Field experience with considerably reduced NOx and Smoke Emissions

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More than 95 % of the world's trade goes by sea and there are approximately 86,000 ocean going merchant ships over 100 gt in operation. About 97 % of them are propelled by large-bore, highly supercharged diesel engines such as shown in fig. 1.

fig. 1

State-of-the-art diesel engines with maximum availability do not only have to be reliable, maintenance-friendly and highly efficient, there are even further strict market requirements including lowest emissions, fig. 2.

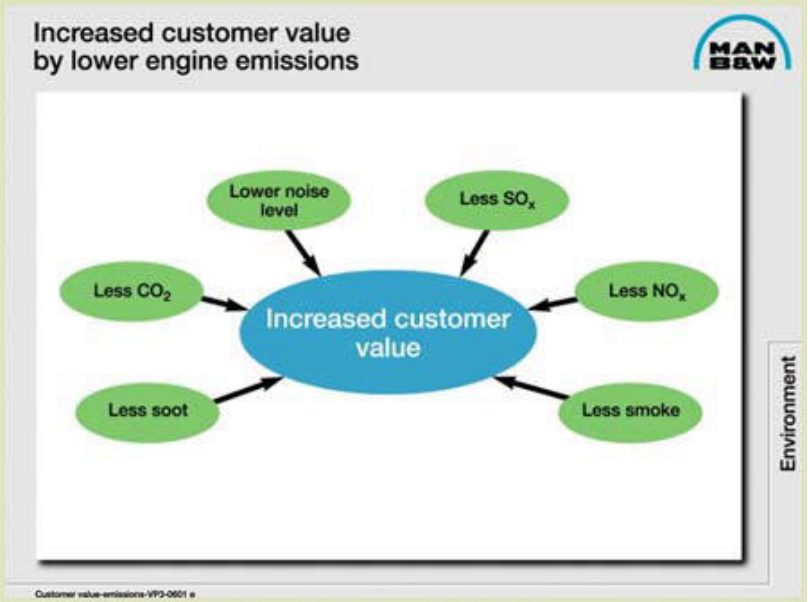

fig. 2

The particular engine shown in fig 1., rated at 19 MW, emits a total of 136 tons of exhaust gases per operating hour (full load). As illustrated by fig. 3, the majority of the constituents are harmless compounds frequently abundant in the atmosphere. The greenhouse gas CO2 amounts to approximately 6 vol-%, a low amount as direct result of the high overall efficiency of diesel engines – by far the highest efficiency (= lowest fuel consumption rate) of all available internal combustion engines. Only 0.35 vol-% in case of a high sulphur heavy fuel oil (HFO) with 4 % S are real pollutants (fig. 3) with about equal amounts of sulphur oxides (SOx) and nitrogen oxides (NOx) and minor amounts of carbon monoxides (CO), hydrocarbons (HC) and particulate matters (PM).

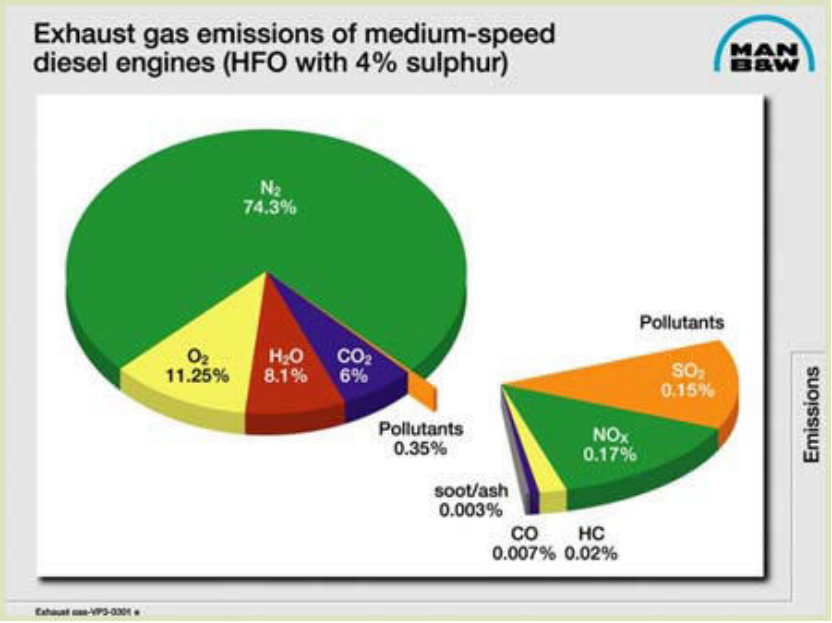

fig. 3

The percentages in fig. 3 refer to unregulated engines where emphasis has been placed on achieving lowest fuel consumption rates. With low sulphur fuels SOx can be easily halved, however at the penalty of a higher fuel price. With such fuels (2 % S), burnt in a NOx-optimised engine complying with IMO's NOx limiting curve, the pollutant fraction amounts to 455 kg/h at full load. This corresponds to 0.3 % of the total exhaust gas flow.

Already today several countries have adopted regional NOx limit values for their own territories which are much stricter than IMO's regulation (MARPOL's Annex VI). Many technical measures are available to reach such NOx levels of, say, 7 g/kWh, or even less. But all of them have disadvantages, higher first and/or operating costs, high space requirements, adding considerable weight to the propulsion plant, higher technical risk, higher maintenance effort, etc. The most disavantageous effect is the so-called diesel dilemma, or in more technical terms the soot-fuel consumption-NOx trade-off, fig.4.

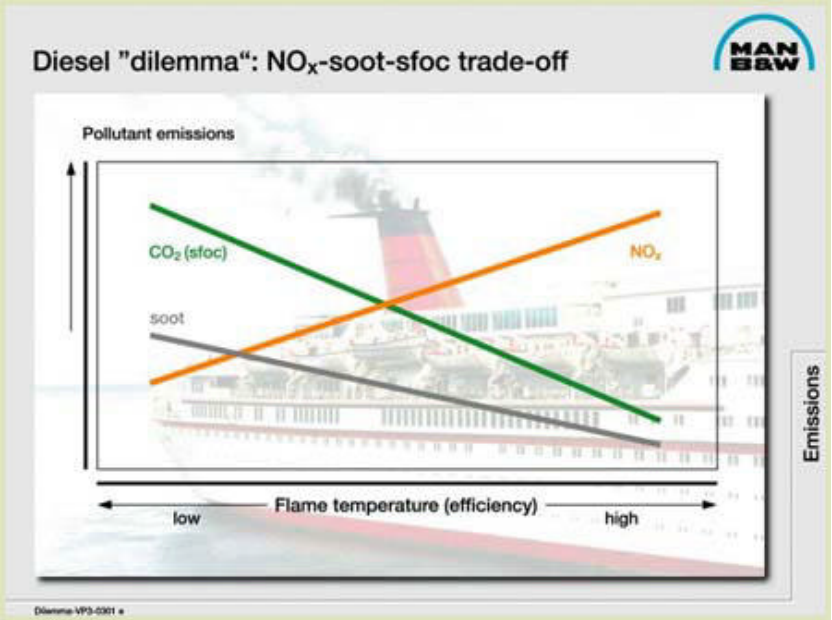

fig. 4

As this graph clearly shows, any steps aiming at a reduction of the combustion temperature level in order to decrease NOx emission will inevitably lead to an increase in fuel consumption (i.e. CO2) and soot. Additional countermeasures are therefore necessary to limit the higher CO2 and soot emissions to an acceptable level.

A few years ago the speaker's company has adopted fuel-water emulsion injection (FWE) in combination with variable injection timing at part load as the most suitable measure to cut NOx emission from MAN B&W medium-speed diesel engines. Emulsification has numerous benefits: among all other known methods of introducting water into the combustion space in order to limit NOx, the lowest amount of (fresh) water is needed for a given NOx reduction requirement. Another highly welcome effect is that, contrary to other possibilities of introducing water, FWE has a soot suppressing effect, in particular at part load and low load. This has also been confirmed by other engine manufactuers, fig. 5. In this graph, HAM stands for Humid Air Motor (humidification of the intake air) and DWI for direct water injection.

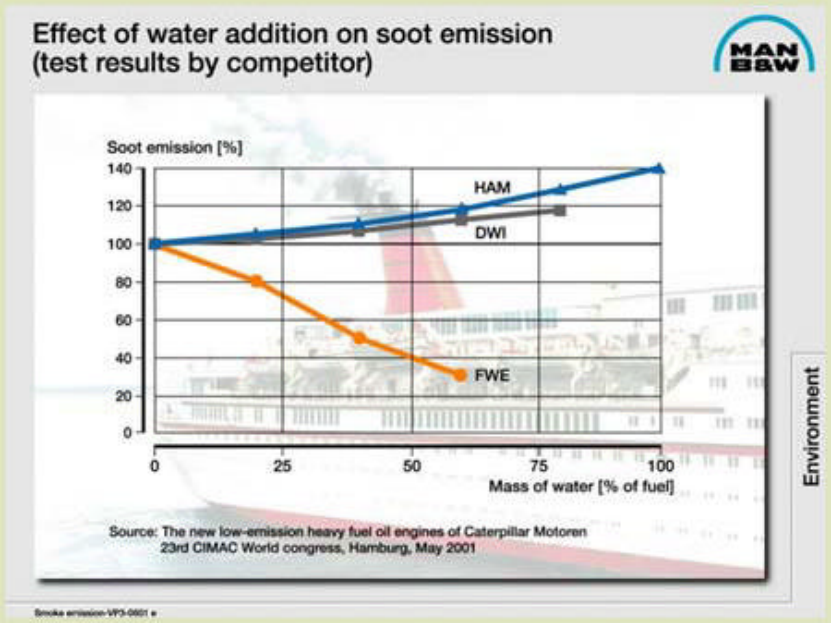

fig. 5

FWE is no unproven and risky NOx reduction technology. Since 1984 already the speaker's company operates a 20 MW slow-speed diesel engine in a Puerto Rico power plant with 22 % water addition to the fuel, and the engines of a further 80 MW power plant in Guam, commissioned in 1995/96, operate with FWE with even 50 % water - without any technical problems so far. Since 2000, four roro vessels equipped with 12V 48/60 type medium-speed diesel engines with FWE (max. 20 % water addition) are in operation. Due to the fact that, in shipping, fresh water needed for FWE has to be produced onboard, the water amount for the emulsion for medium-speed diesel engines has been limited to maximum 20 %. By simultaneously retarding injection at engine loads below 80 %, NOx emission is reduced from 14.5 g/kWh (unregulated engine, status 1996/97) to 6.7 g/kWh + 20 % with the fuel consumption rate kept within a 5 % tolerance (compared to 3 % for an unregulated engine).

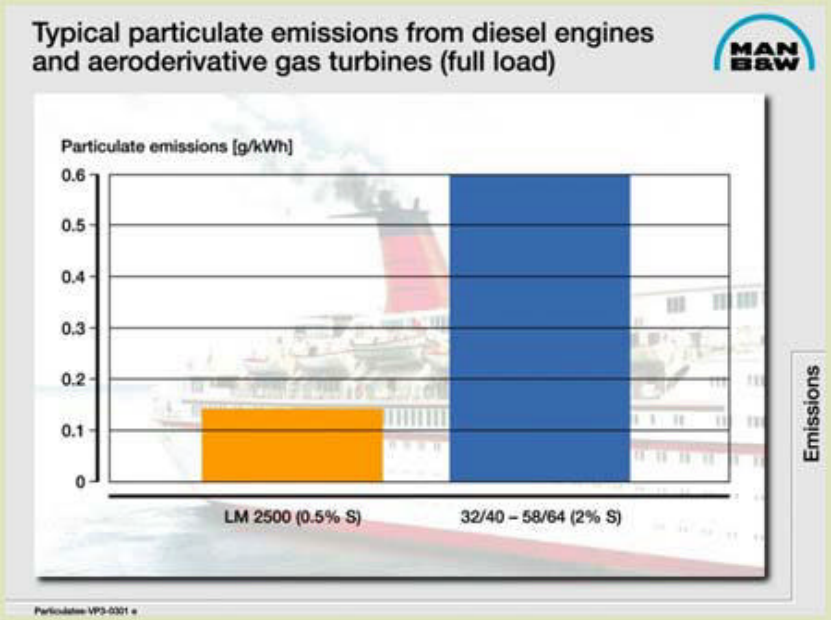

fig. 6

Particulate emission, responsible for visible smoke of a modern medium-speed diesel engine, is around 0.6 g/kWh based on combustion of HFO with 2 % sulphur. A modern aeroderivate marine gas turbine has a typical PM emission of 0.14 g/kWh, fig. 6. Gas turbines, however, use high-quality fuels such as marine gas oil with 0.5 % sulphur and less. The major constituents of the particulates of a medium-speed diesel engine at different loads can be seen from fig. 7. Soot production is clearly enhanced at part load and idling, causing visible smoke from the stacks of a ship during slow steaming.

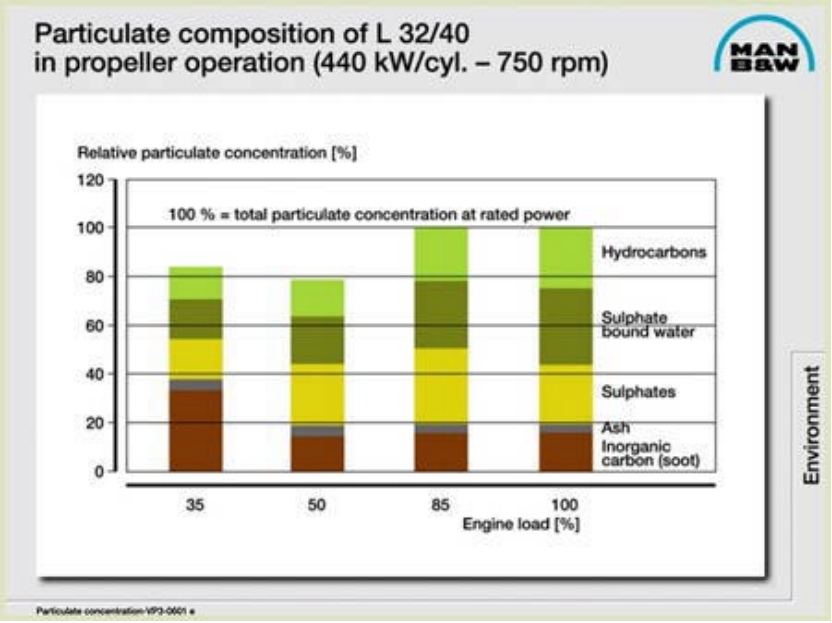

fig. 7

Since a few years smoke emission is restricted in some protected cruise vessel destinations (for instance in Alaska). For this reason engine manufacturers had to improve their prime movers for “invisible smoke” (IS) between idling and full load, a challenging task considering the special trade-off situation (fig. 4). The result of the studies and tests of MAN B&W was the IS engine specification, a combination of a special setting of engine and turbocharger, modification of the injection system together with an FWE module and an electrically driven blower (activated only between 0 and 20 % load) as additional engine hardware.

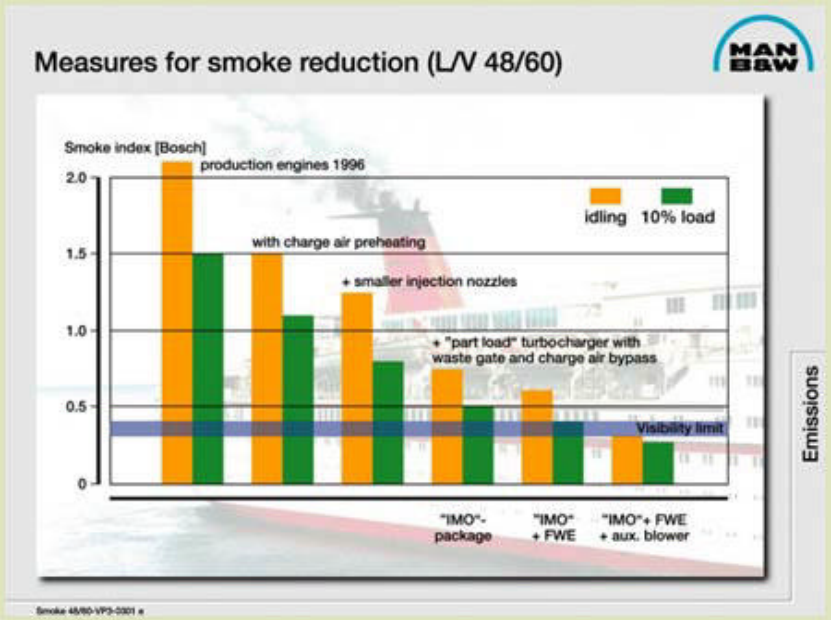

fig. 8

Fig. 8 summarizes the effect of the individual steps: with the complete IS package (suitable for retrofit), the smoke number at idling could be decreased from a base point with more than 2 Bosch down to only 0.3 Bosch, indicating that the soot mass produced during combustion has been reduced by more than a factor of 10. FWE helps to reach this goal (Fig. 9).

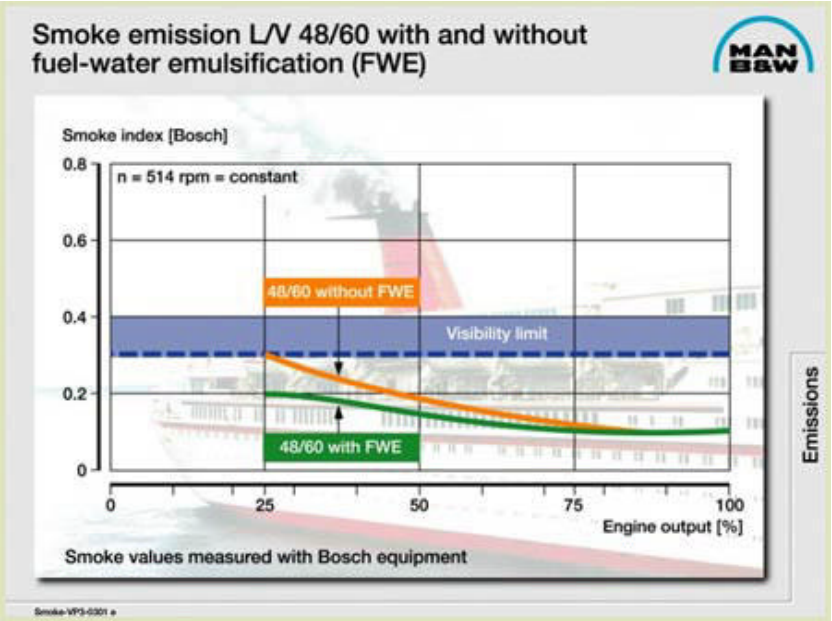

fig. 9

The IS package, thought for existing engines in the field, is a flexible system. If an engine hardly never operates at 20

% load and less, the blower can be dispensed with, and if there are no strict NOx limitation requirements well below the IMO curve, FWE is not necessary either. In this case only the basic engine in its IMO configuration with its in-engine measures remains, which is the standard specification today for all marine production engines from the speaker's company. Many of them are already in daily duty since about 1996/97, and the first complete IS -type engines with blower and FWE modules will shortly be delivered from the Augsburg works of MAN B&W.

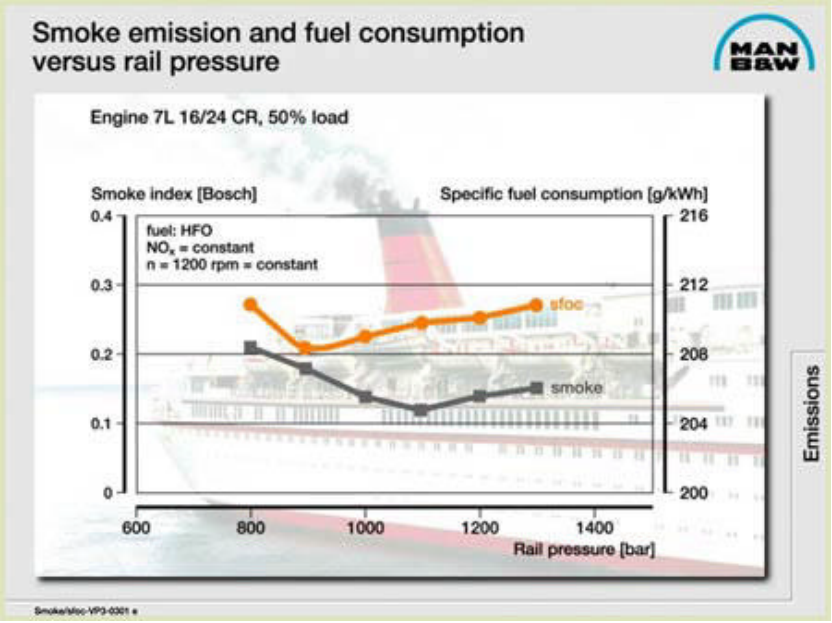

fig. 10

For upgraded and newly designed engines, either optimized injection equipment or the common rail (CR) technology will be applied to cut emissions.Fig. 10 shows some results of tests performed on a test engine 7L 16/24 CR (CR = common rail) in HFO operation for 50 % load at constant speed (1200 rpm): there is a positive influence of the rail pressure on smoke emission indeed, but the increased fuel consumption rate (sfoc) at very high rail pressures has to be taken into account too.