Emissions Reduction for MaK Engines

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Introduction

Medium Speed engines are the main power sources for ship propulsion and electrical power generation applications in the 2 MW to 12 MW range. As the emission levels for ocean-going ships have been announced by the International Marine Organization (IMO) for 2016, Caterpillar Motoren is on the way to develop the right solution for their medium speed engines legislation targets.

Emisions Background

Emission level regulations for pollutants like NO_x, SO_x, CO_2, Particulate Matter (PM) and soot are currently under consideration by different governments. The emission levels of some of these species are more efficiently controlled by sources other than the engine manufacturer. For example, PM and Sulphur related emissions (SO_x) are primarily in the hands of the oil companies (through fuel refinement) or after-treatment manufacturers. Regarding CO_2 emissions, the reduction potential of the engine manufacturer is relatively small (in the range of 1 to 2 %). In this case, the operator of the ship has a significant influence. For example, a reduction of the ship speed by 10 % can reduce the CO_2 emission by up to 40 %. There is potential for NO_x reduction through engine tuning and more sophisticated solutions, but also it can be achieved with a SCR catalyst. The emission of black smoke, however, can be significantly reduced by engine tuning and is therefore more effectively impacted by the engine manufacturer. To summarize, the development activities of the engine manufacturer can focus on NO_x and soot emission reduction. Reduction of CO_2, which is equivalent to fuel consumption efficiency, is traditionally the focus of the operator and the ship development department.

While significant progress in reducing emissions has been achieved in the past, it is foreseeable that in the future the emission requirements will become more and more stringent. Besides the activities by legislative authorities, there are initiatives from the classification societies and port authorities to reduce NO_x emissions. The societies now offer labels for cleaner ships and the harbor authorities offer lower port fees to compliant ships.

The IMO Organization has limited the NO_x emission of Marine Diesel engines by MARPOL Annex VI Tier I came into effect in 2000. Tier II will follow in 2011 and Tier III will be in place in 2016. The engine manufacturers must ensure that their engines comply with all upcoming regulations. The emissions strategy of Caterpillar Motoren focuses on using ‘inside the engine’ technology as long as possible to meet emission requirements through IMO II as it is the most efficient path for the ship owner and the operator. For IMO III requirements, the addition of ‘outside the engine’ technologies such as after-treatment may be required, but it may be also of interest for the ship-owner to have an “on the engine technology” to save space on board of the vessel.

Engine Development for IMO II Emission Limits (2011)

Like for Tier I emission limits in the year 2000, Caterpillar Motoren choose again the path of ‘inside the engine’ technologies to meet IMO II requirements. Water injection, exhaust gas recirculation and SCR catalyst were not considered to be desirable technologies.
The key challenge for achieving low NO_x emissions is how to increase the compression ratio of the engine without creating a flat combustion chamber or a rugged surface (valve pockets) on the piston crown. Flat chambers have a challenge to burn the injected fuel in a short time because the oxygen / fuel mixture is not optimal (resulting in higher BSFC). Twenty years ago, a compression ratio range of 11 to 12 was in use with efficiency optimized standard engines. Ten years ago, the IMO legislation came into effect and the compression ratios increased to a range of 14 to 15. For the next engine generation, which has to fulfill IMO II emission limits, a compression ratio of 17 will be needed. An ap-

proach combining compression ratio increase with Miller cycle allows the reduction of NO_x emission without sacrificing the efficiency of the engine.
With this technique, the peak cylinder pressure can be kept in the range of the existing engines while operating at the same power level. If all options and variables are optimized, a 30 % reduction in NO_x emission should be possible. Hence, the LEE engine concept is the right technology to fulfill the NO_x emission limits of IMO II. But first, two major challenges with the 'fixed element' LEE engine concept have to be addressed:

- Due to the strong Miller effect, the load pick-up from idling would be poor.
- The soot emission at part load would be higher than today and clearly visible.

As a solution, a 'variable element' LEE engine concept was developed by Caterpillar Motoren. The so-called FCT (Flex Cam Technology) system enables variation of the fuel and air system performance during part load operation. With FCT:

- The injection system can advance the start of injection and increase the injection pressure by using a part of the cam profile with higher lifting speed. The combustion process will then be more intensive and the soot emission is reduced by 50 %.
- The inlet valve lift events can be shifted to switch off the Miller cycle. In total, a 25 % soot reduction is possible with this technique.

In 2002, the first M 43 test engine was converted to a LEE type. Due to the long stroke design of that engine, a compression ratio of 17 could be realized without compromises in the combustion chamber design. In combination with a strong Miller cycle, the NO_x emission cycle value could be lowered to 8 g/kWh in test operation. This was a NO_x reduction of 35 %. In the beginning of 2008 a parent engine 9 M 43 LEE passed the emission test. With a low NO_x trim, a 8,3 g/kWh cycle value for E2 was stated by Germanischer Lloyd with a maximum soot emission of 0,5 FSN at 10 % load. With a low soot trim according to DNV "Clean Design" requirements, a NO_x value of 9,9 g/kWh and a soot value of 0,4 FSN were achieved. Also, for transient operation, the FCT system is very beneficial. Load pick-up tests on a 6 M 32 showed that the variable injection system and the ability to switch off the Miller cycle reduced the soot emission by 70 %. Optimal engine operation is achieved by using the turbocharger speed signal to control the FCT system over the various engine operating conditions. After intensive in-house testing, the first customer engines are planned as pilot applications for IMO II emission requirements. A 7 M 43 inline engine was retrofitted in October 2007 and has collected more than 8000 hours since. Several VM 43 engines with this technology have been delivered for large cruise ships in 2008.
In this respect the CCR (Caterpillar Common Rail) System will also become more and more a major player in the technology portfolio. By allowing precise control of rail pressure, injection timing and multi-shot injections, soot and NO_X emissions as well as BSFC can be improved. In particular the load pick up and the transient behavior can be substantially improved. The first field engine, a 9 M 32 C CR, has successfully cumulated 5000 hours in the field now. A second one is planned in the near future.

Further Investigations for IMO III Emission Limits (2016)

On the open ocean, the emission limit values for IMO III will be the same as for IMO II. The real challenge of IMO III regulations is to achieve extremely low NO_X values in ECAS (i. e. in coastal waters and in harbors). The target value will be in the range of 2 g/kWh. This will not be achievable with only 'inside the engine' technology. In addition, the emission of SO_x is also limited in ECAS. Hence, a suitable concept for the future needs to focus on reduction of both pollutants. Some technologies to consider are after-treatment, EGR, Scrubber or Water Injection. This chapter will illustrate potential strategies and will try to identify the best choice for the owner and the operator of the engine.

IMO III Scenario # 1 – "EGR"

Assuming that ECAS und SECAS will become the same in the future, a ship has to operate with expensive clean fuel or use an exhaust gas scrubber in coastal waterways. Needed is a scrubber system with an extremely high efficiency in removing the sulphur and PM. Currently, there are only a handful of scrubbers in service worldwide. With this scenario, there is also the opportunity to operate a large, medium speed engine with EGR to reduce $NO_{x.}$ However, it is not known whether EGR can reduce the NO_X level of 6 g/kWh - assuming that this is achievable with 'inside the engine' technology - down to 2 g/kWh without thermal overload of the engine. With this concept it is possible to run the engine with cheap HFO fuel event in ECAS. If the scrubber is not able to clean the exhaust gas in the required quality, the pass to operate the engine with more expense clean fuel like high speed engines can be followed to achieve the low NO_X emission values.

IMO III Scenario # 2 – "Water"

This scenario is also based on the assumed limit of 'inside the engine technology'. Instead of EGR, water is used as a NO_X reduction agent. Because a 60 to 70 % reduction in NO_x is required, a large amount of water is needed. This leads to the air saturation technology, which is known under the name of HAM. The demonstrated capability of such a system however falls short off achieving 2 g/kWh NO_X. Significant further improvements of water systems would be needed. It seems that water concept also could run with HFO, but the SO_X limitation still forces operation with low sulphur fuel or to add a scrubber.

IMO III Scenario # 3 – "SCR"

The most simple way to reduce NO_x is of course to add a SCR catalyst to the engine. Because of the high efficiency in NO_x reduction, this technology can be used with the standard engine emission base. The economical feasibility has to be determined using the assumed urea / fuel price ratio of 2016 and later. This ratio has become more and more attractive for the use of catalysts. A situation has now been reached where a special engine trim with optimum efficiency, higher NO_X and SCR could be the best solution with respect to operating cost of the ship power plant.
High sulphur fuel limits the lifetime of a SCR catalyst. The first simple idea is to put a scrubber in front of the SCR. But this cools down the inlet gas temperature to the SCR too much causing fouling and reduces the efficiency of the SCR dramatically. Therefore, the operator has to run with expensive, low sulphur fuel to avoid operational problems. The increased fuel cost jeopardizes the commercial attractiveness of this scenario.

IMO III Scenario # 4 – "Gas"

It is well known, that Gas engines operate at much lower NO_X levels as Diesel engines. The average natural gases run almost sulphur free. Emission wise this concept seems to fit perfectly. But a lot of issues have to be taken in consideration before the operators want to have such an engine as power source on board of a ship:

- Infrastructure of the engine room (space for gas storage)
- Safety issues during operation
- Availability of gas worldwide
- Complexity of the power plant
- Lower efficiency in Diesel mode with a Dual Fuel engine
- Lack of transient engine performance (Start and load pick up)

The Dual Fuel concept is already approved for LNG Gas tankers and also may be a good solution for multi engine propulsion systems like cruise ships and ferries. For a single engine system with a Dual Fuel engine running with liquid fuel on the open ocean as used in standard cargo ships will have a significant loss in efficiency. The reason is the low compression ration, which is essential for a Gas engine to avoid knocking. The lack in firing pressure leads to an efficiency loss in the range of nearly 5 %.

IMO III Scenario # 5 – "2-Stage Turbo-Charging"

In recent years, a significant increase in the price of mineral oil products has led to a dramatic increase in the operation cost for ships. For a standard container ship approximately 90 % of the operating cost is fuel cost. While small improvements in fuel efficiency provide only a marginal reduction in green house gas emissions, they lead to big annual savings for the operator. Financial calculations for a mid-size container feeder were conducted to determine cost sensitivities. The case of a 5 MW plant running 6000 hours per year with HFO fuel clearly shows that fuel cost is the major cost driver. If a change of fuel type towards MDO is needed in the future for emission reasons, a dramatic cost impact is obvious.
The lower initial cost for a MDO engine plant is negated after half a year by the higher fuel cost of MDO. After 5 years, nearly 4 Mio Euro higher operating costs are accumulated with MDO. This illustrates that HFO will be the favorite fuel on the open ocean in the future. Also, the recent dramatic increase in fuel cost will put an enormous pressure on the engine manufacturers to improve the efficiency of the engines.

Considering the fading crude oil reserves and increasing worldwide demands (China and India) the efficiency of engines will become more and more important. Another important question for the R&D department is: How much is it worth to improve efficiency? Under the assumption that this action increases the engine price by 10 %, calculations with 1 %, 2 % and 3 % improvements in efficiency show that the return of investment is relatively quick. After a 3 year time period, the higher investment is compensated by a 2 % better fuel consumption. (This example is based on a HFO price of 500 Euro per ton.)

A concept, which takes this into consideration, is based on the Scenario # 3 described earlier. The difference is to implement the LEE concept (instead of the Standard Engine concept) and combine a strong Miller Cycle with a higher compression ratio. Of course, single stage turbo-charging is no longer sufficient. A 2-stage turbo charging system with inter-cooling is required. The potential of this concept is shown in. The development steps from a baseline IMO I engine (stage 1) to IMO II engine (stage 3) towards Concept # 4 engine (stage 4) illustrate the possible BSFC improvements.
The challenge of this concept is that the engine has to be very flexible. A variable air system (like FCT) which allows switching off the Miller Cycle, a variable 2-stage charging system with control valve to improve part load performance and a flexible fuel system such as Caterpillar Common Rail (CCR) are needed for this concept.

On the open ocean, IMO II regulations in the range of 10 g/kWh NO_X have to be fulfilled. In coastal waters a different trim of the engine is needed. To gain the full potential of the concept, the engine has to be trimmed to 16 g/kWh on the fly, the SCR catalyst has to be switched on and the fuel has to be changed to low sulphur fuel when the ship enters ECAS. BSFC improvements in the range of 3 to 4 % in comparison to Scenario # 3 are possible.

When it comes to operational cost, the main issue is the fuel type which has to be used in ECAS. Low sulphur fuel is very costly and may negate any financial benefit from improvement in engine fuel efficiency. In this respect, Concept # 1 may be the right solution because the ship can run with lower cost HFO. But no one can answer the question today as to whether or not a scrubber can clean the exhaust gas sufficiently for use with EGR. If that should not be possible, then Concept # 5 will have the next lowest operational cost but it requires a highly sophisticated engine technology.

Conclusion

For state-of-the-art Medium Speed engines, the long stroke concept is currently the best fit to meet IMO II requirements. For both a power increase and an emission reduction, the combination of a high compression ratio with Miller cycle is the best choice. In addition, soot emission demands require engines with flexible fuel and air systems.

EGR and 2-stage turbo charging seem to be the way for inside the engine technology. SCR clearly is an option but significantly consumes space on board. Gas/dual fuel interest is strongly increasing.

The suitable path for IMO III is not clearly visible today.

Klaus Wirth studied mechanical engineering at the universities in Braunschweig and Kiel. He started as a design engineer at MaK in 1982 and worked on several jobs since, mainly in engineering such as design engineer, test engineer, new product introduction manager, continuous product improvement manager and platform manager but also marketing and production for a certain time. Now he is serving as the engineering manager for Kiel products. He gained international experience as the liaison engineer in the United States of America / Indiana / Lafayette when Caterpillar had acquired MaK in 1997.