Cylinder lubrication of two-stroke crosshead marine diesel engines

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The two-stroke crosshead diesel engine has, for many years, been the preferred prime mover for larger seagoing merchant vessels. This article discusses means of improving piston running and reducing cylinder oil consumption in these engines.

There are a number of reasons for the success of the two-stroke crosshead diesel engine in marine applications:

- It provides a speed and torque that exactly meets the demand of the propeller, i.e. no intermediate gear is needed.
- It is easy to maintain.
- It is – still today – by far the most efficient stand-alone working machine.
- It can operate on heavy fuel oil, which is basically a residual from the crude oil refinery process, and hence much less expensive than refined oil products.

The challenge posed by fuel

Compared with "lighter" diesel fuels, heavy fuel oil (HFO) has a relatively high viscosity. It also contains a number of substances and components that can be harmful to both the engine and the environment if their maximum allowed contents are exceeded, or if not treated properly.

However, residual marine fuels are categorised in international standards, and all marine engine designers have their recommendations as to which types of fuels can be applied in a particular engine, and how these fuels shall be treated and conditioned before entering the engine.

Every time a vessel bunkers fuel, the ship's chief engineer is given a bunker certificate with a chemical analysis and information about the fuel's viscosity and density. From this he can see whether or not the fuel is in compliance with the engine →

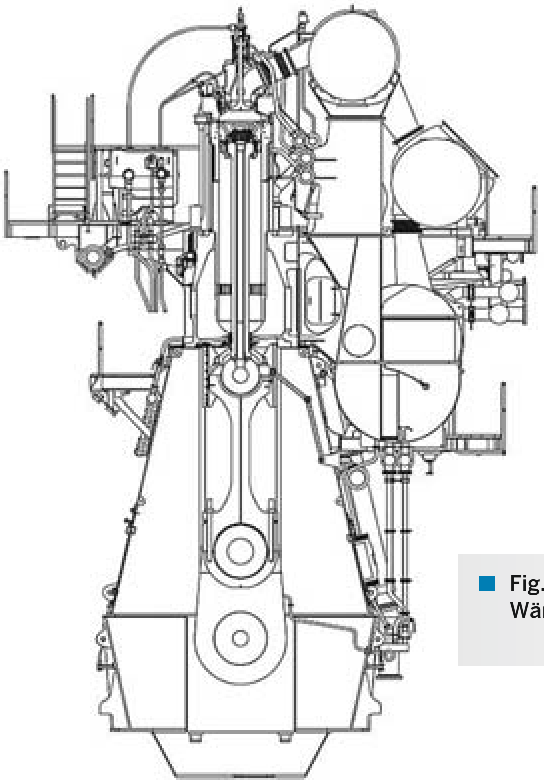


Fig. 1 – Cross section of Wärtsilä RT-flex82C.

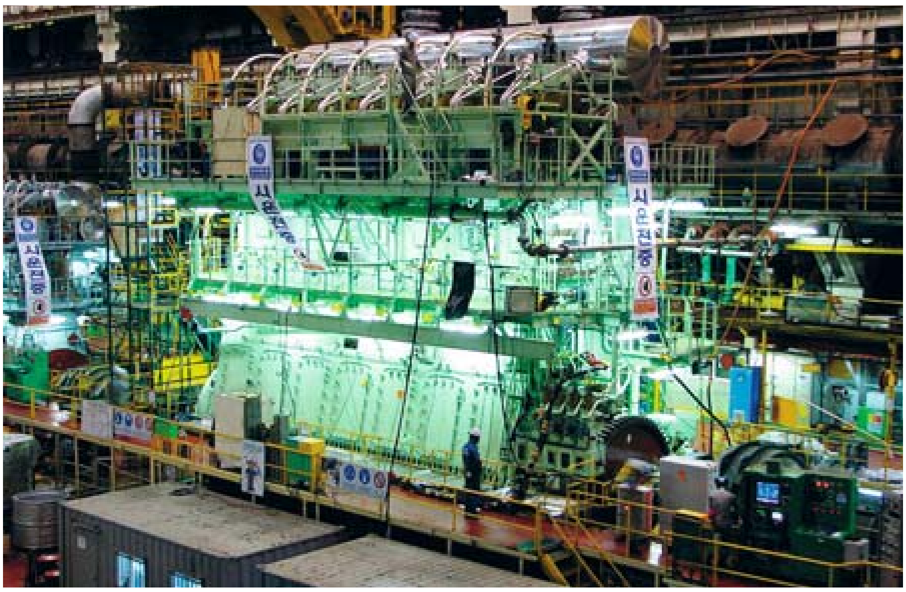


Fig. 2 – Wärtsilä 7RT-flex82C on test bed.

designer's recommendations, and how the on board fuel treatment plant needs to be adjusted.

For environmental reasons, marine diesel engines must be capable of operating on the whole range of diesel fuels. This creates numerous challenges to the machinery on board, and to the engines themselves.

From an engine reliability point of view, and particularly from a piston running point of view, there are two major "enemies" when the engine is operated on HFO:

- Catalyst particles from the refining process
- The natural sulphur content.

In some HFO bunker lots, the content of catalytic particles, also known as "catalytic fines" or simply "cat fines", from the refining process can be extraordinarily high.

These catalyst particles consist mainly of aluminium and silicon oxides typically ranging in size from 10 to 20 µm. They are extremely hard and, therefore, abrasive. If they are allowed to enter the engine, they can cause severe damage to the fuel injection system, as well as to the piston rings and cylinder liners.

To safeguard the engine against such cat fine damage, the allowed maximum content (as Al and Si equivalents) in marine diesel fuels has been set as an international standard. However, it is most important that the centrifuges and filters in the vessel's on board fuel treatment plant are correctly dimensioned and properly working at all times.

Crude oil has a natural sulphur content, which will remain in the heavier fractions of refinery products such as marine diesel fuels. The average sulphur content in HFO worldwide is around 2.8% (of mass), but HFO with a sulphur content of up to 4.5%, which is also the allowed upper limit, is occasionally bunkered.

Today there are no economically viable methods, either at the oil refineries or on board ship, to separate the sulphur from marine diesel fuels. This means that the sulphur cannot be prevented from entering the engine's fuel injection system and combustion space.

Sulphur is an excellent lubricant for the moving parts in the fuel injection

Table 1. – Wärtsilä fuel recommendations.

Parameter	Unit	Bunker limit ISO 8217: 2005 class F, RMK700	Test method *1)	Required fuel quality Engine inlet
Density at 15 C	[kg/m^3]	max. 1010 *2)	ISO 3675/12185	max. 1010
Kinematic viscosity at 50 C	[mm^2/s (cSt)]	– 700	ISO 3104	13–17 –
Garbon residue	[m/m (%)]	max. 22	ISO 10370	max. 22
Sulphur	[m/m (%)]	max. 4.5	ISO 8754/14596	max. 4.5
Ash	[m/m (%)]	max. 0.15	ISO 6245	max. 0.15
Vanadium	[mg/kg (ppm)]	max. 600	ISO 14597/IP501/470	max. 600
Sodium	[mg/kg (ppm)]	–	AAS	max. 30
Aluminium plus Silicon	[mg/kg (ppm)]	max. 80	ISO 10478/IP501/470	max. 15
Total sediment, potential	[m/m (%)]	max. 0.10	ISO 10307-2	max. 0.10
Water	[v/v (%)]	max. 0.5	ISO 3733	max. 0.2
Flash point	[°C]	min. 60	ISO 2719	min. 60
Pour point	[°C]	max. 30	ISO 3016	max. 30

Remark: *1) ISO standards can be obtained from the ISO Central Secretariat, Geneva, Switzerland (www.iso.ch).
*2) Limited to max. 991 kg/m3 (ISO-F-RMH700), if the fuel treatment plant (Alcap centrifuge) cannot remove water from high density fuel oil (excludes RMK grades).
– The fuel shall be free from used lube oil, a homogeneous blend with no added substance or chemical waste (ISO8217:2005–5–1).

system and has no negative impact on the combustion process. However, in combination with water it creates sulphuric acid, which is highly corrosive. In other words, since it cannot be eliminated before entering the engine, it must be dealt with and controlled by other measures, as we will see later on.

Cylinder lubrication

For marine diesel engines operating on residual fuels containing sulphur, cylinder lubrication must generally serve the following purposes:

- Create and maintain an oil film to prevent metal to metal contact between the cylinder liner and piston rings.
- Neutralise sulphuric acid in order to control corrosion.
- Clean the cylinder liner, and particularly the piston ring pack, to prevent malfunction and damage caused by combustion and neutralisation residues.

The four-stroke trunk piston engine case

In four-stroke trunk piston engines, there are a number of different methods for lubricating the cylinder liners and piston rings, depending on engine size and make:

- Splash from the revolving crankshaft
- "Inner lubrication", where the oil is supplied from the piston side
- "Outer lubrication", where the oil is supplied by an external, separate cylinder lubricating device from the cylinder liner side.

In a four-stroke trunk piston engine, the cylinder lubricating oil is identical to the engine system oil used for bearing lubrication and cooling purposes.

A small amount of the cylinder lubricating oil by-passes the piston rings and ends up in the combustion space, where it is "consumed". However, the piston in a four-stroke trunk piston engine has an oil scraper ring that scrapes most of the oil supplied to the cylinder liner back to the engine's oil pan, from where it is drained, cleaned and recycled.

Normally, a large, modern, well maintained four-stroke trunk piston diesel engine will consume some 0.3 to 0.5 g/kWh of lubricating oil.

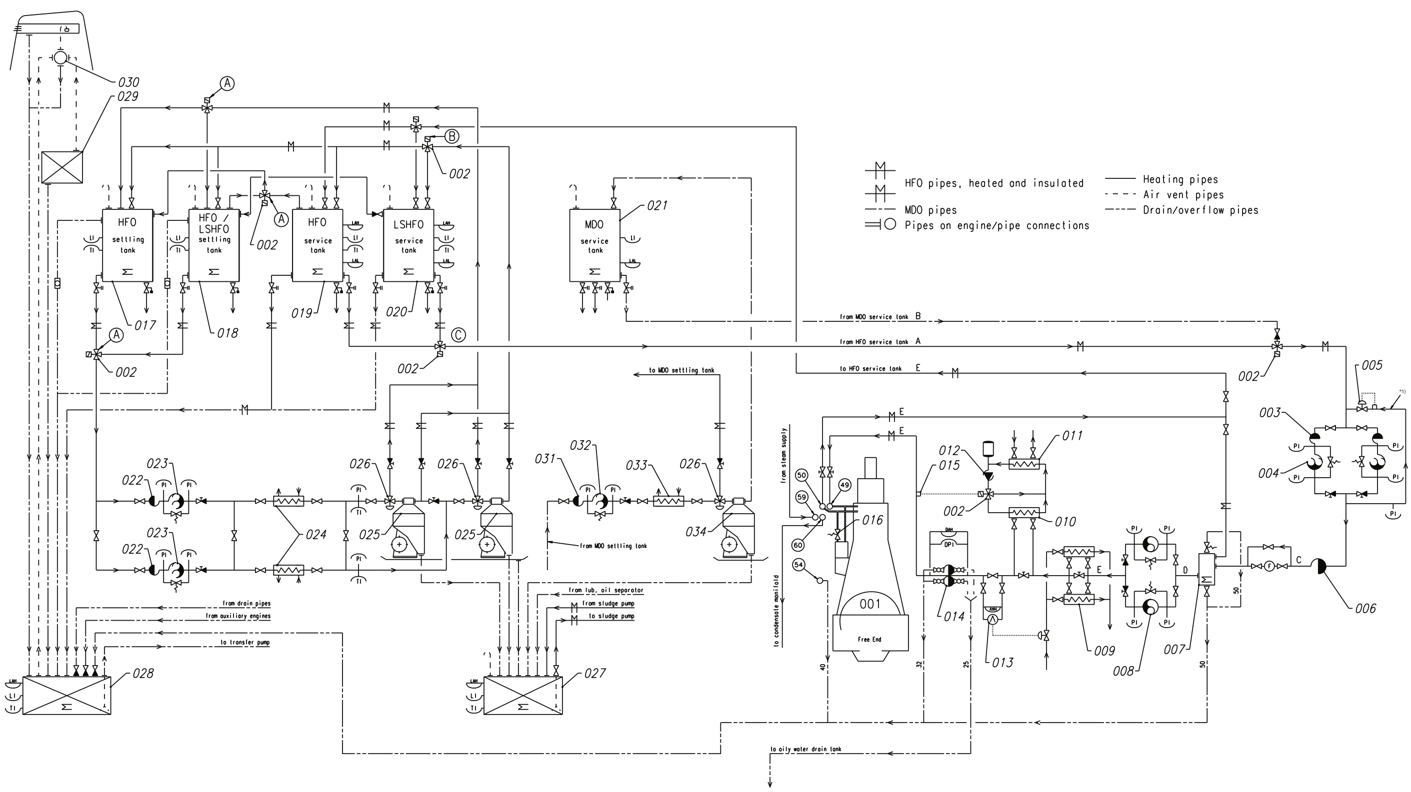
The two-stroke crosshead engine case

In the four-stroke trunk piston engine, the cylinder liner is virtually "over-lubricated" with, as mentioned above, an oil scraper ring on the piston scraping the surplus oil back to the oil pan. However, as can be seen in Figure 1, the two-stroke crosshead engine has no connection between the piston underside space and the bedplate with the oil pan, and hence cylinder lubrication differs considerably from the four-stroke trunk piston engine.

In the two-stroke crosshead engine, the piston has no oil scraper ring and the cylinder oil is not recycled and reused, i.e. once it has left the lubricating device it is virtually "lost", which means that the dosage of cylinder oil is crucial.

The cylinder lubricating oil in a two-stroke crosshead engine is – regardless of engine size and make – usually supplied from an external, separate cylinder lubricating device via quills in the cylinder liner. →

Fig. 3 – Example of on board fuel treatment plant.



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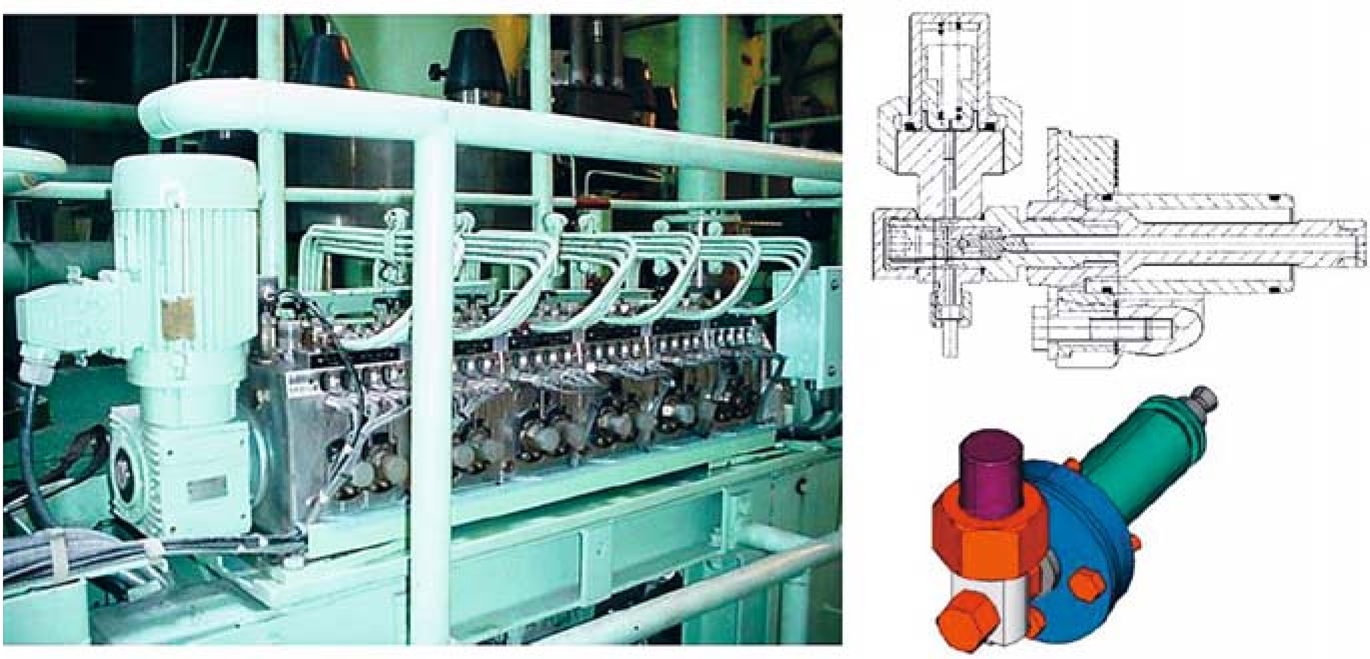

Fig. 4 – CLU3 system.

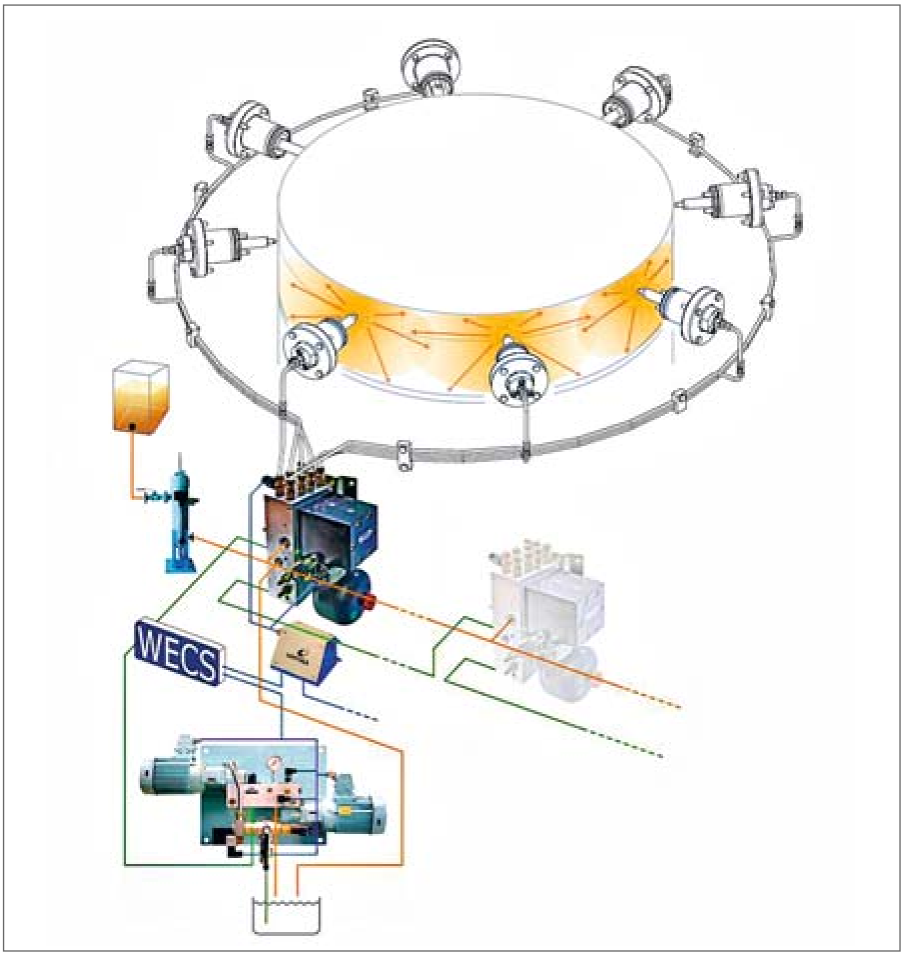

Fig. 5 – Pulse lubricating system.

Special two-stroke cylinder lubricating oil

In the two-stroke crosshead engine, the separation between the piston underside space and the bed plate with the oil pan allows the use of special cylinder lubricating oils, tailored for the cylinder condition and the fuel used. This provides a certain flexibility, which the four-stroke trunk piston engine does not have.

Two-stroke cylinder lubricating oil is mainly characterised by:

- Viscosity grade → Normally SAE50.
- Base Number (BN) → The BN corresponds to the content of alkaline additives, which are used for neutralising the sulphuric acid. When operating on fuels containing 1.5 to 4.5% of sulphur, BN70 oil is normally used, but when operating for longer periods on fuels with a lower sulphur content, a lower BN (BN60, BN50 or BN40) is recommended.
- Detergent additives → The ability to clean the cylinder liner and piston ring pack and minimise deposit formation.

Dosage

As mentioned above, the cylinder lubricating oil dosage is vitally important in a two-stroke crosshead engine. The challenge is to make the oil properly and efficiently fulfil its tasks before it is “lost”, partly to the combustion space where it is burned, and partly to the piston underside space as sludge.

For more than 20 years, CLU3 was the standard cylinder lubricating oil dosage system on Wärtsilä two-stroke crosshead engines. The CLU3 system was developed in co-operation with the German company Vogel (today SKF). It consists of a multi-element pump unit driven by an electric motor, and a so-called progressive distributor for each cylinder unit with a number of quills with a small spring loaded membrane accumulator.

The multi-element pump unit supplies the cylinder lubricating oil to the progressive distributors, ensuring equal distribution of the oil to each individual quill. The oil is accumulated in the quills, and when the pressure inside the cylinder at the quill level, which is normally located in the upper third of the cylinder liner, is sufficiently low, the oil is released by the spring force of the membrane accumulator.

The CLU3 system releases a small amount of oil to the cylinder liner in each engine cycle, but the release of the oil is not timed. The feed rate is controlled by disc settings in the multi-element pump unit, and by varying the rotational speed of the driving electric motor.

The CLU3 system is simple, robust and very reliable, but normally requires a cylinder lubricating oil feed rate in the range of 1.0 to 1.6 g/kWh.

Due to the increasing price of cylinder lubricating oil, for exhaust gas emission and environmental impact reasons, and following the introduction of the Wärtsilä RT-flex engine concept, there has been a need to find a successor to the CLU3 system. The successor product should fit into the concept of the electronically controlled engine, but should also be applicable to the conventional Wärtsilä RTA engine and – most importantly – should facilitate lower cylinder lubricating oil consumption.

Development work for a new cylinder lubricating oil dosage pump was again carried out in co-operation with Vogel, and in 2006 the CLU4 pump and Pulse Lubricating System (PLS) were introduced.

The PLS comprises one CLU4 pump and 6 to 8 quills per cylinder unit. It further comprises a 50 bar servo oil system, which actuates the CLU4 pumps, and a control system.

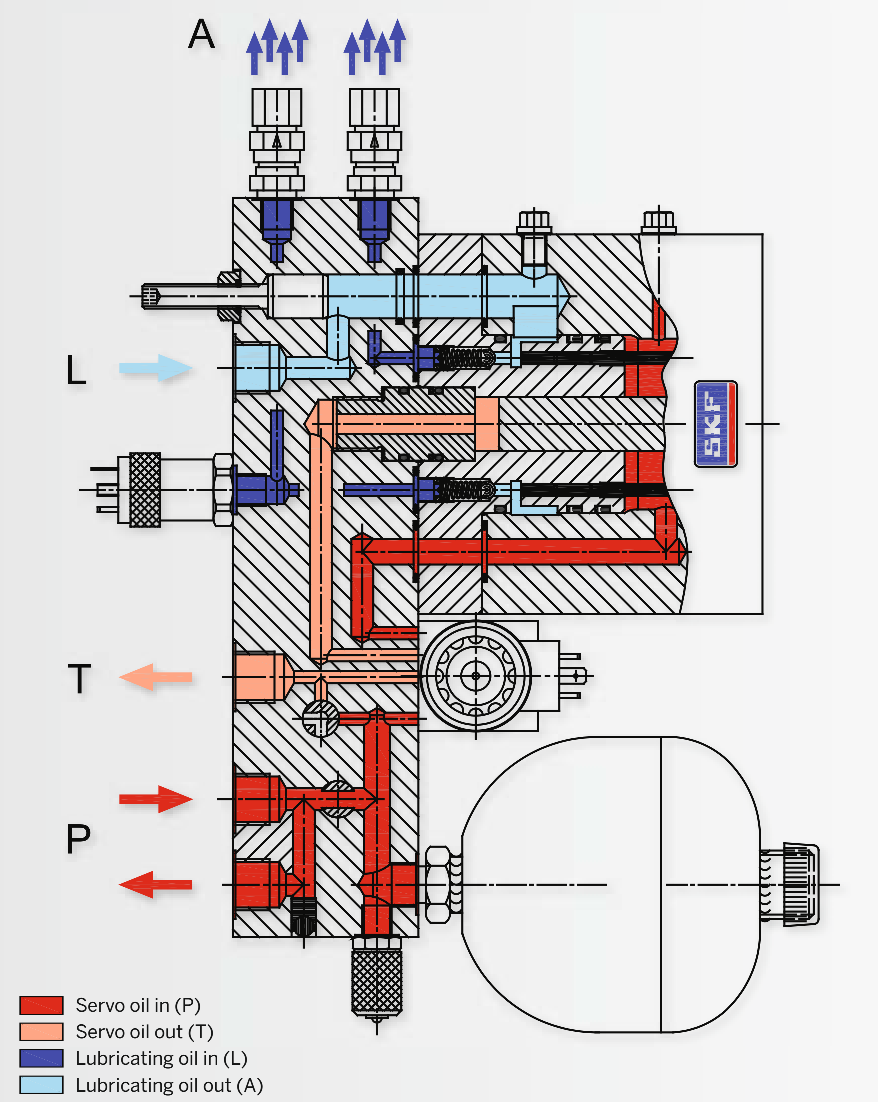

Fig. 6 – CLU4 pump.

The CLU4 pump is a hydraulic, positive displacement device, with a number of independent cylinder lubricating oil outlets corresponding to the number of quills in the cylinder liner. The pump piston is driven by servo oil, which is pressurised to 50 bar, and when the 4/2 solenoid valve is activated, the pump piston delivers a fixed, pre-defined amount of cylinder lubricating oil to each quill in the cylinder liner. When the 4/2 solenoid valve is de-activated, the pump piston returns to its starting point, the cylinder lubricating oil chambers are re-filled from the gravity tank, and the pump is on stand-by for the next delivery stroke.

As in the CLU3 system, the quills of the PLS are mounted in the upper third of →

the cylinder liner, but thanks to the CLU4 pump, the injection of cylinder lubrication oil is independent of the pressure in the cylinder. This injection time is in the range of 8–10 ms, and thus a timed injection is possible, i.e. it is possible to inject the cylinder lubricating oil into the piston ring pack when the piston rings pass the quill level, which is the basic philosophy of the PLS.

As mentioned above, the CLU4 pump delivers a fixed, pre-defined amount of cylinder lubricating oil to each quill with each pump stroke. The control system continuously measures and calculates the actual engine load, speed and crankshaft position, and based on the requested feed rate, calculates the necessary injection frequency. The maximum injection frequency is once each engine revolution, and the cylinder lubricating oil is always injected during the upward stroke of the piston.

The Pulse Lubricating System with the CLU4 pump has proven to be as robust and reliable as the CLU3 system, but is superior in terms of flexibility, and it facilitates a cylinder lubrication oil feed rate in the range of 0.7 to 0.9 g/kWh, which is substantially below the CLU3 level.

Distribution

Once the dosage pump has delivered the cylinder lubricating oil via the quills in the cylinder line to the piston ring pack, the key to success is to facilitate and ensure a proper distribution of the oil on the cylinder liner running surface.

The challenge is not only to ensure that the oil film on the cylinder liner wall is well maintained, but also continuously refreshed in order to provide sufficient additives for the acid neutralization and cleaning processes.

For example, the Wärtsilä 84T engine has a bore of 84 cm and a stroke of 315 cm. Each cylinder liner, therefore, has a running surface of 8.3 m^2 to be lubricated. Each cylinder liner has 8 quills equally distributed at the same level 900 mm from the top, the cylinder oil dosage pump delivers 310 mm^3 to each quill per stroke, and depending on the engine load and the applied cylinder oil feed rate, the dosage pump injects every 2 to 5 engine revolutions. Consequently, a very large cylinder liner running surface has to be maintained by means of a very small amount of oil.

How is this possible when the cylinder oil must be distributed both vertically and horizontally?

The vertical distribution of the cylinder oil is mainly performed by the piston rings during their reciprocating movement. The cylinder oil is injected into the piston ring pack during the piston's upward stroke, and factors such as oil viscosity and feed rate, as well as the amount of oil per injection are important here. A correct viscosity is important in order to ensure the spreadability of the cylinder oil, and the applied feed rate and injected amount of oil per stroke are key factors in the delicate balance between under- and over-lubrication:

- Under-lubrication → If too little cylinder oil is supplied, starvation will occur which might result in corrosion, accumulated contamination from unburned fuel and combustion residues, and in the worst case, metal to metal contact, known as "scuffing".
- Over-lubrication → If too much cylinder oil is supplied, the loss of fresh, unused oil in the scavenge ports will be high, and the piston rings might be prevented from moving (rotating) in their grooves by the so-called "hydraulic lock". Furthermore, the cylinder liner running surface structure might over time become closed and smooth like a mirror, and will no longer be able to retain the lubricating oil. This is sometimes called "chemical bore polish", and when alkaline deposit build-up on the piston top land from excessive cylinder oil is in contact with the cylinder liner running surface, it can cause what is sometimes called "mechanical bore polish". All of these phenomena might eventually result in scuffing.

In attempting to achieve the best possible horizontal or circumferential distribution of the cylinder oil, the first execution of the quill for the Pulse Lubricating System was the so-called Pulse Jet.

The Pulse Jet quill could deliver the cylinder oil either into the piston ring pack or directly to the cylinder liner running surface, and was expected to provide safe and reliable operation.

Service experience, however, revealed a number of piston running problems and scuffing incidents, particularly on the 96C engines. The Pulse Jet principle was then replaced by the so-called Pulse Feed

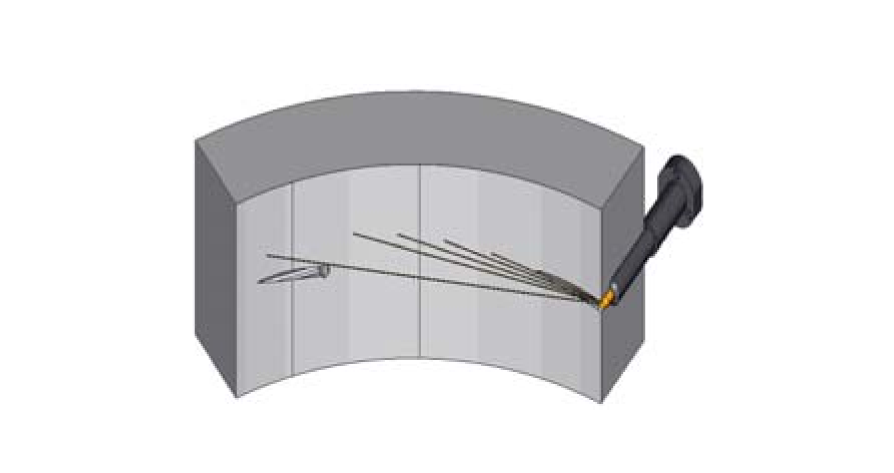

Fig. 7 – Pulse Jet principle.

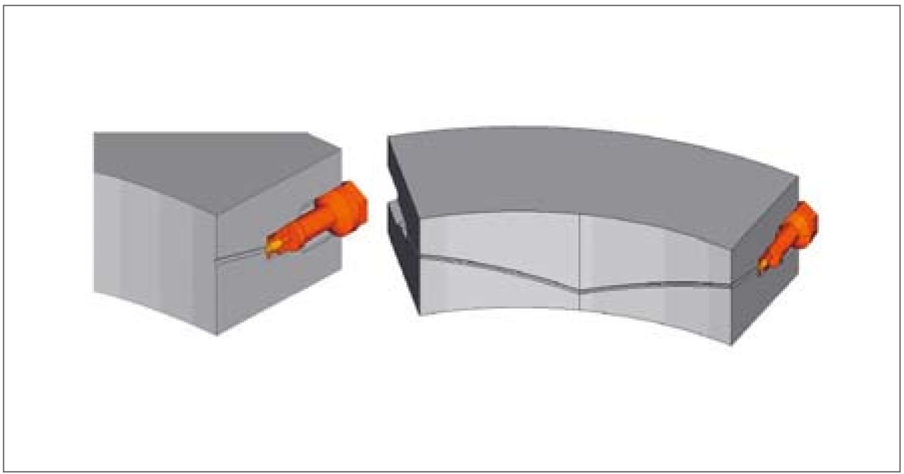

Fig. 8 – Pulse Feed principle with and without “zig-zag” distribution groove.

principle, which had shown good performance on engines where the old CLU3 systems had been retro-fitted with the PLS.

Nevertheless, here too there were problems. Initially the cylinder liner just had outlets from the quills, but soon it became obvious that some additional aid was needed to achieve a proper horizontal distribution of the cylinder oil, and consequently the so-called “zig-zag” groove between the quills was introduced.

As the piston passes the “zig-zag” groove, the groove makes a short circuit and the pressure difference transports the oil concentrated at the quill outlet towards the groove.

The “zig-zag” groove principle has proven to work very well after it was retro-fitted to a high number of large bore cylinder liners →

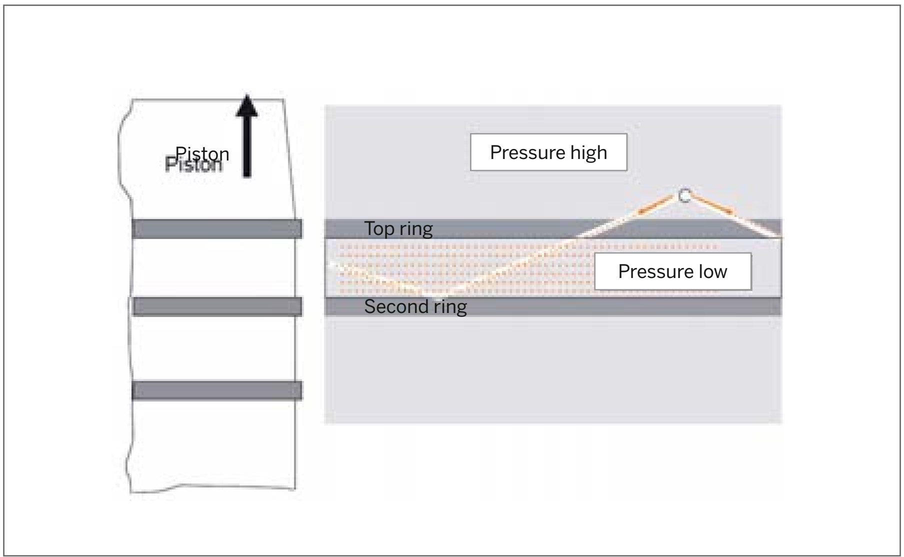

Fig. 9 – Function of the “zig-zag” distribution groove.

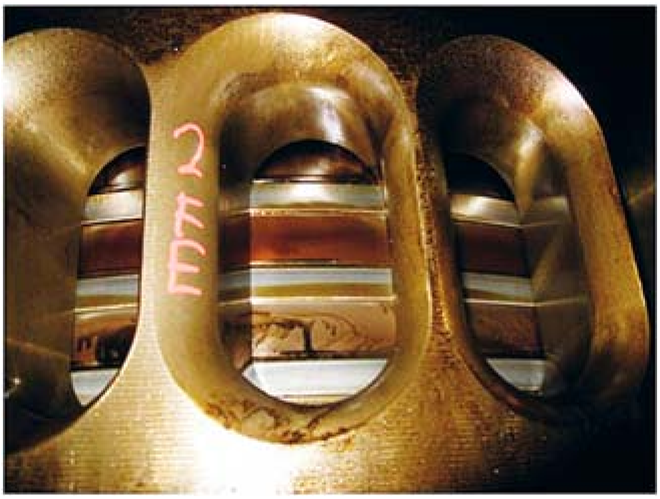

Fig. 10 – Example of good condition.

Fig. 11 – Example of poor condition.

in service. With its introduction, piston running problems and scuffing incidents were substantially reduced, and today it is standard in all Wärtsilä two-stroke cylinder liners.

Surveillance

Today's two-stroke cylinder lubricating systems are essentially pure feed-forward systems, i.e. there are no sensors in the cylinder liners to inform the control system of the actual piston running condition, and to enable the control system to react intelligently in case something is wrong.

Consequently, the cylinder lubrication of a two-stroke crosshead marine diesel engine is highly empirical. Based on thousands of running hours and numerous inspections of different engines, both on test beds and in service, comprehensive instructions with recommendations for handling various situations are available, but at the end of the day it is up to the chief engineer and his crew to monitor the situation and react accordingly.

Today some vessels have the means to measure the BN and iron content of the oil in the piston underside space, and thereby get an indication of the piston running condition. However, the best – and most recommended – way to keep the piston running condition under surveillance is to carry out regular piston underside inspections, where cylinder liners, pistons and piston rings are visually inspected through the scavenge ports.

Wärtsilä offers a piston running surveillance system, known as the MAPEX system, which can be installed on all new engines, but also retro-fitted to engines already in service. This system measures the temperature in two diametrically opposite positions near the running surface in the upper part of each cylinder liner. It then filters and interprets the development of the temperatures, and in case the temperature level escalates, a “high friction alarm” is generated. The alarm alerts the engine crew only, and is not applied in the cylinder lubrication control system.

Economical and environmental aspects

More than ever before, ship owners and operators are focusing on their operational costs, and cylinder lubricating oil costs have become extremely relevant.

Example:

A 6500 TEU container vessel has a 12-cylinder Wärtsilä RTA96C main engine with a MCR power of 63,000 kW. The main engine operates 6000 hours per year at an average load of 65% of MCR. It uses a CLU3 cylinder lubricating system, and the average cylinder lubricating oil feed rate is 1.2 g/kWh.

- CLO consumption = 63,000 x 0.65 x 6000 x 1.2 / 1,000,000 = 295 tons/year
- One metric ton of cylinder lubricating oils cost approximately 1750 USD, meaning: CLO operational cost = 295 x 1750 = 516,000 USD/year

In 2006, when the CLU4 cylinder oil dosage pump and the Pulse Lubricating System were introduced, it became possible to substantially reduce the cylinder oil feed rate, down to approximately 0.8 g/kWh.

PLS became the standard cylinder lubricating system, and was installed on new buildings from May 2006 on. In parallel, however, Wärtsilä developed and introduced the Retrofit Pulse Lubricating System (RPLS). The idea of the RPLS was to offer an upgrade of the old CLU3 based system to a modern CLU4 based system on engines already in service. This offered the potential for significant cylinder lubricating oil cost reductions.

With the specific cylinder lubricating oil consumption reduced from 1.2 to 0.8 g/kWh, the figures from the above example now become:

- CLO consumption = 295 / 1.2 x 0.8 = 197 tons/year
- CLO operational cost = 197 x 1750 = 345,000 USD/year

Thus the annual savings would be:

- CLO consumption = 295 – 197 = 98 tons
- CLO operational cost = 516,000 – 345,000 = 171,000 USD

The first RPLS installation was commissioned and entered into service on a 12-cylinder Wärtsilä RTA96C engine in September 2006. Since then it has been fitted to some 150 engines, to the benefit of both RPLS customers and the environment.

As can be seen, the feed rate reduction results in almost 100 tons less of cylinder lubricating oil being consumed per year. This means - for this particular engine - 100 tons less harmful emissions per year, partly as gases and particulates to the atmosphere from the funnel, and partly as sludge from the piston underside space, which must be removed and incinerated.

Outlook

Because of constantly changing boundary conditions, such as engine specifications towards higher ratings, specifications of fuels and lubricants, legislation, and market prices in general, there will be a continuous need for understanding and improving piston running as well as for reducing cylinder oil consumption.

During recent years, Wärtsilä has developed and tested some very promising tools and methods for assessing the performance of cylinder lubricating systems. From this we have gained a lot of new knowledge and experience, not only about the cylinder lubricating systems themselves, but also about the cylinder lubricating oil.

These tools and methods are today intensively applied for improving and optimising our current systems, and they will be huge assets in the development of future systems. Furthermore, they will help us to support the oil companies in their development of new and improved formulations of cylinder lubricating oils. The focus areas are:

- Distribution and refreshment of the oil on the cylinder liner running surface
- Influence of the fuel's sulphur content on the cylinder lubricating oil's performance
- Influence of engine operation at very low load over longer periods of time
- Influence of engine operation in areas with high ambient humidity
- Investigation of the stress level of the oil on the cylinder liner running surface.

The outcome of the above mentioned focus areas is expected in the short to medium term range. On the slightly longer term perspective , Wärtsilä is involved in a number of activities under the umbrella of HERCULES BETA, a joint development project funded by EU, where the main focus areas are:

- Development of a test rig for intensive studies of the lubricating oil film between a piston ring segment and cylinder liner segment under various conditions, such as contact pressure, piston ring speed (up to 15 m/s) and liner surface temperature (up to 350 °C).
- Development of sensors and methods for dynamic cylinder lubricating oil film thickness measurements on the Wärtsilä RTX4 test engine.
- Development of a mathematical model for advanced simulation of lubricating oil film behaviour.

Also, a number of activities are ongoing on the applied hardware and component side.

For the upcoming 35 and 40 bore Wärtsilä RT-flex engines, a new cylinder oil dosage pump is currently being developed in co-operation with SKF. This new dosage pump, which has been named CLU5, will be double acting in order to fulfil the demands for dynamics and extended time between overhauls, and will be capable of delivering the cylinder lubricating oil into the piston ring pack within 3–4 ms in order to ensure correct injection timing and thus a low feed rate.→

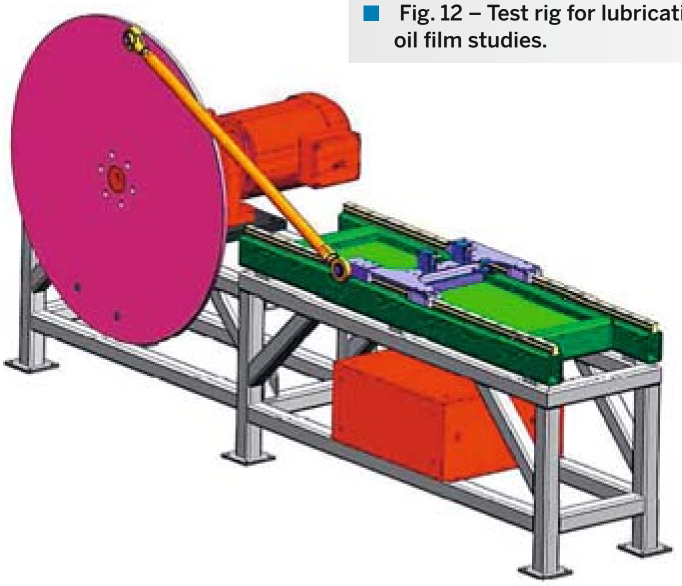

Fig. 12 – Test rig for lubricating oil film studies.

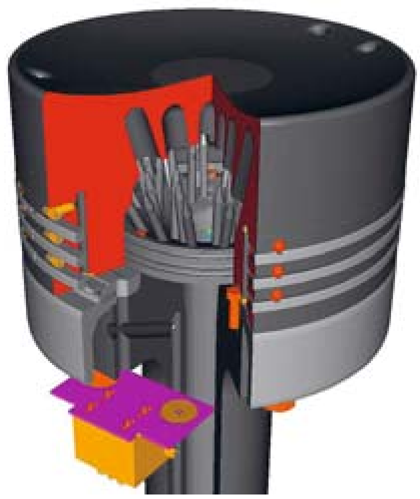

Fig. 13 – Instrumented piston for Wärtsilä RTX4 .

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Some years ago, an Inner Lubrication System concept was studied at Wärtsilä, and a prototype was developed and tested with positive results. Based on this, and on some good results from applying an oil scraper ring in the piston ring pack on a Wärtsilä RTA96C engine, where an oil supply from the piston side might be advantageous, it has been decided to take this concept up again and develop it to a commercially applicable level.

A slightly more ambitious idea is to apply the four-stroke trunk piston engine cylinder lubrication concept to the two-stroke crosshead engine, i.e. to "over-lubricate" the cylinder liner, apply an oil scraper ring, and then collect the surplus oil, clean it, and recycle it. This will of course be a radical change of concept, and whether or not it is viable remains to be demonstrated, but an outline exists and a patent is pending. The aim is to increase scuffing resistance and to achieve the same low specific oil consumption level as on the four-stroke trunk piston engines.

Closing remarks

In many ways, the two-stroke world is quite different from the four-stroke world, and this is particularly the case, when it comes to the testing and validation of new components and systems. A four-stroke engine can be operated on a test bed for a considerable number of hours within a reasonable budget, but this would not be the case for a two-stroke engine, at least not for a large bore, multi cylinder one.

Therefore, most testing and validation of new two-stroke components and systems must be carried out in service, and a prerequisite for our development work is to have access to a number of vessels, which requires good relations with owners and operators.

Testing and validation in service is very often both a time consuming and slow process, because it requires thousands of running hours. In many cases it would be desirable to accelerate this process, and modern advanced computer simulation tools are becoming more and more precise and useful in complement to field tests, but in the meantime we still need to rely on full-scale measurements on board ship.

Fig. 15 – Inner Lubrication System.

Fig. 14 – CLU5.