hydrogen as an alternative fuel based on the gas turbine performance evaluation code (Nikolaidis, 2017). The

Table 1

Main characteristics of the simulated liquid hydrogen (LH2) tanker Alkhaledi et al. (2021).

LH2 tanker parameters	Values	Units
Class	JAMILA	–
Vessel type	LH2 Tanker	–
Total displacement (Δ_{total})	230,000	tonnes
Lightweight	208,000	tonnes
Deadweight	22,000	tonnes
Length overall (LOA)	370	m
Length between perpendiculars	367.5	m
Length on the waterline	367.9	m
Extreme breadth (B)	75	m
Depth (D)	35	m
Full-loaded condition		
Draught (T)	10.012	m
Block coefficient (C_B)	0.819	–
Prismatic coefficient (C_p)	0.824	–
Midship coefficient (C_m)	0.995	–
Water plane coefficient (C_{wp})	0.900	–
Wetted surface area	29,550.906	m ²
Unloaded condition		
Draught (T)	9.263	m
Block coefficient (C_B)	0.813	–
Prismatic coefficient (C_p)	0.818	–
Midship coefficient (C_m)	0.994	–
Water plane coefficient (C_{wp})	0.894	–
Wetted surface area	28,916.458	m ²
Vessel speed	18	knots
Minimum propulsion power required for the full-load condition	27.3	MW
Output power of combined-cycle gas and steam	50	MW

steam turbine was modelled and simulated using MATLAB software (Mathworks, 2020). Additionally, the gas turbine cycle was inspired by an existing advanced LM2500+ gas turbine engine model, which is widely used in marine propulsion systems (Luck, 1998; Oosterveld and van Oossanen, 1975), and a single-pressure non-reheated steam cycle. The general specifications of the gas turbine and steam cycles are presented in Tables 2 and 3, respectively (Alkhaledi et al., 2022).

Consequently, in the design and off-design assessment, ambient temperature variations and a component degradation of 6% were considered. Moreover, two fixed-pitch propellers were assumed to be installed in the pods of the LH2 tanker. The vessel speed guided this selection and power requirement considering the size of JAMILA in accordance with the maximum allowable unloaded draught, which was 9.263 m, as mentioned in Table 1 (Alkhaledi et al., 2021). The propeller design was based on the open-water characteristics of the Wageningen B-series propellers (Oosterveld and van Oossanen, 1975). The main propeller design characteristics are listed in Table 4 (Alkhaledi et al., 2022).

2.2.3. Vessel resistance prediction

The ship resistance model that affects the ship and power requirements in calm water has been comprehensively presented in a previous study on propulsion LH2 tankers (Alkhaledi et al., 2021). The total resistance and power requirements of JAMILA were estimated using the Holtrop and Mennen method based on the ship shape and size (Holtrop and Mennen, 1982; Holtrop, 1984). In the present study, the authors considered the added

Table 2General specifications of a gas turbine cycle [Alkhaledi et al. \(2022\)](#).

Gas turbine cycle	Values	Units
Ambient temperature	288.15	K
Ambient pressure	101.3	kPa
Pressure ratio	23.1	–
Specific fuel consumption	0.07416	kg/kWh
Exhaust gas mass flow rate	84.948	kg/s
Exhaust gas temperature	840.3	K
Turbine inlet temperature	1,550	K
Fuel flow	0.7485	kg/s
Output power	36.2	MW
Thermal efficiency	40.3	%

Table 3

General specifications of a steam cycle [9].

Steam plant parameters	Values	Units
Superheated steam temperature (T_a)	559.8	°C
Steam pressure (P_s)	60	bar
Pinch point temperature difference (ΔT_p)	7.5	°C
Approach point temperature difference (ΔT_a)	20	°C
Steam mass flow rate (m_s)	10.51	kg/s
Condenser pressure (P_{cond})	0.06	bar
Feed water temperature (T_e)	36.2	°C
Steam turbine output power (W_{ST})	14.35	MW
Steam turbine isentropic efficiency (η_{ST})	89.9	%
Pump work (W_{pump})	4.1388	MW

Table 4

Propeller design parameters and performance [9].

Propeller characteristic	Values	Units
Propeller type	Fixed pitch	–
Number of blades (Z)	4	–
Number of propellers	Twin-screw fixed on the pods	–
Propeller diameter (D_{pr})	6.4	m
Pitch ratio (P/D_{pr})	1.0	–
Blade area ratio (A_E/AO)	0.9	–
Thickness-to-chord ratio (t/c)	0.029	–
Propeller rotational speed (n)	124.8	rpm
Open-water efficiency (η_o)	56	%

wave and wind resistance in addition to the calm water resistance. These additional resistance modules, which are presented in the following sections, were expected to increase the accuracy of resistance estimation under the loaded and unloaded conditions for the LH2 tanker in different weather conditions.

2.2.3.1. Added wave resistance module. The added resistance due to the wave motion resulting from the interaction of the vessel with normal waves was considered in this study, in contrast to the calm water resistance model presented in a previous study ([Alkhaledi et al., 2021](#)). The combination of wave and ship motions produces a 20% to 40% increase in water resistance; this percentage cannot be neglected in the total resistance calculations ([Liu et al., 2011](#)). According to Alexandersson ([Alexandersson, 2009](#)), the added wave resistance can be estimated by considering the incident wave angles. This method is one of the most common procedures for accurately estimating the added resistance due to wave motion. The method of Gerritsma and Beukelman ([Gerritsma and Beukelman, 1972](#)) is also used to estimate the added wave resistance. In this method, the linearised formulation is acceptable only for the head waves, for even keel

vessels, especially when radiation-induced resistance is applied. The added wave resistance module used in the present study is based on a method described by [Talluri et al. \(2016\)](#).

2.2.3.2. Wind resistance module. The method used here to estimate the aerodynamic resistance due to headwind was introduced by Jensen ([Schneekluth and Bertram, 1998](#)), expressed as follows:

$$R_{AA} = C_{AA} \frac{\rho_a}{2} \cdot (V + V_W)^2 \cdot A_{FP}, \quad (1)$$

where R_{AA} is the wind resistance, C_{AA} is a coefficient in the range of 0.8–1.0 for cargo ships, ρ_a is the air density, V is the speed of the ship, V_W is the absolute value of wind speed, and A_{FP} is the frontal project area of the ship above sea level.

For all wind directions, the Blendermann model ([Blendermann, 1993, 1996](#)) was used by applying the following equation:

$$R_{AA} = \frac{\rho_a}{2} u^2 \cdot A_L \cdot CD_l \frac{\cos \varepsilon}{1 - \frac{\delta}{2} \left(1 - \frac{CD_l}{CD_t} \sin^2 2\varepsilon\right)}, \quad (2)$$

where u is the apparent wind velocity; A_L is the lateral plane area; ε is the apparent wind angle, which is zero in the case of headwind; δ is the cross-force parameter; CD_l is the non-dimensional drag under the headwind condition; and CD_t is the non-dimensional drag under the beam wind condition.

2.2.3.3. Engine performance. The engine performance model ENGINE was one of the main modules in the numerical software POSEIDON, which was used to implement the combined-cycle model and LH2 tanker design for simulating the performance of the LH2 tanker powered by the hydrogen-fuelled COGAS in different journeys and conditions ([Doulgeris et al., 2012](#)). ENGINE estimated the engine performance using a three-dimensional (3D) interpolation function that obtained the engine power at each operating point. The input values were obtained by varying the turbine inlet temperature and ambient conditions through the combined-cycle performance and stored as a 3D table ([Talluri et al., 2016](#)). In this study, ENGINE was used to simulate the COGAS model with the turbine inlet temperature ranging from 1025 to 1700 K in increments of 25 K and the ambient temperature ranging from –25 to 45 °C in increments of 10 °C; these values were selected to cover a large scale of the turbine inlet temperature variation in the winter, summer, and middle seasons.

2.2.4. Weather and journey management module

In practice, the weather module input variables are the ambient temperatures of air and sea between the hydrogen exporting and importing ports ([Doulgeris et al., 2012](#)). In this study, the operation period of the LH2 tanker was assumed to be 330 days per year; this period was divided into three seasons (winter, summer, and middle) to achieve the actual evaluation results of the ship performance and emission. The winter months were December, January, and February; summer months were June, July, and August; and middle-season months were March, April, May, September, October, and November. The average ambient temperature of each season was applied in the LH2 tanker simulation for different journeys. The journey management model includes the trip distance, ship speed, and time periods with changing weather conditions and estimates the total trip time and the total fuel consumption of the engine ([Doulgeris et al., 2012](#)). This study selected the trips based on the expectation of the hydrogen exporting hubs, which are sunny countries with ports. Therefore, two journeys were selected: from Marseille to Algeria (22 h) and from Tangier to Southampton (81 h). Each season, the journeys were simulated to realise adequate accuracy in the engine performance and emission analysis. In this stage of hydrogen storage technologies, the journeys are assumed to be short (not more than 4 d), owing to the relatively high boil-off rate.

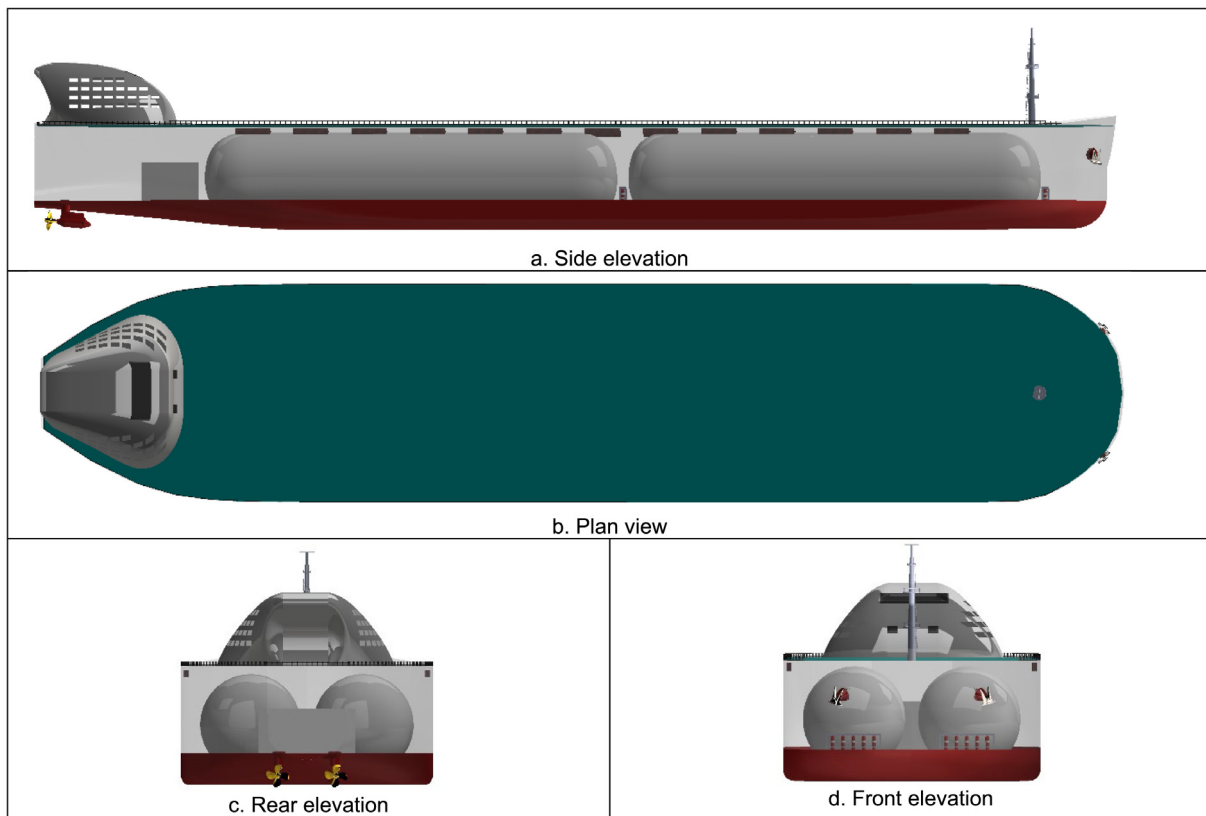


Fig. 1. JAMILA three-dimensional design; (a) side elevation; (b) plan view; (c) rear elevation; and (d) front elevation.

2.2.5. Emission module

The LH2 tanker in this study was assumed to be transporting and fuelled by zero-carbon green hydrogen, producing only low NO_x gaseous emissions (Enable H2, 2022). From an environmental perspective, the model for assessing the NO_x output emissions from a loaded and unloaded green LH2 tanker powered by the hydrogen-fuelled COGAS in different off-design operation conditions and journeys was predicted using emission factor estimation. The emission factor of the 50-MW hydrogen-fuelled COGAS as a prime mover can be calculated using Eq. (3) (Garaniya, 2016):

$$EF_{i,k} = (E_{i,k} \times 10^{-6}) \left(\frac{P \cdot V}{R \cdot T} \times \frac{MW_k}{P_p} \right), \quad (3)$$

where $EF_{i,k}$ is the emission factor (g/kWh); i refers to the engine type; k refers to the emission type; E is the concentration of gaseous species (ppm); P is the pressure (N/m²); V is the engine exhaust flow rate (m³/h); R is the ideal gas constant, which equals 8.3145 J/(mol K); T is the exhaust gas temperature (K); MW is the molecular weight; and P_p is the engine power (kW). The LM2500+ gas turbine, which was used in this study, was not designed to be exclusively fuelled by hydrogen, and there is much scope for future research in this field. Therefore, the authors adopted the maximum value of the concentration of gaseous species for this type of gas turbine, which is 25 ppm (General Electric 2019, 2022). Consequently, the NO_x emission for each journey hour using fuel flow can be calculated by Eq. (4) (Trozzi, 2010):

$$E_{NOx} = F.F. \times EF_{i,k}, \quad (4)$$

where E_{NOx} is the NO_x emission and $F.F.$ is the gas turbine fuel flow per hour during the journey. The LH2 tanker was simulated for three seasons (winter, summer, and middle) using COGAS NO_x emission estimation considering the ship operation hours during two journeys (from Marseille to Algeria and from Tangier to

Southampton). The simulation of ship NO_x emission was studied under the impact of a normal and a 6% degraded engine under loaded and unloaded conditions.

3. Results and discussion

The performance and emission results for the improved design of JAMILA are presented in this section. In this study, a techno-environmental assessment based on engine behaviour for different journeys under loaded and unloaded conditions, a normal and a 6% degraded engine, and varying ambient conditions was conducted to assess the prime mover as an environmentally friendly propulsion system.

3.1. Results of design assessment

Fig. 1 shows the design of the improved LH2 tanker after adding new design elements, such as hydrogen tank pumps, ship anchors, storage facilities, and the crew service tunnel (Alkhaledi et al., 2021). The improved design that includes a hydrogen-fuelled COGAS as the prime mover without any additional propulsion technologies can be used in future applications.

3.1.1. Results of weather and journey routes

In this study, the weather estimation showed a variety of ambient temperatures between different journeys for the winter, summer, and middle seasons. For this reason, two journeys were analysed in terms of the ambient conditions. The Marseille–Algeria journey showed that the maximum temperature in summer was more than 30 °C, compared to 25 °C for the Tangier–Southampton journey. The increase in the ambient temperature may negatively influence the ship engine performance and emissions. The middle season assumed in this study

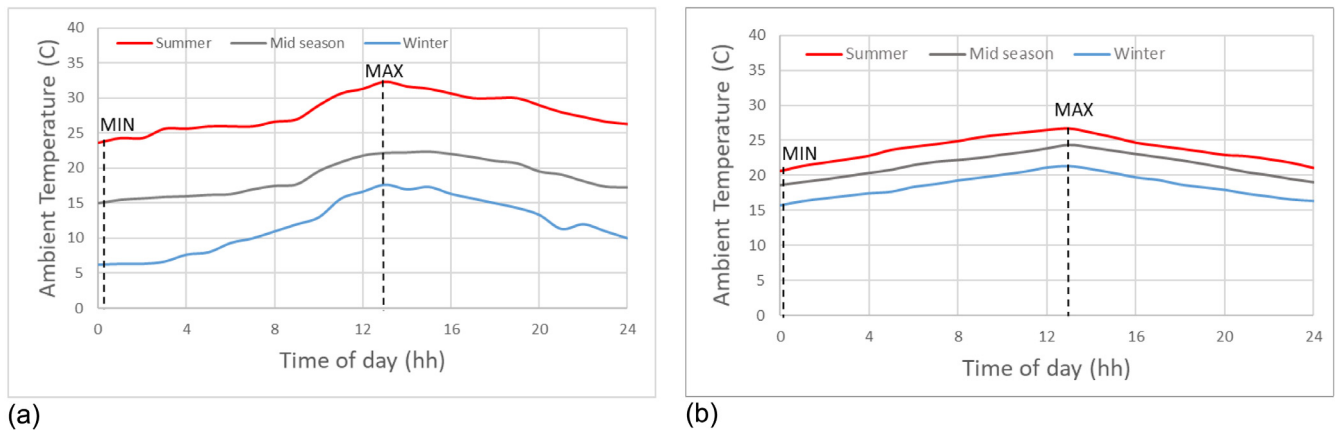


Fig. 2. Weather conditions in different seasons during the (a) Marseille–Algeria and (b) Tanger–Southampton journeys. Credits: timeanddate.com.

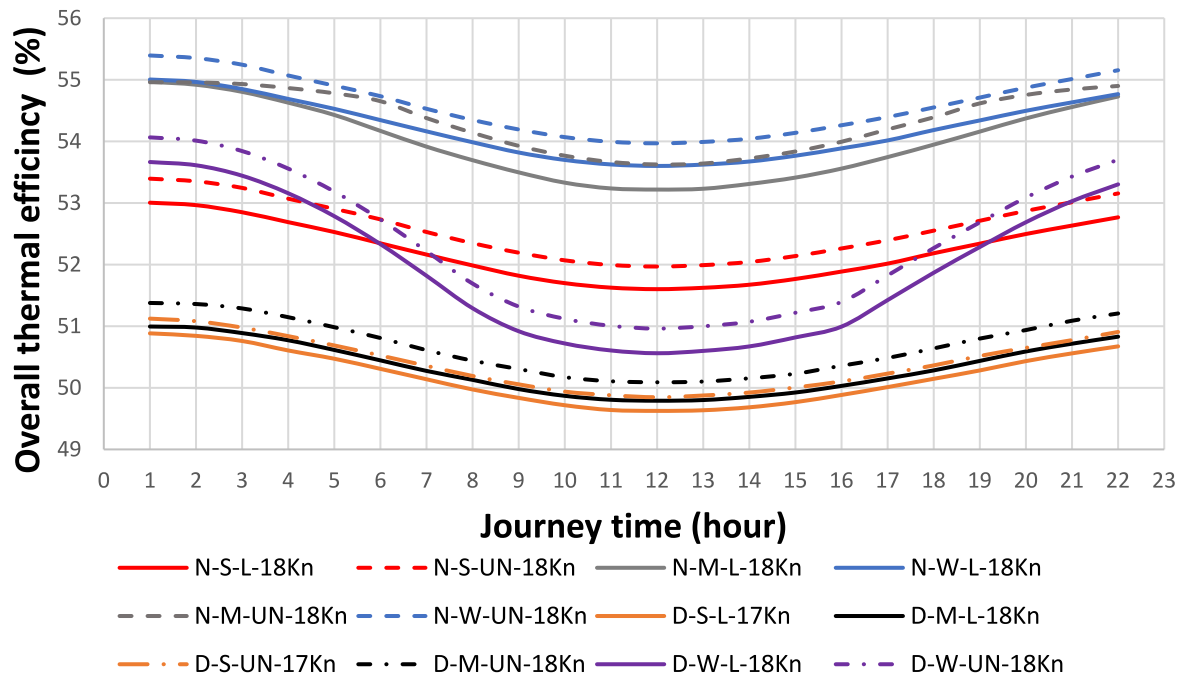


Fig. 3. Overall thermal efficiency of the LH2 tanker with a combined-cycle gas turbine (COGAS) as a function of journey time under different conditions for the Marseille–Algeria journey. N: normal engine, D: degraded engine, W: winter, S: summer, M: middle season, L: loaded condition, and UN: unloaded condition.

represented approximately six months of the year, and the maximum temperature during the Marseille–Algeria journey in this season was approximately 22 °C, compared to 24 °C for the Tanger–Southampton journey. In winter, the maximum temperature during the Marseille–Algeria journey was less than 15 °C, compared to 21 °C for the Tanger–Southampton journey. Fig. 2 shows the weather conditions in the winter, summer, and middle seasons during the Marseille–Algeria and Tanger–Southampton journeys.

3.1.2. Ship performance analysis

Two journeys were selected to assess the performance of the COGAS as a prime mover. The ship off-design performance was analysed in terms of the overall thermal efficiency of the COGAS as a prime mover. The prime mover performance was simulated under the unloaded condition and a loaded of 20,000 tonnes of LH2 for a one-way journey in each case. In addition, the performance of the ship engine was assessed under different weather conditions to investigate the single-pressure COGAS behaviour.

Fig. 3 shows the overall thermal efficiency of the hydrogen-fuelled COGAS during the one-way Marseille–Algeria journey for three seasons (winter, summer, and middle). The result shows that the COGAS as a prime mover could achieve the required power with a ship speed of 18 knots in all conditions except in summer with a degraded engine; in summer, the vessel speed required reducing to 17 knots because the required ship power was more than the COGAS power output due to the high ambient temperature and the influence of 6% degradation. The results showed that the overall thermal efficiency of the normal COGAS under the unloaded condition in winter could reach 55.5%, representing the maximum overall thermal efficiency of all conditions. The minimum overall thermal efficiency was 49.7%, which occurred in summer under the loaded condition with a 6% degraded engine.

Similarly, the Tanger–Southampton journey was simulated for three seasons under different conditions, as shown in Fig. 4. The results showed that the maximum overall thermal efficiency of the normal COGAS under the unloaded condition was 55%. The minimum overall thermal efficiency was 49.2%, which occurred under the full-loaded condition with a 6% degraded engine.

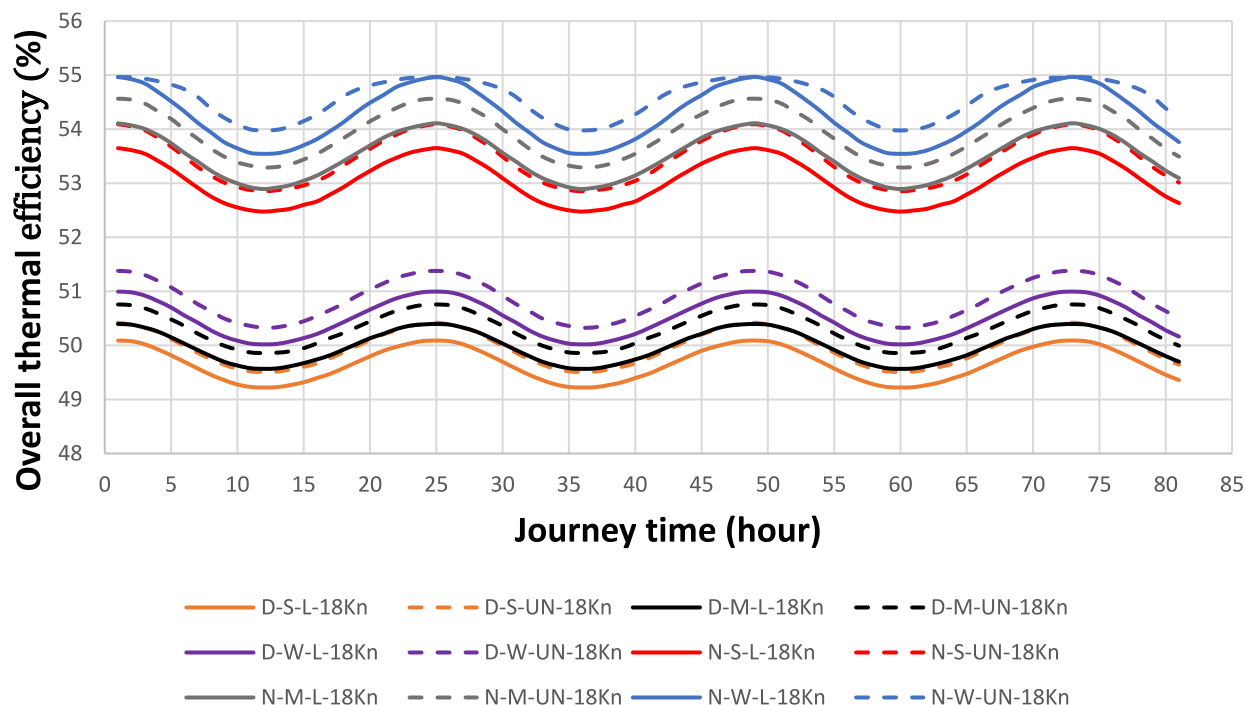


Fig. 4. Overall thermal efficiency of the LH2 tanker with a COGAS as a function of journey time under different conditions for the Tangier–Southampton journey.

The difference of the maximum and minimum overall thermal efficiencies of the LH2 tanker propulsion system between the Marseille–Algeria and Tangier–Southampton journeys was approximately 0.5%. This difference resulted from the ambient temperature variation between the different seasons. In particular, during the Marseille–Algeria journey in summer, the maximum ambient temperature was higher than 30 °C, while the corresponding maximum for the Tangier–Southampton journey was 27 °C, as shown in Fig. 2. Hence, the minimum overall thermal efficiency of the ship engine in the Marseille–Algeria journey should be lower than that in the Tangier–Southampton journey; however, the results showed were the opposite. This happened because the vessel speed decrease from 18 to 17 knots increased the minimum overall thermal efficiency of the LH2 tanker engine in the Marseille–Algeria journey.

3.1.3. Environmental assessment results

This section describes the emission analysis of the LH2 tanker propelled by the COGAS during two different journeys (Marseille–Algeria and Tangier–Southampton). The LH2 tanker was simulated for three seasons (winter, summer, and middle) in terms of the COGAS NOx emissions with respect to the ship operation hours for each journey. The ship NOx emissions were examined in the case of a normal and a 6% degraded engine under the loaded and unloaded conditions. Because the fuel consumed in the COGAS engine is zero-carbon green hydrogen, which produces NOx emissions, only NOx emissions were considered in this study. Fig. 5 shows the NOx emissions from the LH2 tanker propelled by the hydrogen-fuelled COGAS during the one-way Marseille–Algeria journey, which lasted for 22 h, under different ambient conditions. The maximum amount of NOx emissions from the LH2 tanker engine was 3.5 kg/h in the case of degraded COGAS in the middle season at a ship speed of 18 knots. The minimum amount of NOx emissions was 2.6 kg/h in the case of degraded COGAS in summer at a ship speed of 17 knots. From Figs. 3 and 5, the results indicated that the thermal efficiency and NOx emission are higher in the winter and middle seasons compared with the summer season; this represents a particular case for the journey from Marseille to Algeria because usually, increasing the thermal efficiency

will decrease the NOx emissions this is achieved provided that the speed of the ship constant and unchanged for all scenarios during the journey. However, the results clarify that the NOx emissions may decrease with decreasing ship speed regardless of the season and engine condition.

Fig. 6 presents the estimation of the NOx emissions during the one-way Tangier–Southampton journey, which lasted for 81 h, under different ambient conditions for three seasons. The results show that the maximum amount of NOx emissions was 3.5 kg/h in the case of a degraded COGAS under the full-loaded condition in summer at a ship speed of 18 knots. The minimum amount of NOx emissions was 2.95 kg/h at a ship speed of 18 knots. In the case of a constant ship speed of 18 knots, the journey season and cargo weight played a key role in controlling the NOx emissions from the LH2 tankers.

Between the Marseille–Algeria and Tangier–Southampton journeys, the maximum amount of NOx emissions from the LH2 tanker did not vary. The reason for these unusual results is that the maximum amount of NOx emissions in the Marseille–Algeria journey was generated in the middle season, whereas that in the Tangier–Southampton journey was produced in summer. The minimum amount of NOx emissions in the Tangier–Southampton journey was approximately 10% higher than that in the Marseille–Algeria journey. The increased NOx emissions resulted from the increased speed of the LH2 tanker from 17 to 18 knots.

4. Conclusions

An established techno-environmental assessment method was applied to a 280,000 m³ LH2 tanker propulsion system with a hydrogen-fuelled COGAS as the prime mover. The performance and emissions were analysed based on the engine behaviour for different journeys (Marseille–Algeria and Tangier–Southampton) under loaded and unloaded conditions, a normal and a 6% degraded engine, and varying ambient conditions for the LH2 tanker prime mover in different three seasons (winter, middle, and summer). The results were promising in terms of the propulsion system performance and environmental benefits; the key results can be summarised as follows.

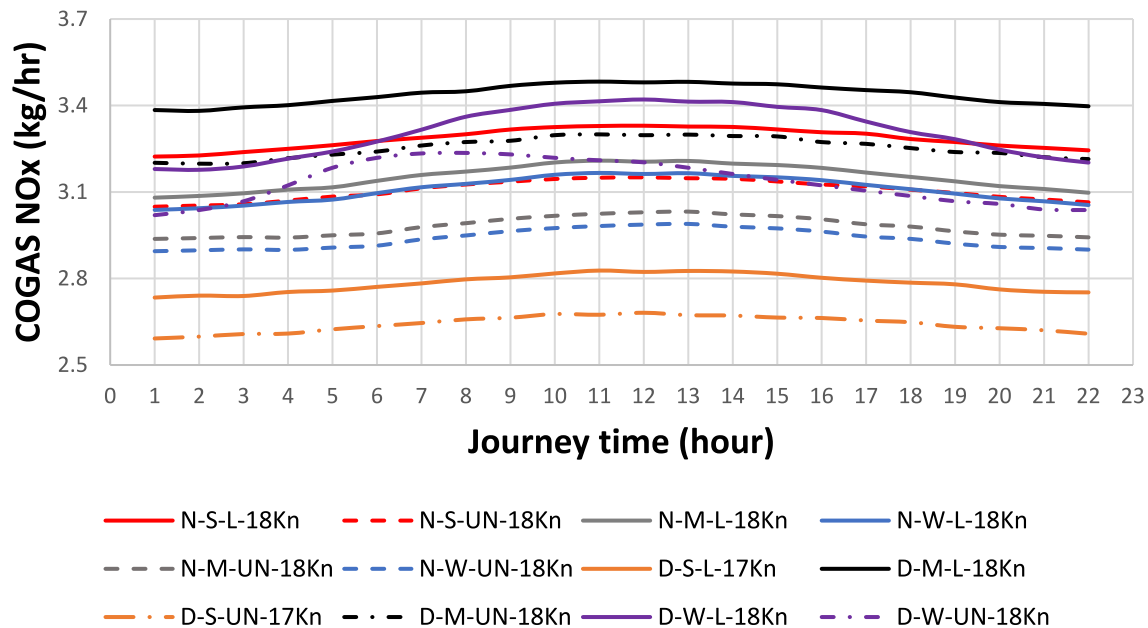


Fig. 5. NOx emissions from the LH2 tanker with a COGAS as a function of journey time under different conditions for the Marseille–Algeria journey.

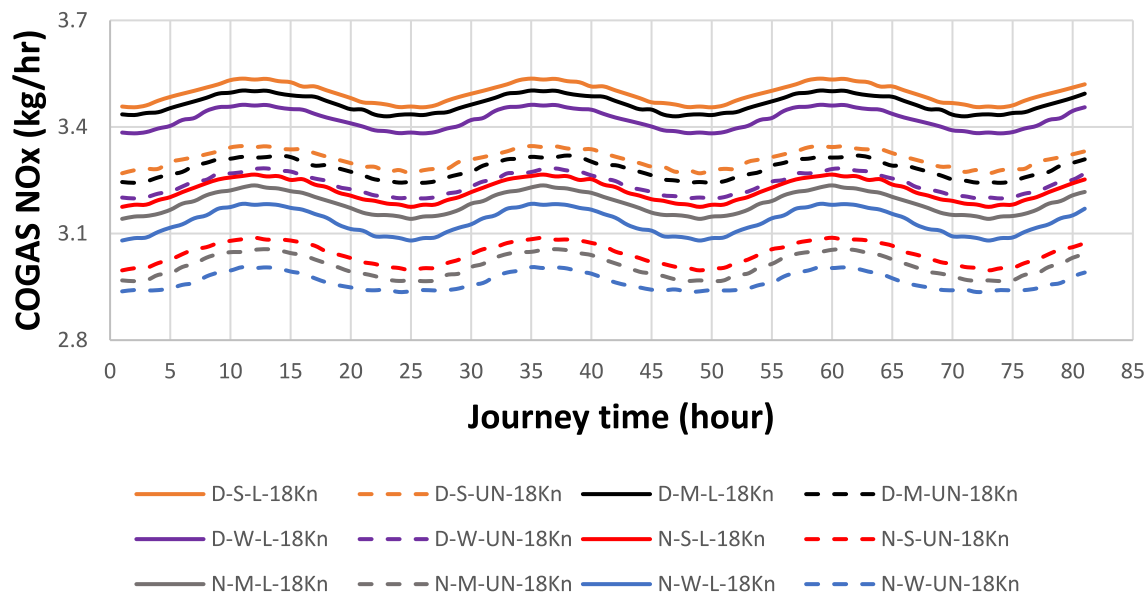


Fig. 6. NOx emissions from the LH2 tanker with a COGAS as a function of journey time under different conditions for the Tangier–Southampton journey.

- An LH2 tanker design was improved to enhance its applicability by adding new design elements, such as hydrogen tank pumps, ship anchors, storage facilities, and a crew service tunnel.
- Technically, the assessment results for the LH2 tanker propulsion system performance indicated that the hydrogen-fuelled COGAS could achieve a maximum overall thermal efficiency of 55.5% in the Marseille–Algeria journey in winter with a normal engine under unloaded conditions; the corresponding maximum for the Tangier–Southampton journey was 55%. The variation in the overall thermal efficiencies depended on ambient temperature, cargo weight, and engine condition.
- Environmentally, the maximum amount of NOx emissions from the 50-MW hydrogen-fuelled COGAS was 3.5 kg/h in the Marseille–Algeria journey with a degraded engine in the

middle season at a ship speed of 18 knots. On the other hand, the minimum amount of NOx emissions was 2.6 kg/h for the same journey in the case of degraded COGAS in summer at a ship speed of 17 knots. Moreover, the minimum amount of NOx emissions during the Marseille–Algeria journey was 10% lower than that in the Tangier–Southampton journey. The decreased NOx emissions resulted from the decreased speed of the LH2 tanker from 18 to 17 knots in the Marseille–Algeria journey. Hence, the amount of NOx emission was substantially influenced by the ship's speed.

To conclude, the assessment results signify that the employment of the hydrogen-fuelled COGAS for a large-scale LH2 tanker has significant benefits, compared to the conventional propulsion systems, in terms of achieving the required overall thermal efficiency and reducing the NOx emissions of the prime mover.

CRediT authorship contribution statement

Abdullah NFNR Alkhaledi: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software. **Amit Batra:** POSEIDON Software. **Suresh Sampath:** Supervision. **Pericles Pilidis:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

The authors are grateful to the Government of the State of Kuwait and the Public Authority for Applied Education and Training (PAAET), State of Kuwait for the provisions and financial support.

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2022-08-27

Elsevier

<https://doi.org/10.1016/j.egy.2022.08.202>

Alkhaledi ANFNR, Batra A, Sampath S, Pilidis P. (2022) Techno-environmental assessment of a hydrogen-fuelled combined-cycle gas turbine for a liquid hydrogen tanker, Energy Reports, Volume 8, November 2022, pp. 10561-10569