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# CR PUMP TEST & VALIDATION GUIDE

Wärtsilä Finland Oy

Technology and Communication
2019

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# TIIVISTELMÄ

| | |
|---|---|
| Tekijä | Jaakko Malmimäki |
| Opinnäytetyön nimi | Yhteispaineruiskutuspumpun testaus ja validointi ohje |
| Vuosi | 2019 |
| Kieli | Englanti |
| Sivumäärä | 41 |
| Ohjaaja | Marko Rantasalo |

Opinnäytetyön tarkoituksena oli tuottaa Wärtsilä Finland Oy:lle yhteispaineruiskutuspumpun testaus ja validointi ohje. Ohjeeseen kuuluu ohjeet yhteispaineruiskutuspumpun testaukseen testipenkissä ja moottorilla. Lisäksi ohjeeseen kuuluu myös pumpun komponenttien tarkistusohjeet.

Ohjeelle on tarvetta yrityksessä, sillä nykyisin testaus ja validointi suoritetaan pääasiassa ruiskutuspumppujen parissa työskentelevien ammattitaidon pohjalta. Ohjeen avulla pyritään helpottamaan testausta ja vakioimaan pumpuille tehtäviä testejä.

Työssä perehdyttiin yhteispaineruiskutuspumpun toimintaan, sille tehtäviin testeihin ja mittauksiin tällä hetkellä. Työn lopputuloksena oli ohje pumpun validointiin, joka tulee löytymään Wärtsilän sisäisestä tietokantajärjestelmästä.

Avainsanat Yhteispaineruiskutuspumppu, testaus, validointi, ohje

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## ABSTRACT


| | |
|---|---|
| Author | Jaakko Malmimäki |
| Title | CR Pump Testing and Validation Guide |
| Year | 2019 |
| Language | English |
| Pages | 41 |
| Name of Supervisor | Marko Rantasalo |


The purpose of the thesis was to produce a common-rail injection pump testing and validation guide for Wärtsilä Finland Oy. The guide includes instructions for testing the common-rail injection pump on the test bench and the engine. In addition, the instructions also include instructions for checking the pump components.

There is a need for this guideline in the company as testing and validation is currently carried out based on the knowledge of those who mainly work on injection pumps. The aim of this manual is to facilitate testing and standardize the tests of the pumps.

This thesis focuses on the common-rail pump operation and the tests, which are made on the pump. The result of the thesis is a guide for the pump testing and validation, which will be found in the Wärtsilä internal database system.

Keywords Common-rail pump, testing, validation and guide

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**LIST OF ABBREVIATIONS**

| | |
|---|---|
| BTDC | Before Top Dead Center |
| CR | Common-rail |
| DF | Dual Fuel |
| HFO | Heavy Fuel Oil |
| HP | High Pressure |
| LFO | Light Fuel Oil |
| PDSV | Pressure Drop and Safety Valve |
| RIG | Test bench for testing a single subsystem/part, of some system |
| TDC | Top Dead Center |

# 1 INTRODUCTION

## 1.1 Aim of thesis

The aim of this thesis is make a testing and validation guide for a common-rail pump. There is a need for that in the company, because there is no guideline how to test and validate a common-rail pump. At this moment the common-rail pump testing is based on the knowledge of persons, who are working on it. In case these persons retire or change the work place, the knowledge of these pumps testing disappears, the need for a guideline is significant.

In the beginning of the thesis, the pumps that will be included into the guide were defined. The guide is intended for common-rail pumps that are:

- Multi- plunger pumps (more than two plungers).
- Supplier designed and manufactured pumps.
- Engine driven pumps.
- Meant for LFO or HFO use, no other fuels.
- No pilot fuel injection pump, if they are secondary pump.

# 2 WÄRTSILÄ CORPORATION

## 2.1 General introduction to Wärtsilä

Wärtsilä is a Finnish public limited company, whose main product is diesel, gas and dual-fuel engines for ships and power plants. The company employs over 18000 persons around the world. Wärtsilä has previously worked with sawmill, paper machine, shipyard and ceramic industry. In 2017 Wärtsilä's turnover was 4923 million euros.

Wärtsilä has started engines manufacture in 1938 with a license to manufacture Krupp diesel engines. The company's first own designed diesel engine manufacturing started in 1961 in Vaasa. Today the company's biggest production facilities are in Vaasa, Finland and Trieste, Italy. /1/

## 2.2 Research & development in Wärtsilä

The objective of Wärtsilä's research and development activities is to develop products that meet the customer's expectations of expected lifetime, efficiency, flexibility and emissions. Wärtsilä tests its products in engine laboratories and also in the field. Products will be released in the market after that they have passed all validation process in laboratory and field- testing.

The company invested 141 million euros in research and development in 2017, which was 2.9% of the company's turnover. /2/

# 3 MEDIUM-SPEED DIESEL ENGINE

## 3.1 Introduction

A medium speed diesel engine is an internal combustion engine whose normal operating speed is 200rpm-1000rpm. This type engines is normally used in the ships or power plants. Most engines can use light fuel oil or heavy fuel oil for operating. Diesel engines are compression- ignited engines, which means that the compressed hot air-fuel charge will ignite spontaneously in the cylinder.

Medium speed engines have been manufactured in four- stroke cycle and two- stroke cycle, but the four- stroke engine is more common than two- stroke. These types of engines have been made in V-type and in-line cylinder configurations. /3/

## 3.2 Operating Cycles

Engine operating cycles can be two- or four stroke cycle. In two- stroke engines the power output stroke is for every revolution of the crankshaft, in four stroke it is only every other revolution of the crankshaft. /3/

### 3.2.1 Four stroke engine

A four- stroke cycle engine has four piston steps or two revolutions of the crankshaft for each power output strokes. These cycles are:

- Suction.
  - In the suction stroke, the inlet valve is open and the piston moves downwards and then pressurized air flows into the cylinder. At the end of the suction stroke, the intake valve is closed.
- Compression.
  - In the compression cycle the piston moves upwards and the air in the cylinder is compressing. Near the top dead center the fuel injector sprays an amount of fuel in the cylinder.
- Power.
  - The air fuel mix ignites when the temperature and the pressure is right, which means that the pressure in the cylinder is rising up. The pressure

rise causes the torque which transmits to through the connecting rod to the crankshaft.

- Exhaust.
  - In the exhaust cycle the piston is moving upwards by a crankshaft motion and the exhaust valve is open, when exhaust gases are forced out of the cylinder. /3/

## 3.3 Main Components

### 3.3.1 Engine Block

The engine block is largest part of engine. The engine block supports all the other parts which are attached to the engine. Passages are machined into the cylinder block for lubricating oil and coolant. The engine is attached to ship structure or to the generating set from the block. The block has places for main bearings, cylinder liners and camshaft housing. The engine block is typically made of cast iron, and it is made as single casting. /3/

### 3.3.2 Crankshaft

The main task of the crankshaft is to transmit the torque which is made in the engine operation to the propeller shaft or generator.

The crankshaft is of solid forging; the material is single alloy steel ingot. In medium speed engines the crankshaft usually consists of three main components which are crankshaft, counterweights and gear wheels. The crankshaft is installed into the cylinder block, between the block and crankshaft the main bearings are assembled. The crankshaft is tightened into place with main bearing caps. /3/

### 3.3.3 Camshaft

The purpose of the camshaft is to operate the opening and closing of the intake and exhaust valves at the right time. In four- stroke cycle engines the camshaft rotates at half of the engine speed. The camshaft rotation is handled by the gearwheels from the crankshaft. In some engines the camshaft drives also the fuel injection pump. Most V-type engines have their own camshaft for both banks.

In medium speed engines the camshaft usually consists of three main components which are camshaft piece, bearing piece and gear wheels. Some engine manufacturers make a camshaft in just one piece. /3/

### 3.3.4 Connecting Rod

The main task of the connecting rod is to transfer the piston power to the crankshaft, during the power stroke the combustion in the cylinder chamber pushes the connecting rod downwards. The connecting rod is usually made of two or three pieces. Typical connecting rods are made of forged alloy steel. /3/

### 3.3.5 Piston

The main task of the piston is to compress the air in the cylinder and to keep the combustion pressure in the cylinder during the power stroke. The piston assembly normally consists of four main parts: piston skirt, piston crown, piston rings and piston pin.

Typically, in medium speed diesel engines the piston crown is made of alloy steel, the skirt is made of nodular cast iron. The skirt and the crown are usually attached together with bolt joints. /3/

### 3.3.6 Cylinder Head

The main tasks of the cylinder head is to keep the pressure in the cylinder and also to provide housing for all parts which are connected to the cylinder head. The cylinder head assembly in medium speed engines usually consists of these main parts: intake valves, exhaust valves, valve seats, valve springs, valve actuating system, fuel injector, start air valve and relief valve.

The cylinder head is usually made of cast iron, and it must be resist high pressures and high thermal load. Channels for lubricating oil and cooling water are cast and machined into the cylinder head. /3/

### 3.3.7 Turbocharger

The purpose of the turbocharger is to supply more air into the cylinder. In the suction stroke more air flows into the cylinder when it is pressurized, which means more air in the combustion. The turbocharger takes the energy from exhaust gases. The turbocharger consists of turbine housing, compressor housing, center housing, diffuser, nozzle ring, compressor wheel, turbine wheel and shaft. /3/

### 3.4 Diesel Engine Fuel Injection

The diesel engine is an internal-combustion engine and compression ignited. The combustion process in the diesel engine is linked to engine performance, fuel consumption, combustion noise, and emission composition, all of these depends on how the air/fuel mixture is prepared.

Fuel injection in the cylinder starts just before the end of the compression stroke. In the compression stroke, the piston compresses only air in the cylinder, then it heats the air up strongly in this high pressure and the temperature allows the fuel spontaneously to ignite when it is injected. /4/

#### 3.4.1 Mixture Distribution

The excess-air factor λ (lambda) indicates the ratio of intake air mass to the required air mass for stoichiometric combustion. The diesel engine is not tied to operate with only one overall excess of air, like that the gasoline engines. The rich areas of mixture in diesel engines are responsible for sooty combustion, so the diesel engine has always to operate with excess air.

In the combustion chamber, there is a heterogeneous mixture of fuel and air at the ignition moment. A heterogeneous mixture means that the localized excess-air factor can cover the entire range from $\lambda=0$ (pure fuel) in the near of the injection valve to the $\lambda=\infty$ (pure air).

$$\lambda = \frac{\text{Air mass}}{\text{Fuel mass} * \text{Stoichiometric ratio}}$$

The excess air factor is in turbocharged diesel engines at full load between $\lambda=1.15$ and $\lambda=2.0$, at idling it can be $\lambda<10$. /4/

### 3.4.2 Fuel Atomization

In the fuel injection system the substantive thing is to get the fuel atomized in the cylinder. Atomization has a major impact on the engine combustion and emissions. Fuel atomization is more efficient with high pressures, therefore the injection pressures can be at even 2000 bar. The high- speed difference between the fuel droplet and the surrounding air causes the fuel jet atomization. Therefore, the higher density of the air gives, the more fine fuel atomization.

Easily combustible areas are created in around the individual fuel droplet; therefore the droplets should be as small as possible and as much as possible in the cylinder. With effective fuel atomization and excess-air factor, many combustible areas can be produced in to the cylinder. /4/

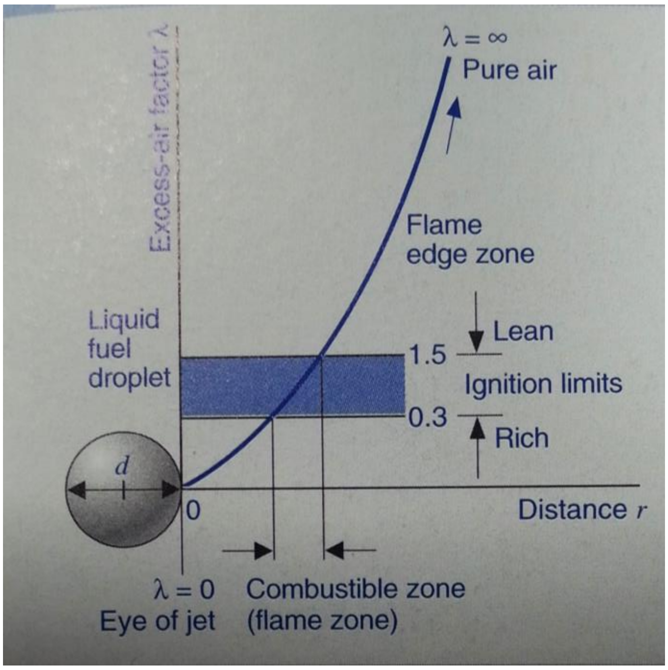


**Figure 1.** Air/fuel ratio curve for a static fuel droplet./4/

### 3.4.3 Fuel Injection Parameters

The start of injection (Injection timing) has a major impact on combustion; it has an impact relatively on combustion temperature, fuel consumption, emissions and combustion noise. The injection timing specifies the crankshaft position in degrees before the piston top dead center (TDC), at this point the injection nozzle opens and fuel injection starts.

The start point of the injection varies according to the engine speed, load and temperature. In a common-rail system, the injection timing is easily manageable, when using the solenoid actuated injection valve, the engine control unit controls it depending on the engine operating point. Different type diesel engines use the different injection timing but mostly the timing is in idling/no load 4°-12° BTDC and at full load 4°-15° BTDC.

One parameter is injection duration, the time that the injection nozzle is open, and fuel flows to the combustion chamber. This parameter can be measured as crankshaft/camshaft rotation in degrees or duration in milliseconds. Engine control unit controls the injection duration depending of the ambient conditions, operating point and rail pressure. The injection duration can be in direct injection commercial vehicle at 25-36° crankshaft angle.

Another main parameter in common-rail engines is injection pressure. In common-rail engines the main benefit is that the injection pressure is not dependent on the engine speed like in the traditional fuel injection systems. Because the fuel atomization is tied to the injection pressure, it can be optimized regardless of engine speed in common-rail engines. The benefits of optimized injection pressure better combustion process and reduced emissions and smoke. /4/

### 3.5 Fuels

Medium speed diesel engines can usually operate with light fuel oil and heavy fuel oil, but some medium speed diesel engines can only operate at light fuel oil. In the shipping industry, the International Maritime Organization specifies the requirements of petroleum based fuels in standard ISO 8217. /5/

#### 3.5.1 Light Fuel Oil

Light fuel oils/distillate fuel oils used in medium speed diesel engines are increasing because the tightening emission limits. The benefits of distillate fuel oils are purity and naturally low sulphur. Distillate fuel oils have a considerably lower viscosity than heavy fuel oils have, so they do not need to be preheated before pumping to the engine. The disadvantage of distillate fuels is a considerably higher price than that of heavy fuel oils. /5/

**Table 1.** Distillate fuel specifications for Wärtsilä W32-type engine. /6/

<table>
<tr><th rowspan="2">Characteristics</th><th rowspan="2">Unit</th><th rowspan="2">Limit</th><th colspan="4">Category ISO-F</th><th rowspan="2">Test method(s) and references</th></tr>
<tr><th>DMA</th><th>DFA</th><th>DMZ</th><th>DFZ</th></tr>
<tr><td rowspan="2">Kinematic viscosity at 40 °C</td><td rowspan="2">mm²/s</td><td>Max</td><td colspan="2">6,0</td><td colspan="2">6,0</td><td rowspan="2">ISO 3104</td></tr>
<tr><td>Min</td><td colspan="2">2,0</td><td colspan="2">3,0</td></tr>
<tr><td>Density at 15 °C</td><td>kg/m³</td><td>Max</td><td colspan="2">890,0</td><td colspan="2">890,0</td><td>ISO 3675 or ISO 12185</td></tr>
<tr><td>Cetane index</td><td></td><td>Min</td><td colspan="2">40</td><td colspan="2">40</td><td>ISO 4264</td></tr>
<tr><td>Sulphur</td><td>% m/m</td><td>Max</td><td colspan="2">1,0</td><td colspan="2">1,0</td><td>ISO 8754, ISO 14596, ASTM D4294</td></tr>
<tr><td>Flash point</td><td>°C</td><td>Min</td><td colspan="2">60,0</td><td colspan="2">60,0</td><td>ISO 2719</td></tr>
<tr><td>Hydrogen sulfide</td><td>Mg/kg</td><td>Max</td><td colspan="2">2,0</td><td colspan="2">2,0</td><td>IP 570</td></tr>
<tr><td>Acid number</td><td>Mg KOH/g</td><td>Max</td><td colspan="2">0,5</td><td colspan="2">0,5</td><td>ASTM D664</td></tr>
<tr><td>Oxidation stability</td><td>g/m³</td><td>Max</td><td colspan="2">25</td><td colspan="2">25</td><td>ISO12205</td></tr>
<tr><td>Fatty acid methyl es-ter (FAME)</td><td>% v/v</td><td>Max</td><td>-</td><td>7,0</td><td>-</td><td>7,0</td><td>ASTM D7963 or IP 579</td></tr>
<tr><td>Carbon residue – Mi-cro method on 10% distillation residue</td><td>% m/m</td><td>Max</td><td colspan="2">0,3</td><td colspan="2">0,3</td><td>ISO 10370</td></tr>
<tr><td rowspan="2">Pour point<br>Winter<br><br>Summer</td><td rowspan="2">°C</td><td rowspan="2">Max</td><td colspan="2">-6</td><td colspan="2">-6</td><td rowspan="2">ISO 3016</td></tr>
<tr><td colspan="2">0</td><td colspan="2">0</td></tr>
<tr><td>Appearance</td><td></td><td>-</td><td colspan="4">Clear and bright</td><td>-</td></tr>
<tr><td>Ash</td><td>% m/m</td><td>Max</td><td colspan="2">0,01</td><td colspan="2">0,01</td><td>ISO 6245</td></tr>
</table>

### 3.5.2 Heavy Fuel Oil

A large part of the medium speed diesel engines uses heavy fuel oil for operating. The main reason for using heavy fuel oil is the cheaper price compared to light fuel oils. Heavy fuel oils with a high viscosity and high sulphur are cheapest.

Engines that use a heavy fuel oil needs a special equipment for external fuel oil feeding, because of high viscosity of the heavy fuel oil. Viscosity is a directly proportional to temperature, so the heavy fuel oil needs heating before feeding to the engine fuel system. The fuel oil viscosity should be right so that the engine fuel system can work properly./5/

**Table 2**. Residual fuel specifications for Wärtsilä W32-type engine./6/

| **Characteristics** | **Unit** | **Limit**<br><br>**HFO 1** | **Limit**<br><br>**HFO 2** | **Test method reference** |
|---|---|---|---|---|
| Kinematic viscosity at 50 °C, max. | mm²/s | 700,0 | 700,0 | ISO 3104 |
| Density at 15 °C, max. | kg/m³ | 991,0 | 991,0 | ISO 3675 or<br>ISO 12185 |
| CCAI | - | 850 | 870 | ISO 8217, Annex F |
| Sulphur | % m/m | Statutory requirements | | ISO 8754 or<br>ISO 14596 |
| Flash point, min. | °C | 60 | 60 | ISO 2719 |
| Hydrogen sulfide, max. | mg/kg | 2,0 | 2,0 | IP 570 |
| Acid number, max. | mg KOH/g | 2,5 | 2,5 | ASTM D664 |
| Total sediment aged, max. | % m/m | 0,10 | 0,10 | ISO 10307-2 |
| Carbon residue, micro method, max. | % m/m | 15,0 | 20,0 | ISO 10370 |
| Asphaltenes, max. d) | % m/m | 8 | 14 | ASTM D3279 |
| Pour point (upper), max. | °C | 30 | 30 | ISO 3016 |
| Water, max.<br>Water bef. engine, max. | % v/v | 0,5<br>0,3 | 0,5<br>0,3 | ISO 3733 or |

| | | | | |
|---|---|---|---|---|
| | | | | ASTM D6304-C |
| Ash, max. | % m/m | 0,05 | 0,15 | ISO 6245 or LP1001 |
| Vanadium, max. | mg/kg | 100 | 450 | IP 501, IP 470<br>or ISO 14597 |
| Sodium, max.<br>Sodium before engine, max. | mg/kg | 50<br>30 | 100<br>30 | IP 501 or IP 470 |
| Aluminum + Silicon, max.<br>Aluminium + Silicon bef. engine, max. | mg/kg | 30<br>15 | 60<br>15 | IP 501, IP 470 or ISO 10478 |

# 4 PLUNGER FUEL PUMP

A plunger pump is a positive displacement pump. In the plunger pump the sealing is fixed and the plunger moves inside this sealing, this separates the plunger and the piston pump. This sealing type allows to use higher pressures than a piston pump. The reciprocating move to plungers can be produced in many ways, but usually it is produced by the rotating camshaft or crankshaft. Most of these type plunger pumps are lubricated with oil.

The reciprocating positive displacement pump displaces the cylinder volume much liquid. The pump produced volume depends on the cylinder filling and the speed of the pump. The efficiency of the plunger pumps is in between 0.78-0.92.

The material of pump components varies depending on the pumping fluids. Usually used materials are cast iron, steel alloy, stainless steel, aluminum, brass, bronze and ceramics. Plunger pumps are usually used in industry where a high pressure is needed, for example in hydraulic systems, hydro demolition, mining, and power plants.

A multi-plunger pump is a plunger pump which consist of more than two plungers. Multi-plunger pumps can be manufactured with many possible layouts, for example in-line, V-type, boxer and star. /7/

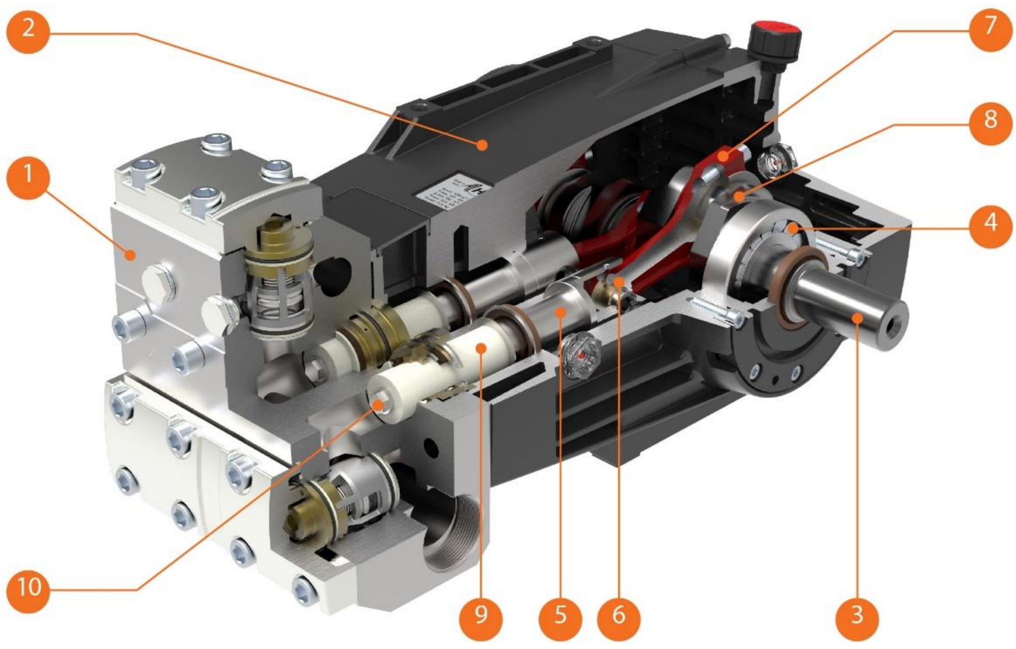


**Figure 2.** In-line plunger pump. /7/

1. Head
2. Crankcase
3. Shaft
4. Bearings
5. Drive piston
6. Pin
7. Connecting rod
8. Eccentric
9. Plunger
10. Screw

## 4.1 Cam-roller Type Driven Pump

In a cam-roller type pump the roller follows the rotating camshaft lobes and this generates the reciprocal movement of the plunger. In this design the spring is needed for the return of the plungers on a non-pressure stroke.

The advantages of a cam-roller design are many possible layouts, possibility to multiple plungers at one cam lobe, less reciprocating mass, possibility to tune the cam lift profile. Weaknesses in this design are the risk to cam and unequal contact of the roller at high speed and the need of return spring.

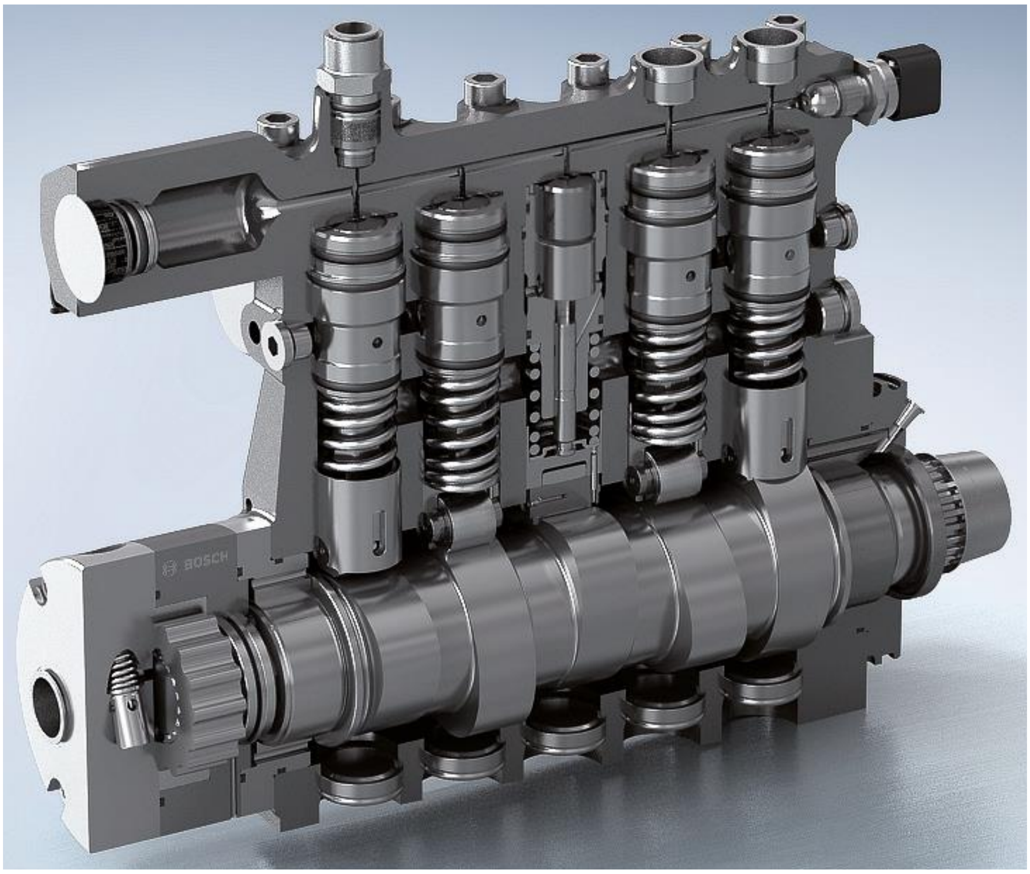


**Figure 3.** Bosch CP9.1 high pressure pump, cam-roller type. /8/

## 4.2 Crank Mechanism Type Driven Pump

In a crank mechanism type driven pump the reciprocal movement of the plunger is generated with the connecting rod and pump crankshaft. In this design the connecting rod needs a mechanical solution for guiding.

The advantages of the crank mechanism design are many possible layouts, no return springs needed, no possibility to cam-roller jumping, large pumping capacity due to a long stroke of plunger. Weaknesses in this design are the lubrication of connecting rod upper bearing, and more reciprocating mass than in the cam-roller design.

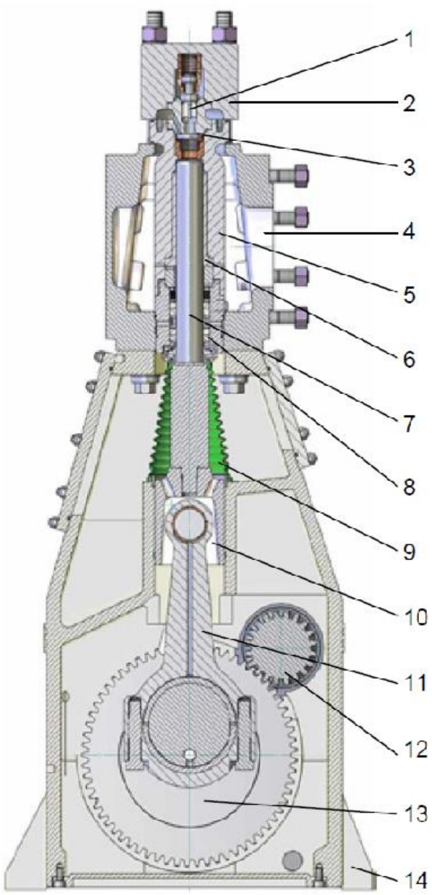


**Figure 4.** Crank mechanism type pump. /9/

1. Discharge valve
2. Valve housing
3. Suction valve
4. Suction chamber
5. Sleeve
6. Labyrinth insert
7. Plunger
8. Low pressure seal pack
9. Bellows
10. Crosshead
11. Connection rod
12. Gear
13. Crank shaft
14. Crank section housing

**Figure 5**. Heinzmann HDP-K4-HFO Crank mechanism type driven CR pump. /10/

### 4.3 Multi Plunger Fuel Pumps in Medium Speed Diesel Engines

In medium speed diesel engines the multi plunger common-rail pumps have three or even eight pumping elements. There may be only one or several pumps in the engine. The pump can be driven with the engine camshaft, crankshaft or even with electric motor.

Usually in the medium speed diesel engines the pump drive type is a camshaft-roller or crankshaft system. Multi plunger pumps manufacturers for medium speed diesel engines are for example Bosch, Heinzmann, Liebherr and L'Orange,

**Table 3.** Comparison of high pressure pumps from three different. /8, 10/

| Pump | Fuel type | Drive type | Pressure up to | Pumping strokes/rev | Delivery rate | Cylinders/Pump elements |
|---|---|---|---|---|---|---|
| **Bosch CP9.1** | LFO | Cam-roller | 2200 bar | 2 | ? | 1-5 |
| **Heinzmann HDP-K3 HFO** | LFO & HFO | Crank mechanism | 2200 bar | 1 | 15 l/min | 3 |
| **L'Orange PCO-G074** | LFO & HFO | Cam-roller | 2000 bar | 1 | 30 l/min | 4 |

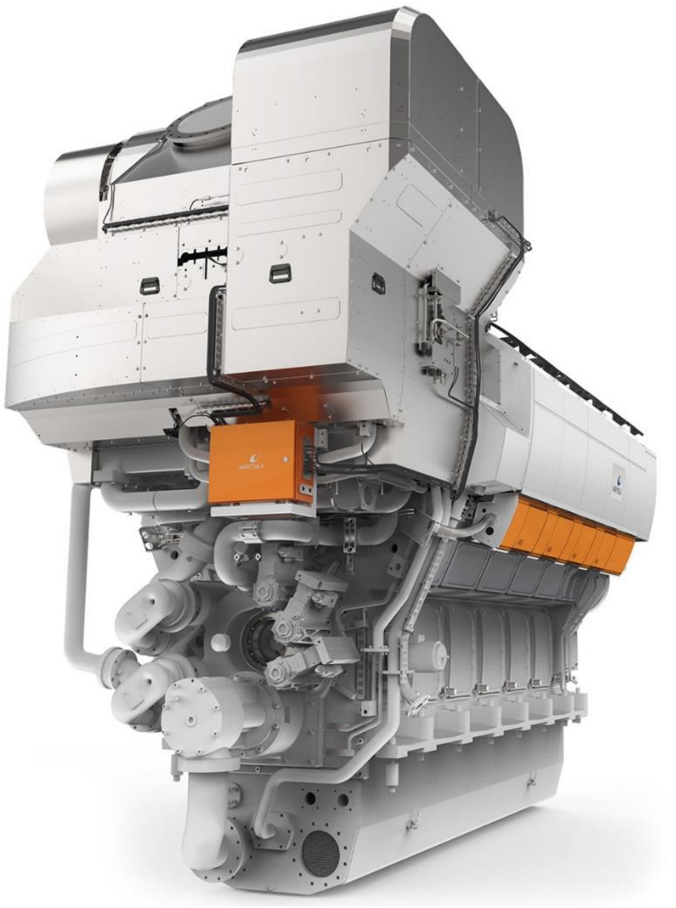

**Figure 6.** Three CR pumps in Wärtsilä W31. /11/

### 4.3.1 Principle of L'Orange Multi Plunger Pump

An external fuel system feeds low pressurized fuel to a CR pump through an electrically controlled flow control valve (FCV).The flow control valve controls fill fuel to the pump. From the fuel control valve the fuel flows to the pumping element, when the plunger goes down the pressure in the barrel decreases and the supply valve opens, then fuel flows to the pumping chamber. The supply valve is a one-way valve and it closes when the pressure in the barrel starts to rise because the plunger changes direction to upwards.

When the plunger goes upwards, the pressure in the barrel starts to rise and the delivery valve opens and the fuel flows to high pressure pipes. The delivery valve is also a one-way valve and prevents the fuel to flow to high pressure pipes to the pumping chamber.

**Figure 7.**Suction stroke of L’Orange multi plunger pump. /12/

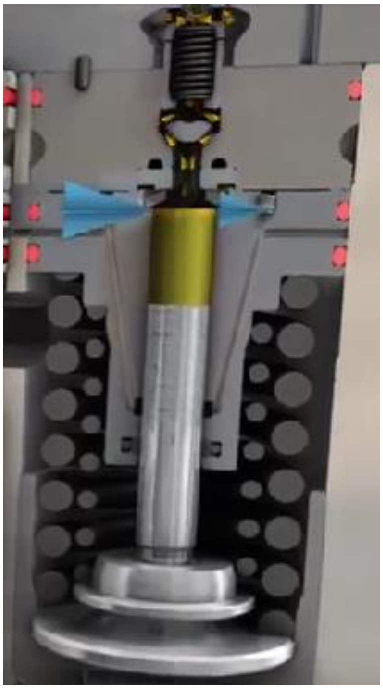

**Figure 8.** Pumping stroke of L’Orange multi plunger pump. /12/

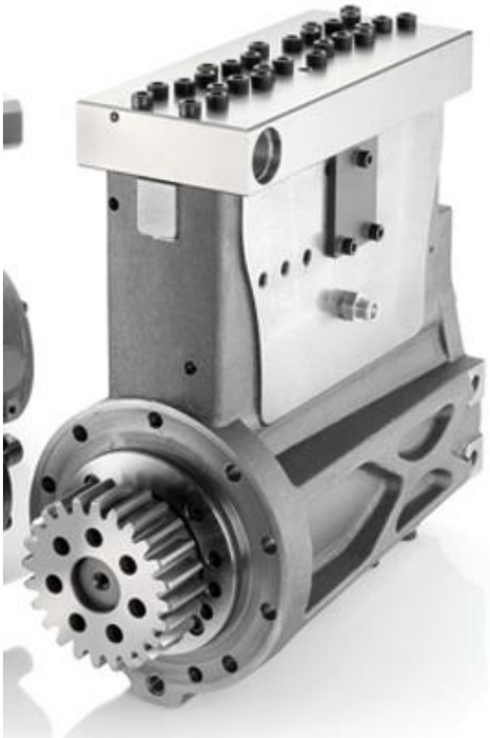

**Figure 9.** L’Orange multi plunger pump. /13/

# 5 COMMON-RAIL SYSTEM IN MEDIUM SPEED DIESEL ENGINE

## 5.1 Common-rail System in Overall

The common-rail system is a modern fuel injection system in a medium speed diesel engine. The aim of the common-rail system is to deliver the right amount of high pressurized fuel to the cylinder at the right time. The starting point, duration and pressure of the injection is more manageable with a common-rail system than older fuel injection systems. Therefore, the fuel injection can be optimized at any operation speed and load of the engine.

The common-rail system in medium speed diesel engines is still today quite unusual compared to automotive industry, but their share is increasing sharply due to constantly increasing emission rules.

The common-rail system includes a lot of automation. The engine control unit adjusts and controls the parameters for fuel injection, depending on the engine operating point. The engine control unit reads the sensors of for example crankshaft position, engine temperature, load, charge air pressure, intake air temperature, and based on these selects the right fuel injection parameters from predefined maps.

In the common-rail system the high pressure pump produces continuously up to 2200bar pressure to the fuel rail and fuel injectors. The higher injection pressure means the smaller droplet size, which means the better mixture and the more complete combustion in the cylinder.

Medium speed diesel engine common-rail systems usually work on light fuel oil and heavy fuel oil, but some engines can operate only on light fuel oil. The benefits of a common-rail system main are decreased fuel consumption and emissions. /4/

Picture removed for confidential reasons

**Figure 10.** Flowchart of modern common-rail system. /14/

### 5.2 Main Components of Common-rail System

The common-rail system consist of many parts, but four main parts are high pressure fuel pump, high pressure fuel pipes, fuel injector and PDSV (pressure drop safety valve). The common-rail system also includes an automation system. /14/

#### 5.2.1 High Pressure Fuel Pump

The purpose of the high pressure fuel pump main is to transfer the low pressurized fuel oil to high pressurized fuel oil. The pump feeds the up to 2200bar pressurized fuel to fuel rail/high pressure pipes. Because these type of pumps do not affect the timing of the injection, the camshaft lobes can be softer than in a traditional fuel injection pumps. Some pumps have two lobes in one cam, this helps to keep the pressure in the rail at the low speed of engine.

The multi plunger pumps are usually driven by the crankshaft and pumps are located in the free end of the engine or the side of the engine. In multi plunger pump systems there are typically one to three pumps for the whole engine. /13/

**Figure 11.** L'Orange HP-pump & fuel injector. /13/

### 5.2.2 High Pressure Fuel Pipes

The main purpose of the high pressure fuel pipes is to deliver and storage the high pressurized fuel to the fuel injector. High pressure fuel pipes are double walled, the inner pipe is for high pressure and the outer pipe is for secure if the inner pipe or connector leaks. In case the inner pipe leaks fuel, the leakage is led in between the pipes to the leakage indicator. The high pressure fuel pipes are distributed to each fuel injector.

In engines that use heavy fuel oil, the high pressure pipes have a very big thermal expansion due to differences in the fuel temperature. The fuel temperature can be between 20°C-140°C, and this is a very big challenge during the designing of the fuel rail. /13/

**Figure 12.** Double walled high pressure pipe without connecting piece. /15/

### 5.2.3 Fuel Injector

The purpose of the fuel injector is to deliver the right quantity of fuel oil to the cylinder at the right time. In the common-rail system the opening of the fuel injector needle is electronically operated with a solenoid. Usually in medium speed diesel engines each injector has its own integrated fuel reservoir, and this reduces pressure pulses in the system. A modern fuel injector can have one or two injection needles for optimizing the different loads of the engine and in a dual- fuel engine one needle is for pilot fuel injection in gas mode and the large needle is for diesel mode operation. /13/

### 5.2.4 Pressure Drop and Safety Valve

The tasks of the pressure drop and safety valve is to secure the high pressure system at over- pressure and drop the high pressure from the system. When the system pressure for some reason rises too high, the PDSV drops the system pressure to a limited level, with this pressure the engine operation is still possible with a low load.

During an engine shut- down pressurized air opens the PDSV and releases the high pressurized fuel to the low pressure system through discharging chambers. The PDSV allows the fuel circulation in the system when the engine is not running; this is needed for the system warm-up when the engine is operating on heavy fuel oil. /13/

# 6 VERIFICATION & VALIDATION IN ENGINEERING

Verification and validation is a process where it is checked that the item meets the required and specified requirements. Validation and verification is also a part of the quality control, it can be used to indicate that the process or device produces the required and designed values. /16/

## 6.1 Validation

Validation is a procedure for assessing the suitability of a product or process for a particular use. The purpose of validation is to produce reference values for parameters that describe the reliability of the method. Another purpose of the validation is to ensure that the test results are in compliance with the law, are suitable for the intended purpose, are in accordance with the classifications, and customer requirements. /16/

## 6.2 Verification

Verification is the presentation of objective results that a particular product/object meets the requirements for it. Verification is narrower in scope than validation. Verification can be done as an example when validation is done by someone else. /16/

## 6.3 Verification and Validation in This Thesis

In this test and validation guide the word validation has been used partly to mean verification, because in this work the validation is actually a part of quality control. The guide applies only to pumps which have been designed and manufactured by the supplier which have been also done validation for the pump.

# 7 MAKING OF THE CR PUMP TEST AND VALIDATION GUIDE

This objective of this thesis is to make a test and validation guide for a common-rail pump for Wärtsilä. There is a need for that in the company because there is no guideline for how to test a common-rail pump. At this moment the common-rail pump testing is based on the knowledge of persons whose are working with CR pumps.

When starting to make this CR pump test and validation guide, a meeting was arranged with the fuel injection expert and with my thesis supervisor at Wärtsilä. At the meeting the frame of the guide was discussed, a decision was made divide it into three main parts which was a rig testing, engine testing and component inspection. The purposes and definitions of these sections are explained in the following sections of this thesis.

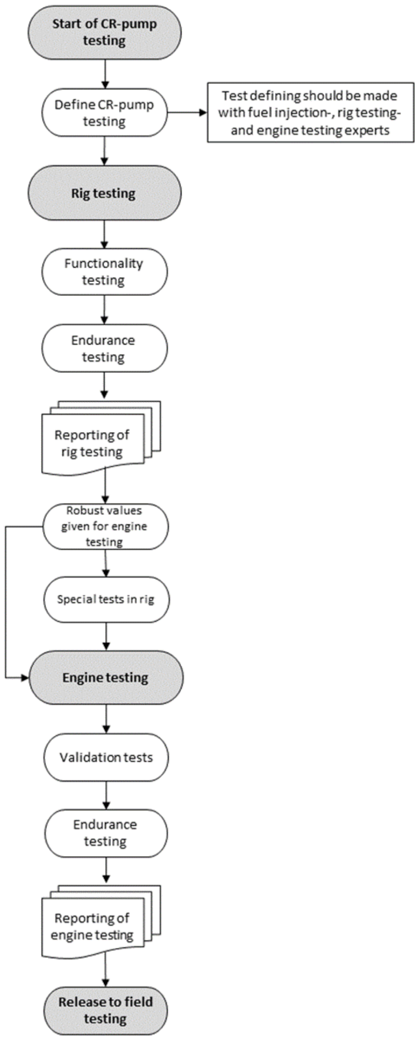


**Figure 13.** Flow chart of CR pump test and validation procedure.

### 7.1 Collecting the information

For making the test and validation guide some information of the common-rail pumps and the test and validation guides in Wärtsilä was needed.

Information of the common-rail pump operation was obtained the from fuel injection expert in Wärtsilä, when a component inspection was made on a CR pump after the 1000 hours endurance test run on a laboratory engine. Information was also collected of the test reports which was made previously in the engine laboratory.

Rig testing information was collected in the several meetings that were -arranged during this spring. Two rig testing experts and two fuel injection experts have participated at the meetings. In these meetings the test and measurements have been discussed which will be good to test in the rig conditions.

Engine testing information was collected in the several meetings that were arranged in December and this spring. At the meetings three engine testing experts were present. During these meetings the test, measurements and the load points of the engine/CR pump during the validation were discussed.

Information for the test and validation guide was mostly obtained from the previously made test and validation guides. The matter has also been discussed at the meetings.

### 7.2 Measurements during the testing and validation

During the pump testing and validation the conditions of the pump should be measured with precision. Pump supply (input) and delivery (output) values should always be measured when testing the pump, without these it is impossible to analyze the pump operation. The internal measurements of the pump are also very important. The measurement data should be logged and saved at required time. Data is needed for an analysis if damage is found in the pump. Lube oil and fuel oil quality should be also analyzed during the testing.

#### 7.2.1 Supply Values to the Pump

At least these supplying values of the pump should be measure:

- Fuel oil
    - Pressure

        - Fuel oil pressure, before the CR pump
    - Temperature
        - Fuel oil temperature, before the CR pump
    - Flow
        - Fuel oil feed flow to CR pump
    - Viscosity
        - Fuel oil viscosity before the CR pump
- Lube oil
    - Pressure
        - Lube oil pressure, before the CR pump
    - Temperature
        - Lube oil temperature, before the CR pump

### 7.2.2 Delivery Values of the Pump

At least these delivery values of the pump should be measured:

- Fuel oil
    - Pressure
        - Fuel oil pressure in the rail
    - Temperature
        - Fuel oil temperature in the rail
- Lube oil
    - Temperature
        - Lube oil temperature, after the CR pump

### 7.2.3 Pump Internal Measurements

At least these measurements are needed of the pump operation:

- Flow control valve
    - FCV position, with a displacement sensor if possible
    - FCV control signal
- Bearings
    - Temperatures of all main bearings
- Housing
    - Surface temperature in the pump head and housing
- External leakage
    - Spill leakage of the plungers

## 7.3 Rig Testing

Aim of the rig testing is to verify that the pump meets the supplier given values, find robust operating values for the CR pump and prove the durability of the pump in all operating modes. The rig testing is a part of supplier's quality control. Also one purpose is to perform some tests that the supplier does not have a possibility to do.

In the rig testing, it is important to test the pump in all CR pump destination engine speeds and loads to ensure the operation of the CR pump in all situations. The conditions in the rig testing should be simulated as close as possible to the conditions in the pump destination engine. In the rig testing the pump with variable speed and load, so that the pump gets a different thermal and pressure loads.

The rig tests are divided into the three main parts which are functionality tests, endurance test and special tests. For confidential reasons the detailed information of tests is not published in this thesis.

### 7.3.1 Functionality Test

The purpose of the functionality tests is to test the most necessary functions of the pump. These tests can, be for example, confirming that the pump can reach the values of pump delivery given by the supplier, find the operating values for electrical control of the pump, and ensure that the pump can resist the required loading points.

### 7.3.2 Endurance Test

The purpose of the endurance test is to prove the durability of the CR pump and find if some load causes the fatigue or other wearing in some component of the pump. The loading cycle of the endurance test loading should include variable speed operation and different loading points. The aim of this variable speed and load is that the pump is stressed with varying thermal and pressure loads. The endurance test gives indication of the expected lifetime of the pump.

### 7.3.3 Special Test

The purpose of the special test is to ensure the durability of the CR pump at the border of the CR pump limits. These tests can be, for example, a test with low lube oil pressure, pump over- speeding test, low fuel oil viscosity test, or low speed testing.

## 7.4 Engine Testing

The aim of the engine testing is to prove the durability of the CR pump in all engine operating modes. Diesel engines are one of the main products of Wärtsilä, so the CR pump needs to work with promised values, because without a CR pump engine does not work. All engine running in the laboratory is also the testing of the CR pump, but in this test and validation guide some test are performed that should be tested when a CR pump needs to be validated. The engine testing part is made in cooperation with three engine testing engineers. The tests to be performed have been decided in the team.

The CR pump engine testing is divided into the two main parts which are validation tests and endurance test. For confidential reasons the detailed information of tests is not published in this thesis.

### 7.4.1 Validation Tests

The purpose of the validation tests is to test the pump in all engine operating modes and get the parameters for engine operating. In validating test a CR pump with special measurements is needed, for example, the main bearing temperatures of the CR pump are needed when finding the engine fuel injection operating parameters, so that the bearing temperature limits of the pump are not exceeded. Also the position of the fuel flow control valve is needed the measure with a displacement sensor and compared it to the control signal.

During the engine testing the pump attachment to the engine also needs to be validated, due this vibrations of the pump is needs to be measured. Also the pump torsional vibrations should be measured from the CR pump camshaft/crankshaft, because the pump is driven with a gear train and the backlash of gears can cause the damaging vibration to the pump.

These engine operating modes should be tested when validating the CR pump:

- Start
  - Normal preheated engine start, with all fuels
  - Fast start
  - Black start (Without pre-lube)
- Stop.
  - Normal stop from idle speed/load
  - Emergency stop from full speed/load
- Operation
  - Clutch in
  - Variable speed operation
  - Nominal speed operation
  - Load steps
  - Breaker open at full load
  - Trip from gas to diesel, in DF-engines

### 7.4.2 Endurance Test

The aim of the CR pump engine endurance test is to prove the durability of the pump but also to prove the attachment of the pump to the engine. The endurance test should be driven at least 500 hours, after the endurance test the pump should be inspected for possible fretting on the mounting surface. Also the durability of the high pressure pipe connection will be proven in the endurance test.

## 7.5 Component inspection

In the component inspection section the purpose is to give tips and advice for the visual inspection of common-rail pump components. In this section the CR pump has to be disassembled into parts, so in the disassembly one has to be careful with the order of the parts if the pump is still going to be assembled again.

It is not possible to find all of these faults only visually, so the inspection should be done in the laboratory conditions. If the pump is going to assembled after the inspection, non-destructive techniques should be used in the inspection.

For example these type faults can be found in the pump:

- Cavitation on high pressure areas
  - For example at in the pump elements
- Fretting on mating surfaces
  - For example pump housing and connecting piece contact surface
- Leakage of high pressure contact surfaces
  - For example between pump elements
- Polishing on sliding surfaces
  - For example lifter tappets
- Wear of bearing surfaces
  - For example wear of the main bearing bushes

### 7.6 Result

The final result was a completed common-rail pump test and validation guide, which includes rig, engine testing and component inspection sections. Because the guide includes different designs of pumps, the guide is partly universal. In the future the functionality of the guide can be proven when the first common-rail pump will be tested according to this guide.

# 8 CONCLUSION

The share of common-rail systems in medium speed diesel engines is increasing sharply. Because the common-rail systems use 2000-2500 bar pressures the structure and the materials of the pump need to be designed at really good precision. When are using so high pressures, the pump design can be really close to the sustainability limits in some components. The common-rail pump is the one of the key elements in engine operation, without it the engine running is not possible. So it is really important that the pump is tested and validated to operate in all engine operating points.

In this thesis the subscriber company has a need for this CR pump test and validation guide, because there is no prior guideline for CR pump testing. Making a useful guideline with these limitations that are defined at the beginning of this thesis, was really challenging and it is impossible to make a guide that works perfectly with every manufacturers pump.

Because these pumps are designed and manufactured by the supplier, the supplier has done also testing and validation for the pump, so the rig testing is really hard to decide. Therefore, the rig testing is also a part of supplier’s quality control, but the rig testing is very important because the pump operation can be verified in the rig and then it is not limiting the engine testing if the pump breaks in the rig and not in the engine.

In the engine testing section it was easier to decide the tests because the diesel engines are one of the main products in the Wärtsilä, so the needed operating points of the pump are in well known. The CR pump engine testing is also a very important because the pump is needed to work in all situations.

The component inspection section lists all the main inspection points that should be inspected in the pump. Because the pump designs vary it is possible that something important is not listed, but the future will show how this work.

In overall, the guideline can be considered usefully. In the future we will see how suitable this guideline is for the purpose, after it has been used for the CR pump testing and validation. Making of this thesis gave at least me a lot of new information about the common-rail system and engineering work.

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