Marine Engines and their Impact on the Economy, Technical Efficiency and Environment

Mohan Anantharaman**, Vikram Garaniya**, Faisal Khan**, Barrie Lewarn**

Commercial shipping industry employs a large number of bulk carriers, crude oil tankers, LNG vessels and mega container vessels. Needless to say; these huge vessels would require great magnitude of power to propel them in high seas. More than 85% of these vessels are propelled by large slow speed engines, directly coupled to the propeller. Last decade has observed considerable development in these large slow speed engines in terms of its design, operational safety, maintenance and fuel efficiency. Major engine builders strive to achieve a high level of efficiency on these engines. From the shipowner’s point of view, commercial shipping has become highly competitive and there is a dire need to reduce operation and maintenance costs to survive under the present market condition. Here comes the economical aspect of running ships which is a very crucial commercial factor. The maritime regulators led by IMO (International Maritime Organisation) ensure that the marine environment is clean and free from pollutants, which in this case would be controlling of various pollutants discharged from the exhaust funnels of these large marine diesel engines. This paper provides a comprehensive review of the various stages of development of large marine slow speed engines over the past four decades, and the factors that have influenced these developments. However, in the present day context and the near future need to closely look at the commercial aspect of merchant shipping, and specifically address the three big factors: economy, efficiency and environment protection. The paper also analyses the methods available that can address these three factors and what is in store for the maritime engineering world in the future.

1. Introduction

In the present day commercial shipping world uses Very Large Bulk Carriers ranging up to 365,000 tonnes. Some of the large crude oil Tankers are up to 300,000 tonnes and Container vessels are now capable of carrying 18000 containers, [1]. These large vessels would require mammoth size of engines to propel them. The world’s merchant fleet represents almost 80% of all the vessels ordered each year. Of these, 85% are powered by two-stroke engines and the remainder by four-stroke [2]. Overall, more than 85% of vessels are propelled by large slow speed engines, directly coupled to the propeller.

Two stroke slow speed engines have been utilised for a long time for propulsion of vessels like Bulk carriers, Tankers and Container vessels. The main reason favouring this option is the fact that these engines can be directly coupled to the propeller, negating the need for a very expensive gear box. It is worth noting that the reduction gear box used for steam turbine propulsion on the existing LNG carriers is a highly expensive piece of engineering machinery, which could cost one third of the total cost of an LNG carrier. This expensive engineering component can be done away with; when the large slow speed engine forms the drive for propulsion of large vessels. Moreover, the slow speed is linked to large propeller diameter and thus resulting in higher propeller efficiency. Ideally the engine running between 60 to 100 RPM is suitable for the direct propulsion and large diameter propellers (up to 10 metres) could be utilised. It is imperative that engines should be economical to run. This challenge has been addressed very well by engine manufacturers. The modern marine slow speed engines use residual fuel oil of high viscosity (up to 700 cST, measured at 50 °C). Efficient burning of such residual fuels requires the viscosity to be reduced to 10-12 cST at the inlet to the fuel pump, which in turn requires the fuel to be heated to 150 °C. Present day slow speed engines have long and superlong strokes to make this happen. The stroke to bore ratio for modern superlong-stroke engines may rise up to 4.2 [3]. This figure is more than double than the four decades ago (in the 70’s). The main propulsion engines are getting taller, but fortunately not a hindrance in terms of engine room space on huge vessels. According to MAN Diesel [4], larger the propeller diameter higher the propeller efficiency and lower the optimum propeller speed, providing an optimum ratio of propeller pitch and propeller diameter. These large marine slow speed engines need to comply with the exhaust emissions limit prescribed by the International Maritime Organisation (IMO). It is worthwhile to mentioned that the engine manufacturers have been proactive in this matter and are mostly one step ahead in complying the needs of the IMO by providing various alternative technologies to support clean marine environment [5].
2. Changes in the design features of the large slow speed engines contributing to economy

In the 1970’s the slow speed engine market domain was dominated by Sulzer, MAN and B&W. All these engine manufacturers had a fairly good share of the shipping market, each enjoying its own patent in terms of design. One of the major factors was the design of the gas exchange process and scavenging efficiency of the engine. Sulzer and MAN adopted port scavenging as their patent. In fact, Sulzer employed a loop scavenging system compared to MAN’s cross flow scavenging system. This involved cutting of special ports in the cylinder liner - an expensive proposition, but this was justified by avoiding the necessity of an exhaust valve and its associated heavy gears. On the other hand B&W adopted uniflow scavenging system as their patent, whereby the scavenge air would enter the cylinder through scavenge ports on the downward stroke of the piston and discharge the residual exhaust gases through the centrally operated exhaust valve. The B&W scavenging system provided a better efficiency than the Sulzer or MAN. Their design involved addition of the exhaust valve and the associated gears to drive resulting in a higher power to weight ratio for the engine. The exhaust valve was centrally loaded, which eliminated the complexities of exhaust ports being cut in the cylinder liner. Moreover, there was a major design problem in the temperature differential between the cold scavenge belt and the relatively hot exhaust belt in the cylinder liner, which led to cracks around the port and causing failures of the cylinder liner. Scavenge efficiency for B&W was almost 100 per cent, as compared to 75 to 80% for their counterparts Sulzer and MAN. Most engines utilised the pulse system of scavenging, which involved use of pulse energy from the exhaust gas blown down from a cylinder to drive one or more turbocharger. This demanded the exhaust gas pipe connections from manifold to the turbochargers and also involved tuning of the cylinders to avoid possible interference of exhaust gas flow from various other cylinders. Most of these engines ran on Intermediate Fuel Oil. The Thermal efficiencies of these engines were around 40% and the fuel cost was approximately 17% of the running cost of the vessel. The specific fuel oil consumption of these engines was around 210 g/kWh [6]. The impetus to reduce the fuel consumption was not a top priority owing to availability of good freight rates to ship owners. Engine designers made improvement in the design in terms of operation and maintenance and a marginal reduction in the specific fuel oil consumption, dropping from 210 g/kWh in the 60’s to 202 g/kWh in the late 70’s, which meant a reduction of 8g/kWh over two decades. Figure 1 shows the reduction in Specific Fuel Oil Consumption (SFOC) over the last four decades. This is based on data recorded from Sulzer and MANB&W, during the author’s sailing experience between 1978 to 2000.

![Figure 1: Reduction in the Specific Fuel Oil Consumption for the large slow speed engines over the last 4 decades.](courtesy : Sulzer and MANB&W literature)

The gulf war of mid 1980’s created havoc in the shipping market. The fuel costs rose from 20 to 50 dollars per barrel, pushing the fuel costs to 35% of the operational costs of the vessel. At this time, to provide better efficiency and economy ship’s engine had to run on the reduced speed. Many engines had to run at an economical speed of around 55% MCR for optimum fuel consumption. However, this economical vessel operation led to undesirable carbonaceous deposits in the engine cylinder scavenges spaces and the exhaust boiler, consequently calling for more frequent maintenance. One of the positives which arose from this was the development of long stroke and superlong stroke marine slow speed diesel engines. Engine designers came out with more fuel efficient engines, the specific fuel oil consumption dropped from 202 g/kWh to 171 g/kWh within a span of three years from late 70’s to early 80s as shown in Fig 1. Moreover, the diesel plant efficiency improved from 40% in 1970 to 52% in the mid-80s. The most efficient system of uniflow scavenging was adopted by all major engine builders. This era also saw the taking over of B&W by MAN and subsequently in 1980 MAN B&W was established. Also in 1997 Wartsila merged with Sulzer and then all the engines were referred as Wartsila New Sulzer. Presently the three major players manufacturing large slow speed engines in the maritime industry are Wartsila, MAN Diesels and Turbo & Mitsubishi. All these engines adopted the Uniflow method of scavenging and...
constant pressure system of turbocharging. Furthermore, these engines had the capacity to burn the residual fuel oil with viscosities ranging from 380 to 700 cSt and achieve specific fuel consumption of 171 g/kWh at maximum MCR.\[4\]. Burning of such low grade fuels was possible on doubling of the stroke to bore ratio from 2.0 in 70s to 4.2 in the late 1980, as shown in Figure 2. Also the adoption of the delayed opening timing of the exhaust valve was able to increase the effective expansion ratio, that is, to realize higher thermal efficiency on the engine cycle. Hence these tall superlong stroke slow speed engines are able to burn the residual fuels very efficiently.

Figure 2: The changes to stroke to bore ratios of the large slow speed engines over the last 4 decades.
(courtesy: Sulzer and MANB&W literature)

In all large two stroke diesel engines, besides the fuel the other major consumable is the cylinder lubricating oil. This oil had the BN (Base Number) - the alkalinity content of the oil between 70 to 80. Besides reducing friction between the liner surface and the piston rings, the cylinder oil has an important function of neutralising the acidic content of the products of combustion. The measure of cylinder lubricating oil is expressed as g/kWh and this figure was around 1.5 for most yesteryear engines. With selection of superior quality materials, coupled with electronic control of cylinder oil injection, precise and timely injection of cylinder oil is now achieved in modern diesel engines. This has reduced the cylinder oil consumption by 50-60% resulting great savings in costs at the same time also reduction of particulate emissions\[7\]. Fuel consumption is also related to speed. Hence running high speed container vessel at a lower speed when feasible can have a huge impact on the economics of shipping. The latest design features incorporated on the slow speed marine diesel engines allow engines to be run on ultra slow speed if required, without having an adverse effect on engine components and the associated systems. In combination with other variables of a container vessels’ profit function, this may lead to the profit optimizing speed of a container carrier \[8\]. Present day fuel costs for these large container vessels have nearly touched 70% of the operating costs of the vessel \[9\].

Besides fuel and cylinder lubrication oil costs, the maintenance cost of these large two stroke marine diesel engines was also worth considering. Based on past experience on similar engines and requirements of the classification societies, the time between overhauls of the engine components referred as ‘TBO’ is set by the engine manufacturers. The use of a superior quality material and efficient monitoring system has increased the TBO by many folds over the past 4 decades. To cite an example, the exhaust valve for engines in the 80s would require an overhaul every 1000 hrs. This TBO) has now increased to 15,000 and in some cases even 20,000 hrs of running resulting in considerable savings.

3. Changes in the design features of large slow speed engines contributing to efficiency

Technical efficiency and economic aspects of engine developments go hand in hand. However, few factors are analysed here which has a direct impact on the efficiency of these large slow speed engines. Superlong stroke engines could develop a high compression pressure ranging up to 110 bars and more. The modern engines have a maximum cylinder pressure as high as 150 bars as shown in Figure 3. The high peak pressure is a measure of high thermal and mechanical efficiency of the engine. However this requires the cylinder surface temperatures to be high too. The cylinder liner design called for a thick top section on account of high temperatures and pressures, and a relatively thin lower section to prevent undercooling. This was possible by combination of a superior material and introduction of bore cooling of the cylinder liner top flange and cylinder heads. Bore cooling is generally achieved by drilling of radial holes in the cylinder liner top flange and conveying the cooling water as close to the liner surface as possible. This ultimately maintains efficient cooling and also assists in cylinder lubrication of the upper part of the cylinder liner. The cooling water outlet temperature rose to 80 to 85 °C, in comparison to earlier engines which maintained cylinder outlet temperatures of 66 °C.
Figure 3: The increase in maximum firing pressure (Peak pressure) of the cylinders for the large slow speed engines over the last 4 decades. (courtesy: Sulzer and MANB&W literature).

Figure 4: Higher Pmax with delayed ignition on modern superlong stroke engine.

Design of engine piston and piston rings also contributed towards the engine efficiency. With the availability of modern software like CFD and FEM, the design of the piston crown and the geometry of the combustion chamber could be optimised to achieve very efficient gas flow and combustion. Also the fact that modern slow speed diesel engines which employ residual fuel oil has led to higher compression and peak pressures. This has led to a dip in the compression curve after reaching its maximum compression pressure. This peak pressure can rise to 150 bars at the same time restricting the ignition jump to less than 35 bar, as shown in Figure 4. Also as shown in Figure 5, the mean effective pressure has risen from 12 bar to 19.5 bar in the last four (4) decades.

Figure 5: Increase in mean effective pressure (MEP) of the cylinders for the large slow speed engines over the last 4 decades. (courtesy: Sulzer and MANB&W literature).

Over the years the power requirement of the engines have been enormous, ranging up to 80 MW, especially on container ships sailing at 25 knots. This has been made possible using superior materials and manufacturing methods of engine components. The compatibility of the cylinder liner and piston ring pack, coupled with the correct grade and quantity of cylinder oil goes a long way in prolonging the life of a cylinder liner. The top piston ring which is subjected to very arduous working condition is designed to withstand load under high working temperatures and pressures. The ring is of Controlled Pressure Relief type, where a double lap joint replaces the angle joint of the earlier design [10].

Figure 6: Controlled Pressure Relief (CPR) top ring (courtesy MANB&W publications).

As shown in Figure 6, CPR ring allows almost constant pressure drop across the ring irrespective of the ring and liner wear. Nodular cast iron ring provides sufficient strength and resistance to thermal cracking, while also providing self-lubricating properties. Earlier Sulzer and MAN engines adopted water as a cooling medium for their pistons. Water is a very efficient cooling medium on account for its high specific heat capacity and maximum temperature differential can be achieved between the hot and cold side. However this system needed a separate piston cooling arrangement by way of dedicated pumps, coolers, pipings and conveying mechanism. The conveying mechanism was in the form of a telescopic pipe, which reciprocates in stationary pipes in the crankcase. This also required an effective sealing between the reciprocating telescopic pipe and the stationary pipe (also referred to as stand pipes). Failure of the sealing arrangement could lead to contamination of the crankcase lubricating oil. Presently most engines pistons are oil cooled. The system of lubricating oil for the bearings is used for cooling of the piston crown. This could result a penalty in the cooling efficiency which is offset by efficient design of the crown and in some cases by effective bore cooling of the
crown. However, the elimination of possible contamination of the lubricating oil sump by water is still a major advantage. Also use of one grade of oil for bearing lubrication, piston cooling, camshaft lubrication and exhaust valve operation provided more flexibility. Also lubrication of turbocharger bearings is utilised by the same system oil in some engines. Thus dedicated grade of oil eliminates storage of various grades of lubricants on board the vessel.

The engine crankshaft is the main component which transmits the reciprocating motion of the piston to the rotary motion at the crankshaft. The power requirements have increased in the last three decades, going up to 100 MW. Now days, crankshafts weigh up to 400 Metric tonnes for large engines. The crankshafts are supported by shell type main bearings mounted on the saddle of the bedplate. In earlier engines the shells were in two parts; top and bottom shells. It is noticed that the bottom shell provides the load bearing capacity. Accordingly the modern engines have done away with the top shell, each of which could weigh more than 100 kg. This has resulted in weight savings. Other areas where the reduction in weight achieved is the bedplate foundation, which is mounted on tank tops. The holding down bolts holds the bedplate to the tank top between chocks. In earlier designs these chocks were made of cast iron, which called for specific skills for alignment and installation. This days, these are been replaced by resin chocks with lower weight, superior strength, 100% surface contact, easier and quicker to install.

Choice of the material for the main engine components like cylinder liner, cylinder cover, exhaust valve, piston rings, piston crown and bearings have had a great impact on the maintenance of these large engines. An example is, the exhaust valves on earlier engines required to be overhauled between 500 to 1000 running hours and a complete cylinder overhaul would be performed every 6000 hours or annually. Presently the exhaust valves and cylinder overhauls could be carried out between 15,000 to 30,000 hours, depending upon the monitored condition.

Piston rings perform an important function of sealing the exhaust gas from blowing past the combustion chamber, besides assisting lubrication of the rings. These rings are replaced at a normal overhaul interval. However a periodic assessment needs to be done to look at the rate of wear. This usually happens during a scavenge space interval normally done every 1000 – 1500 running hours. The ring gap could be measured during the inspection and the wear rate can be estimated using the formula given by one leading manufacturer. Also continuous measurement of piston ring wear is possible on certain Wartsila Sulzer engine where such arrangement referred as SIPWA (Sulzer Integrated Piston Wear Analysis). This provides a good scope for planning of spares and estimating the maintenance schedule. A superior design of stuffing box design, as shown in Figure 7, has led to very minimal loss of crankcase oil.

Figure 7: Highly efficient piston rod gland box modern marine diesel engines (courtesy Wartsila)

4. Changes in the design features of large slow speed engines leading to protection of the marine environment

Diesel engines are generally noisy and the engine room personnel are subjected to noise pollution. Many areas of the engines have been looked at to attenuate the engine noise and keep within limits. The IMO has prescribed a maximum noise level of maximum 120 db(A) which is yet to be enforced [11]. The replacement of mechanical loaded exhaust valves by hydraulic operated ones have resulted in a great improvement in terms of efficiency and reliability. These valves operate very smoothly and noiseless compared to the earlier ones. Turbocharger is a great contributor to the efficient operation of the large slow speed engine. Hence the design of turbochargers with superior quality air intake filter and innovative design of compressor has greatly contributed to lower the levels of noise. Modern Turbochargers are designed for a high pressure greater than 5 bar, which makes them very efficient. Also a Variable Turbine Inlet (VTI) feature, as shown in Figure 8, is incorporated where the gas inlet angle could be varied to suit the load conditions, resulting in fuel savings while operating at part loads [12].
Superior design methods and software employed have led to a reduction in emissions too. The IMO Marpol Annex V specifies limits on air pollution [13] by ships. NOx and SOx were the primary emissions to be dealt with when it first came into force in 2005, maximum NOx limit set was 17 g/kWh. In the near future this limit will reduce by 80% of the present maximum value of 3.4 g/kWh, as shown in Figure 9, proposed in special designed NOx emission control areas (NECAs). Similarly, the control of SOx will be achieved by reducing the sulphur content in the fuel and also using exhaust gas cleaning system like scrubbers. The cap on sulphur fuel will be reduced from 4.5% in 2000 to 0.5% globally by 2020. In special areas SECAs, the maximum limit will be capped at 0.05% in 2020, as shown in Figure 10. Coming to Green House Gas (GHG) emissions, IMO was looking into this issue before 2000 but haven’t had much success for long. However, a first step in the right direction was taken in July 2011, when the IMO adopted an Energy Efficiency Design Index (EEDI) regulation which sets minimum efficiency standards for new ships built after 2013 [14].

Engine builders have been proactive in designing of engine components to ensure they meet the IMO requirements of...
NOx and SOx limits. The main areas are: designing of fuel injection equipment, combustion chamber design, selective catalytic reactors (SCR), one arrangement shown in Figure 10 and scrubbers, arrangements as shown in Figures 12 and 13. The design of electronically controlled 2-stroke diesel engine has particularly high efficiency and has naturally results in less fuel consumption and correspondingly fewer exhaust emissions. Furthermore, the engine provides different tuning capabilities to achieve the optimal fuel consumption at different load profiles, such as part and low load [5]. One observation with regards to Modern Electronic controlled engines is the training of personnel to run these engines. Inadequate training has led to major accidents on these modern engines. A report by the Marine accident Investigation Bureau, stated that the ship’s engineers on a modern electronically controlled ship did not have a sufficient good knowledge of the main engine control system or specific system engineering training to successfully diagnose faults [16].

5. Conclusion

It is clear that the large slow speed diesel engines will continue to dominate the propulsion of giant size vessels. With grueling bunker fuel costs one needs to be judicious in running these vessels economically, efficiently and simultaneously protecting the marine environment. Engine manufacturers are continuously working on research and development, but further improvement in specific fuel oil consumption does not appear to be on cards in the very near future. However, the slow steaming of vessels especially in mega container vessels is seen as a big way in reducing fuel consumption. Electronically controlled engines offer a great precision in terms of fuel injection and exhaust emission control. However, there is a dire need to provide adequate training to the personnel who will be the in-charge of these complex control systems, and also provide the necessary knowledge to troubleshoot various problems. Development of turbochargers will play a major role in complimenting and improving the overall efficiency of the slow speed marine diesel engine. Complying with the future IMO limits of NOx and SOx can be seen as a great challenge. The introduction of the Energy Efficiency Design Index (EEDI) and ship energy efficiency management plan (SEEMP) is a good step in dealing with GHG emission.

References

Authors

Mohan Anantharaman, born in 1953, completed a Bachelor’s degree in Mechanical Engineering in 1975, from the University of Bombay, India. He obtained First Class certificate of Competency (Motor) in 1983 from Bombay, India, Master of Research (Marine Technology) in 2001 from the University of Newcastle upon Tyne (UK). He is a Senior Lecturer and Course Coordinator (Marine Engineering) at the Australian Maritime Engineering, University of Tasmania. His area of interest are latest development on Marine Engines, Condition based Maintenance for ship’s system and Port State Control and Ship Management. Mohan Anantharaman is a Fellow of the Institute of Marine Engineering, Science and Technology and Member of the Royal Institute of Naval Architects. He is also a Chattered Engineer (UK).

Dr Vikram Garaniya, born in 1982 in India completed a bachelor degree in Chemical Engineering in India. He obtained a master of engineering science degree from the UNSW in Sydney in 2005. From 2005-2009 Dr Garaniya completed a Doctor of Philosophy at the Australian Maritime College (AMC) - an institute of the University of Tasmania. Dr Garaniya is currently the course coordinator for BE (Marine and Offshore Engineering) at the AMC. Chemical and Thermal engineering related areas, such as combustion science, computational fluid dynamics (CFD) modelling of engines, mathematical modelling, evaporation, pyrolysis, thermal cracking, coke formation, soot burnout, heavy fuel oil, continuous thermodynamics are his most areas of interest. Dr Garaniya is member of Engineers Australia.

Dr. Faisal Khan is a professor and the Yale Research Chair of Process Safety and Risk Engineering. In 2000, he founded and leading the Safety and Risk Engineering Group (SREG) at Memorial University of Newfoundland which currently has 40+ team members including academics, research engineers, and graduate students conducting research on a wide range of theoretical and applied research activities mainly related to process safety and asset integrity management. He is involved in research, and consulting projects related to safety and risk engineering, and process/plant integrity studies. His areas of research interest include: safety and risk engineering, inherent safety, risk management, and risk-based integrity assessment and management. He is actively involved with multinational oil and gas industries on the issue of safety and asset integrity. He has successfully completed over 15 major industry funded research and development projects. He has spent few months as risk and integrity expert with Lloyd’s Register a risk management organization. He also served as Safety and Risk Advisor to Government of Newfoundland, Canada, Lloyd’s Register EMEA, SBM, ABS, Modco, Qatargas and others. From 2008-10, he visited Qatar University and Qatargas LNG Company as Process Safety and Risk Management Chair. In 2013-14 he served as Associate Dean (globalization) at Australian Maritime College, Australia, where he led the development of the offshore and risk engineering group and initiative of global engagements. He has authored over 200 research articles in peer reviewed journals and conferences on safety, risk and reliability engineering. He has authored five books on the subject area. He is the editor to the Journal of Process Safety and Environmental Protection, and Journal of Process System Engineering. He regularly offers training program/workshop on safety and risk engineering in different places, including St John’s, Chennai, Dubai, Beijing, Aberdeen, Doha and Kuala Lumpur.

Prof. Barrie Lewarn completed his BSc (Nautical Studies with Commendation) Plymouth Polytechnic 1973; Grad Dip Ed (Technical Teaching with Distinction) Sydney Teachers College 1979; PhD (Port Waterfront Redevelopment Strategies) University of Wales 1998; Master (Foreign-going) UK 1970; Fellow of the Chartered Institute of Logistics and Transport (FCILT). Prof. Barrie Lewarn is the Research Director, Maritime Transport Policy Centre, Australian Maritime College, University of Tasmania.