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Dual Fuel Electric System as an alternative Propulsion for LNG Carrier

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ABSTRACT

Liquefied natural gas (LNG) is expected to play an increasingly important role in the natural gas industry and global energy markets in the next era. The combination natural gas prices, rising gas import demand, and the desire of gas producers to monetize their gas reserves is setting the stage for increased global LNG trade. The LNG value chain necessarily involves LNG shipping. Traditionally liquefied natural gas carriers (LNGC) have used steam turbine propulsion systems since that allows easy disposal of cargo Boil Off. The steam turbine has surely performed high reliability for a long time since it was installed on LNGC, except for just a few problems with high-speed reduction gearing part, low efficiency, and high emissions.

The present investigation proposes and studies an alternative to the traditional propulsion system which is dual fuel electric propulsion. The electric propulsion system is proved an efficient operation in cruise ships. In additional the dual fuel engines improve the environmental impact assessment with the annual operating cost and meet the classification society's regulations. An actual case study is carried and *NavCad* software is used to predict and analysis the vessel speed and power performance. The environmental and economical output results, of the proposed ship propulsion power plant, are compared with the existing systems. The values are acceptable and encouraging. The results indicated that, the proposed installation is more green and clean with economical operation.

1- INTRODUCTION

Ship Owners are today under increasing pressure to either totally renew their ship power production equipment or to modify propulsion installations to meet new standards. Three main reasons underlie this trend**.** Except for the initial investment cost of an installation, the primary source of production costs for the owner will be the fuel expense. There is also a worldwide requirement to have more environmentally friendly power production installations in ship propulsion power plants. In order to reduce emissions, environmental legislations worldwide have been made stricter; a fact that is evident in raised HFO costs (environmental tax, subsidies removed). Thirdly, the availability of gas is growing as new gas pipelines are built and unloading terminals for LNG ships are taken into operation. Converting power plants to operate on fuels other than they were originally designed for provides operators and owners with environmental, operational and financial benefits. New efficient fuel burning technologies and the ability to source other fuels at more competitive prices now makes plant conversions commercially viable [1-4].

Since the beginning of the 21st century, LNG has been very much in the picture. Oil majors are expecting that LNG will be taking a much larger share in the energy mix in the next 25 years. That's why the capacity and size of LNGCs have been increasing rapidly from 500,000 m^3 in 1990 to 10,000,000 m^3 in 2009 [5].

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In LNGC, a part of the cargo becomes converted to boil off gas (BOG) due to heat from the open air and ship motions. Up to date, steam turbines have been predominantly used for propulsion systems of LNG carriers, because this BOG can be used as fuel for boilers. Typical values are about 0.1 to 0.15% of the full cargo contents converted to BOG per day, which over a 21 day voyage, becomes a significant amount. Even today, ships have employed gas compression and use of the boil-off gas as fuel for the propulsion systems that's why steam turbine installations have dominated LNG carrier propulsion and electric power generation for the past 40 years [6]. The ease with which these installations can utilize boil-off gas and their apparent reliability have kept them in a position that has long been lost to diesel engines in all other segments of the shipping industry.

Steam turbine installations are however not very efficient. Losses in the boilers, steam turbine, high-speed reduction gear and shafting bring the efficiency of the propulsion machinery to a level below 29% at full load. The efficiency of the electric power generation machinery is below 25% at full load. Part-load efficiencies of both the propulsion and electric power generation machinery are even lower [7]. The loss of efficiency has a negative impact on both the ship's operating economy and its exhaust gas emissions. Exactly these issues play an increasingly important role in LNG shipping today.

The introduction of the dual fuel diesel electric LNG carrier and the slow speed diesel driven LNGC with onboard re-liquefaction are radical departures from the currently dominant steam turbine drive technology. Encouraged by the latest developments in its gas engine technology, Wärtsilä [8] started looking for a more economic and environmentally friendly way to power LNG carriers. Also ABB marine [9] which is a global leader in power and automation technologies that enable utility and industry customers to improve performance while lowering environmental impact has introduced alternative propulsion systems to overcome the disadvantages of the traditional system.

Recently studies have been carried out on oil fired diesel propulsion engines with re-liquefaction units, electric propulsion systems using dual fuel diesel generator, or on dual fuel diesel propulsion engines instead of steam turbine propulsion systems and some of these systems are already in service. Nowadays, highly efficient steam turbines using reheating systems have been developed. Henceforth, optimum propulsion system will be selected considering the cost of BOG as fuel as well as fuel oil and operation with maintenance expenses. Therefore, the scope of the present investigation is to propose and study an alternative to the traditional propulsion system which is dual fuel electric propulsion. The electric propulsion system is proved an efficient operation in cruise ships [10]. In additional the dual fuel engines improve the environmental impact assessment with the annual operating cost and meet the classification society's regulations. Actual case study of 155,000 m^3 LNGC is carried and *NavCad* software is used to predict and analysis the vessel speed and power performance. *NavCad* is unlike any other resistance and propulsion software. Not limited to a few routines for the prediction of one or two aspects of performance, *NavCad* provides a complete platform for the steady-state equilibrium analysis of performance from hull to engine. The environmental and economical output results, of the proposed ship propulsion power plant, are compared with the existing system. The values are acceptable and encouraging. The output results indicated that, the proposed installation is most attractive alternative to steam turbine installations. The system is greener and cleaner, in addition the operating and maintenance costs are reduced.

2- MARINE PROPULSION SYSTEMS

There are several technical options available to propel the ship. These options include: Diesel engines, which are available in three main types, namely high-speed, medium-speed and slow-speed units. The high-speed diesel engines are normally rated up to 5MW and are not a practical solution for use in marine's power plants. Medium-speed units are commonly used on smaller ships and low-speed units are used on larger commercial vessels. Gas turbines are available in both open- and combined-cycle variants. A conventional steam turbine installation consists of two boilers, most commonly fired with boil-off gas and heavy fuel oil (HFO). A steam turbine is driving a fixed-pitch propeller through a high-speed gearbox. Two additional steam turbines and one or two diesel engines are driving alternators to generate electric power combined propulsion systems are recently applied. The thermal efficiencies of various prime movers as a function of load are illustrated in Figure 1. Diesel engines have the ability to maintain good efficiency through a range of loads than other prime movers, at loads between 50 to 100 percent of rated output as seen in figure 1.

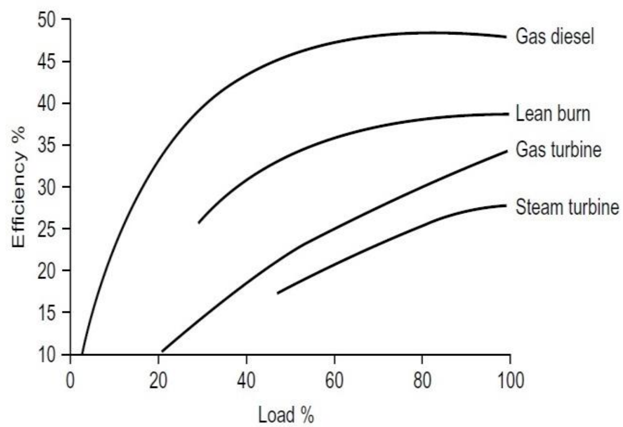

Fig. 1 Thermal efficiencies of various prime movers as a function of load [11]

2-1. Steam Turbine Propulsion Power Plant

The steam turbine represents the 'base case' since steam turbine installations have dominated onboard LNG carriers for the past 40 years [7]. A typical steam turbine installation consists of two boilers supplying steam to a cross-compounded double reduction geared steam turbine plant driving a single propeller. A reduction gearbox is used to provide a low-speed drive for the propeller shaft because the steam turbine rotates at a very high speed, in the order of 6000 rev/min [12].

A double reduction gear steam turbine installation adds more weight than other alternatives. Steam is also supplied to auxiliary services, the main one being the turbo generators which provide the electrical power. The capacity of the turbo generators is dictated by the electrical load required during discharge using the electric cargo pumps. Two turbo generators are sized to meet the discharge port load, one of which fully satisfies any load at sea. Two auxiliary diesel engines are installed, the combined capacity being equal to one turbo generator as shown in figure 2.

Steam turbine installations are however not very efficient compared to diesel engine as seen in figure 1. This has a negative impact on the operating economy and exhaust gas emissions of the ship. Exactly these issues play an increasingly important role in LNG shipping these days [13]. The present investigation is an attempt to find an alternative to the steam turbine propulsion system.

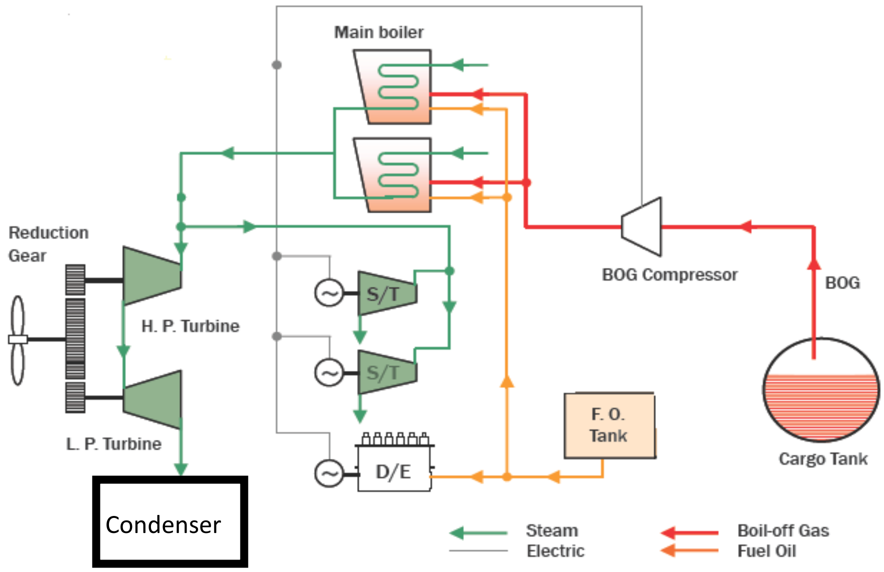

Fig. 2 Steam turbine propulsion system

2-2. Slow Speed Diesel with Re-Liquefaction

This option employs conventional slow speed diesel engine technology for propulsion purposes and a re-liquefaction plant to turn the boil-off gas back to liquid and return to the cargo tanks. These re-liquefaction plants require a substantial amount of electric power to operate and are costly, heavy and have only been applied in the marine environment on a very limited scale [14].

As the LNG trade sets high standards with respect to ‘maintainability’ and redundancy, the most simple and straightforward diesel engine installation onboard an LNG carrier will likely feature twin two-stroke engines connected to a fixed pitch propeller through gearbox. In order to keep the complexity low and the operational flexibility high, electric power will likely be generated by a group of four-stroke diesel generating sets. The system installation is explained in figure 3. The exhaust emissions of two-stroke engine installations are reasonable, but certainly not excellent. Without additional equipment like Selective catalytic reduction units or direct water injection, NOx emissions are substantial. As an inevitable consequence of using HFO as a fuel, SOx emissions are high too [14].

2-3 Dual Fuel Diesel Engine Propulsion System

A dual fuel diesel propulsion system is a propulsion system currently being studied for application mainly in large low speed two stroke dual fuel engines used as main engines, as seen in figure 4. The main feature of this system is that gas pressurized to 250 to 300 bar by a high pressure gas compressor installed in the cargo area is supplied to the main engines in the engine room [13]. Consequently, high reliability is required not only in main engines, but also in the high pressure gas compressor and high pressure gas piping system. Although such high pressure gas compressors have been used successfully onshore, they have not yet been used onboard ships. Furthermore, considering that this is a diesel engine with comparatively high levels of main engine vibrations, the design should be implemented with particular attention given to the pipe supporting method, expansion joints, and other components of the high pressure gas piping system.

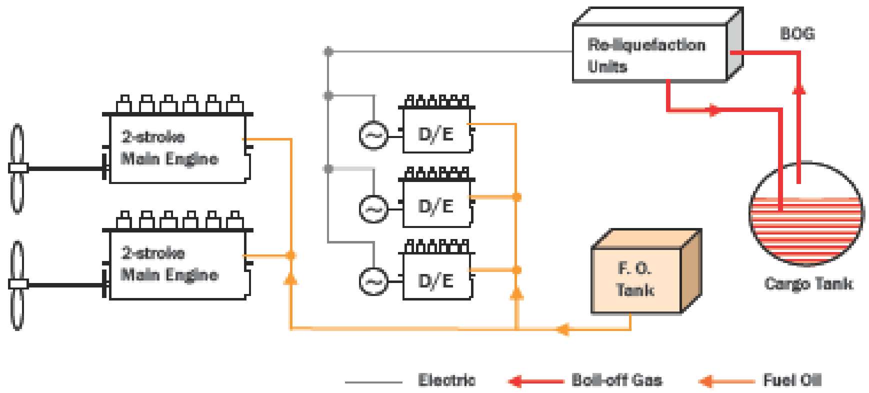

Fig. 3 Diesel engine propulsion system with BOG re-liquefaction unit

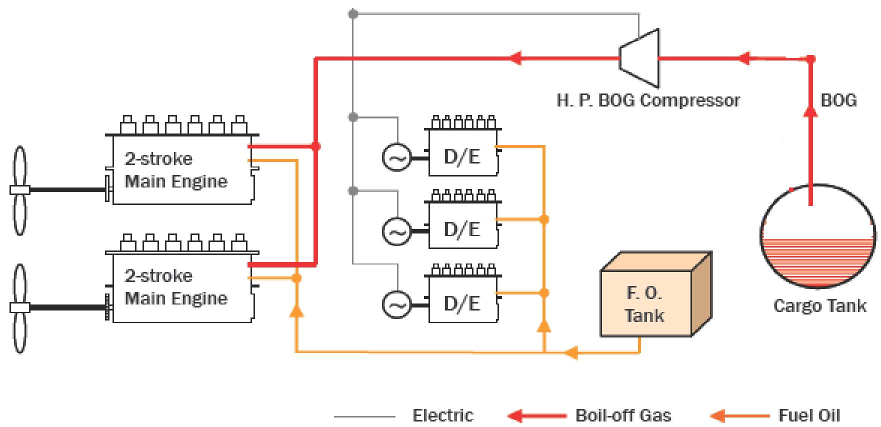

Fig. 4 Dual fuel diesel engines propulsion system

2-4. Dual Fuel Electric Propulsion

A system that uses BOG as fuel for power generating engines and driving propulsion motors is the most common system replacing the steam turbine system. In this case, two propulsion motors and four generating sets are generally provided. The generating sets are installed as two independent groups in a gastight generator room, or all four sets are installed in one generator room with gas fuel supply piping made of double wall pipes. A four-stroke electronically-controlled engine is used as the principal power generating engine. Marine diesel oil is supplied for igniting the engine, and either marine diesel oil or heavy fuel oil is supplied as back-up fuel, see Figure 5. In this system only the minimum quantity of heavy fuel oil required may be provided as fuel; thus, the ship's weight can be reduced, and as a result, a greater quantity of LNG can be transported. Moreover, since this is an electric propulsion system, the advantages are that both vibration and noise are minimal, and plant efficiency is higher than that of a steam turbine propulsion system. However, a re-liquefaction unit or a BOG combustion unit must be provided in such a system to treat the excess BOG generated while the ship is in port or during low-load operation. In addition to running on gas, dual-fuel engines can run on MDO. When running on MDO, the dual-fuel engine acts as a normal diesel engine [15]. In case the engine is running in gas mode and the supply of gas is interrupted or an alarm situation occurs, it automatically and instantly trips to diesel mode, without loss of engine power and speed.

Transfers from gas mode to diesel mode can also be carried out on demand, at any load, and again without loss of engine power and speed [7].

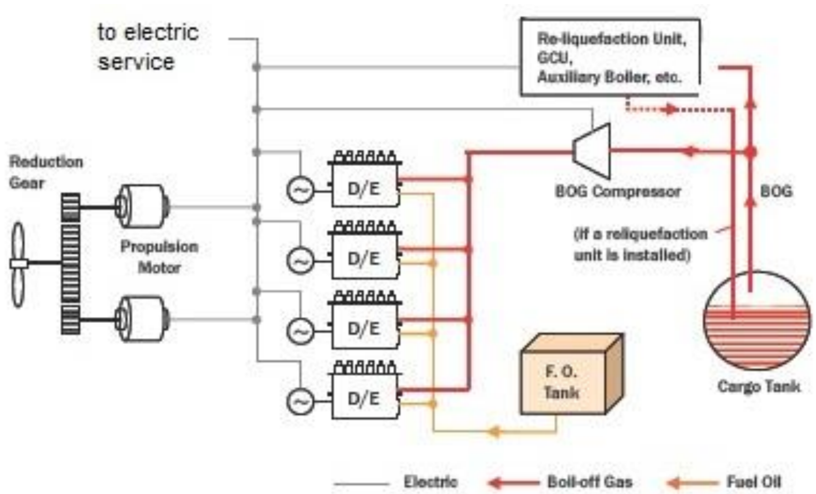

Fig. 5 Dual fuel electric propulsion system

2-4-1 Advantages of dual fuel electric propulsion system

- Improved thermal efficiency of the propulsion plant;
- Lower installed power, as the power plant serves both the propulsion load as well as the harbor load;
- Increased redundancy with 4 prime movers;
- Increased cargo capacity within the same overall dimensions of the vessel;
- Electric propulsion system is easier to operate and faster to start up and to shut down;
- dual-fuel electric solution shows unrivalled emission values because steam turbine suffer from the use of HFO, either used uniquely or in combination with natural boil-off gas.
- Dual-fuel engines can be operated and maintained by regular diesel engineers.
- The lean burn improves the maintenance period due to reducing engine wear.
- The full load operation improves the performance and reduces the environmental impact.

2-4-2 Disadvantages of dual fuel electric propulsion system:

- Steam turbines have proven to be very reliable over time, more reliable than diesel engines;
- Steam turbine plants need less maintenance than diesels;
- Diesel engines have higher lube oil consumption than steam turbines.

Gas turbine installations could also potentially be applied in LNG carriers. Their rather low efficiency at part-load, difficulty in coping with high ambient temperatures, need for high gas pressure and the required special skills and procedures for maintenance, make them less attractive.

3- COMPARISON OF ALTERNATIVES

The propulsion power efficiency's comparison of propulsion power alternatives will be as shown in figure 6.

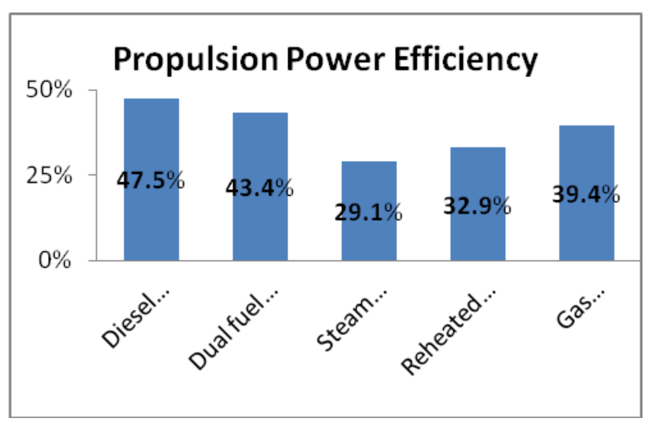

Fig. 6 Propulsion power efficiency comparison [16]

Slow speed Diesel with re-liquefaction plant is better than dual fuel electric plant when we compare the propulsion power efficiency but if we compare the Electric Power Efficiencies of the different alternatives we will find that dual fuel electric plant is the best option as shown in figure7.

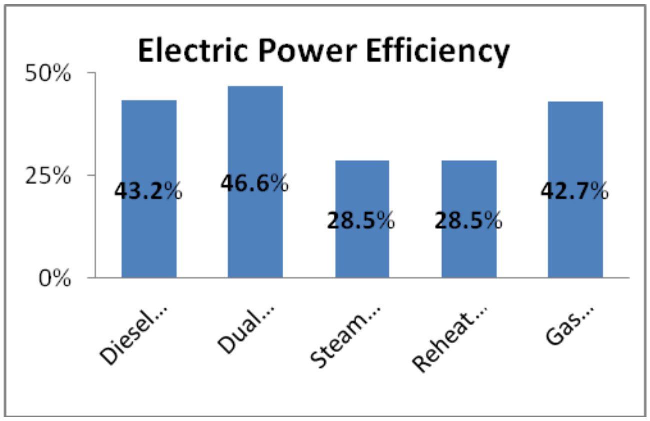

Fig.7 Electric Power Efficiency Comparison [16]

4- LNG RE-LIQUEFACTION SYSTEM

When comparing the operational economy of the various alternatives, it is important to take the whole machinery installation into account. Two-stroke diesel engines have a high efficiency, but the need to re-liquefy the boil-off gas gives installations featuring this type of engines higher total energy consumption. The BOG re-liquefaction concept is based on a closed nitrogen cycle extracting heat from the boil-off gas.

The LNG boil-off is compressed by the low duty (LD) compressor (BOG compressor), and sent directly to the so-called cold box. The cold box in which the boil-off is re-liquefied is cooled by a closed refrigeration loop. The cargo cycle consists of an LD compressor, a plate-fin cryogenic exchanger, a separator and an LNG return pump. Boil-off is evacuated from the LNG tanks by means of a conventional centrifugal low duty compressor. The vapor is compressed to 4.5 bar and cooled at this pressure to approximately –160°C in a plate-fin cryogenic heat exchanger. This ensures condensation of hydrocarbons to LNG.

The fraction of nitrogen present in the boil-off that cannot be condensed at this condition remains as gas bubbles in the LNG. Phase separation takes place in the liquid separator. From the separator, the LNG is pumped back to the storage tanks, while the nitrogen-rich gas phase is discharged (to atmosphere or burnt in an oxidizer). The specific power consumption of the Re-liquefaction plant of 150000 m^3 LNGC is about 920 W/Kg/hr [17].

The most attractive alternative to the traditional steam turbine installation turned out to be dual-fuel-electric machinery. As a runner up but at clear distance to dual fuel- electric machinery, an installation featuring twin two-stroke engines, a re-liquefaction plant, and a group of four stroke diesel generating sets emerged.

5- OPERATING PROFILE OF SHIPS

There are ships that are operated in partial load conditions for a significant portion of their time such as research vessels, navy cruisers and destroyers and fast yachts [18]. It is very important that the power plant is efficient also in part-load operation which is not accomplished in diesel engine propulsion alternative because of higher specific fuel consumption at partial load as shown in figure 8 which will increase the running cost of the ship.

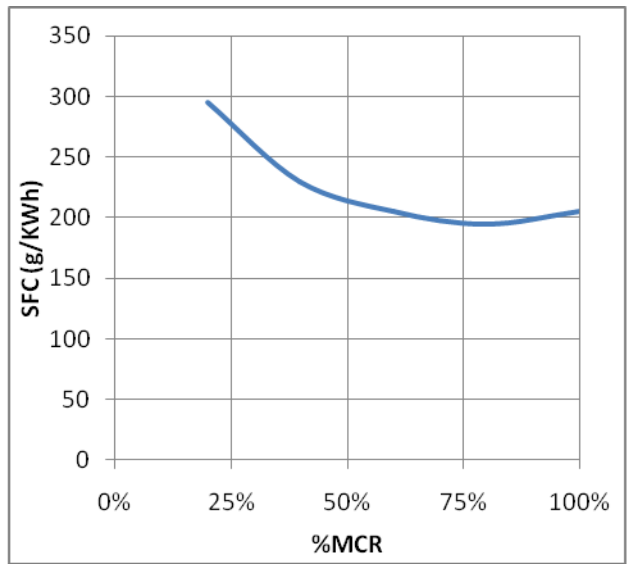

Fig.8 Diesel engine specific fuel consumption [19]

The efficiency of diesel engine is decreasing in partial load as shown in figure 9 which can be avoided using electric propulsion system because as an alternative to running one big engine at low or part load which mean lower efficiency, one of a set of smaller engines can be run at full load which will maintain the high efficiency.

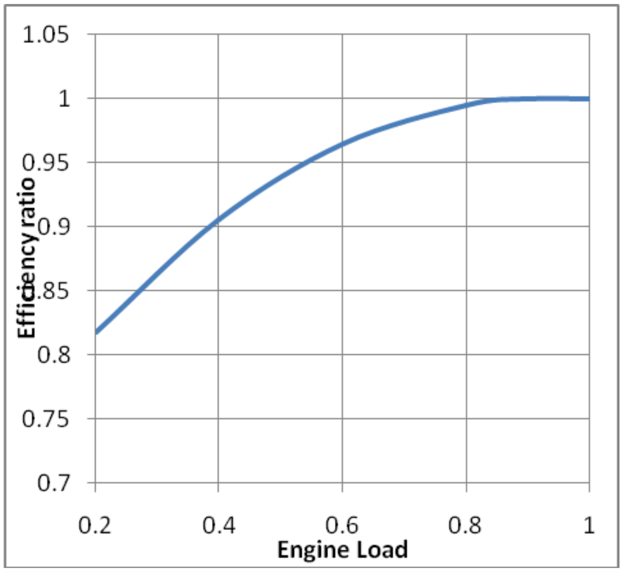

Fig. 9 Efficiency ratio of diesel engine part load performance [20]

6- CASE STUDY

For an LNG carrier with a cargo capacity of 155,000 m^3 , LPP=274 m, B=43.4 m, T=12.5 m and for a service speed of 19.5 Kn will require one six- and three twelve cylinder Wärtsilä 50DF engines [15]. The generated electric power is fed to an electric drive fairly similar to those used on contemporary cruise ships. Two high-speed electric propulsion motors drive a fixed-pitch propeller through a gearbox. The installation and layout of the system explained in figure 5. The other option will consist of 2 slow speed diesel engines MAN B&W 6S70ME and 4 generating sets 8L32 [15]. The total installed power will be 52680 KW which is higher than the total installed power in the dual fuel electric propulsion and that is because of the re-liquefaction plant. The layout and machinery arrangement of the propulsion system is explained in figure 4.

As dual-fuel engines have the ability to run on both gas and liquid fuel, the choice of fuel is up to operator. Several independent studies have however confirmed that forcing additional boil-off gas to complement the natural boil-off gas is the way to profit most from the potential of the dual-fuel-electric solution [7]. Firstly, forced boil-off gas is cheaper than alternative fuels. Secondly, it is lighter than alternative fuels. Fuel's 'bunkers' weight is thus reduced, and at a given displacement, the ship will be able to carry more cargo weight and volume. Even when using a small part of the cargo as fuel, a dual-fuel-electric LNG carrier will deliver more cargo to the unloading port in this way. Adding the cheaper fuel of the dual-fuel-electric LNG carrier to the equation, this solution clearly excels in terms of operating costs.

Figure 10 presents a plot of the total resistance versus the speed. Total resistance is a function of ship's length L, velocity V, density ρ, kinematic viscosity of the water ν, and the gravitational acceleration g as shown in equation (1).

NavCad software is used as a professional program for the prediction and analysis of vessel speed and power performance. The total resistance of the ship and the required brake power to overcome the resistance is predicted. The prediction accuracy of the program is insured by offering the largest available suite of prediction methods (over three dozen for bare-hull resistance alone), compatible components between methods, calculations built from contemporary state-of-the-art methodologies, and a complete analysis environment where critical components (like shallow water resistance) cannot be forgotten. In addition, *NavCad* contains HydroComp's Method Expert prediction method ranking system. This feature takes vessel data and ranks all monohull prediction methods based on speed regime, ranges of hull parameters and the availability of hull details (i.e., if bulb or immersed transom data, for example, has been entered and is used in the method). It also takes into account HydroComp's extensive knowledge about prediction method behavior and reliability. Warnings are raised if a method has shown poor results for the given vessel information.

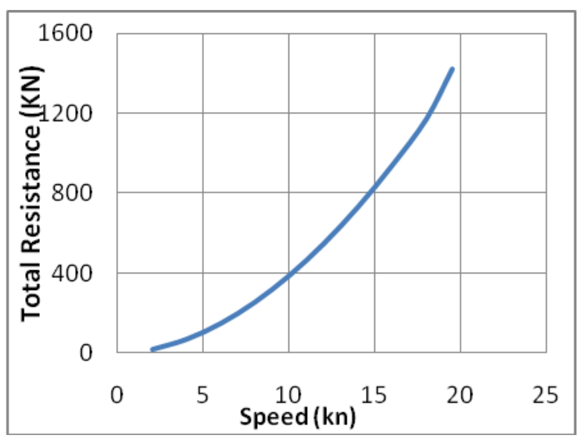

Fig. 10 Resistance-Speed Curve of the Studied Ship

$$R \propto (\rho^a V^b L^c \nu^d g^e) \qquad (1)$$

By using Dimensional analysis which is the basis for similarity theory, the total resistance will be:

$$R = \frac{1}{2} \rho \, C_R V^2 S \qquad (2)$$

Where C_R is the non-dimensional resistance coefficient, that's why total resistance is increasing while ship's speed is increasing as shown in fig. 10.

6-1 Operating Economy

According to the assumed operating profile and from the engines' specific fuel consumption curves, total fuel consumption of the two propulsion options and its cost are calculated and plotted in figure 11. As dual-fuel engines have the ability to run on both gas and MDO and by maximization the use of natural gas there will be a big saving in fuel cost beside, diesel mechanical propulsion will consume a substantially higher amount of electric power due to the presence of the liquefaction plant.

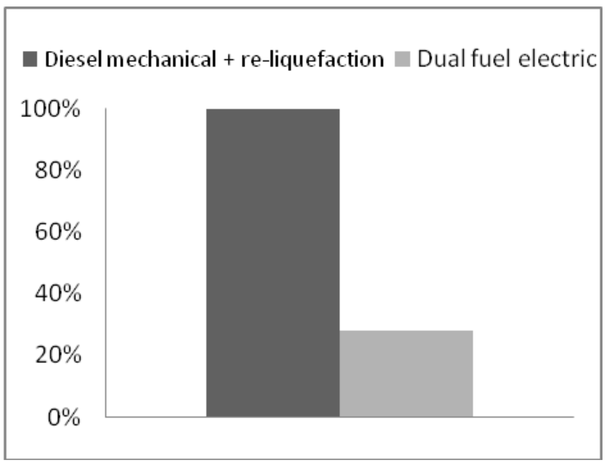

Fig. 11 Fuel Cost Saving For the Assuming Operating Profile

Figure 11 indicates that, the fuel costs for diesel mechanical and re-liquefaction power plant increases by 3 folds more than dual fuel electric power plant.

6-2 Environmental Comparison

A common trend is seen in the emissions charts as shown in figure 12, where prime mover machinery is forced to operate away from its design operating point, specific emissions tend to become worse. For this reason, at low powers the diesel mechanical propulsion has the worst emissions compared to the dual fuel electric propulsion whose redundancy, maintainability and plant efficiency at part load increase with the number of dual-fuel engine-driven generators. The maximization of using natural gas will increase the environmental benefits in the dual fuel electric propulsion because all other machinery alternatives suffer from the use of HFO, either used uniquely or in combination with natural boil-off gas. The exhaust emissions are calculated for the proposed power plants and plotted in figure 12 as taken from the given values in table 1 [21].

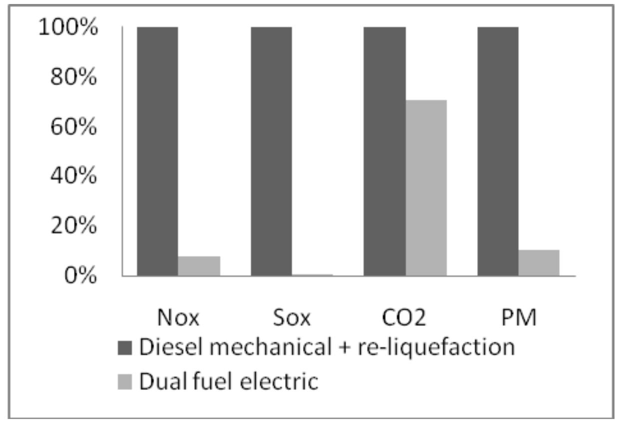

Fig. 12 Comparison of Emission

As shown in table 1 and figure 12, in dual fuel propulsion the CO_2 emissions are typically reduced by about 20%, the corresponding reduction in NO_X is 85-90%, with SO_X and particulate emissions almost eliminated. The reduced CO_2 emissions are a result of high hydrogen/carbon ratio of gas compared to HFO/MDO. SO_X and particulate emissions are practically eliminated due to the very low pilot injection only about 1% of the total energy input comes from pilot fuel.

Table 1 Emission from Marine Prime Movers [21]

	NOx (g/kWh)	**SOx** (g/kWh)	**CO_2** (g/kWh *100)	**PM** (g/kWh)
2 stroke diesel	17	12.9	5.8	0.5
4 Stroke Diesel	12	13.6	6.12	0.4
Dual Fuel Diesel Electric	1.3	0.05	4.2	0.05

7- CONCLUSION

Steam turbine installations have dominated LNG carrier propulsion and electric power generation for decades because no suitable alternatives were available but diesel engines with onboard re-liquefaction plants and dual fuel electric propulsion systems have managed to break the steam turbine dominance in LNG shipping.

Dual-fuel engines in combination with an electric drive have turned out to be the most attractive alternative to the traditional steam turbine installation, especially in terms of operating economy and environmental friendliness.
In dual fuel electric propulsion system only the minimum quantity of heavy fuel oil required may be provided as fuel; thus, the ship's weight can be reduced, and as a result, a greater quantity of LNG can be transported. Moreover, since this is an electric propulsion system, the advantages are that both vibration and noise are minimal, and plant efficiency is higher than that of a steam turbine propulsion system

Both concepts outperform the steam turbine concept on economy, redundancy, and emissions. The dual fuel electric propulsion outperforms the diesel engine concept on economy and maintainability, and clearly outperforms both the diesel engine and the steam turbine concepts on emissions.

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