

Optimization of Tribodynamic Effects to Improve the Reduction Potential of Particulate Matter Concentrations in the Exhaust Gas of Large Two Stroke Marine Diesel Engines

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ABSTRACT

Understanding tribodynamic effects is crucial when aiming to reduce lube oil consumption and related exhaust gas emissions. This report briefly describes the lubrication concept of large two stroke marine diesel engines and different contributors to the lube oil balance of such an engine.

Addressing possible measures to influence the contribution of lubrication system parameters on exhaust gas emissions requires a detailed analysis of possible actions to achieve the expected improvement. Activities to enhance lubrication system performance concentrate on:

- Modifications of relevant engine components
- The application of experimentally gained data to support computational simulation models
- The application of suitable validation approaches

This report in particular highlights piston ring pack optimizations on basis of computational simulation. One major step in developing a new piston ring pack dynamic simulation tool was achieved by implementing two stroke engine specific measurement results of general engine performance data, as well as complex information of tribo- and gas-dynamic effects on piston ring motion and lube oil film.

This report consequently describes experiments which were performed to validate piston ring pack performance in a full scale engine test and lead to improved understanding of tribodynamic effects.

CITATION: Stark, M. and Mittler, R., "Optimization of Tribodynamic Effects to Improve the Reduction Potential of Particulate Matter Concentrations in the Exhaust Gas of Large Two Stroke Marine Diesel Engines," *SAE Int. J. Fuels Lubr.* 7(3):2014, doi:10.4271/2014-01-2844.

INTRODUCTION

Upcoming emission regulations and power demands for large two stroke marine diesel engines call for a detailed investigation focusing on cylinder lubrication impacts on the exhaust gas composition. The content of this paper focuses on recent developments towards the design of an emission optimized lubrication concept, helping to significantly reduce lube oil consumption and related particulate matter concentrations in the exhaust gas.

The described approach involves the application of substantially modified engine components in a full scale engine

test, as well as the application of dedicated measurement technologies combined with intensive simulation activities in order to achieve the desired reduction of lubrication system parameter influences on the exhaust gas composition.

This paper highlights measures to enhance lubrication system performance considering key components of the tribosystem. The main focus in this context is to clearly understand lube oil transportation mechanisms which is supported by adequately describing the interaction between lubricant, piston ring pack and lubrication system in order to highlight the importance of a consistent view upon combined component design aspects.

Another part of this paper covers investigations related to tribodynamic effects on the lube oil flow considering piston ring profile design effects on lube oil transportation mechanisms. Looking at the piston ring profile as an essential design parameter when aiming to control the lubricant flow on the cylinder liner requires advanced measurement technologies to assess hydrodynamic performance parameters such as lube oil film thickness and distribution of the lube oil film. Therefore dedicated sensor applications were further developed to increase accuracy of the measurement system.

ENGINE DESCRIPTION AND OPERATION

Engine testing was performed on a uniflow scavenged four cylinder two stroke marine diesel engine. A cross sectional view and engine details are given in [figure 1](#) and [2](#) below.

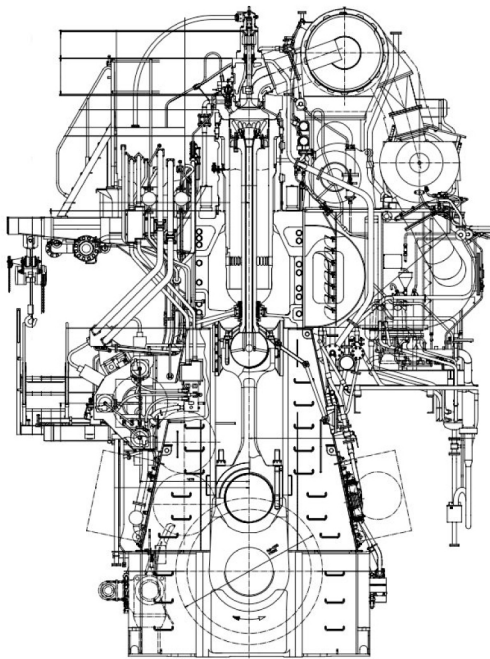


Figure 1. Cross sectional view of the RTX-4 test engine

Engine designation	RTX-4
Year installed	2008
No. of cylinders	4
Cylinder bore, mm	600
Piston stroke, mm	2250
Nominal speed, rpm	114
Break mean effective pressure, bar	21
Mean piston speed, m/s	8,6
Max. cylinder pressure, bar	168
Cylinder power output, kW/cyl.	2540
Power output, kW	10.160
Dimensions, LxWxH,m	11,0x9,7x10,8
Mass, tonnes	200

Figure 2. RTX-4 test engine details

Wärtsilä's RTX-4 test engine is based at the Diesel Technology Center in Winterthur Switzerland. Mentioned RTX-4 is a four cylinder low speed two-stroke engine of 600 mm cylinder bore size which develops 10.160kW at a nominal speed of 114 rpm. The engine features the RT-flex common-rail technology with integrated full electronic control and hence can be considered a powerful research tool to investigate on future technologies.

One of the differences compared to automotive engines can be found in the lubrication system. Electronically controlled lubrication systems are designed to meet appropriately defined lube oil feed rates in order to optimize cylinder lube oil consumption without comprising piston running reliability. Mentioned lubrication systems deliver accurately metered, main engine load and fuel quality dependent quantities of lubricant to the cylinder liner with a very precise timing. This circumstance provides the possibility of adjusting lubrication system parameters on basis of operational requirements.

[Figure 3](#) below shows a schematic of a "Pulse Jet" two stroke lubrication system, a typical setup of a lubrication system applied on Wärtsilä's large two stroke diesel engines. It consists of a lubricant tank, a filter system, lube oil dosage pumps and the lube oil injectors. The cylinder lube oil is applied onto the running surface of a cylinder liner by means of appropriately designed lube oil injectors.

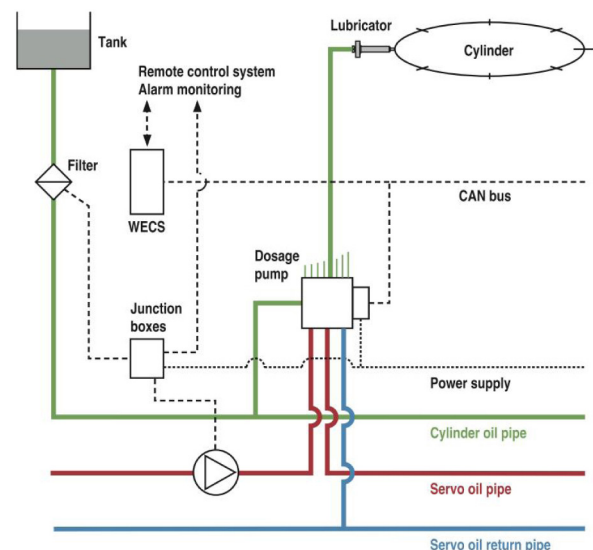


Figure 3. Typical setup of a large two stroke diesel engine lubrication system

The cylinder lube oil is delivered to the injectors by a dosage pump which is powered by pressurized servo oil drawn from the engines system oil circuit. The lube oil feed rate and timing are electronically controlled by a solenoid valve of the dosage pump providing full flexibility in setting the injection timing over the full load range of the engine.

The tribosystem, in this context consisting of piston rings, cylinder liner and lubricant, is designed to evenly distribute the lube oil on the running surface in order to perform obvious

functions like sealing the combustion chamber against the piston underside, to reduce friction and besides this, the most important purpose, to neutralize combustion products like sulphuric acid on the running surface. In order to address neutralization capabilities of the lube oil adequately, adjusting the lube oil feed rate has to be taken into consideration following a function of engine load and the sulphur content of the fuel oil.

Hence, in the design of high quality lubrication systems, factors have to be balanced such as:

- The definition of an appropriate amount and introduction of lubricant
- Controlling wear mechanisms affecting the engine life-time
- Environmental aspects related to the contribution of the lubricant to the exhaust gas composition

Lubrication of large two stroke diesel engines typically is performed on a total loss basis. After lubricating the piston ring - cylinder liner interface, much of the lubricant is lost in the combustion chamber and is removed through the exhaust system. The engine-out emissions of burned or unburned oil are among the shortcomings of this type of two stroke engine and are evident as a serious contribution to particulate matter formation in the exhaust gas. Total engine particulate emissions are generated from fuel and lubricant. Estimates of the amount of particulate matter emissions that can be directly addressed to lubrication performance vary between 40% and 60% [1,2].

LUBE OIL TRANSPORTATION MECHANISMS

Approaching a characterization of different contributors to the lube oil balance of an engine becomes important when aiming at enhancing lubrication performance and reducing its contribution to exhaust gas emissions. It is essential to quantify relevant data helping to estimate lubrication losses referring to present lubrication regimes of the engine. Possible contributors to the total lube oil consumption are shown in [Figure 4](#) below.

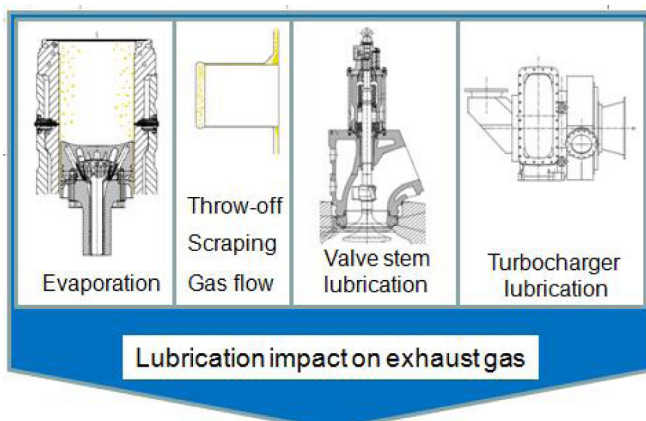


Figure 4. Schematic of a typical 2 stroke diesel engine lube oil balance

Froelund et al have shown, that the piston ring - cylinder liner system is the major contributor to total lube oil consumption [1, 2]. Hence primary lube oil transportation effects necessarily have to be addressed to the piston ring pack - cylinder liner tribosystem, as modifications in this context most significantly influence the desired reduction of lubrication effects on the exhaust gas composition. Consequently it is important to have a closer look at the piston ring pack and evaporation effects on the running surface of the cylinder liner leading to lubricant fractions in the exhaust gas.

[Figure 5](#) schematically demonstrates the main contributors of the tribosystem which most significantly affect the exhaust gas composition and were investigated in detail.

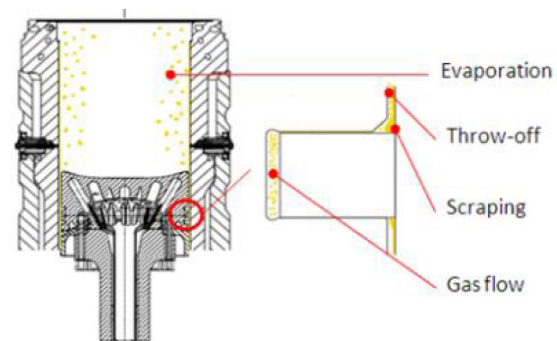


Figure 5. Major lube oil consumption mechanisms

Evaporation of lubricant on the cylinder liner wall is a function of engine load dependent cylinder liner surface temperatures and is considered a major contributor to total lube oil consumption which increases its dominance with higher engine loads, resulting in higher thermal loads on engine components. Different studies show, that volatility of the lubricant plays an important role in terms of a possible reduction of vaporized lube oil on the cylinder liner surface [2]. Lower volatility synthetic oil instead of baseline oil reduces lube oil consumption in higher engine operating conditions. This indicates that evaporation of the lubricant substantially contributes to total oil consumption at high speed and load conditions [2].

Piston ring motion, pressure distribution in the piston ring pack, as well as tribodynamic effects on the lube oil film considerably influence total lube oil consumption as these parameters heavily influence lube oil transportation characteristics of the piston ring pack. Hence optimizing the piston ring pack shows potential to considerably enhance total lube oil consumption. Detailed investigations were performed to determine the interaction between hydrodynamic effects on piston ring motion, gasdynamic effects on the piston ring pack and lube oil distribution related to different piston ring profiles.

In this context a novel piston ring pack simulation tool was developed which provides possibilities to enhance the axial piston ring stability and therewith control the gas-flow in the piston ring pack as well as lube oil transportation. This leads to a superior performance of the piston ring pack [1].

Besides primary effects characterizing the lubrication impact on the exhaust gas, other lube oil consuming effects must not be neglected. These can be subsumed under **lubrication losses** and appear in form of deposits, leakage and secondary effects like uncontrolled lubricant admission through the scavenge air ports as a result of so called ring pack spray.

Lube oil related deposits, most pronounced, appear on the piston crown, the exhaust duct or in the scavenge air receiver. Secondary lube oil consuming effects can be described as a consequence of the nature of the uniflow scavenged two stroke engine and **leakage** inevitably occurs on every moving part of an engine. The advantage of these kinds of losses is that they are more or less constant and not affected by foreseen modification of engine components, lubrication system parameter adjustments or engine load profiles.

The focus in this context relates to a clear determination of piston ring pack performance and associated improvements of total lube oil consumption.

TRIBO SYSTEM COMPONENT DESIGN

Addressing possible measures to influence the contribution of lubrication system parameters on the exhaust gas emissions requires a detailed analysis of possible actions to achieve the expected improvement. Activities to enhance lubrication system performance concentrate on:

- Modifications of relevant engine components
- The application of experimentally gained data to support computational simulation models
- The application of a suitable validation approach

This report hence highlights recent piston ring pack developments in order to comply with future emission legislations.

Piston Ring Pack Design Modifications

A proper prediction of piston ring motion and tribodynamic effects is essential to design a superior piston ring pack in terms of an optimized piston running behaviour and lube oil transportation. Key parameters to focus on are inter-ring pressure related to blow-by values and piston ring motion due to hydrodynamic effects and lube oil properties.

A significant part of performed investigations focus on development and application of suitable measurement technologies to properly validate the piston ring pack simulation model.

One major step in the development of the novel 3D piston ring pack simulation model for large two stroke marine engines was achieved by implementing two stroke engine specific

measurement results of general engine performance data as well as complex information related to tribo- and gas-dynamic effects on the piston ring pack and lube oil film. In the context of properly validating the piston ring pack simulation model, different experiments were designed to address characteristic influences. Rig testing, being the first phase of the generation of suitable database, was designed to provide detailed insights into tribo dynamic effects and lube oil film build up, whereas more coherent data was generated by utilizing the test engine for a full scale engine test.

PISTON RING PACK SIMULATION TOOL DEVELOPMENT

A proper prediction of piston ring motion and hydrodynamic effects is essential to design new piston ring packs in terms of an optimized piston running behaviour and lube oil transportation. Key parameters to focus on are inter-ring pressures related to blow-by values and piston ring motion due to hydrodynamic effects and lube oil properties. One major step towards the successful completion of the 3D simulation model for large two stroke marine engine piston ring packs was accomplished with the implementation of two stroke marine diesel engine specific performance characteristics. Therefore based on the knowledge from 4 stroke engines simulations, the mathematics and structure of the F-M PRiME3D tool was used to implement the specific conditions of a 2-stroke engine [4].

Fast and direct simulation tools are required to understand the interaction between pistons, piston ring and liner systems in a complex mechanical-tribological system. The simulation of piston ring dynamics consists of three major cores that influence each other: The gas flow, the hydrodynamics and the ring motion. Already small variations of single system components can change the whole system completely. Therefore it is very important to investigate the whole field of tolerances to understand the sensitivity of design variations impacting the stability of the real system.

The F-M PRiME3D tool is designed to apply thermodynamic boundary conditions to calculate the gas flows, hydrodynamics and piston ring motion.

The gas flow in the clearance is a subsonic flow, therewith the sound velocity cannot be exceeded. This means also that the impact of the real heat exchange has to be taken into account, an isothermal or adiabatic assumption between the gas particles and the ring and piston flanks are not valid.

Especially for the boundary situation of large bore engines, based on the long strokes and therewith the big variations of liner dimensions between BDC and TDC and on the other hand the circumferential length and wall thickness of the ring design makes it even more important to understand the subsonic gas flow in the system [5]. The subsonic gas flows sets the

boundary condition for a friction based choked flow. With this condition convergent or divergent clearances at the groove flanks have a significant impact on the results. With solving the real gas flow equation, the kinematic acting mechanism for the stability of the piston ring position on the groove flanks can be solved for straight cut gaps [5,8].

The mathematical model of the piston ring motion has to be modulated for the application of a gas tight piston ring gap of the top ring as both gap ends are not longer interacting independently. The motion of the gap ends are blocked partly by each other and will be transferred to torsion to reach a stable position. Normally a piston ring can be modeled as a curved beam with a constant cross section. A piston ring with an overlapping gap instead changes its cross section at the gap ends and therewith the moments of inertia. Consequently the gas flow through the flanks in the area of the gap ends is minimized, but hydrodynamic effects are strongly influenced by the independent barrel faces of the overlapping ring gaps, which leads to a different contact situation and opens possible gas flow areas over the running surface.

Ring Design

Large Bore Engines do not only distinguish from other engines by their size. Due to the specific requirements of those engines like life time, fuel, speed, lubrication etc. several design characteristics and features vary from the other engine concepts. Characteristic design parameters like extreme circumferential length and wall thickness of the ring design have to be taken into consideration carefully to address calculations of the gas flow which is limited by the Mach number.

$$M(x) = \frac{V}{c} \quad (1)$$

Especially in the condition of divergent clearances M reaches its maximum already at the beginning of the gap. For convergent gaps M reaches the maximum at the end of the clearance. By wall thicknesses of up to 24 mm the mathematics of calculating the gas speed has to be adapted to the functions of $p(x)$, $V(x)$, $T_s(x)$ and $A(x)$ inside the clearance to get the real result for the position related pressure on the piston ring. The flow rate is constant in the gap, but the gap geometry has a significant influence for the gas pressure, on the other hand the function $p(x)$ influences the forces and moments of the ring and therewith directly the gap geometry.

Engine Kinematics

To obtain realistic simulation results for the 2-stroke engines, some major changes or adjustments were necessary to solve the kinematics of slow rpm's and long strokes combined with the special conditions of the oil distribution.

Due to the size of Large Bore Engines the engine speeds are much slower than the speeds of automotive engines (up to 40 times slower) but the strokes are also up to 20 times longer.

For that reason calculation steps were set to a specifically defined crank angle width, which means that the time increments become larger. To be able to keep the high accuracy of the program, those time increments had to be reduced by an extension of the software with multiple elevations of the resolution.

A typical simulation run for automotive applications returns about 10 million single values. Applying the modified simulation model for slow speed two stroke engine designs returns about 50 million single values per simulation run which increases the predictive capability of the simulation tool considerably

Hydrodynamics

Piston ring height and the nature of lube oil injection of large two stroke marine diesel engines considerably affect the piston ring profile design. The piston ring profile is described by large curvatures with pivoting points in either symmetrical or asymmetrical positions. The particular lubrication approach in this context calls for solving the Reynolds's differential equation no longer with a numerical relaxation method. Numerical relaxation methods allow reaching continuous transitions of pressure by Reynolds, but violate the condition of continuity of the oil flow. Introducing constant variables f and h in Formula 2 solves this problem, where f describes the oil flow and h represents the additional oil flow from the displacement when the ring surface changes its distance from the cylinder liner wall.

$$\frac{d}{dx} \left(\frac{h^3}{12\mu} \frac{dp}{dx} + U_s \frac{h}{2} \right) = \frac{d}{dx} (-f) + \frac{dh}{dt} \quad (2)$$

Additional to the oil flow in vertical direction, it is necessary to address circumferential flow directions as well, depending on the amount and position of the oil injection points.

Lube Oil Distribution

To analyze lube oil distribution effects related to piston ring profiles, a mathematical model was developed to calculate the oil flow based on the components and resulting pressure distribution. It is clear that the main flow is distributed in vertical direction whereas only app. 1% of the lube oil is distributed circumferentially. Fig.16 shows that a circumferential component of the oil flow can only build up if a difference in hydrodynamic pressure is present in circumference. Mentioned pressure distribution occurs as a consequence of the application of lube oil distribution grooves in the cylinder liner, as well as cylinder liner distortion [6].