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Design and experimental development of a new electronically controlled cylinder lubrication system for the large two-stroke crosshead diesel engines

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Abstract: Accurate, stable and reliable lubrication for the cylinders is very important to ensure the trouble-free operation of the marine diesel engines. A new electronically controlled cylinder lubrication system has been developed to remedy the defects of the conventional mechanical lubrication system. This new system's design method, composition and implementation are described. The sensitivity tests are conducted on the test bench and the verification tests are also fulfilled on operating vessels. The main performance data are as follows: oil injection pressure about 3.0MPa; oil injection timing precision 0.1ms; oil injection duration 15°CA or less. The oil injection concentrates onto the piston rings pack to ensure the good lubrication and neutralization, and the oil injection frequency is regulated according to engine load, the sulphur content in fuel, TBN of cylinder oil, cylinder liner running-in condition and so on. This results in the cylinder oil consumption rate falling approximately 25% compared with that of the conventional mechanical lubrication system. As a retrofit on vessels in service, the lubrication system has been fitted more than 120 main engines and has a payback period of less than two years.

Keywords: Cylinder lubrication; Two-stroke diesel engine; Cylinder lube oil; Electronic control; Oil-saving; Emission reduction

1 Introduction

Marine diesel engines are deemed the "hearts" of ships and it is very important for them to work efficiently, safely and reliably.[1] Among many crucial factors affecting the normal operation of diesel engines is the lubrication between cylinder liner and piston rings due to the harsh environment of high temperature, high pressure and high-speed moving parts.[2,3] Especially in recent years, with the wide application of high supercharged, and long-stroke large-bore low-speed two-stroke marine diesel engines, together with the increased use of high viscosity, low quality and high sulphur fuel oil,[4] the main engine's cylinder lubrication has drawn increasing attention.[5]

With the development of world shipping market and the rising of oil prices, marine diesel engines (especially main engines) are required to have low fuel consumption, less harmful emissions, high power and reduced size.[6] To achieve these goals, and with the development of improved metal materials and electronic control technology, the piston stroke is getting longer and longer, the compression ratio, the maximum explosion pressure, and the mean effective pressure go higher and higher. Taking the mean effective pressure as an example, it was only about 1.2 MPa in the early 1980s, but nowadays it reaches 1.9 ~ 2.2MPa for Wärtsilä RT-Flex, X-type engines and MAN Diesel & Turbo ME, L, S And G-type marine engine. As a result, the fuel consumption rate dropped from 210 g/kW·h to 170 g/kW·h.[8] However, the COCR (Cylinder Oil Consumption Rate) has risen sharply in order to ensure good lubrication of cylinder liner and neutralization of combustion products.[7] According to MAN Diesel & Turbo's statistics on different types of marine diesel engines, the COCR has risen from less than 0.5 g/kW·h to more than 1.6 g/kW·h.[8] Therefore, after saving fuel consumption, controlling the cylinder oil consumption becomes another significant way to reduce the operating cost of ships and improve the ship economic efficiency.[9]

Environmental issues have drawn the increasingly wide attention of the international community.[10] The shipping industry also formulates many laws and regulations to limit the emissions of harmful exhaust gas from marine engines.[11] The value of the COCR has a great influence on the PM (Particulate Matter) content in the exhaust gas.[12] These solid particles are composed of DS (Dry Soot), MO (Metal Oxide), sulphate and SOF (Soluble Organic Fraction) . Reducing the COCR can obviously reduce the amount of SOF and MO in the exhaust emissions of marine diesel engine, [13] as shown in Figure 1. This shows that reducing the cylinder oil consumption is conducive to environmental protection.[14,15]

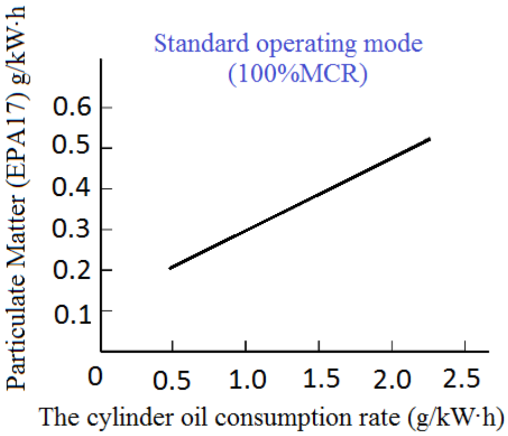

Figure 1. Relationship between cylinder oil consumption and particulate emissions

At present, the main propulsion system generally used for large-scale ships are the large-bore, low-speed, two-stroke and crosshead type marine diesel engines.[16] With this type of diesel engine, the upper part of the engine frame is provided with a diaphragm and a piston rod stuffing box, which separates the cylinder from the crankcase. This structural feature determines that an independent cylinder lubrication system must be installed between the piston group and the cylinder liner. [17] The roles played by cylinder lubrication include anti-wear, neutralization,[18] cleaning, sealing, antiseptic, noise-reducing and cooling.[19] The common lubricator includes the following types.

A conventional type of mechanical cylinder lubricator incorporates a number of oil pump units, driven by its camshaft rotation through the mechanical sprocket from the engine crankshaft, and those cams, in turn, move their small plungers for the reciprocating motion.[20] The oil pumping frequency synchronizes with the main engine speed, and its oil injection quantity is mainly adjusted manually by changing the plunger stroke of each oil pump unit. Obviously it has the following technical defects: (1) it cannot adapt to the changes of the actual working conditions of the engine to achieve the best COFR (Cylinder Oil Feed Rate); (2) at any lubrication point, the timing of the injection is not very precise, and the amount of cylinder oil injected is not sufficiently uniform; (3) the oil injection pressure is relatively low, resulting in poor lubrication on the cylinder liner wall; (4) the COFR cannot be automatically adjusted consequent upon the sulphur content of the H.FO, the alkalinity of cylinder oil and the running status of the engine; (5) the cylinder oil injection is unstable especially when the main engine is operating at low speed or under low load.

HJ (Hans Jenson), the world's leading manufacturer of marine diesel cylinder lubricator, has developed the SIP (Swirl Injection Principle) cylinder lubrication system based on the conventional mechanical cylinder lubricator. HJ SIP cylinder lubrication system is based on the principle of swirling jet. The cylinder oil with higher pressure is periodically and quantificationally sprayed in the form of droplets to the cylinder wall through a nozzle similar to the fuel injector at a certain angle along the tangential direction of the cylinder wall. Subsequently, those drops of cylinder oil are distributed on the cylinder wall by the centrifugal force of the scavenging vortex. In this way, the piston rings can easily bring the cylinder oil to the entire friction surface of the liner to achieve the purpose of cylinder lubrication with a small amount of cylinder oil.[21] However, HJ SIP cylinder lubricator system cannot get rid of and overcome the deficiency of conventional mechanical cylinder lubricator, with back-pressure timing, load-independent cylinder lubrication, and it also tends to lead to the eccentric wear of the cylinder liner wall after long-term use. As a retrofit on vessels in service, the cylinder liner needs to be modified with a small jet slot to replace the traditional polyline groove.[22]

The ALPHA electronic control cylinder lubricator system, developed by MAN Diesel & Turbo, automatically controls the timing and quantitation of cylinder oil and injects in fan shape onto the cylinder wall and piston rings, and its power comes from a specialized pumping station or common rail. Subsequently, this company introduced the ALPHA ACC (Adaptive Cylinder-oil Control) electronic control cylinder lubricator system with a better performance.[23] The injected amount of cylinder oil was dynamically controlled by the control unit to match the COFR to the sulphur content in fuel, TBN (Total Base Number) of cylinder oil, engine load, ship sailing status and other parameters. Results have shown that, compared with the conventional mechanical lubricator, the COCR of ALPHA ACC and the cylinder liner wear have been reduced significantly, saving more than 20% of the cylinder oil. However, The Alpha system is unreasonable to accept the principle of intermittent lubrication when the engine runs under low load conditions.[24] Allowing up to 15 cycles without oil injection, risks the friction regimes of the surfaces between cylinder liner and piston rings becoming dry due to a shortage of cylinder oil.[25] And it is also not suitable for retrofitting the existing and older engines, because this lubricator system needs to modify the oil grooves on the cylinder liner or replace the nozzles, and with associated expense.

Wärtsilä CLU series lubrication system is currently one of the mainstream products on the marine diesel engine market, and mainly used for the Wärtsilä diesel engine. The latest CLU-4 pulse feed lubrication system is based on the original pressure accumulator’s lubricator. PLS (Pulse Lubrication System) utilizes the intelligent function of diesel RT-flex common rail electronic control technology, and organically combines sensors, solenoid valves and electronic control technology. It achieves the modular design of cylinder lubrication and the flexible regulation of cylinder lubrication parameters. And it can enhance the optimization of control parameters and its matching with the conditions when engine load changes. PLS can inject cylinder oil onto the surface of cylinder wall with precise timing and accurate quantity. At the same time, through the optimization and improvement of cylinder oil distribution on the surface of cylinder wall and cylinder lubrication characteristics, PLS can reduce the COCR. Wärtsilä has tested PLS cylinder lubrication systems on some specified types of engine and found that cylinder wear was reduced and cylinder oil consumption was saved by more than 20% compared with that of the conventional mechanical lubricator. However, there are some deficiencies in the CLU series cylinder lubrication system. For example, the CLU-3 system still uses quills of accumulator type, resulting in inaccurate lubrication timing. In the CLU-4 system, although the pressure accumulator has been eliminated, the retrofit type nozzles need to be replaced.

A new electronically controlled cylinder lubrication system, has been developed jointly by Wuhan University of Technology and a marine technology company in the PR China (People's Republic of China), is suitable for large-scale low-speed two-stroke diesel engines (main engine). They obtained the national patent for this invention and completely independent intellectual property rights. The new system has been applied to electronic control upgrading of cylinder oil lubrication system for more than 120 main engines in different types of ships. At present, the system is operating on a safe and reliable condition, also the cylinder oil saving effect is obvious (more than 25% of the oil is saved). This paper will introduce this system with its design, structure, implementation, experimental research and application.

2 System design and implementation

Cylinder lubrication can be defined as: The cylinder lubricator injects cylinder oil onto the cylinder wall or piston rings through the oil nozzles which are uniformly arranged at circumferentially in the cylinder liner wall. The amount of cylinder oil injected can be adjusted and this oil cannot be recycled; it will either be burned or be scraped off by the piston rings as waste oil.

2.1 Parameter design

The parameters of cylinder lubrication system directly affect the cylinder lubrication effect, such as the cylinder oil dosage, cylinder liner wear and tear, overhaul time and the particulate emissions. The main parameters are as follows.

2.1.1 The number and location of oil nozzles

The number of oil nozzles on the cylinder liner is generally 4-20 according to the size of cylinder bore, and they are evenly distributed along the cylinder wall. MAN B&W MC and ME engines often adopt a single-layer oil nozzle, while Sulzer RTA, Wärtsilä RT-flex and Mitsubishi UEC engines usually adopt a double-layer oil nozzle. For the lower speed engine, the oil nozzles are located in the middle of the cylinder liner, while for the higher speed engine, the oil nozzles are located in the lower part of the liner.[26]

2.1.2 Cylinder oil selection

Cylinder oil selection depends mainly on the quality of fuel oil (especially sulphur content), cylinder oil quality (especially the TBN) and viscosity (affecting fluidity and lubrication effects), diesel engine intensification and scavenging type, and so on. Generally, the types of fuel oil and cylinder oil used in the operation of ships are not easily changed. As a rule, when the sulphur content of H.F.O is more than 2.5%, a cylinder oil with TBN 65-70 should be used; when it is less than 2.5%, the TBN is about 40; while the TBN is about 10-14 for the normal diesel.

Figure 2 shows control of cylinder oil dosage proportional to the sulphur percentage in the fuel, which is based on a standard TBN 70 cylinder oil. Just as the oblique line in Figure 2, the cylinder oil amount is controlled such that it is proportional to the amount of sulphur entering the cylinder with the fuel. For example, if the sulphur percentage in the fuel is below 1%, it is recommended to change to a cylinder oil with a lower TBN (i.e. TBN 40-50 cylinder oil). While the horizontal line in Figure 2, a minimum cylinder oil dosage is set in order to account for other duties of the cylinder oil (securing sufficient oil film, detergency, etc.).[27] It is preliminary given the efficient lubrication achievable with the new lubrication system, and it should be able to further reduce cylinder oil consumption in the future.

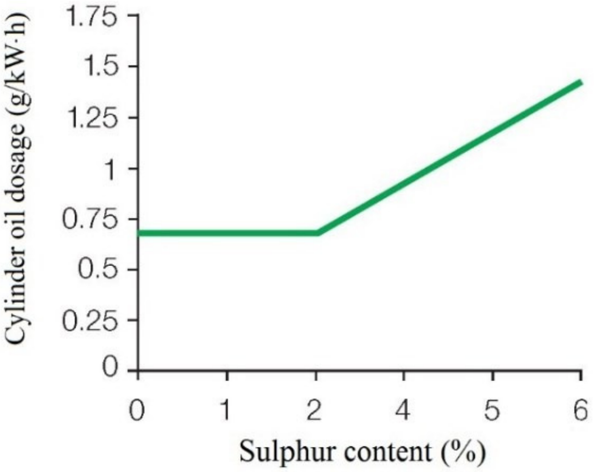

Figure 2. Cylinder oil dosage proportional to sulphur percentage in the fuel

2.1.3 Oil injection timing

Oil injection timing refers to the starting or ending moment during which time cylinder oil is injected into the cylinder, and it is generally indicated by the crank angle that deviates from the TDC (Top Dead Centre) or BDC (Bottom Dead Centre). Only when the pressure in the cylinder is lower than the oil pressure in the nozzle which is essentially a check valve, can the cylinder oil be injected into the cylinder. For the short-skirt piston, there are two injection chances in one rotation of the crankshaft: the first chance is when the piston lower edge just passes through the oil nozzle in the cylinder wall, the piston goes up to the TDC; the other chance is when the piston goes down to near the BDC and the cylinder is scavenging. As for the long skirt piston, there is only one chance during each revolution of the crankshaft, that is, when the cylinder is scavenging time. [28] The principles of determining oil injection timing are: (1) the cylinder pressure at the oil nozzle cannot be too high during the period of injection, usually not more than 1.0MPa; (2) after the cylinder oil is injected into the cylinder, the cylinder oil film should be able to form and maintain itself easily, and the cylinder oil scraped by the piston ring should be kept to a minimum; (3) the location of the oil nozzle should be as close as possible to the combustion chamber; (4) the maximum amount of cylinder oil should be injected into the piston rings pack.[29]

The implementation of the above four criteria will lead to an optimal oil injection timing for the new cylinder lubrication system. That is, the cylinder oil injection begins when the piston goes up and the first piston ring just passes across the oil nozzle and ends with the last piston ring passing through the oil nozzle. It is quite complex cylinder lubrication conditions during engine operation. Theoretical oil injection timing does not necessarily meet the actual needs, due to changes in the viscosity of the cylinder oil, the length of the oil supply pipes and the lubricator itself, etc. Cylinder oil cannot be recycled and eventually consumed. The cylinder oil supplied is either burned or scraped by the piston rings, and there is a reasonable ratio between burned and scraped cylinder oil, so the actual oil injection timing can be adjusted to keep the cylinder oil residue to a safe minimum at the bottom of the scavenging box.

2.1.4 The cylinder oil consumption/feed rate

The appropriate COFR is an important prerequisite to ensure that the cylinder is kept in good condition, and the cylinder's status is the criterion to verify whether the COFR is at the correct level. The COFR is determined by the following factors.

(1) Engine characteristics: such as the degree of turbocharging, piston speed, scavenging type, cylinder bore size and material characteristics of the cylinder liner and piston rings.[30] The higher strengthening degree of the cylinder, the higher the COFR should be.

(2) Quality of fuel oil and cylinder oil: Poorer fuel quality and higher sulphur content result in the need for an increased COCR, whereas a higher TBN of cylinder oil leads to a lower the COCR.

(3) The operating status of vessels and their diesel engines: Higher engine load and frequent load changing will require a higher the COFR.

(4) Cylinder status, i.e., the status of piston, piston rings and cylinder liner: The COFR should be increased during the period of engine running-in after the replacement of a new cylinder liner or piston rings and abnormal wear of cylinder liner;[31,32] it also should be increased when the vessel is manoeuvring during significant big storms or severe sea condition.[33]

The objective in controlling cylinder oil consumption should be a dynamic and comprehensive optimization process rather than some static regulation. The COFR of the new cylinder lubrication system, in addition to meeting the above criteria, is designed to follow the following principles:

(1) The principle of upper limit: The COFR is selected according to the upper limit stipulated in the manual of that engine. It should not be less than 1.16 g/kW·h during the period of engine running-in or trials, and also not less than 0.6 g/kW·h during normal operations. This figure should be increased by 50% when the vessel is maneuvering during significant big storms or when the cylinder is in a poor condition.[34]

(2) Regular inspection and monitoring of the cylinder condition. Observation of the cylinder wall and piston rings, noting the surface colour, brightness, wear marks, the state of oil film and the

carbon deposition on the piston head,[35] are important in assessing the appropriate COFR.[36] To be specific, the criteria when judging the appropriateness oil rate are: 1) the wear rate of liner is approximately 0.01mm per thousand hours for IF-180 H.F.O and about 0.02mm per thousand hours for IF-380 H.F.O. 2) lubrication effect: the cylinder wall is not dry but moist; the friction surfaces of the piston rings are bright like a mirror after being touched with a finger, and without any burr; the first ring groove of the piston has no carbon or oil collection, and the carbon deposition on piston head is moderate.[37] In particular, careful monitoring of the wear rate of the cylinder liner is very important to inspect any significant change and therefore a need to timely adjust the COFR.

(3) Analysis and comparison of the COCR and cylinder wear status for the same type engine are important to control reference factors in determining appropriate COFRs. It is worth a comprehensive analysis for those COCR if it is too low, too high or other abnormal conditions caused by the cylinder status changes.

2.1.5 Oil injection pressure

The following two criteria determine whether the oil injection pressure is appropriate: (1) The oil injection pressure at the oil nozzle should ensure that the oil film is easily formed and maintained; (2) The cylinder oil scraped by the piston rings should be at a safe minimum. An oil injection pressure exceeding 4.0MPa restricts the formation an oil film, whilst an oil injection pressure of less than 2.0MPa can restrict the injection distance and lead to an insufficient oil film area in the circumferential direction of the cylinder liner, and lead to partial wear.

2.2 Schematic design

To ensure the effectiveness of the lubrication, the quantity of cylinder oil injected by the new electronically controlled cylinder lubricator must be a fixed amount each time.[38] The lubrication principle is spacing lubrication,[39] that is, the lubricator injects cylinder oil once every a certain number of crankshaft revolutions.[40,41] The injection rate is determined by injecting frequency of the electronically controlled cylinder lubricator, which in turn is controlled by the stepper motor. Therefore, the system operation principles are as follows:

(1) An OFU (Oil-Feed Unit) provides the appropriate temperature, pressure and clean cylinder oil for the new electronically controlled cylinder lubricator.

(2) Oil injection timing is based on the two signals coming from the crank angle encoder, one is the BDC signal, and the other is the crankshaft position sensor signal. That ensures the accuracy of oil injection timing.

(3) Cylinder lubrication supplies fixed quantity cylinder oil injection, by controlling the frequency of the stepper motor; the control unit regulates the injecting frequency of the electronically controlled

lubricator to maintain the optimum COFR.

(4) The injecting frequency is calculated from the accelerator scale of fuel pump and speed of the main engine. According to the requirement, different control modes may be applied to the calculation. The modes are: power mode (P_e mode), mean effective pressure mode (P_{me} mode) and speed mode (n mode), with their COFR being proportional to power, mean effective pressure and speed respectively.

(5) On the HMI (Human Machine Interface), the COFR may be adjusted from 50% to 200% according to cylinder liner running condition; the base value of the system is set at 100%.

(6) The MCU (Main Control Unit) of the electronically controlled lubricator receives the signals of main engine crank angle from the angle encoder (the BDC signal), main engine speed, the main engine load from the load sensor, fuel sulphur content and other digital signals, then calculates the oil injection timing and frequency according to the set control mode, controls stepper motor action to achieve the required cylinder oil injection.

(7) Various kinds of fault alarm devices are equipped with this system. A cylinder oil cut-off sensor is fitted on the glass tube of the E/M CSD (Electronical control / Mechanical Control Switching Device) to monitor the real-time operation, in order to ensure the reliability of the system.

(8) When operating normally, the entire system is controlled by the MCU. Once the security and alarm system unit detects a failure on the control unit, they will alert and display alarm parameters in detail on the HMI panel.

2.3 Implementation

The new electronically controlled cylinder lubrication system consisted of the following four parts, as shown in Figure 3: (1) Main control unit (MCU), (2) Lubricator unit (Lub.U), (3) Electronical / Mechanical control switching device (E/M CSD), (4) Oil-feed Unit (OFU).

The original mechanical lubricator is retained and a device is installed to switch between the mechanical lubricator and the new lubrication system. That is, when the new electronically controlled cylinder lubrication system is working, cylinder oil pumped by the mechanical lubricator will bypass back to the tank, and the new lubricator injects oil to the cylinder.

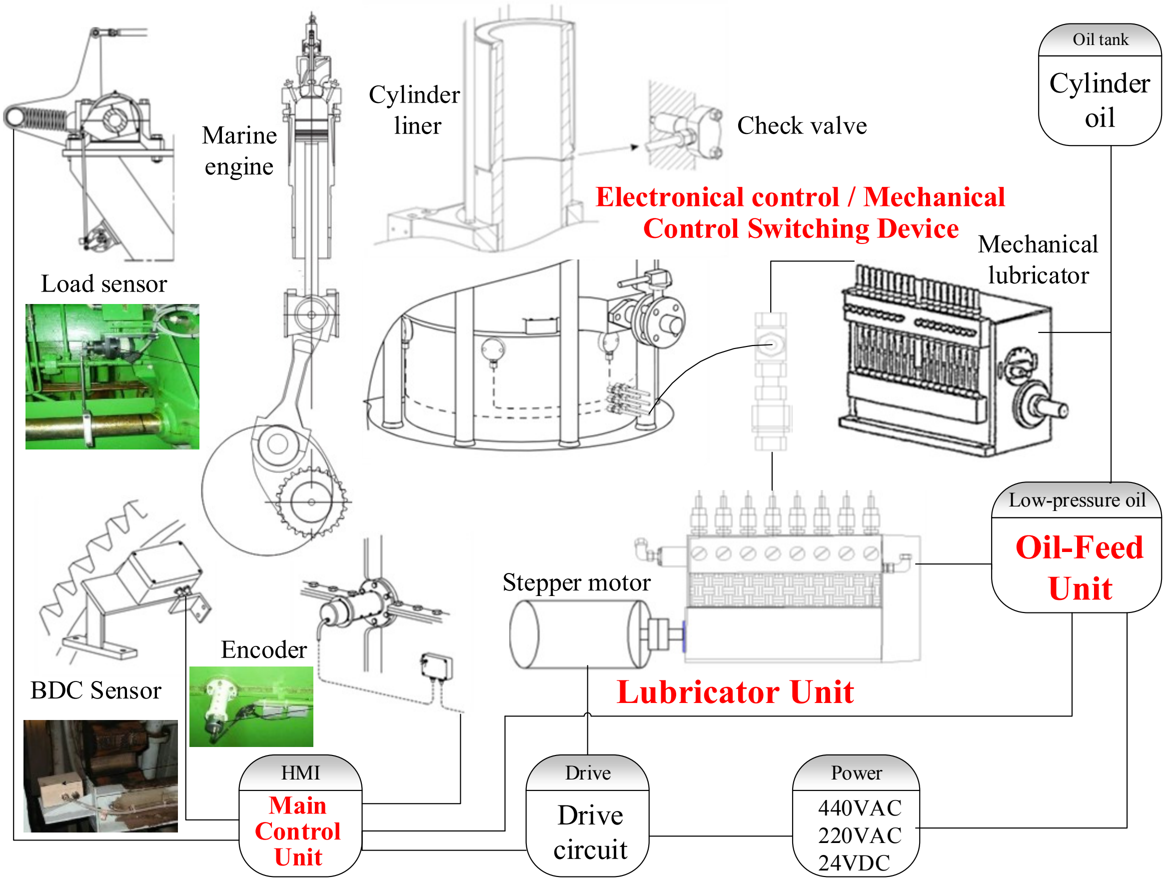

Figure 3. The composition and principle diagram of the new electronically controlled cylinder lubrication system

2.3.1 Main Control Unit (MCU)

MCU is composed of MCS (Main Control System), ACAS (Auxiliary Control and Alarm System), OFU and PSS (Power Supply System). The equipment of the MCU consists of OP (Operation Panel), MCB (man control box), OFUCB (Oil-Feed Unit Control Box), PDB (Power Distribution Box), and some peripheral equipment, as shown in Figure 4.

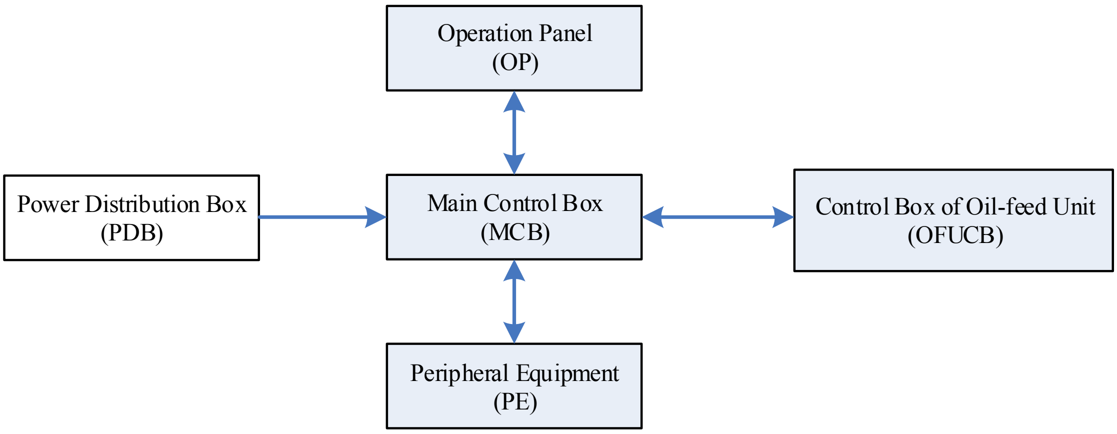

Figure 4. The composition of MCU

(1) Main Control System（MCS）

MCS of the new lubrication system, whose block diagram is shown in Figure 5, consists of a main control panel with its software, a HMI with its software, sensors, actuators and input controls, etc. The MCS activates cylinder oil injection.

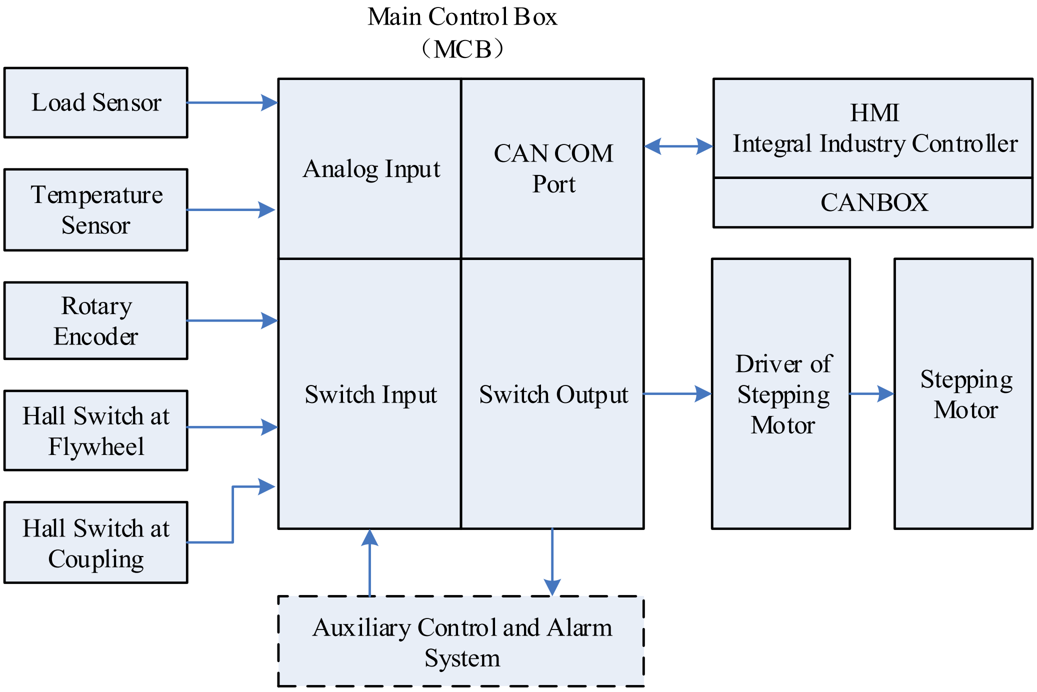

Figure 5. Block diagram of the MCS

(2) Auxiliary Control and Alarm System (ACAS)

The ACAS consist of the main control PLC (Programmable Logic Controller), HMI with software, OFUCB with PLC, sensors, actuators, and control device with the signal, etc. It can achieve auxiliary control of the oil-feed unit, as shown in Figure 6.

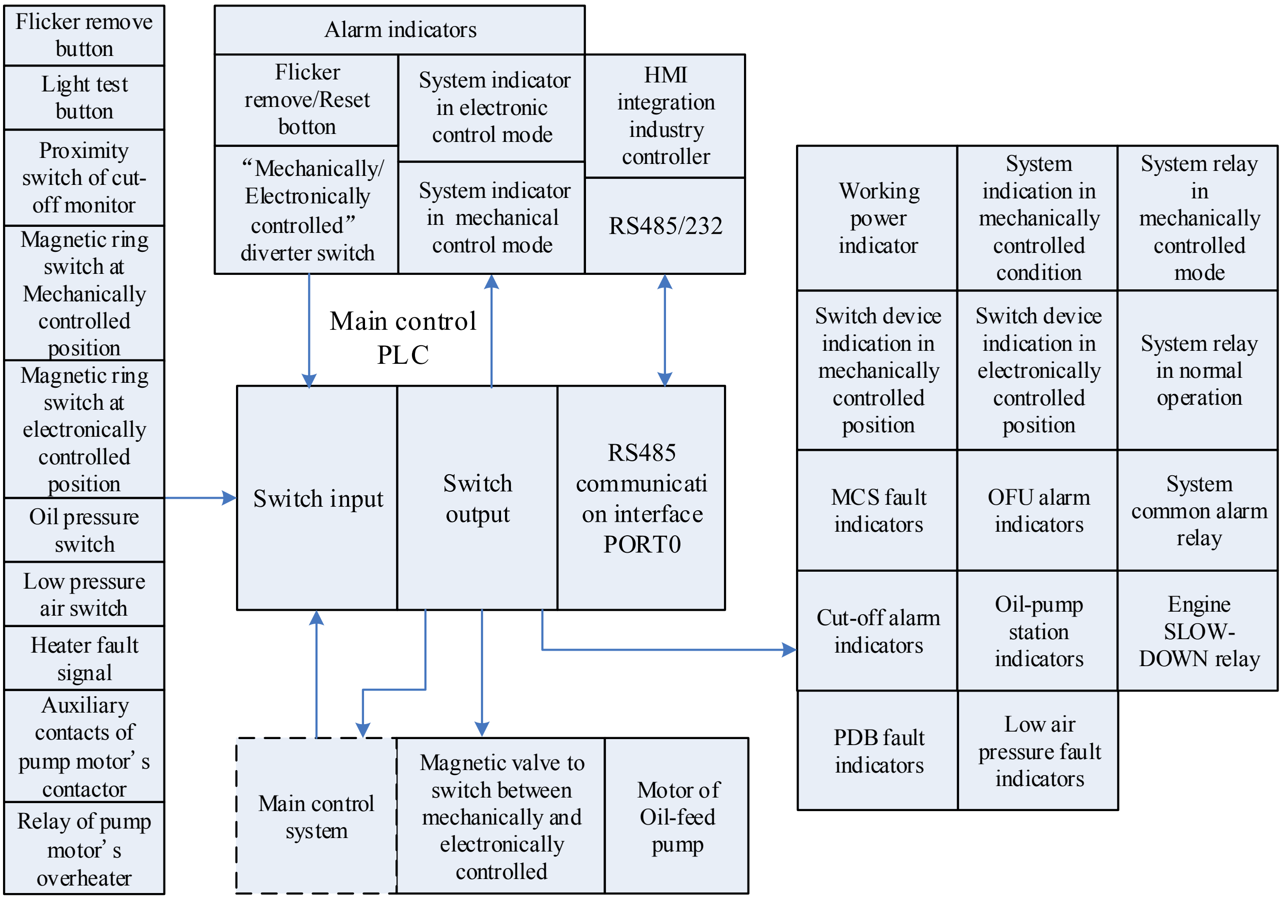

Figure 6. Block diagram of the ACAS

(3) Power Supply System (PSS)

The PSS consists of the power input circuit, switching power supply, UPS (Uninterrupted Power Supply), cell module, power distribution air switch, and power output circuit, etc. This system supplies power to the new lubrication system.

The power module consists of two 24V DC circuits which are supplied by two independent power source. One is a UPS unit with breakers, and another is 24V DC power supply for an emergency. The power supply for OFU is three-phase 440V AC. The block diagram of PSS is shown in Figure 7.

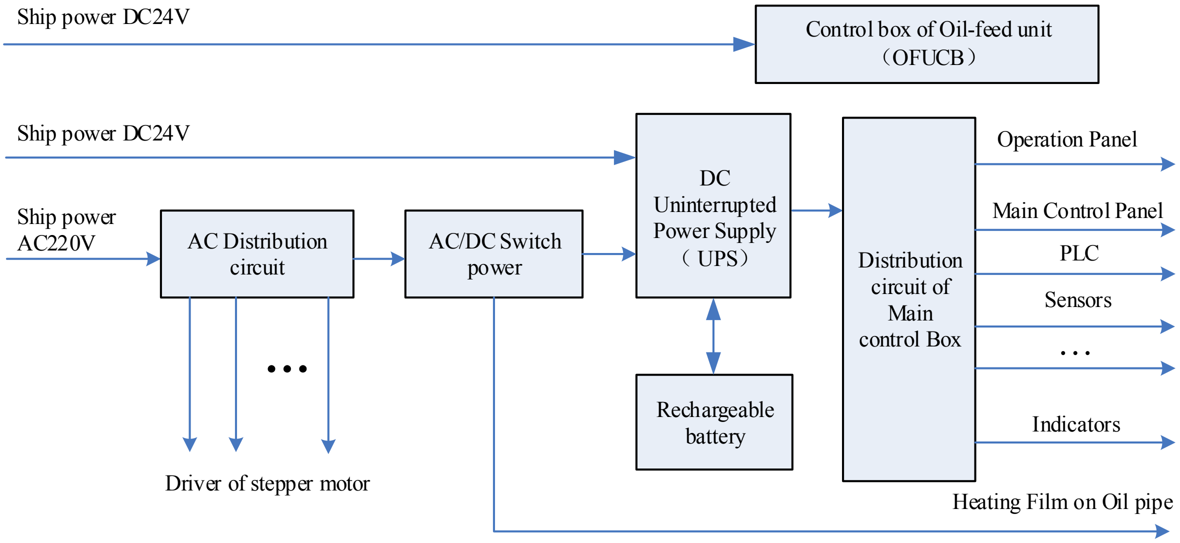

Figure 7. Block diagram of PSS

(4) Peripheral Equipment (PE)

The peripheral equipment consists of actuators (such as the driver, motor, solenoid valve and so on), sensors (such as crank angle encoder, proximity switch, magnetic switch, pressure switch and so on), field control box, PDB, junction box, cable, etc.

The sensor module consists of various main engine monitoring sensors such as load sensor, crank angle encoder, BDC position sensor on the flywheel end, etc.

2.3.2 Lubricator Unit (Lub.U)

Each cylinder of the main engine is equipped with a lubricator. The driver of stepping motor receives a signal from the MCU and drives the stepping motor, and then the stepping motor can drive an oil pump to inject cylinder oil into the cylinder. Lub.U is showing in Figure 8.

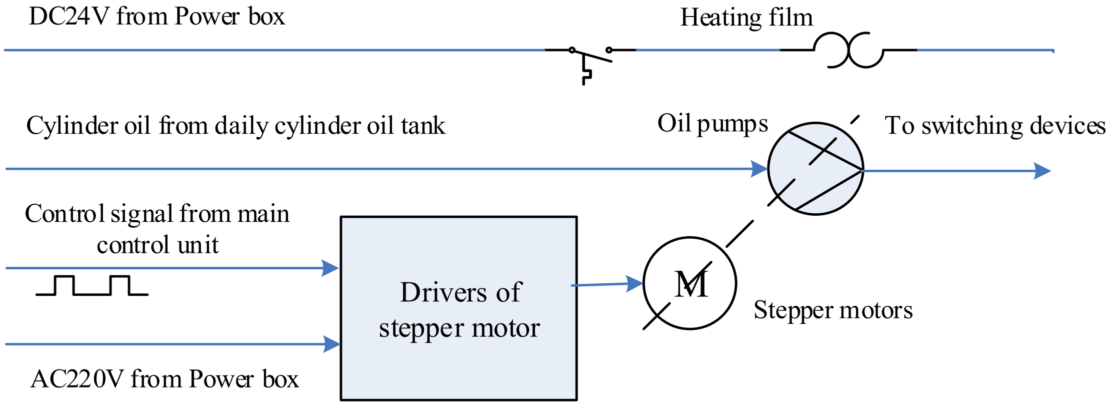

Figure 8. The composition of cylinder oil-Pump Unit

2.3.3 Electronical control / Mechanical Control Switching Device (E/M CSD)

In order to ensure the safety and reliability of marine engine's cylinder lubrication, the original mechanical lubricator is retained. Then a switching device is installed between the mechanical lubricator and the new electronically controlled cylinder lubrication system.

This device is equivalent to a two-position four-way reversing valve. The micro-air motor can change the position of the sliding spool shaft switching between the mechanical lubricator and the new lubricator. In effect, when the new lubrication system is working, cylinder oil pumped by the mechanical lubricator will bypass back to the tank, and the new lubricator injects cylinder oil to the cylinder. However, if the new lubrication system fails to work in whole or in part, the micro-air motor will change the position of the sliding spool shaft, allowing the mechanical lubricator to carry out the cylinder oil injection.

2.3.4 Oil-Feed Unit (OFU)

The OFU provides clean, pressure-constant cylinder oil of a certain temperature range.[42] It includes a cylinder oil pumping station (including an oil pump, a motor and a relief valve), ring valves, filters and oil tank (with a liquid level alarm, a heater and an oil thermometer inside, and a liquid indicator showing temperature outside). The pumping station is equipped with two pumps (One acting as a backup should the main pump fail. The standby pump starts to provide cylinder oil for electronically controlled cylinder lubricator), and there are two individual circuit breakers on the switchboard corresponding to each pump. A pressure gauge and a pressure switch are installed at the exit of the pumping station.

The OFUCB monitors the temperature sensor signal in cylinder oil tank. A temperature controller can automatically control the temperature heater's operating state. The OFUCB can receive the control command from the MCU to activate pumping station's pump motor, and can also upload the pump motor's working status signals and the overheat alarm signal.

3 Sensitivity test on test bench

The new electronically controlled cylinder lubrication system was fully tested in the laboratory together with calibration work prior to the actual ship commissioning test,[43] and one of them is sensitivity test.[44]

3.1 Test condition

Taking the main engine "MAN B&W 6S60MC" as the trial engine. The original mechanical lubricator was set to standby status, and cylinder lubrication carried out under the new electronically controlled cylinder lubrication system, the parameters of main engine shown in Table 1.

Table 1. The parameters of the main engine

No.	Parameter/Item name	Variables	Unit	Value
1	Engine type	-	-	MAN B&W 6S60MC
2	Rated power	P_e	kW	12240
3	Rated speed	n_e	r/min	105
4	NCR(Normal Continuous Rating)	P_{ncr}	kW	10404
5	Service speed	n_s	r/min	99.5
6	Number of strokes	τ	-	2
7	Number of cylinders	i	-	6
8	Cylinder diameter	D	mm	600
9	Piston stroke length	S	mm	2292
10	Number of oil quills per cylinder	j	-	6
11	Cylinder oil injection quantity per cylinder and cycle	q	g/str.cyl	0.8587
12	The running status coefficient	K	%	100
13	Sulphur content in the H.F.O	S	%	3.37
14	TBN of cylinder oil	TBN	-	70
15	VI (Viscosity Index) of cylinder oil	VI	-	50

3.2 Results and analysis

The sensitivity test have focused on the specific influence of its structural and operation parameters on the oil injection pressure, timing and the duration of injection.

3.2.1 Speed of stepping motor

Figure 9 shows how the speed of the stepping motor used to drive the electronically controlled oil pump affects the pressure at the nozzle. As can be seen from the Figure 9, increasing the speed of the stepping motor can increase the oil injection pressure and shorten the duration of oil injection. Therefore, it can control the stepper motor speed to adapt to the change of the oil injection’s duration which caused by the change of diesel engine speed, to ensure that the cylinder oil is injected in the piston rings pack. However, an overspeeded stepper motor may result in a rapid decrease in drive torque.

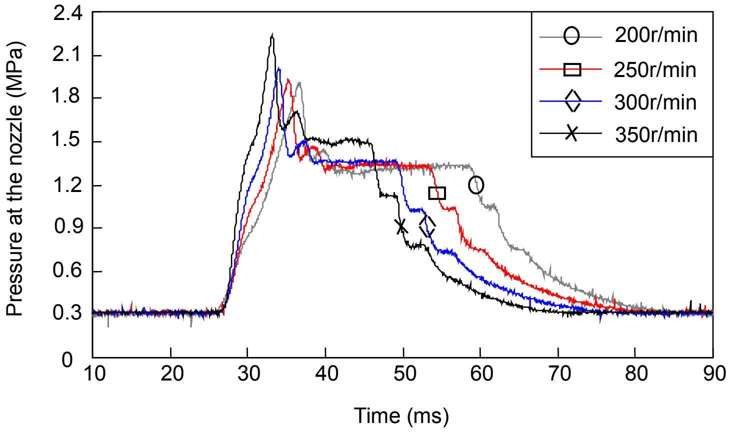

Figure 9. Effect of stepping motor speed on pressure at the nozzle

3.2.2 Effective plunger stroke of oil pump

For cylinder lubrication of different cylinder bore engines, the reference oil injection quantity per cycle can be determined from the plunger diameters and effective plunger stroke, and must take into account the pressure and the duration of oil injection. Figure 10 shows the effect of different plunger effective stroke on the pressure at the nozzle when the plunger diameter is 10mm.

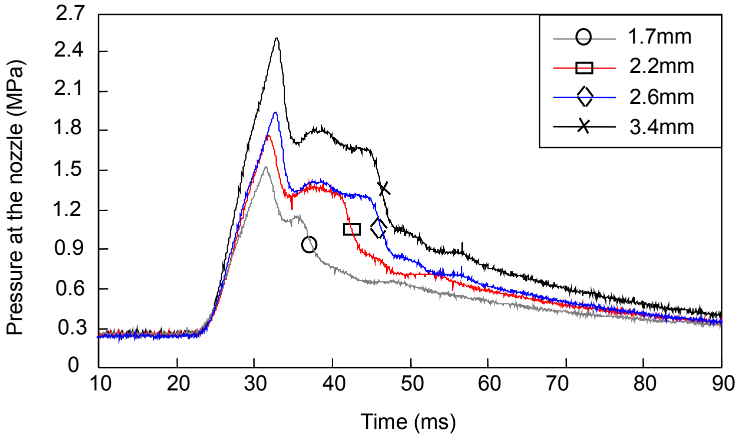

Figure 10. Effect of plunger effective stroke on pressure at the nozzle

3.2.3 Cylinder pressure

During the period of cylinder oil injection, the gas pressure in the cylinder is continuously changing, and this experiment simulates the injection condition under several constant backpressures, as shown in Figure 11. It can be seen from the Figure11 that the increase of backpressure is beneficial to the increase of oil injection pressure, but has little effect on the timing and duration of oil injection.

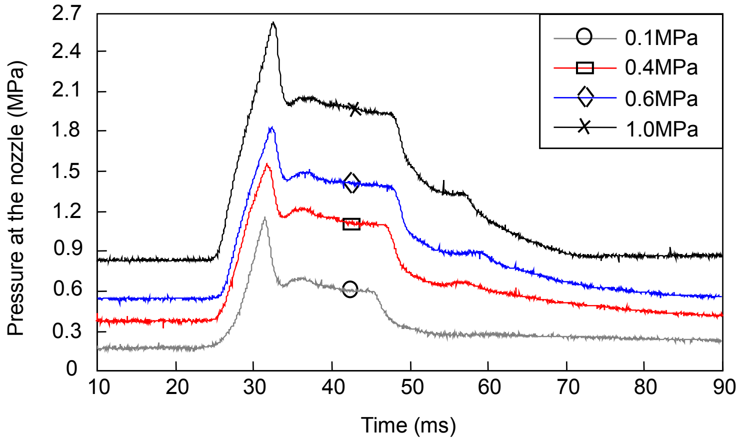

Figure 11. Effect of cylinder pressure on pressure at the nozzle

3.2.4 Cylinder oil temperature

The temperature affects the viscosity of the cylinder oil, which in turn affects the flow resistance in the oil pipe and lubrication on the cylinder wall. Figure 12 shows the pressure curve at the nozzle of the four temperature conditions. It can be seen from the Figure 12 the appropriate cylinder oil temperature can be set at 40℃~ 60℃.

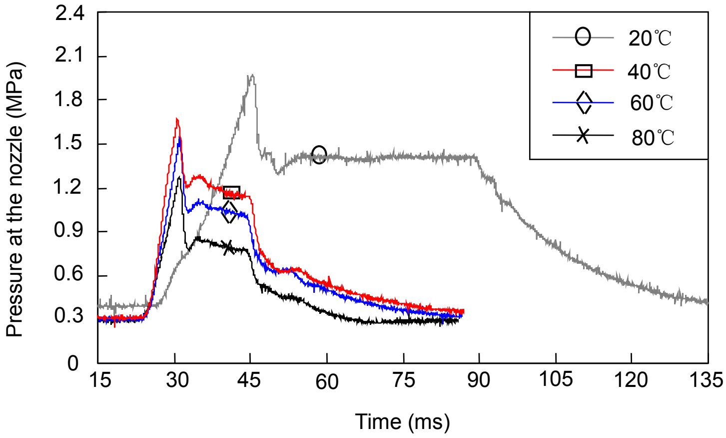

Figure 12. Effect of cylinder oil temperature on pressure at the nozzle

3.2.5 Oil pipe length

The length of the oil pipe affects the hydraulic delay and the maximum oil injection pressure. Figure 13 shows the effect of different oil pipe lengths on the pressure at the nozzle. In order to ensure the synchronization of 4 to 10 oil filling points in a cylinder, the oil pipe length of all the oil filling points should be equal as much as possible.

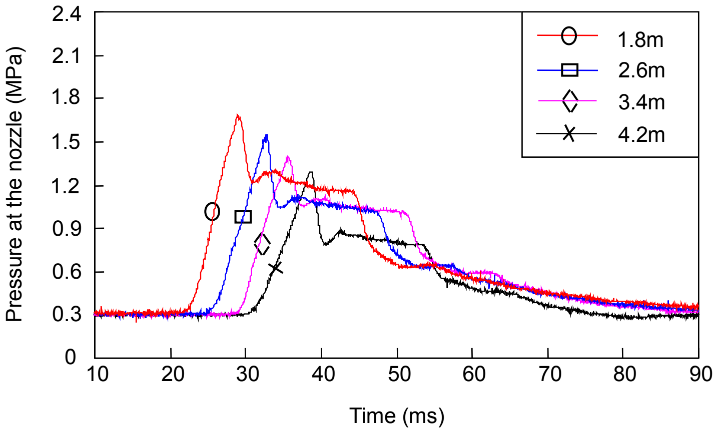

Figure 13. Effect of pipe length on pressure at the nozzle

4 Verification test on actual ship

The aim of the testing programme is to determine the level of savings in cylinder oil consumption when taking advantage of the new electronically controlled lubrication system. An added benefit is that such savings in cylinder oil consumption will reduce the environmental impact from operating vessels with the new lubrication system. Also more uniform and optimal cylinder liner wear rates can be expected.[45]

4.1 Test condition

Taking the vessel "GREAT GLEN" of Sinotrans Shipping Management Co., Ltd as the trial ship, whose main engine type is MAN B&W 6S60MC. The ship was fully loaded and cruised at a constant speed.[46] The original mechanical lubricator was set to standby status, and cylinder lubrication carried out under the new electronically controlled cylinder lubrication system. The verification test conditions are shown in Table 2.

Table 2. The verification test conditions

No.	Parameter/Item name	Variables	Unit	Value
1	Ship name	-	-	GREAT GLEN
2	Main engine type	-	-	MAN B&W 6S60MC
3	Rated power	P_e	kW	12240
4	Rated speed	n_e	r/min	105
5	Measuring date	-	-	12th January 2017
6	Sea condition	-	-	5 (Rough)
7	Air classification	-	-	6
8	Wind direction	-	-	NEX
9	Course	-	(°)	25

No.	Parameter/Item name	Variables	Unit	Value
10	Slip rate	-	%	18.5
11	Stem draft	-	m	14.90
12	Stern draft	-	m	15.20
13	Navigation speed	V	knot	11.04
14	Engine compartment temperature	T_a	℃	38
15	Measured speed of main engine	n	r/min	83.95
16	Measured power of main engine	P_s	kW	6255.7
17	Sulphur content in H.F.O	S	%	3.37
18	Fuel index of fuel pump	R	mm	60
19	H.F.O consumption	M_{fuel}	ton	9.99
20	Converted H.F.O consumption per day	m_{fuel}	ton/Day	29.97
21	TBN of cylinder oil	TBN	-	70
22	VI (Viscosity Index) of cylinder oil	VI	-	50

4.2 Results and analysis

During the period of test, the operating parameters of the main engine are normal and stable, and the oil injection pressure, timing and cylinder oil consumption are measured.[47]

4.2.1 Lubrication effect

After the main engine shutdown, the exhaust valve and the scavenging box manhole are opened to take pictures of the cylinder, as shown in Figure 14 and 15, which are photographs of the piston rings and the bottom of the scavenging box. Figure 14 shows the condition when using a mechanical lubricator and Figure 15 shows the situation when using the new electrically controlled cylinder lubrication system. It can be seen from the pictures that no abnormal scratches were found on the cylinder wall, piston and piston rings.[48]

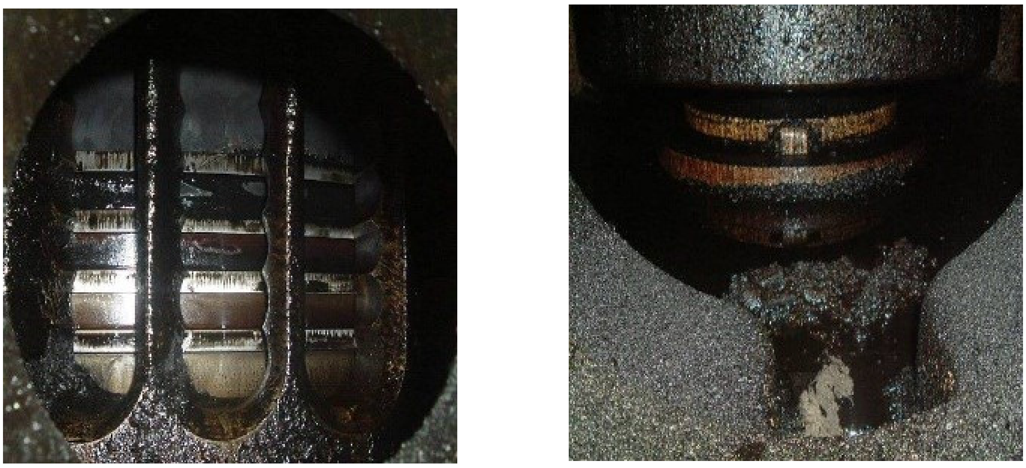

Figure 14. The piston rings and the bottom of scavenging box when using mechanical lubricator

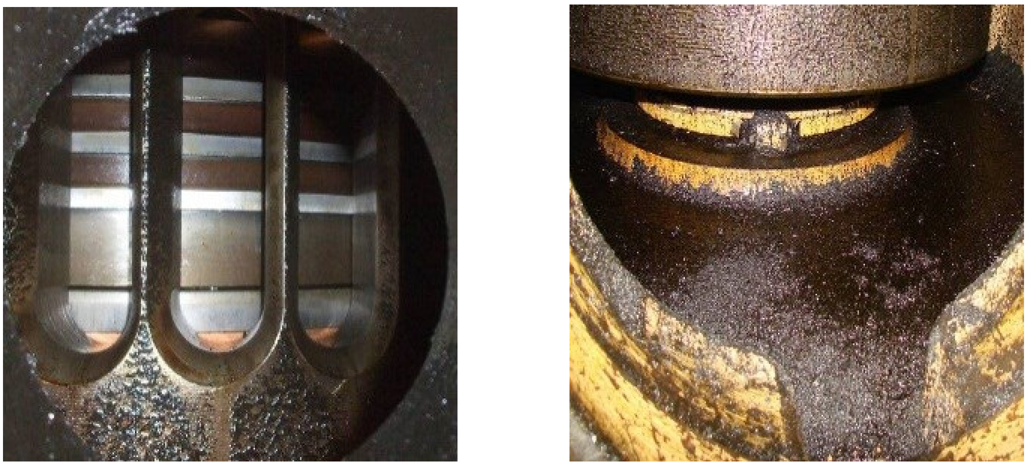

Figure 15. The piston rings and the bottom of scavenging box when using the new system

4.2.2 Injection pressure and timing

During the operation of the new electronically controlled cylinder lubrication system, two pressure signals and two position signals were measured in the course of an oil injection cycle, as shown in Figure 16. The pressure signals were obtained from two pressure sensors. One was mounted at the inlet of the nozzle and used to measure the injection pressure. The other was mounted in the existing nozzles for the nozzles to measure the oil quill pressure, which is cylinder gas pressure at lubricating level (near the nozzle). The piston position signal was from a magnetoelectricity transducer which was mounted on the flywheel. BDC signal was from a crankshaft encoder which was mounted on the free end of the engine crankshaft. It can be seen from the Figure 16 that the oil injection pressure at the nozzle is about 3.0 MPa and starts to rise at the moment when the first piston ring passes through the nozzle. Furthermore, oil injection duration is 15°CA or less, which means the cylinder oil injection concentrates into the piston ring pack. These properties fully ensure the good lubrication and neutralization.

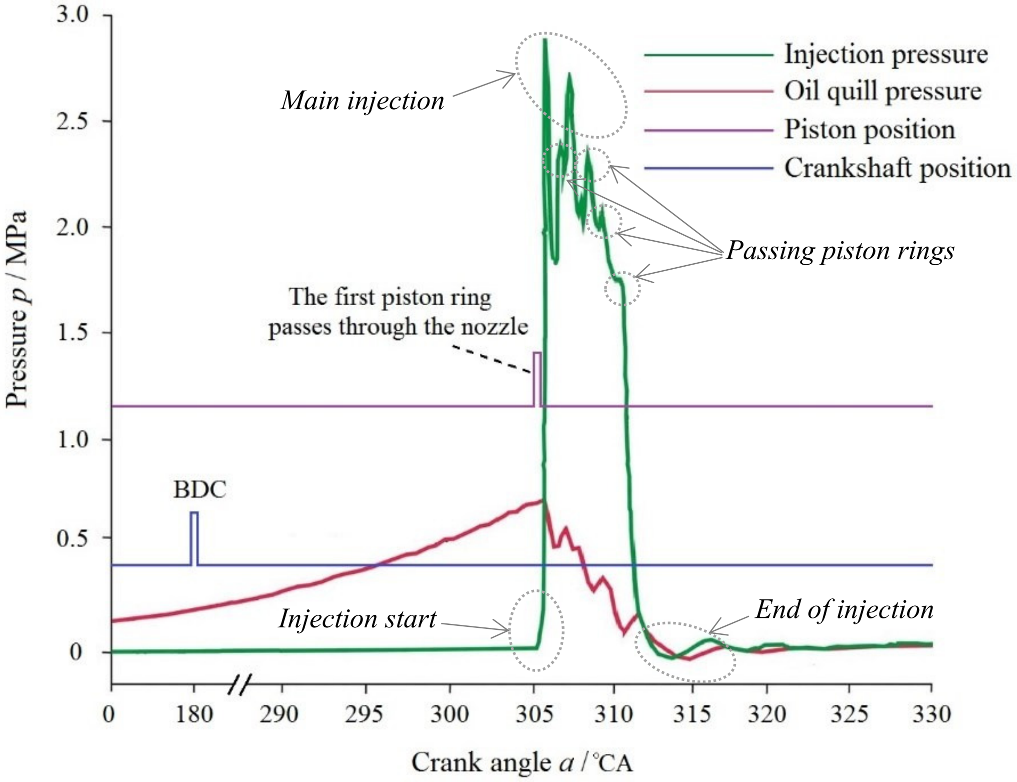

Figure 16. The timing curve between the cylinder oil pressure and BDC in a cycle of the engine

There are four interesting inflection spots in the injection pressure curve as shown in Figure 16. (1) Injection start: The driver of stepper motor receives the oil injection signal from the MCU and immediately drives the motor. Subsequently, the oil-pump starts to move, which in turn, moves their plungers in reciprocating motion. The cylinder oil in the pipes starts to accelerate and the pressure rises. When the injection starting pressure of the nozzles are exceeded, the non-return valves opens. (2) Main injection: Cylinder oil flow reaches the highest speed and all non-return valves are full open. At this stage, there is severe fluctuation in pressure due to interaction with the oil quill pressure and passing piston rings. (3) Passing piston rings: The green injection pressure curve shows four passing piston rings (see steps in the curve). The moment of injection pressure fluctuation is in one-to-one correspondence with the moment of oil quill pressure change and confirms each other. However, it still belongs to the stable injection. Injection is coming to an end as passing the last piston ring. (4) End of the injection: All the non-return valves are closing, and the pressure is still fluctuating a phenomenon in the pipes like a long train which starts to stop.

4.2.3 Injection quantity and cylinder oil consumption rate

Due to some movement of the hull during operation, the cylinder oil consumption cannot be measured from the level of the daily service tank. For this actual ship trial, a specialized oil consumption meter is fitted to give an accurate measurement of cylinder oil consumption, and the results are shown in Table 3. The comparison of the cylinder oil consumption between the two lubrication systems is shown in Table 4. If this ship uses the new electrically controlled cylinder lubrication system, it can save 48.6 kilograms of cylinder oil per day, which is equivalent to a saving of 24.65% compared with the original mechanical lubricator.

Table 3. The table of cylinder oil consumption measurement

No.	Item name	Unit	The mechanical lubricator	The new electronically controlled Cylinder lubrication system
1	Measurement time interval	-	12:00~20:00	04:00~12:00
2	Runtime	hour	8	8
3	Measured speed of main engine	r/min	83.95	83.98
4	Engine load value at the system display （HMI）	-	108~111	106~110
5	Running-in coefficient	%	-	100
6	Frequency coefficient of oil injection	rev./inj.	-	4.3
7	Measured cylinder oil consumption	kg	65.7	49.5
8	Converted consumption per day	kg/Day	197.1	148.5

Table 4. Comparison of daily cylinder oil consumption

No.	Item	Unit	The mechanical lubricator	The new electronically controlled Cylinder lubrication system
1	Main engine speed	r/min	83.95	83.89
2	Measured cylinder oil consumption	kg	65.7	49.5
3	Converted consumption per day **	kg/Day	197.1	148.5
4	Ratio of Cylinder oil saving	%	-	24.65

Notes:

**: When the mechanical lubricator does not share the same measuring speed with the new electronically controlled cylinder lubrication system, in order to compare the cylinder oil consumption in this case, it should convert daily cylinder oil consumption of mechanical lubricator according to the proportion of main engine speed, which is the same speed as that of electronically controlled state.

5 Application

The new electronically controlled cylinder lubrication system is very easy to install and convenient to use, because there are only a small number of connections with other systems of the main engine, and it is able to run independently from the main engine. Another advantage of the new system is its wide range of applications. It is not only suitable for new marine engines but also applicable to upgrading and transforming non-electronically controlled cylinder lubrication, even during operation of the ship. Specifically, the new system is suitable for cylinder lubrication of almost all large-bore low-speed two-stroke marine engines, including the MC, ME, L, S and G-type series from MAN B&W, the RTA, RT-flex and X-type series from Wärtsilä, and the UEC series from Mitsubishi. This means that the new system can fully meet the requirements of cylinder lubrication for all types of main engines, including cylinder diameters from 35 cm to 98 cm, speeds from 25 r/min to 200 r/min, and stroke lengths from short, long to super long, such as MAN B&W K98MC or Wärtsilä RTA96C and so on.

So far, the new electronically controlled cylinder lubrication system has been fitted as an upgrading and regeneration of more than 120 main engines cylinder lubrication systems. Its customers include most of the shipping companies in China, Such as China Ocean Shipping (Group) Company (COSCO), China International Marine Containers (Group) Ltd (CIMC), China Shipping Container Lines (CSCL), Sinotrans & CSC Holdings Co., Ltd (Sinotrans-CSC), Orient Overseas Container Line (OOCL), China Merchants Energy Shipping Co., Ltd (CMES).

The use of the new electronically controlled cylinder lubrication system can significantly reduce the consumption of cylinder oil, and the recommended value of COFR can be set to 0.95 g/kW·h ~ 1.09 g/kW·h. Taking “Gao River” for example. Before upgrading, the main engine equipped with a mechanical cylinder lubricator had a daily cylinder oil consumption of 316 kg, according to the statistics of the log record. Currently, after fitting the new lubrication system, average daily cylinder oil consumption is 219 kg, a saving of 97 kg cylinder oil every day (30.7% saving). If the sailing time per year is 290 days (about 7,000 hours), 28 130 kg cylinder oil can be saved, equivalent to a saving of $ 56,260 each year, taking the price of cylinder oil at 2,000 U.S. dollars/tons.

6 Conclusions

The paper first analyses the development background, necessity, and research status of the electrically controlled cylinder lubrication system. This led to a new type of electrically controlled cylinder lubrication system being developed. The above research concentrated on the system parameter design, system composition and implementation. Laboratory bench tests and subsequent verification tests on an actual ship were carried out. Finally, this paper briefly analyses the advantages of the new system and its installation on many ships. The main conclusions are listed as follows.

(1) Electrically controlled cylinder oil injection technology is one of the development directions for the cylinder lubrication system.[49] It offers independent control of the COFR, oil injection pressure, and oil injection timing, and greatly improving the controllability of the cylinder lubrication system.

(2) The new electronically controlled cylinder lubrication system can meet the following cylinder lubrication requirements: oil injection pressure about 3.0MPa, oil injection timing precision 0.1ms, oil injection duration 15ms or less; oil injection concentrates onto the piston rings pack, which has

guaranteed the cylinder liner lubrication effect.[50] The oil injection frequency can be adjusted in accordance with engine load, the sulphur content in fuel, TBN of cylinder oil, ship sailing status, cylinder liner run-in condition and various other parameters.

(3) The new electronically controlled cylinder lubrication system is currently being tested in the large-scale in-service tests on a wide range of different marine engines. The preliminary test results are very promising with respect to the savings of cylinder oil. The COCR was reduced from 1.36 g/kW·h ~ 1.63 g/kW·h for the mechanical lubricator to 0.68 g/kW·h ~ 1.09 g/kW·h or even lower, achieving the goal of energy conservation and emission reduction. As a retrofit on vessels in service, the new electronically controlled cylinder lubrication system will have a payback period of less than two years on most types of marine engines.

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8 Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

9 Abbreviations

9.1 Notation

AC	Alternating Current
ACAS	Auxiliary Control and Alarm System
ACC	Adaptive Cylinder-oil Control
ATDC	After Top Dead Centre
BDC	Bottom Dead Centre
BTDC	Before Top Dead Centre
CIMAC	the International Council on Combustion Engines
CIMC	China International Marine Containers (Group) Ltd
CMCR	Specified Maximum Continuous Rating
CMES	China Merchants Energy Shipping Co., Ltd
Co.,Ltd	Company Limited
COCR	Cylinder Oil Consumption Rate
COFR	Cylinder Oil Feed Rate
COSCO	China Ocean Shipping (Group) Company
CSCL	China Shipping Container Lines
DC	Direct Current
DS	Dry Soot
E/M CSD	Electronical control / Mechanical Control Switching Device
H.F.O	Heavy Fuel Oil
HJ	HANS JENSEN
HMI	Human Machine Interface
IMO	International Maritime Organization
Lub.U	Lubricator Unit
MCB	Main Control Box
MCS	Main Control System

MCU	Main Control Unit
MO	Metallic Oxide
NCR	Normal Continuous Rating
OFU	Oil-Feed Unit
OFUCB	Oil-Feed Unit Control Box
OOCL	Orient Overseas Container Line
OP	Operation Panel
PDB	Power Distribution Box
PLC	Programmable Logic Controller
PLS	Pulse Lubrication System
PM	Particulate Matter
PR China	the People's Republic of China
PSS	Power Supply System
Sinotrans-CSC	Sinotrans & CSC Holdings Co., Ltd
SIP	Swirl Injection Principle
SOF	Soluble Organic Fraction
TBN	Total Base Number
TDC	Top Dead Centre
UK	The United Kingdom of Great Britain and Northern Ireland
UPS	Uninterrupted Power Supply
VI	Viscosity Index of cylinder oil

9.2 Functions and variables

D	cylinder bore diameter
L	length
M_{fuel}	H.F.O consumption
m_{fuel}	converted H.F.O consumption per day
n	speed
n_e	rated speed
p	pressure
P_e	rated power

P_s	measured power of main engine
P_{me}	mean effective pressure
q	the oil injection quantity per cylinder and per cycle
R	Fuel index of fuel pump
S%	sulphur content in the fuel
T	temperature
T_a	Engine compartment temperature
t	time
V	Navigation speed

9.3 Units

$	U.S. dollar
°	degree
%	percent
℃	degree centigrade
cm	centimetre
g/kW·h	grams per kilowatt hour
g/str.cyl	grams per stroke and per cylinder
h	hour
kg	kilogram
kg/Day	kilogram per day
knot	miles per hour
kW	kilowatts
l	litre
m	metre
mm	millimetre
MPa	megapascal
ms	millisecond
r/min	revolutions per minute
rev. /inj.	revolutions per injection
t	ton

t/Day ton per day

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