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ORIGINAL ARTICLE

Computer based selection and performance analysis of marine diesel engine

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KEYWORDS
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Engine management system;
Engine heat balance;
Performance analysis

Abstract The major steps in two-stroke diesel technology have been surprisingly few over the past century, now we have another major step – electronically controlled marine diesel engines. This paper will discuss how the use of computer helps to select diesel engines, compare between different types, increase the performance of the conventional diesel engines and generate the different performance curves for such engines.

1. Introduction

Over the past century the marine diesel engines did not have big development: airless fuel injection in the 1930s, welded construction in the late 1940s, and exhaust gas turbocharging and the use of heavy fuel oil both in the 1950s. Nowadays many developments have been introduced to the marine diesel engine by continuously updating its design to adapt them to the latest market requirements and to deliver the benefits of technical improvement. Also they introduced to facilitate the compliance with the new regulations which force the ship owners to reduce their ships emissions, and as a result of the bad economical situations and the incredible increase in the fuel prices in the few past years the manufacturers have been focusing their efforts to reduce the fuel consumption.

After a big number of trials from the manufacturers to achieve the preceding points they realized that this could not be done only by improving the design of the mechanical parts but through introducing a new generation of the diesel engines which are computerized and controlled electronically [1,2].

Apart from the environmental and economical point of views the use of computer offer a number of interesting benefits to ship-owners and operators such as the ease of selection of the diesel engines and comparing between different types. There are many computer programs now available for most of the world leading companies in this field. In such programs each company offer a number of options which help the engineers and ship-owners to make a proper decision during the selection process as shown in Fig. 1, ships plans and piping

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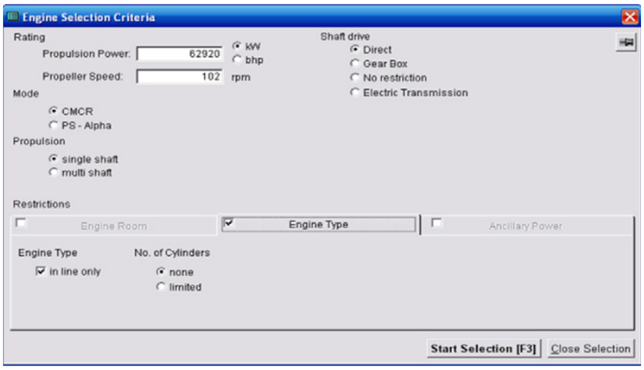
Nomenclature

BSFC	brake specific fuel consumption (g/kWh)
CV	calorific value (KJ/kg)
C_{pcw}	specific heat capacity of cooling water (kJ/kg K)
C_{pex}	specific heat capacity of exhaust gas (kJ/kg K)
CR	compression ratio
D	bore (m)
ISFC	indicated specific fuel consumption (g/kWh)
L	stroke (m)
$m \cdot_f$	fuel consumption (kg/s)
m_{cw}	quantity of jacket cooling water (kg/s)
m_{ex}	quantity of exhaust gas (kg/s)
$m_{sc,cw}$	quantity of SAC cooling water (kg/s)
n	engine speed per second
P_B	brake power (kW)
P_{mb}	brake pressure bar
P_f	frictional power (kW)
P_1	indicated power (kW)
Q_{cw}	heat rejected by jacket cooling water (kW)
Q_{ex}	heat rejected by exhaust gases (kW)
Q_{scav}	heat rejected scavenge air cooler (kW)
$Q_{lub.oil}$	heat rejected by lubricating oil (kW)
Q_{rad}	heat rejected by radiation (kW)
Q_{add}	heat supplied by the fuel (kW)
RPM	engine speed per minute
SAC	scavenge air cooler
tEaT	temperature of exhaust gas after turbocharger (°C)
V_{cyl}	cylinder volume (m^3)
Z	number of cylinders
△Tcw	temperature difference between outlet and inlet of jacket cooling water (°K)
△Texh	temperature difference between outlet and inlet of exhaust gas (°K)
△Tscav,cw	temperature difference between outlet and inlet of SAC cooling water (°K)
λ	excess air factor
η_m	mechanical efficiency
η_{th}	indicated thermal efficiency
η_{bth}	brake thermal efficiency



Rating
Propulsion Power: 62920 ● kW ○ bhp
Propeller Speed: 102 rpm
Mode
● CMCR
○ PS - Alpha
Propulsion
● single shaft
○ multi shaft
Shaft drive
● Direct
○ Gear Box
○ No restriction
○ Electric Transmission
Restrictions
☐ Engine Room ☑ Engine Type ☐ Ancillary Power
Engine Type
☑ in line only
No. of Cylinders
● none
○ limited

Figure 1 Input window for engine selection program.

systems were very difficult stages but now there are many computer programs which can be used to generate and produce such plans, it was tradition for many years that the performance of the diesel engine can be calculated and monitored using the indicator card which is an exhausting method. Now many of the newly produced engines have facilities to make online monitoring on the engine and its performance through the integration between sensors, monitors and computers which help the operator to discover the faults in its earlier stages and with less efforts. One of the most important benefits of using the computer that it allows to carry out the engine heat balance calculation and generating many performance curves by using computer aided programs. It should be noted that the most successful maintenance programs and plans are based on using the computer and the computer analysis (Computerized Maintenance Management System).

2. Engine selection

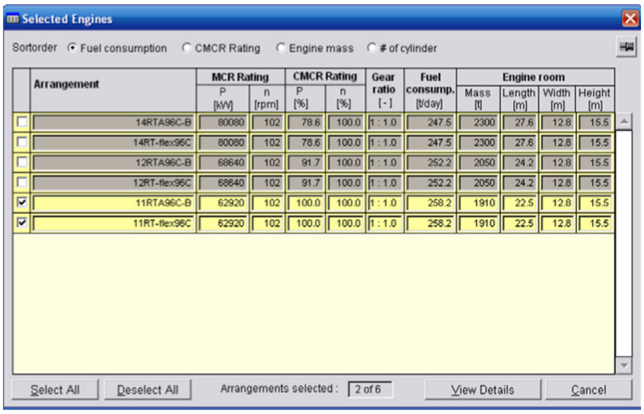
Most of the world leading companies in the marine field offer number of the computer programs which help in comparing between many types of engines and showing the different performance curves for such engines to show the user the advantages and disadvantages of the different engines. Also the user can reduce the results through increasing the restrictions which will lead to fewer options and therefore easier decision as shown in Fig. 2.

Such a selection process and some of the results which is very useful and helpful for the decision makers will be shown .The selection process will start with few restrictions: propulsion power and propeller speed , but there are many other limitations which can be used such as engine room dimensions, engine type, shaft drive, propulsion and ancillary power [3].

A comparison is performed between 11RTA96C-B engine and 11RT-flex96C engine can be shown in Fig. 3. These two engines are selected as both of them comply with the requirements.

It is noted that the 11RT-flex96C engine compared with the 11RTA96C-B engine has more economical fuel consumption at part load, and this is due to the use of the electronic fuel injection that allow the engine to use one or two fuel injectors only out of the three at the part load [4].

It is to be noted from Fig. 4 that the 11RT-flex96C engine are environmentally friendly engines because it has less emission.



Sortorder ● Fuel consumption ○ CMCR Rating ○ Engine mass ○ # of cylinder

	Arrangement	MCR Rating		CMCR Rating		Gear ratio	Fuel consump.	Engine room			
		P [kW]	n [rpm]	P [%]	n [%]	[-]	[t/day]	Mass [t]	Length [m]	Width [m]	Height [m]
☐	14RTA96C-B	80080	102	78.6	100.0	1 : 1.0	247.5	2300	27.6	12.8	15.5
☐	14RT-flex96C	80080	102	78.6	100.0	1 : 1.0	247.5	2300	27.6	12.8	15.5
☐	12RTA96C-B	68640	102	91.7	100.0	1 : 1.0	252.2	2050	24.2	12.8	15.5
☐	12RT-flex96C	68640	102	91.7	100.0	1 : 1.0	252.2	2050	24.2	12.8	15.5
☑	11RTA96C-B	62920	102	100.0	100.0	1 : 1.0	258.2	1910	22.5	12.8	15.5
☑	11RT-flex96C	62920	102	100.0	100.0	1 : 1.0	258.2	1910	22.5	12.8	15.5

Arrangements selected : 2 of 6

Figure 2 Result window for engine selection program showing the available engines complying with the restrictions.

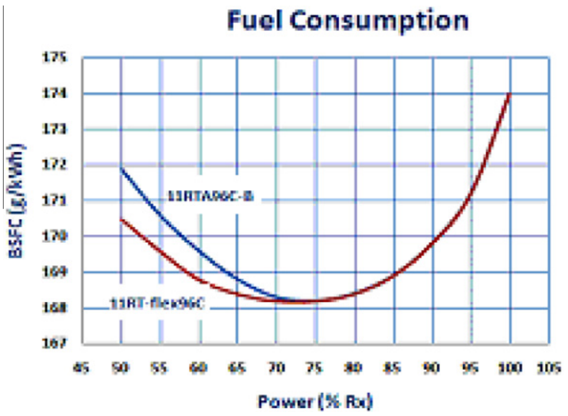


Figure 3 Relationship between the power and the specific fuel consumption.

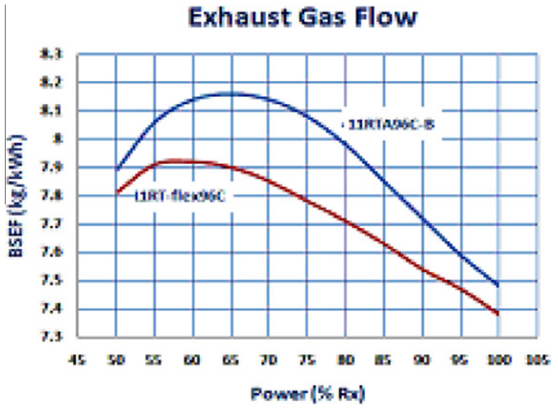


Figure 4 Relationship between the power and specific exhaust gas flow.

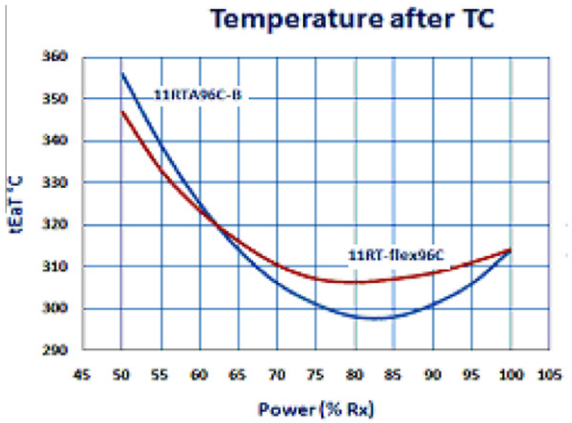


Figure 5 Relationship between the power and the exhaust gas temperature after T/C.

Exhaust temperature after T/C for the 11RT-flex96C engine is higher than 11RTA96C-B is shown in Fig. 5 which will be more useful in case of using waste heat recovery system.

Due to the lower BSFC at part load and slow speed operation, reduced exhaust emissions and the higher exhaust gas temperature after turbo-charger of the 11RT-flex96C engine, it is considered to be better than 11RTA96C-B.

It should be clarified that although both engines have the same construction specifications this difference in the performance is due to the engine control system as the 11RTA96-B is controlled by conventional camshaft on the other hand the 11RT-flex96C is controlled by electronic camshaft which consists of set of electronic cards instead of the mechanical camshaft [5,6].

3. Engine control system

The computerized engine control system has been specially designed for two-stroke engines. It mainly controls the following functions:

- Starting, reversing and stopping.
- Injection timing and exhaust valve timing.
- Fuel rail pressure.
- Servo oil pressure for exhaust valve drive.
- Redundancy and monitoring functions.

The Remote Control System (RCS) works independently of the control system, but is closely linked to it, and serves as the interface between ship operator and engine control.

3.1. System components

Principal components of the control system as in Fig. 6:

- Common Electronic Unit (COM–EU),1 × per engine.
- Cylinder Electronic Unit (CYL–EU),1 × per cylinder.

3.2. Engine related control functions

The engine related functions are controlled and monitored by the Main Controller Module (MCM).

Functions controlled by the Main Controller Module (MCM):

- Fuel pressure control.
- Servo oil pressure control.
- Communication between control system and external systems.
- Monitoring functions.
- Control oil pumps.

3.2.1. Fuel pressure control

At starting, the fuel pump actuators are set to start setting position.

The fuel pressure is dependent on the engine load. Fig. 7 shows that, the control loop for the fuel rail pressure can basically be described as follows:

- MCM receives the engine speed signal from the Cylinder Control Modules (CCM) via crank angle sensor.
- Signal output from MCM to the actuator drivers and actuators.
- Depending on number of cylinders two actuators each regulate two to four fuel pumps via regulating linkage.
- The resulting fuel rail pressure is measured by two pressure transmitters as feedback to MCM.

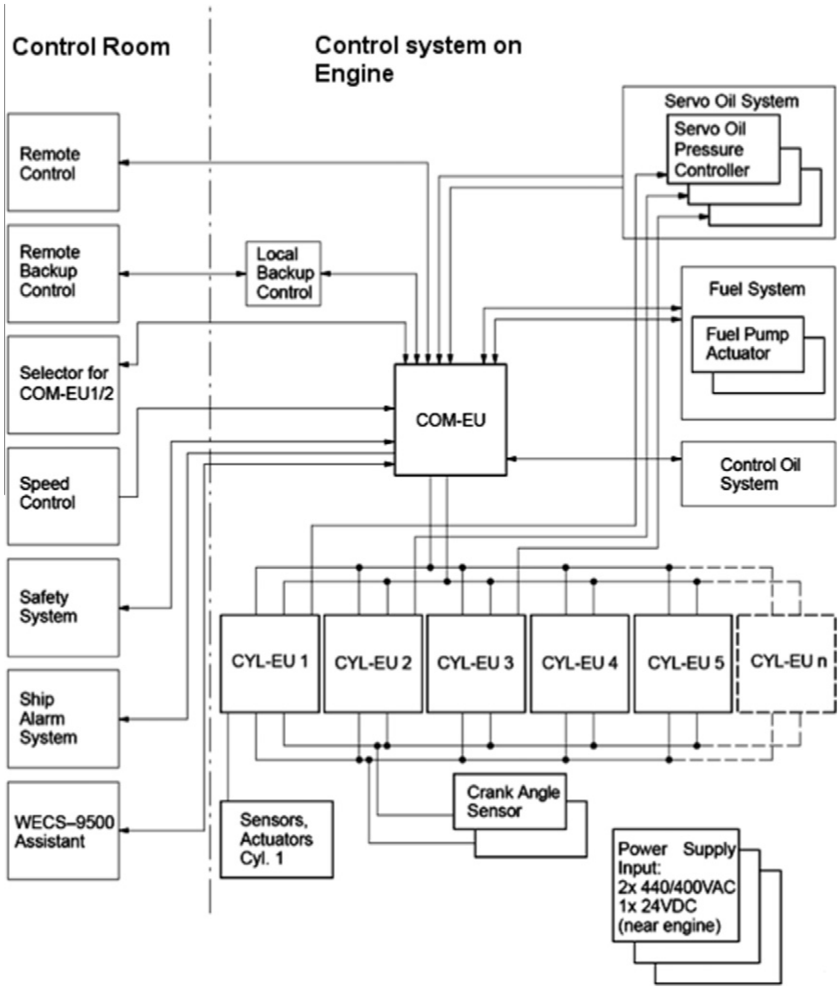


Figure 6 Control system components.

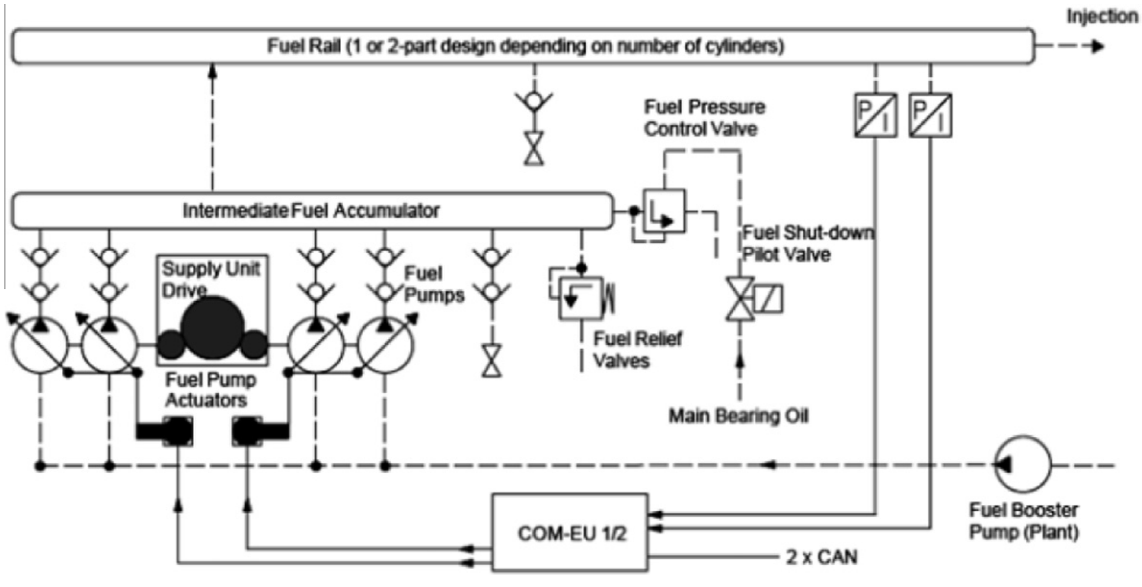


Figure 7 Fuel pressure control diagram.

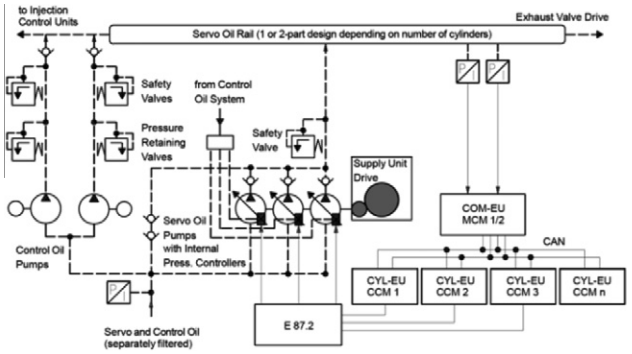


Figure 8 Servo oil pressure set-point control diagram.

At shut-down the fuel pump actuators are set to position 'zero' and the fuel shutdown pilot valve is activated by the safety system.

3.2.2. Servo oil pressure set-point

For each servo oil pump, an internal pressure controller is provided for set-point monitoring as shown in Fig. 8.

The set-point is mainly a function of engine load. It is generated in MCM and transmitted via the corresponding CCM to the control cards.

Every pressure controller of 4–6 pumps is connected to a CCM. This decentralization increases the availability of the servo oil system.

3.3. Cylinder related control functions

Every cylinder is equipped with a CYL-EU containing a CCM and Valve Duration Module (VDM).

Functions controlled by the CYL-EU:

- Volumetric injection control including Valve Injection Time (VIT).
- Exhaust valve control including Valve Exit Open and Close (VEO/VEC).
- Starting pilot valve control.
- Control signal for one servo oil pump.
- Monitoring and initiation functions.

3.3.1. Volumetric injection control

All injection valves, respectively the injection rail valves of a cylinder, are controlled individually, but with one common feedback signal for the injected fuel quantity.

Normally all injection valves are activated together, injecting in one single-stroke. Special operation modes enable injection with only one or two injection valve as shown in Fig. 9.

In order to improve atomizing at low load one or two injection valves are cut out automatically.

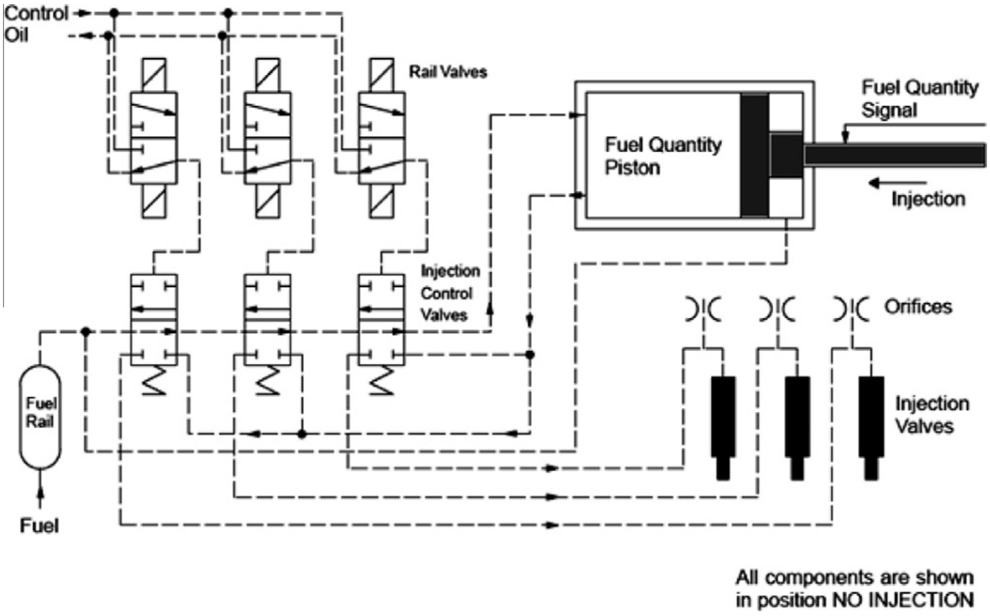
Fuel injection is controlled as follows:

- Calculation of injection begin angle with reference to crank angle and VIT.
- Triggering the injection by actuating rail valves.
- The time difference between injection trigger signal and effective begin of injection is called 'Injection begin deadtime'. The effective injection begin is detected with the movement of the fuel quantity piston.
- Measuring of the really injected quantity via fuel quantity piston stroke.
- End of injection calculated by comparison of injected fuel quantity and fuel command signal from speed controller.
- For the next injection cycle the begin deadtime is calculated with respect to the measured deadtime of the previous cycle.
- The functionality of the injection system is monitored at each cycle and necessary action taken in case of irregularity.

3.3.2. Exhaust valve control

The exhaust valve opens and closes once per revolution. Its movement is measured by two position sensors as shown in Fig. 10.

The CCM controls the exhaust valve opening and closing.



All components are shown in position NO INJECTION

Figure 9 Volumetric injection control.

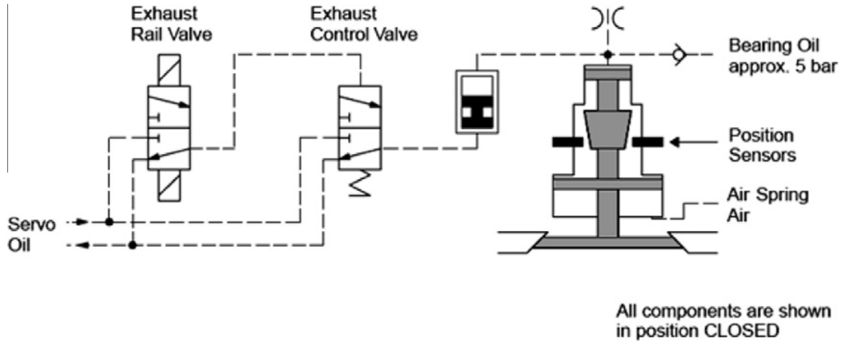


Figure 10 Exhaust valve control diagram.

The exhaust valve movement is controlled as follows:

- The opening command of the exhaust valve is calculated with reference to crank angle and VEO.
- Triggering of the opening rail valve.
- Measuring opening deadtime.
- The closing command is calculated with reference to crank angle and VEC.
- Triggering of the closing rail valve.
- Measuring closing deadtime.
- After a completed revolution the timing control for the next cycle is corrected according to the deadtime of the previous one.

4. Engine management system

Developments in engine management systems (EMS) are focused on the latest trends in ship automation that tends to always higher integration levels.

Computer based tools under the designation of the product family MAPEX (Monitoring and maintenance Performance Enhancement with expert knowledge) enable ship-owners and operators to improve the operating economy of their diesel engines.

An intelligent engine management system also needs to include functions such as the monitoring of specific engine parameters, analyzing data, and managing maintenance and spare parts purchasing activities.

Diesel companies provide range of equipment for carrying out these functions, called the MAPEX Engine Fitness Family, MAPEX, or 'Monitoring and maintenance Performance Enhancement with expert knowledge', encompasses the following principles:

- Monitoring of critical engine data, and intelligent analysis of that data.
- Advanced planning of maintenance work.
- Management support for spare parts and for maintenance.

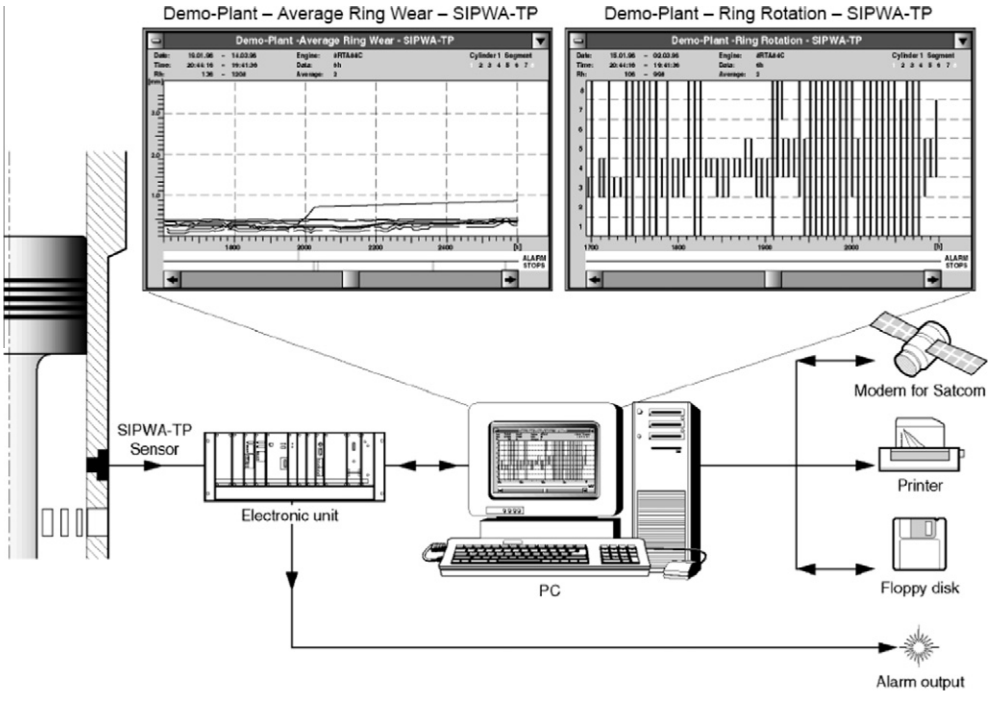


Figure 11 SIPWA-TP (piston-ring wear sensor).

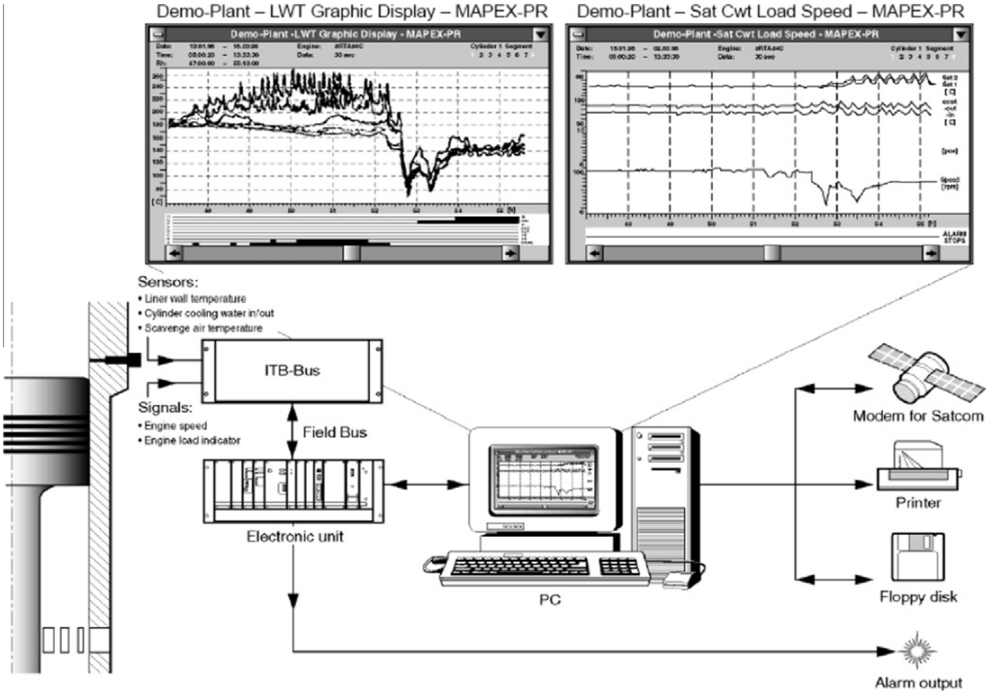


Figure 12 Mapex-PR (piston-running reliability sensor).

- Full support of data storage and transmission by floppy disk and by satellite communication.
- Reduced costs and improved efficiency.

The MAPEX Engine Fitness Family comprises the following systems:

- Online monitoring the piston-ring wear.
- Online monitoring the piston-running reliability.
- Torsional vibration/axial vibration detection system.
- Administration and planning of spare parts and maintenance.

4.1. Online monitoring of the piston-ring wear

This is a powerful system for online monitoring the piston-ring wear as illustrated in Fig. 11. The newly developed system is avoiding all the shortcomings of the past design:

- No electrical plug.
- The measuring coil is shifted away from the hot cylinder liner running surface.
- Easy installation procedure.

The sensor is located in each cylinder liner just above the scavenge air port in order to measure the width of the triangular shaped brass which insert in one of the piston rings. The reduction in the width of this triangular section directly corresponds to the wear of the piston ring.

The following data are monitored and graphically displayed over periods of 400, 1000 and 3000 engine running hours:

- Average piston-ring wear.
- Piston-ring segment wear.
- Piston-ring wear distribution.
- Piston-ring rotation.

4.2. Online monitoring the piston-running reliability

This system continuously monitors the piston-running behavior on large-bore two-stroke diesel engines with an alarm if adverse conditions should appear. It complements piston-ring wear monitoring system by providing a shorter response and alarm function. For example, an alarm is signaled if the local temperature on the liner is abnormally high due to piston-ring scuffing or inadequate ring sealing.

The following data are monitored over periods of 1, 4.5, 24 or 400 engine-running hours and displayed graphically as can be shown in Fig. 12:

- Liner wall temperature (two sensors per cylinder).
- Cylinder cooling water temperature inlet and outlet.
- Scavenge air temperature after each cooler.
- Engine speed.
- Engine load indicator position.
- Alarms.

The following alarms can be connected to the ship's alarm system to inform the engineers about any unexpected situation:

- High–High alarm for: High friction on one or both side of the cylinder liner.
- High alarms for: Deviation of temperature of one cylinder.
- Average temperature of the engine.
- Cooling water fluctuation.
- Scavenge air temperature.
- System alarm for: System failure.

4.3. Torsional vibration/axial vibration detection system

TV/AV is the tool to keep an eye on your engine vibrations.

TV detecting system

- Detects misfiring.
- Measures torsional vibrations.
- Prevents you from wrong alarms during rough sea or when maneuvring.
- AV detecting system.
- Measures axial vibrations of two-stroke engines.

4.4. Administration and planning system of spare parts and maintenance

This is an advanced management tool for the administration and planning of spare parts and maintenance. The system is user friendly and operates on windows compatible computers. Features include purchasing of engine spare parts, inventory control, statistical reporting, issuing of work orders, maintenance history recording, and much more.

5. Engine heat balance and performance analysis

The engine heat balance calculations and the performance analysis become now very easy with the computer help, many computer programs allow the engineer to carry out such calculations through inserting the equations and the givens then the computer solve this equations and find the unknown values and express the results in very simple forms, furthermore it also generate the different relations between the variables and represent it in graphs as shown in the following case study.

5.1. Ship particulars

Type	A7 container vessel
Length overall	306 m
Length between perpendicular	292 m
Breadth molded	40 m
Depth molded	24.5 m
Draft	14 m
Air draft	62 m
Service speed	25.5 knot
Gross tonnage	74,700 ton
Container capacity	6804 TEU
Reefer capacity	459 FEU
Endurance	20700 N.Miles

5.2. Engine data [9]

Type	Sulzer 11RT-flex96C
Power	62,920 kW
Speed	102 rpm
Bore size	960 mm
Stroke	2500 mm
MEP	18.6 bar
Piston speed	8.5 m/s
Length	22,273 mm
Weight dry	1910 ton
E/R crane capacity	11.5 ton
BSFC	171.0 g/kWh
System oil consumption	12 kg/(cyl.day)
Cylinder oil consumption	0.9–1.3 g/kWh

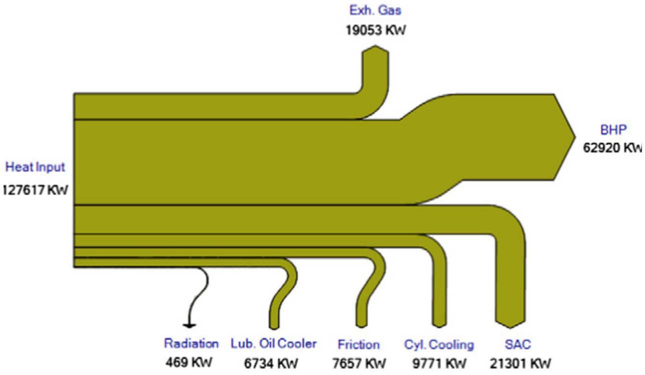


Figure 13 Sanky diagram showing simply the heat balance for the engine.

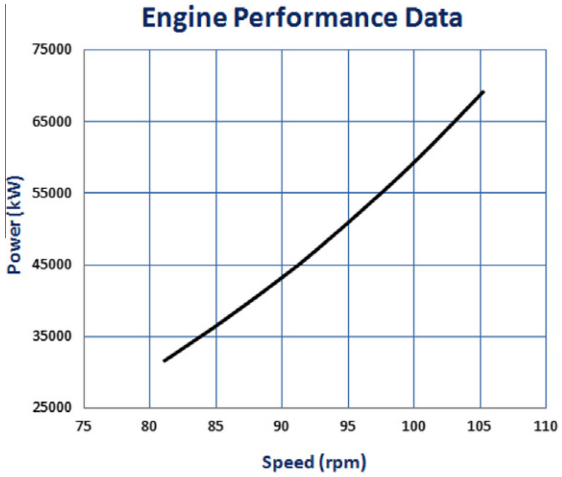


Figure 14 The relation between the engine speed and the developed power.

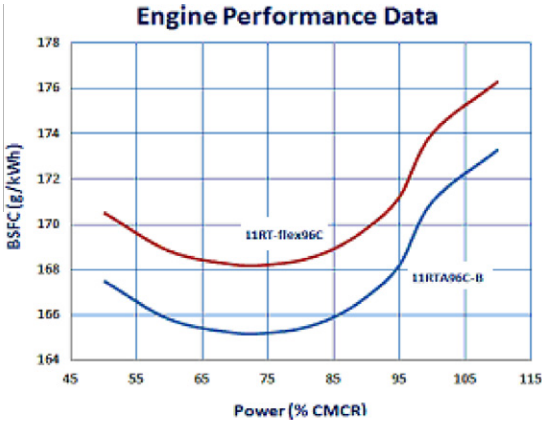


Figure 15 The relation between the engine power and the specific fuel consumption.

5.3. Engine heat balance and performance analysis using engineering equation solver program [7,8]

Engine heat balance, shown in Fig. 13, can be written as

$$Q = P_{\mathrm{B}} + P_{\mathrm{f}} + Q_{\mathrm{C.W}} + Q_{\mathrm{exh}} + Q_{\mathrm{sac}} + Q_{\mathrm{lub.oil}} + Q_{\mathrm{rad}}$$

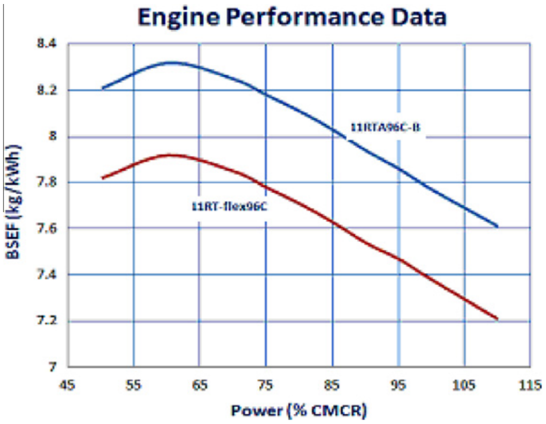


Figure 16 The relation between the engine power and the break specific exhaust gas flow.

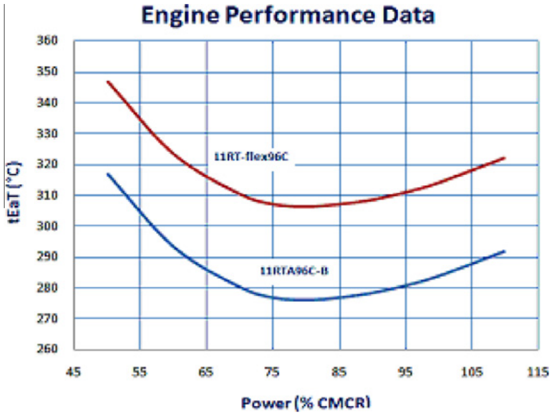


Figure 17 The relation between the engine power and the exhaust gas temperature after T/C.

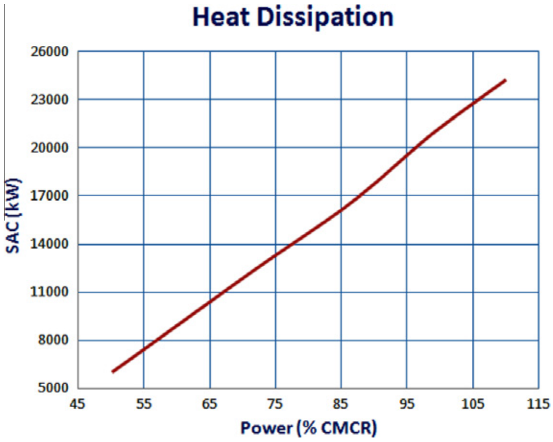


Figure 18 The relation between the engine load and the heat rejected in the scavenge air cooler.

where,

Brake power, $P_{\mathrm{B}} = P_{\mathrm{mep}}{}^{*}V_{\mathrm{cyl}}{}^{*}n^{*}Z^{*}100$

The friction power, $P_{\mathrm{f}} = 0.06^{*}Q_{\mathrm{add}}$

Cooling losses, $Q_{\mathrm{C.W}} = m\cdot_{\mathrm{C.W}}{}^{*}C_{\mathrm{pc.w}}{}^{*}\triangle T_{\mathrm{c.w}}$

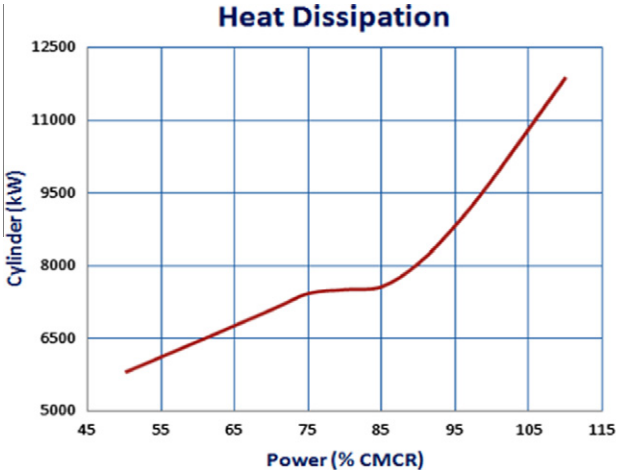


Figure 19 The relation between the engine load and the heat rejected in the cylinder cooling.

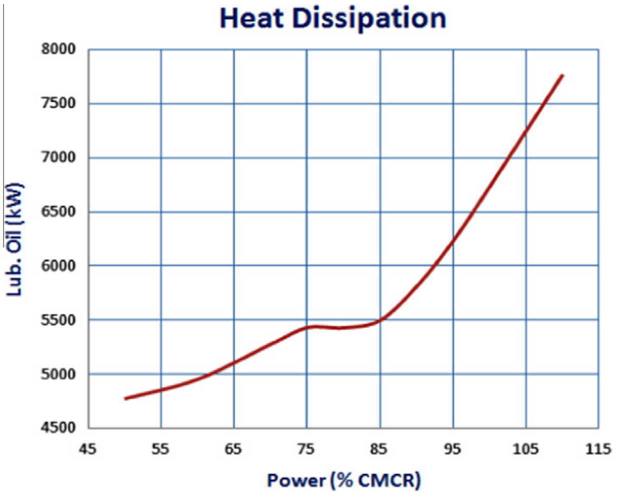


Figure 20 The relation between the engine load and the heat rejected in the lubricating oil.

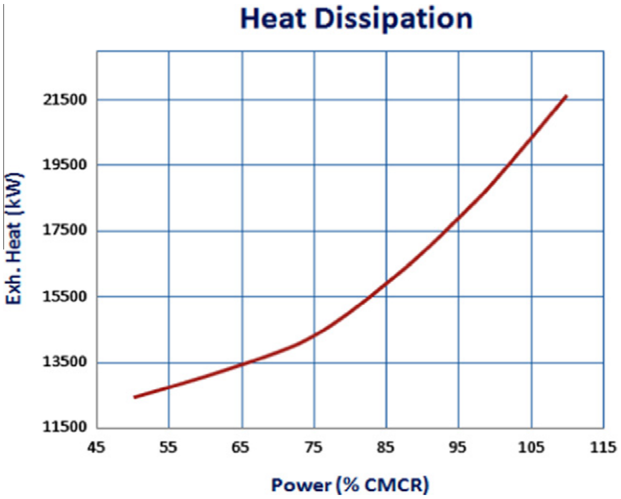


Figure 21 The relation between the engine load and the heat rejected in the exhaust gas.

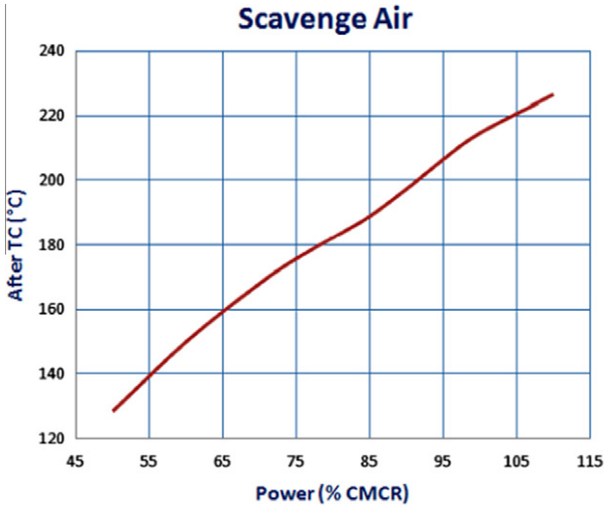


Figure 22 The relation between the engine load and the scavenge air temperature after T/C.

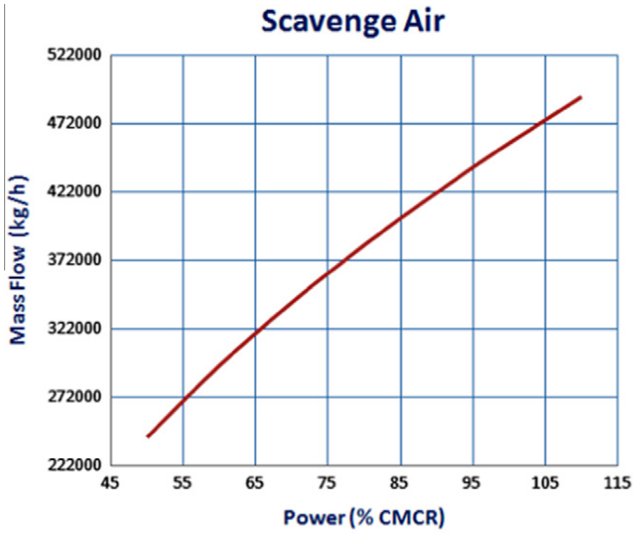


Figure 23 The relation between the engine load and the scavenge air mass flow rate.

Exhaust losses, $Q_{\text{exh}} = m\cdot_{\text{exh}}{}^{*}C_{\text{pexh}}{}^{*}\triangle T_{\text{exh}}$
Scavenging air losses, $Q_{\text{sac}} = m\cdot_{\text{sacc.w}}{}^{*}C_{\text{pc.w}}{}^{*}\triangle T_{\text{sacc.w}}$
Lubricating oil losses, $Q_{\text{lub.oil}} = 0.05^{*}Q_{\text{add}}$
Radiation losses, $Q_{\text{rad}} = 0.003^{*}Q_{\text{add}}$
$Q_{\text{add}} = m_{\text{f}}{}^{*}\text{CV}$

The computer package (EES) shows a great advantage in marine power plants and in energy conservation [10].

Two conditions will be used in the performance calculations to show the effect of the ambient temperature on the engine performance.

	Reference condition (°C)	Design condition (°C)
Air temp. before blower	25	45
Engine ambient air temp.	25	45
Coolant temp. before SAC	29	36

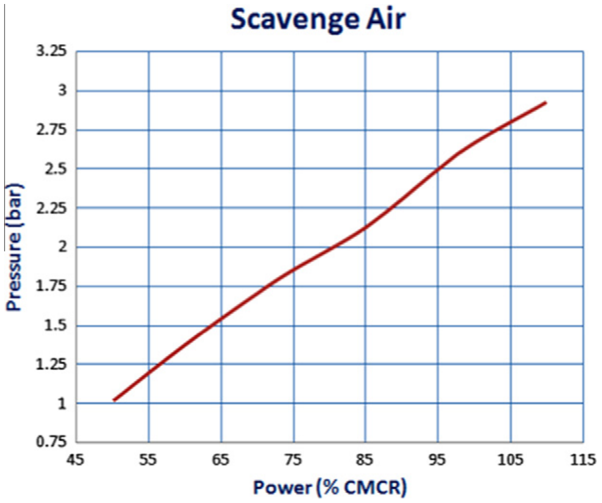


Figure 24 The relation between the engine load and the scavenge air pressure.

The engine developed power as a function of engine speed can be illustrated in Fig. 14 that shows the increase of power with the increase of engine speed. The results for the selected case study can be divided into three characteristics. The first is engine performance data as shown in Figs. 15–17. The second is heat dissipation as shown in Figs. 18–21. The third is the scavenge air as in Figs. 22–24.

6. Conclusion

Using computer in the marine field and the integration between the electronics and diesel engines result in many benefits:

- Lower SFOC and better performance parameters thanks to variable electronically controlled timing of fuel injection and exhaust valves at any load.
- Improved emission characteristics, with lower NOx and smokeless operation.
- Easy change of operating mode during operation.
- Control system with more precise timing, giving better engine balance with equalized thermal load in and between cylinders.
- System comprising performance, adequate monitoring and diagnostics of engine for longer time between overhauls.
- Lower rpm possible for maneuvering.
- Better acceleration, astern and crash stop performance.
- Reduced running costs through lower part-load fuel consumption and longer times between overhauls.
- Reduced maintenance requirements.
- Reduced maintenance costs through precise volumetric fuel injection control leading to extendable times between overhauls.
- Using a computerized based maintenance and management system helps reducing the human faults.
- Engine heat balance calculations and the performance analysis become now very easy with computer help.

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