

Next steps in exhaust emissions control for Wärtsilä low-speed engines

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With the IMO (International Maritime Organisation) emissions control regulations now in force, discussion in the marine industry has turned to the next steps in reducing air pollution from shipping. At Wärtsilä, various emissions control measures have already been developed or are in the course of development, including tuning flexibility, water injection, exhaust gas recirculation, selective catalytic reduction (SCR), fuel flexibility, reduced cylinder oil feed rates and high-efficiency waste heat recovery.

Since May 2005, all sea-going ships built after January 2000 have had to comply with the emissions control regulations set out in Annex VI of the MARPOL 73/78 convention. These regulations set limits on exhaust emissions for nitrogen oxides (NO_x) and sulphur oxides (SO_x). The NO_x limit is set according to a function of nominal engine speed and SO_x emissions are restricted by a global cap of 4.5% on the sulphur content of fuel. In addition, fuels with no more than 1.5% sulphur may be used in SO_x emission control areas (SECA).

Work at IMO has since progressed with consideration of the next steps in further reduction of NO_x and SO_x emissions, together with controls for other engine emissions including carbon dioxide (CO₂) and particulate matter (PM).

The next step to lower NO_x emissions levels is expected for the year 2011, known as IMO Tier 2, and discussions have been started at IMO to define the size of the step. Reductions in NO_x emissions to between 10 and 30% less than the current IMO limit have been proposed.

A further step, to an IMO Tier 3, is

also being discussed for around 2016, with NO_x levels of 40–80% less than the IMO Tier 2 limit being discussed.

These target maximum emission levels provide the engine industry with clear objectives on which to focus research and development resources.

The first approach to reducing NO_x emissions is to extend the internal measures that are already employed to comply with the current IMO limit (which can be regarded as IMO Tier 1). These include increased compression ratio, delayed injection timing and adapted exhaust valve timing, as well as different fuel nozzles. The measures are applied in various combinations according to the degree of NO_x reduction necessary for the specific engine type and its rating point. These measures are simple and effective yet have no detrimental effect on engine reliability and have only minimal effect on fuel consumption. Extending these measures as Low-NO_x Tuning in Wärtsilä RTA low-speed

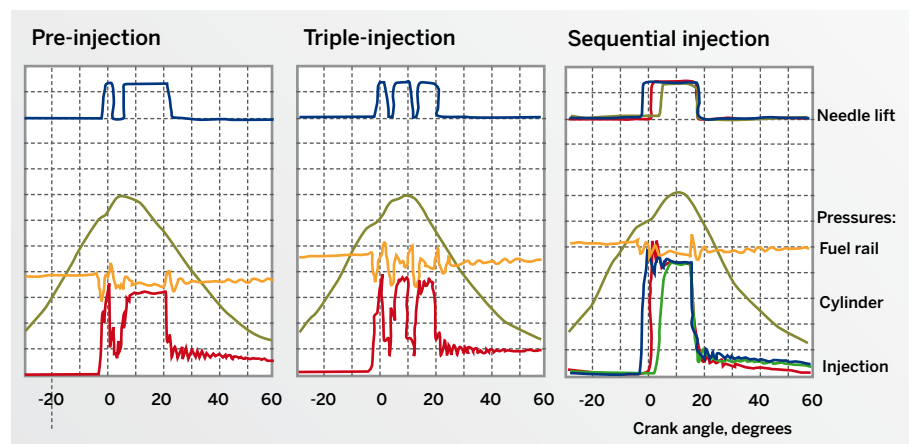
engines can result in further reductions in NO_x emissions to perhaps 5% below the IMO Tier 1 limit while incurring a fuel penalty of some 2 g/kWh greater BSFC (brake specific fuel consumption).

In Wärtsilä RT-flex engines, their electronically-controlled common-rail fuel injection systems are capable of various injection patterns. These can be employed as a Low-NO_x Injection option which would be expected to reduce NO_x emissions to perhaps 15–20% below the IMO Tier 1 limit.

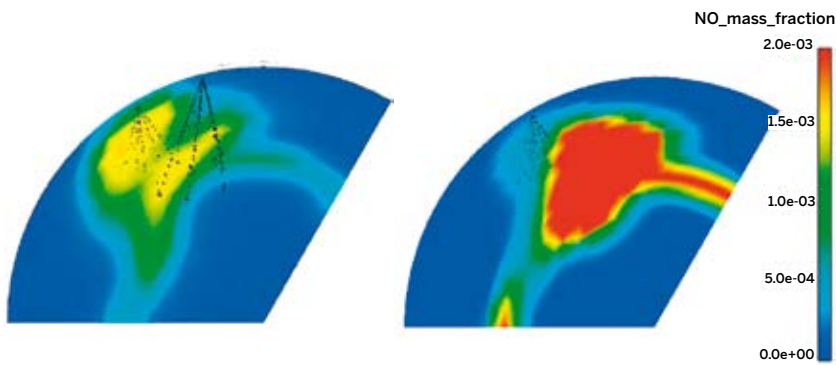
'Wet' techniques

It has long been well known that introduction of water into the combustion chamber reduces NO_x formation. Of the various possible 'wet' techniques for doing this, water-fuel emulsion is the longest studied.

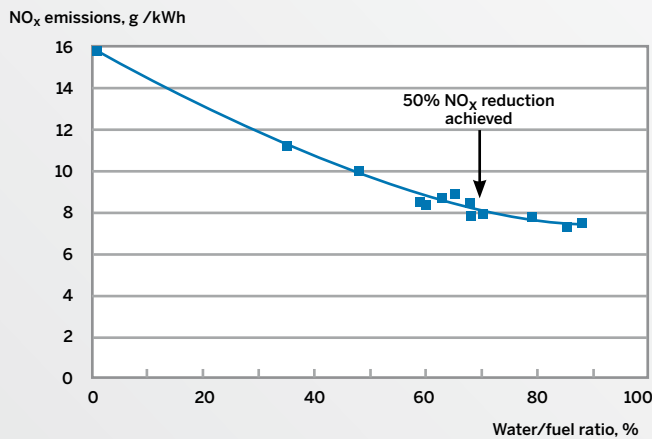
Flexibility in engine setting in RT-flex common rail engines makes it easier to adapt them to the requirements of emulsions. With the current pumping



■ Fig. 1 – Injection characteristics for three different fuel injection patterns which can be obtained using the Wärtsilä RT-flex common rail fuel injection system. In pre-injection and triple injection, the three injectors in each cylinder operate in unison, while for sequential injection the three injectors operate in turn separately.



■ Fig. 2 – CFD simulation of the combustion process with (left) and without direct water injection (DWI) indicates the levels of NO_x . These pictures show that the water is sprayed directly into the area of highest NO_x concentration. The NO_x concentrations are calculated for 12 degrees crank angle after the start of fuel injection.



■ Fig. 3 – The NO_x emissions measured in the Wärtsilä RT-flex research engine at one engine load point when using Direct Water Injection for different water-fuel ratios in a common rail system. The testbed results show that 50% reduction in NO_x is possible with 70% water.

capacity in RT-flex engines, it should be possible to reduce NO_x emissions to some 20% below the IMO Tier 1 limit.

Direct water injection

Another technique for introducing water into the combustion process for lowering NO_x emissions is to inject the water directly into the combustion chamber separately from the fuel. Under development for Wärtsilä low-speed engines since 1993, this direct water injection (DWI) technique directly reduces cycle temperatures and thus NO_x formation. It enables the water to be injected at the right time and place to obtain the greatest NO_x reduction.

The water is handled by a fully independent, second common rail injection system under electronic control. It offers the possibilities of injecting very

large amounts of water. The quantity of water injected could even be more than 100%, that is a 1:1 ratio of water to fuel.

With DWI, the water and fuel can also be injected with different timings. For example, the water can be injected in parallel with the fuel or before the fuel during the compression stroke. An RT-flex common rail engine with DWI could be provided with fuel injection that is optimised separately for when water injection is turned on or off.

DWI has been tested on the full-scale research engine in Winterthur, Switzerland. With about 70% water, DWI has been shown to be capable of reducing NO_x emissions down to around 8 g/kWh, or to some 50% below the IMO Tier 1 limit. The associated fuel consumption penalty was in the range of 5g/kWh or less.

Although the DWI system operated for

numerous hours on the research engine without problems even when running on heavy fuel oil, the tests were by no means sufficient for assessing its performance under service conditions. Accordingly, shipboard tests with DWI are to be started in summer 2007 in one cylinder of an 8-cylinder Wärtsilä RT-flex96C engine in a containership under normal service conditions. These tests are being carried out under the EU-funded research project HERCULES in collaboration with the shipowner.

Whichever 'wet' technique is employed, consideration must be particularly given to the logistics of providing sufficient fresh water on board ship.

Combining water injection and exhaust gas recirculation

Although DWI can be applied alone, it can be applied in combination with internal exhaust gas recirculation (EGR), as in WaCoReG (water-cooled residual gas) by which we expect to obtain up to 70% reduction in NO_x emissions below the IMO Tier 1 limit. This would bring NO_x emissions down to about 5g/kWh.

Exhaust gas recirculation reduces NO_x formation at source by reducing the oxygen available in the engine cylinder and increasing the heat capacity of the cylinder charge. With internal EGR, the purity of gas in the cylinder at the start of compression is decreased by reducing the height of scavenge ports to reduce the scavenge air quantity flow.

Internal recirculation normally increases the thermal load of the engine, so water injection is applied to reduce temperature levels, thereby keeping thermal loads much the same as when running without internal EGR.

Selective catalytic reduction (SCR)

When reductions in NO_x emissions of 80% or more below the IMO Tier 1 level are required, the currently available solution is aftertreatment of the exhaust gases by selective catalytic reduction (SCR). This can provide up to 90% reduction in NO_x emission levels.

SCR technology is already well-established, involving the metered injection and mixing of urea solution into the exhaust gas flow before the catalyst unit. With low-speed engines, the SCR unit is arranged between the engine's exhaust manifold and the turbine inlet of →

the turbocharger. This location is chosen to ensure sufficiently high exhaust gas temperatures for the catalyst process.

At present, SCR is only being applied in special cases. For example, three Ro-Ro paper products carriers delivered in 1999/2000 are powered by single 7-cylinder RTA52U engines equipped with SCR equipment. Their NO_x emissions are just 2 g/kWh or less.

If an RT-flex common rail engine is equipped with SCR then the engine could be optimised for the lowest possible fuel consumption using the full flexibility of the RT-flex concept, leaving the SCR to ensure minimum NO_x emissions.

Reducing SO_x emissions

The only possibilities for reducing SO_x emissions are either to burn fuels with lower sulphur content or to treat the engine exhaust gases. At present, SO_x emissions are restricted by limits on the sulphur content of marine fuels. Annex VI of MARPOL imposes a global cap of 4.5% on the sulphur content of fuel and specifies that fuels with no more than 1.5% sulphur may be used in SO_x emission control areas (SECA) such as the North Sea, English Channel and the Baltic.

Further global reductions in fuel sulphur content together with further SECAs have been proposed and local emission control limits, such as in the European Union and California, are being imposed. As a solution various bodies have suggested a global switch to distillate fuel for all ships but for both low-sulphur fuels and distillate fuels there are logistics obstacles in the availability of these fuels and limitations in refinery capacities. Wärtsilä RTA and RT-flex engines run satisfactorily on low-sulphur fuel oils (sulphur less than 1.5%) and on distillate fuels.

The use of low-sulphur fuel oil or distillate fuel are preferable for both DWI and SCR as these NO_x control techniques are both sensitive to fuel sulphur.

The alternative of flue-gas scrubbing, whereby sea water is sprayed into the engine exhaust gases to wash out the SO_x gases, is being developed by specialist companies and shipboard trials are underway. Flue-gas scrubbing takes advantage of the natural alkalinity of sea water to buffer the acidity of SO_x gases.

In 2006, Wärtsilä initiated a two-year programme to test a scrubbing plant. The project will study the equipment's

performance in realistic applications, to identify any difficulties in utilising such scrubbing equipment onboard ships and to design complete exhaust gas cleaning system compliant with IMO requirements and other regulations. The project will investigate the effect of scrubber design on performance, lifetime and economy, the effect of scrubbing equipment on engine performance, installation requirements, discharge water criteria, ecological impact, etc.

Countering global warming

Public and political attention regarding emissions are now focused on their effect on global warming and the need to counter it by cutting the global emissions of 'greenhouse' gases such as CO₂.

The Kyoto Protocol concerning 'greenhouse' gases came into force in February 2005. IMO, as the responsible body for shipping under the protocol, is already addressing the subject.

For shipping, CO₂ emissions are a function of the fuel consumed by ships' engines. Yet shipping is the most efficient form of transport. It carries about 90% of world trade by volume. At the same time, it has been estimated that shipping generates 1.4–1.8% of world CO₂ emissions.

Over past decades, the shipping industry



■ Fig. 4 – Arrangement of an SCR plant (cylindrical vessel at the top) between the engine's exhaust gas manifold and turbocharger on a Wärtsilä low-speed engine. This indicates the relative space requirement for the SCR plant.

has achieved significant improvements in engine fuel efficiency, propellers and hull designs, and is using ships with larger cargo-carrying capacities. The result has been reductions in both fuel consumption and exhaust emissions with respect to tdw-mile of freight transport.

The gains in transportation economy have been achieved by more than improvements in marine diesel engines. Most has been gained by optimising the ship design and its operation, even the overall transport system. For example, it can be shown that large ships need less fuel to transport a unit of cargo (tdw-mile or TEU-mile) and therefore discharge less emissions. Furthermore large ships can be operated faster than smaller ships for the same fuel requirement in terms of tdw-mile or TEU-mile. Similar benefits are obtained in terms of reduced air emissions.

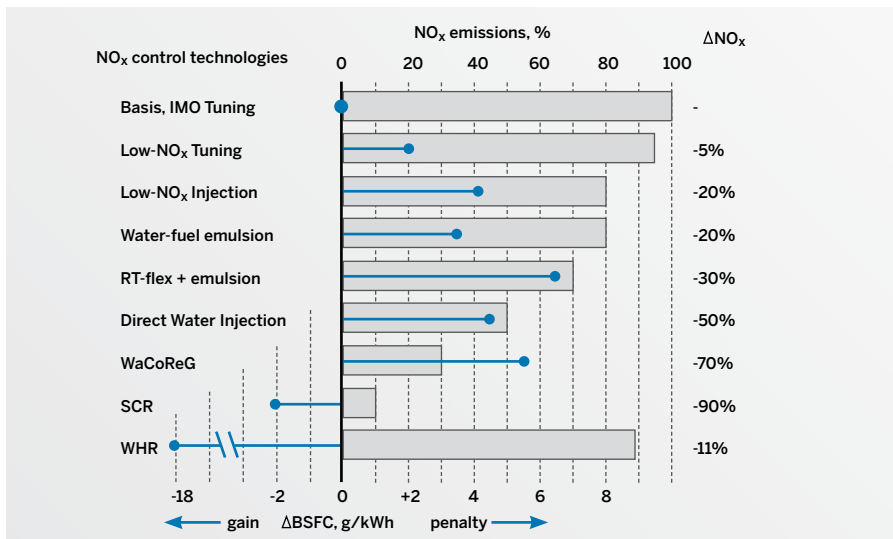
Although significant gains in fuel consumption have been achieved over the years – BSFC has been cut by about 19% over the past 40 years – the laws of physics restrict any further reductions. Though further fuel consumption improvements of a few % may be achieved with large diesel engines themselves, the greatest gains in fuel efficiency will no doubt be gained, as before, in further improvements in ship design, economies of scale and optimisation of sea transport.

Yet there are two possibilities for making worthwhile improvements in fuel efficiency and thus emissions – exhaust heat recovery for a Rankine cycle and turbocompound. They are the only technologies that are commercially available today which provide both lower fuel consumption and lower exhaust emissions, including lower CO₂ emissions.

Waste heat recovery with turbocompound

The High-Efficiency Waste Heat Recovery system developed by Wärtsilä combines exhaust heat recovery with turbocompound to deliver up to 12% of the engine shaft power as electrical power for shipboard services and additional ship propulsion.

The waste heat recovery (WHR) plant follows the well-established concept of passing the exhaust gases of the ship's main engine through an exhaust-gas economiser to generate steam for a turbine-driven generator. The quantity of energy that can be recovered from the exhaust gases



■ Fig. 5 – Summary of typical changes in NO_x emissions and specific fuel consumption (BSFC) for various emissions control technologies.

is maximised by adapting the engine to the lower air intake temperatures that are available by drawing intake air from outside the ship (ambient air) instead of from the ship's engine room. The engine turbochargers are matched for the lower air intake temperatures thereby increasing the exhaust energy.

At the same time, today's high-efficiency turbochargers have surplus capacity at the engine's upper load range when matched for ambient air intake. Thus about 10% of the engine's exhaust gas flow can be branched off in a turbocompound arrangement to drive a power turbine which is incorporated in the turbogenerator package.

The overall result of the new concept is that the quantity of energy recoverable in an exhaust-gas economiser and in the power turbine is increased without affecting the air flow through the engine. There is thus no increase in the thermal loading of the engine and there is no adverse effect on engine reliability.

The first such plants entered service in six 7500 TEU "Gudrun Mærsk"-class containerships from June 2005 onwards. During sea trials and in operation, the plants' performances have exceeded expectations. The vessels have 12-cylinder Wärtsilä RT-flex96C common rail main engines, each of 68,640 kW output. The heat recovery plant includes a 6 MWe turbogenerator set with both a multi-stage dual-pressure steam turbine and an exhaust-

gas power turbine, and a shaft motor.

These ships have since been surpassed by the 11,000 TEU "Emma Mærsk" class. They are each powered by a 14-cylinder Wärtsilä RT-flex96C engine of 80,080 kW supported by two shaft motors, and have a High-Efficiency WHR plant with an 8.5 MWe turbogenerator.

For lower-powered vessels in which the payback period for the investment in a full WHR system with shaft motor could not be justified, there is still the possibility of installing a WHR system with turbogenerator to supply only the ship's services at sea.

For example, a 29,400 kW seven-cylinder Wärtsilä RT-flex84T engine in a VLCC could be equipped with a WHR plant able to deliver just over 1000 kW. This would enable the tanker to operate without running its auxiliary engines while at sea. It would save more than 1400 tonnes of fuel a year, with corresponding savings in all types of air emissions, especially CO₂.

Reduced cylinder lubricating oil usage

Reduction of the usage of cylinder lubricating oil has been recognised as a promising means of reducing both hydrocarbon (HC) and particulate matter (PM) emissions as it did for automotive engines in cars, trucks, etc.

In the past, the recommended guide feed rate for cylinder lubricating oil in RTA and RT-flex engines was 1.37 g/kWh (1.0 g/bhph) though higher feed

rates were often employed by ships' engineers. Then in 2003, after good experience with the latest piston-running design measures, the guide feed rate was reduced to 1.1 g/kWh, or 0.9 g/kWh with appropriate monitoring. Both recommendations were for engines equipped with the accumulator cylinder oil system that has been long employed in Wärtsilä low-speed engines.

In 2006, the new Pulse Lubricating System (PLS) was introduced which allows guide feed rates to be reduced to 0.7 g/kWh of cylinder lubricating oil. With electronic control, PLS provides more accurate metering and timing, and better distribution of the cylinder oil to allow such lower feed rates.

Measurements have shown that if the cylinder oil feed rate is reduced by 0.8 g/kWh, particulate matter emissions fall by up to 40%, and hydrocarbon emissions by up to 20% at engine full load.

Towards the future

From the above developments, it can be seen that we are ready to meet the challenges of reduced emission levels for Wärtsilä low-speed engines. Reductions of about 15% in NO_x emissions can be obtained by further adaptation of existing internal measures while around 50% reduction can be achieved with more elaborate measures, especially when combined with the flexibility of Wärtsilä RT-flex engines. Yet greater NO_x reductions will most probably involve SCR aftertreatment. Benefits in terms of less emissions will also come from the greater use of low-sulphur fuels and also of distillate fuels such as marine diesel oil though exhaust gas scrubbing is a possibility.

The main contributions to lowering CO₂ emissions will no doubt come from further optimisation of ships in terms of their design and operation. Yet it must not be forgotten that there will be a significant role for high-efficiency WHR plants, especially for larger ships which justify the extra cost of shaft motor systems to aid propulsion.

The choice of emissions control measures and technologies applied in future shipping and the speed of their application will be largely dependent upon the new limits imposed in legislation such as IMO amendments to Annex VI of the MARPOL 73/78 convention. ●