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MODULARIZATION OF CBM SERVICE AND REQUIREMENT SPECIFICATION FOR DATA ACQUISITION

Wärtsilä Technical Service

School of Technology
2018

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TIIVISTELMÄ

Tekijä	Kristian Anneberg
Opinnäytetyön nimi	CBM palvelun modularisointi sekä siihen tarvittavien moottorin sisäisten järjestelmien ja käyntiarvojen määrittely
Vuosi	2018
Kieli	Englanti
Sivumäärä	110
Ohjaaja	Marko Rantasalo

Opinnäytetyössä käsitellään konepajakonserni Wärtsilän valmistamien 4-tahtimoottoreiden CBM-valvonnan modularisointia sekä siihen tarvittavien moottorien sisäisten järjestelmien ja käyntiarvojen määrittelyä.

CBM lyhenne tulee englanninkielen sanoista condition based maintenance, eli vapaasti käännettynä kuntoon perustuva huolto.

Opinnäytetyössä kehitetään CBM-valvontaa luomalla asiakkaiden tarpeita vastaavia moduuleita, jotka kohdentuvat tietyille moottorin operoinnin tai asiakkaan liiketoiminnan osa-alueille. Moduulien sisältö päätetään sisäisten sidosryhmien haastattelujen perusteella.

Opinnäytetyössä kehitetään valittuja moduuleita määrittelemällä, mitkä järjestelmät ja suoritusarvot vaaditaan toimivan moduulin aikaansaamiseksi. Järjestelmällä tarkoitetaan esimerkiksi moottorin polttoainejärjestelmää ja suoritusarvolla esimerkiksi polttoaineen lämpötilaa.

Materiaalina käytetään lopputyön tekijän tietotaitoa ja osaamista lopputyön aihealueesta sekä yhtiön sisäistä materiaalia, että yleisesti saatavissa olevaa tietoa. Lopputyön tilaajayhtiö tulee käyttämään lopputyötä nykyisen CBM palvelun jatkokehittelyyn. Lopputyössä löydettiin useita potentiaalisia mahdollisuuksia jatkokehittelyn toteuttamiseksi ja CBM liiketoiminnan laajentamiseksi. Tätä tukee myös yhtiön tämän hetkinen voimakas panostus digitalisaatioon.

Avainsanat CBM valvonta, modularisointi, järjestelmä ja käyntiarvo

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ABSTRACT

Author	Kristian Anneberg
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The purpose of the thesis was to evaluate possibilities to modularize CBM monitoring of 4-stroke engines manufactured by technology company Wärtsilä.

Abbreviation CBM stands for Condition Based Maintenance, describing the principle, perform maintenance based on actual condition of equipment.

In this thesis the CBM deliveries was developed further by creating suitable modules beneficial for certain engine operation or a specific business area.

Material used for thesis was the knowhow of the thesis author in the field, and internal technical material within Wärtsilä and material available from open sources for example the Internet. The client of the thesis will utilize the work for further development of CBM monitoring services. In the thesis several potential opportunities were found which are also supported by Wärtsilä's strong investments in digitalization at the moment.

Keywords CBM monitoring, modularization, system and operation parameter

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TIIVISTELMÄ

ABSTRACT

LIST OD ABREVIATIONS

CBM	Condition Based Maintenance
RPM	Round Per Minute
DF	Dual Fuel
SG	Spark (Ignited) Gas
GD	Gas Diesel
T.D.C	Top Dead Centre
B.D.C	Bottom Dead Centre
LFO	Light Fuel Oil
CRO	Crude Oil
MDO	Marin Diesel Oil
HFO	Heavy Fuel Oil
LNG	Liquefied Natural Gas
ME	Main Engine
AE	Auxiliary Engine
SOGAV	Solenoid Operated Gas Admission Valve
GRU	Gas Ramp Unit
EFED	Engine Fuel Efficiency Diagnostic
RAD	Risk Avoidance Diagnostic
IMO	International Maritime Organization
EIAPP	Engine international Air Pollution Prevention
SECA	Sulphur Emission Control Area
MCR	Maximum Continuous Rating

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1 INTRODUCTION

The technology group Wärtsilä is a globally positioned company providing sustainable energy production solutions for marine and energy markets. Wärtsilä plans and produces tailor made solutions fulfilling customer needs, and is committed to lifecycle care of the delivered products and entire installations. The Wärtsilä net sale was 4923 million euros in 2017 and employed approximately 18000 professionals. The company has operations in over 200 locations in more than 70 countries around the world. Wärtsilä is listed on Nasdac Helsinki. /1/

Wärtsilä consists of three business area; Marine Solutions, Energy Solutions and Services.

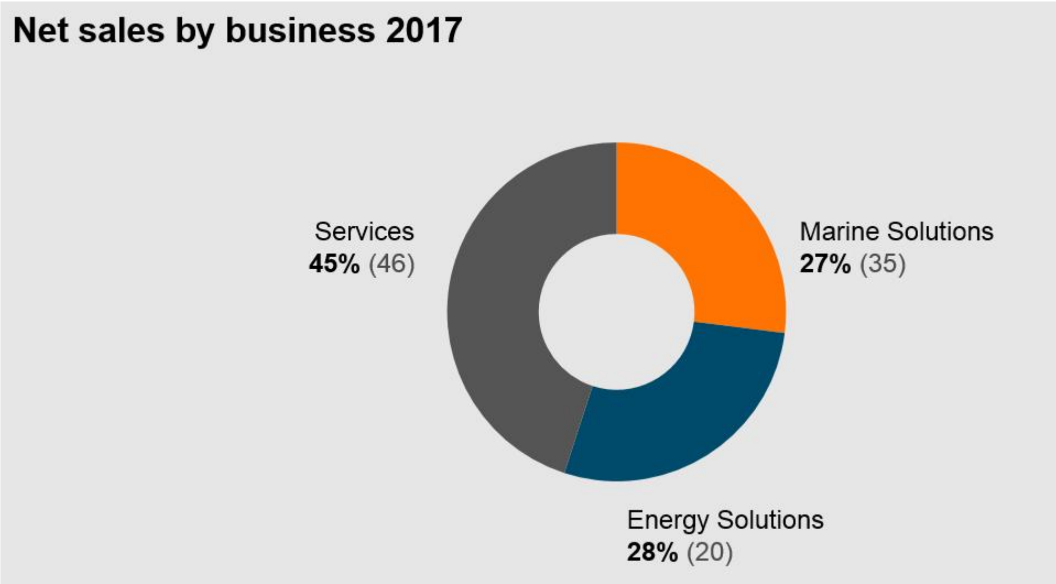


Figure 1. Net sales by business area 2017. /1/

1.1 Business Area Description

Wärtsilä Marine Solutions enhances the business of its marine and oil & gas industry by providing innovative products and integrates solutions that are safe, environmentally sustainable, efficient, flexible and economically sound.

Wärtsilä Energy Solutions is a leading global energy integrator offering a broad range of environmentally sound solutions, such as gas engine based power plants, solar power plants and energy storage & integration solutions.

Wärtsilä Services is the biggest and still growing business area, supporting its customers throughout the lifecycle of their equipment or entire installation by providing service solutions and optimising efficiency and performance. The company's service network of approximately 11,000 professionals in 160 global locations delivering services to more than 12,000 customers every year. /1/

Technical Services, is an expert organization within Wärtsilä Services. Its mission is to maintain, develop and make available the needed technical knowledge for Wärtsilä Services in an efficient and effective way for the benefit of the end customers. Technical Service aims to be the most efficient and effective provider of expert support in problem solving, product development, documentation and training for internal as well as external customers.

1.2 CBM Concept Description

The Wärtsilä Condition Based Maintenance (CBM) concept has been developed by engine and installation experts to support installation owners and users in their daily work, reducing at the same time operating costs for the owners. The CBM concept has been available since 2000. More than 500 marine and power plant installations, over 2000 engines are monitored by Wärtsilä CBM Centre at the moment.

The CBM system calculates the ideal operation parameters based on the engine type design. Correction factors based on ambient conditions, load levels, as well as installation specific settings are used to calculate reference values for actual conditions. Wärtsilä Condition Based Maintenance service optimises the availability, reliability and performance of your equipment, through the diagnostics of key parameters and decision support. On-time decision support is provided to the crew or operator by Wärtsilä experts. The service is available as a part of a service agreement for both marine, power plant and oil and gas installations.

Optimised maintenance is achieved by continuously keeping track of the condition of the equipment. Scheduled maintenance is optimised when combined with Wärtsilä's maintenance planning and on-site inspections. Unscheduled maintenance is minimised thanks to the predictability of the actual condition of the equipment.

2 CBM MONITORING AND REPORTING

The traditional CBM concept consists of engine operation data acquisition from engines, supplied by Wärtsilä, locating around the world, and frequent CBM reporting. The engine operation data is collected from engines into CBM computer, which is creating a daily average value of each recorded parameter, and sending a data package via Internet into the CBM server once in a day. The stored data is used to create engine specific CBM reports, an engine condition report. The CBM report is utilized by customers and Wärtsilä Maintenance Planning Team for support in maintenance planning and trouble shooting.

The traffic light system used in the report gives a clear overview of the installations condition. The large traffic light picture presents the overall condition of the engine while the smaller lights present the condition of specific areas on the engine.
"Green" engine means that all measured important and critical engine parameters are within the normal operation window.

"Yellow" engine means that one or more of the measured important or critical engine parameters are slightly outside the normal operation data window.

"Red" engine means that one or more of the measured important or critical engine parameters are outside both the "Green and Yellow" operation data window.

"Blue" engine means that the engine is stopped, or that the pre-set load limit has not been exceeded.
See Figure 2 on next page.

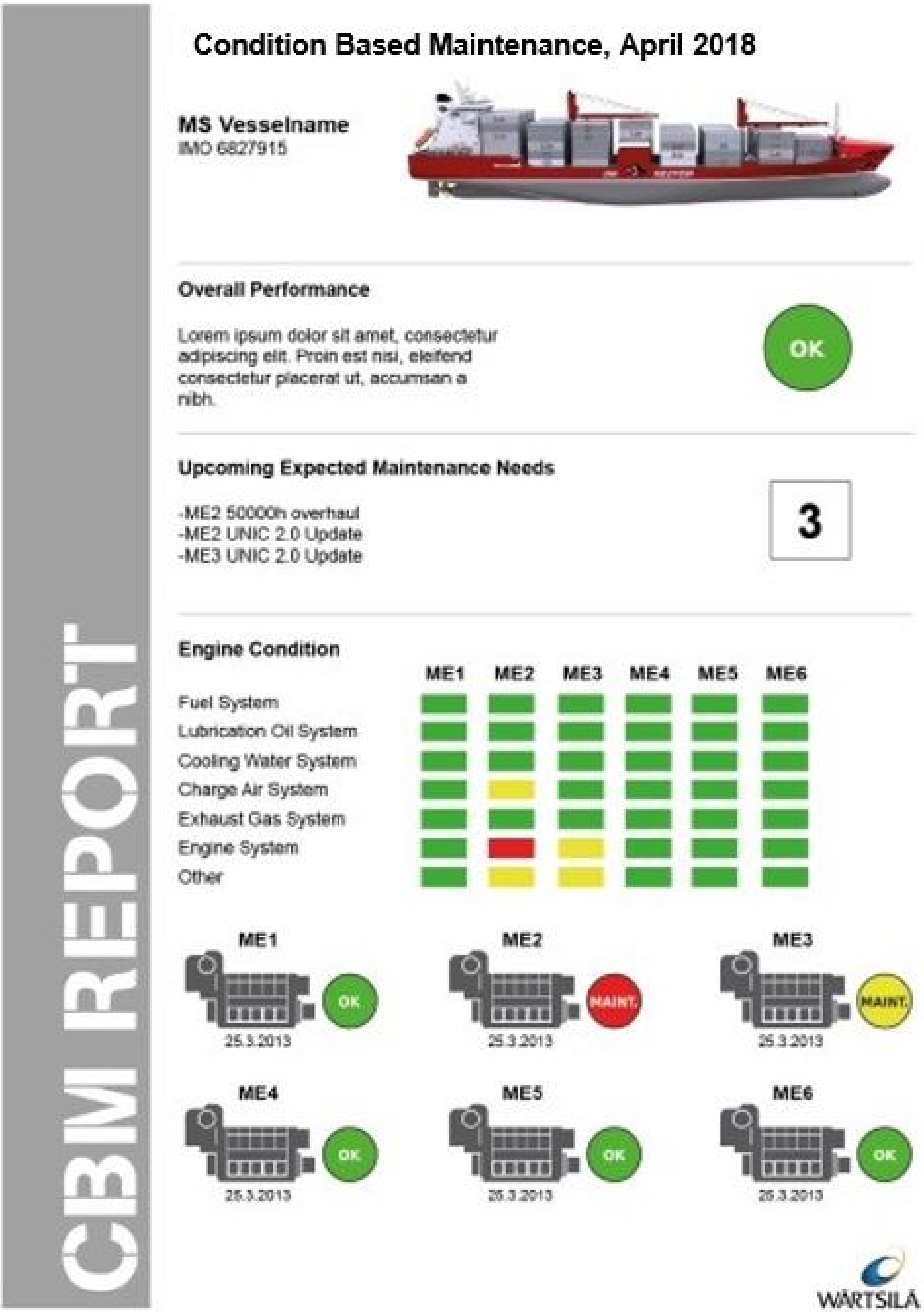


Figure 2. CBM Report cover page. /2/

2.1 CBM Reporting

Reports to the customer begins with the filtering of the digital data through the system. Data analysis, which deals with processing incoming data and trend and history data to maintenance advicements, involves the human factor of the analyst. It is not only individual deviation which determines the equipment condition, but also the combination of excisting deviations and trends. The human factor of the analyst is needed to recognize the excistence of these combinations. The Wärtsilä expert processes the data analysis into a CBM report, which is then sent to the customer via the Wärtsilä Customer Portal.

2.2 Operation Data out of Limits

Below a typical ``Operation data out of limits`` list from a Diesel-electric vessel can be seen. Deviations seen on the screen are low fuel oil temperature, engine inlet, high lubrication oil temperature, engine inlet, low HT water temperature, engine inlet, low HT water temperature, A/B bank outlet (common), low charge air pressure, several high exhaust gas temperatures, after cylinder and high cylinder liner temperature. Site values are measured as daily average values and High/Low spread limits are load based values for 85% engine load.

The data is withdrawn from the server by the CBM analysing tool and is to be analysed further by an engine specialist. The result of the analysing work is a CBM report.

WÄRTSILÄ

Operation data analysis

Detailed operation data analysis

CBM- Condition Based Maintenance

Date/time: 21.03.2018
Load (kW): 4057
Load (%): 85

Air int. temp. 35

Operation data	Unit	Site values	High-spread	Low-spread	Comment(s)
Fuel oil temperature, engine inlet	°C	81	135	100	
Lubrication oil temperature, engine inlet	°C	68	67	58	
HT water temperature, engine inlet	°C	80	86	81	
HT water temperature, A/B bank outlet (common)	°C	85	92	86	
Charge air pressure	bar	1,9	2,4	2,0	
Exhaust gas temperature, after cylinder A2	°C	441	434	354	
Exhaust gas temperature, after cylinder A3	°C	446	434	354	
Exhaust gas temperature, after cylinder A4	°C	470	434	354	
Exhaust gas temperature, after cylinder B4	°C	447	434	354	
Exhaust gas temperature, after cylinder B5	°C	442	434	354	
Exhaust gas temperature, after cylinders average	°C	435	434	354	
Cylinder liner temperature A4	°C	142	140	105	

Figure 3. Operation data out of limits. /3/

3 FURTHER DEVELOPMENT OF THE CBM SERVICE

3.1 Development Work

While Wärtsilä is converting from an equipment supplier to a service company, different life cycle service models have been executed in Wärtsilä during the years and several projects are ongoing at the moment targeting for better installation performance and customer service. All in all the purpose of the service models is to enable a higher utilization rate of state-of-the art installations and so on higher business profit for the customer. The strong development of ICT-technology enables nowadays online communication between customer and Wärtsilä. The standard requirement is that the customer can reach a Wärtsilä technical specialist 24/7. The connection can also be made from Wärtsilä directly to an installations operation computer in case of need for urgent problem solving. Also equipment maintenance planning and logistic arrangements can be done by Wärtsilä on behalf of the customer. By using Wärtsilä for afore mentioned tasks, the customer can be sure that their equipment is maintained always in the best possible way in order to secure a safe and trouble free operation. With this service model provided by Wärtsilä the customer can concentrate resources on their core business. The purpose of this thesis is to develop further the existing CBM concept. The development work consists of two main parts; modularization of CBM service and requirement specification for data acquisition. The result of this thesis work is not engaged into the existing CBM platform, but can be utilized also for future platforms.

4 ENGINE TYPE PRESENTATION

4.1 Wärtsilä 20 & Wärtsilä 20DF

The Wärtsilä 20 is a 4-stroke engine with a cylinder bore of 200 mm, and available in Diesel and Dual Fuel (DF) versions. The engine is available in 4, 6, 8 and 9 cylinder configurations and has a power output ranging from 740 to 1800 kWh at 900 and 1000 rpm.

The Wärtsilä 20DF engine is available in 6, 8 and 9 cylinder configurations and has a power output ranging from 1110 to 1600 kWh at 1000 and 1200 rpm.

The W20 engine is typically used as a main engine in a smaller vessels, for example in ferries, or as an auxiliary engine driving a generator. /3/

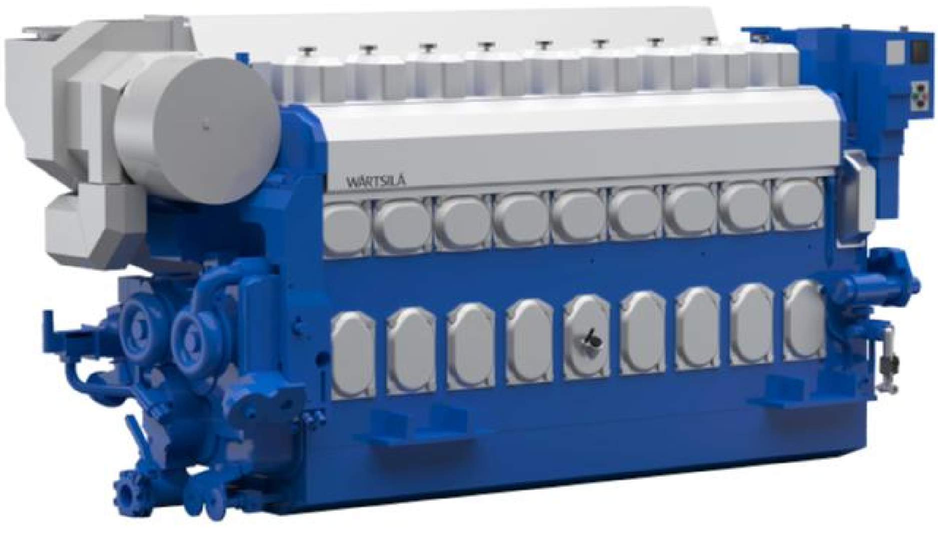


Figure 4. Wärtsilä 20 engine. /4/

4.2 Wärtsilä 31 & Wärtsilä 31DF

The Wärtsilä 31 is the newest member in the Wärtsilä 4-stroke engine family. The Wärtsilä 31 is a 4-stroke engine with a cylinder bore of 310 mm, and available in Diesel, Dual Fuel (DF) and Pure Gas (SG) versions. The engine is available in 8, 10, 12, 16 and 20 cylinder configurations and has a power output ranging from 4880 to 12200 kWh at 750 rpm.

The Wärtsilä 31 is designed to be suitable for a broad range of ship types and applications, both as a main propulsion engine, in diesel electric configurations, or as an auxiliary engine. /6/

Figure 5. Wärtsilä 31 engine. /5/

4.3 Wärtsilä 32 & Wärtsilä 34DF

The Wärtsilä 32 is a 4-stroke engine with a cylinder bore of 320 mm, and available in Diesel and Dual Fuel (DF) versions. The engine is available in 6, 8, 9, 12 and 16 cylinder configurations and has a power output ranging from 3480 to 9280 kWh at 750 rpm.

The Wärtsilä 32 is designed to be suitable for a broad range of ship types and applications, both as a main propulsion engine, in diesel electric configurations, or as an auxiliary engine. /6/

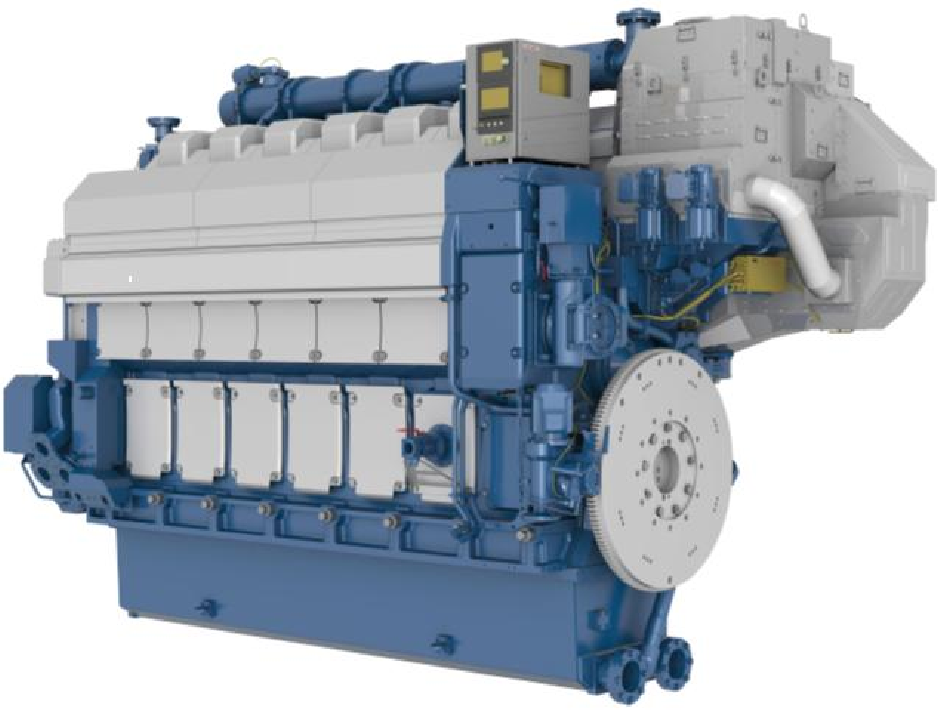


Figure 6. Wärtsilä 32 engine. /6/

4.4 Wärtsilä 46F & Wärtsilä 46DF

The Wärtsilä 46F is a 4-stroke engine with a cylinder bore of 460 mm, and available in Diesel and Dual Fuel (DF) versions. The engine is available in 6, 7, 8, 9, 12, 14 and 16 cylinder configurations and has a power output ranging from 7200 to 19200 kWh at 600 rpm.

The Wärtsilä 46F is designed to meet specific customer needs in a wide range of shipping and power plant applications. /7/

Figure 7. Wärtsilä 46F engine. /7/

4.5 Wärtsilä 50DF

The WÄRTSILÄ® 50DF tri-fuel engine is the ultimate ‘fuel flexibility’ solution. It is a four-stroke engine that runs on light fuel oil (LFO) or heavy fuel oil (HFO), and can switch over from gas to LFO/HFO and vice versa smoothly during engine operation. The Wärtsilä 50DF is manufactured in configurations from 6L up to 16V giving 950/975 kW per cylinder and a total maximum mechanical output of 15,600 kW. The engine speed is 500 or 514 rpm for use with 50 or 60 Hz applications.

Wärtsilä 50DF is suitable for a wide range of applications. The engine can be installed and optimised for constant speed generating sets, as well as variable speed for mechanical drive applications for main engines. Wärtsilä 50DF offers various machinery opportunities for different vessel applications, such as small cargo vessels, ferries or tug boat installations. Wärtsilä 50DF is also optimal for generating set application for a wide range of vessel types.

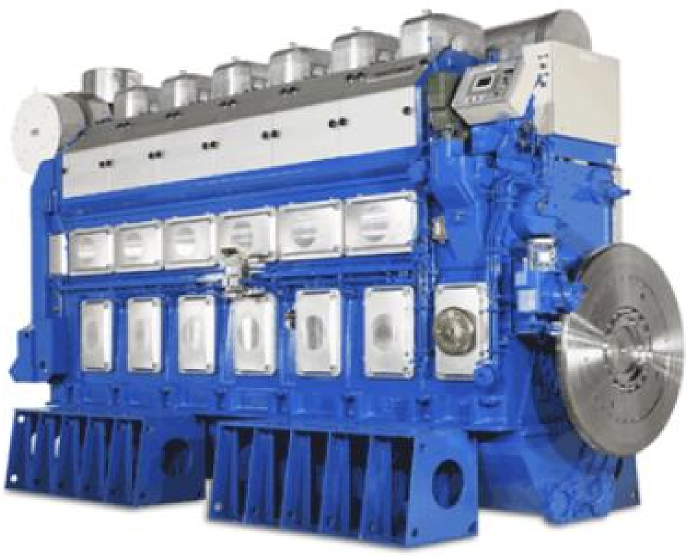


Figure 8. Wärtsilä 50DF engine. /8/

4.5.1 Cross Section of the Wärtsilä 46F In-line Engine

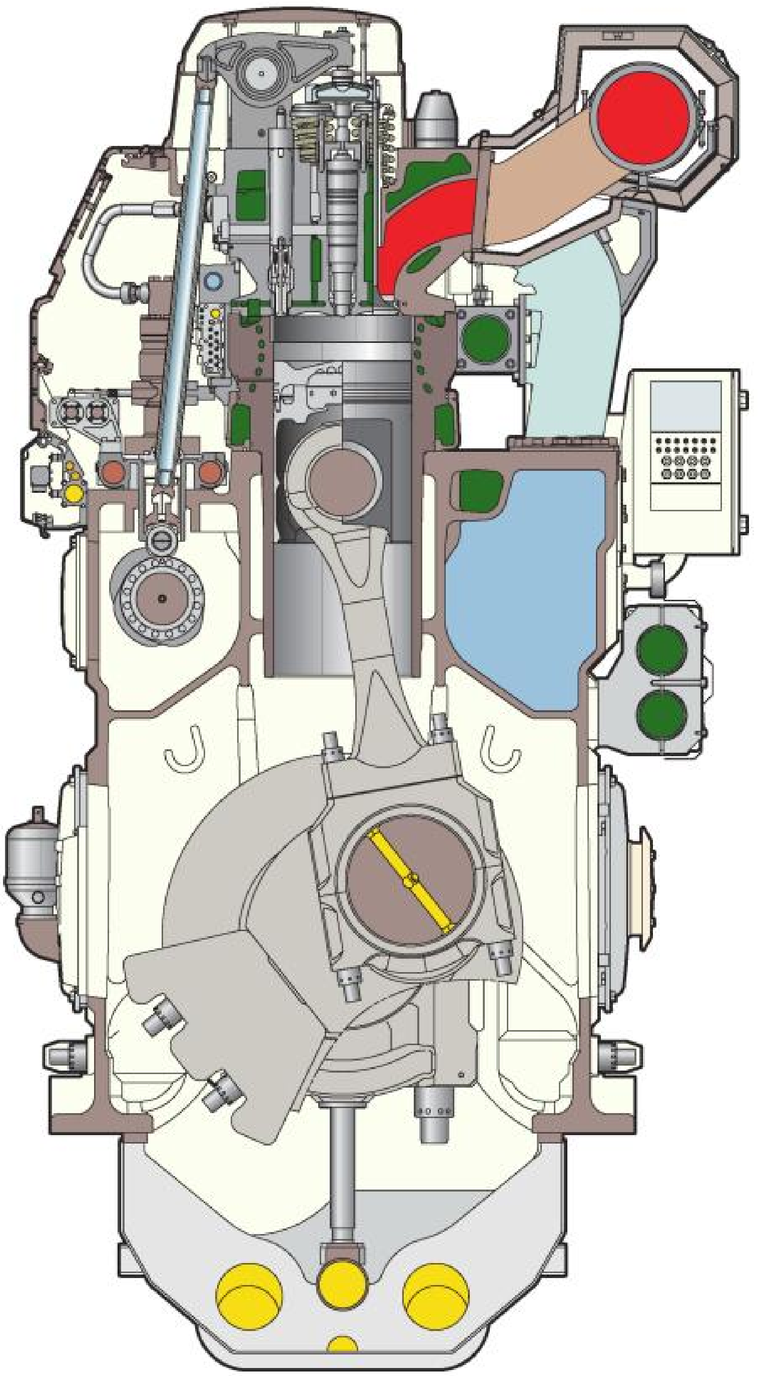


Figure 9. Cross section of the Wärtsilä 46F in-line engine. /9/

4.5.2 Cross Section of the Wärtsilä 46F V-engine

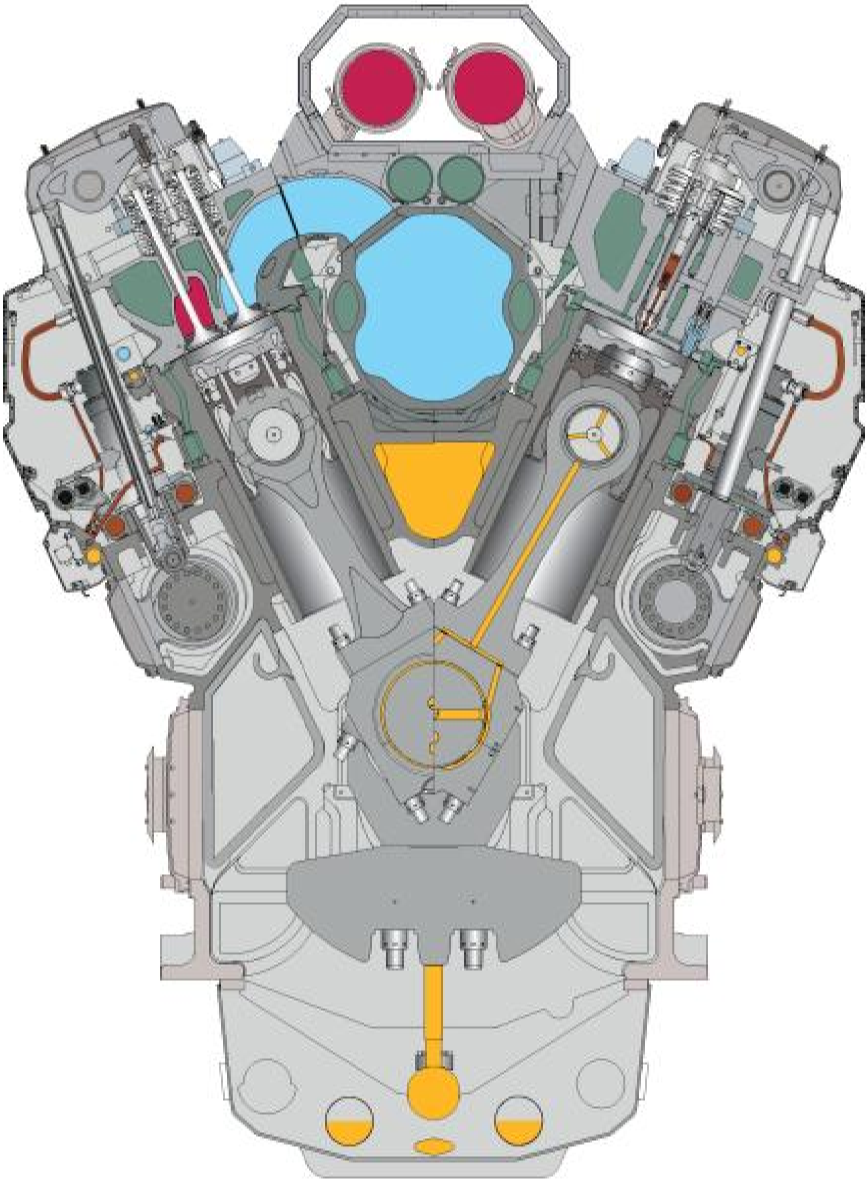


Figure 10. Cross section of the Wärtsilä 46F V-engine. /10/

4.6 4-stroke Engine Working Principle

A 4-stroke Diesel-engine is an internal combustion engine in which the piston completes four separate strokes while turning the crankshaft. A stroke refers to the full travel of the piston along the cylinder, in either direction. The four separate strokes are named as follows:

1. Inlet stroke

The inlet stroke of the piston begins at the top dead centre (T.D.C.) and ends at the bottom dead centre (B.D.C.). In this stroke, the intake valve must be in the open position while the cylinder is filled with charge air by the downward motion of the piston. In Wärtsilä dual fuel (DF) and spark ignited gas (SG) engines, the fuel gas is fed into the cylinder during the inlet stroke.

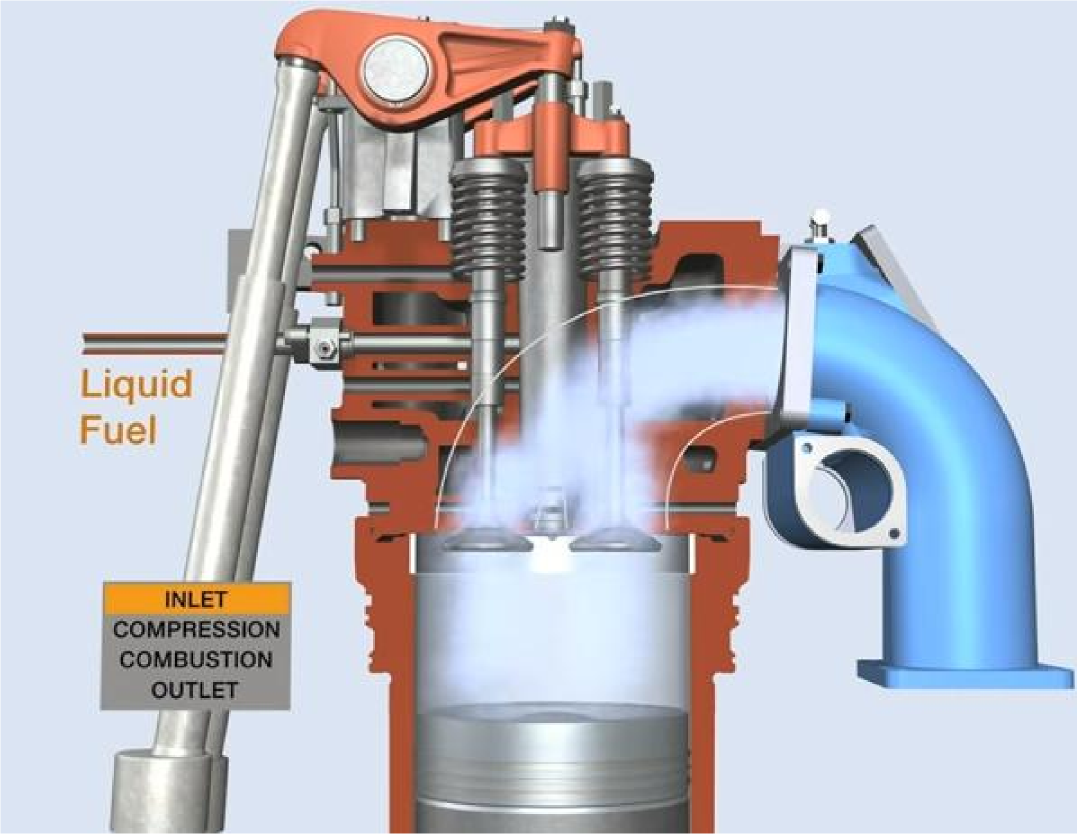


Figure 11. Inlet stroke. /11/

2. **Compression stroke**

The compression stroke of the piston begins at the B.D.C, or just at the end of the suction stroke, and ends at the T.D.C. In this stroke the piston compresses the air in preparation for ignition of the fuel, injected at the end of compression stroke. Both the intake and exhaust valves are closed during this stage.

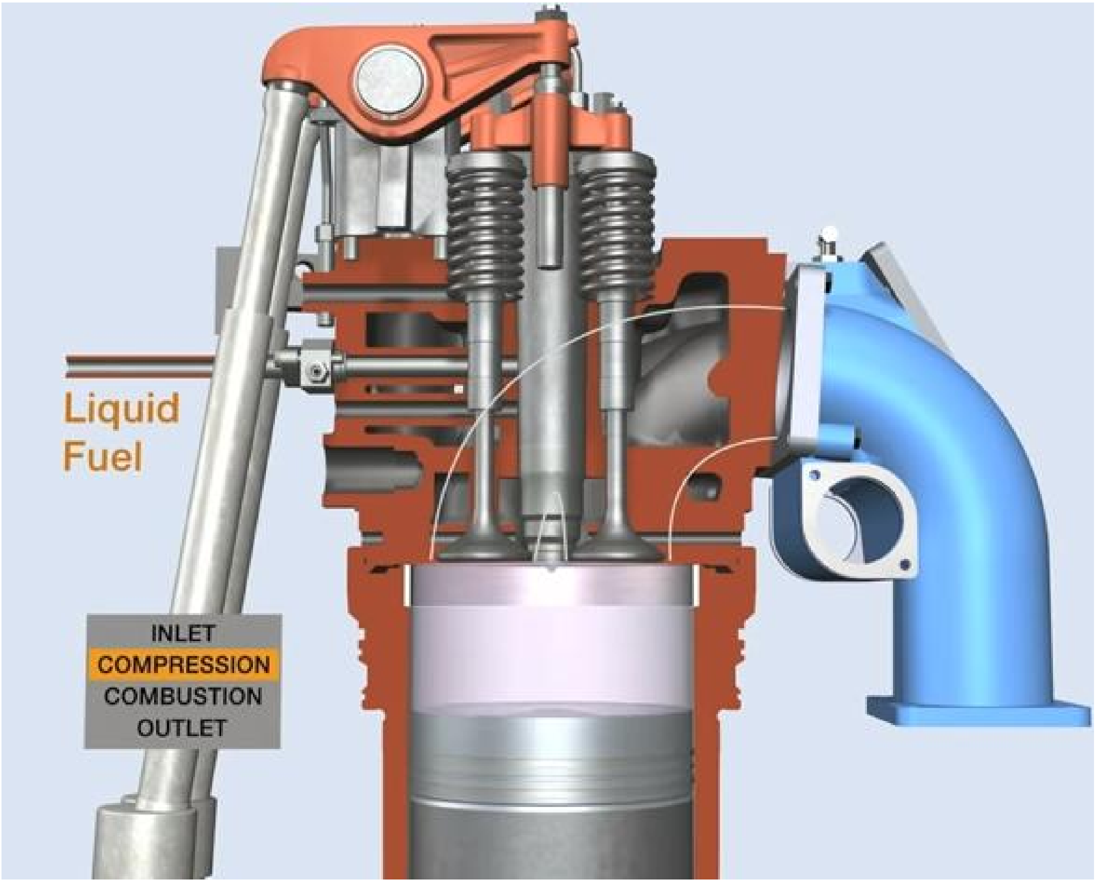


Figure 12. Compression stroke. /12/

3. **Work stroke**

The work stroke is the start of the second revolution of the four-stroke cycle. At this point the crankshaft has completed a full 360 degree revolution. While the piston is at the T.D.C. the compressed air-fuel mixture is ignited by heat generated by high compression, forcefully returning the piston to the B.D.C. This stroke produces mechanical work to turn the crankshaft.

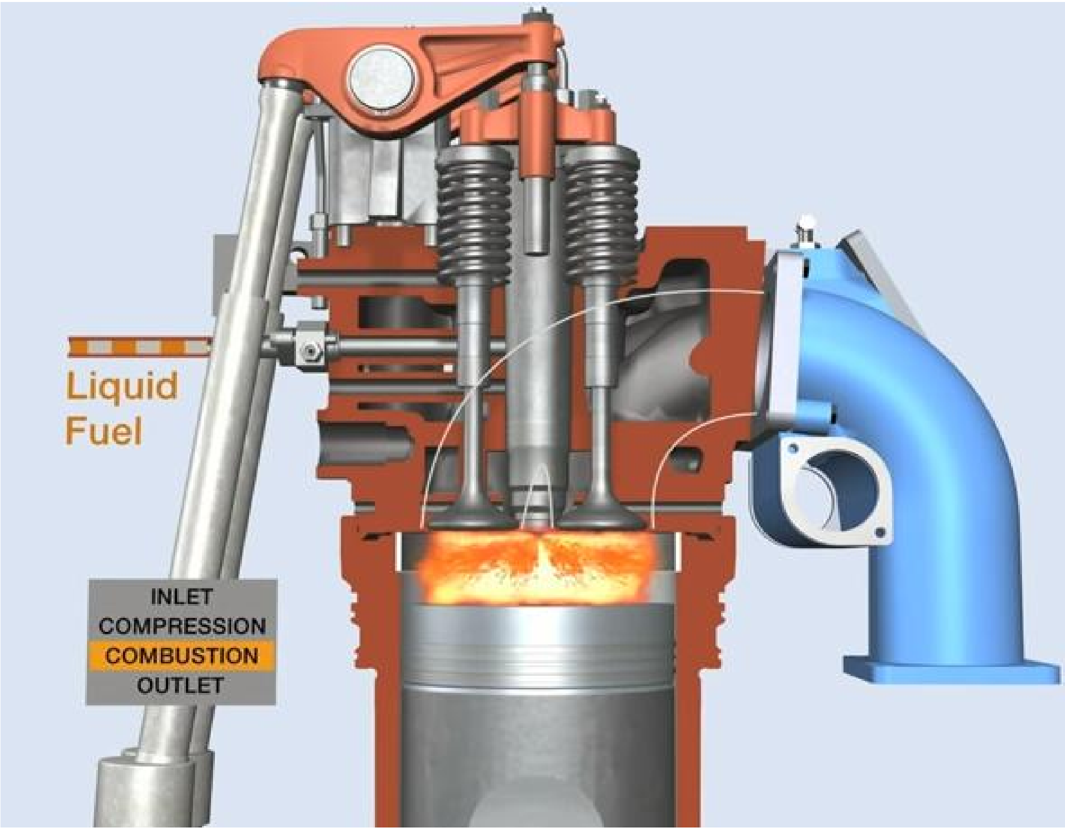


Figure 13. Work stroke. /13/

4. Outlet stroke

During the outlet stroke, the piston once again returns from the B.D.C. to the T.D.C. while the exhaust valve is open. This action expels the spent air-fuel mixture through the exhaust valve into atmosphere.

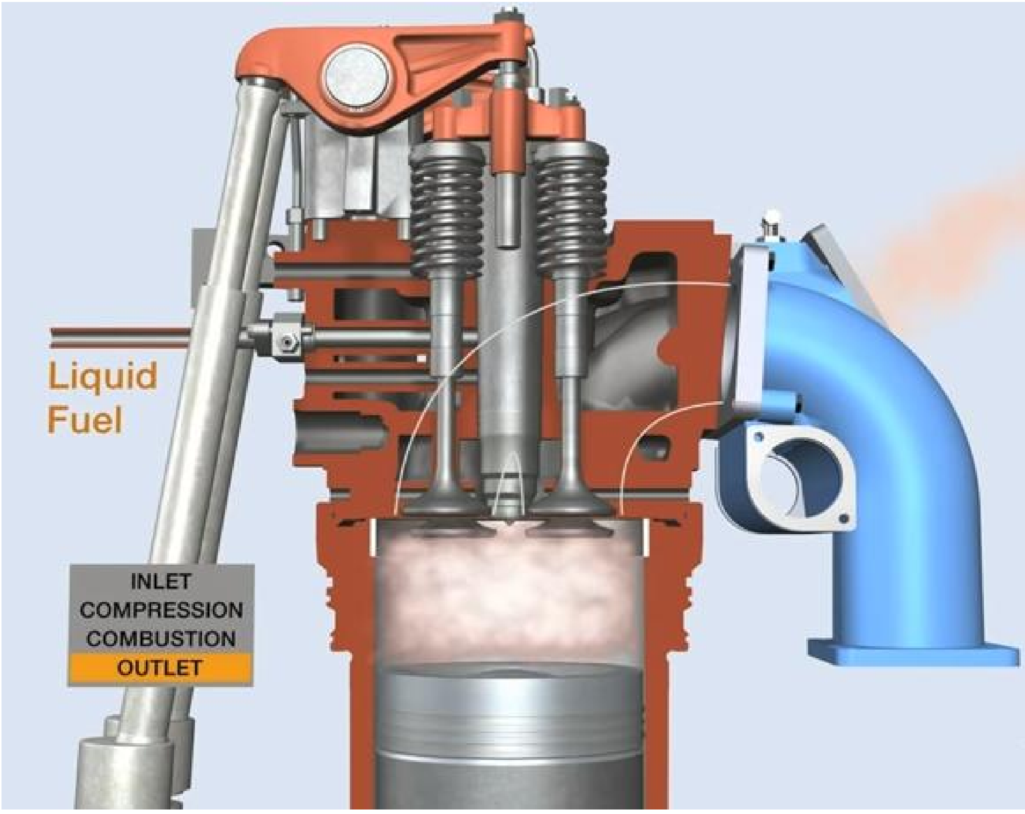


Figure 14. Outlet stroke. /14/

5 MODULARIZATION

When CBM monitoring was presented in the year 2000, it was a revolutionary step towards digitalization, even though term digitalization was not widely used at that time. CBM monitoring is today well established and popular amongst customer operating Diesel- or gas engine powered installations, ships, offshore installations and power plants.

The modularization of CBM service means that the existing CBM Service is developed further by creating task specific functions being useful for customers business. Tasks can be for example assisting in achieving better fuel economy, improving engine uptime and reliability and detecting abnormalities in engine operation parameters.

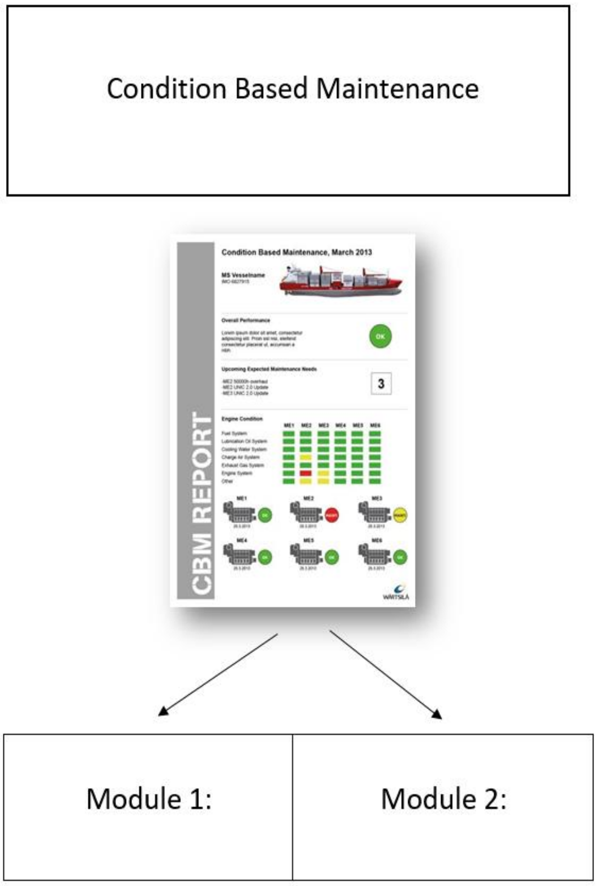


Figure 15. CBM report modularization.

5.1 Module

A module is a function in the CBM report, consisting and executed by utilising engine specific CBM data and further enabling a specific task, consentrating on chosen function. The decision of what kind of modules should be developed is based on arguments and opinions from internal key stake holders, Support and Development, Marine agreements and Global Contract Centre.

Typically the operation data is originated from a Wärtsilä brand 4-stroke engine, but can be also originate from an auxiliary device providing that a sufficient amount of sensors are installed on the device in question. With an auxiliary device is meant those devices placed in the proximity of engines supporting engines vital functions, such as fuel oil supply, fuel oil separation, lubrication oil separation and fuel gas supply in case of gas engine. Modern 4-stroke Diesel- and gas engines are equipped comprehensively with sensors measuring temperatures, speed and such in numerous points', enabling data collection for CBM monitoring. However, auxiliary devices are traditionally not equipped with so many sensors which may be hinder for remote monitoring.

When modules are specified, it to be investigated and decided which systems and operation parameters each module should include in order it can fulfil its intended task. This has to be done separately for each agreed engine type and configuration. Presently most common engine types which are CBM monitored and reported are Wärtsilä Vasa 32, Wärtsilä 32, Wärtsilä 46 and gas operated version of mentioned engine types, DF and SG configurations.

5.2 The Engine System Structure

With a system is meant different functional and structural sections in a 4-stroke engine. All Wärtsilä 4-stroke engine regardless of type or size have following main systems:

1. Engine control system
2. Engine safety system
3. Fuel system
4. Lubrication oil system
5. Cooling system
6. Exhaust gas system
7. Charge air system

Each system has its vital operation parameters that are important to monitor all the time in order to maintain safe and economic engine performance.

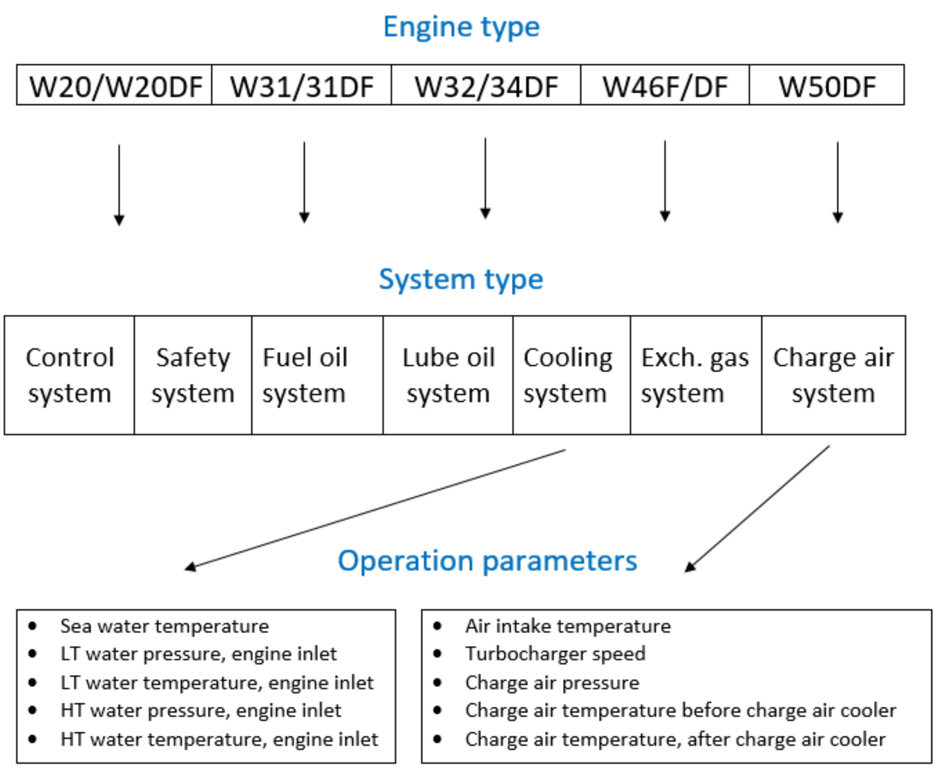


Figure 16. The engine system structure.

5.3 Engine Control System

Diesel-engines are monitored by an engine control system. The system consists of different sensors placed on selected positions in the engine. The system can be divided roughly to a safety system and an operation monitoring system. Sensors are typically pressure sensors, temperature sensors, speed pick up or position sensors, but also knocking sensors and firing pressure sensors are used in Gas-engines. The data from sensors is collected to the engine monitoring system and is visible in the engine built screen and in the monitoring and operation computer in the engine control room.

Operation monitoring system

The operation monitoring system tells how the engine is performing. It is monitoring such parameters, which have desired pressure-, temperature- or speed level. Such parameters are for example charge air pressure and charge air temperature. If these parameters are outside the low or high spread limits, it tells that the engine performance is not on the desired level. The system may reveal a single parameter outside the limits, but which is a result of combination of several factors.

In Gas-engines the engine control system is monitoring cylinder specific exhaust gas temperatures, firing pressures and knocking values after every ignition and controls cylinder specific fuel gas admission valves based on measured values and therefore has an important function for engine performance.

Figure 17. UNIC engine control system. /15/

Engine safety system

The purpose of the engine safety system is the monitoring of critical functions and components. A failure in such a function or component may jeopardize the safe engine operation and lead to a major breakdown. A typical function and component monitored by the engine safety system are lubrication oil pressure and main bearing temperatures. The engine safety system gives a warning when a certain lower or upper limit of pressure or temperature is exceeded.

Figure 18. Engine safety system. /16/

5.3.1 Vital Parameters and Factors

The monitoring of **main bearing temperatures** in marine installations is mandatory by rules from classification societies. A main bearing damage may lead into a major breakdown and leaving a marine installation without electricity and in the worst scenario, without manoeuvrability. Typical root causes for a main bearing damage are poor lubrication oil quality and material fatigue in bearing metal bonding and layers.

Figure 19. Main bearing pair, upper and lower part. /17/

The monitoring of **big end bearing temperature** is a fairly new feature in Diesel- and Gas engines. The challenge has been in transferring the measured data from a rotating connecting rod to the control system. The development of wireless data transfer made this possible and the system for monitoring the big end bearing temperature is available at the moment for most of Wärtsilä engine types. The big end bearing, similarly to the main bearing, is one of the most critical components in an engine and therefore consequences are serious in case of a breakdown. Typical root causes for big end bearing damage are poor lubrication oil quality, material fatigue in bearing metal bonding and layers and errors made in the bearing assembly work.

Figure 20. Big end bearing temperature sensor pair. /18/

The monitoring of **cylinder liner temperatures** in marine installations is also mandatory by rules from classification societies. Also a cylinder liner damage may lead into a major breakdown and leaving a marine installation without electricity and in the worst scenario, without manoeuvrability. Typical root causes for cylinder liner damage is poor lubrication oil quality or neglected maintenance.

The **crankcase pressure** indicates the over-pressure level in the crankcase. The crankcase over-pressure compared to the atmospheric pressure is very small, typically from 1 to 3 mbar. However, it is a very important indicator of cylinder tightens. If the crankcase pressure is rising, continual amount of gases (air, unburned fuel, combustion gases) leaks from the combustion chamber past the piston rings. The phenomenon is called blow-by. A crankcase pressure over 3-mbar indicates wear in cylinders or in piston rings. If such readings are measured unexpectedly, the reason for it should be investigated in order to ensure a safe engine operation. Crankcase pressure can be measured continuously by means of a pressure sensor or periodically by means of a water filled U-tube.

Because the blow-by phenomenon is present always to certain extent, the crankcase has to be ventilated via the crankcase ventilation valve to the atmosphere.

If the installation is equipped with an oil mist separator, which is removing oil from ventilated air, crankcase pressure readings may be negative. In other words a small vacuum may be created in the crankcase. The oil mist separator should be by-passed for periodical crankcase pressure measurements in order to achieve correct pressure readings.

Crankcase explosion may lead into fatal person injuries for persons present in the engine room. **Oil mist detection** is mandatory for marine installations for safety reasons. The rule comes from the SOLAS regulations. The abbreviation SOLAS stands for Safety of Life At Sea, and the first version of SOLAS treaty saw its daylight in 1914 in response to the disaster of the RMS Titanic and prescribed for example the number of lifeboats and other emergency equipment along with safety procedures, including continuous radio watches.

When an engine is running and lubrication oil has reached its normal operation temperature, a stoichiometric oil mist is present in the crankcase. Even if the oil mist is flammable, there is no risk for a crankcase explosion as long as an ignition source does not exist. Ignition sources are typically related to mechanical failures such as damage to main bearing, big end bearing or drive train bearing of cam mechanism and further on bearing seizure causing high temperature due to friction. In case of a bearing seizure, the oil mist is getting darker while approaching the explosion. The task of the oil mist detector is to control the oil mist colour and raise an alarm and stopping the engine when changes in the oil mist colour are seen. The device is sucking oil mist from the crankcase through a sensor, which is able to recognise changes in the oil mist colour.

Figure 21. Oil mist detector installed in Wärtsilä Vasa 32 engine. /19/

5.4 Fuel System

· **Fuel oil system for liquid fuels**

The purpose of the fuel oil system is to provide a sufficient amount of clean fuel oil for the engine in correct pressure and temperature. The amount of fuel oil circulating through the engine is typically four times the amount required for combustion process.

The external (non-engine built) fuel oil system of the installation typically consist of storage tank, buffer tank, fuel oil separator, day tank, feeder unit, mixing tank, booster with heater and viscometer for Heavy Fuel Oil, cooler for Marine Diesel Oil or Light Fuel Oil and fuel oil filter and all required piping. The engine built equipment includes low-pressure fuel oil piping, cylinder specific injection pumps or common rail pump, high pressure fuel oil piping and injection nozzles. Nowadays many installations are also equipped with fuel oil flow meters in order to follow up fuel oil consumption vs. generated engine power.

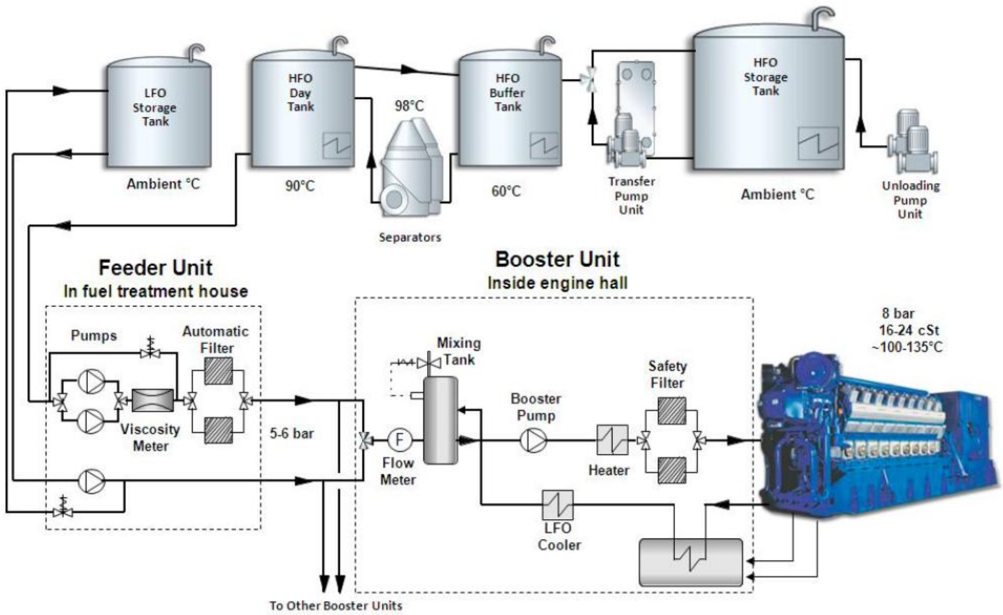


Figure 22. Power plant fuel oil system scheme. /20/

- **Fuel system for gas fuel**

The function of the fuel gas system is to provide a sufficient amount of fuel gas for the engine in correct pressure. The engine capable to run on gas can be **a** pure gas engine (SG) or a dual fuel engine (DF), capable to run on both gas and liquid fuel oil. The requirements for gas engines used in marine installations states that the engine must be able to run on both gas and liquid fuel oil. Land-based installations, such as power plants, are free of that kind of requirement, and can be operated on gas only. However, the option for using dual fuel engines in land-based installations is not closed out. Capability to run a land-based installation on liquid fuel oil enables undisturbed power generation in case that gas is not available.

The fuel gas source for a marine installation is boil-off gas from LNG. In case of LNG carriers, the boils of gas originates from the LNG the carrier is transporting. In case of other type of marine installations, for example passenger vessels and tug boats, the boil-off gas is originated from a separate LNG fuel gas tank.

The gas source for a land-based power plant installation is often a gas pipe line built from the gas source to the power plant. The gas coming to the power plant along the gas pipe line is in gaseous form.

The fuel gas system is rather simple in both marine and power plant installations. The boil-off gas in marine installations and gas in gaseous form in power plants is led through the pipe lines to the Gas Valve Unit, which regulates the fuel gas pressure before gas is entering the engine. In the engine, cylinder specific gas admission valves (SOGAV) operated by the engine operation computer, are feeding fuel gas the right amount at the right moment into the cylinder.

5.4.1 Fuel Types Used in Marine and Power Plant Installations:

Commonly used fuel oil types in marine installations:

- Light Fuel Oil (LFO)
- Marin Diesel Oil (MDO)
- Heavy Fuel Oil (HFO)

Commonly used fuel oil type in power plant installations:

- Heavy Fuel Oil (HFO)

Commonly used gas fuel type in marine installation:

- Liquefied Natural Gas (LNG)

Commonly used gas fuel type in power plant installations:

- Methane

- **Description of fuel oil type**

Crude oil, the base of all refined petroleum oil products, can be used as an engine fuel providing that it is suitable for installations fuel handling equipment. In many cases pre-handling is required before the crude oil can be used. Certain components, such as water to be separated from crude oil. In some cases the natural gas content can be challenging for the engine fuel system, requiring arrangements to avoid cavitation damages for example in low pressure fuel pipes. The exact specification can vary a lot and depends on where the crude oil type in question is discovered.

Light Fuel Oil (LFO) belongs to the group of middle distillates with a boiling point between 180°C and 360°C. Light Fuel Oil is widely used by medium speed and medium/high speed marine diesel engines. It is also used in the larger slow speed and medium speed propulsion engines. Its density varies between 0.96 kg /dm³, and has an approximate caloric value of 43.02 MJ/kg.

Marine Diesel Oil (MDO) is a blend of gasoil (Diesel-oil) and heavy fuel oil, with less gasoil (Diesel-oil) than intermediate fuel oil used in the maritime field. Marine Diesel Oil is widely used by medium speed and medium/high speed marine diesel engines. It is also used in the larger slow speed and medium speed propulsion engines. Its density varies between 0.98 kg/dm³ and has an approximate caloric value of 42.26 MJ/kg.

Heavy Fuel Oil (HFO) is a high-viscosity residual oil. Residual means the material remaining after the more valuable cuts of crude oil have boiled off. The residue may contain various undesirable impurities, including 2% water and 0.5% mineral soil. Its density varies between 0.9 – 1.0 kg/dm³, and has an approximate caloric value of 11.8 kWh/litre or 40.6 MJ/kg. Its sulphur content can be up to 4%. Heavy fuel oil is widely used in all type of marine installations and power plants. HFO requires separation to remove harmful particles before fed into the engine. It requires pre-heating to 104–127 °C (219–261 °F) depending on the viscosity. Preheating is required also for transportation, storage and feeding into the engine fuel oil system.

Figure 23. Heavy Fuel Oil. /21/

Liquefied natural gas (LNG) is natural gas, mostly methane, with some mixture of ethane that has been converted to liquid form for ease and safe of non-pressurized storage or transport. It takes up about 1/600th the volume of natural gas in the gaseous state. It is odourless, colourless, non-toxic and non-corrosive. Hazards include flammability after vaporization into a gaseous state, freezing and asphyxia. The liquefaction process involves removal of certain components, such as dust, acid gases, helium, water, and heavy hydrocarbons. The natural gas is then condensed into a liquid at close to atmospheric pressure by cooling it to approximately −162 °C. /9/

A common solution in transporting LNG by sea is an LNG carrier, the cargo tank of which is designed for a cold liquid form cargo. LNG carriers typically do not have very big bunker tanks for LFO and HFO fuel for main engines, but are equipped with so called dual fuel 4-stroke engines (DF) capable to utilize the boil off gas from LNG as a fuel. /22/

Figure 24. LNG carrier, equipped with Wärtsilä 8L50DF and 12V50DF dual fuel engines. /23/

Figure 25. Passenger ferry (Ro-Pax, Roll-On-Roll-Off-Passenger-ship), equipped with Wärtsilä 8L50DF dual fuel engines. LNG tanks seen on aft deck. /24/

Methane, CH_4, is colourless and odourless gas that occurs in nature and as a product of certain human activities. Methane is the simplest member of the paraffin series of hydrocarbons and is among the most potent of the greenhouse gases. Methane is lighter than air and only slightly soluble in water. It burns in air, forming carbon dioxide and water vapour. The flame is pale and very hot. The boiling point of methane is −162 °C and the melting point is −182.5 °C. Methane is very stable, but stoichiometric mixtures of methane and air, with the methane content between 5 and 14 percent by volume, are explosive.

Figure 26. Methane flame in flare tower. /25/

5.4.2 Vital Parameters and Factors

- **Fuel oil temperature, engine inlet, Light fuel oil (LFO)**

The temperature range for LFO is wide, from 5 to 50°C. Problems may occur when running on LFO if its temperature becomes higher than the recommended 50°C. Problems may occur for example during the fuel switching from HFO to LFO, because the fuel system, piping and injection equipment, are still hot after running on HFO. If the temperature of LFO is higher than 50°C, its viscosity becomes very low and loses its capability to lubricate injection pump element parts, barrel and plunger, which may lead into the seizure of the element. Other typical problem may occur when starting the engine with high temperature LFO. Because of its very low viscosity, the pump element is not able to create high enough fuel injection pressure to allow the engine starting. Worn injection pump elements increase the risk for starting problems.

- **Fuel oil temperature, engine inlet, Heavy fuel oil (HFO)**

The fuel oil temperature control process is very important when running the engine on HFO because the viscosity of HFO is very high at room temperature. Its viscosity at room temperature is far too high also for all fuel handling equipment from transfer pumps to fuel injection pumps in the engine.

The recommended viscosity range at the engine inlet is 13-17 centistokes (cSt). The preheating temperature to reach 15 cSt is usually reported in bunker reports, but can also be estimated from the approximate viscosity/temperature chart in the engine instruction manual. For example, standard 380 cSt (at 50°C) must be preheated to about 130°C. See Viscosity / temperature diagram on the next page.

The maximum viscosity of the bunkered fuel that can be used in installations depending on the heating and fuel preparation facilities available.

· **Heavy fuel oil Viscosity / temperature diagram**

For example, standard HFO 380 cSt (at 50°C) must be preheated to about 130°C to achieve 13-17 centistokes viscosity.

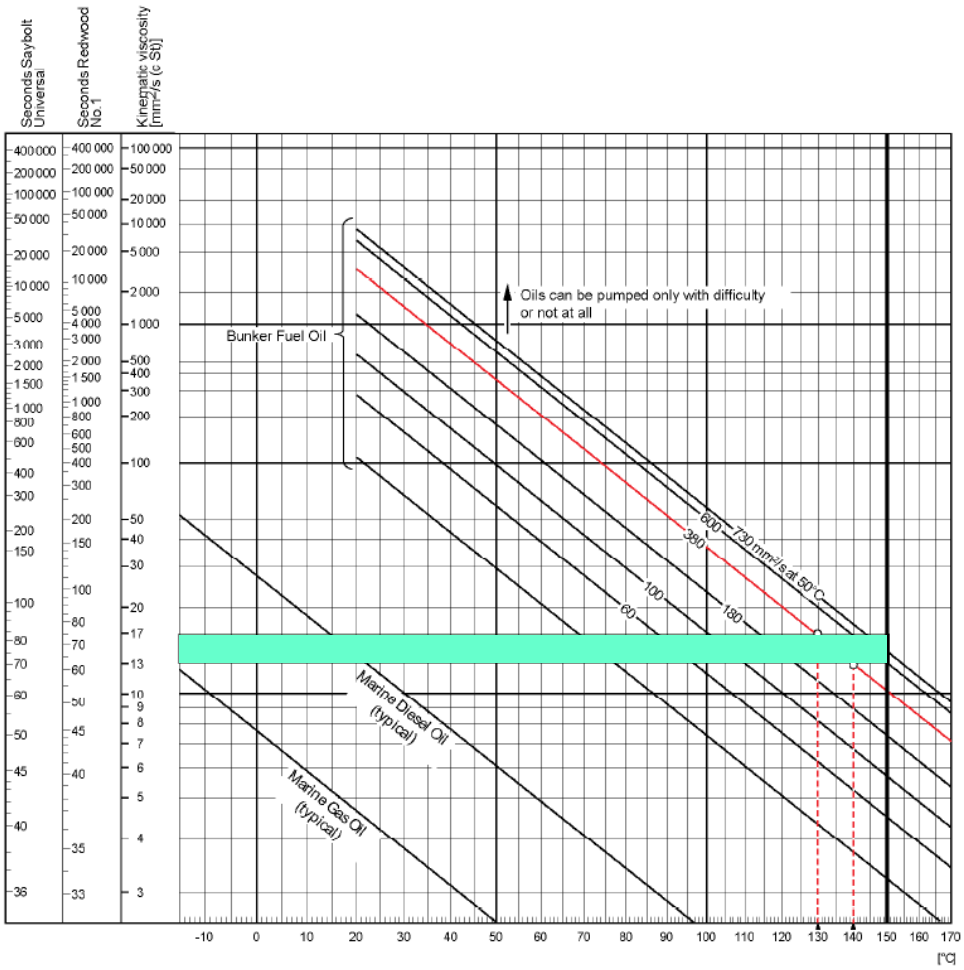


Figure 27. Heavy fuel oil viscosity diagram. Recommended viscosity range before fuel injection pumps is shown in green. /26/

Fuel oil pressure, engine inlet is measured at engine fuel oil inlet port. The fuel oil pressure is needed to enable proper fuel oil circulation over the engine and complete filling of injection pumps. If the fuel oil pressure is too low, it may cause cavitation in low-pressure fuel oil pipes and in the pump element. Cavitation in low pressure fuel oil pipes may cause fuel oil leakages and further engine room fire, whereas cavitation in the injection pump element may cause erosion and further element seizure.

Fuel rack position depends on how much output, engine power, is wanted from engine. The function of the engine fuel oil injection system is to feed the correct amount of fuel at the right time for the combustion process. The injection of the fuel oil is created in a conventional fuel system by the fuel cams of the camshaft, locating directly beneath the fuel injection pump (jerk pump). The camshaft rotates at half of engine speed at a 4-stroke engine. Other, a newer system, is common rail system, which is equipped often with an engine driven high pressure pump.

The fuel rack position may depend also on fuel oil quality, injection pump condition, and charge air pressure and charge air temperature. If the caloric value of fuel oil is low, a higher amount of fuel is required to create the needed engine power. In the other words, the gas pedal ’’needs to be stepped on’’. In big Diesel-engines the fuel rack position tells what the ’’gas pedal position’’ is. Also, if charge air pressure is low or charge air temperature is high, the amount of oxygen required for a successful combustion process is not adequate. Therefore, the engine output is lower per fuel rack millimetre than what it would be if the charge air pressure and charge air temperature were on the recommended level. The output gap is compensated with excess fuel oil injection, which is seen as a higher injection pump fuel rack position. If the injection pump element, barrel and plunger, is worn, a certain amount of fuel oil is flowing back due to the gap between barrel and plunger, never reaching the combustion chamber. Because of the fuel losses in the element, an excess fuel rack is needed again. The fuel rack position is measured by means of a sensor, measuring the position of the common fuel rack shaft for all cylinder specific injection pumps. Reading from an individual pump can be read from the scale in the fuel rack.

A complete injection pump from a Wärtsilä Vasa 22 engine is shown in Figure 28.

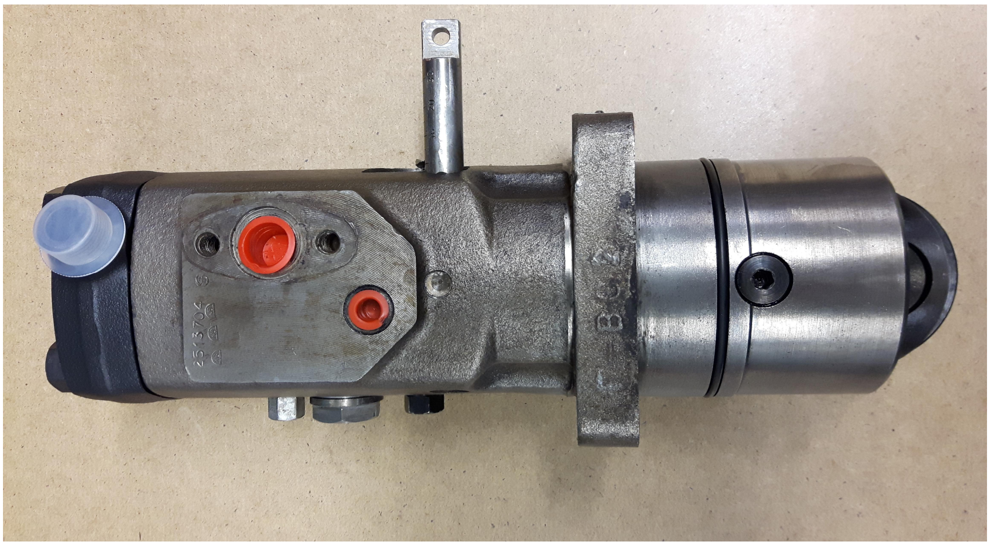


Figure 28. Wärtsilä Vasa 22 injection pump. /27/

Injection pump barrel, plunger, fuel rack and rotator from a Wärtsilä 20 injection pump can be seen in Figure 29.

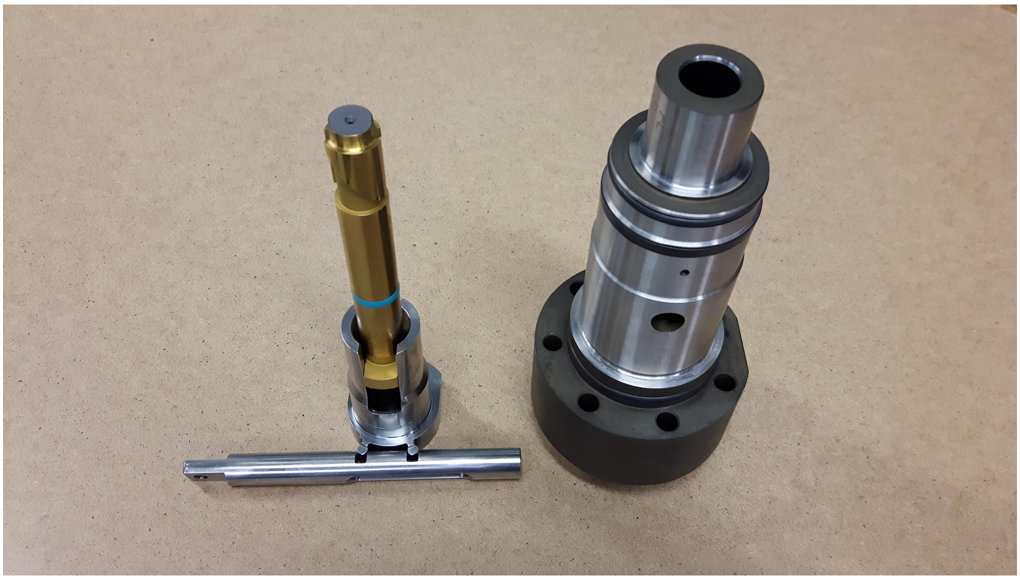


Figure 29. Wärtsilä 20 injection pump parts. /28/

- **Common rail Diesel-engine**

The common rail is a method of fuel injection that eliminates the principle of one fuel injection pump per cylinder. The fuel oil pressure in the common rail engine is created by crankshaft driven common rail pumps. The injection pressure is adjusted as desired and the injection timing (start and end) is controlled electronically.

Calculated fuel oil rail pressure is a mathematically calculated value for fuel oil pressure needed at a certain load. This is also the fuel pressure behind the electronically controlled cylinder specific injection nozzle before it is opened for fuel injection into cylinder.

Fuel injection pump temperature describes the temperature of each common rail pumps. The number of the pumps depends on the engine configuration.

Fuel injection timing tells when the fuel is injected into the cylinder. The fuel must to be injected into the cylinder before the piston reaches the top dead centre. The time point for injection is specified by crankshaft degrees before the top dead centre. Advancing the injection timing from specified by the engine manufacturer, will increase the exhaust gas temperature whereas retarding the injection timing will decrease the exhaust gas temperature. If fuel the injection timing is changed by 1º, the maximum firing pressures will change 3 – 5 bar.

- **Gas-engine**

Managing the gas combustion process in 4-stroke engines is very demanding due to very narrow window for air-gas mixture. The mixture consisting of a certain amount of gas and charge air pressure has to be exactly correct. If the mixture is outside of the operation window, it may resulting in knocking or misfiring. Therefore, engine experts say that managing the gas combustion process in a 4-stroke engine is like trying to hold a ball on top of a ball, whereas managing the Diesel combustion process is like a holding a boll inside the ball.

Main gas pressure, after regulating valve is pressure after the gas ramp unit (GRU), the unit controlling gas pressure before engine.

Main gas pressure, reference is a reference value of how high the main gas pressure, engine inlet, should be. The reference value is based on the engine load.

Main gas pressure, engine inlet is the pressure, which is in common rail gas pipe behind the SOGAV- valve, just before the cylinder. The main gas pressure is approximately 1 bar higher than the charge air pressure. If the pressure difference increases to over 1.5 bar, there is potential risk that part of the gas will enter the charge air receiver.

Main gas injection duration reference is a common reference value of gas feed duration for all SOGAV-valves. The duration reference value is based mainly on the load, but also ambient condition and gas quality can have an on it.

Gas injection duration offset, cylinder XX is a cylinder specific value describing the duration cylinder specific SOGAV-valves are deviating from the reference value of the main gas injection duration. Every ignition in a Gas-engine is evaluated by means of cylinder specific knocking or firing pressure sensors engine control system called UNIC. Gas injection duration is based on this evaluation. The next gas injection duration can be shorter or longer, based on how successful the previous combustion process was.

In addition, wear and leakage in the electrically controlled SOGAV-valve will have an effect on duration reference. The low value may indicate leakage in the Gas Admission Valve. If gas leaks through the Gas Admission Valve into the cylinder, the engine control system are then trying to compensate for this by making the individual opening time, main gas injection duration offset, shorter. The high value may indicate wear in the Gas Admission Valve. The injection duration becomes longer if the valve is worn and its opening gap becomes smaller. When the opening gap is smaller than required with a fully open valve, not so much gas will come into the cylinder. The engine control system are then trying to compensate for this by making the individual opening time, main gas injection duration offset, longer.

Pilot fuel oil pressure, pump inlet. When running the engine in gas mode, the air - gas mixture is ignited with a small quantity of MDO pilot fuel, less than 1% of full-load fuel consumption. The pilot fuel injection system uses the same external fuel feed system as the main fuel oil injection system. The pressure is fairly low, from 5 to 10 bar.

Pilot fuel oil pressure, pump outlet. The pilot fuel oil pump raises the pressure approximately up to 900 bar. Pressurized pilot fuel is delivered from the pump unit into a small-diameter common rail pipe. The common rail pipe delivers pilot fuel to each injection valve and acts as a pressure accumulator against pressure pulses.

Figure 30. A power plant equipped with Wärtsilä 34SG gas engines. /29/

5.5 Lubrication Oil System

The function of the lubrication oil system is to provide a sufficient amount of clean lubrication oil for the engine in correct pressure and temperature. The lubrication oil system in Wärtsilä 4-stroke engines consists typically of engine built oil sump (usually a power plant installation) or a so called system oil tank (usually in marine installations), engine driven lubrication oil pump with integrated electric motor driven pre-lubrication pump, lubrication oil filter, lubrication oil cooler and thermostat for lubrication oil temperature regulation.

Functions of lubrication oil

1. Separate the contact surfaces, thereby decrease static and dynamic friction to prevent wear and tear
2. Remove heat generated within the bearings and moving components
3. Protection of the metal surfaces against corrosion
4. Removal of combustion process borne contaminants

Every single moving engine component from main components to small parts is lubricated. In case the lubrication fails, major damage may occur causing economical losses. Most critical bearings and engine components requiring proper undisturbed lubrication are all white metal bearings, cylinder liner, piston skirt and piston rings.

Lubrication oil separators are required if engines are running on HFO. The reason to have separators is the natural content of harmful particles in HFO, and harmful particles originated from combustion process. These particles contaminate the lubrication oil, deteriorating its quality and further its properties to lubricate and protect engine components against friction and corrosion, if not separated.

5.5.1 Vital Parameters and Factors in Lubrication Oil System

Pre-lubrication oil pressure is typically created by electric motor driven pump, integrated into an engine driven lubrication oil pump. The purpose of the pre-lubrication is to secure that all moving and rotating parts in the engine are lubricated and that a certain minimum pressure is created before the engine is started up.

Lubrication oil pressure, engine inlet is created typically by engine driven lubrication oil pump. The pressure is measured at the engine lubrication oil inlet port. If the lubrication oil pressure falls below low limit, the engine safety system will give an alarm. If the lubrication oil pressure falls even more reaching the shutdown limit, the engine safety system will stop the engine in order to prevent fatal damage in any moving or rotating engine parts.

Lubrication oil temperature, engine inlet is the temperature measured at the engine lubrication oil inlet port. The lubrication oil temperature must to be high enough before the engine can be started safely. If the lubrication oil is too cold, the viscosity of lubrication oil is high, the pressure may rise at start to an excessively high level. Lubrication characters will also suffer of low temperature. If the lubrication oil temperature is too high, viscosity and lubrication oil character are also out of specified range. Immediate consequences are that the lubrication oil is unable to form a lubricating film decreasing friction between moving or rotating engine parts and further causing component overheating due to lack of proper lubrication oil film.

- **Lubrication oil quality analyses**

The engine lubrication oil to be analysed frequently to make sure the lubricant fulfils specifications set by engine manufacturer. Specifications may vary a lot based on the operation profile and used fuel type. The lubrication oil sample has to be taken from a running engine and analysed by an authorised laboratory. From a lubrication oil analysis protocol water content, kinematic viscosity at standard temperature (40 or 100°C), flash point, base number (BN) and metal content can be seen.

The metal content reveals possible wear and tear problem in engine components. A list of typical metals found in the analysis and their possible sources:

- Copper; charge air cooler fins
- Iron; piston skirt and cylinder liner
- Chromium; piston rings
- Tin; white metal bearings
- Lead; white metal bearings
- Nickel; white metal bearings
- Vanadium; Heavy Fuel Oil (HFO)

- **Base number (BN)**

Base number additives are used to neutralise acidic contamination resulting from fuel oil combustion. As such, they are only found in diesel engine oils. High BN numbers are associated mainly with medium speed marine and power plant engines using fuel with high sulphur content, for example HFO. The lube oil base number is one of the parameters evaluated in the lubrication oil quality analysis

5.6 Cooling water system

A cooling water system is needed to remove the waste heat from an engine, but it also maintains the engine operating temperature where it works most efficiently. Without adequate cooling, engine components, exposed to high temperatures as a result of burning fuel, would rapidly damage. Only the fixed parts of the engine, such as the engine block, cylinder heads, charge air cooler and lubrication oil cooler are cooled directly by the cooling water system. The function of the cooling water system is to circulate cooling water around the internal and external water channels within the engine in order to achieve sufficient cooling for engine parts, lubrication oil and charge air.

The cooling water is heated up in the engine and is cooled in the central cooler or radiator, before entering again the engine. The cooling water to central cooler often comes directly from the sea in marine installations. The central cooler in marine installations is often the plate cooler type of solution. The radiator type of cooling solution is common in power plants, where the cooling system is of closed circuit type. The cooling water circulating in the internal and external water channels within the engine is always fresh water with certain additives.

The cooling water system in Wärtsilä 4-stroke engines consists of engine built and engine driven LT- and HT cooling water pumps, internal and external water channels within the engine depending of the engine type, central cooler or radiator and thermostats for cooling water temperature control.

The cooling system is divided to LT- and HT water-cooling circuits. LT cooling water circulates within the charge air cooler and lubrication oil cooler, while HT cooling water circulates around the cylinder liners and cylinder heads.

The central cooler system is common in marine installations. Usually LT- and HT cooling water circuits both have their own central coolers. The cooling water to the central cooler comes directly from the sea chest. The sea chest, locating underneath of the water line of the ships, provides an intake reservoir from which the piping systems draw seawater into the central cooler. The intake surface area of sea chests varies from less than 1 m² to several square metres.

Nowadays central coolers are often of plate cooler type for easy and quick cleaning. If the central cooler is dirty or clogged, it may have an effect on the engine LT- and HT water cooling system. Also in case the sea water temperature is very low or vice versa very high, it can often be observed for example from the LT water temperature, measured at the engine LT water inlet port. The sea-water temperature is not available in the CBM monitoring, but could often indicate and give more information especially in problems with LT water temperature.

Figure 31. Plate cooler. /30/

A Radiator cooling system is common in power plants. The radiator cooling system is a closed circuit - type system without an external water supply. The radiator size and height from the ground is specified based on the required cooling capacity. Radiators are also equipped with electric motor driven fans to improve air-flow through the radiator. Similarly as in cars, anti-freeze coolant must be used in cold conditions to avoid radiator freezing damage.

Figure 32. Power plant radiator field. /31/

5.6.1 Vital Parameters and Factors

LT water pressure, engine inlet is typically created by an engine driven centrifugal pump. The LT water pressure is measured immediately after the LT water pump. The LT water pressure has to stay on a specified level to ensure all the time 100% filling of the LT cooling water system and adequate cooling water flow through the charge air- and lubrication oil coolers.

LT water temperature, engine inlet is measured immediately after the LT water pump. Correct LT water temperature is important in order to maintain the charge air temperature, after charge air cooler and lubrication oil temperature (in in-line engines) in a specified level.

LT water temperature, engine outlet (before LOC) is measured from the outlet port in the charge air cooler. The statement ’’ (before LOC)’’ means that LT water has not yet passed through the lubrication oil cooler (LOC = Lubrication Oil Cooler).

HT water pressure, engine inlet is typically created by an engine driven centrifugal pump. The HT water pressure is measured immediately after the HT water pump. The HT water pressure has to stay on a specified level to ensure all the time 100% filling of the HT cooling water system and adequate cooling water flow through the engine.

HT water temperature, engine inlet is measured immediately after the HT water pump. The HT water temperature at the engine inlet port must be correct because after passing the engine, the HT water temperature is higher but must still be within the recommended limits.

HT water temperature, engine outlet (common) is measured from the collection pipe immediately after cylinder heads. The temperature sensor is located in the HT water collection pipe on top of the engine. The ’’common’’ means that HT water from both A-and B-bank is collected into the same pipe after cylinder heads. The HT water has an important role in the engine. It is cooling down cylinder liners and cylinder heads, but has also a role in preventing cold corrosion in the combustion chamber and exhaust gas port. In case the HT water temperature is too low, a risk of cold corrosion is high when operating the engine on Heavy Fuel Oil. If the HT water temperature gets too high and reaches the alarm limit, the engine safety system will give an alarm. If the temperature is still increasing from this level, the engine safety system will stop the engine in order to prevent fatal damage in any moving or rotating engine parts.

5.7 Exhaust Gas System

On marine and power plant installations, the work done by 4-stroke engines to keep the plant running, propelling a ship or drive a generator to produce electricity, requires burning of fuel. The energy converted inside the cylinder of the engine is not 100% energy efficient conversion, as part of it is lost in the form of exhaust gases. Roughly saying the purpose of the exhaust gas system is to lead exhaust gases in a controlled manner out from the engine room to the atmosphere.

As said, exhaust gases originate from the combustion process, from burning fuel in the cylinder. The temperature and emission content of exhaust gases vary a lot depending on what fuel is used and what are the circumstances for combustion process. When exhaust gas has been formed in the cylinder, its way to the atmosphere starts with the outlet stroke of the piston, via the camshaft operated exhaust gas valves. The next step is the engine build exhaust gas manifold and further turbocharger. Its way in the engine built construction ends at the outlet port of turbocharger. At this stage part of the thermal energy the exhaust gas still contains, has been utilised in the turbocharger by means of creating rotating movement in the turbocharger rotor.

As simplest, the external exhaust gas system (after the turbocharger) consist of thermal bellows, insulation and exhaust stack with silencer. In certain cases, the exhaust gases must be cleaned before led in to the atmosphere. The remaining exhaust gas energy can also be utilized for example in a waste heat recovery system to increase the overall energy efficiency of the installation.

In marine installations exhaust gases may need cleaning if the engine does not meet IMO Tier 3 regulations for Nitrogen Oxides or if the engine is running on fuel having higher sulphur content than allowed on Sulphur Emission Control Area (a.k.a SECA-area)

The control of Diesel-engine NO_x emissions is achieved through the survey and certification requirements, leading to the issue of an Engine International Air Pollution Prevention (EIAPP) certificate and the subsequent demonstration of in service compliance in accordance with the requirements of the mandatory regulations.

SO_x and particulate matter emission controls apply to all fuel oil, as defined in regulation, combustion equipment and devices on board and therefore include both main and all auxiliary engines. Regulations are applicable inside Sulphur Emission Control Areas (SECA) established to limit the emission of SO_x. The fuel sulphur content limit in SECA areas is 0.1% by mass. The limit will be globally 0.5 % by mass from 2020 onwards. Sulphur in fuel originates from plant and animal protein, transformed to sulphur during the putrefaction process.

Figure 33. A heavily smoking ship. /32/

5.7.1 Vital Parameters and Factors

Exhaust gas temperature, after cylinder temperature is traditionally measured from behind the exhaust gas valves. In some newer Wärtsilä engine types the temperature sensor is placed in the exhaust gas channel, so called multiduct, locating behind the cylinder head. Exhaust gas is waste heat from combustion process created for work stroke that forcefully returning the piston to the bottom dead centre. This stroke produces mechanical work from the engine to turn the crankshaft.

When work stroke is completed, the piston once again returns from bottom dead centre to top dead centre while the exhaust valve is open. This action expels the spent air-fuel mixture through the exhaust valve into atmosphere. The exhaust gas temperature is a good indicator of combustion process, and will react when something disturbing the engine performance. High exhaust gas temperatures are usually the limiting factor for the maximum load. If the exhaust gas temperature, after the cylinder gets too high and reaching the alarm limit, the engine safety system will give an alarm. If the temperature still increases from this level, the engine safety system will reduce the load in order to prevent exhaust gas valves from burning.

Exhaust gas temperature deviation, after cylinder. All cylinder specific exhaust gas temperatures are compared to average exhaust gas temperature, after cylinder, and if the cylinder specific exhaust gas temperature, after cylinder is certain degrees higher or lower than the average temperature, it indicates either disturbed combustion or problems in fuel injection.

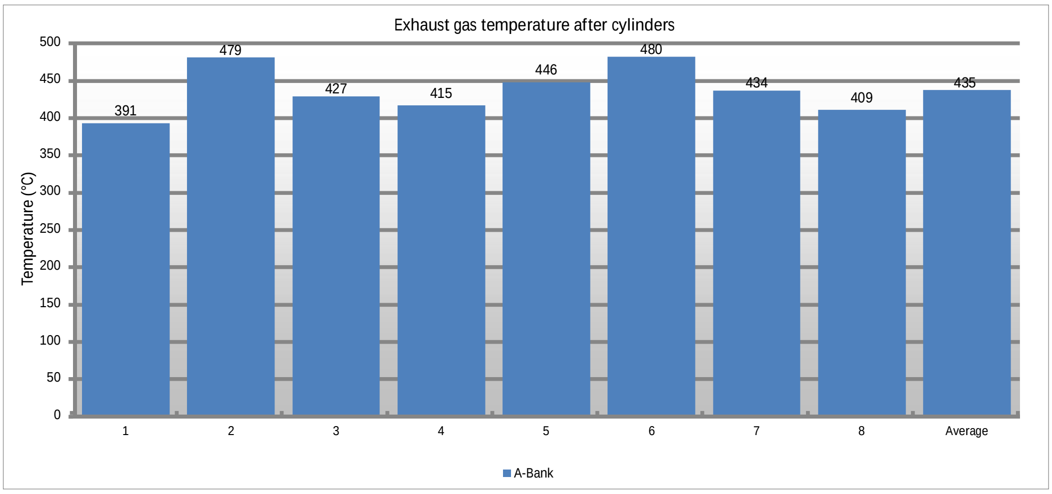


Figure 34. Graph of average exhaust gas temperature, after cylinders. /33/

Exhaust gas temperature, before turbocharger is measured at the exhaust gas inlet port of the turbocharger. The temperature depends on the cylinder specific exhaust gas temperature, after cylinders. The temperature reading measured from the exhaust gas inlet port is higher than the average exhaust gas temperature, after cylinders, because the exhaust gas temperature, after cylinders is measured directly after the exhaust gas valve, where the exhaust gas flow is not even and continuous. If both air inlet valves and exhaust gas outlet valves are open simultaneously at the end of the outlet stroke and at the beginning of the inlet stroke, the exhaust gas is partly mixed with fresh air, affecting the temperature of out flowing exhaust gas.

Exhaust gas temperature, after turbocharger is measured at the exhaust gas outlet port. The turbine wheel converts the exhaust gas thermal energy into mechanical energy. While the exhaust gas is passing across the turbine wheel, the exhaust gas temperature become lower.

Exhaust gas temperature difference Δ_t (Delta T), before and after turbocharger. Certain exhaust gas temperature drop is expected when exhaust gas is passing the turbine wheel. If the temperature difference is smaller than expected, it indicates an exhaust gas blow-by between turbine wing tips and exhaust gas inlet casing surrounding the turbine wheel.

· **Back pressure**

The exhaust gas system of marine engines is designed so that the unused gases coming out of the cylinders are further directed to the turbocharger and usually further to silencer. Nowadays exhaust gas cleaning systems to reduce NOx and SOx emissions are also integrated into the exhaust gas systems. The most important thing to consider while designing the exhaust piping system is the back pressure. The back pressure in the exhaust gas system at the specified maximum Continuous Rating (MCR) of the engine depends on the gas velocity, and it is inversely proportional to the pipe diameter to the 4th power. If the back pressure is measured to be on an acceptable level at test run of the installation, there is usually no need to repeat the measurement. However, if the exhaust gas system is later on modified, also its impact on the back pressure has be taken into consideration.

5.8 Charge Air System

The energy converted inside the cylinder of the engine is not 100% energy efficient conversion as part of it is lost in the form of exhaust gases. The charge air system has a crucial importance in modern turbocharged Diesel-engines to utilize energy from exhaust gases. Without the charge air system the efficiency and performance of Diesel-engine would be much lower.

Major components of medium speed Diesel-engines charge air system are turbocharger, charge air cooler and charge air receiver.

Major components of turbocharger are suction air inlet casing, charge air outlet casing, exhaust gas inlet casing, exhaust gas outlet casing, suction air filter, rotor with turbine- and compressor wheel and nozzle ring and diffuser ring.

When exhaust gas, originated from the combustion process, meets the nozzle ring and further the turbine wheel, the rotor starts rotating. Because the turbine wheel and compressor wheel are on same rotor shaft, the compressor starts to create charge air pressure from suction air entering the compressor side of the turbocharger from the atmosphere. Compressed charge air passes next through the charge air cooler, where the temperature is decreased on a specified level. Now the charge air is ready to enter the charge air receiver and further cylinders for the combustion process.

5.9 Description of Turbocharger Components

Intake air filter

The intake air filter can be built on the turbocharger or locate separately outside of the installation. In case of marine Diesel-engines the suction air filter is built on the turbocharger, locating just before the compressor wheel. The intake air is taken from engine room air. The engine room has to be ventilated by mean of air fans in order to have a certain level of over-pressure all the time in the engine room. The over pressure enables enough air for the charge air system of the diesel engine.

Exhaust gas inlet port

The exhaust gas from engine enters the turbocharger via an exhaust gas inlet port, facing the nozzle ring and turbine.

Exhaust gas outlet port

The exhaust gas from engine exits the turbocharger via an exhaust gas outlet port to the atmosphere or alternatively to exhaust gas cleaning system, for example catalysator, or exhaust gas boiler.

Intake air port

The fresh air from atmosphere is sucked into the turbocharger's compressor via a suction air inlet port.

Charge air outlet port

The charge air pressure, created in compressor, exits the turbocharger via a charge air outlet port. The charge air temperature is at this stage very high and cannot be led into the engine as such, but to be led through the charge air cooler.

Nozzle ring

The nozzle ring is where the energy in the exhaust gas is converted to velocity.

Turbine wheel

The turbine wheel converts the engine exhaust gas energy into mechanical energy to drive the compressor wheel mounted on the same shaft with the turbine wheel.

Compressor wheel

With the rotational speed of the compressor wheel, air is drawn in axially via the suction air inlet port, accelerated to high velocity and then expelled in a radial direction through the diffuser ring.

Diffuser ring

The diffuser ring is where the air pressure, created by the compressor wheel, is converted to velocity.

Charge air receiver

The charge air receiver is a chamber type of space in the engine block. The charge air is stored there before entering the cylinder, via the air inlet valve in cylinder head, for the combustion process.

Figure 35 below shows a turbocharger cartridge, consisting of compressor wheel (on left side), turbine wheel (on right side) and main casing with shaft connecting compressor and turbine wheels.

Figure 35. Turbocharger cartridge. /34/

Figure 36 below shows a nozzle ring (on left side) and turbine wheel (on right side).

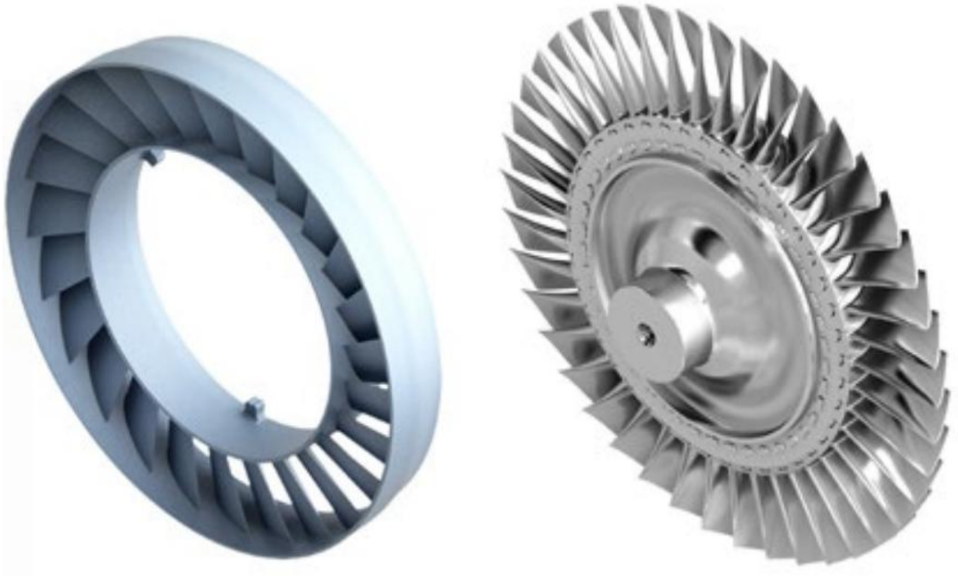


Figure 36. Turbocharger nozzle ring and turbine wheel. /35/

5.9.1 Vital Parameters and Factors

Intake air temperature is measured at the air intake port before entering the compressor wheel. It depends totally on the atmosphere air temperature at the location of the installation. Intake air has an impact on exhaust gas temperature after cylinder. If ambient temperature changes 1°C, the exhaust gas temperature after cylinder will change 1.5 – 2.0°C.

Charge air pressure indicates the amount of air provided by the turbocharger for the combustion process. The engine needs a certain amount of air for every single combustion cycle to burn the fuel, injected into the cylinder by the injection pump. The needed amount of charge air depends on the load and further the amount of fuel. If the charge air pressure is lower than expected, it means that less oxygen is available for the combustion process, which often leads to incomplete combustion and further higher exhaust gas temperature and carbon emissions. High charge air pressure is not a common problem and therefore not dealt in the thesis.

Charge air temperature, after charge air cooler depends on the ambient temperature and cooling water temperature passing the charge air cooler. If the charge air receiver temperature changes 1ºC, exhaust gas temperatures will change 1.0 – 1.5 ºC.

Turbocharger rotating speed depends on the thermal energy from exhaust gas. When the exhaust gas from cylinders faces the nozzle ring, the energy in the exhaust gas is converted to velocity and further to rotating movement in the turbine wheel. However, certain factors may have an effect on turbocharger rotating speed. When the engine is operated on HFO, the turbocharger must be equipped with a cleaning system because both the nozzle ring and turbine wheel will be contaminated from residuals from HFO.

Continuous exposure for contamination will decrease the exhaust channel cross section of the nozzle ring and further increase the exhaust gas velocity, which in turn increases the turbocharger rotating speed. In case the turbine wheel wing tips are contaminated, or coated, with residuals from HFO, the wing tips may touch the exhaust gas inlet casing surface and wear it out. The gap between wing tips and casing surface still remains still within the stated limits, because the contamination acts like a sealing material. In such of case problems occur often after turbocharger maintenance where also the turbine wheel is cleaned and the contamination from the wing tips is removed. Now the gap between wing tips and casing surface becomes bigger allowing an exhaust gas blow by.
Due to exhaust gas blow by, part of the exhaust gas energy is lost, deteriorating the turbocharger efficiency, in other words to its capacity to create charge air pressure.

Charge air temperature after turbocharger, before charge air cooler is not measured in Wärtsilä engines because it is not relevant parameter for the engine performance analysis.

Charge air pressure difference, Δ_P (Delta P), over the charge air cooler is measured using a hand held measuring device. Wärtsilä engines are not equipped with a fixed measurement system because this parameter does not need continuous monitoring. The pressure difference is typically measured every second week or once in a month because it will not chance rapidly. The Delta P value increases when the charge air cooler becomes contaminated of dirt from intake air passing the intake air filter of the turbocharger. When the dirt covers cooling fin surfaces, heat from charge air cannot transferred to the cooling water circulating in the charge air cooler. This increases the charge air temperature, after charge air cooler and deteriorates engine performance. See chapter 5.8.1.
From the CBM monitoring point of view it would be valuable if Delta P values could be seen in the CBM analysing tool.

The **dew point** is the temperature to which air must be cooled to become saturated with water vapour. When further cooled, the airborne water vapour will condense to form liquid water (dew). When the air cools to its dew point through contact with a surface that is colder than the air, water will condense on the surface. When the temperature is below the freezing point of water, the dew point is called the frost point, as frost is formed rather than dew. The measurement of the dew point is related to humidity. A higher dew point means there will be more moisture in the air. /36/

Ships operating in variable ambient conditions often run engines with a high charge air temperature, keeping the charge air temperature at a constant level without taking humidity levels into account. Condensation occurs when the air temperature decreases below the dew point temperature. The water condensation in the charge air is harmful especially when running the engine on HFO with high sulphur content. Humidity together with sulphur will result in Sulphuric acid, H_2SO_4. Sulphuric acid is highly corrosive for metal parts and may damage surfaces in the combustion chamber. By controlling the charge air temperature automatically in relation to the ambient humidity, water condensation can be avoided. This will also improve fuel consumption and reduce emissions.

Figure 37. Dew point controller. /37/

5.10 Firing Pressure and Knocking Value in Gas-Engines

Firing pressure is measured directly from the combustion chamber by means of a firing pressure sensor. Firing pressure, the result of burning of air – fuel mixture, is the highest pressure in the cylinder during combustion.

Figure 38. Firing pressure sensor. /38/

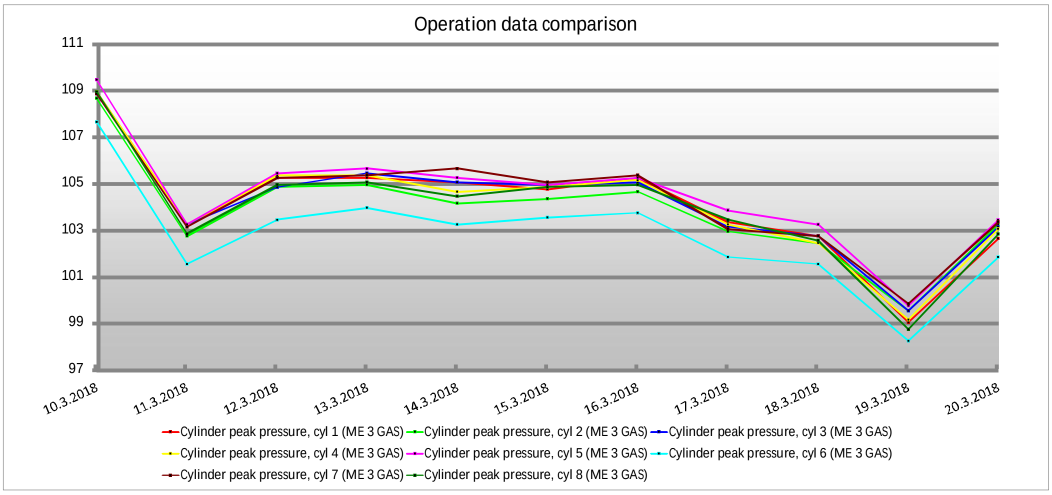


Figure 39. Firing pressure graph. /39/

The knocking value is measured by means of a piezoelectric knocking sensor mounted outside the cylinder head. Under ideal conditions, the internal combustion engine burns the air - gas mixture in the cylinder in an orderly and controlled fashion. Knocking in Wärtsilä gas engines (DF and SG) occurs when the combustion of the air - gas mixture in the cylinder does not start off correctly, but one or several pockets of air - gas mixture detonate outside the range of the normal combustion front. A local shockwave is created around each pocket and the cylinder pressure may rise sharply above its design limits. If knocking continues over many engine cycles, the engine component may suffer from damage or be destroyed. Typical effects are particle wear caused by moderate knocking. Particles may pass the lubrication oil system and cause wear on other components before filtered in the oil filter. Heavy knocking instead can cause rapidly catastrophic failures.

Figure 40. Knocking sensor. /40/

6 DIFFERENT MODULE OPTIONS AND ARGUMENTS

In discussions with the main stake holders within Wärtsilä, which are Service Agreement Sales and Global Contract Centre, opinions and suggestions were received concerning CBM monitoring. Key words from these stakeholders were fuel economy, predictive maintenance and performance improvements. Fuel economy and carbon foot print are today some of the most discussed topics globally. The thread of climate chance and global warming is forcing all consumers to review how to reduce especially carbon dioxide (CO_2) but also nitrogen oxide (NOx) emissions. Nitrogen Oxide emissions are considered hazardous for humans causing respiratory diseases and premature deaths. Proper engine maintenance may have a significant impact on fuel economy and further on healthier environment and higher business profit and lower emissions.

6.1 Example of Savings in Fuel Costs and Cutting CO2 Emissions

An example of how to save in fuel costs and cut carbon dioxide emissions in a 100 MW power plant is given next. The calculations are based in the assumption that the approximate fuel consumption is 190g/kWh and the price of HFO is 320€/ton.

Annual fuel consumption:

100 000 kW * 190 g / kW * 24 h * 355 days = 161 880 000 000 g =
161 880 000 kg

Annual fuel costs:

161 880 000 kg * 0.32 € / kg = **51 801 600 €**

Annual CO_2 emissions:

The mass flow of carbon from fuel C / kWh = 0,855*190 g / kWh = 162.45 g / kWh.

(44.01/12.01)* 162.45 g = 595.3 g CO_2 / kWh

100 000 kW * 595.3 g CO_2 / kWh * 24h * 355 days = 507 195 600 000 g = **507 195 600 kg**

If the fuel consumption increases with 3 g/kWh due to improper maintenance, the total fuel consumption, total fuel costs and carbon dioxide emissions will increase as follows:

Annual fuel consumption:

100 000 kW * 193 g / kW * 24 h * 355 days = 164 436 000 000 g =
164 436 000 kg

Difference:

164 436 000 kg - 161 880 000 kg = 2 556 000 kg

Annual fuel costs:

164 436 000 kg * 0,32 € / kg = **52 619 520 €**

Difference:

52 619 520 € - 51 801 600 € = 817 920 €

Annual CO_2 emissions:

The mass flow of carbon from fuel C / kWh = 0,855*193 g / kWh = 165.02 g / kWh.

(44.01/12.01) * 165.02g = 604.71 g CO_2 / kWh

100 000 kW * 604.71 g CO_2 / kWh * 24h * 355 days = 512 212 920 000 g = **512 212 920 kg**

Difference:

512 212 920 kg - 507 195 600 kg = 5 017 320 kg

As seen in calculations above, a small increase in fuel consumption may cause huge impact on fuel expenses and emissions. The increase of 3 g/kWh in fuel consumption is typical if for example the charge air cooler is dirty or fuel injection nozzles are in poor condition. The engine maintenance manual states clearly at which running hours the charge air cooler should be cleaned and injection nozzles replaced. Both mentioned service tasks are low cost tasks that should be done according to the engine maintenance manual and even more often depending on the fuel type and ambient conditions.

6.2 Example of Major Breakdown in Marine Installation

Neglecting proper maintenance stated in the engine maintenance manual does not only increase fuel consumption but also increases the risk of mechanical failures which further may lead to troubles to run the engine or in the worst case, to a major breakdown. Typical engine breakdowns requiring possibly dry docking of the ship are for example crankshaft or engine block replacement, or replacement of a complete engine. There are shipyards providing possibility for dry docking around the world along major shipping routes. However, shipyard schedule and size of vessel may become a problem for quick fixing of major breakdown. The daily fee of the shipyard for a big vessel, such as a modern cruise vessel, can be from 50 to 100 K

USD. Even if the well-planned repair takes a month, only the dry-docking may cost for several million US dollars. Spare parts and labour to perform the job may cost other 2 to 3 million US dollars. Additional losses are coming from cancelled cruises. The compensation from the insurance company depends on the contract between the ship owner and the insurance company.

6.3 Modules chosen for development work

With the references explained and calculated above several different modules can be created but due the limited extent of the thesis, the decision turned to modules concentrating on fuel economy and equipment condition diagnostics.

The two modules chosen for development work in this thesis are called as:

1. **Engine Fuel Efficiency Diagnostic, EFED**
2. **Risk Avoidance Diagnostic, RAD**

6.4 Module Development

Module development of the chosen modules begins with a question what systems and parameters needs to be included to achieve a module that meets its intended functional task. Systems and and parameters are roughly the same for all engine types, but however there are differences especially between Diesel- and Gas engines, but also some differences between the engine types regardless of fuel type. All these differences have to be taken into account when developing modules. This is sketched in the pattern below. As this thesis will be a basis for further development of the CBM function at a later stage, Wärtsilä 32 and Wärtsilä 34DF engines were chosen to be as a reference engine type for modules.

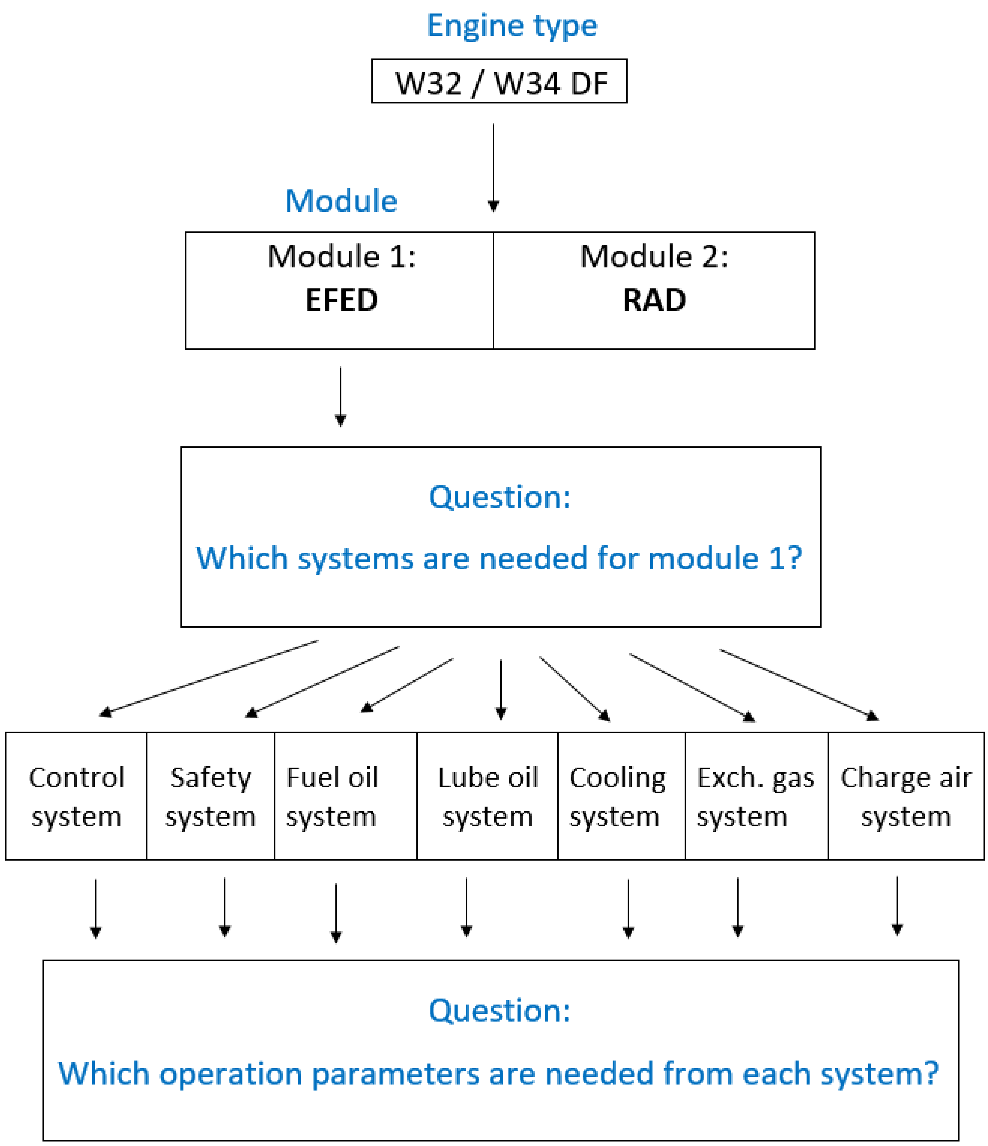


Figure 41. Sketch of module development.

7 MODULE 1, ENGINE FUEL EFFICIENCY DIAGNOSTIC

Fuel consumption is the biggest single proportional expenditure of power plant operation costs, representing approximately 76% of all costs. As seen in the example in chapter 6.1, installation fuel costs can be annually tens of millions. The percentage in the marine installations is lower, between 40 and 50%.

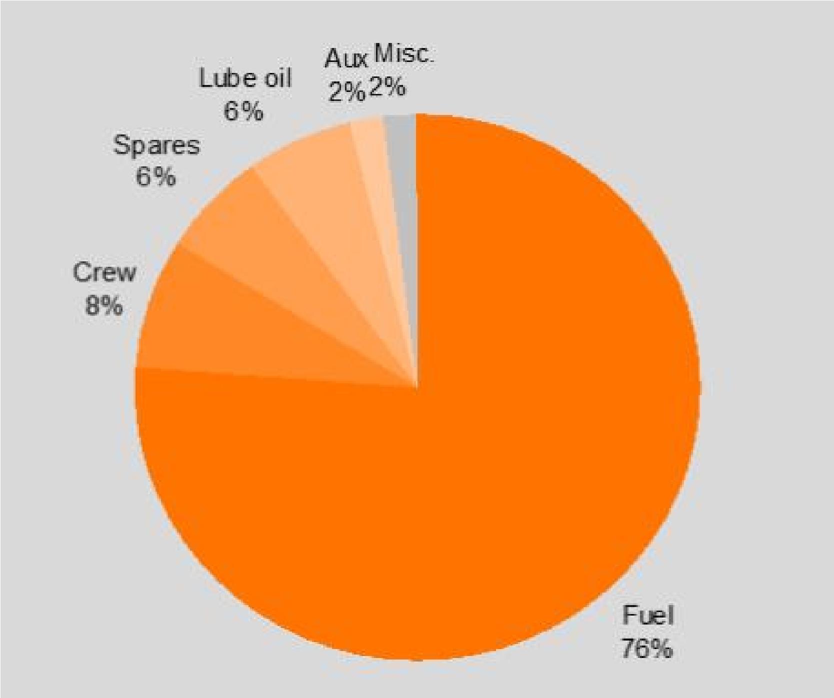


Figure 42. Percentages of different operation cost of a power plant. /41/

When customers buy fuel, they actually buy energy in liquid or gas form which is to be converted to thermal energy in an engine and further to electricity in the engine driven alternator or to the rotating movement of the propeller shaft. The fuel consumption has a huge role in the total operation costs. Even if the engine is optimised to run with as low as possible a fuel amount per kWh, there are a lot of variables affecting negatively the fuel consumption and operation costs. In most of cases it is possible to avoid operating the installation with factors increasing the fuel consumption. Even if most of these variables are not monitored by the Wärtsilä CBM system, methods to avoid them are common knowledge as well as the averness of the importance of maintenance. Below is a list of the most common variables that may affect the fuel consumption strongly but on the other hand are also avoidable with correct local monitoring and maintenance.

Water in the fuel. 1% of water in the fuel will increase the fuel consumption with 1%. Therefore fuel separation is recommended.

Operating with dirty intake air filters. If intake filters are dirty or even partially glogged, the charge air system cannot provide with a sufficient amount of charge air as specified for optimal combustion. It increases both the fuel oil consumtion and exhaust gas temperature after cylinders.

Operating with dirty nozzle ring, turbine wheel or compressor wheel will increase the fuel consumption. The turbocharger performance is disturbed when mentioned components are dirty and the engine will suffer of insufficient amount charge air.

Operating with dirty or partly blocked charge air cooler. If the charge air cooler is dirty or partly blocked, air mass flow through the cooler is reduced. Additionally its cooling capasity is lower. The effect is the same as operating with dirty intake air filters, resulting in a higher fuel consumption.

Operating with worn injection pumps. If the injection pump element, barrel and plunger are worn, fuel injection is retarded leading to retarded combustion. When injection timing is something else than specified, late in this case, the fuel injection is higher.

Operating with poor injection nozzzle. When the injection nozzle is worn and possibly has carbon deposits accumulated around the nozzle tip, the fuel spray pattern is poor and the injected fuel is not atomised in a proper manner for optimized combustion.

Operating with partly clogged exhaust gas system. Exhaust gas systems are nowadays often much more than the exhaust gas pipe only. Due to stringent rules for environmental emissions, exhaust gas systems are equipped with cleaning devices in many cases. Such devices are for example catalysator, nitrogen oxide reductor and sulphur oxide scrubber. These devices also need to be cleaned frequently. Othervise back pressure in the exhaust gas system increases and causes a higher fuel consumption.

7.1 Engine Fuel Efficiency Diagnostic Module for Wärtsilä 32

7.1.1 Engine Fuel Efficiency Diagnostic Module Scheme for Wärtsilä 32

The engine fuel efficiency diagnostic module scheme for Wärtsilä 32 is presented in Table 1.

Table 1. Engine Fuel Efficiency Diagnostic module scheme for Wärtsilä 32 engine. /42/

7.2 Engine Fuel Efficiency Diagnostic module for Wärtsilä 34DF

7.2.1 Engine Fuel Efficiency Diagnostic module scheme for Wärtsilä 34DF

The engine fuel efficiency diagnostic module scheme for Wärtsilä 34DF is presented in Table 2.

Table 2. Engine Fuel Efficiency Diagnostic module scheme for Wärtsilä 34DF engine. /43/

8 MODULE 2, RISK AVOIDANCE DIAGNOSTIC

8.1 Engine Maintenance

Each engine has a engine specific maintenance manual, marked with an engine serial number, which is drawn up to guide in engine maintenance planning based on the engine manufacturer's knowledge of an engine type. The maintenance manual typically states maintenance tasks and checks at a certain running hour intervalls. Manufacturer's intention is in that way to give the best possible prerequisitions to the engine owner for safe and economical engine operation. Neglecting maintenance tasks stated in the engine specific maintenance manual will increase the risk of machanical failures and decreased operation costs in form of increased fuel consumption. The mechanical failure often stops the engine until fixed. The failure can be minor, such as malfunctioning fuel injection nozzle, but can also be a major breakdown, such as crankshaft damage. In case of a single main engine vessel the engine stop may lead to a dangerous situation especially if the damage occurs during the manouvering the vessel for example into the harbour. However, all damages are not a result of bad maintenance. Mechanical components may break unexpectedly for other reasons as well. Typical reasons for unexpected failures are material fatigue, inclusions in material and vibrations.

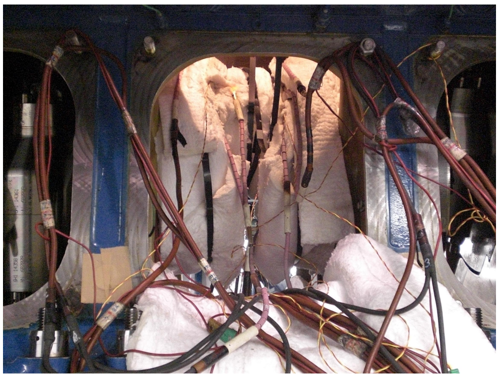


Figure 43. Crankpin annealing. /44/

Figure 44. Repair machining ongoing. /45/

8.2 Engine Maintenance Manual and Service Intervals

Below is an excerpt from an engine specific maintenance manual, stating which maintenance tasks to be performed at 16000 operating hours.

04.3.12 Interval: 16 000 operating hours v6

Part or system	Maintenance task	Chapter
Camshaft	Inspect the intermediate gears. Replace worn parts.	06 13
Fuel feed pump	Overhaul the fuel feed pump. Replace worn parts. See the manufacturer's instructions.	17
Gas admission valve	Replace the main gas admission valve or the valve stack.	17
Gas system	Replace the sealings in pipe connections. Check the sealing faces for wear and corrosion. Perform the leak test with 3 bar compressed air or 3 bar nitrogen pressure.	
Governor	Overhaul the governor. You can send the governor to the engine manufacturer for overhaul.	22
Injection valve	Replace the complete fuel injection valve.	16
Turning device	Change the oil in the turning device. Regrease the drive shaft.	02
Vibration damper (Geislinger)	Check the vibration damper. Dismantle the vibration damper at every 32 000 hours. See the manufacturer's instructions.	11

Figure 45. Excerpt from a maintenance manual. /46/

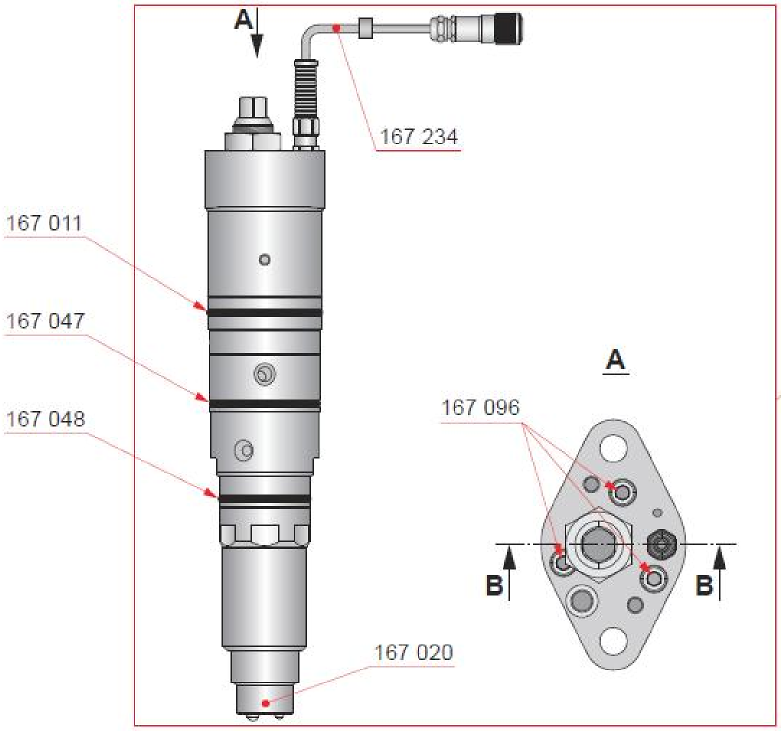
The maintenance manual states a service task for following operation hour intervals:

24, 48, 100, 500, 1000, 2000, 4000, 8000, 12000, 12000-24000, 16000, 16000-20000, 24000 and 48000

8.3 Spare Part Manual

The engine specific spare part manual describes the component structure and available spare parts. An excerpt from a section, which describes the structure and spare parts of fuel injection valve, is shown in Figure 48.

Injection valve



Part No.	Description	Qty [Pcs]	Wt. [Kg]
167 005	Injection valve	1	-
167 020	Nozzle	1	1.0
167 096	Screw	3	0.1
167 234	Cable set	1	0.1
167 011	O-ring	1	-
167 047	O-ring	1	-
167 048	O-ring	1	-

Figure 46. Excerpt from a spare part manual. /47/

8.4 Vibration and Resonation

Vibrations and further resonation is often a combination of factors present in a ship. There are a lot of vibration sources in a ship which in combination may lead into difficulties in a place which originally was not itself a source of harmful vibrations. The biggest vibration sources in a ship are ship’s hull, engine, propulsion system including gear box, propeller shaft and propeller. Hull borne vibrations are difficult to prevent afterwards and therefore vibrations from other sources must be in harmony with hull borne vibrations to avoid resonance. Especially in older ships the hull borne vibrations can be noted in a form of vibration wave going frequently through the entire ship. If vibrations from different sources meets in a certaing vibration range, it may result into resonation. Resonation is harmful for steeel components and constructions and may lead into breakage. Usually better supporting of machinery, modules and components reduces vibrations.

Figure 47. Vibration measurement from a Wärtsilä 32 engine ongoing. /48/

8.5 Risk Avoidance Diagnostic Module for Wärtsilä 32

8.5.1 Risk Avoidance Diagnostic module scheme for Wärtsilä 32

The risk avoidance diagnostic module scheme for Wärtsilä 32 is presented in Table 3.

Table 3. Risk Avoidance Diagnostic module scheme for Wärtsilä 32 engine. /49/

8.6 Risk Avoidance Diagnostic module for Wärtsilä 34DF

8.6.1 Risk Avoidance Diagnostic module scheme for Wärtsilä 34DF

The risk avoidance diagnostic module scheme for Wärtsilä 34DF is presented in Table 4.

Table 4. Risk Avoidance Diagnostic module scheme for Wärtsilä 34DF engine. /50/

9 CONCLUSIONS

9.1 CBM consept

CBM monitoring and reporting are connecting Wärtsilä and Wärtsilä's customers enabling interactive communication and follow up of equipment condition. The purpose of the CBM concept is to release customers' capital to their core business and assist to keep the installation in highly productive condition. Finding the hidden failures with potential risk factors for safe operation also has high priority within the CBM concept. The CBM concept is executed by collecting operation data from installations locating around the world. CBM reporters are utilising this data by analysing it using the in-house developed CBM analysing tool. The CBM concept is always part of a maintenance agreement between Wärtsilä and the customer. There are several maintenance agreement models that can be tailored for the customer. The CBM concept is nowadays an important part of the maintenance agreement giving added value for both Wärtsilä and customer.

Customers' awareness of digitalization has stepped up also Wärtsilä's investments to the digitalization. New concepts have been developed and existing ones are updated. The competence between digitalized services providers is though and no one has exclusive rights toward customers. The modularization of the CBM concept is also part of this competition by making it even better than before. Customers can choose one or several modules giving best added value for their business.

9.2 The Summary of the Thesis

The technology company Wärtsilä has a 184 years long history of designing and manufacturing of metal products and machines. Nowadays delivered solutions in marine and power production branches are often tailored to fulfil customers' needs. Digitalization has today a permanent foothold in industrial solutions. Wärtsilä started with digitalization already at the end of the 20th century by developing the CBM concept. The CBM concept has been since its launching a leading solution for monitoring equipment remotely regardless of their location.

The purpose of this thesis was to develop further the existing CBM concept, by creating different modules for more focused diagnostics. The thesis was written mainly on the basis of existing Wärtsilä documents and the thesis writer's knowledge of the topic. Additionally main stakeholders close to the CBM concept were interviewed for gathering more knowledge and detailed information of customer needs. Two modules are presented in this thesis, Engine fuel efficiency diagnostic and Risk avoidance diagnostic module, both for Wärtsilä 32 and Wärtsilä 34Df engines. This thesis will be used as a base for further development work for all other Wärtsilä engine types as well.

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/41/ Percentages of different operation cost of a power plant.
Internal presentation material. Access rights required.

/42/ Engine Fuel Efficiency Diagnostic module scheme for Wärtsilä 32 engine

/43/ Engine Fuel Efficiency Diagnostic module scheme for Wärtsilä 34DF engine

/44/ Crankpin annealing.
Photo by Kristian Anneberg.

/45/ Crankpin in-situ repair machining.
Photo by Kristian Anneberg.

/46/ Draft from a maintenance manual.
Internal material. Access rights required.

/47/ Draft from a spare part manual.
Internal material. Access rights required.

/48/ Vibration measurement from a Wärtsilä 32 engine ongoing. Internal material. Access rights required.

/49/ Risk Avoidance Diagnostic module scheme for Wärtsilä 32 engine

/50/ Risk Avoidance Diagnostic module scheme for Wärtsilä 34 DF engine