Marine Dual Fuel Engine Control System Modelling and Safety Implications Analysis

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Synopsis

The present study focuses on the modelling of a marine dual fuel engine and its control system with an aim to study the engine response at transient conditions and identify and discuss potential safety implications. This investigation is based on an integrated engine model developed in GT-ISE™ software, capable of predicting the steady state performance as well as the transient response of the engine. This model includes the appropriate modules for realising the functional modelling of the engine control system to implement the ordered engine load changes as well as switching the engine operating mode. The developed model is validated against available published data. Subsequently, two test cases with fuel changes, from gas to diesel and diesel to gas were simulated and the derived results were analysed for investigating the safety implications that may arise during operation. The results showed that the matching of the engine and the turbocharger as well as the exhaust gas waste gate control are critical factors for ensuring compressor surge free operation during fuel changes.

Keywords: marine dual-fuel four-stroke engine; 0D/1D simulation in GT-ISE™; control strategy modelling; control system design; safety implications.

1. Introduction

In the last decade, the maritime industry has been pursuing the reduction of gas emissions driven by more stringent regulations coming from international and national regulatory bodies. Specific areas have been designated, the so-called Emission Control Areas (ECAs) where stringent limits for NOx and SOx emissions are applied, whilst considerable reduction of the aiming at the reduction of the Energy Efficiency Design Index (EEDI), which is used to regulate the CO_2 emissions, were imposed by the International Maritime Organisation (IMO) in 2020 and 2025. This renders attractive the use of alternative fuels and propulsions systems including dual fuel (DF) engines, which can be used to meet the regulatory requirements in a cost effective way.

Considering that the DF engines are currently becoming the industry standard not only for liquefied natural gas (LNG) carriers but also for all LNG-fuelled vessels (WinGD, 2017), it becomes clear that continuous engine development and optimisation procedures are essential to the marine industry. These procedures usually employ a number of techniques including experimentation, design, prototyping and engine mathematical modelling. The latter is considered as one of the most economic methods for obtaining a better understanding of the engine operation as well as their performance and emission characteristics in a number of conditions since it can be implemented in a virtual environment.

Most of their operational time, marine engines run under steady conditions with relatively slight power demand fluctuations and using the same fuel type. However, a change in power demand may occur due to alteration in operating conditions, interactions with other systems or user request. Switching to a different fuel mode is implemented either when approaching or leaving the ECAs or when a failure is present in the fuel systems and their components, i.e. pressure loss of the gaseous fuel supply. Thus it is required to assess the behaviour of the engine both during steady and transient conditions including operating mode changes.

Except for ensuring the DF engines efficiency during steady and transient operating conditions, it is also necessary to guarantee that a dual-fuel engine operates safely, where safety is a state when the system operates without causing any harm to humans, environment and assets (Vincoli, 2014). As every system, a dual-fuel engine operates with inherent hazards. Misfiring, knocking and turbocharger compressor surging may lead to considerable damage to the engine, whilst deviations of its performance may trigger the engine safety functions rendering the plant temporarily unavailable, which may lead to system-level hazardous conditions including a loss of ship position or a total blackout associated with a high potential for human losses. Oil mist explosions can lead to hazards such as engine room fires, whilst it may also cause occupational accidents if occur in close proximity to operational or maintenance personnel (Cicek and Celik, 2013). The NOx and particulate matters emissions generated during the combustion process are considered as carcinogen, thus increasing the potential for human deceases (International Agency for Research on Cancer, 2012).

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Pertinent studies focusing on the investigation of marine four-stroke and two-stroke DF engines by using simulation tools are thoroughly described in Stoumpos et al. (2018) and Mavrelos and Theotokatos (2017). However, it was concluded that very few studies have been published focusing on the modelling/simulation of marine DF engines (Mavrelos and Theotokatos, 2017, Cameretti et al., 2016) and an even smaller number of studies have been published investigating the transient operation of marine DF engines and the potential safety implications. The fuels control system design of a marine DF engine to accommodate the effective fuels transitions by employing a model-based approach is reported in Wang et al. (2015), who also presented an applicable and comprehensive control strategy of an automotive natural gas/diesel engine. Fathi et al. (2017) introduced a homogeneous charge compression ignition (HCCI) engine control structure in order to appropriately control DF engines and obtain acceptable performance and emissions characteristics. Doppelbauer et al. (2013) examined the potential of burning compressed natural gas and diesel fuel by performing tests on a four cylinder, commercial vehicle engine and developing a control unit with a developed in-house software. Hence, the engine gas operation was calibrated by optimising the injection and combustion parameters under stationary and transient conditions. Aldawood et al. (2012) investigated a dual fuel approach to control combustion in a HCCI engine and presented an applicable and comprehensive control strategy of an automotive natural gas/diesel engine.

Considering the above, the aim of this paper is to focus on the investigation of the performance characteristics and the response of a marine four-stroke DF engine during transient operation through simulation for identifying potential safety implications. A suitable functional control strategy modelling based on the engine manufacturer specifications and the acceptable engine response has been implemented as described in the next section. Then, the behaviour of the validated model is investigated during fuel changes, from gas to diesel and from diesel to gas. Based on the derived simulation results, it is examined whether the system operates safely or whether specific safety implications may arise. A summary of findings and recommendations for the system design and further analysis are provided in the conclusions section.

2. Engine modelling

2.1. Model description

In the present study, the four-stroke, non-reversible, turbocharged and intercooled 9L50DF engine was investigated (Wärtsilä, 2015). The engine details are reported in the manufacturer product guide (Wärtsilä, 2015). In addition, the main engine characteristics are illustrated in Table 1.

The engine modelling is performed by employing the GT-ISE™ software, which is a widely used simulation program for the engine modelling and analysis (Gamma Technologies, 2016). As the 0D/1D engine model of the investigated engine had previously been developed for steady state conditions as described in Stoumpos et al. (2018), the existing model was extended to incorporate the engine combustion modelling at fuel changes as well as the engine control system modelling. The complete engine modelling including the engine control system was realised by using the following sub-assemblies: (a) the 0D/1D engine model assembly; (b) the user input; (c) the Engine control system (ECS); (d) the engine monitors and alarms. The schematic representation of the utilised assemblies is illustrated in Figure 1. The user can order a specific transient operation (i.e. load changes at either the gas or the diesel modes, a fuel change at constant load, or extreme load changes that may result in a fuel change) by employing the user input assembly. The developed ECS model controls the gas, diesel and pilot fuel injectors as well as the engine waste gate and can identify step-wise load changes in the gas mode that exceed the maximum allowed load change (for instance, gas mode load reduction from 100% to 0%; i.e. Diesel Generator set (D/G) shutdown), and subsequently implementing a fuel change from gas to diesel as specified by the engine manufacturer requirements. In such scenarios, the engine operation is immediately switched to the diesel mode via a fast acting signal, which controls the gas, diesel and pilot injectors as well as the engine waste gate valve.

However, a fuel change request from diesel to gas above 80% engine load is not allowed according to manufacturer due to engine operational limitations. Regarding the 0D/1D engine model assembly, the existing injector components and the combustion model were initially modified, so that the injected amount of each fuel and the required combustion model parameters (e.g. fraction of fuel injected) are adjusted accordingly by the engine control system to accommodate the engine operation in transient conditions.

Table 1: Engine main characteristics.

Power / speed at MCR	kW / r/min	8775 / 514
BMEP at MCR	bar	20
BSFC at MCR (Diesel mode)	g/kWh	190
BSEC at MCR (Gas mode)	kJ/kWh	7300
Bore/Stroke	mm	500/580
No. of cylinders / Turbocharger units	(-)	9/1

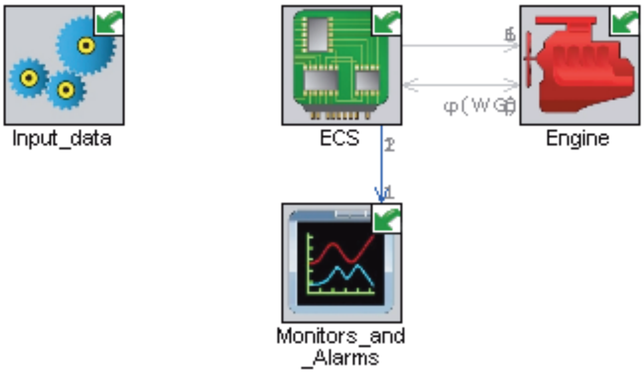

Figure 1: Schematic layout of the assemblies of the full engine model.

2.2. Model validation

Steady state runs were performed in a number of operating points and the performance and emission parameters were derived and compared with the respective data experimentally obtained from the engine shop trials. The percentage errors between the measured and the predicted parameters are provided in Table 2. From the data presented, it can be inferred that the model accuracy is sufficient in all the investigated operating points.

The GT-ISE™ model was extended in order to accommodate the transient engine simulation, including the engine load changes and the fuel changes. For validating the model response at transient engine operation, two cases for which experimental data are published were investigated; in specific: (a) engine operation at 100% load in the gas mode and a fuel change to the diesel mode and (b) engine operation at 80% load in the diesel mode and a fuel change to the gas mode (Ölander, 2006).

The predicted variation of the engine parameters including the normalised rotational speed, the engine load and the normalised fuels amount (for the gas and diesel fuels) along with the respective experimentally measured parameters variations for the two investigated cases are presented in Figure 2. As it can be inferred from the presented results, the model can predict the engine parameters response with an adequate accuracy.

Table 2: Percentage error between the measured and the predicted values.

	Diesel mode					***Gas mode***				
Load (% MCR)	100	85	75	50	25	100	85	75	50	25
Brake power	2.6	2.36	1.88	1.14	1.22	-0.42	-1.15	-0.41	1.7	1.34
Maximum cylinder pressure	0.16	-0.6	0.19	0.42	1.77	0.37	0.33	0.51	0.42	0.6
Turbocharger speed	0.04	-0.02	-0.06	-0.79	0.02	0.75	-0.32	-0.9	-0.27	1.14
Brake efficiency	-3.11	-2.9	-2.43	-1.64	-2.22	2.49	3.43	2.32	-1.16	-0.9

3. Results & Discussion

Following the validation of the developed engine model against the available published data, a number of derived simulation parameters including the boost pressure, the maximum cylinder pressure, the exhaust gas temperature after turbine, the turbocharger (TC) speed, the waste gate (WG) opening, the equivalence air-fuel ratio (λ), the engine NOx emissions and the compressor operating points trajectory superimposed on the compressor map are shown in Figures 3 and 4 for the two simulation cases, respectively.

For the first investigated case (Gas to Diesel (GTD) fuel change, it can be observed from the results presented in Figure 3 that the exhaust gas temperature temporarily drops due to the instantaneous reduction of the gas fuel and the slow increase of the diesel fuel, thus leading to a turbine inlet exhaust gas energy reduction, which adversely affects the TC speed. This in turn, temporarily reduces the air mass flow rate and the boost pressure, which instantaneously drives the compressor operating point towards the compressor surge line. The captured instantaneous inlet boost pressure drop is also observed in the experimental results from Ölander (2006). In addition, the waste gate valve controlled from the developed control system model closes at the 10th second, as shown in Figure 3, when the fuel change is ordered, to avoid the surge effect at the compressor during the fuel transient. Based on the preceding discussion, it can be inferred that: (a) the GTD fuel change is a very fast transient, which proves to be challenging for the engine and its systems operation; and (b) the waste gate control affects the variation of the engine operating parameters and can lead to the compressor surging effect. Compressor surging can be hazardous conditions as it results in TC shaft torsion vibrations of large amplitude, which may lead to potential catastrophic failure of the turbocharger and other engine components.

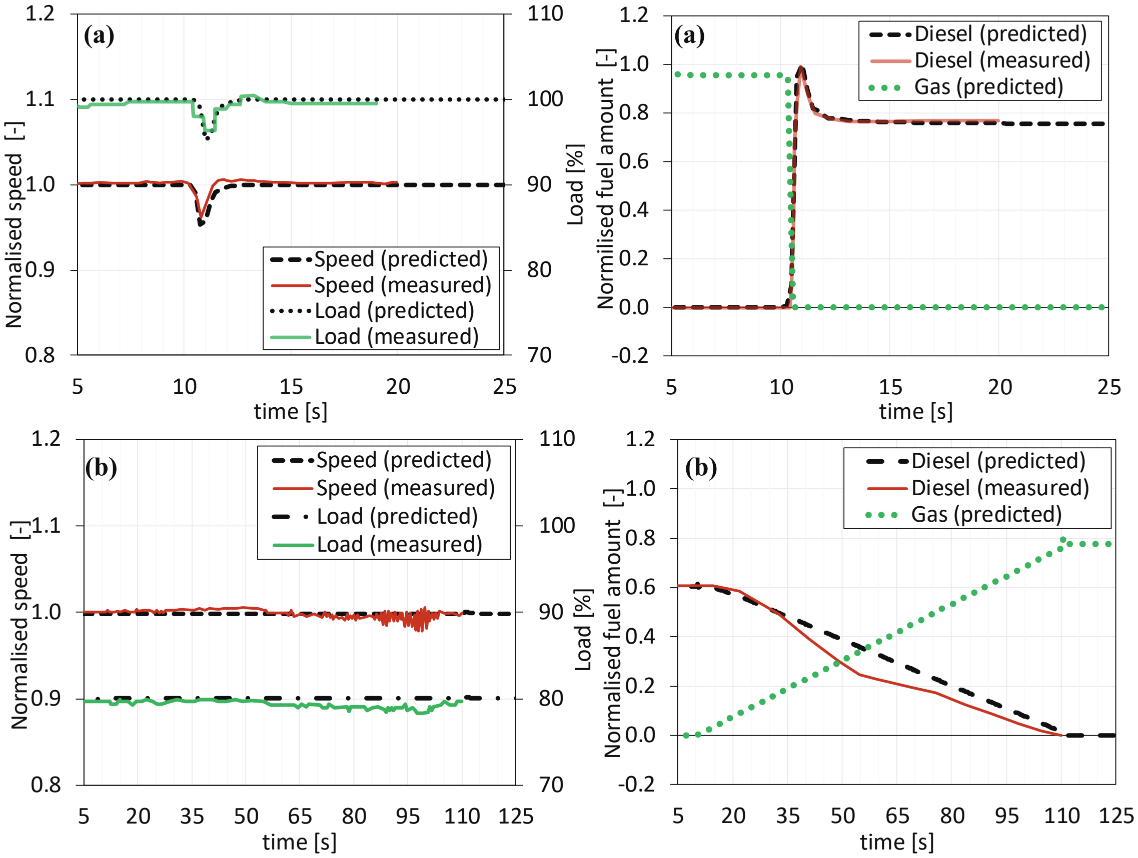

Figure 2: Comparison of the derived engine response parameters with experimental data taken from (Ölander, 2006); GTD fuel change at 100% load (a) and DTG fuel change at 80% load (b).

Following the ordered GTD fuel change, an overshoot of the exhaust gas temperature is observed, which, despite being below the manufacturer alarm limit (550°C) may cause engine tripping under the presence of exhaust valves failures. The maximum cylinder pressure reaches its maximum value (approximately 145 bar) at the 11th s, and subsequently it quickly restores to respective steady conditions value. An increased pressure may lead to extra mechanical load for the cylinder components and the piston rings, resulting in increased wear and potential blow-by, which in turn causes exhaust gases and unburned hydrocarbons flowing into the engine crankcase, thus increasing the risk for a crankcase explosion (Cicek and Celik, 2013). The exhibited lambda reduction can lead to potential smoke generation, which may lead to increased soot deposits on the engine components. This in turn may lead to faster components degradation and higher maintenance requirements increasing the engine unavailability.

It can be also noticed from the results presented in Figure 2 that the drop in engine speed and consequently the drop in power during GTD fuel change is lower than 5%, reaching the stable conditions in around 3 seconds after the fuel change order, in line with requirements set by the classifications societies for the variation in speed and frequency; a speed drop up to 10% and a recovery time of 5 seconds are allowed according to DNV GL (2017). The difference in loads between D/G sets is also expected to be in acceptable regions, well beyond the 15% of MCR.

For the second investigated case (Diesel To Gas (DTG) fuel change), for which the derived simulation results are shown in Figure 4, the engine operating parameters demonstrate a smooth variation due to the fact that the transition is slow (taking place within 2 minutes). The TC speed and the engine boost pressure reduce following the ordered fuel change as also shown from the measured parameters (Ölander, 2006). This is attributed to the waste gate control response (waste gate valve opens) resulting in lower mass flow rate in the turbine and consequently, in reduced turbocharger speed. Nevertheless, as the waste gate control affects the boost pressure, and because of the reduction in the equivalence air-fuel ratio (λ), knocking or/and misfiring conditions may occur whilst compressor surging must also be avoided. Thus, the countermeasure adopted to avoid these conditions and provide a stable, secure and reliable transient in terms of engine performance is to apply a threshold (limiter) for the waste gate maximum opening during the fuel change.

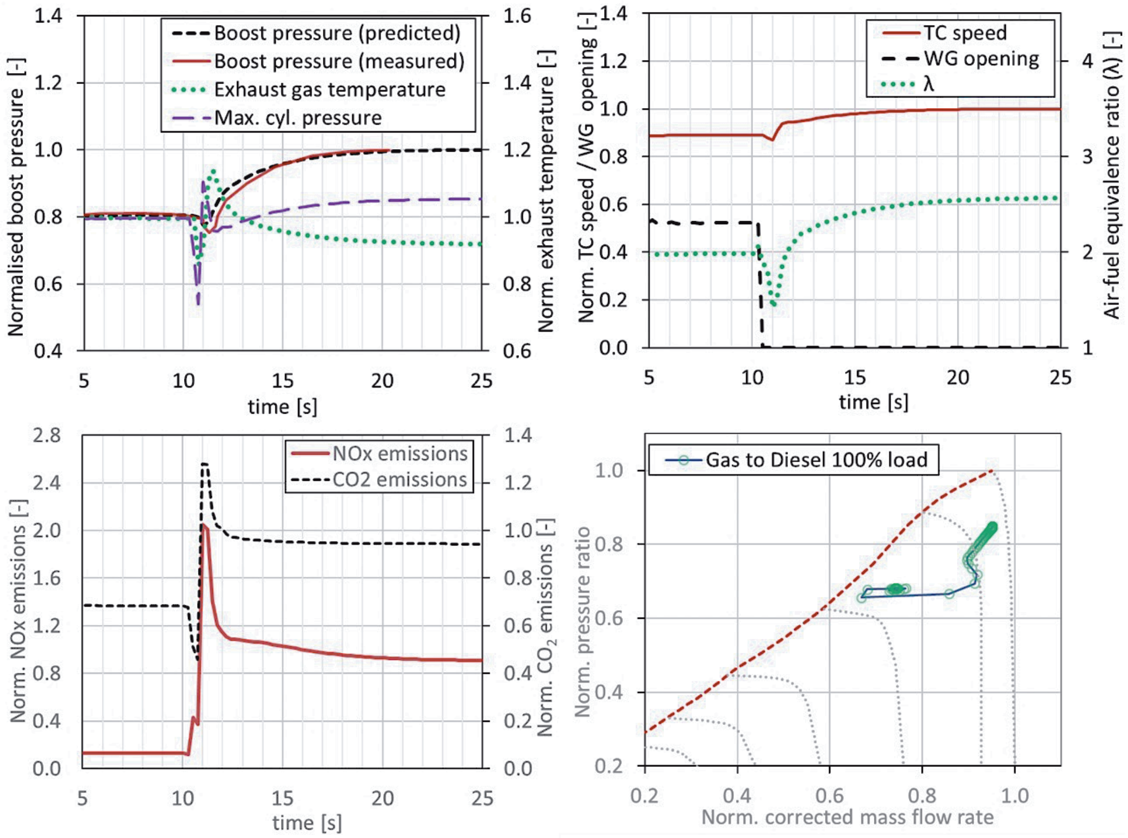

Figure 3: Predicted engine response parameters for GTD fuel change at 100% load.*

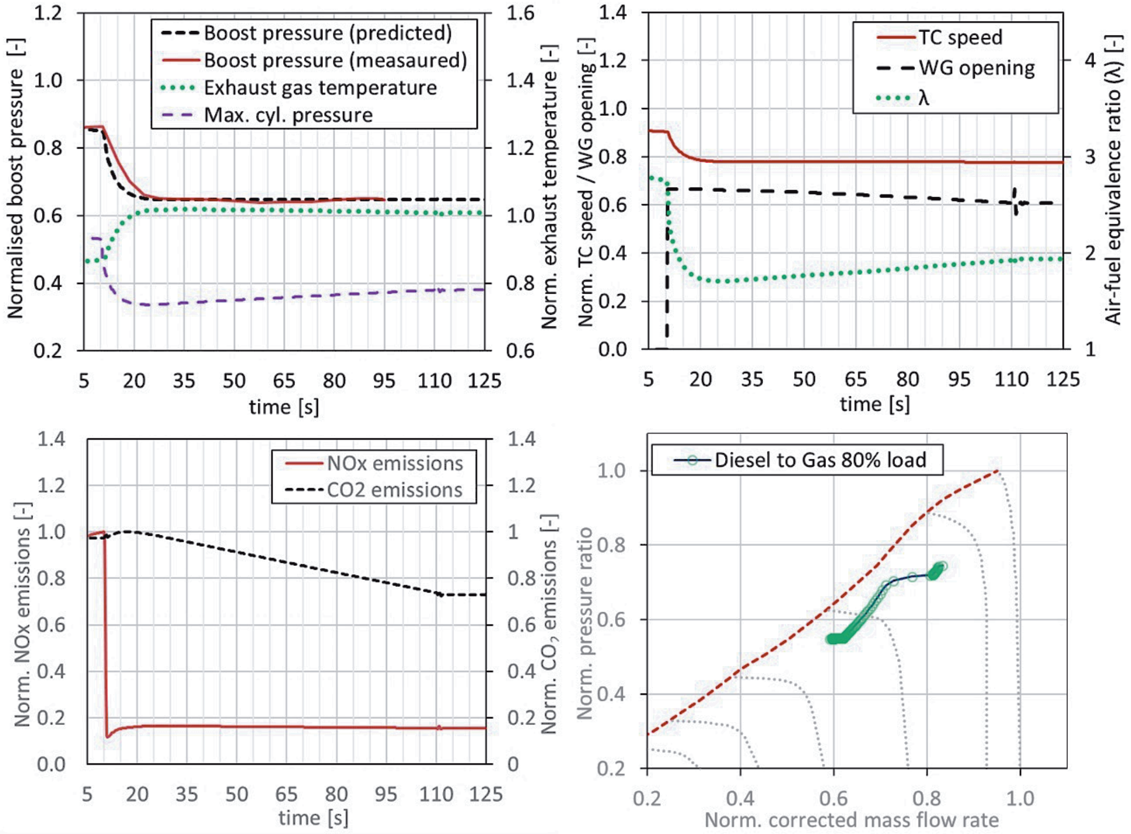

Figure 4: Predicted engine response parameters for DTG fuel change at 80% load. *

*The parameters except for the equivalence air−fuel ratio are provided in a normalised basis by using the corresponding values of the parameters at 100% load of the diesel mode. The exhaust gas temperature was normalised in [K].

As the DTG transient operation is much smoother, the exhaust gas temperature after cylinders reaches its maximum value corresponding to steady state conditions, which is below the manufacturer alarm limit. However, this should be also investigated under the presence of other engine faults. Similarly, the cylinder maximum pressure exhibits a smooth transition towards lower values due to the boost pressure reduction, which consequently reduces the mechanical load of the engine cylinder components. No implications to the engine safety are expected unless other engine component failures are present.

As it is shown from Figure 2, only slight oscillations of the engine load and speed are observed, however the high frequency fluctuations are attributed to combustion knocking. The engine behaviour is stable not causing tripping during DTG fuel change. However, malfunctions in the engine control system and actuators may result in incorrect fuel amount supplied to the engine cylinders leading to uneven cylinders load sharing, which can be exacerbated during transients, and thus should be further examined with special attention.

The potential safety implications arising during transients are analysed in Table 3, following a similar format for a Preliminary Hazard Analysis (PHA) table (Vincoli, 2014).

Table 3: Potential safety implications during transient for two investigated cases.

a/a	Hazard	Monitored Cause	Effect	Recommendation
1st investigated case GTD fuel change	TC compressor surging	TC speed reduction due to rapid drop in fuel supply	Torsional vibrations for TC shaft and lambda fluctuations	Proper design of waste-gate control and selection of TC should be ensured
	Smoke	Low lambda during transient	Deposits formation leading to increased wearing of engine components	Increased lubrication to avoid formation of deposits
	Alternating thermal and mechanical stresses	Lambda fluctuations	Fatigue problems	Proper control of injection timing during transient
	Tripping of D/G set	High exhaust temperature	Power unavailability with a number of safety implications	Predictive monitoring of engine parameters
	Piston rings blow-by and potential crank case explosion	High maximum combustion pressure	Damage to the engine and adjacent machinery	Frequent testing of oil mist sensor
2nd investigated case DTG fuel change	Knocking	Imbalanced lambda	Damage to the cylinders	Proper design of waste-gate control should be ensured
	Misfiring	Imbalanced lambda	Power network instability, Torsional vibrations	As above

4. Conclusions and future work

In the present work, the modelling of a large marine four-stroke dual-fuel engine and its control system was presented. The developed model is capable of capturing the engine transient operations with fuel and load changes. The applicability of this model for supporting the investigation and analysis of potential safety implications that may arise during the engine operation was demonstrated by using the simulation results for the GTD and DTG engine operating mode changes.

The main findings of this study are summarised as follows.

- The GTD fuel change is a very fast transient that must take place within 3 s and therefore, has a profound effect on all the engine operational parameters resulting in a number of potential hazards including turbocharger compressor surging, smoke, fluctuating mechanical and thermal stresses, exhaust gas blow-by and D/G set tripping.
- As the DTG fuel change is slower transient taking place within 2 min, the engine operating parameters demonstrated a smooth variation. However due to the temporal air-fuel ratio variation, misfiring or knocking can occur during this fuel change.

The following safety recommendations were developed and can be used during the design and operating phases of marine DF engines.

- To avoid problems with knocking/ misfiring effects and compressor surging during the engine transients, the waste gate control system design must be carefully addressed.
- It is important to ensure appropriate matching of turbocharger with the engine to avoid compressor surging effects during transient operations and the presence of other engine components faults.
- Monitoring of a number of the engine operational parameters is required to avoid the engine tripping during GTD fuel changes and the presence of other engine components faults.
- Appropriate fuel injection control should be provided to reduce the mechanical and thermal stresses and formation of deposits during GTD fuel change.

The developed engine and its control system model was proved to be a useful tool for obtaining a better understanding of the engine processes and components interactions as well as for investigating potential implications on the engine safety. Some proposals for future research are as follows. The model extension is proposed by employing a number of sub-models for predicting and analysing additional engine parameters including methane slip and particulate matter emissions, cylinder wall temperatures and shafts stresses. This will allow for the more holistic consideration of the safety implications to include additional effects and hazardous situations. The developed model can also be used as a digital twin of the actual system to investigate the system behaviour in both steady and transient modes either in healthy conditions or under the presence of DF engine components failures. In addition, the development of a computerised approach for identifying the potential safety implications based on the actual engine monitored parameters could be investigated.

5. Acknowledgements

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6. Abbreviations list

0D	Zero-dimensional
1D	One-dimensional
BMEP	Brake Mean Effective Pressure
CO_2	Carbon Dioxide
DF	Dual Fuel
D/G	Diesel Generator
DTG	Diesel to Gas fuel change
ECA	Emission Control Area
ECS	Engine Control System
EEDI	Energy Efficiency Design Index
GTD	Gas to Diesel fuel change
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
MCR	Maximum continuous rating
NOx	Nitrogen Oxides
PHA	Preliminary Hazard Analysis
SOx	Sulphur Oxides
HCCI	Homogeneous Charge Compression Ignition
WG	Exhaust gas waste gate
TC	Turbocharger

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