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Evolution and Trends in LNGC Propulsion Systems

Khaled Senary[1], Elsayed Hegazy[2], Adel A.Tawfik[2]and Amr Ali Hasan[1]

ABSTRACT

The increase of marine shipping industry leads to search for the use of clean source of energy such as natural gas to use in the primary propulsion systems. The LNG propulsion systems have been applied for years in different disciplines. Recently, the same are reused with the modern technologies and improvement. Over the years the steam turbine propulsion proved to be the dominant type of propulsion system used in Natural Gas Carriers, even though this system has been for years there was always the need to search for further improvements with the main goal to meet the mandatory requirements of the International Marine Organization. The current trend in the market is the implementation of a waste heat recovery system with dual fuel diesel engines with two main goals, first is to reduce the emission and second is to increase the overall efficiency. The current study is concerned with seeking further improvements that coincide with the market trend, thus a proposed system of a dual fuel diesel engine with a waste heat recovery system implemented is studied to investigate the possibility of those improvements and compared with the available propulsion systems.

Keywords— Propulsion System, LNG Carriers, Evolution, Emission, Reduction, Comparison

1. Introduction

Natural Gas is being used heavily in the marine shipping industry, mainly driven by emission standards by IMO Regulation which is taking place in 2016 together with the low cost of the natural gas as an energy source. Traditionally large carriers use bunker fuel such as HFO which leads to increase the emission and fuel consumption [1].

Selection of the propulsion system in LNG Shipping industry requires a certain criterion to be met, the most common type of propulsion system used in the LNG Carriers is Steam Turbine that has been an exclusive option for carriers for the past few decades. Cryogenic LNG is stored in an insulated tank at around -160 degrees Celsius under atmospheric pressure. Some of the cargo evaporates and is called BOG which is used to fire the boilers to produce steam in a steam-turbine propulsion system, the steam then drives the steam turbines to produce necessary work [2].

Alternative propulsion systems have been introduced in the last couple of years including dual fuel electrical engines which has two main types either mechanical or electrical Dual fuel engines. In DFEE the BOG is used as a fuel in gas-mode, otherwise it will be recovered in a reliquification plant. The DFEE incorporates the same classification as diesel engines which are slow and medium speed engines. New technologies arise in the DFEE which are low pressure and high pressure dual fuel electrical engines [2]. The purpose of this study is to show the improvement in the LNG Fleets over the years showing the effect of new trends of propulsion systems and auxiliary propulsion systems effect on speed, emission and fuel consumption

2. LNG AS AN ALTERNATIVE FUEL OPTION

LNG is colorless, odorless, flammable gas that can be ignited by static electricity. The boiling point of natural gas is -161.5 °C at normal conditions which when compared to heavy fuel oil has some advantages and disadvantages that can be summarized as below:

TABLE I. COMPARISON OF HFO AND LNG PROPERTIES

	Heavy Fuel Oil (HFO)	LNG
Liquid Bunkering Temperature	>60 °C	-162 °C
Emissions to atmosphere	Hydrocarbon Volatile organic Compound	Contributes about 25 times more to the global warming compared to carbon dioxide
Explosion Risk	Flash Point above 60 °C	Flammable in 5-15% Mixture with air and explosive clouds can occur

1-Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt, kzohary@yahoo.com
2- Faculty of Engineering ,Port Fouad, Port Said University, Egypt. Adil.tawfiq@gmail.com

Conventional engines work with HFO/LNG Dual fuel which is either direct or electric propulsion with the goal of reducing the emission of CO_2 and NO_x.LNG is emerging as a better alternative to HFO due to reduction in emission by 20-30% achieved when using this fuel. The necessity to meet the IMO's Tier III Requirements which includes reduction in overall emission leading to reduction in maintenance costs and increase in the thermal efficiency of the engine [3].

2.1. Primary Propulsion Systems using LNG fuel

There are mainly five LNG fuel propulsion options are applied onboard ships:

1. Steam Boiler and Turbine.
2. Medium Speed Diesel Engine (Dual Fuel - LNG/Diesel Fuel)
3. Medium Speed Spark Ignition Diesel Engine (LNG Fuel Only)
4. Low Speed Diesel Engine (Dual Fuel)
5. Gas Turbine with Waste Heat Boiler (Dual Fuel)

Most of the natural gas carriers nowadays in service use the steam turbine propulsion system with the aid of a dual fuel boiler. The Conversion of the propulsion system has been made in some carriers by using slow speed diesel engine coupled with a propeller but most systems now adopt the theory of using boil-off gas as a fuel or using a reliquification plant for the sake of decreasing the percentage of cargo loss and increase the efficiency of the ship. In most cases the use of boil-off gas doesn't give the required propulsive force which lead to the use of additional burning fuel such as HFO, also known as bunker oil with the aid of systems that are able to use/switch between two fuels for the most economical fuel mixture [4].

2.1.1- Requirements for LNG Propulsion System

There are few requirements for improving thermal efficiency and ensuring safe and efficient use/treatment of BOG. There are two methods for efficient use of BOG:

- Use a re-liquefaction plant.
- Use a dual-fuel engine.

2.1.1.1-Re-liquefaction plant

This Type of LNG Carrier was built in November 2000 at MHI's Nagasaki Shipyard; it is equipped with the world's first on-board re-liquefaction plant. The system has been operational for nearly four years after it passed inspection phase with the conventional steam turbine type adopted as its propulsion system. This carrier used Heavy fuel oil (HFO) as its primary fuel and the boil-off gas (BOG) was reserved by the means of a reliqufaction systems. It's a cooling system as shown in figure 1where nitrogen was used as a refrigeration by the means of Brayton cycle. The BOG was stored by the means of reliquefaction and subcooling at standard conditions, hence no consumption from either the BOG or nitrogen since it is produced from on-board air. The BOG is compressed by a system of two-centrifugal compressors used for sharing it for boiler supply. Compression of nitrogen is done on three stages where the first two stages are driven by steam turbine and last stage is driven by expansion inside of the power turbine during the expansion process [5].

2.1.1.2-Dual Fuel Engine

This type of engine is based on four-cycle where it is capable of achieving high thermal efficiency (48% on lower calorific value basis) and low nitrogen oxide emission rate (up to 3 kg/kWh: on gas fuel burning).it has been used as a primary propulsion system since 2004 where the engine is able to work in two mode [6,7]. The first one is Gas Mode (Otto-cycle) where fuel in the form of gas and diesel oil (pilot fuel) are injected into the cylinder for the beginning of combustion process and the second one is the oil mode or diesel cycle. This engine has important features where gas supply pressure is very low which means excellent safety when compared with diesel engine high pressure gas injection type .It can operate on both fuel or simply on diesel oil where there is no LNG Loaded [8].

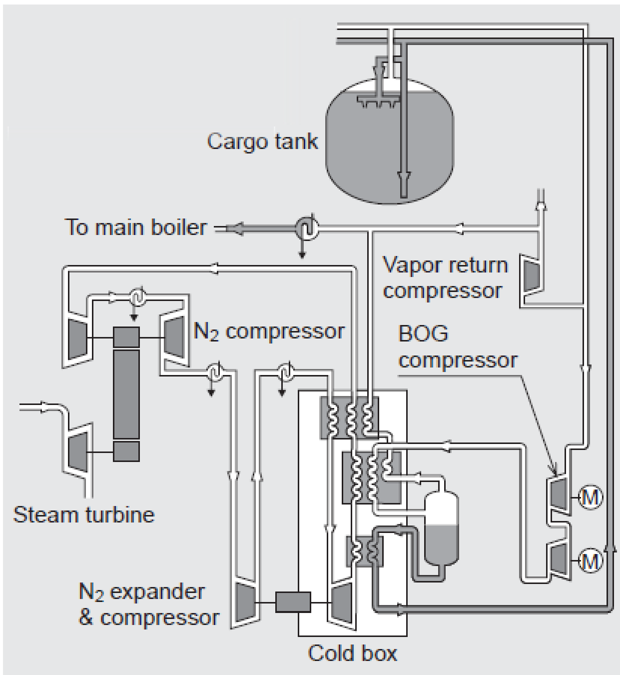


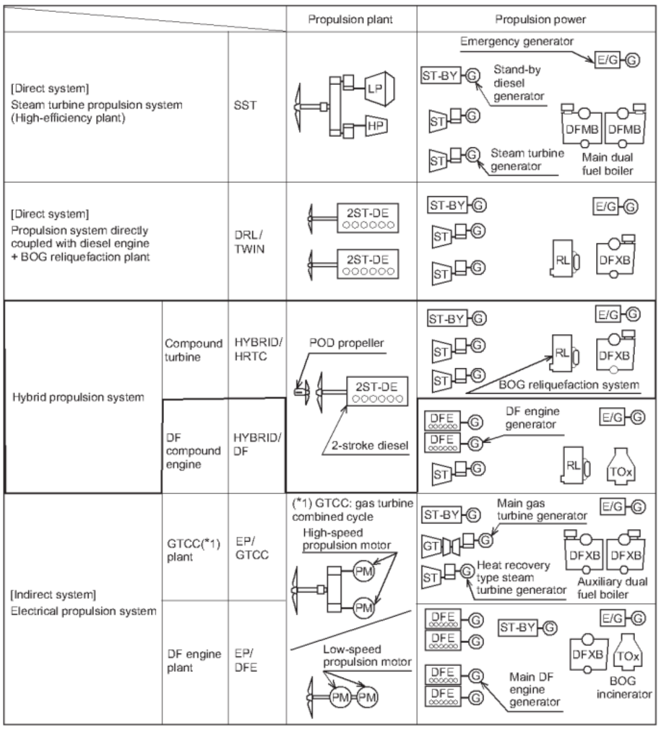
FIG.1 OUTLINE OF LNG JAMAL RE-LIQUEFACTION SYSTEM [4]

Currently other promising propulsion systems are under development for marine application where utilization of high efficiency steam turbine or gas turbine is being one of the best options used from late 1900s till this date. The Propulsion systems can be divided into two categories based on the propeller driving force:

1. Directly Couple System (Directly Coupled with Engine): One of the promising engine is the low speed diesel engine where it has higher performance at various power ranges and can be directly coupled with the propeller since the speed is controllable. However, it is used for large ships where it is superior than steam turbine engine due to high serviceability ratio and maintenance load. Two units of same engine are required in many cases in order to secure redundancy for maneuvering. The slow speed diesel engine has been used due to the high pressure gas injection in a power-generation facility, hence it is not preferred to be used as a marine engine due to several reasons mainly reliability, operation results and high pressure handling thus it is combination with a reliqufaction plant for treating boil-off gas as an additional system [9].

2. Indirect System (Electrical Propulsion): it is considered unsuitable to couple a dual fuel diesel electric engine and a gas turbine directly with a propeller due to the high rotation speed, thus an indirect system is used where electrical propulsion is selected where the case of propeller driving a two motors high speed type are coupled together and a low speed type is directly couple system. The electrical propulsion is used for passenger ships due to high reliability and low noise and vibration but it is not used in large scale ships due to the high cost [10].

TABLE II. TYPES OF PROPULSION SYSTEMS WITH PROPULSION PLANT CONFIGURATION [9]



			Propulsion plant	Propulsion power
[Direct system] Steam turbine propulsion system (High-efficiency plant)		SST	LP, HP	Emergency generator, E/G, ST-BY, Stand-by diesel generator, ST, DFMB, DFMB, ST, Steam turbine generator, Main dual fuel boiler
[Direct system] Propulsion system directly coupled with diesel engine + BOG reliquefaction plant		DRL/ TWIN	2ST-DE, 2ST-DE	ST-BY, E/G, ST, ST, RL, DFXB
Hybrid propulsion system	Compound turbine	HYBRID/ HRTC	POD propeller, 2ST-DE, 2-stroke diesel	ST-BY, E/G, ST, ST, RL, DFXB, BOG reliquefaction system
	DF compound engine	HYBRID/ DF		DFE, DFE, DF engine generator, E/G, ST, RL, TOx
[Indirect system] Electrical propulsion system	GTCC(*1) plant	EP/ GTCC	(*1) GTCC: gas turbine combined cycle, High-speed propulsion motor, PM, PM	ST-BY, Main gas turbine generator, E/G, GT, DFXB, DFXB, ST, Heat recovery type steam turbine generator, Auxiliary dual fuel boiler
	DF engine plant	EP/ DFE	Low-speed propulsion motor, PM, PM	DFE, DFE, ST-BY, E/G, DFXB, TOx, DFE, DFE, Main DF engine generator, BOG incinerator

Table (II) shows the illustrative figure of direct and indirect couple systems, the figure indicated the main schematic figure for the direct system which is a steam turbine propulsion system, this system is coupled with the engine and consist of two main turbine a high pressure and a low pressure turbine with a speed reduction gear system for the ease of control of speed .the indirect system is also shown where it includes two types of configuration, a gas turbine combined cycle and low high speed propulsion motor, the hybrid system which is another type of propulsion.

3. LNG AS AN ALTERNATIVE FUEL OPTION

The emissions from commercial shipping are heavily under pressure to decrease the emissions of GHG over the controlled areas and the overall emission rates. According to Kyoto protocol to the United Nations convention on climate change (1977) a definite measures to reduce one of the GHG gases (CO_2) emissions are necessary in order to reduce the GHG gasses worldwide. Other non-green-house gases are under radar by international maritime organization (IMO).
Approaches and methods to improve the overall Ship Energy Efficiency design index (EEDI) by reducing the emissions and reducing the specific fuel consumption of the engine [11].

This study was conducted with the following objectives: (a) shed light on the most used propulsion systems during the years 1970 till 2016 of the available LNG Carrier's Fleet in operation (400) carriers were reviewed gathering all the technical data [Power, Emission, Capacity, Speed] (b) Review previous literature related to the scope of this work. (c) Review the exhaust gases emissions (CO_2, NO_x) of the specific type of engines. (d) Compare the results from previous work with a case study to ensure that they meet with the regulations of IMO [11].

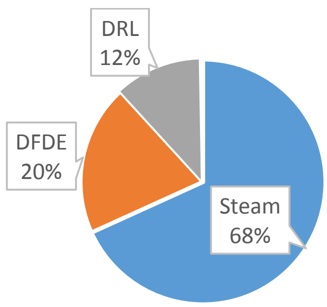


Fig.2. Common Propulsion chart on LNG Carriers.

TABLE III. AVERAGE VALUES FOR COLLECTED CARRIER'S DATA

Propulsion	Number	Average Power	Average Speed (knots)	Average Capacity (cu.m.)
Steam	249	35,008	19	134,883
DFDE	73	36,656	19	159,575
DRL	42	50,750	20	225,771
Diesel	1	13,900	18	19,100

Reviewing the literature on the area of this paper including regulations document released by IMO and scientific work, summarize almost 400 carriers with the specified detailed as power, engine type used, speed and capacity. The data acquired was plotted (Shown in Fig.2 and Table III) and it was found that 68 % of the carriers within the period of 1970s to 2010s used steam propulsion as the primary propulsion system with Dual Fuel Diesel Electric Engine in 2nd place with 20% and Diesel engine with Reliquification Plant with 12% and almost 0%(1 ship) that used slow speed diesel engine as the propulsion system .The following result is not a surprise since the steam propulsion has been the propulsion machinery for most LNG carriers since 1960s.the most used type at that time was a system that employs two main boilers which can burn both heavy fuel oil and boil-off gas to generate superheated steam fed to turbine for propulsion or electric supply. Although the system is quite complex but it is considered as a reliable with its ease of handling the boil-off gas with liquid fuel simultaneously. But it still has few problems with high-speed reduction gearing part [12].

From the gathered data shown , the results are plotted (Shown in Fig.3) showing the average speed, capacity and power of ships between 1970s till 2016. During the 1970s the dominated propulsion system was steam propulsion system which included 40 carriers working with that system at an average of 35,700 HP during that period with the increase of capacities of the carriers seems to be almost stable.

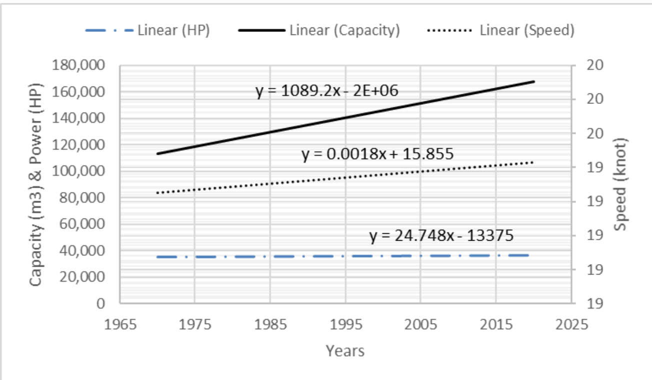


Fig.3 - Average Capacity, Power and Speed Evolution for LNG Carriers.

From Figure 4, it can be shown that almost 242 carriers used steam propulsion system during that period, although the dual fuel diesel engine was introduced in the late 2000s the steam turbine propulsion system seemed to be preferred over DFDE mainly cause of the high reliability of that propulsion system. With the beginning of 2010s the shipping industry shifted to the use of DFDE and the DRL which indicated the option of either saving the cargo fuel (LNG) by reliquifying the boil-off gas or using it as a secondary fuel with only 10% of heavy fuel oil used for ignition [13].

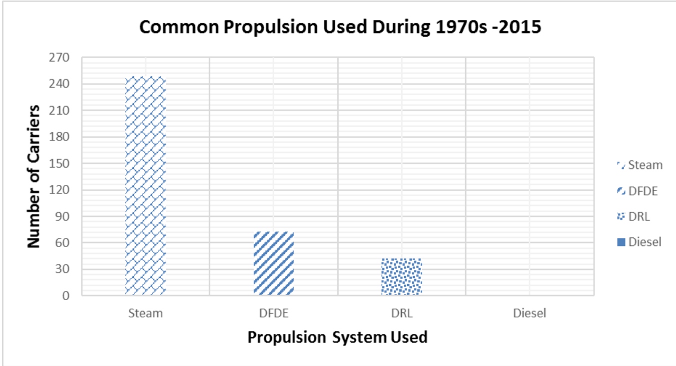


Fig.4- Bar-Chart of Common Propulsion on LNG Carriers

During that period of time the need to reduce the emission in emission controlled areas (ECA) and the regulations that were imposed by the IMO for ships to meet the requirements for carbon dioxide and nitrogen oxide emission. the Mandatory Marpol Annex VI emission standards are shown in Figure 5.

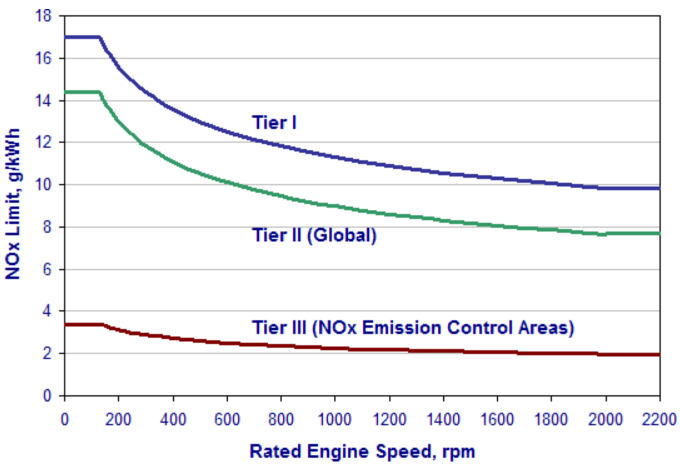


Figure 5 - Mandatory Marpol Annex VI emission standards [5]

The specific fuel consumptions of the engines were based on the type of propulsion system used where an average value was set for each type of engine during a time-period for the purpose of comparison later on with the proposed system Shows in Table (III), is the average values of specific fuel consumption for LNG Carrier's Engines with engine age as the main parameter [14,15].

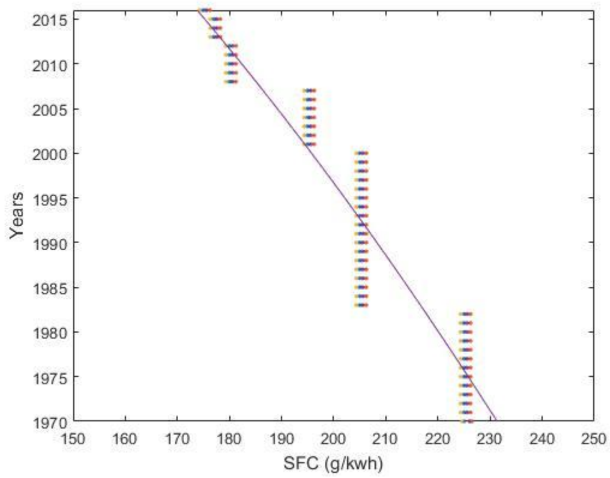
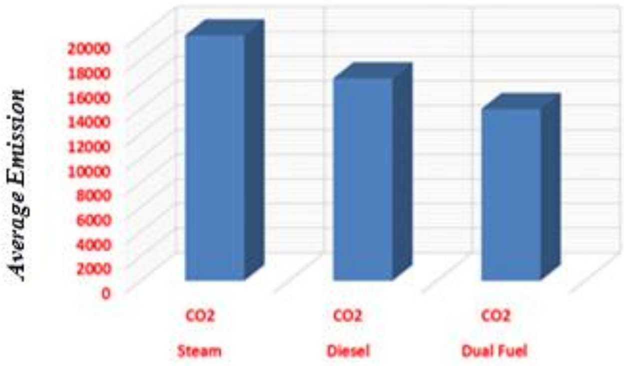
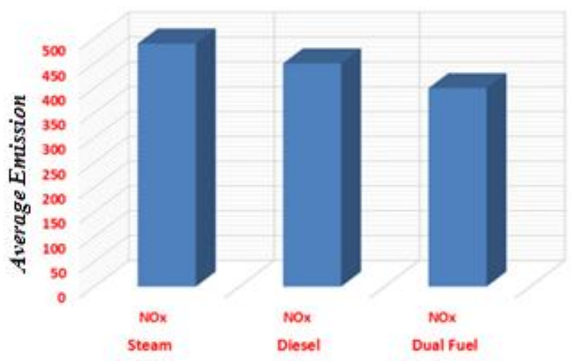


Figure 6 - Specific Fuel Consumption for LNG Carriers.



[a]



[b]

Figure 7 - Average Emission Values for Common Types of propulsion Systems ,[a] Co_2 Emission ,[b] No_x Emission

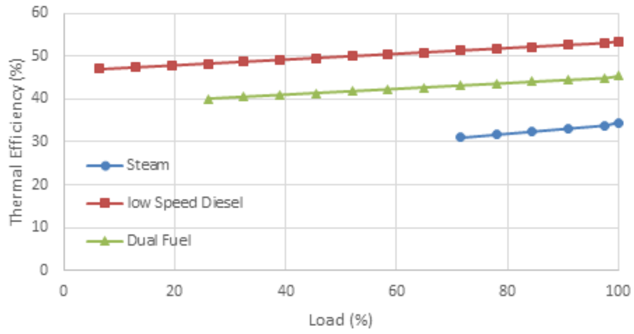


Figure 8 - Efficiency of Various Propulsion Systems.

Through the years 1970 till 2006s the most common type of propulsion system was the steam propulsion where it was used in old ships(retrofit) or with the new built ships going into service. Figure (6), shows the average values of specific fuel consumption through the years. the reduction in the fuel specific consumption along the years can be related to the introduction of both technologies of dual fuel diesel engines and also the integration of reliquifaction systems on slow speed diesel engines with the goal to reduce the cargo losses, decrease the fuel consumption and reduce the emission to meet the IMO regulations as shown in figure 7(a,b) is the average emission values for the steam, diesel and dual fuel propulsion system with it can be found that the steam propulsion has the highest values of emission although it was one of the promising propulsion, the diesel engine comes in second place with almost 10 % reduction in emission and finally the dual fuel that reduced the overall emission to almost 30% of the initial values of steam propulsion.

From the previous figures (3,6,7 and 8), it was found that the best system to perform was the slow speed diesel engine with the reliqufaction plant but due to the high pressure injection for the gas it in not used as much currently, so the best system to be modified is the dual fuel diesel engine where it will be fitted with a waste heat recovery system.

3.1 - Proposed System and Results

The proposed system for the current study is a dual fuel diesel engine carrier, the technical data of the ship is shown in Table IV, where three dual fuel diesel engines as shown in Fig.9 are used of the type 12V50DF.The exhaust gases from the engines is our main concern in the current study, so the exhaust gases are to be used in a waste heat recovery system as shown in (Fig.9,10) for the purpose of reduction of emission, increase plant efficiency. These goals will lead to the improve overall ship efficiency to meet the IMO regulation and Energy Efficiency Design Index (EEDI).

The evaluation of the systems performance and parameters was done by a construting a heat balance equations for Fig.10 and Fig.11 ,where these set of equations were solved by EES and Matlab for the ease of presenting the data.

The proposed system consists of the following:

1. Three dual fuel diesel engines from Wartsila
2. Steam Turbine
3. Boiler (Economizer, Evaporator and Superheater)
4. Feedwater Pump
5. Condenser

TABLE IV. AVERAGE VALUES FOR COLLECTED CARRIER'S DATA

Technical Data	
Overall Length	289.6 m
Depth	26.25 m
Breadth	43.35 m
Gross Tonnage	97741 Ton
Maximum Speed	20.45 knot
Main Engine Type	3 Engines (Wartsila 12V50DF)
Power	11700 KW @ 514 rpm

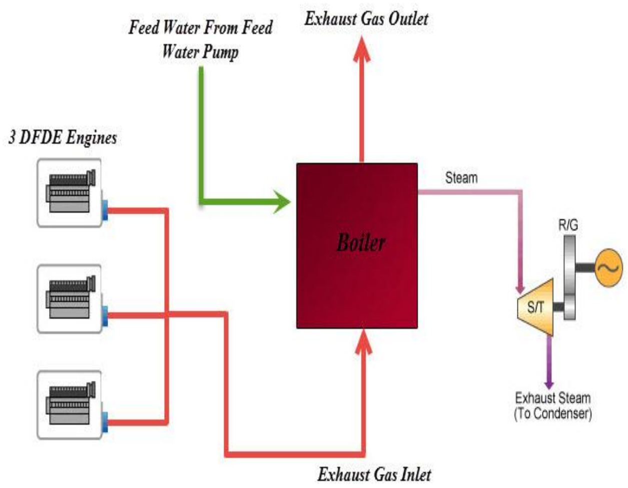


Figure 9. Schematic Diagram of Proposed System

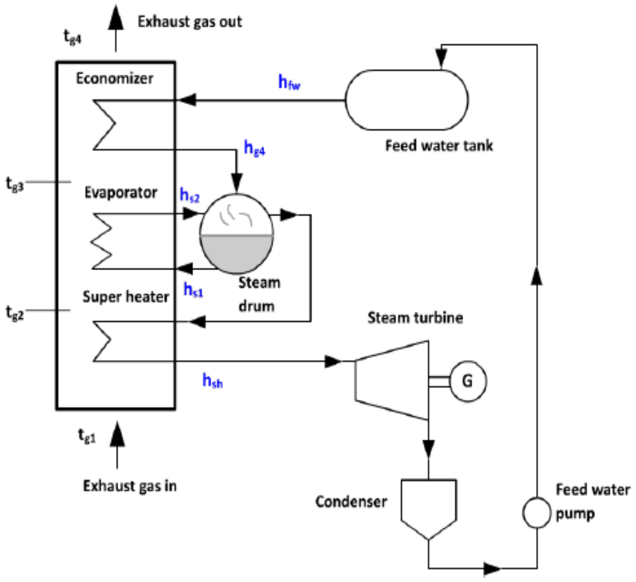


Fig.10. Simplified Rankine Cycle

The steam cycle conditions are summarized as:

1. Inlet steam is super-heated at 17 bar and 280 ℃
2. Condenser pressure is 0.07 bar
3. Variable steam turbine power output (first assumption = 3MW).
4. Isentropic efficiency of steam turbine = 93%.
5. Mechanical efficiency of the steam turbine = 98%
6. Losses to the surrounding about 2%.

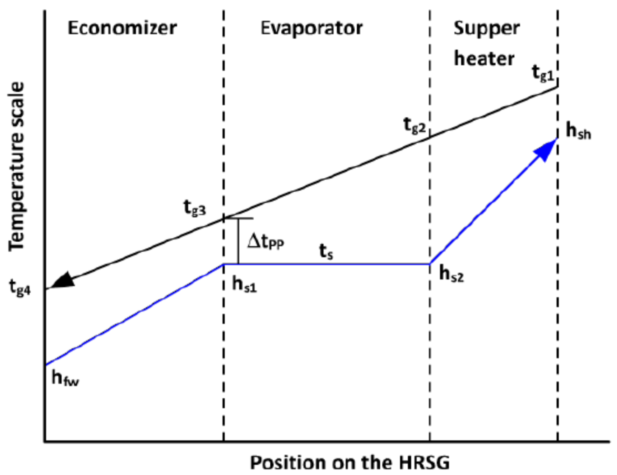
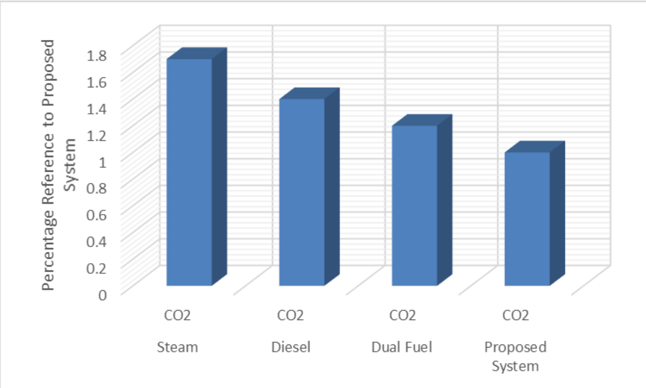
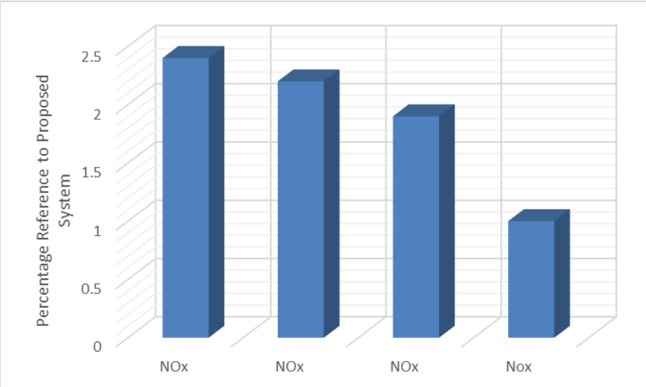


Fig.11 - HRSG Temperature Profile



[a]



[b]

Figure 12. Average Emission Values of proposed System compared to the other propulsion systems,
[a] Co2 Emission and [b] Nox Emission.

Figure 12 shows the emission of multiple propulsion systems compared to the proposed propulsion system. which uses a dual fuel diesel engine with a WHRS installed to reduce the effects of $\boldsymbol{NO_x}$ **and** $\boldsymbol{CO_2}$.the emissions of steam , low-speed diesel and dual fuel engines were acquired from Siemens and warstila catalogs as an average value for the emissions for this type of engines.it can be shown that the proposed system reduced the emissions of nitrogen oxide by almost 15 % when compared to the dual fuel engine , 30 % decrease when compared to diesel engine and 40 % when compared with steam engine.

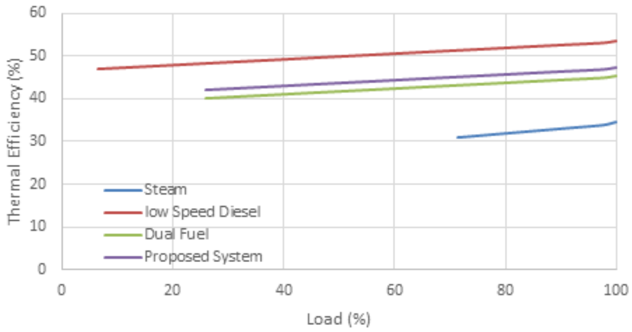


Figure 13. Proposed System Efficiency

Figure 13, shows the efficiency of the overall systems where the proposed system is superior to the ordinary dual fuel engine system but less performance is anticipated when compared with the low speed diesel engine which has increased efficiency, the steam turbine propulsion has the lowest efficiency when compared to the other three systems. The proposed system shows a great potential where a 15% reduction in the overall emission was achieved when using the dual fuel engine with a waste heat recovery system which meets with the regulations of the IMO for the Tier III regulations which began in 2016.Another benefit that can be found from Figure 13 is an increase in the overall efficiency of the system where the increase can be of about 2% of the initial value for the dual fuel propulsion system.

4- Conclusions

Liquefied Natural Gas is a promising alternative to the available fuels due to the fact it can help in the reduction of emissions by almost 98 % for SO_x,increase the engine efficiency and reduce the overall costs. It has been used for many years in the maritime shipping industry but the increase demand for the reduction of the overall emissions from the shipping industry lead to the development of such systems.
Although steam propulsion system is still considered one of the high reliable systems till this date but other alternatives are being used like the dual fuel engine and slow-speed diesel engine.

The dual fuel engine is the better solution with which a reduction in emission and fuel consumption is shown according to the results shown in the previous sections, while on the other hand these systems are hard to handle with its complex layout.

The propulsion systems available on the market were compared but the results shows that the slow speed diesel engine with a reliquifaction plant gives better performance that the proposed system but due to the fact of high pressure injection which is considered a hazard the slow speed diesel engine is not widely used , hence in our proposed system the dual fuel diesel engine was the 2nd best choice of propulsion system to seek further improvement with the available trends and new technologies on the market. The waste heat recovery system was designed with a specific pinch point temperature for the optimum heat extraction through the steam turbine where it was shown that increased efficiency compared to the regular dual fuel engine, on the other hand a 15% reduction in emission of carbon dioxide and nitrogen oxide was achieved while using the waste heat recovery system thus coinciding with the rules and regulation of the IMO,however less satisfying results are shown with the fuel and energy consumption with the prior results of the dual fuel engine thus seeking further improvement with new technologies as hull redesign ,air bubbles along the hull which may lead to better results regarding the specific consumption.

Nomenclature

BOG Boil-off Gas.
CO_2 Carbon Dioxide.
DFE Dual Fuel Engine
DFEE Dual Fuel Electric Engine.
DRL Diesel with Reliqufaction Plant
EEDI Energy Efficiency Design Index.
GHG Green House Gases.
h Enthalpy [kJ/kg]
IMO International Maritime Organization.
LNG Liquefied Natural Gas.
NO_x Nitrogen Oxide.
SO_x Sulphur Oxide.
T, t Temperature [K]
WHRS Waste Heat Recovery System.

Greek symbols

η Thermal Efficiency

Subscripts

fw Feedwater.
Pp Pinch Point Temperature
g1 Flue gas temperature into Steam Generator.
g2 Flue gas temperature after Economizer
g3 Flue gas temperature after Evaporator.
s1 Enthalpy Steam after the Economizer
s2 Enthalpy Steam after the Evaporator
sh Superheated Steam.

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