WinGD low-speed Engines
Licensees Conference 2015

Tier III Programme,
Technical Position, Status and Outlook

ABSTRACT

This paper considers IMO Tier III candidate technologies and their current development status in the context of WinGD 2-stroke low-speed engines.

Firstly, fuel related measures and arguments are addressed. One focus is low sulphur liquid fuel alternatives, but gas as fuel is also briefly mentioned.

Secondly, technologies for the abatement of oxides of nitrogen (NO_X) will be investigated, focusing on Selective Catalytic Reduction (SCR) and Exhaust Gas Recirculation (EGR).

Besides technical advances, this paper also highlights trends detected in the market place and their potential influence on the direction of further development.

INTRODUCTION

IMO Marpol 73/78 Annex VI, the International Convention for the Prevention of Pollution from Ships, Regulations 13 and 14 have become reality.

Regulation 14 addresses emissions of oxides of sulphur (SO_X). Starting on 1st January 2015, it limits the maximum sulphur content in marine fuels to 0.1% in Sulphur Emission Control Areas (SECAs). Alternatively, instead of limiting fuel sulphur content, scrubbers can be used to reduce sulphur in gaseous emissions to less than 20 ppm (parts per million).

Furthermore, Regulation 13 governs NO_X emissions. The global application of the Tier III NO_X regulation in Emission Control Areas (ECAs) as defined in the NO_X Technical Code, IMO Resolution MEPC.177 (58) and originally due on 1st January 2016 failed ratification and was delayed. Nevertheless, the North American Emission Control Area (NECA) will implement the NO_X cap as originally planned and as specified by the relevant United States Environment Protection Agency (EPA) directive (Regulatory Announcement EPA-420-F-10-015).

Over the past decades, scientists have come up with various means to address the challenge of reducing SO_X and NO_X emissions from internal combustion engines. The measures include alternative fuels which aim to avoid those hazardous chemical reactions during the combustion process which change the composition of existing chemical properties of gases or particulate matter (PM).

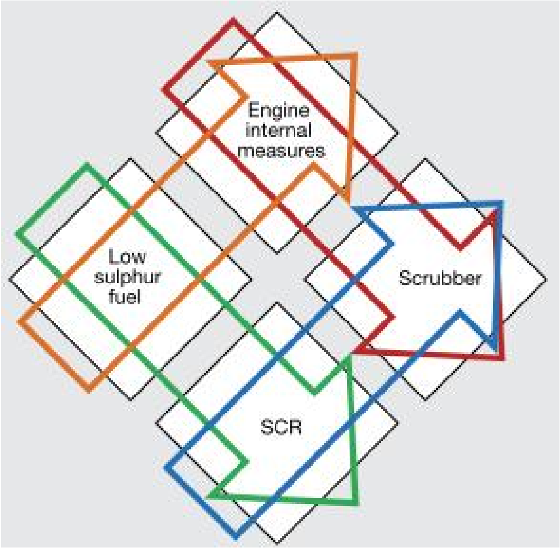

Figure 1: Possible combinations of SOx and NOx control technologies.

As an alternative to preventing the formation of hazardous emissions by primary means, one approach is to clean exhaust gases as a secondary measure by removing or converting SO_X or NO_X emissions, amongst others, mainly by means of exhaust gas scrubbers or Selective Catalytic Reduction (SCR).

The technology with the biggest influence on the design and performance of the 2-stroke low-speed internal combustion engine is Exhaust Gas Recirculation (EGR), which reduces the oxygen content in the combustion cycle and, in combination with cooling of the recirculated exhaust gases, avoids high NO_X formation during the combustion process by limiting peak temperatures. However, since this primary technology only reduces NO_X, additional main stream scrubbers are required for fuels with sulphur contents higher than 0.1/ 0.5%.

This paper discusses the current status of the listed emissions abatement technologies alternatives with regard to technology acceptance and proposals from the viewpoint of WinGD. The paper also focusses on alternative fuels, selective SCR and EGR. Unless related to EGR system integration onto 2-stroke low-speed engines, scrubber technologies are omitted.

In spite of this, it has to be said that the shipping industry is still in the process of analysing the overall situation and no clear trends have emerged as to which approach will prevail. Thus, conclusions and recommendations made here are temporary judgements that might soon be overtaken by events.

FUEL ALTERNATIVES

Despite the widespread application of low sulphur distillate oil (LSDO) to control sulphur emissions, alternative are appearing on the market in the form of hybrid fuels, biofuels, emulsified fuels and gases. In this chapter experience with these fuels are considered and evaluated.

Low Sulphur Distillate Fuel

LSDO, consisting of Marine Diesel Oil (MDO) or Marine Gas Oil (MGO) is generally accepted to be the simplest solution to meeting SO_X requirements in ECA areas. The quality of these fuels is categorised under the ISO8217:2012 standard as Distillate Marine (DM) fuels.

Despite the wide acceptance of LSDO on-board ships, these fuels carry certain risks. Ship's fuel equipment is traditionally configured to treat and inject residual heavy fuel oil (HFO), with related heating and viscosity controls.

That LSDO can be a disadvantage shows during fuel change-over procedures when entering SECA areas. If MDO/ MGO is too hot during the transition from HFO, the distillates' viscosity will fall too low, with consequent damage to the mechanical equipment in the fuel system. Obviously, automatic fuel change-over valves can control such a process accurately. However, the high cost pressure on shipbuilders leads to the situation where low price manual change-over valves are applied, with the consequence that not all change-over attempts end successfully when a vessel is in service. Although the responsibility for correct fuel change-over procedure according regulators and classifications requirements lies with the ship designer and shipbuilder, WinGD is strongly advocating that automatic change-over valves be applied. Considering that additional ECAs are expected, hence increasing the frequency of change-overs, a declaration of mandatory automatic change over valves is under serious consideration.

Further, with modern, highly advanced fuel injection equipment, the low viscosity of MDO/ MGO is causing increased leakage rates of the fuel used to cool and lubricate injection units, injectors and fuel pumps on the main engine and in the fuel supply systems. This leakage fuel is clean and can still be used for combustion in Tier III areas, provided it can be contained and re-circulated. Generally, on-board fuel systems provide a single tank for collection of both HFO and MGO/MDO leakage from the main engine and returning it to the HFO service tank. This procedure causes a financial loss since the higher quality distillate is fed into to the lower quality HFO part of the system. Thus, previously leaked LSDO will be burned in a blend with the HFO outside the SECAs. Consequently, it should be recommended that a split main engine fuel leakage collection arrangement is adopted, so that it will become possible to return clean, high quality LSDO back into the LSDO storage tank for use in SECAs. At WinGD, fuel system layout guidelines are updated accordingly and will be gradually introduced over the entire portfolio.

In addition, due to their unique design, having the injection control element located at the injector, a new generation of timed injection valves is reducing leakage rates compared to traditional injection systems by avoiding additional leaks at quantity dosing units, like fuel pumps or injection control pistons. At WinGD, these new generation injectors are already applied on all X-engine sizes between 35 and 72 cm bore.

Besides technical concerns, the supply of LSDO could be an issue in future and is an industry-wide concern. These fuels are increasingly demanded not only for shipping but also in emerging markets where regulators are starting to address environmental concerns. They are requiring land-based engine applications to use Ultra Low Sulphur Fuel Oils (ULSFO). According to a CONCAWE[1] study in 2009, an investment of USD 17.5 billion is needed to comply with the additional demand from shipping in Europe alone. This is without considering either the higher demands from shore-based installations and transportation, or from the fast increasing demands of the Rest of the World. As oil majors are naturally not inclined to make such high investments, it is presumed that as SECA zones increase, the price differential between HFO and LSDO will increase and affect the operating costs of vessels trading in those SECAs.

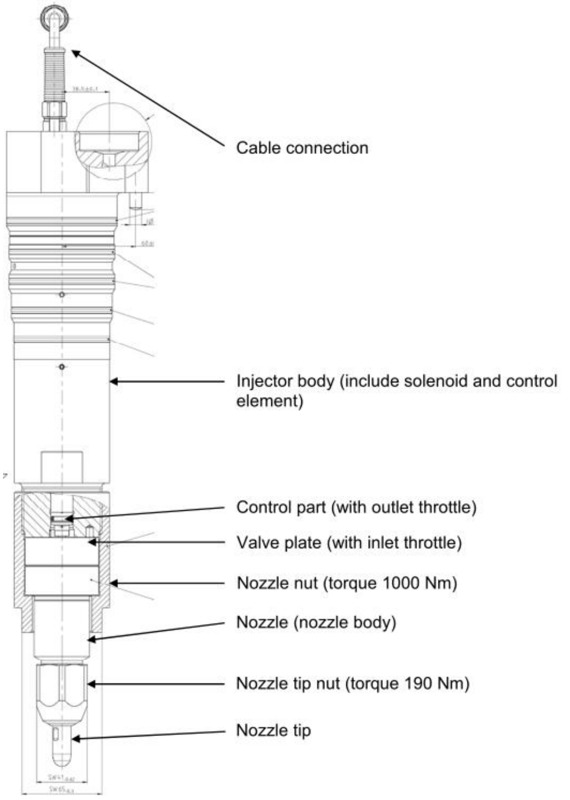

Figure 2: W-X62/ 72 FAST injector

Low Sulphur Hybrid Fuels

New residual fuels with sulphur contents lower than 0.1% are starting to appear on-board ships. These fuels are claimed to be more cost effective and are therefore increasingly attracting customers. The fuels are being marketed by companies such as Exxon-Mobile, Chemoil, Shell, SK Energy, BP and Lukeoil, among others.

The term hybrid fuel refers to fuels categorised as heavy distillates or HFO based products, often recovered from side-streams in the refineries. Their technical data can be summarised as follows:

Table 1: Technical Details Hybrid Fuels

S:	< 0.1% m/m
Viscosity/ 50°C:	10 – 65 mm^2/s
Flashpoint:	> 60°C
Density:	~790 – 930kg/m^3
Pour Point:	+7 ~+25°C

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[1] CONCAWE was established in 1963 to carry out research on environmental issues relevant to the oil industry.

Despite the positive aspects of new hybrid fuels, like improved combustion characteristics and low levels of metals, ash and catalytic fines, WinGD recommends careful planning of their use, together with the fuel supplier and the makers of the purifiers and filters. Experience has shown that these fuels can be very paraffinic with all related disadvantages like fuel segregation, fuel compatibility issues and required adjustments to separator plants.

Several Classification Societies like Lloyds Register (LR) and Det Norske Veritas-Germanischer Lloyd (DNV-GL) have already issued recommendations and guidelines. Due to the fact that hybrid fuels might be blended, the guidelines address the potential risk of mobilising deposited asphaltenes in tank and pipe systems. Moreover, compatibility with previously bunkered HFO fuels can cause flocculation of asphaltenes and the risk of sludge collecting in filters and purifiers is cited.

Figure 3: Hybrid Sludge Formation (picture courtesy of DNV-GL)

At WinGD, the potential risk of fuel injection nozzle sticking with such fuels is considered high. Therefore, design improvements to the injection valves have been initiated and are deployed for new engine deliveries.

The biggest challenge with hybrid fuels, however, is that they are not standardised under the ISO8217:2012 norm. Hence, recommendations and limitations need to be determined on a case by case basis. On the one hand, at this moment WinGD does not accept any liability or responsibility for engine performance or potential damage caused by the use of such fuels. On the other hand, as this fuel type might indeed be an attractive option for ship owners and operators, WinGD is interested in finding practical solutions which enable the controlled use of hybrid fuels. In the author's opinion, this is only possible when the fuel is standardised in the previously mentioned ISO norm.

The following checks are recommended by the industry before applying hybrid fuels (derived from DNV-GL recommendations) and are generally accepted.

Table 2: Operation Recommendations Hybrid Fuels

1. Compatibility test with previous bunkers
2. Empty & clean settling and service tanks used for hybrids
3. Clean bunker and transfer system
4. Adapted purifying system
5. Adapted/ separate supply system to/ from engine.
6. Adapted tank and trace heating

Biofuels

Bio-derived products and Fatty Acid Methyl Esters (FAME) can be found in marine fuels and can cause a decrease in greenhouse gases and SO_X emissions. Most bio-fuel components in diesel are FAME, which derive from a special chemical treatment of natural plant oils. These components are mandatory in automotive and agricultural diesel fuel in some countries. FAME is specified in ISO 14214 and ASTM D 6751.

FAME has good ignition properties and very good lubrication and environmental properties, but other more negative properties of FAME are equally well known. These are:

- Possible oxidation and thus long-term storage problems.
- A chemical attraction to water and a nutrient for microbial growth.
- Unsatisfactory low temperature properties.
- FAME deposits particles on exposed surfaces, including filter elements.

Where FAME is used as a fuel, it should be ensured that the on-board storage, handling, treatment, service and machinery systems are compatible and suitable for handling the product.

WinGD is running endurance tests with FAME fuels on injection test rigs to determine their long term effect on fuel injection equipment. So far no conclusive results are available.

Emulsified Fuels

Unlike the previously mentioned fuels which mainly address SO_X emissions, emulsified fuels are a candidate technology for reducing NO_X emissions.

Emulsified Fuels can be categorised as “water-in-fuel” and “fuel-in-water” types. While the water-in-fuel systems mixes the emulsion on board ship, the fuel-in-water mixtures are conditioned onshore in specialised plants.

Water-in-fuel emulsions have been under test since the early 1980s when it was claimed, that with an homogenous mixture, fuel consumption could be further reduced. Nowadays the focus is more on reducing NO_X exhaust gas emissions. The evaporation of the water detracts energy from the combustion of the fuel, hence lowering the combustion process temperature, which in turn reduces NO_X formation.

The challenges with the water-in-fuel emulsions are to achieve an homogenous mixture that remains stable until injected and during circulation through fuel pumps. The standard viscosity control and related heating temperature might influence such emulsions in such a way that the water might start to boil, with related negative effects.

Tests started on WinGD’s RTX research engines showed that although the emulsion is stable over long periods it is not easy to handle. In order to have an injection viscosity of 13-20 cSt, the emulsified fuel has to be reheated to temperatures over 100°C after the mixing of the HFO and water. As stated previously, these temperatures involve a certain danger in cases where pressure drops very fast to below vapour pressure and water vapour expands, e.g. in drain and leakage pipes. The same tests showed that NO_X reduction potential is very limited without fuel penalties and will not be sufficient to reach Tier III levels. Hence, other technologies need to be combined and will add complexity and cost to the system.

More promising are fuel-in-water technologies, in which fuel is added to water with the help of additives that enable an homogenous, stable mixture. Temperatures are kept below boiling point, hence there is a relatively low risk of vaporizing.

With such fuels, WinGD has been able to attain NO_X reductions of up to 50 %, and more might be possible with further optimisation. Obviously, this is still not achieving the 80% reduction required under IMO Tier III, but the method seems to have higher potential than water-in-fuel mixtures.

With both type of emulsion fuels, the challenge centres on the reliability for engine components. In order to avoid increased wear and tear, it is probably necessary to equip an engine with different injection equipment materials. Similarly, the effect on combustion chamber components cannot be ignored. Higher humidity concentrations in the cylinder environment caused by the water in the fuel, is likely to increase condensation on liner walls at temperatures below the dew point. The condensate will react with sulphites from the base fuel and might form harmful and aggressive sulphuric acid (H_2SO_4).

At WinGD, both options are under continuous test and technologies under further development. Some approaches do have positive signals and might become viable options in future. However, the technology and availability of the systems and fuels does not yet seem mature enough to employ it on wide range of vessels in operation.

Liquid Natural Gas

A lot of discussion has centred on Liquefied Natural Gas (LNG) as a fuel. Obviously LNG can deal with SO_X limitations, merely by its natural chemical composition. Hence no other measures will be required to reduce SO_X levels to the 20 ppm prescribed in Regulation 14 other than applying this gaseous fossil fuel. Existing liquid fuel engines cannot, however, operate on LNG unless they are converted, with consequent investment costs. Further, an on-board storage and transfer plant needs to be installed and requires both space and energy. Hence, at WinGD we conclude that it is likely that these gaseous fuel systems will only be applied on new buildings and will only as an exception be seen as a measure to meet SO_X requirements for existing engine installations.

For new buildings however, WinGD is clearly promoting the Dual-Fuel (DF) solution, involving switching between liquid and gaseous fuels as a viable solution to meet not only SO_X emissions limits, but also by applying the lean burn using the Otto combustion cycle to meet Tier III NO_X emission limits in ECAs. The detailed functions and applied technologies, with all their advantages and disadvantages, is explored in a separate conference paper and will not be examined further here. The LP-DF application is a particularly attractive solution when vessels are deployed mainly in ECAs, as no further SO_X and NO_X abatement is required for compliance with legislation.

SELECTIVE CATALYTIC REDUCTION

General Assessment

Selective Catalytic Reduction (SCR) installations have been around for a considerable time and the technology has been applied to 2-stroke low-speed engines since the 1980s. It is generally agreed to be a mature, well understood abatement method which causes few issues when operated properly. Typically, the systems consist of:

- Urea storage and transfer system
- Engine load dependant urea dosing
- Mixing arrangement with urea injection
- Reactor with catalytic elements
- Soot blowing system
- Controls

The urea dosing system delivers an aqueous 40 % urea solution as the reducing agent into the mixing duct where it evaporates and releases ammonia (NH_3). This ammonia then reacts on the active catalytic element substrate, converting the NO_X and ammonia into nitrogen and water (vapour), as shown in Figure 4.

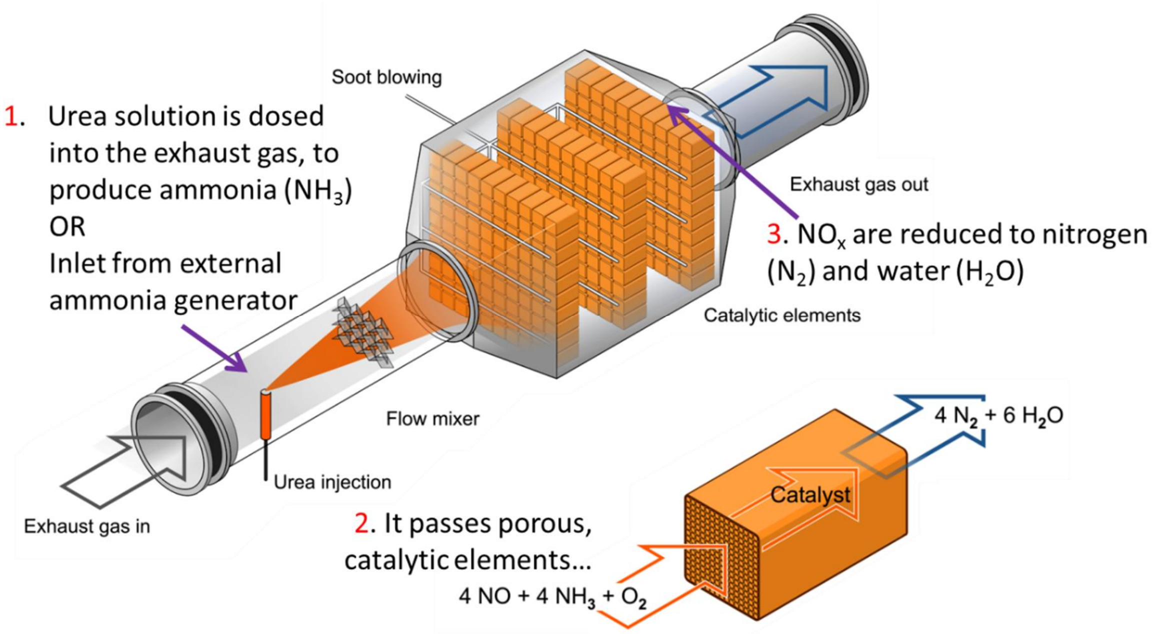

Figure 4: SCR principle; the same on HP and LP applications

SCR systems are installed on numerous 4-stroke marine engine installations and can currently be considered the industry standard for NOx abatement. However, for 2-stroke applications, only a few owners have taken the decision to install an SCR system. Incentives were mostly driven by NOx tax regulations, NOx funds for territorial waters or voluntary incentive schemes.

Integrated SCR applications also offer ship operators a fuel reduction benefit, since the engine can be tuned for optimised fuel consumption, with the SCR system compensating for the increase in raw NOx after the cylinders. This fuel saving benefit can be achieved simply by optimising engine parameters without installing more complex turbocharger strategies or increasing firing pressures, as applied on EGR engines. In this tuning flexibility aspect, WinGD's electronically controlled common-rail engines offer full flexibility and are superior to other technical approaches presented to the market.

Compared with other NOx abatement technologies, the SCR solution is rather simple, involves little equipment and incurs low installation and operating costs. However, the urea is a consumable which has to be taken into account in Opex calculations and should be set against potential fuel saving scenarios.

On low-speed 2-stroke engines, SCR is, on the one hand, applied at the low-pressure (LP) side, downstream of the turbocharger turbine. From an engine point of view this is the simplest approach, as it does not influence the design and operation of the engine since the exhaust gases are cleaned afterwards. This principle is applied in most on- and off- highway applications and on 4-stroke marine engines with SCR. In technical application terms, the industry refers to LP-SCR systems in this case. A detailed exploration of the LP-SCR in the view of WinGD can be found in the following chapter.

Due to high thermal efficiency, exhaust gas temperatures after the turbocharger turbine on a 2-stroke low-speed engine are rather low and below the optimal operating temperature range for the ideal chemical reaction. Hence, even in early applications, designers started to place the SCR reactor on the high-pressure side, before the turbine, where temperatures are considerably higher. The industry commonly refers to HP-SCR applications in this case. A detailed exploration of HP-SCR in the view of WinGD can be found in the chapter HP-SCR.

One of the biggest advantages of SCR technology is its wide supplier base. Shipbuilders and designers can choose not only from various established suppliers but also new market entrants. This puts price pressure on the supply side and makes Capex more attractive. However, during recent months, we have started to detect that the prime contractor for SCR systems is not the shipyard or related ship designers, but seems to be the engine builders, who supply an entire IMO Tier III compliant package. Hence, SCR suppliers tackling the maritime market should focus on the engine builder.

Consequently, SCR solutions represent a business opportunity for engine builders. At WinGD the belief is that once the major engine builders have standardised their IMO Tier III offerings, there will be a decline in the numbers of active players trying to sell SCR systems to the low-speed 2-stroke market.

LP-SCR

Besides maturity and availability, LP-SCR offers several other advantages. It is quite a simple system which, in case of issues, can be bypassed without affecting engine performance or causing prime mover downtime.

The reactors can be flexibly arranged in a horizontal or vertical layout inside or outside the engine room. Particularly on vessels that have accommodation and funnels located at the stern, there is the option of placing an LP-SCR above deck in a funnel housing that is slightly wider or longer. The SCR can also be placed between mooring winches and the funnel in a horizontal arrangement, requiring only minor modifications to vessel design.

With its long development pedigree, in a low-pressure application the reactor housing can be light and maintenance access to the catalysts remains simple. Especially with horizontal applications on deck, catalyst layers can be replaced using a deck derrick crane. Such LP-SCR deck arrangements are also one of the most viable NO_X abatement retrofits available.

Compared to HP-SCR or EGR application, described later, LP-SCR offers a clear advantage on multi turbocharger main engine installations. Since the system is placed downstream of the turbochargers, it will not influence their balancing and control. Hence, complicated control systems and algorithms are not needed and the SCR system is simply put into the exhaust stream when required. If control regimes are applied, they could be used to operate only a part stream to the reactor on high powered engines running at low loads.

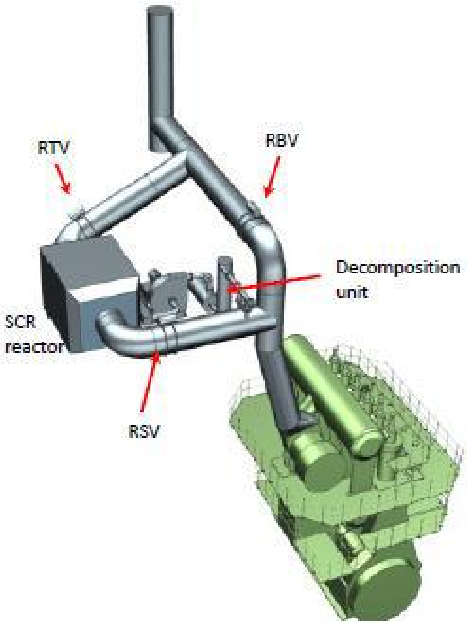

Figure 5: Horizontal arrangement of a LP-SCR reactor (picture courtesy of Doosan)

Suppliers have come up with combined solutions for SCR reactors and exhaust gas boilers. The combination of exhaust gas economisers and SCR functions in a single housing has a significant benefit in terms of installation space requirements, which is one of the biggest downsides of LP-SCR systems. Additionally, such arrangements reduce the pressure drop over the system.

As well as simplicity, shipowners also have to consider their exact operation pattern when considering LP-SCRs. These patterns define additional technical measures that might be required to achieve satisfactory performance from the installation.

Due to the high thermal efficiency of low-speed 2-stroke engines, temperatures at the reactor inlet are lower than the optimum range needed for an ideal chemical reaction. Measures to increase reactor inlet temperatures can be partly achieved via the main engine by artificially increasing exhaust temperature after the cylinders.

One strategy is to reduce turbocharger turbine efficiency using a proportional by-pass valve that diverts the hot exhaust gases past the turbine. With a by-passed turbine, the air-flow through the cylinder is reduced.

With the cyclic scavenging of the cylinder the amount of residual gas will increase and thus the combustion process temperature level will increase. Obviously, this approach is simple but includes the drawback of increased fuel consumption, slightly increased raw NO_X emissions and, under certain circumstances, an increased risk of liner/piston ring cold corrosion due to the residual gas.

At WinGD these circumstances were recognised and the newest common-rail engines now offer a potential alternative technology, featuring timed injection valves, as introduced in the chapter “FUEL ALTERNATIVES”. A quick acting valve enables injection patterns that allow, together with flexible exhaust valve timings, to control the exhaust gas temperatures in a monitored approach.

In this way the catalyst can work in an ideal temperature range for the chemical reaction without adding much extra heat from auxiliary burners. Currently WinGD is developing and optimising this adaptive injection technology and validation tests will be started soon.

Auxilary burners however are still needed for the application of LP-SCR. They have the function of increasing the temperature of the exhaust gas to a level where the urea can vaporise efficiently over a short distance before forming a homogenous ammonia gas mixture at the static mixer. Besides increasing the engine’s exhaust gas temperature in case it is too low, burners can also pre-heat the catalyst to its operating temperature while the vessel is still at the quay preparing to depart.

Another useful function is the regeneration of the catalyst substrates. Over a certain operating time and temperature, condensation forms at the substrate inlets, diminishing the reduction rate of the reactor and increasing back-pressure. Another mechanism of deposit formation is an undesirable parallel reaction where sulphur dioxide is oxidised to sulphur trioxide (SO_3), which can react with ammonia to form ammonium sulphate and bisulphate (ABS).

The deposited layers on the catalysts reduce their effective area, NO_X conversion is reduced and more ammonia will slip past the catalyst. The substrates can be regenerated by applying the burner to heat the catalysts and burn off the ABS layer. The soot resulting from this regeneration function is blown off to the normal exhaust stream while the SCR system is by-passed (in Tier II mode).

Figure 6: Tier III package; including main engine and LP-SCR system with burner arrangement. (picture courtesy of Doosan)

Contrary to a white paper published in December 2012 by IACCSEA[2] with most major SCR suppliers contributing, WinGD sees the LP-SCR as an attractive option in terms of Capex. In its paper the IACCSEA proposes costs of an SCR installation in the range of 25 – 62 €/kW of engine power. Additionally, they claim that the burner will contribute to making the LP-SCR route a higher investment than HP-SCR.

While the price range given is still valid today, it has become obvious that an LP-SCR system still has advantages when taking into account the necessary engine modifications and the project-specific piping and control interface adaptations, which result in additional engineering

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[2] **IACCSEA** - The International Association for Catalytic Control of Ship Emissions to Air

work and manufacturing costs for the HP-SCR arrangement on the engine.

At WinGD the view is that, based on equal boundary conditions, a Tier III package with engine and LP-SCR involves lower Capex compared to the HP-SCR solution.

Based on technical maturity, the previously discussed pros and cons of the system and the analysis of structured market feedback, WinGD has decided to fully support LP-SCR installations and to make them operational.

An LP-SCR interface specification has been drafted and is currently under validation with LP-SCR system providers. In this interface, WinGD provides:

- Active exhaust gas temperature control within the engine's physical limits.
- Active Tier II/ Tier III switching for optimised performance in each mode.
- An integrated engine control interface providing high flexibility in additional control functions and monitoring.
- Concepts for the entire engine portfolio including all cylinder and turbocharger numbers.
- Publishing engine performance data and guarantees for LP-SCR operation (GTD).

The preliminary interface specification is available and now needs confirmation from the first installations in service. As the interface specification is a lean, simple, derived version of the HP-SCR interface specification which has been tested successfully at sea on pilot installations, no major challenges are foreseen.

It is expected that the approved LP-SCR interface specification, validated on an operating system, will become available in the drawing system in Q4 2015. The impact on engine performance has already been released with an update to the GTD programme.

HP-SCR

The HP-SCR reactor is an integrated part of the engine's system and has thus received high attention from WinGD. As the reactor is placed before the turbine, it influences turbocharger performance and, as a consequence, engine performance. Additional flap valves and bypass lines must be installed on the engine and require design changes to the engine's basic structure.

Provided that all boundary conditions such as the fuel and catalyst used are the same, HP-SCR requires a reduced catalyst volume, by a factor of approximately three, compared to an LP-SCR application. This is due to the higher gas density under higher pressure and the higher temperature of the exhaust gases.

The HP-SCR system can be prepared for MGO and HFO. There is a potential to reduce the reactor size if a 0.1 % S distillate is used as the design fuel. With MGO catalysts can have a higher density due to lower soot and ash emissions forming during combustion. The vanadium content of HFO also has to be considered, since vanadium is part of the substrate which accommodates the chemical reaction.

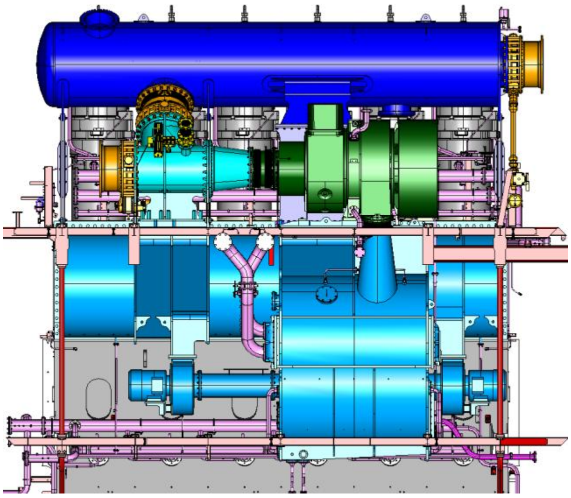

Figure 7: W6X72 with an HP-SCR interface, showing the axial TC inlet and T-connection.

When limiting HP-SCR application to 0.1% sulphur fuels, as applied in ECA areas, the reactor can be optimised for distillate fuel operation that has zero or only limited vanadium content and low soot and ash formation during combustion. The catalysts' density, designated in "cells per square inch" (CPSI), is selected higher and the reactor becomes more compact. This compact sizing, together with sufficient exhaust gas temperature for an ideal chemical reaction, are the prime advantages of the HP-SCR solution.

Low-speed 2-stroke engines designed by WinGD accommodate the application of HP-

SCR by having generally higher exhaust gas temperatures than other 2-stroke engine products on the market. This high temperature is only possible by the application of efficiently bore-cooled combustion chamber components in combination with an optimised cylinder scavenging concept. These are the two factors in which WinGD products are differentiated in their design.

The above mentioned scavenging concept, including high compressor pressure ratios at the turbochargers and higher auxiliary blower capacities, is already applied on Tier II engines. With this scavenging approach, WinGD has not so far detected a need to improve gas exchange to cope with transient engine load conditions while in Tier III HP-SCR mode.

Detailing the transient mode issue, the challenges with the HP-SCR application are, on the one hand, related to the reactor fouling. Fouling and Δp will not be an issue, provided temperature management is adequate. On the other hand, the catalyst elements have a significant thermal capacity which absorbs exhaust energy when starting and loading up the engine. In such transient conditions, the turbocharger is affected and starts to lack exhaust energy. As a consequence, the compressor will reduce the fresh air supply into the scavenge space and scavenge air limiters might become active.

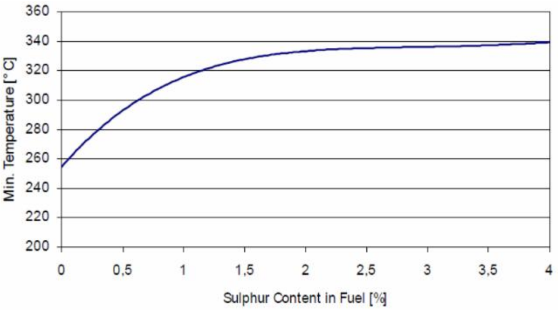

Figure 8: Minimum temperature for long term operation, below blue line increased risk of ABS formation. (Graph courtesy of IACCSEA)

With the modern generation of common-rail engines, an automated detection algorithm for fuel used is already implemented. With this algorithm in the background, the minimum required operating temperature of the SCR, according to the figure 8 below can be calculated (shown for atmospheric pressure).

At low engine loads with a Tier II tuned engine, the available exhaust gas heat after the cylinder is insufficient to reach the ideal reaction temperature in the SCR reactor, hence turbine by-pass valves are applied to raise the overall level, as described in the Chapter "LP-SCR". When MGO is used instead of HFO, the target temperature can be lower, hence a lower or zero turbine by-pass ratio is required. This gives a fuel consumption benefit when operating in Tier III mode.

Another viable measure for controlling catalyst inlet temperatures without endangering engine reliability are specific injection patterns, as now possible on the new X-engine generation. This methodology was described in the Chapter "LP-SCR" and is applicable on the X-35 to X-72 bore engines.

As required by Classification Societies and applied with LP-SCR, the HP-SCR solution also requires an exhaust gas by-pass in Tier II mode or when the SCR system fails. Unlike LP-SCR, with HP-SCR the control valve arrangements and related control strategies are fully in the responsibility of WinGD as the engine designer. This is reflected in the higher degree of integration into the engine design compared with LP-SCR.

Figure 9: WinGD pilot SCR on CMD test bed

This high degree of integration was the reason why WinGD explored SCR technology further. On the one hand, a single turbocharger engine was equipped with WinGD's own HP-SCR design. On the other hand, multi-turbocharger installations are now under preparation for a similar field test. Here, the aim is not to become an HP-SCR supplier, but merely to establish the potential for further engine concept optimisation, taking into account the entire Tier III package. As this technology is still applied only rarely on low-speed 2-stroke applications, WinGD expects some major technology steps in a rather short time and wants to be prepared for these developments.

At the beginning of 2015, WinGD was able to demonstrate its own HP-SCR system to the public at CSSC-MES Diesel Co., Ltd. (CMD) in Shanghai, China. The pilot system was the result of a two-year cooperation with Hudong Heavy Machinery (HHM) and an expert team at WinGD in Winterthur, Switzerland. While the initial technical backbone of the SCR system was derived from standard 4-stroke SCR systems already on the market, a lot of new knowledge and expertise was created and exchanged during this project. The project now serves as a basis for further collaborations between the companies, with continuously improving skills and expertise.

The pilot application is on a 5RT-flex58T-D V2 engine in a 22 kDWT Multi-Purpose Vessel (MPV). The owners operate the SCR as frequently as possible in order to gain experience and clock operating hours. These endurance tests will show if the specifications of the catalysts and the scaling of the reactor are correct for the given target of 10,000 running hours in Tier III operating mode. It will also show whether the applied measures for reactor inlet temperature control will have any unexpected long term effects on the engine.

The pilot reactor was designed for HFO with an expected operation time of 10,000 running hours. Hence, for this installation reactor sizing was rather big. The system employs a catalyst which is used as standard supply for Wärtsilä LP-SCR applications, but on the high-pressure side. The reason to employ such a catalyst is that sufficient long term experience exists with it, which avoids surprises in the early stages.

The urea dosing equipment is also a standard component from the market. Urea injection nozzles, static mixers and soot blowing needed to be adapted to the high-pressure application and were hence specially designed.

The test at CMD was commenced according scheme A, which means that the engine and SCR system were fully assembled on the test bed. Tier III compliance was demonstrated several times and confirmed by the attendant representative from Lloyds Register.

Besides meeting Tier III requirements, the test-bed trials also showed that the promised fuel consumption values can be achieved. The exothermic reaction of the ammonia on the catalyst's substrate actually boosts the turbine slightly, which ensures that fuel consumption in Tier III does not increase compared to Tier II.

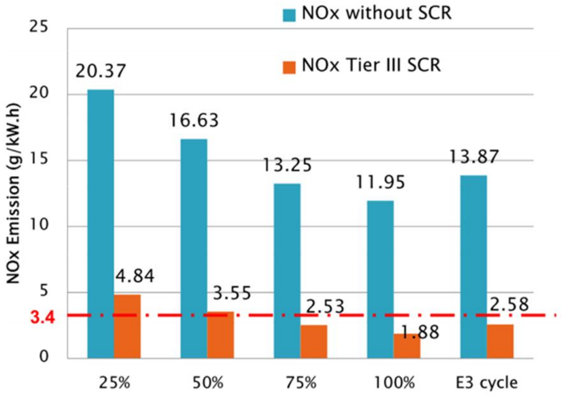

Figure 10: Measured NOx values with pilot HP-SCR at the defined IMO points

WinGD has invested considerable time and effort into the development of its own HP-SCR system, mainly to understand the technical details and challenges. In future, this knowledge will be further expanded and used for continuously optimising the technology of the SCR system integrated onto a low-speed 2-stroke engine. The expertise and understanding gained is currently being utilised to develop a multi-turbocharger SCR application that needs further integration into the engine's total system.

The challenges of the multi-turbocharger HP-SCR application are with the load balancing of the individual turbochargers and the use of even bigger reactors, based on the relevant engine power. These larger reactors absorb still more heat before the turbocharger and the previously mentioned issues will become more acute.

To counteract these limitations, WinGD is continuously working on optimising cylinder scavenging strategies and injection patterns, utilising the great flexibility of the common-rail system applied on the WinGD engines.

Further investigations include cascading reactor solutions and fully integrated control strategies, allowing closed-loop reactor temperature control, urea dosing and acceleration boosts in case of high thermal inertia caused by the reactor. Such a strategy could include isolating turbochargers at low load to have more boost efficiency from the turbochargers remaining in operation. The effect is the same as already applied in turbocharger cut-out solutions on vessels in service, or as applied on EGR engines in order to compensate for fuel penalties. Such optimising strategies will make the application of SCR on a large bore engine an attractive alternative in terms of even lower fuel consumption.

As a consequence, studies of a large engine with three turbochargers and with an HP-SCR installation are well advanced and details will be published soon. Also with this arrangement, the short term target is to have a pilot running to gain long term experience. WinGD is positive that this pilot installation can be announced soon.

WinGD has invested in building extensive knowledge of SCR technology and now shares this knowledge in detailed interface documentation. The control interface specification for integrating an HP-SCR system with the reactor located off-engine has been finalised and is available, as is a requirement specification documentation for the reactor itself.

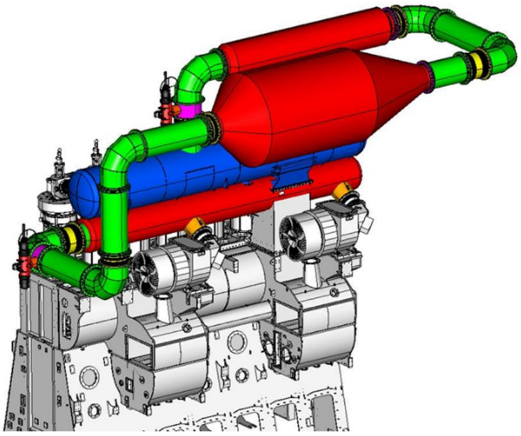

Figure 111 Multi TC arrangement with collector pipe

As well as recommendations for sizing and arrangement options, this document gives engine related limitations and process data. Another document available is a piping and installation guideline, which guides the ship designers through reactor and piping arrangements in the ship's hull.

The Interface Specification, which is now available, was prepared with the utmost attention and care. It incorporates knowledge from several years of specific developments and is regarded as having a good, advanced status with a high technical standard.

Economiser By-Pass Requirement

In recent months, there has been frequent discussion on the requirement to implement an exhaust economiser by-pass line with SCR installations.

In the case of insufficient matching of the SCR system to the engine exhaust gas flow, there exists an increased risk of ABS formation. Besides the existing chemical components in the exhaust gases, downstream formation of ABS after the reactor is mainly temperature dependent, being a form of condensation. ABS collects as a deposit layer downstream at the exhaust economiser inlet where it starts to block gasways. This leads to rapidly increasing exhaust gas back-pressures and reduced economiser efficiency. Increased back-pressures due to the economiser will reduce engine efficiency because of reduced expansion over the turbine. This, again, will have the effect that temperature levels are generally increased. Hence, the blocking of the economiser by deposit layers causes as a consequence hotter exhaust gases, which in turn are able to remove/burn off some of the ABS condensate. The system then reaches a state of equilibrium and stabilises.

Due to the higher sulphur content, it is likely that ABS formation will be more pronounced in an HFO application, but also to a lesser extent in MGO applications, unless Ultra Low Sulphur Fuel Oils (ULSFO) with a specified sulphur content of 10 – 50ppm are used.

So far, for the many SCR installations applied in the marine industry, economiser by-pass pipes were not requested, either by authorities or by experts. Many of these installations operate the SCR permanently and need the energy from the economiser in parallel. To now introduce by-pass as a requirement for Tier III SCR operations on low-speed 2-stroke represents a fundamental change of approach.

WinGD believes that with correct matching of the catalyst substrate, integrated temperature control and urea dosing for the reactor and possible regeneration mode, an economiser by-pass is not needed. This has been shown in the many existing applications. The availability of such experience is one of the advantages of applying a mature technology like SCR.

With proper monitoring of SCR conditions, either by a Continuous Emissions Monitoring System (CEMS), recording for example ammonia slip (NH_3 sensor), or by frequent visual inspections of the catalyst layers, the risk of by-products such as ABS condensate layers can be reduced to a minimum. Thus, reliable system operation is guaranteed and a need for eco-bypass is not foreseen.

EXHAUST GAS RECIRCULATION

Exhaust Gas recirculation is a primary technology directly affecting combustion in the cylinder. Exhaust gas is recirculated in to the cylinder by a blower or auxiliary turbine. As the exhaust gas consists of harmful components like SO_X, soot and particulate matter, efficient cleaning of these gases is mandatory. Further, since high combustion temperatures would benefit NO_X formation, the recirculated exhaust gas needs additional cooling, which represents a considerable loss of heat energy. In the case of gas cleaning or cooling failures, EGR carries the highest risk of engine damage of all the candidate technologies.

In general, there are three feasible ways of applying exhaust gas recirculation on a diesel engine. These technologies are widely researched and applied on engines in on- and off- highway applications burning low and ultra-low sulphur fuel oils. The technologies are:

- High-pressure EGR (HP-EGR); exhaust gas is re-circulated outside the cylinder, taken from before turbine, cleaned, cooled and then blown into the scavenge air after the compressor. This solution is typically applied on smaller diesel engines.
- Low-pressure EGR (LP-EGR); exhaust gas is taken after the turbine, cleaned, cooled and blown in before compressor. This technology is not applied on small engines but is feasible for low-speed 2-stroke applications.
- Internal EGR; exhaust gas is retained in the cylinder during scavenging. Commonly applied on smaller engines for lower EGR rates, often in combination with a secondary SCR catalyst.

High-Pressure Exhaust Gas Recirculation

At WinGD, the first test on high-pressure exhaust gas re-circulation was carried out in 1993. Already then it was clear the technology can reduce NO_X formation. With EGR the oxygen content of the air available for combustion is reduced. This leads to a slower combustion process, reducing the temperatures peaks that favour NO_X formation but, likewise related to the slower heat release, also reducing combustion fuel efficiency. The lessons learned at that time generated the knowledge that EGR is a viable technology to reduce NO_X, but comes with a considerable fuel penalty. Moreover, issues with failing water supply to wet scrubbers were observed, causing the harmful components to pass to the cylinders and corrode them, and on the way also attacking coolers and the downstream EGR blowers. Hence, the technology was rated high risk and put aside.

It reappeared however with the IMO Tier III discussions and in the new millennium it was possible to prove on a lab installation in Winterthur that IMO Tier III levels can be achieved with HP-EGR.

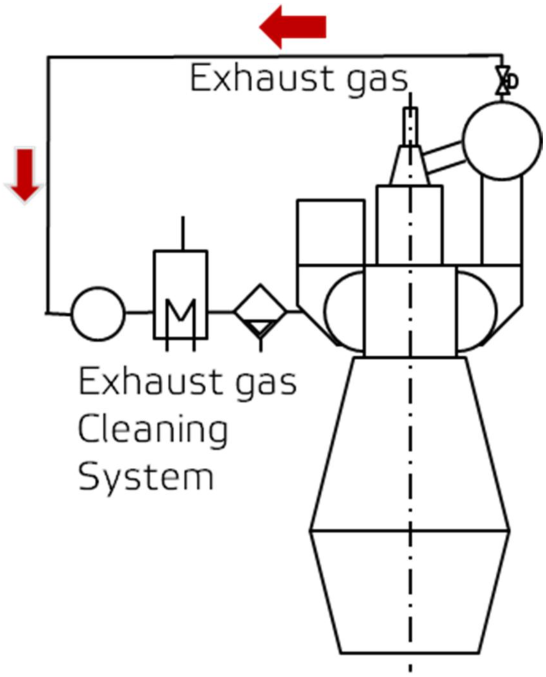

Figure 12: principle sketch of a HP-EGR

Regardless of the risk of internal engine damage in the case of scrubber failures, applied wet scrubbers produce scrubber water that needs neutralisation by caustic soda. This water's aftertreatment causes additional sludge which needs to be removed from the ship. Obviously the amount of caustic soda needed and hence storage capacity and Opex, and the amount of sludge formation depends on the fuel used (HFO vs. MGO) and the period in Tier III areas.

When ULSFO is applied, however, the claim regarding potentially severe engine damage then becomes void, as SO_X only exists in negligible quantities in the exhaust gases. This is why the on- and off-highway industry can apply EGR as one of their main technologies for compliance with EURO 6, for example. Obviously, in case ULSFO also becomes available to the maritime industry, which seems to be the case in North America, the arguments against sulphuric acid formation and its effects on engine components is no longer valid and EGR becomes a viable solution for Tier III compliance.

Another argument against an HP-EGR system is the required cooling of the recirculated gas. To attain IMO Tier III levels, 40% of the exhaust gas mass flow needs to be recirculated into the cylinder. As this gas is taken from before the turbine, temperatures are significantly high and need to be reduced to scavenge air levels. This absorbs a considerable amount of heat energy, which then needs then to be re-cooled in the central cooling system aboard ship. Thus, the cooling capacity of the EGR coolers, combined with the wet scrubbers, is an energy loss to be taken into account in a vessel’s total fuel consumption balance.

Another variable with HP-EGR applications on the engine is sizing. Where a system is designed for HFO, the scavenge trunk with the underslung receiver will require considerably more space due to the scrubbers, coolers and blowers which need to be applied. This might, conflict with slim aft-ship designs that are optimised for high propeller efficiency. Where the same ship is specified for ULSFO, no major changes will be needed to the scavenge trunk.

The top structure of the engine is, however, influenced, particularly in the case of multi-turbocharger HP-EGR application. The additional weight on the top of the engine with additional, smaller turbochargers for EGR operation has a considerable influence on engine design. The whole structure needs re-enforcement and alternative cylinder block materials need to be considered.

With the HP-EGR system, blowers and turbines and generally all material exposed to SO_X in the re-circulated exhaust gas, need to be made either from stainless or coated materials. This is more pronounced for an HFO installation than for an MGO installation. Also, scrubbers used with MGO will be smaller and the system slightly simpler. However, all these factors result in rather higher Capex for an HP-EGR system.

On the other hand, investment in more engine design margin has the advantage that the measures applied to enable HP-EGR, and control fuel consumption in EGR mode, can be utilised in Tier II mode. A higher maximum cylinder pressure used to limit the Tier III fuel consumption penalty has the same effect in Tier II, hence Tier II consumption is reduced. Moreover, the different sizes of turbochargers which are fundamental to EGR, can applied sequentially in Tier II, further adding to the fuel consumption benefit at lower loads. Both these fuel consumption reduction measures are, however, fundamental technology that can be applied to any 2-stroke engine to achieve the same result. Hence an SCR installation equipped with sequential turbocharging and high cylinder pressures will also benefit of higher combustion efficiency.

Considering all the above, with a wide understanding of advantages and disadvantages, WinGD is investing further in HP-EGR technology development. There is a sound market potential, with shipyards and shipowners signalling interest, and the technology is continuously advancing. We are convinced that EGR will become a technology applied to specific types of vessel, like ultra large container vessels (ULCV) and small vessels of less than around 75,000 DWT. For both vessel types space for SCR reactors is very limited and if MGO fuel is agreed, HP-EGR technology becomes a viable alternative.

At WinGD, the validation testing of scrubber systems for serial application is in full progress. As a next step, it is planned to equip one of the lab engines for a full scale EGR test, probably including an endurance trial before the system is launched to a pilot application. The target is to have a pilot vessel equipped with a WinGD HP-EGR system by 2017.

Low-Pressure Exhaust Gas Recirculation

A good alternative to HP-EGR, is LP-EGR. With this technology exhaust gas is recirculated, cleaned and cooled after the turbine and before the compressor, i.e. at the low-pressure side of gas exchange.

This approach has several advantages. Installed equipment does not have to be designed for up to 5 bar absolute pressure. As the exhaust gas is taken after the turbine, its temperature is considerably lower than before the turbine and it needs less cooling. Many scrubber designs and applications exist from the chemical process and heating industries for this type of low-pressure installations, thus there is much experience and the technology is mature.

As with LP-SCR, LP-EGR has also larger space requirements. Again, if MGO fuel is specified, this argument is not as pronounced as with HFO. Consequently, LP-EGR suppliers, like LP-SCR suppliers, currently offer their systems for MGO only.

At WinGD, extensive tests with LP-EGR systems and components were carried out from 2011 to 2013. Again, they clearly showed that Tier III NO_X levels can be achieved with this technology as well. Challenges experienced were sludge formation in the scrubbers with high sulphur HFOs. Also of concern was the space required for the whole installation on the rather moderately powered test engine. Arguments regarding higher fuel consumption in EGR mode and energy loss through exhaust gas cooling are also as valid for LP-EGR as they are for HP-EGR and measures to reduce fuel consumption with LP-EGR are also required.

Despite being a proven technology in the process industry, the LP-EGR approach on a low-speed 2-stroke engine needs to be validated. The first pilot installations should be in service by the time this paper is issued. Regardless of all the counter-arguments, it seems that suppliers to the industry have responded to findings and more compact LP-EGR systems will become available.

Based on accumulated experience with test installations, WinGD is supporting further testing with LP-EGR systems and will also accommodate the required adaptations to the engine design. As with LP-SCR, LP-EGR is seen as a third party offering which needs a rather simple interface to the engine. However, as EGR directly affects internal combustion, individual agreements defining quality standards and liabilities need to be reached with potential suppliers before it can be commercialised on WinGD engines.

Internal Exhaust Gas Recirculation

The high internal EGR rates needed to comply with strict emissions limits are used only on high-speed experimental engines. A relatively high boost pressure will be needed to compensate for the negative impact of internal EGR, i.e. more compression work has to be done before the cylinder in order to stay within desired compression and combustion temperatures. This can be achieved with two-stage turbocharging, for example.

Of all the EGR approaches, internal EGR has the lowest number of components exposed to fouling from the exhaust gases.

Due to the required residual gas quantity needed to achieve high EGR rates, combustion starting temperatures are considerably increased. This leads to higher NO_X formation, which has then to be compensated by even further oxygen reduction, hence leading to a further increase in the EGR rate. It remains to be seen if internal EGR is a technology that can achieve IMO Tier III levels on its own. With exhaust gas re-circulation rates higher than 40% it seems difficult to achieve this goal in reasonable terms.

However, if the combustion temperature can be controlled and the residual gases remain in areas in the cylinder where they cannot condense on component surfaces, the technology is viable and can, at least partly, contribute to achieving lower NO_X levels.

At WinGD, intense investigations in the area of internal EGR were carried out in the years between 2002 and 2007. In order to control peak temperatures during combustion, water spray was directly injected into the combustion chamber. This worked well with distillate fuels and the technology also showed potential with HFO.

The experience gained in such an investigation led to the decision to introduce a small rate of internal EGR with the introduction of the Tier II engines in 2011. Hence, every Tier II tuned

WinGD engine design has an internal EGR function. This is achieved by exact timing of the exhaust valve, which is controlled according to the scavenge air pressure and engine speed, hence roughly entrapping the same amount of air at the same load point. To maintain the combustion process temperature as low as possible, and therefore avoid NO_X formation, the bore-cooled cylinder components were further optimised.

More decisive for efficient Tier II engines, however, is the application of an extreme Miller Cycle. With this technology, the pressure ratio and efficiency of the turbochargers are increased, which allows a further delay in the closing of the exhaust valve without losing total engine efficiency.

Considering that the high boost pressure needed for Miller is already applied and that, in theory, the internal EGR rate can be readily increased, this technology might become a big contributor to IMO Tier III emissions compliance in future.

The technology has its biggest potential when applied with other candidate technologies. An internal EGR system that can further reduce raw NO_X from the cylinder at the same fuel efficiency and, without major changes to the engine can, for example, help to reduce the size of an SCR installation considerably. In the meantime, such strategies are commonly applied in EURO 6 on-highway applications and could serve as technology examples.

However, the fuel used for marine applications must be seriously considered. In the case of higher sulphur content, internal EGR might cause corrosive attack to the combustion chamber components, as with the other EGR technologies. Hence, it again seems better to limit increases in internal EGR rates to MGO fuels only.

One possible measure to avoid corrosive attack to components with EGR is to avoid condensation on the components' surface. Hence a low-speed 2-stroke engine liner will in future not only be cooled, but conditioned. This means, that twin circuit cylinder cooling systems might become standard.

WinGD is continuously exploring possibilities to increase internal EGR rates and, in combination, further optimising the cylinder scavenging strategy. Lessons learned from these efforts are continuously being applied to IMO Tier II and Tier III tuned engines. Thus, internal EGR is considered an important technology and it will prevail on WinGD engines for a long time, whichever IMO tuning is applied.

CONCLUSION

At WinGD, several of the candidate IMO Tier III technologies are now approved and applied in the field. In order to control SO_X emissions, low sulphur distillate oils (LSDO) are in the lead, but the DF technology also fulfils this requirement. The hybrid fuels now appearing on the market are being validated and more guidelines are expected soon. However, a first requirement is to standardise such hybrid fuels.

With regard to NO_X abatement technologies, WinGD considers SCR solutions to be mature and safe. The solutions can be a simple LP-SCR application or a more complex HP-SCR application before the turbocharger turbine. For both solutions, WinGD considers the technology mature and widely proven enough to apply it on the entire engine portfolio, regardless of cylinder count or numbers of turbochargers. A multi-turbocharger pilot installation is now progressing and a running engine is expected within 2016.

In terms of EGR, WinGD is well advanced with internal EGR approaches and considers them a core competency. For LP-EGR systems, WinGD is open to the integration of third parties supplying these systems, provided a strict quality and liability regime is in place. HP-EGR is seen as a viable technology and a further development driver. A full-scale engine test is planned for 2016 and the first pilot installation is expected to follow.

BIBLIOGRAPHY

IACCSEA. (2012). *The Technological and Economical Viability of Selective Catalytic Reduction for Ships.*

Lloyds Register Marine. (2015). *Your options for emmisions compliance; Guidance for shipowners and operators on the Annex VI SO_X and NO_X regulations.* London.

MHI-MME. (2015, May 18). *The World's First Confirmation of IMO NO_X Tier III Regulation using Low Pressure EGR system.* Retrieved from Mitsubishi Heavy Industries, Marine Machinery & Engine Co., Ltd.: http://www.mhi-mme.com/news/0038.html

Millius, J. (2015). Change from HFO to Low Sulphur Fuel: Basics and Experience's. *The Green Ship Technology Conference* (pp. 8-9). Copenhagen: DNV-GL.

AUTHOR

Dominik Schneiter
General Manager
IMO Tier III Programme
Product Management
dominik.schneiter@wingd.com