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# Interaction between ship operation and cylinder lubrication of marine two-stroke diesel engines

05 Components & Tribology

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# ABSTRACT

Recent years have shown significant changes in the way, how marine two-stroke Diesel engines are operated. Slow-steaming has reduced average load of such engines and load profiles have become more disperse. The more frequent operation at low engine loads lead to a phenomenon called cold corrosion, which means the corrosion of cylinder liner running surface due to attack of sulphuric acid from burning sulphur-containing fuels, yielding pronounced wear and tear of cylinder liner and piston rings. This paper aims at displaying the measures taken by Winterthur Gas & Diesel Ltd. to investigate the physics behind the described phenomena and to implement design features to reduce the leverage of negative effects of slow-steaming in favor of ship operators and ship owners.

The measures taken comprise the following:

- Lubricant oil deposit control and optimised material combinations and surface machining to achieve minimal running-in wear and consecutive wear
- Engine design adaptations to minimize condensation of sulphuric acid on the liner running surface and optimize distribution of cylinder lubricant strokewise and circumferentially
- Investigations to understand the influence of recent engine layout (lower power and speed) and operation regimes (slow-steaming, turbocharger cut-off) and definition of measures to compensate adverse effects of these

The success of above mentioned measures can be summarized as follows:

- The current material combination with plateau-honed cylinder liner and Chrome-Ceramic piston ring running surface coating attains maximum corrosion protection and lowest possible wear over component life time. If, by any means, significant corrosive attack takes place, wear rate of cylinder liner and piston rings will increase during this period and goes back to regular level after suitable lubrication conditions have been re-established, because the piston ring coating does not disintegrate even under severe corrosive conditions. Corrosion scares will wear off in operation and normal wear regime will return
- Gas-tight top piston ring lock design keeps lube oil and combustion deposits out of the ring pack and reduce the lubricant loss to both combustion chamber and piston underside space. Free moving piston rings are the prerequisite for trouble-free piston running over entire engine lifetime
- Liner cooling bore insulation and - for latest engine designs - liner cooling water feed system with high temperature help to keep liner running surface temperature above dew point of water over the entire load range, which reduces the intensity of sulphuric acid condensation
- Cylinder lubricant injection nozzles optimized by simulation algorithms in combination with distribution and retaining grooves on the cylinder liner surface ensure a perfect circumferential distribution of the cylinder lubricant
- Optimised piston ring running surface profiling on the three-piston ring pack on latest engine designs keeps cylinder lubricant longer in the ring pack before releasing it for disposal
- By choosing suitable (fuel-dependent) cylinder lubricant and controlling cylinder lube oil feed rate by appropriate piston underside drain oil sample analysis for remaining base number according to specified limit, cold corrosion of cylinder liners and consequential damage on piston rings can be avoided
- Extensive operator information released for improving and optimizing operation on slow-steaming regime and with turbocharger cut-off translates innovation in technology to a monetary benefit for ship owners and operators

Further design features planned for release during the next years will enhance the position of engine designs engineered by Winterthur Gas & Diesel Ltd., such as reduction of piston rings from three to two or one, inclined inlet ports, improved piston centering by a revolutionary piston skirt and closed-loop piston underside lube oil base number control. Investments into skilled personnel and simulation tools during the past years will now pay off both for ship owners and operators and the engine designer.

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# INTRODUCTION

Between the start of world's recent financial crisis in October 2008 and today, there is a significant change in the way, how marine two-stroke Diesel engines are operated. An operation regime called "slow-steaming" has reduced average load of such engines from about 65 % of rated power to about 45 %. Furthermore, load profiles specifically of container vessels have become less predictable as port stays are usually shorter than before due to shortage of cargo as a consequence of the crisis and thus ship speed got lower. However, the raging piracy apparent in some areas as e. g. Gulf of Aden, east coast of Africa and Strait of Malacca gives incentive to ship operators to run main engines sometimes at high load for relatively short periods of time. This lead to the requirement of highly rated engines with the ability, however, to operate reliably at low part load.

The more frequent operation of a cargo vessel's main engine at low load leads to a phenomenon called cold corrosion, which means the corrosion of cylinder liner running surface due to attack by sulphuric acid. The origin of sulphuric acid is from burning sulphur-containing fuels in the combustion chamber, where a part of the sulphur is converted to sulphur trioxide, which, in contact with water (abundantly available in the combustion chamber), forms sulphuric acid. Such corrosion yields in pronounced wear of cylinder liner running surface, but also on piston ring running surface coating, as will be shown in detail later. This paper aims at displaying the measures taken by Winterthur Gas & Diesel Ltd. to investigate the physics behind the described phenomena and to implement design features to reduce the leverage of negative effects of slow-steaming in favour of ship operators and ship owners. The authors pick up seamlessly the results given in [1] and worked during the past years consequently towards a design solution for a cylinder liner-lubricant-piston ring tribology set-up that offers robust safety margin against operational uncertainties and the requirements given by a cargo market of such tough business conditions that the industry has not seen since the oil crisis in the early 1970ies.

# INTERACTION BETWEEN SHIP OPERATION AND CYLINDER LUBRICATION

## ENGINE TRIBOLOGY SET-UP BEFORE SLOW-STEAMING INTRODUCTION

Piston ring - The basis of piston ring development later mentioned here is described in [2]. Cast iron is a price-effective choice as base material for piston rings, because it is easy to machine by turning and grinding. Chrome Ceramic (CC) coating with a ground and lapped finish on the running surface of the piston ring features a well-defined contact surface and resistance against scuffing even in difficult operating conditions. Furthermore, trouble-free running-in in service on the vessel and at engine manufacturer’s workshop is provided. Finally, profiling the ring’s running surface is used to optimise vertical oil transport in the ring pack. An asymmetric barrel shape profile was chosen for the top ring and the lower rings have symmetrically shaped profiles.

Cylinder liner - The in [2] described liner running surface machining is still and nearly unchanged since then. The running surface is usually machined by different degrees of turning and a subsequent step of honing, followed by plateau finish (brushing). These three manufacturing steps have been optimised in the past years to achieve the required surface roughness with shorter machining time and tailored tools for cost-effective production of cylinder liners. The target to give the newly produced liner a running surface comparable to one of a liner already in operation for thousands of hours still applies, as it is state of the art e.g. also in automotive applications. It ensures trouble-free running-in both at engine manufacturer’s workshop and in service aboard vessel.

Cylinder lubricant - Before slow-steaming became important for the cargo shipping market, ship operators could usually choose products from various suppliers having mainly two grades of base number (BN = 40 mg KOH/g oil, BN = 70 mg KOH/g oil), with the exception of a few lubricants available with especially low or high BN for particular applications. However, such products played a minor role in comparison with the huge two-stroke engine cylinder oil market world-wide. Potassium hydroxide (KOH) is used as equivalent for assessment of the acid neutralising ability of cylinder lubricants, where calcium carbonate ($CaCO_3$) is the commonly used chemical species that acts as an antagonist of sulphuric acid ($H_2SO_4$). In [2], it was mentioned that lubricants of different brands perform quite differently, when it comes to high-temperature detergency and high-temperature oxidation stability, although all the oils comply with the same specification. Retrospectively seen, the reason for this result might be that two-stroke engine cylinder lubricants are blended from a bulk of so-called base stock (distillate from raw oil) and an additive package providing extra features like alkalinity, detergency and dispersancy needed to comply with the requirements of the particular conditions occurring in the marine two-stroke Diesel engine. As mineral oil properties are quite variable depending on its origin, base stock oils have varying properties, too. And as additive packages are different in terms of composition of alkalinity-, detergency- and dispersancy-providing agents, whereas those agents are again being put together from various ingredients depending on the additive package producer and the requirements put forward by the lubricant manufacturer to the additive package producer, it is not a surprise that performance of different lubricants can vary significantly in bench tests, like it has been mentioned in [2].

## IMPACT OF SLOW-STEAMING OPERATION ON ENGINE TRIBOLOGY

In the very beginning of the upcoming issue of slow-steaming after the initiation of world's financial crisis at the end of 2008, it appeared that corrosion of cylinder liner running surface might be caused by the lower surface temperatures of cylinder liner as a result of lower engine operating load, as such cases had been observed relatively rarely in earlier times. Picture 1 shows a cylinder liner with such a pronounced corrosive running surface, whereas Picture 2 represents a case with regular surface condition.

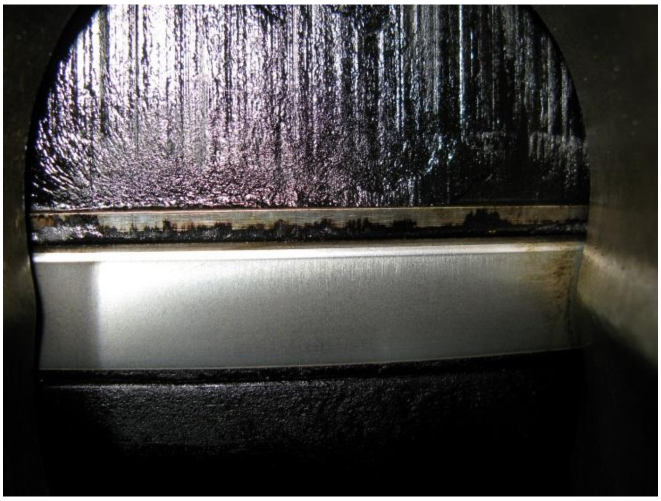
*Picture 1: Cylinder liner surface with signs of extreme corrosive attack*

*Picture 2: Cylinder liner surface with regular running surface appearance*

The appearance of some piston ring running surfaces was so severe that it was hard to believe, corrosion could yield such extensive damages on the coating of piston rings as can be seen from Picture 3. However, the later described investigation on piston ring coating demonstrated that such damage can very well be caused by exposure of the piston ring running surface to a corrosive environment, although it was still surprising, how acidic the solution or a rig test arrangement must be to mimic a similar effect.

*Picture 3: Piston ring running surface with signs of extreme corrosive attack*

This in comparison to what is considered a regular appearance of such piston rings as shown in Picture 4:



*Picture 4: Piston ring running surface with regular appearance*

## SOLUTION DEVELOPMENT STEPS

Lubrication model - Before being able to define areas of improvement for the existing tribology set-up, it is necessary to understand the influences acting on the tribology partners in the given system, as they are as shown in Figure 1:

- Piston ring running surface
- Cylinder lubricant film
- Cylinder liner running surface.

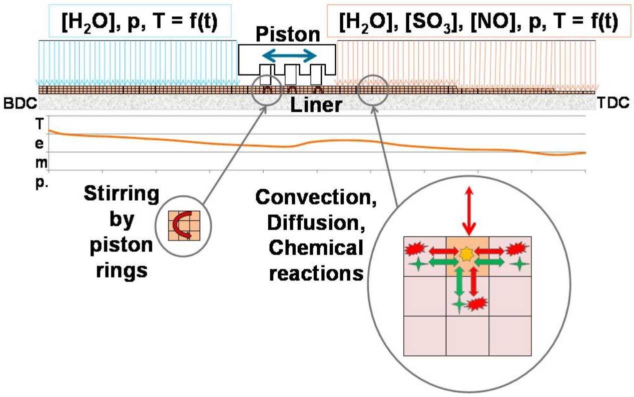


*Figure 1: Visualisation of lubrication model applied for understanding the physics and chemistry of piston ring-lubricant-cylinder liner tribology system (BDC = bottom dead centre, TDC = top dead centre)*

Physical and chemical parameters are acting on the tribology partners as given below:

- Pressure as well as local temperature of combustion chamber gas
- Local concentration of water, sulphur trioxide and nitric oxide in exhaust and residual gas
- Pressure as well as local temperature and concentration of water of scavenge air
- Piston rings stirring the lubricant film on cylinder liner running surface in regular intervals
- Temperature of cylinder liner running surface as a function of stroke
- Chemical reactions in the lubricant film.

<u>Temperature of cylinder liner running surface and piston ring coating type</u> - Based on experience such designs it was apparent that cylinder liner running surface temperature and piston ring coating type have significant influence on cylinder liner wear. In order to consolidate that knowledge, four units of the same engine were prepared with a test set-up shown in Table 1. To calculate the specific cylinder liner wear rates in TDC achieved during this test, each test liner was calibrated at begin and end of the test period.

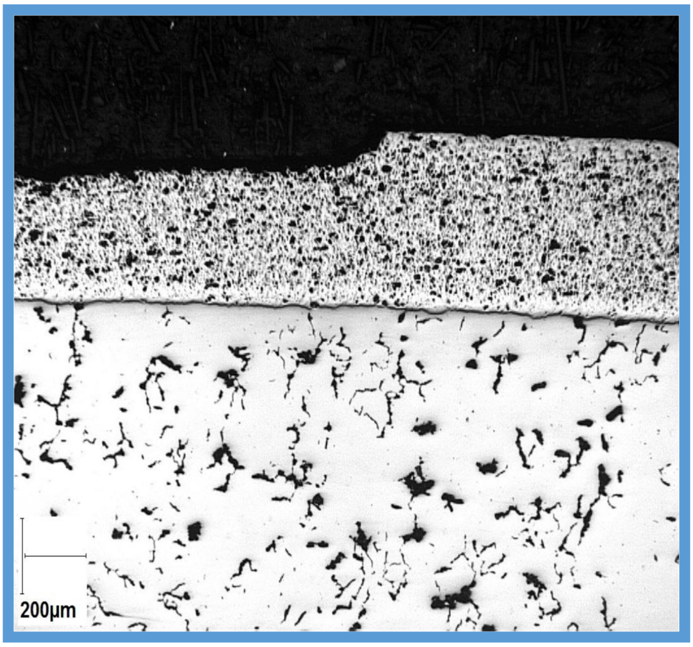
*Table 1: Comparison of cylinder liner wear for four combinations of piston ring coating and liner cooling*

| Test unit description | Relative cylinder liner TDC wear |
|---|---|
| 1 Piston ring coating: CKS 37; regular liner cooling | 29 % |
| 2 Piston ring coating: CKS 37; reduced liner cooling | 7 % |
| 3 Piston ring coating: PM2; regular liner cooling | 100 % |
| 4 Piston ring coating: PM2; reduced liner cooling | 24 % |

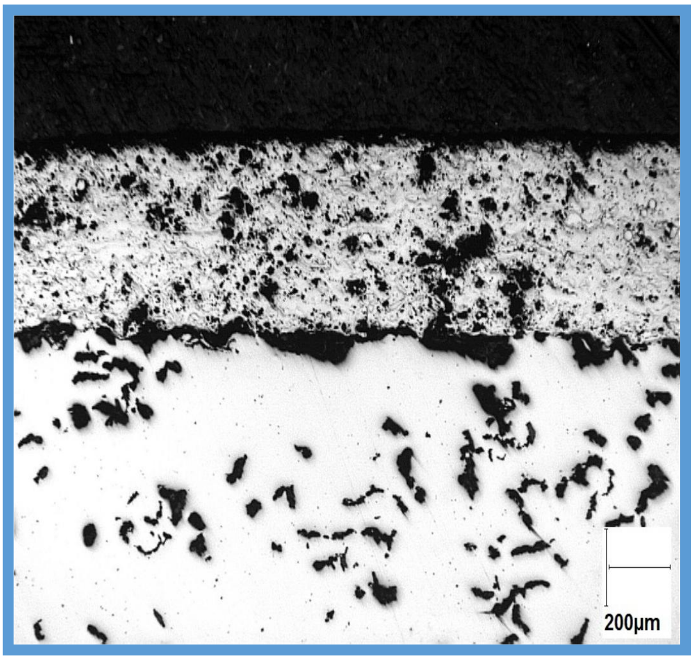
The test pistons had a top ring with gas-tight lock and three lower rings with straight-cut lock. The engine was operated on fuels with sulphur content around 4 % and the cylinder lubricant had a BN of 70 mg KOH/g oil. The results shown in Table 1 were interpreted so that reduced liner cooling causes less condensation of sulphuric acid on the lubricant film and liner surface, which results in lower TDC wear. Assumingly and compared to plasma-sprayed PM2, the less rough and harder surface of galvanically deposited CKS 37 CC-coating contributed also to this result. The presented result gave clear indication to optimize the tribology system based on CKS 37 coating in combination with reduced liner cooling. Reduced liner cooling means TDC liner surface temperature being above the dew point of sulphuric acid and at the same time being well below the start of evaporation of cylinder lubricant to avoid deposit formation from overheated cylinder lubricant.

<u>Benchmark for piston ring coating resistance against sulphuric acid corrosion</u> - The extraordinarily abnormal appearance of piston rings suffering from slow-steaming conditions as shown in Picture 3 was the incentive to study, if CKS 37 is the optimal coating when it comes to sulphuric acid attack and therefore the appropriate choice for slow-steaming operation. Such coating is state of the art since decades for car and heavy duty applications and its capabilities regarding resistance against sulphuric acid were challenged by the plasma-sprayed coating PM2. The test set-up was such that the samples were exposed to diluted sulphuric acid and a potential difference was applied in between the sample and the solution in order to avoid the build-up of the chemically very stable Chromium oxide layer that forms on the surface of CKS 37 otherwise. A part of that sample was masked to generate a reference surface, where no dissolution of the coating took place during the test, unlike the PM2 sample.

The result of this comparison is shown in Picture 5 and Picture 6. The CKS 37 coating was dissolved layer by layer by the sulphuric acid, but the coating stayed intact underneath and protected the cast iron base material from corrosion during the test period. The PM2 coating, however, lost some elements prone to being dissolved by sulphuric acid during the test period, leaving a sponge-like layer behind, where sulphuric acid could reach the base material underneath. Cast iron, however, is rather sensitive to corrosion by sulphuric acid. Such underlayer corrosion of the piston ring's base material can cause a catastrophic failure of a part or the entire coating with a presumed scuffing incident and an unforeseen maintenance for the affected unit. Conclusion of this test is that the CKS 37 coating is superior in terms of corrosion resistance. Thus, this coating was preferred as solution for further development of this tribological system. However, to overcome the situation of heavily corroded piston rings as shown in Picture 3, it was obvious that measures needed to be taken to improve corrosion protection of the piston ring running surface, which means at the same time an improved corrosion protection of the cylinder liner running surface.



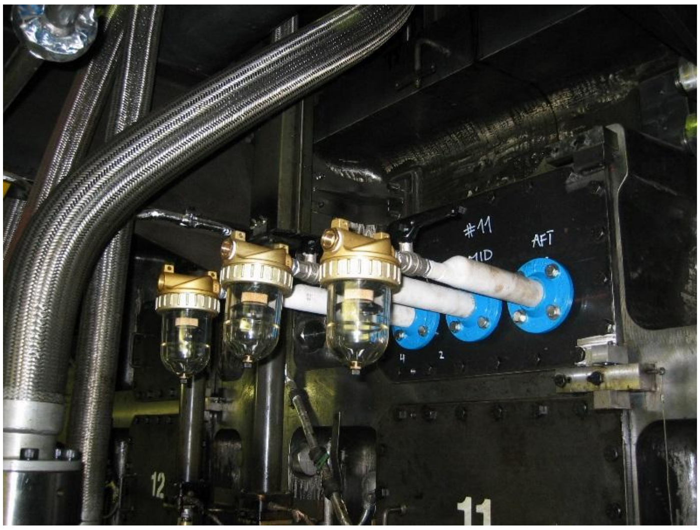
*Picture 5: CKS 37 coating after exposure to diluted sulphuric acid (upper half of picture, whereas the right part was masked, i.e. protected, and the left part was exposed to the solution; the lower part is substrate). The coating is reduced, but intact, and protects the substrate still from corrosion impact*



*Picture 6: PM2 coating after exposure to diluted sulphuric acid (upper half of picture, lower part is substrate). The coating features a sponge-like appearance and the substrate shows severe corrosion impact in the bonding layer. The coating is subject to delamination, potentially leading to a scuffing incident*

Lubricant distribution on cylinder liner surface - As it was not clear in the early stage of the investigation, which of the two factors, acid neutralization property of cylinder lubricant of or the oil distribution on the cylinder liner running surface, is dominant for producing cases like shown in Picture 1 and Picture 3, both were investigated for improvement potential.

In [1], the so-called ring-pack-spray sampling (RPSS) system was introduced. This sampling technique allows to collect cylinder lubricant from one single inlet port of a cylinder liner without contamination neither by system oil leakage from the gland box nor by oil from other units of the same engine. To deliver data for the distribution of lubricant properties along the cylinder liner circumferential, the system was further developed in a way that lubricant samples were taken from the same cylinder liner, but at different circumferential positions. Such a RPSS arrangement is shown in Picture 7.



*Picture 7: Further developed RPSS arrangement mounted on unit 11 of a 12RT-flex96C engine. Sampling pipes marked “AFT” and “FWD” (not visible) are mounted at position in line with a cylinder lubrication quill; sampling pipe marked “MID” is mounted at position in between of two cylinder lubrication quills*

In order to evaluate the distribution performance of a cylinder lubrication system, sampling positions in line with inlet ports were established such that the sampling point was either below a cylinder lubrication quill or in between two quills. In this way, the circumferential distribution can be quantified by the comparison of analysis of chemical and physical properties of the samples taken at the same time.

For this it is assumed that the piston rings transport the oil up and down along the cylinder liner, but not in circumferential direction. The justification of this assumption is given by the fact that piston rings in use at the time of the study did not have structures giving the lubricant an impulse to move circumferentially, but just in direction of engine stroke. Recent developments in piston ring technology, however, try to incorporate such structures to actively distribute lubricant also in circumferential direction [3].

To quantify the results of analysis of chemical and physical properties of samples taken from such measurements, the so-called “Inhomogeneity Index” was established, signifying to create a single number that represents the differences between properties of samples of different position on a cylinder liner taken at the same time. In fact, “Inhomogeneity Index” is the average deviation of a measurement value of three samples from the mean measurement value of these three samples divided by the mean measurement value of these three samples as explained in Figure 2:

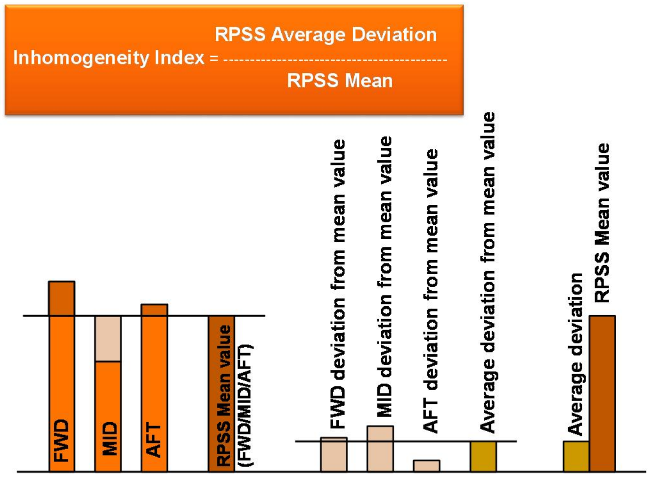


*Figure 2: Definition of Inhomogeneity Index for quantification of lubricant sample properties, whereas samples are taken at different locations of the same unit*

This index can be applied to any simultaneously measured property of lubricant samples and shall be minimal for best homogeneity, which means that the samples are chemically close to identical, indicating a nearly perfect lubricant distribution in circumferential direction. Thanks to the normalisation applied, indexes from different engines, loading conditions, lubricants, lubrication systems, etc. can be compared without further measures. Figure 3 shows a comparison of Inhomogeneity Indexes from RPSS measurements taken on four different engines (vessels) with varying ambient conditions, having two different set-ups for cylinder lubricant distribution quills. The data shows a significant difference between quill nozzle Mk.1 and quill nozzle Mk.4. As quill nozzle Mk.4 has rather low Inhomogeneity Index values compared to Mk.1, it is concluded that the lubricant distribution with regard to BN is rather equal over the entire circumference for that quill type and is therefore the preferred design solution.

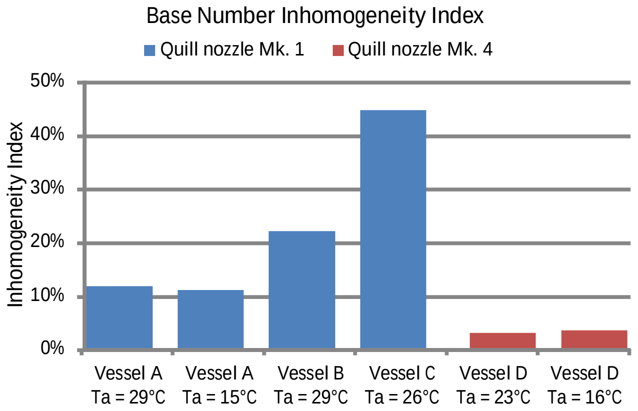


*Figure 3: Inhomogeneity Index for RPSS samples taken aboard of four different vessels under various ambient conditions with two different cylinder lubrication quill types (Ta = ambient temperature)*

Knowing that quill nozzle layout has a significant impact on circumferential cylinder lubricant distribution, a test rig was set up for scientifically evaluating the impact of small details of quill nozzle design like length-to-bore ratio of nozzle holes, nozzle hole angles, etc. Figure 4 shows the schematic setup of that test cell, where the propagation of lubricant from the quill to the liner surface and on the liner surface can be precisely monitored by means of high speed camera under engine-like conditions as there are:

- Pressure, temperature and swirl of combustion chamber gas
- Delivery pressure and temperature of lubricant
- Quill nozzle hole geometry and angles
- Cylinder liner curvature.

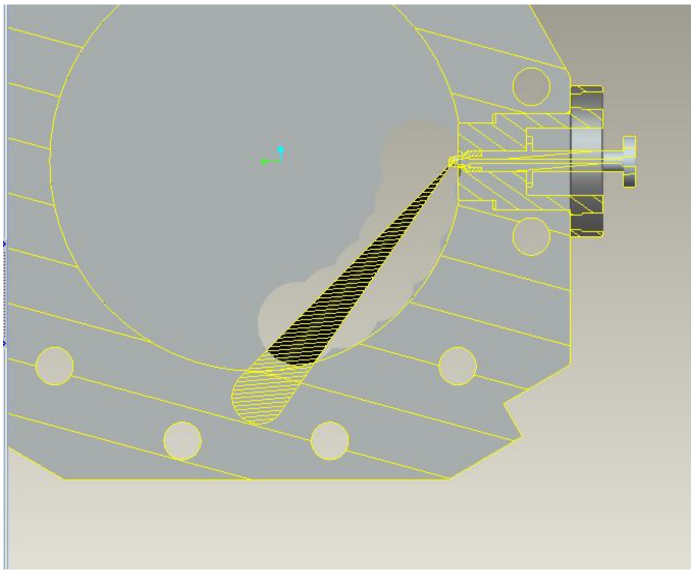


*Figure 4: Setup of test cell for studying the propagation of lubricant oil from the quill to the liner surface under engine-like conditions*

The results of the above study were used to establish an empirical model to predict jet propagation and impingement of lubricant on the cylinder liner wall of a multiple-hole lubrication quill nozzle. The software allows to quantitatively compare the distribution and impingement area of various combinations of parameters in order to optimise the quill geometry for both high-load and slow-steaming engine operation. The parameters of variation in the software are the same as mentioned above for the test cell shown in Figure 4. The cylinder lubrication quills for Wärtsilä X-type engines are laid out using this tool, where an example output can be seen in Figure 5.

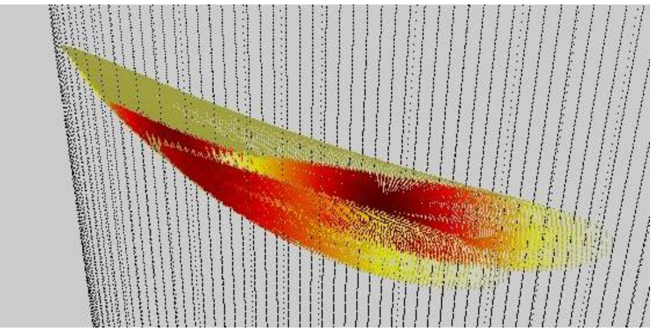


*Figure 5: Output of simulation software for optimising cylinder lubrication quill nozzle geometry*

As optimal circumferential distribution has been achieved by optimising various parameters of the cylinder lubrication system, a challenging issue is to distribute cylinder lubricant up to the TDC position of the top piston ring, because it is difficult to move the oil quills up to this position due to practical reasons. Thus, the application of tailored grooves in the cylinder liner was tested. Such grooves are used since long times to re-distribute oil from one spot on the liner to a different one using pressure difference generated by engine operation. Amongst various possible designs, the two versions shown in Figure 6 were tested extensively.

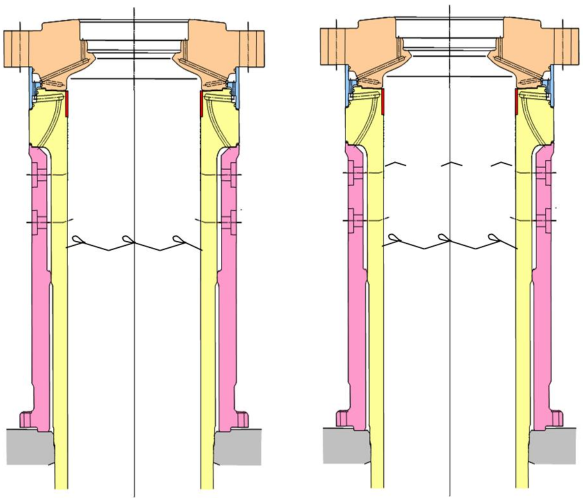


*Figure 6: Test liner executions without "Umbrella grooves" (left) and with "Umbrella grooves" (right)*

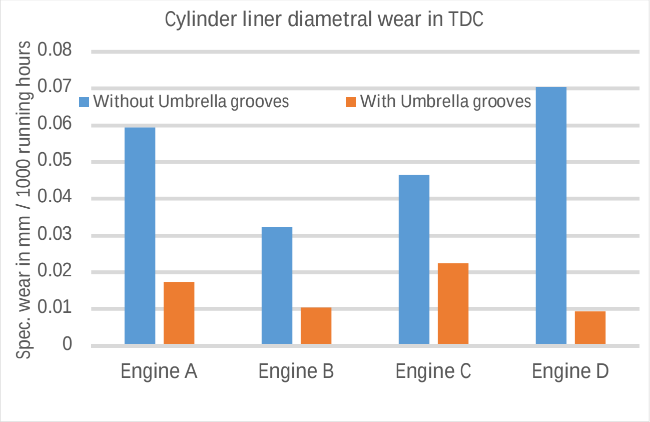


*Figure 7: Evaluation of test results using liners with and without "Umbrella grooves" for several engine types having different configurations of piston rings and cylinder lubrication systems*

The results presented in Figure 7 indicate a significant reduction of cylinder liner wear in TDC position by application of "Umbrella grooves" for oil distribution above to lubrication quills on the cylinder liner wall.

The cylinder lubrication system of Wärtsilä X-type engines does incorporate even more parameters that have been optimised using the method of quantitative and statistical evaluation of RPSS samples as shown before. The following lubrication system parameters and design elements were evaluated and optimised:

- Timing of lubricant injection in relation to piston position
- Engine load and exhaust valve timing
- Lubricant pump feed volume.

These factors together with the optimised quill geometry yield a highly reliable cylinder lubrication system. However, if cylinder lubrication feed rate and lubricant type are not carefully chosen by the ship operator, the best lubrication system cannot prevent damage caused by human interference, taking the correct decision for cylinder lubrication feed rate and lubricant type. In order to moreover minimise this risk, additional effort was necessary as will be explained in the following section.

Cylinder lubricant properties - Operating conditions for a ship's main engine can vary considerably by load, ambient conditions, fuel and cylinder lubricant in use as well as by parameter settings like cylinder lubrication feed rate. Especially under slow-steaming conditions, cylinder liner and piston ring degradation as shown in Pictures 1 and 3 was claimed many times. Therefore, an additional effort had to be taken to allow the crew on board to measure and evaluate the circumstances that the main engine is currently confronted with, in order to take appropriate countermeasures immediately, if the situation requires so. To be able to give according recommendations, several engines of ships operating on different routes were equipped with a RPSS system as described in [1] for precise analysis of cylinder lubricant properties without influence of neighbouring units and system oil dilution, which it is a common disadvantage of piston underside (PUS) drain oil sampling.

As RPSS is a quite delicate and time-consuming measurement method with regard to system cleaning and maintenance, the question was, if same trends would be detectable also by the in the industry well-established and much simpler PUS drain oil sampling. The crews of the test vessels were therefore instructed to take also PUS drain oil samples, whenever they were taking RPSS samples. The samples were then filled in according sample bottles and sent to a designated laboratory for analysis of chemical composition. In the lab, the lubricant samples were analysed for total iron using inductively coupled plasma atomic emission spectroscopy (ICP-AES) and BN (earlier called total base number, TBN) derived by titration according to ASTM D2896. The results of this measurement campaign is shown in Figure 8.

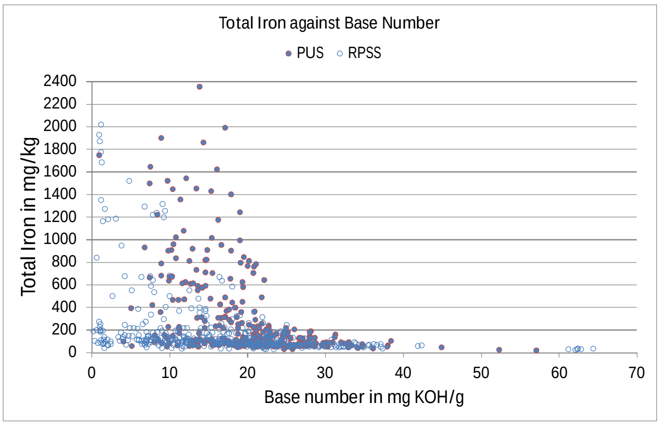


*Figure 8: Comparison of BN measurements and its correlation to Total Iron for several hundred samples using both RPSS and PUS drain sampling method*

From experience of the past years it was obvious that a low iron concentration in the sample indicates low wear of the respective cylinder liner, whereas low is rated as 200 mg iron per kilogram oil sample or below. High values for iron concentration, however, such as 1000 mg/kg or above, indicate severe corrosive attack of the cylinder liner running surface or even, with extremely high values, such as 2000 mg/kg or above, an on-going scuffing between piston ring and liner. Looking at Figure 8, it is quite obvious, that with BN of about 22 mg KOH/g oil sample or higher, no cases appear, where total iron is above 200 mg/kg. Furthermore, it can be seen that results from PUS sample analysis show an even more clear discrimination between the operating modes with or without corrosive attack of cylinder liner running surface at about the same BN compared to samples taken with RPSS. Furthermore, PUS samples are comparable with the mixture of the three ring-pack-spray samples of one unit plus dilution with a certain amount of unused lubricant by scraping effect of the piston rings. This add-on of unused lubricant makes it understandable that PUS values for BN tend to be higher than RPSS values of the same parameter.

Conclusion from the above is that for a BN value of about 22 mg KOH/g or higher, corrosion inhibition for the cylinder liner-running surface is intact, whereas for values below about 22 mg KOH/g corrosion occurs more or less pronounced depending on engine operating conditions. This result gave reason for an immediate information to all operators of Wärtsilä two-stroke marine Diesel engines as can be seen from Figure 9. There it is recommended to measure the BN value regularly at the PUS drains of the main engine and to make sure that the value does not go below 25 mg KOH/g (including a safety margin taking into account the accuracy and repeatability of the measurement method itself). Such target can be achieved by adjusting the cylinder lubrication feed rate and, if necessary, the BN of the cylinder lubricant product. This measure keeps the lifetime of cylinder liners and piston rings up to expected levels even under slow-steaming conditions. However, the saying “the more, the better” is not applicable to two-stroke marine Diesel engine cylinder lubrication. Over-lubrication is causing build-up of hard calcium carbonate deposits on piston crowns, especially on the top land of them, and therefore the recommendation in Figure 9 includes also a upper limit of BN around 50 mg KOH/g PUS drain oil sample that should not be exceeded to avoid such deposit build-up.

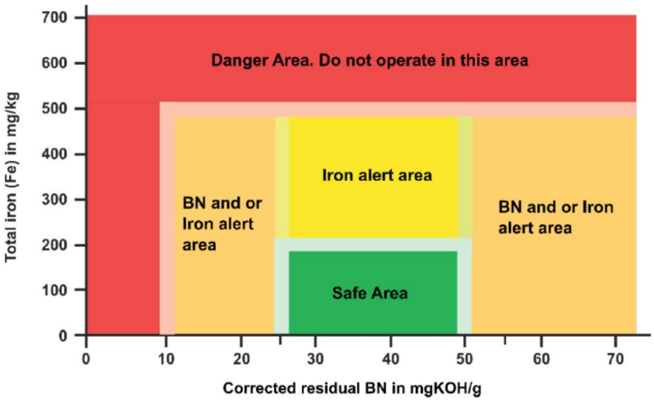


*Figure 9: Information for ship operators, how to keep BN in an appropriate range to protect the engine from excessive corrosive attack and over-lubrication*

Thanks to the above findings, Winterthur Gas & Diesel Ltd. recommends to measure BN on board regularly and regulate the cylinder lubrication feed rate accordingly to prevent the tribology system of piston rings, cylinder lubricant and cylinder liner entering a corrosive regime. In order to make sure that the tribology system does not enter an abrasive or adhesive wear regime, e.g. due to interference by catalytic fines entrained by the fuel, it is still highly recommended to regularly send PUS drain oil samples to a laboratory for analysis to assess the level or total iron and abrasive iron from an independent data source. Visual inspections of piston rings and cylinder liners at port stays are another way to judge the actual state of the tribology system that complement the information obtained from lubricant sample analysis. A guideline to assess the information obtained of such inspections is available in [4].

However, for an optimised engine operation as given above, measurement of BN must be carried out on board vessel. The industry has developed two types of measurement instruments for this purpose, the so-called shaker kit, as an example of many choices available can be seen in Picture 8, and the portable infrared spectrometer, as can be seen in Picture 9.

*Picture 8: Shaker kit for BN measurement*

*Picture 9: Infrared-spectrometer for BN measurement*

A comparison of these two measurement systems can be seen in Table 2.

*Table 2: Pros and cons of available measurement devices for on-board Base Number assessment*

| Measurement system | Advantage | Disadvantage |
|---|---|---|
| Shaker kit | Low first cost | Operator-incurred measurement error probable<br>Consumables (reagent and cleaning fluid) |
| Infrared spectrometer | Operator-incurred measurement error excluded<br>No consumables<br>Capability for multi-parameter measurement<br>Integrated data storage | High first cost |

To obtain optimal effect of the above methodology, BN measurement should be done, whenever a significant load change has occurred, a new batch of fuel is in use or after changing cylinder lubrication feed rate. The more precise the measurement, the closer the limit of 25 mg KOH/g sample can be envisaged. Out of this reason, the use of most precise measurement equipment with least operator-incurred error potential is recommended as given in [5].

Interaction between engine thermodynamics and tribology - Slow-steaming ship operation lead to activities to reduce main engine fuel consumption at low part load operation. One way to achieve such savings is to blind a turbocharger on engines with two or more turbochargers working in parallel. As a two-stroke engine is flow-wise rather an orifice than a pump (like a four-stroke engine is), increasing scavenging air pressure and therefore reducing volume flow does not only influence engine efficiency positively, but restricts the scavenging process of the engine. This yields in larger amounts of exhaust gas remaining in the combustion chamber after the scavenging phase and therefore also more $SO_3$ and water remaining, thus potentially more sulphuric acid to form and to corrode the cylinder liner.

Such effect can be indirectly proven by analysing drain oil from piston underside space as follows: the total amount of iron in a sample is measured by using ICP-AES. Abrasive and therefore magnetisable iron is measured with a so-called Particle Quantifier (PQ). The difference between the ICP-AES value and the PQ index of one particular sample represents corrosive wear. If a series of samples has been taken under comparable conditions and the samples have been analysed by the same lab with the same analysis equipment, it is possible to make comparisons between those samples as can be seen in Figure 10.

To quantify this effect and to evaluate according countermeasures, a field study was carried out. An engine equipped with two regular turbochargers and one turbocharger that could be switched on and off by means of a set of valves was run at several loads once with all turbochargers in operation and once with one turbocharger switched off up to the speed limit of the turbochargers. The results were such as can be seen in Figure 10 that for operation with one turbocharger switched off, corrosive wear of cylinder liner material increased significantly, whenever engine load was above a certain limit. This limit is assumed to be the moment, when scavenging ratio goes below 1, i.e. not enough volume flow is available from the turbochargers to flush the liner completely with fresh air and more exhaust gas remains in the combustion chamber than normal.

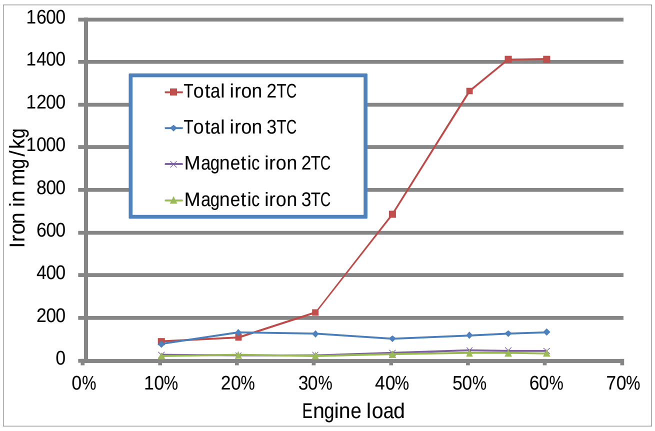


*Figure 10: Comparison of PUS drain oil analysis for slow-steaming engine operation, once with all turbochargers and once with one turbocharger switched off*

Countermeasures against corrosive attack on cylinder liners in engine operation with a turbocharger blinded are manifold:

- Restrict engine load to values with acceptable total iron level
- Increase cylinder lubrication feed rate for engine loads with pronounced corrosive attack
- Use of cylinder lubricant with higher BN for operation with turbocharger blinded.

Similar effects like described above may occur also when applying other measures currently used to achieve fuel consumption saving by reducing the air flow through the engine's combustion chambers as e.g. turbochargers with variable turbine geometry or late timing of exhaust valve opening (nonexhaustive enumeration). The applicable countermeasures are the same as mentioned above.

## CONCLUSIONS

When [2] was published, the tribology system of cylinder liner-lubricant-piston ring for Wärtsilä large-bore marine two-stroke Diesel engines was well optimised for the market situation and requirements at that point in time, mainly focused on engine operation with high power output and continuous use of high-sulphur-containing fuels. In order to overcome the challenges imposed by the new operating regime called slow-steaming as a consequence of shortage of cargo due to a world-wide financial crisis after 2008 and the recently introduced IMO-imposed (International Maritime Organisation) emission regulations for sulphur oxides, which makes it mandatory to use low-sulphur-containing fuels in dedicated sea and coastal areas, innovative methods were needed to further analyse, quantify and consequently optimise the performance of cylinder lubrication system and cylinder lubricant. Thanks to the developed methods as described in this paper and the knowledge gained by numerous tests and measurements, it was possible to further optimise the tribology system for more robustness and reliability regarding corrosive attack due to slow-steaming. Then, this enabled to instruct ship owners and operators on how to choose the appropriate cylinder lubricant depending on fuel in use and how to apply it in the most efficient way by measuring BN on board in order to adjust the cylinder lubrication feed rate according to the requirements imposed by actual engine operating conditions. Furthermore and in parallel, the lubricant suppliers made enormous efforts to widen their product portfolio to comply with the changed conditions in the market.

The investigations presented in this paper yield results that ask for further developments in some design areas. Such developments could go in direction as listed below:

- Cylinder lubrication system with two or more rows of oil quills being able to feed different oil types, e.g. high-BN oil near TDC and low-BN oil below mid-stroke, but with lowest possible feed rate to bring the oil additives to exactly the position on the liner, where they are needed for a specific purpose
- Piston with only two piston rings giving the possibility to use assumingly more expensive high-end coating materials and to place the piston rings at a position in the piston with optimum temperature and heat flux for longest time between overhauls
- Closed-loop control of cylinder lubrication feed rate by means of an online measurement device giving feedback about actual lubricant properties and communicating with the engine control system
- Inclined inlet ports, giving new possibilities for deposit control on the piston top land by removing deposits homogeneously from the piston top land. Excessive deposits on piston head may form as a consequence of over-lubrication
- Piston skirt with active centring function giving new possibilities to reduce tolerance between piston head and cylinder cover. Such reduced tolerance is feasible, if forming deposits on piston top land are constantly removed, e.g. by inclined inlet ports
- Cylinder liner wear sensor for optimised planning of unit overhaul and just-in-time ordering of spare parts.

However, as future findings might reveal other techniques or other ways of implementation, the above mentioned design proposals might be realised in a different way than we think about it today.

Such improvements of engine design will lead to even more robust and reliable products that are easier to operate and less prone to consequences of human error, which is still the most important cause of failures, leaving vessels adrift or stuck in port. Such situations, however, shall be definitely avoided by application of clever design solutions in the future.

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