PROPULSION ALTERNATIVES FOR MODERN LNG CARRIERS

Dongil Yeo
Project Manager

Byungsam Ahn
General Manager

Jinmo Kim
Senior Manager

Ilyong Kim
Senior Engineer, Marine

Samsung Heavy Industries Co., Ltd
Geoje-Si, Kyeongsangnam-Do, South Korea
http://www.shi.samsung.co.kr

ABSTRACT

Certainly, the steam turbine driving LNG carrier has been ordered very seldom at present and other propulsion systems take the place of main engines for LNG carriers. New demands in LNG shipping industry and increasing concern about environmental protection are supposed to lead the trend toward an alternative propulsion application for LNG carriers other than steam turbine, which had dominated propulsion power generators onboard the vessels for decades.

The steam turbine has been acknowledged as a well-proven and reliable system, but not so efficient and quite complicated for operation. Thus the LNG shipping industry came to look for alternative ones, e.g. the diesel engine application that is common in the other fields of the shipping, and the latest developments in gas engines technology and gas handling machinery seem to satisfy the needs in the market. Furthermore, as the size of LNG carriers is getting bigger, alternative propulsion should be considered due to the practical limitation in steam turbine plant.

The feasible and already realized alternatives at the moment are the conventional 2-stroke slow speed diesel engine with re-liquefaction plant and the dual fuel 4-stroke diesel electric propulsion system. And, encouraged by the demands in the market, the gas turbine application and the gas injection 2-stroke diesel engine have been also evaluated in great detail.

In order to have more concrete idea about the alternatives, it is worth summarizing them technically and sharing what we have learned during evaluation of various propulsion alternatives at this stage.

Total 14 ships of slow speed diesel engines with re-liquefaction plant and 16 ships of dual fuel diesel electric propulsion are on order in Samsung Heavy Industries as of December 2006.

INTRODUCTION

In this paper, various aspects of alternative propulsion systems for LNG carrier will be addressed in the shipbuilder’s point of view for the readers to be able to compare them and we hope this will be a good reference to help selection of proper propulsion system for potential customers. Some of opinions in this paper might be controversial especially by the suppliers of propulsion machinery but we believe that exchange of different ideas and further discussion on the issues would contribute to developing the technology.

In principle, most of the propulsion systems already introduced in marine field can be used for LNG carriers as well, but there are unique features to be considered in LNG carrier operation, which also influence the design of propulsion system, as following:

- Disposal of boil-off gas from cargo tanks
- Demand of high reliability

Due to the nature of liquefied natural gas and its storage facility, the boil-off gas from the cargo tanks is unavoidable – boil-off rate of nominal 0.15% of full cargo per laden day but the lower actually – and the natural boil-off gas (NBOG) must be treated properly and safely. It can be used as a fuel in the propulsion machinery, or re-liquefied and sent back to cargo tanks for sale. Disposal of boil-off gas to atmosphere is banned by regulations, except for an emergency situation. And, because the LNG trade is generally based on long-term time charter – although the spot/niche markets are emerging recently, the system reliability is very important for on-time delivery of LNG cargo.

TECHNICAL REVIEW

Steam Turbine Propulsion

It has been the propulsion machinery for LNG carriers since 1960s. Steam turbine propulsion system employs two main boilers, which can burn both of heavy fuel oil and boil-off gas to generate superheated steam fed to turbines for propulsion or electric power supply, and quite complex apparatus & piping systems are associated with the steam plant of regeneration cycle for utmost use of energy. Normally two steam turbo generators are installed for electric power generation with one conventional 4-stroke diesel generator as a standby.

Disposal of NBOG is carried out by burning them in main boilers and simultaneous dumping of surplus steam into sea water cooled condenser in engine room is carried out. Single-stage centrifugal type LD (Low Duty) gas compressor is used to supply boil-off gas to boilers from cargo tank vapour and the compressor is equipped with inlet vane and variable speed electric motor to control the amount of gas supply.

The steam turbine has surely performed high reliability for a long time since it was installed on LNG carriers, except for just a few problems with high-speed reduction gearing part. It has been considered as well-proven, reliable and infrequent & low-cost maintenance machinery. However the drawback is mainly in its efficiency. The maximum total plant efficiency of the steam propulsion system is approximately 30% at full load and the efficiency becomes lower as the turbine load goes down. The efficiency of e turbo generators is even lower than main propulsion turbine. And, on the contrary of reliable and steady operation during normal sea going, the maneuverability at part load is considered worse so that fuel oil burning together with gas burning in main steam boilers is required to response the load fluctuation during operation in & out of port.

In order to enhance plant efficiency of steam turbine propulsion system, the newly developed concept has been introduced in the market, so called as Ultra Steam Turbine. (Figure 1)

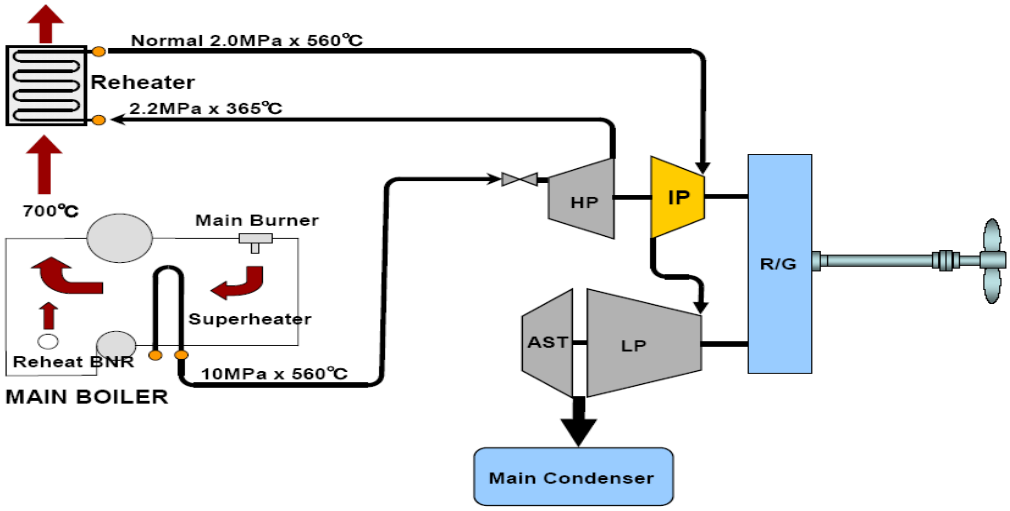


Figure 1. Schematics of Ultra Steam Turbine System (MHI)

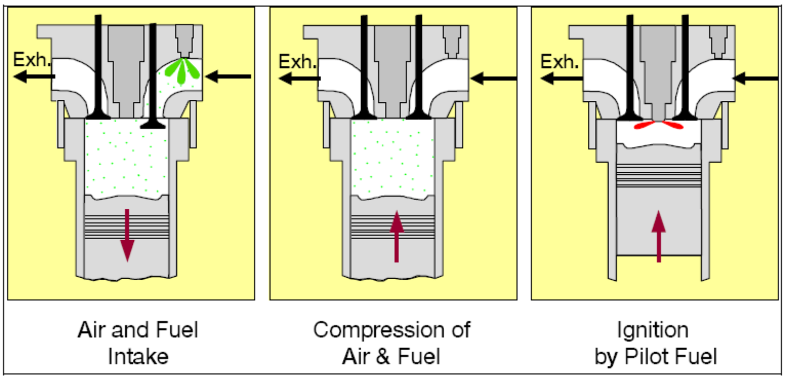
Comparing with the existing steam system, the reheating cycle was added to improve thermodynamic efficiency and the intermediate pressure turbine section is incorporated in addition to HP (High Pressure) and LP (Low Pressure) turbines. It is expected that this development will enhance the efficiency of steam ship by about 15%, but still lower than other solutions with diesel engines.

As the capacity of LNG carriers are getting bigger and they require more power, it seems that the application of steam turbine shall be carefully considered in case of very large LNG carriers due to the limitation in its output power and engine room space.

Dual Fuel Diesel (4-stroke) Electric Propulsion

Lots of orders prove that this is one of the directions toward propulsion system for LNG carriers. Since 2003, 29 DF Electric LNG carriers – including re-gasification vessels – have been ordered by various shipowners out of 159 LNG carriers worldwide as of December 2006.

DF engine adopted the lean-burn concept of Otto cycle and small amount of diesel oil (pilot fuel, about 1% of energy input) is used for ignition in combustion chamber [1] (Figure 2). The BOG as a fuel is led to the charge air supply port of each cylinder and the gas fuel - charge air mixture is compressed in the chamber until ignited by the pilot fuel. This mechanism enables the low pressure (about 5 bar) gas burning and rather safe operation with gas fuel evaporated in cargo tanks. Both of gas fuel and liquid fuel can be used alternatively in DF engines, and a.m. lean-burn process is applied in gas mode and DF engine works just like a diesel engine by using conventional jerk pumps in liquid fuel mode. Due to the fact that diesel engines are used as prime movers for ship power, the efficiency more than 40% is easily achieved, that is a definitely big advantage comparing with the steam turbine propulsion. Furthermore the engines can dispose BOG from cargo tanks through a two-stage centrifugal type gas compressor with constant speed motor as safely as the steam boilers do.



Air and Fuel Intake

Compression of Air & Fuel

Ignition by Pilot Fuel

Figure 2. Combustion Process in DF engine [2]

Four DF engines, two in each DF engine compartment, are normal design at present in engine room considering redundancy and voyage profile of LNG carriers. Each pair of DF engines has a separate gas fuel supply line branched from main line on the deck and electric power generated by alternators is fed to switchboards for distribution, transformers for voltage regulation, frequency converters for rpm adjustment, electric propulsion motors, rpm reduction gearing and finally to propeller for propulsion in order. (Figure 3)

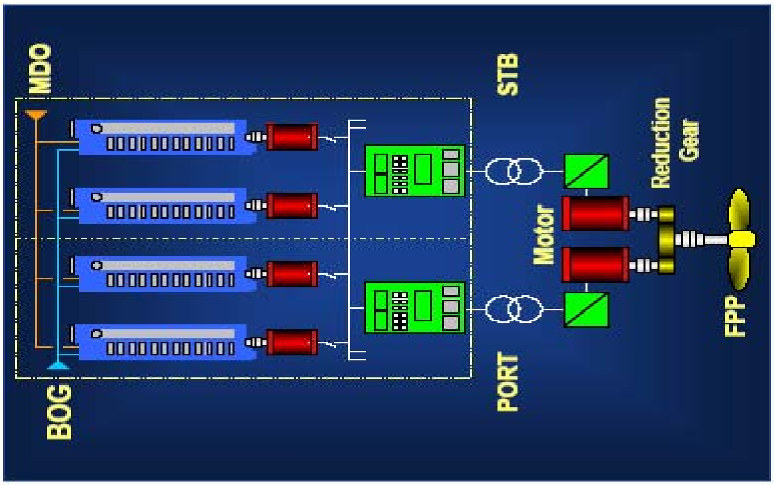


Figure 3. DF Diesel Electric Propulsion System

Comparing with the complex steam system of steam turbine propulsion, the diesel engine is more familiar and easier to crews, but due to many cylinders the maintenance cost and overhaul scheduling might be weak points.

There have been several technical issues in designing related systems onboard as following:

- Methane Number of gas fuel

- Nitrogen content in gas fuel
- Use of heavy fuel oil
- Lube oil selection according to sulphur content of used fuel

Methane Number. Because the temperature of air-gas fuel mixture in combustion chamber is increased typically in excess of 540 °C during the compression cycle, the methane number – resistance against self-ignition – shall be high enough not to cause knocking phenomena by pre-ignition. Minimum methane number of 80 is required at 100% engine load and the less methane number may be allowed at lower load in accordance with manufacturer's recommendation.

The methane number depends on the composition of gas fuel from LNG cargo tanks. Heavy hydrocarbons like butane, ethane, propane, etc. will decrease methane number, because they are easier to be ignited than methane.

In case of natural BOG, the methane number is not a problem for the reason that the evaporating temperature of methane (- 161.5 °C) is much lower than heavier hydrocarbons and the natural boil-off gas temperature (max. - 90 °C) in cargo tank is normally lower than evaporating temperature of heavier hydrocarbons. Please refer to properties of various hydrocarbons as shown on Table 1 and also please be reminded that LNG contains high content of methane.

Table 1. Properties of Hydrocarbons

Name	Composition	Evaporating temp. [˚C]	Ignition temp. [˚C]	Calorific value [kcal/Nm^3]
Methane	CH_4	- 161.5	595	9,520
Ethane	C_2H_6	- 88.6	515	16,820
Propane	C_3H_8	- 42.1	470	24,230
i-Butane	i-C_4H_{10}	- 11.7	462	32,020
n-Butane	n-C_4H_{10}	- 0.5	365	31,780

However, the forced BOG is intentionally evaporated by using steam heater in order to use it as a fuel in prime movers, so there is probability of relatively higher content of heavy hydrocarbon in gas fuel. Therefore the steam heater – forcing vaporizer – setting temperature shall be controlled well lower than - 100 °C not to evaporate heavy hydrocarbons and the mist separator is installed to return liquid gas which may retain heavy hydrocarbons into cargo tank. This is a norm in design of LNG carriers burning forced BOG as a fuel.

Sometimes the operator considers methane number monitoring in gas fuel supply line against engine knocking, but this is unnecessary for the following reasons. Firstly, the consequence is same with or without methane number monitoring. Without the monitoring, the engine knock sensor on each cylinder head detects abnormality in combustion, and then immediately changes over the fuel from gas fuel to diesel oil automatically. Thus the engine will keep running without any interruption. With the monitoring, a crew will change the fuel to diesel oil when alarm occurs. Secondly, there is no other action to be taken to increase methane number onboard. The methane number control facilities – forcing vaporizer and mist separator – have their own monitoring devices for successful functioning.

Generally the operating window between misfiring and knocking becomes narrower as the engine load goes up along with mean effective pressure (Figure 4), thus the accurate electronic control of every single cylinder is necessary for DF engines.

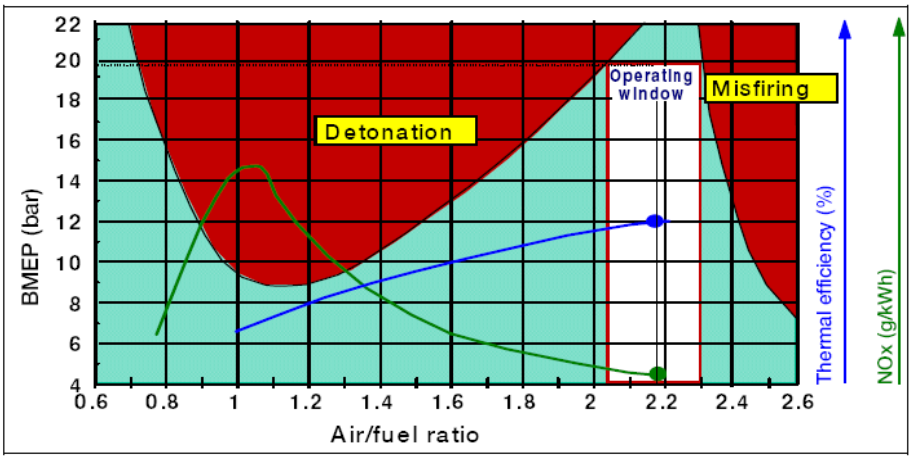


Figure 4. Operation Window of Gas Burning DF Engine [2]

Nitrogen Content. It has something to do with calorific value of gas fuel. The higher nitrogen content is the lower calorific value of gas fuel, hence limit in engine loading due to the lack of energy. The supply amount of gas fuel shall be increased to get necessary energy and it could be attained by longer opening time of gas admission valve or by higher gas fuel supply pressure. Those measures are limited physically and practically on engine. But, considering realistic conditions during LNG carrier operation, the engine has been well designed to cope with this challenge. Maximum nitrogen content of about 20% in gas fuel is acceptable for engine running on 100% load. Approximate 20 ~ 30% of nitrogen is considered as actual maximum in BOG from cargo tanks right after LNG loading and this amount of nitrogen is still acceptable, taking the actual generator load of less than 90% into consideration. The more nitrogen content may be allowed at lower engine load in accordance with manufacturer’s recommendation.

Use of Heavy Fuel Oil. It has been raised by shipping industry to burn cheaper fuel oil than quality diesel oil as a back-up fuel. Originally DF engine was developed to use diesel oil only, because DF engine has been deemed to burn BOG – Natural BOG or Forced BOG – as a main fuel during laden & ballast voyage and normally the diesel oil was only for 1% pilot fuel supply and as a back-up fuel just in case. As the LNG price goes up rapidly, the operators came to call for the cheap heavy fuel oil application rather than use of forced BOG and it was easily realized with minor modifications on engine, because the DF engine is a diesel engine that has traditional jerk pumps and has heavy fuel oil burning capability basically.

The fuel transfer shall be always carried out in the order of “Gas Fuel ↔ Diesel Oil ↔ heated Heavy Fuel Oil” to avoid thermal shock on engine and abnormal burning of gas fuel due to hot carbon deposit in the chamber normally caused by heavy fuel oil combustion. In order to prevent thermal shock, fuel transfer operation to/from heavy fuel oil must be slow and careful.

In principle, operation of engines with any different fuels between them is feasible. But the fuel supply systems and engine control shall be carefully approached to enable such an operation and an independent fuel supply unit per engine would be the best solution.

Lube Oil Selection. Viscosity and TBN (Total Base Number) is considered in lube oil selection for engine operation. Normally the system oil of SAE 40 is used for 4-stroke diesel engines and the TBN differs from sulphur content of used fuel. Higher TBN lube oil is required for high sulphur fuel, in order to neutralize and prevent cylinder liners from scarffing. It is said that optimum TBN is essential for ideal engine operation. But in case of DF engine operation concept with pure gas fuel and high sulphur heavy fuel oil used alternatively, it is not so easy to have both of low TBN and high TBN engine oils together in engine room due to space restriction and time-taking procedure for oil change. The latest laboratory data from manufacturer’s test bed shows that the higher one only can be used without any sign of abnormal condition in combustion chambers. [3]

Dual Fuel Diesel (4-stroke) Mechanical Propulsion

This concept has been investigated to improve the efficiency further by using DF engines for direct propulsion, not as a prime mover for electric power generator. The propulsion efficiency is improved by 8%, as much as the electrical losses in the electric propulsion system. The propulsion system consists of DF engines of variable rpm for propulsion, reduction gearboxes with clutch device, shafts and controllable pitch propeller. Shaft (PTO) generators are provided for electric power generation during maneuvering and conventional auxiliary diesel engines are provided for electric power supply onboard. The PTO generators can be used as a PTI for boosting propulsion and an emergency. (Figure 5)

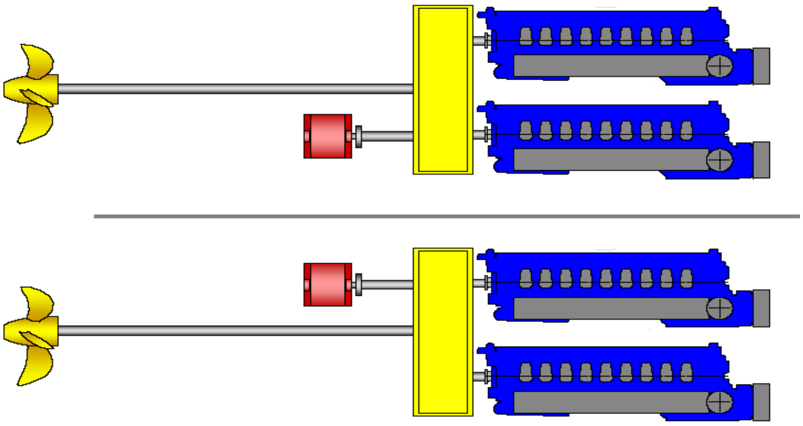


Figure 5. Layout of DF Diesel Mechanical Propulsion

The system is similar to other medium speed diesel propulsion systems, but DF engines burn gas fuel. Gas supply system and safety systems are in line with the DF diesel electric propulsion case and the auxiliaries shall be designed in consideration of redundancy requirements for main propulsion engine.

The gas fuel is compressible and worse in engine loading capability, so liquid fuel might be better to be used during ship's maneuvering in/out of port where engine load is fluctuating and the quick response of propulsion engine is required for safety, as the same is done onboard the steam turbine propulsion LNG carriers. This aspect needs to be investigated more with the manufacturers although the controllable pitch propeller is applied.

Slow Speed Diesel (2-stroke) Propulsion with Re-liquefaction Plant

It is another majority in propulsion systems for LNG carriers nowadays, especially for the LNG carriers of very large – more than 200,000 m^3 – capacity and the long distance trading vessels, which are the factors coming simultaneously in general. It has been a little controversial which one is more efficient system between DF diesel electric propulsion system and this conventional slow diesel application, which have been main trends of LNG carrier propulsion recently. Usually the designers carry out economic evaluation on their own, but the final conclusion is on the operators who evaluate operation cost on the basis of their input data about values of fuel oil, LNG cargo, natural BOG and forced BOG, initial investment, maintenance cost, etc under the given trading & operating profile.

This propulsion system is identical to those used in most of the merchant ships. 2-stroke diesel engine is installed on the tank top in engine room and a shaft line is directly coupled to the engine for propulsion. No doubt this is the most efficient ship propulsion machinery at the moment in marine field. And 4-stroke diesel auxiliary generators are provided for electric power supply.

Sometimes shaft disconnecting devices are provided for each shaft line in case of twin skeg vessels, in order to disconnect the failed engine from propulsion shaft line as soon as possible and keep on voyage. Nevertheless it seems ineffective solution for the following reason: although the disconnecting device is active for separating the propeller from engine, there will not be complete isolation between them due to the tangential inertia of hydraulic fluid in the device during wind-milling of the propeller and the engine – exactly the turning gear – cannot withstand the torque from the passive propeller to hold and enable the repair of engine. Thus a shaft-locking device designed for wind-milling torque comes to be necessary and in other words only the locking device could be enough. Of course, the disconnecting device could be useful so that the engine can be repaired by using turning gear during ships moving ahead. (Figure 6)

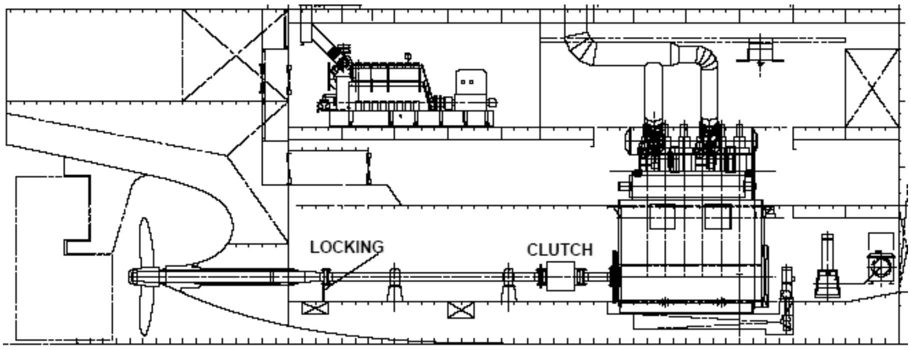


Figure 6. Arrangement of Slow Diesel Propulsion Line

One of the unique features of this type of LNG carriers is that the vessels have Re-liquefaction plant for BOG handling. Because the prime movers do not consume gas fuel at all, the natural BOG from cargo tanks shall be liquefied by the plant and sent back to cargo. The re-liquefaction plant is incorporated with N_2 cycle as a refrigerant and installed in cargo machinery room on the upper deck. A drawback of this system is that power consumption by re-liquefaction plant is considerable so it seems the high efficiency of slow diesel direct propulsion is counterbalanced by much more electric power consumption comparing with other propulsion alternatives.

And the 2-stroke slow diesel engine needs cylinder oil which is consumed during operation and shall be taken into the cost evaluation.

Another concern in the slow diesel engine application to LNG carriers is the vibration aspect – esp. external unbalanced moment – that may influences cargo containment system. Therefore the vibration aspect shall be examined and proper countermeasures must be taken as necessary, e.g. a moment compensator.

Slow Speed Diesel (2-stroke) Propulsion with Gas Injection

Another way of gas fuel burning in diesel engine is to directly inject the gas fuel into combustion chamber rather than admission of gas-air mixture into the chamber. (Figure 7) In order to carry out gas fuel injection into the compressed scavenging air, gas fuel pressure up to about 150 - 250 bar.g is required according to the engine load and this fact calls for high pressure gas compressor of piston type. All the related systems shall be designed in consideration of this feature.

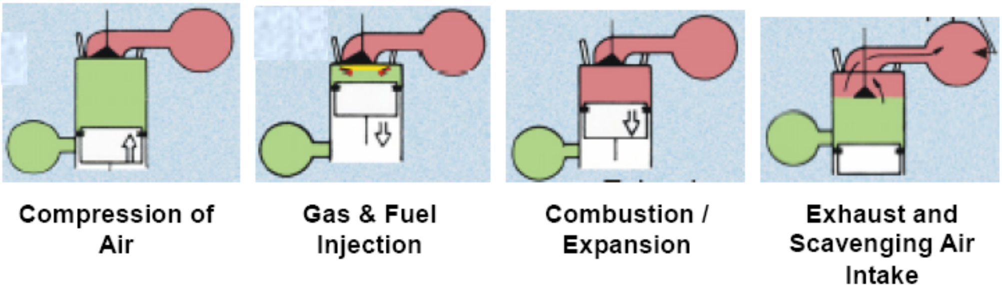


Figure 7. Combustion Process in Gas Injection Diesel Engine

The expected advantages with the gas diesel engine are the high efficiency and the capability to burn the mixture of gas fuel & liquid fuel. Needless to say, the high efficiency of 2-stroke slow diesel propulsion engines has been a major factor that makes it used in merchant ships for a long time and, comparing with the lean-burn DF engines that use gas fuel and liquid fuel alternatively, the gas injection diesel engines can burn gas fuel and heavy fuel oil at the same time with adjustable mixing ratio. The minimum engine load for gas fuel only mode is about 30% for stable combustion, and the pilot fuel oil – heavy fuel oil – of about 8% of input energy is injected.

Because of big amount of high pressure gas supply, the related systems shall be carefully investigated and designed for safety. Although 250 bar of gas fuel is commonly used on land for CNG vehicles, some of the operators are quite reluctant to have the high pressure gas supply piping in engine room under accommodation for safety. However it can be treated properly and technically feasible.

A multi-stage piston type gas compressor is necessary for gas supply to engine, on the contrary of centrifugal type gas compressor that has been used for LNG carriers so far. The high pressure gas compressor technology has been used in LNG terminals. Loading & unloading control, bypass pressure control valves, buffer units and inter-coolers are provided for gas pressure, flow and temperature control for the engine demands. Even the gas pressure of about 5 bar for GCU (Gas Combustion Unit) can be obtained by extracting the gas from 1st stage discharge of the compressor in the event of emergency BOG disposal. A separate lubrication unit and a cooling water unit are needed and installed in safe area, e.g. motor room.

Electric power consumption of high pressure piston type gas compressor is around a half of the Re-liquefaction plant. And due to the vibration feature of reciprocating machinery the vibration aspects shall be considered when designing its foundation with reinforcement and structure in cargo machinery room against possible damage.

The material of gas pipe shall be of stainless steel for its design pressure & temperature. The piping in gas safe area shall be of double-wall type and both of inner and outer pipes shall be made of stainless steel as well. In terms of design temperature, the gas supply temperature is well controlled by BOG heater as required by consumers. But, in the event of pipe leakage, the sudden temperature drop is expected, which is cause by sudden expansion of leaked high pressure gas. In the gas supply system, necessary safety measures required by IGC code must be considered, including the ventilation for annular space of the double-wall piping, gas detection devices, pipe venting/purging/inerting system, silencer at the open end of venting line, control & safety equipments, etc.

On the gas diesel engine itself, the necessary facilities are provided as shown on Figure 8, which is the existing design for 2-stroke diesel engines installed in power plant in Japan.[4] Gas injection & safety equipments are added on to a normal electronic engine and additionally the high pressure sealing oil system is required to prevent the servo oil system from gas ingress. The seal oil is fed to gas injector and burned together with fuel.

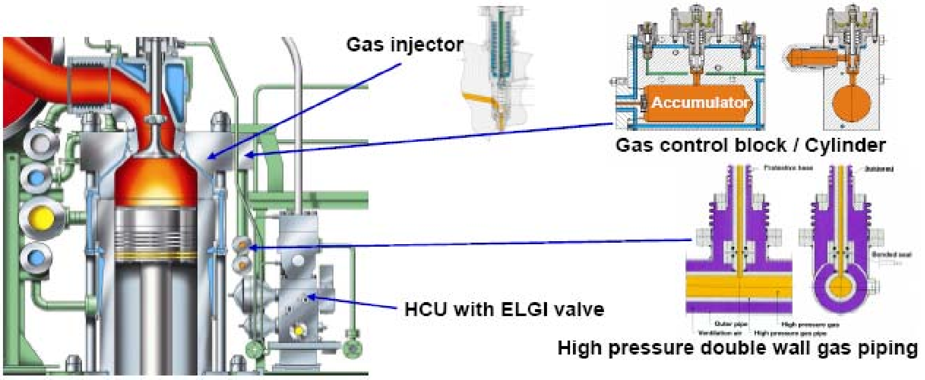


Figure 8. Gas Injection Devices on 2-stroke Diesel Engine (MAN B&W)

As mentioned above, the risk assessment for high pressure gas system in engine room is requisite, especially the fire & explosion analysis – full-bore leakage and jet fire –

seems essential to secure the safety in engine room. Though the probability of gas leakage and fire risk is fairly low, the severity is high. Against any unexpected event, the length of gas pipes in engine room should be kept as short as possible and a quick closing shut-off device in gas supply line just outside the engine room is recommended in order to minimize the leaked gas volume. Furthermore, gas pipe arrangement shall be in accordance with the risk assessment results to keep it away from critical walls like fuel tanks or to protect the pipes from rupture. Engine room ventilation shall be well designed and effective to avoid gas accumulation.

The gas diesel engine technology was already introduced and used in other parts of engine application, but in order to enter into the marine field as a propulsion alternative for LNG carriers more investigation and study in depth to be implemented.

Combined Gas Turbine Electric Propulsion

It was introduced to LNG shipping industry, emphasizing the dual fuel (gas and diesel oil) burning capability, high reliability of aero-derivative gas turbine application and very high power density – compact size. The gas turbine has been used as an electric package for offshore facilities, propulsion machinery for navy ships and electric power generator combined with steam or diesel generators for cruise vessels. In order for the LNG carrier application, basically the self-contained gas burning package concept from offshore field and the combined electric power generation concept from cruise ships were adopted.

The poor specific fuel consumption and use of clean & costly fuel – minimum DMA grade, ISO8217 – made the gas turbine unattractive to operators. However, owing to the latest improvement in efficiency up to about 40% at maximum load, a waste heat recovery system to enhance total plant efficiency and the use of boil-off gas as a main fuel on LNG carriers, now the gas turbine is prepared to be considered as an option.

Because the gas turbines applicable to LNG carriers do not have their line-up of engine types for the customer’s selection upon various power demands like diesel engines, its application is quite limited and not so flexible. Thus, the subject of investigation has been a very large LNG carrier, of which power consumption is well match with the output of the combined gas turbine electric propulsion packages proposed by manufacturers.

One of the Combined Gas turbine Electric & Steam system (COGES) is made up of one big gas turbine with an associated heat recovery steam generator & steam turbo generator and a small gas turbine generator as a standby. Due to the system redundancy in case of the main gas turbine failure and the blackout recovery capability, a conventional diesel engine or a standby duct burner were considered. Another COGES package consists of two identical gas turbine generators associated with the heat recovery steam systems, which provides better redundancy but more expensive solution. The layout of two systems is shown on Figure 9.

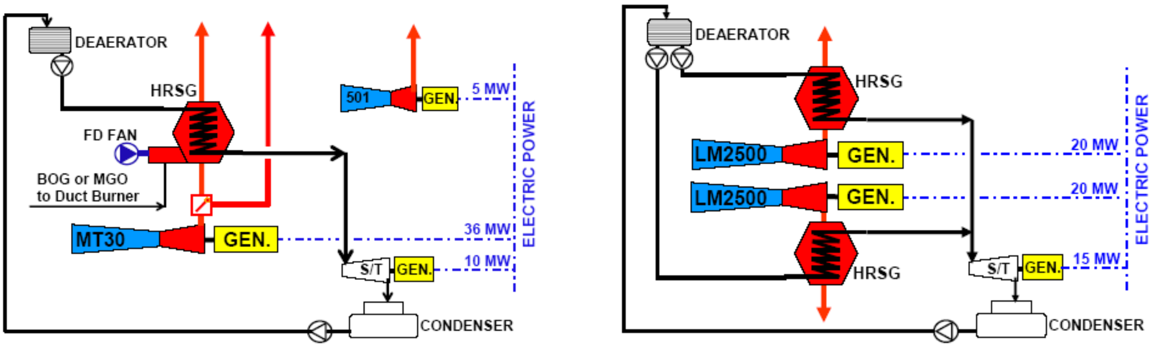


Figure 9. Layout of the Combined Gas turbine Electric and Steam system, proposed by Rolls-Royce and GE respectively

As mentioned above, the reliability of gas turbine itself is as high as 99 % and more. However the auxiliary systems around gas turbine should be evaluated carefully to assure the equivalent or higher reliability and redundancy as the existing LNG carriers have performed over the years.

The gas fuel supply system is similar to that for other gas burning propulsion alternatives, but the gas pressure is up to 40 bar depending on the type of gas turbine and the screw type gas compressors are used for BOG supply to gas turbines. The gas compressor needs its lube oil system for lubrication and sealing during gas compression and an oil separator is provided at delivery line of the compressor. The gas fuel line in machinery space is of the ventilated double-wall pipe and kept as short as possible to reduce the probability of gas leakage into safety area, and it is connected to the gas turbine package directly.

The gas turbine package is delivered with self-contained design, which includes all the necessary instruments within the container, e.g. gas turbine engine, gas valves, local fire extinguisher, gas detecting sensors, ventilation fans & dampers, interlocking device at entrance door, control system, etc. Electric starting motor in the package or a separate hydraulic starting module is provided for gas turbine start-up and a lubrication system is also self-contained. The lubrication system is for bearings and the lube oil is not burned but just a natural consumption. Any cooling water system is not required for the gas turbine package, because it is cooled by air induced by compressor section of turbine. The liquid fuel oil – gas oil – system is provided as a back-up fuel. (Figure 10)

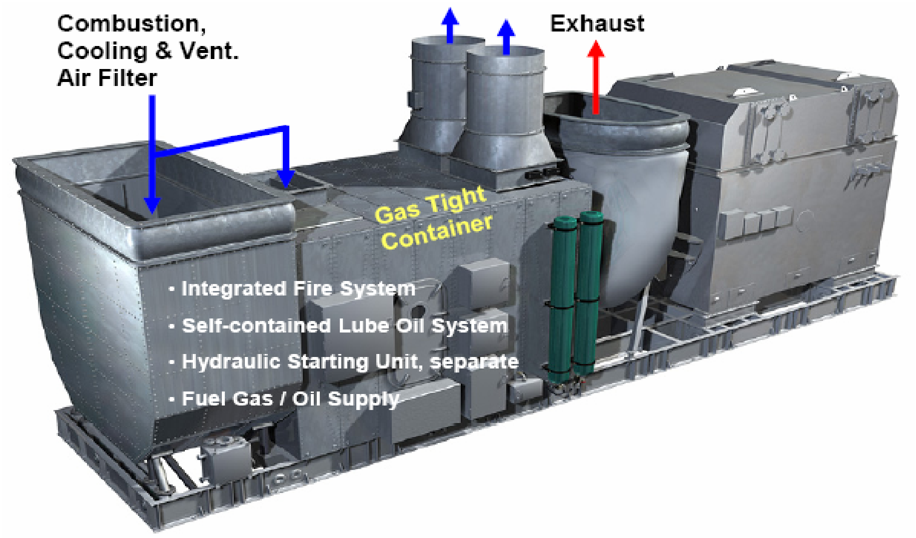


Figure 10. Gas Turbine Electric Package (Rolls-Royce)

The gas turbine can control and burn any ratio of gas fuel and fuel oil, and the governor follows up rotating speed and control the fuel amount injected into combustors. The power turbine is connected to electric generator via reduction gearing.

Hot exhaust gas from turbine is led to the heat recovery steam generator, which makes superheated steam to be supplied to steam turbo generator, so we need the superheated steam system as steam ships but it is a small scale.

Another merit of the gas turbine electric propulsion is its compact size that leads to minimum engine room and bigger cargo capacity. In order to maximize this advantage, the package and related auxiliaries are recommended to be installed at high level in casing above engine room or over the after-mooring deck. This location will also supplement its sensitivity to intake and exhaust losses. However please keep in mind that extension of cargo containment is limited due to hull shape of the ship’s after body and necessary space for accommodation block. The accommodation could be moved to forward, but traffic way between forward accommodation and after engine room must be investigated for safety in trading ships.

When selecting gas turbine for required power, its sensitivity to intake air temperature shall be considered as well.

SAFETY

The safety cannot be compromised. As the LNG carriers’ safety performance has been higher than any other part of marine transportation, it shall be maintained in the other propulsion alternatives as well. In this perspective, risk management is required for gas burning engines with relatively high pressure gas supply. Proper safety measures shall be implemented on the basis of careful risk assessment for novel design.

REDUNDANCY

LNG shipping industry demands high reliability of the propulsion machinery and it can be achieved not only by the reliability of the equipments themselves, but also by installation of redundant system against unexpected failure of single equipment. The propulsion alternatives mentioned in this paper have been developed to secure redundancy concept and should be acceptable to LNG carriers. Very high reliability of gas turbine might interest operators and the dual fuel diesel electric propulsion system will provide better redundancy and flexibility with multi-engine installation.

EMISSIONS

Due to the trend of environmental-friendly design and the regulations that limit emissions worldwide, it becomes an important factor to be considered during ship design. Use of boil-off gas as a fuel is a big advantage to reduce emissions from ships and the additional equipments for flue gas treatment could be considered case by case upon the selected propulsion system and the applicable regulations. Please refer to the comparison of emissions between some of the alternatives as shown on table 2.

Table 2. Emissions from Propulsion Systems [5]

	NOx [g/kWh]	SOx [g/kWh]	CO_2 [g/kWh x 100]	Particulates [g/kWh]
2-stroke Diesel (Slow speed)	17.0	12.9	5.5	0.5
4-stroke Diesel (Medium speed)	12.0	13.6	6.12	0.4
Dual Fuel Diesel Electric	1.3	0.05	5.0	0.05
Steam Turbine	1.0	11.0	9.3	2.5
Gas Turbine	2.5	0	5.9	0.01

ECONOMICS

A propulsion alternative and its technology is realized when the overall economic evaluation proves to be attractive for certain business case, and the result of evaluation is very much dependent on the factors and assumptions used in actual study.

Initial Investment

This is the price of propulsion machinery including the features to be applied for a selected propulsion system. For example, 2-stroke slow speed diesel propulsion shall include a re-liquefaction plant and the different specifications – type of used gas compressors – of gas supply systems needs to be also considered when estimating initial cost.

Fuel and Lube Oil Cost

Firstly, the total system efficiency will be a key factor for fuel cost. Low efficiency of steam ship has been a reason that alternative propulsion systems were considered, thus the diesel engines mainly used in other sector of marine transportation come to be adapted to LNG carriers and the direct driving diesel propulsion is more efficient than the electric propulsion system for the losses in energy transmission like transformers and converter controls.

And total power consumption onboard is another point to be considered. Although the fuel efficiency is better than others, the higher power consumption will compensate gains from efficiency. Re-liquefaction plant and high pressure fuel gas compressors are example of considerable power consumers onboard LNG carriers.

Lube oil consumption is different from the alternatives. Slow speed diesel engine has a separate supply system for cylinder oil which is costly. On the contrary, lube oil consumption for gas turbine is negligible.

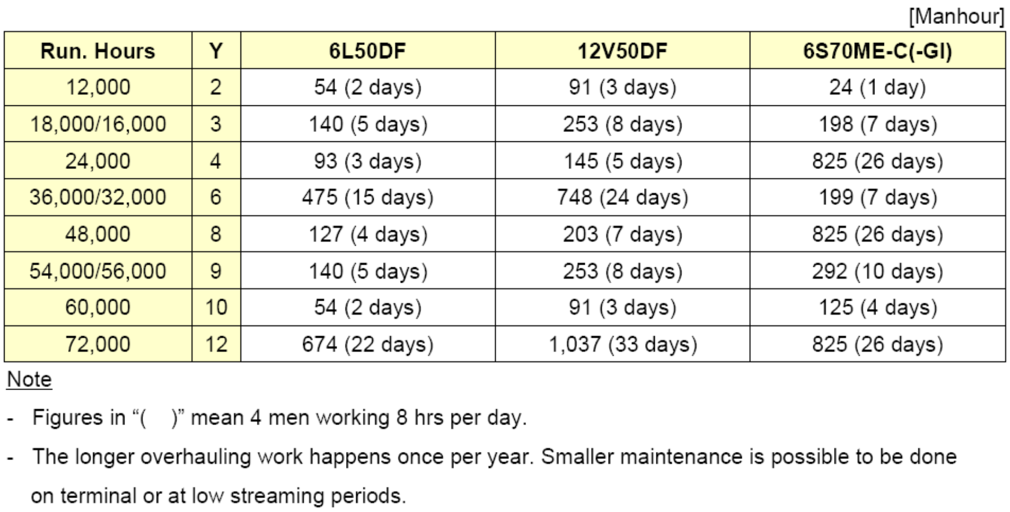
In the fuel cost evaluation and comparison, the conclusion depends on price of fuels, i.e. price of diesel oil, heavy fuel oil, natural BOG and forced BOG used in economic evaluation calculation. And the prices are related to the contents in LNG supply & purchase agreement for a project and they vary according to the obtainable fuel in trading route. The natural BOG could be considered as a free fuel or valuable cargo.

Maintenance Cost

In most cases, the maintenance aspect during ship lifetime is not considered by a shipbuilder, but it is quite important one when evaluating operation cost of the vessels. Availability of a part, time between overhaul and parts cost are to be evaluated for propulsion machinery selection. In case of diesel engines, more cylinder number means more cost for maintenance, and it is said that gas turbine is maintenance free and it is recommended a set of gas turbine engine is reserved as a replacement for complete overhauling work at manufacturer’s shop. Maintenance cost for steam turbine system has been proved to be low enough to be an advantage.

And, according to the TBO(Time between Overhaul) of the prime movers, down-time aspect shall be addressed in operation schedule. An example is given in table 3.

Table 3. Example of Down Time for Periodic Overhauling Work



[Manhour]

Run. Hours	Y	6L50DF	12V50DF	6S70ME-C(-GI)
12,000	2	54 (2 days)	91 (3 days)	24 (1 day)
18,000/16,000	3	140 (5 days)	253 (8 days)	198 (7 days)
24,000	4	93 (3 days)	145 (5 days)	825 (26 days)
36,000/32,000	6	475 (15 days)	748 (24 days)	199 (7 days)
48,000	8	127 (4 days)	203 (7 days)	825 (26 days)
54,000/56,000	9	140 (5 days)	253 (8 days)	292 (10 days)
60,000	10	54 (2 days)	91 (3 days)	125 (4 days)
72,000	12	674 (22 days)	1,037 (33 days)	825 (26 days)

Note

- Figures in “(   )” mean 4 men working 8 hrs per day.
- The longer overhauling work happens once per year. Smaller maintenance is possible to be done on terminal or at low streaming periods.

CREWING

Recent difficulty in shipping industry to hire steam experts is also one of the reasons for new system applications. Diesel engine alternatives are most preferred in this aspect.

CONCLUSION

Technical descriptions and findings in the various propulsion alternatives were explained. Evolution of LNG carriers' propulsion systems may continue until a set of norm in LNG propulsion is justified in the industry and it is certain that some of the suggested alternatives will become major propulsion systems for LNG carriers.

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