DESIGN OF SHIP ENGINES FOR REDUCED EMISSIONS OF OXIDES OF NITROGEN

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Abstract

Oxides of nitrogen (NOx) emissions from ship engines are significant on a global level. NOx emissions participate in the formation of photochemical smog and acid rain. Marine sourced emissions have significant impact on air quality on land. The challenge is to control NOx emissions without increasing fuel consumption and smoke. Most engine manufacturers can meet the current IMO limits by engine tuning measures. These include increased compression pressure in conjunction with retarded injection timing, increased injection intensity, optimised fuel spray patterns, optimised combustion chamber shape, reduced charge air temperature, electronically controlled common rail fuel injection and variable valve timing. Reductions below IMO limits require measures such as water injection or after-treatment. Such measures are generally only in use in high priority coastal waterways.

1. INTERNATIONAL PERSPECTIVE

Worldwide, ship oxides of nitrogen (NOx) emissions have been estimated at about 10 million tonnes per annum, equivalent to about 50% of the land based NOx emissions from the USA or 14% of total global NOx emissions from fossil fuels.[1] The world's fleet includes approximately 55% slow speed diesel, 40% medium speed diesel and 5% other engine types. Slow speed diesels tend to produce higher NOx emissions than medium speed diesels. Ship engines are very fuel efficient, but have a relatively high output of NOx emissions. They use very poor quality fuel for economic reasons.

NOx emissions participate in the formation of photochemical smog and acid rain They contribute to greenhouse warming and are toxic in their own right. Marine sourced emissions can have significant impact on air quality on land, especially near busy coastal waterways. NOx emissions have residence times of 1 to 3 days, which may mean they are transported 400 to 1200km.[1]

The International Maritime Organisation (IMO) has adopted a convention for control of air pollution from ships (Marpol Annex VI). When the convention is adopted, NOx controls will apply to engines installed in new ships constructed from 1/1/2000 and engines in existing ships undergoing a major conversion. The engine has to meet certain NOx limits when operating over a test cycle. The engine has to be certified according to a NOx Technical Code.

Marpol Annex VI aims to limit NOx emissions to about 17g/kWh for slow speed marine diesels and less for medium speed diesels, depending on rated speed. It is likely that further restrictions will occur. Sweden has established its own system of differentiated harbour fees. This requires that vessels with higher NOx emissions pay higher fees.[2] Norway and Denmark also apply an eco tax to shipping, based on emissions. The Clean Design notation of DNV calls for NOx emissions 40% below Marpol. The 1997 Marpol Conference Resolution 3 calls for 5 yearly reviews of the NOx limits. Resolution 8 calls for consideration of CO_2 emissions. This is related to NOx control as there can be a fuel consumption penalty associated with NOx reduction strategies. A US EPA rule is due in April 2002 and final standards are scheduled for 2003.[3]

It is estimated that with a 1.5% yearly fleet replacement rate, NOx controls which reduce emissions by 30% to 50%, would reduce global ship NOx emissions by less than 1% per annum. [1]

Most engine manufacturers are now producing standard engines which comply with the Marpol NOx limits, with a slight increase in fuel consumption (around 2%). Interim certificates of compliance with Annex VI are being issued. Engine manufacturers are now aiming for much greater NOx reductions than required by Marpol Annex VI, along with reduced fuel consumption and smoke, in anticipation of further restrictions and market demand.

Primary control measures, which affect the in-cylinder formation of NOx, are preferred by engine users. Secondary control measures such as Selective Catalytic Reactors (SCR) are expensive and require space and a reducing agent.

Many reduction measures increase fuel consumption, which is a disadvantage. The challenge is to control NOx emissions without increasing fuel consumption and smoke. Most engine manufacturers can meet the current IMO limits by engine tuning measures.

2. MECHANISM OF NOx FORMATION IN DIESEL ENGINES

Nitrogen is normally an inert gas. At the temperatures of the burning fuel spray, (about 2000K to 2500K) the nitrogen in the air is no longer inactive and some will combine with oxygen to form oxides of nitrogen. Initially mostly nitric oxide (NO) is formed. Later, during the expansion process and in the exhaust, some of this NO will convert to nitrogen dioxide (NO_2) and nitrous oxide (N_2O), typically 5% and 1% , respectively, of the original NO. The mix of oxides of nitrogen is called NOx.

The reactions involving oxides of nitrogen are slower than the reactions involved in oxidation of the fuel, so oxides of nitrogen formation mainly takes place in the high temperature burnt gas which arises from the combustion process. The rate of reaction is controlled by the concentration of oxygen and the temperature. The temperature dependence is exponential. NO formation rate can increase by a factor of 10 for every 100K temperature rise.

Thus, NOx formation depends on the temperature of the burnt gas, the residence time of the burnt gas at high temperature and the amount of oxygen present. The burnt gas arising from the part of the combustion which occurs before peak pressure is compressed due to the rising pressure in the combustion chamber. This means it remains at high temperatures for a long time compared with the burnt gas from the later stages of combustion. This allows more time for NO to form. Slow speed engines produce more NOx than medium speed engines because the combustion process spans a longer time period so there is more time available for NO formation.

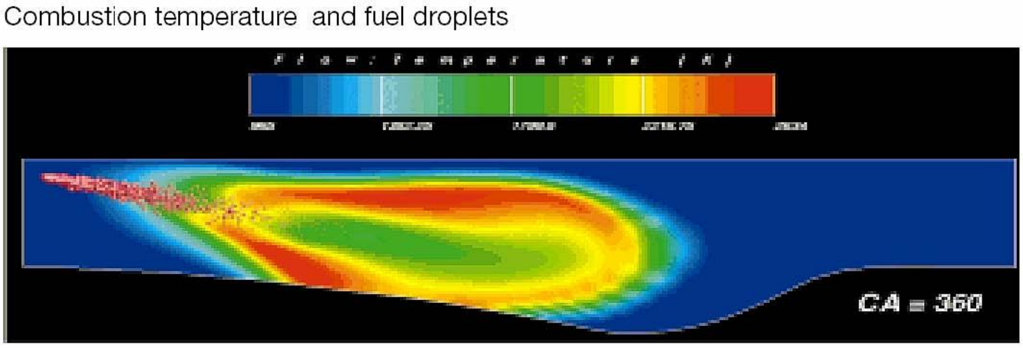
2.1 Three Phases of Combustion

Combustion in diesel engines can be divided into 3 different phases. The first phase involves evaporation and mixing of the early injected fuel with the air in the cylinder. During this phase, certain pre-reactions occur prior to actual combustion. During this delay period, fuel air mixture is forming continuously. As soon as the actual combustion starts, the fuel air mixture formed during the delay period ignites and burns rapidly, as it is already mixed and ready to burn. This is the second phase of combustion or premixed phase, which typically produces the highest pressure rise rates. After this pre-mix of fuel and air formed during the delay period is consumed, the combustion rate becomes controlled by the rate of evaporation and mixing of the fuel and air. This is the third phase or diffusion controlled phase.

The length of the delay period is a function of the fuel ignition characteristics and the temperature in the combustion chamber. Reducing the length of the delay period reduces the amount of fuel consumed in the second phase. The length of the delay period is basically independent of engine speed, so the proportion of total fuel injected during the delay period is greater in medium speed diesels than in slow speed diesels. The second phase of combustion involves high temperatures and pressures because the combustion rate is high. Also, because it happens early in the combustion process the burnt gas from this phase will remain at high temperatures for a relatively long time due to further compression by the rising cylinder pressure. This phase is likely to produce high NOx concentrations and is more important in medium speed engines.

2.2 Spray combustion

Figure 1 shows combustion temperatures and NOx concentrations for a medium speed engine at one instant, calculated using Computational Reactive Fluid Dynamics (CRFD). Combustion occurs in a region where the fuel has vaporised and mixed with air over a range of fuel to air mixture strength, around chemically correct. The rate of combustion is mostly controlled by the rate at which fuel vapour can evaporate and mix with air, which is a function of spray characteristics, air motion and injection rate. Slow speed engines tend to use a high degree of tangential air motion (swirl) to promote fuel/air mixing. Combustion chamber shape is also important. Slow speed engines tend to have higher stroke to bore ratio than medium speed engines, so the combustion space is of a more favourable shape.


Combustion temperature and fuel droplets

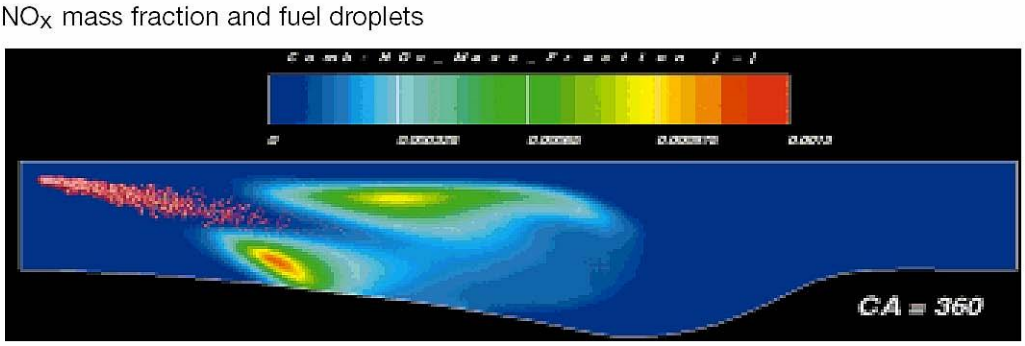

NOx mass fraction and fuel droplets

Figure 1 CRFD simulation of temperature and NOx in a burning fuel spray for a Wartsila medium speed engine [4]

Orientation and size of the fuel nozzle holes define the depth of penetration, included angle and location of the fuel spray. These affect the evaporation process, turbulence, mixing and combustion.[5] Figure 2 shows schematic spray patterns for medium speed and slow speed engines. Wartsila report that there is more freedom in changing the nozzle parameters in 2 stroke (slow speed) engines than in 4 stroke (medium speed) engines, mainly because the medium speed engine generally has a central injector and a flat combustion chamber (low stroke to bore ratio). This requires an equal distribution of the holes. The slow speed engine uses side injection and the interference of the sprays coming from the two or three nozzles can be used to influence the combustion process.[5]

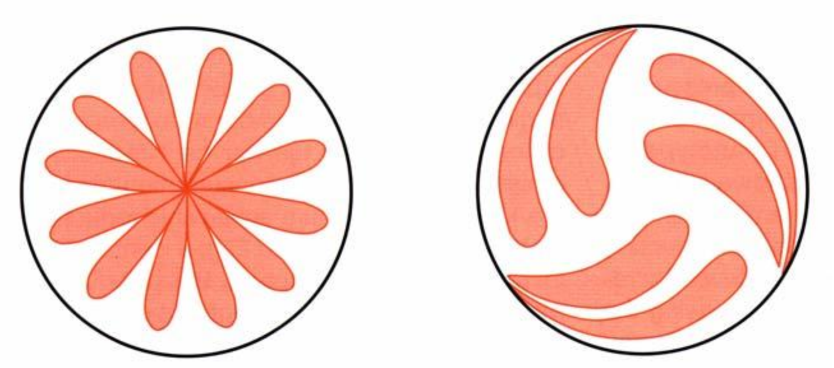


Figure 2 Schematic spray patterns for a medium speed engine (left) and a slow speed engine (right) [5]

2.3 Smoke and NOx

Smoke (soot) arises primarily from within the fuel spray during combustion. Fuel heated in the absence of oxygen partially reconstitutes into particles with a high carbon content. It is the burning of these particles that leads to the high rate of visible and thermal radiation from diesel combustion. It is generally considered that there are two main processes determining soot levels. The first is the rate of formation of particles in the flame and the second is the rate of oxidation of the particles.

Good atomisation and air entrainment reduce soot. If combustion temperatures are too low, oxidation of soot is inhibited. However, low combustion temperatures are used to reduce NOx. Increased compression ratio, injection timing retard, increased charge air cooling, exhaust gas recirculation, inlet air humidification and direct water injection all can increase soot. The problem is greatest at low loads where spray penetration and atomisation and air entrainment are least. Common rail injection systems improve the situation at part load by maintaining high injection pressures. Auxiliary blowers and Jet-Assist turbochargers help maintain charge air pressure at low loads and during load changes. The new low sac volume fuel injectors have also made a significant contribution to smoke reduction, as they avoid the problem of dribble after injection and subsequent inefficient burning of the leaked fuel. Higher injection intensities and good air motion are used in combination with retarded injection timing and increased compression ratio for NOx control. Higher injection intensities and air movement improve atomisation, penetration and air entrainment, thus tending to compensate for the negative effects on smoke of other changes.

3. NOX CONTROL MEASURES

3.1 Engine Tuning

Most engines can meet the Marpol Annex VI limits by tuning the combustion process. Options include modifying the spray pattern, injection timing, intensity of injection and injection rate profile (injection rate shaping), compression ratio, scavenge air pressure and scavenge air cooling. Delayed injection timing is very effective in reducing NOx but increases fuel consumption and smoke. It is usually combined with increased compression pressure and decreased injection duration to minimise or avoid increase in fuel consumption.

3.1.1 Fuel Injector Valves and Nozzles

Recent developments in low NOx engines involve fine tuning of the fuel injection process. CRFD models of the dynamics of the burning fuel spray in the engine combustion chamber have been used successfully by engine manufactures, in conjunction with experiment, to develop low NOx fuel nozzles.

Slow speed engines use two or three fuel injectors located near the outer edge of the combustion chamber. (Figure 2) Each injector nozzle has a number of holes. The interaction between the sprays from individual nozzle holes has a significant impact on NOx. There exists an optimum number of nozzle holes for minimum NOx. CRFD simulations have shown that for individual fuel sprays, an annular region of high NO formation rates tends to form around the burning fuel spray. For a small number of nozzle holes, late interaction of the individual high temperature regions in the presence of oxygen in the gap between the sprays leads to increased NO formation rates. For intermediate numbers of nozzle holes, isolated high temperature zones form but they are closer so less oxygen is available from surrounding unburnt gas. For a large number of nozzle holes, the individual sprays interact early and produce a large high temperature NO formation region.[6]

Wartsila report that the location of flame zones in relation to metal surfaces was of considerable importance in controlling NOx in their medium speed engines.[7] It can be seen in Figure 1 that the hottest combustion zones are close to the piston and cylinder head. Cooling of the flame and/or burnt gases by surfaces reduces NOx. Too much cooling, or impingement of unburnt fuel on metal surfaces would increase smoke. Wartsila found that the combustion space that was optimal for NOx was also ideal for low smoke [7]

Wartsila [8] used computational methods to “reduce the space around the burning areas” in the Wartsila 64 medium speed 4 stroke diesel. They state that there was too much space around the burning areas available for NOx formation, that there is a layer where NOx build-up is greatest. They also increased the excess air ratio to “relocate and shrink the layer where NOx production is greatest”.

For a medium speed Ruston engine (RK215), reducing spray core angle from 140 deg to 130 deg reduced NOx (measured in ppm) by 32% and increased fuel consumption by 6% (at a single operating condition). [9] The smaller spray angle reduced the air entrainment into the spray resulting in less prepared mixture for the premixed combustion phase. The group optimised the piston shape. With the new shape, there is less distance between the spray and the piston near the centreline of the piston, so there is less air entrainment in the early stages of injection, which reduces the premixed phase. The new design enhances turbulence and mixing for the later stage of the combustion, which improves fuel efficiency and decreases emissions overall.

MAN B&W has introduced the slide-type fuel valve as standard on slow speed engines. [10, 11] The slide-type has zero sac volume so the entry of fuel into the combustion chamber after injection ceases is minimised. This leads directly to reduced CO and HC emissions as any fuel leaking into the cylinder after the main combustion process is finished is likely to burn incompletely. The fuel nozzle was optimised for NOx simultaneously with the development of the slide valve. Tests on a 12K90MC engine (55MW at 94 revs/min) at 90% load, showed a 23% reduction in NOx emissions for a slide-type valve compared with a standard valve and nozzle, with a 1% fuel consumption increase.[12]

Using a low NOx fuel injection valve in its UEC52LSE slow speed engine, Mitsubishi reduced NOx from 18.5 g/kWh to 15 g/kWh, but at 2 percent fuel consumption penalty.[13]

3.1.2 Intelligent (Camshaftless) Engines

The new electronically controlled camshaftless engines allow great flexibility for optimisation of the combustion process over the full range of operating conditions. Some of the features have been available on conventional engines with electronic control, but the camshaftless computer controlled engines have allowed greater operational flexibility. As far as NOx is concerned, the main features are computer control of variable injection timing (VIT), injection rate shaping, variable injection pressure and variable exhaust valve closing (VEC). Variable exhaust closing gives the ability to change the effective compression ratio. With VEC and VIT, it is possible to optimise the interplay of injection timing retard and increased compression ratio over the whole load range, to maintain peak pressures at low load while avoiding excessive peak pressures at high load. Common rail injection gives high injection pressures and thus good spray characteristics even at low loads

3.1.3 Injection Timing Retard

NOx formation depends on temperature as well as residence time. The burnt gas arising from the part of the combustion which occurs before peak pressure is compressed due to the rising pressure in the combustion chamber. This means it remains at high temperatures for a long time compared with the burnt gas from the later stages of combustion. This allows more time for NOx to form. Delayed injection leads to lower pressure and temperature throughout most of the combustion. Delayed injection increases fuel consumption due to later burning, as less of the combustion energy release is subject to the full expansion process and gas temperatures remain high later into the expansion stroke, resulting in more heat losses to the walls. Smoke also increases due to reduced combustion temperatures and thus less oxidation of the soot produced earlier in the combustion.

3.1.4 Injection Rate Shaping

Sulzer describe the use of different injection patterns in the RT-Flex common rail, slow speed engine [14], as illustrated in Figure 3. With pre-injection, a small part of the fuel charge is injected before the main charge. With triple injection (pulsed injection), the fuel charge is injected in separate, short sprays in succession. With sequential injection, each of the three nozzles in a cylinder is actuated with different timing. The results are shown in figure 13. For HFO, pulsed injection gave about 20% NOx reduction with about 7% increase in fuel consumption. Sequential and pre-injection gave less NOx reduction and less fuel consumption increase. The effects are the result of changes in the overall pressure development and interaction between fuel sprays. The NOx/fuel consumption trade-off is apparent.

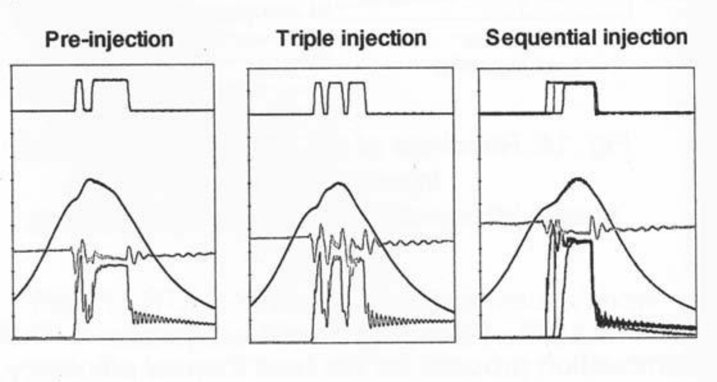


Figure 3 Injection patterns for Sulzer RT-flex

Pre-injection can be used to shorten the delay period in medium speed engines and thus decrease temperature and pressure during the early stages of combustion, resulting in reduced NOx.[9] Pre-injection can reduce particulates which are increased by other NOx control measures, thus allowing greater flexibility in NOx control.

3.1.5 Compression Ratio, Injection Timing and Injection Rate

The most common engine tuning measure is increased compression ratio combined with retarded injection timing.

Figure 4 shows the combination of increased compression ratio and delayed injection timing for a slow speed engine. The peak pressure is the same as for the standard engine and occurs at about the same crank angle, even though combustion begins later than for the standard engine. This means that there is less after-compression of the earlier burnt gas, so it does not reach as high a temperature as in the standard case and it resides at high temperature for less time. Increased compression ratio also tends to offset the increases in fuel consumption resulting from retarded injection timing.

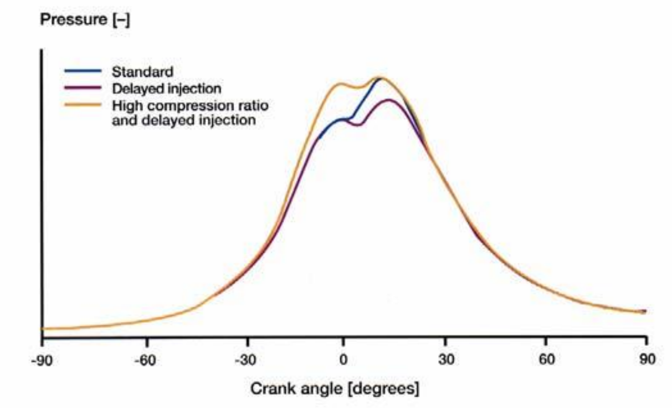


Figure 4 Cylinder pressures for a Sulzer RTA engine with standard compression ratio, delayed injection, and delayed injection combined with increased compression ratio [5]

Caterpillar Motoren found that for a medium speed engine, increasing the compression ratio from 15.5 to 17 while retarding injection timing to limit the increase in peak cylinder pressure to about 20 bar (from 180 bar), gave NOx reduction from about 12 g/kWh to about 8 g/kWh, without increasing fuel consumption.[15] Sulzer estimate that for a slow speed engine, the maximum NOx reduction achievable with increased compression ratio and retarded timing is 25% with about 1% fuel consumption penalty. [5]

The compression ratio can be increased by increasing geometric compression ratio or advancing exhaust valve closing. Advancing exhaust valve timing would increase the charge mass. This would increase the amount of mass available to absorb the combustion energy but would also increase the amount of oxygen available for NOx production. Wartsila NSD found that increasing the scavenge air pressure together with retarded injection timing may increase or decrease NOx, depending on the engine design.[5] If the geometric compression ratio is increased by reducing the clearance volume, the combustion space will be flatter, which could result in more cooling of the flame by the surfaces and thus increased soot with an additional decrease in NOx due to the cooling. Combustion chamber shape and fuel spray geometry may need to be adjusted to compensate for reduced combustion chamber height. For 4 stroke medium speed engines, very high compression ratio may require reduced valve overlap to avoid contact between the valves and the pistons.[15] This reduces scavenging efficiency and cooling of the exhaust valve. Reduced scavenging efficiency can lead to reduced NOx.

Wartsila reported a NOx lowering conversion for the Vasa 32 medium speed diesel in 1999.[16] The conversion aims for the ideal combination of compression ratio, injection timing and injection rate. By increasing compression ratio and increasing combustion pressure while retarding fuel injection and increasing injection rate, they reduce NOx from 15 g/kWh to 10-11.5 g/kWh and reduce fuel consumption by up to 4%. The conversion requires a new piston, designed to withstand the higher pressures, and modified fuel injection equipment.

Vestergren reports that the implementation of “Low NOx combustion” on Wartsila medium speed and high speed engines has reduced NOx by between 25% and 35% with unaffected or slightly improved fuel consumption. [45] This involves retarded injection timing, increased compression ratio, optimised combustion chamber optimised fuel injection and early inlet valve closing. Optimised combustion chamber and fuel injection have kept smoke non-visible despite the increased compression ratio.

Mitsubishi states that all UEC engines meet Marpol Annex VI NOx levels by engine fine tuning (injection timing retard, low NOx fuel injection valve, etc). [17]

MTU has described its NOx control measures on the new MTU Series 8000 (1150 RPM, 450 kW per cylinder). They use injection timing retard, increased compression ratio, and optimised injection. The optimised injection improves mixing and reduces soot generation by optimising number of nozzle holes, hole shape and spray angle. Electronically controlled common rail fuel injection allows optimisation of the engine for NOx and fuel consumption.[18] The combustion chamber shape was also optimised.

MAN B&W have used increased compression ratio in combination with retarded injection timing in their slow speed engines, but not to the extent used by Sulzer. They contend that the fuel consumption penalty from retarded injection timing is too great. Optimised fuel injection and nozzle design have been their main strategy for reaching IMO levels.

A MAN B&W 48/60 medium speed diesel (514RPM), when strictly optimised for lowest fuel consumption, has a typical NOx emission of about 16g/kWh. When optimised for low NOx using engine tuning, it yields about 12g/kWh NOx. (With fuel water emulsions at 15% water to fuel, the NOx output comes down to about 7-8 g/kWh.) [19]

Yanmar Diesel [20] used increased compression ratio, retarded injection timing and shortened injection duration to reduce NOx from their medium speed auxiliary engines to Marpol Annex VI levels, with a 10 g/kWh reduction in fuel consumption. They employed intake induced swirl and a deep bowl combustion chamber which induced squish, to enhance the combustion rate by enhanced mixing. An increased number of injection nozzle holes and smaller nozzle holes gave good fuel distribution through the deep bowl combustion chamber. This arrangement gave low smoke at low loads, without the need for common rail injection.

3.1.6 Scavenge Air Temperature, Miller Supercharging

Reduced scavenge air temperature reduces combustion temperatures and thus NOx. For every 3 ^{o}C reduction, NOx may decrease by about 1%.[5] Reduced charge air temperature results in lower overall temperatures and less heat losses, resulting in improved thermal efficiency. The potential for this measure using standard air cooling techniques is limited. However, on 4 stroke engines, the Miller concept can be applied to achieve low scavenge air temperature. Using a higher than normal pressure turbocharger, the inlet valve is closed before the piston reaches bottom dead centre on the intake stroke. The charge air then expands inside the engine cylinder as the piston moves towards bottom dead centre, resulting in a reduced temperature. Miller supercharging can reduce NOx by 20% without increasing fuel consumption. Sulzer ZA40S medium speed engines use Miller supercharging.[5] Wartsila NSD report the implementation of early inlet valve closing on its medium speed engine range. [4] Caterpillar Motoren (MaK) introduced the Miller supercharging concept by earlier closing of inlet valves and slightly increased charge pressure.[15] The degree of NOx reduction was limited by the available pressure from a single stage turbocharger.

Excessive cooling of the inlet air can lead to increased smoke due to poor oxidation of soot formed during combustion. Caterpillar Motoren found that increased smoke at low load limited the applicability of Miller supercharging.[15]

3.2 Water Injection, Fuel/water Emulsion, Humidification

Engine manufacturers are able to bring NOx levels below Marpol Annex VI levels by engine tuning measures. Water injection/emulsion/humidification and Selective Catalytic Reactors are used for further reductions.

Introduction of water into the combustion chamber reduces combustion temperature due to the absorption of energy for evaporation and the increase in the specific heat capacity of the cylinder gases.

Water can be introduced in the charge air (humidification), through direct injection into the cylinder or through water/fuel emulsion. Water/fuel emulsions can reduce smoke, while humidification can increase smoke. Water/fuel emulsions and direct injection of water place the water more directly in the combustion region, where it has maximum effect on NOx production. Generally, water/fuel emulsions or direct water injection give about

1% NOx reduction for every 1% of water to fuel ratio. Humidification requires about twice as much water for the same NOx reduction. Not all the injected water will end up in the combustion zone. It depends on how the water is injected.

Humidification can reduce NOx levels down to 2 to 3 g/kWh without fuel consumption penalty. Humidification has been thoroughly tested in the field on a medium speed engine. It has yet to be proven for slow speed engines. MAN B&W offer humidification for their 4 stroke propulsion engine range.

Direct Water injection is available now in Wartsila NSD medium speed engines for NOx levels down to about 5 or 6 g/kWh without significant fuel consumption increase.

Mitsubishi offer stratified fuel-water injection as an option on UEC LS2 slow speed engines.

MAN B&W offer fuel-water emulsions for slow speed and medium speed engines. Using fuel water emulsion combined with injection timing retard on its medium speed engines, MAN B&W claim about 7 g/kWh NOx.

3.3 Exhaust Gas Recirculation

Exhaust Gas Recirculation (EGR) lowers the combustion temperature, thus lowering NOx. EGR reduces combustion temperatures by increasing the specific heat capacity of the cylinder gases and by reducing the overall oxygen concentration. EGR tends to increase smoke, by reducing the O_2 concentration, increasing the combustion duration and decreasing the combustion temperature. Because the combustion rate is reduced, the exhaust temperature and thermal load on engine components is increased.

In engines operating on poor quality fuel, external EGR can lead to fouling and corrosion problems. The residue from cooling and cleaning the exhaust gas on ships using heavy fuel oil contains sulphur in a form which is difficult to dispose of. [12]

Kawasaki found 28% EGR yielded 69% reduction in NOx on a MAN B&W 5S70MC engine, with a small rise in smoke and fuel consumption.[21] Wartsila NSD found 6% EGR yielded 22% NOx reduction on the 4RTX54 research slow speed engine, with a rise in thermal load on engine components and a rise in exhaust temperature.[5]

Wartsila NSD are developing internal EGR in two-stroke engines as an extended measure beyond engine tuning techniques.[7, 22] By reducing the height of the scavenge ports the scavenge air flow into the cylinder is reduced, so more of the burnt gases remain in the cylinder for the next cycle. Lowering the scavenge ports also increases the effective expansion stroke length, resulting in reduced fuel consumption. To overcome the increased thermal load on the engine with internal EGR, Wartsila NSD are developing the “Water Cooled Residual Gas” method which involves injection of water during the compression stroke to bring the temperature in the combustion chamber back to that without internal EGR. The temperature of the combustion chamber is high enough to avoid acid deposits. The injected water also reduces NOx.

3.4 Selective Catalytic Reactors

Selective Catalytic Reactors (SCR) are widely used in areas of high NOx restriction, to achieve NOx levels around 2 g/kWh.[23] The method involves mixing of ammonia with the exhaust gas which is passed over a catalyst where more than 90% of the NOx can be removed. The products are nitrogen and water.

The ammonia is usually supplied as a solution of urea in water, injected into the exhaust stream upstream of the reactor. Sulphur trioxide in the exhaust gas can react with ammonia to form ammonium sulphate, which is an adhesive and corrosive substance. For this reason, SCR units should not be operated below about 300 °C. Some ammonia can pass through the reactor (ammonia slip) and become an exhaust contaminant. There are no changes in engine design necessary and no detrimental effects on engine operation. Disadvantages include high investment cost and the cost of supplying the ammonia. Control of the SCR plant is achieved by regulating urea dosing rate. The degree of NOx removal depends on the amount of ammonia added. The SCR system can replace the exhaust silencer. SCR in combination with other measures such as water injection could reduce NOx to 0.5 g/kWh. [4]

4. CONCLUSIONS

Most engine manufacturers are now producing standard engines which comply with Marpol Annex VI NOx emissions levels. This has been achieved by engine tuning measures, which commonly involve increased compression ratio, retarded injection timing, increased injection intensity and optimised spray patterns.

Wartsila NSD and MAN B&W have absorbed the fuel increases due to NOx control in their Marpol Annex VI compliant slow speed engine specifications by widening the tolerance on rated fuel consumption from 3% to 5%.

Marpol Annex VI will reduce global ship sourced NOx emissions at a small rate because it only applies to new installations or major conversions.

For NOx levels below Marpol Annex VI, or for retrofitting, the main measures available now are fuel/water emulsions, direct water injection, inlet air humidification and SCR.

Humidification on medium speed engines can reduce NOx levels down to 2 to 3 g/kWh without fuel consumption penalty. SCR can reduce NOx levels down to 2 g/kWh or less without fuel consumption penalty. SCR systems are expensive and consume ammonia.

Market and legislative pressure on emission levels and fuel consumption will continue.

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