05.04.2019

Final report

Retrofitting 5 Pielstick PC 2.2 engines on icebreaker YMER with HEINZMANN Common-Rail injection technology

Written by:
Hubert Kienzler
Vasily Leytes
Simon Serrer
Mario Kühfusz

1. Background and purpose

The Swedish Maritime Administration's icebreakers have older engines which, in comparison with today's, have a greater emissions discharge and lower efficiency. Over the past few years, new fuel injection technology resulting in better combustion has been developed. Technology for retrofitting fuel injection systems has not yet been developed and tested. The Swedish Maritime Administration and HEINZMANN GmbH intend to collaborate on a research and development project in order to ascertain whether it is possible to retrofit the old main engines on board the icebreaker Ymer.

The expected reductions in emissions from the engines were:

- 40 - 80 % less soot
- 20 - 40 % less NOx
- 40 - 80 % less HC

In addition, a fuel savings of 5 - 10%, and thus a corresponding reduction of CO2 emissions, was expected.

Against this background, the Swedish Maritime Administration wished to carry out a pilot development project as part of WINMOS (Winter navigation - Motorways of the sea).

2. The project

Black smoke and emissions from vessels constitute a growing problem. Common Rail (CR) is a fuel system that has the potential to reduce discharges into the air from marine diesel engines, as compared with a conventional fuel system. In addition, CR systems reduce fuel consumption through higher combustion efficiency. The possibility of retrofitting CR systems onto existing engines in order to improve their eco-performance would be of benefit to the environment, and at the same time involve cost savings through reduced fuel consumption.
At project start there was no system ready for installation that is suitable for the main engines (of type S.E.M.T Pielstick 12PC2-2V @ 3680 kW) on the icebreakers. HEINZMANN, which has declared itself willing to participate in the Project, had a system that was suitable for adaptation to retrofitting on older marine diesel engines.
The purpose of the project for reduced environmental impact burden as concerns Swedish Maritime Administration icebreakers was verified, through a research and development project with actual tests, whether the CR system in practice yields the expected environmental improvements and the expected lower fuel consumption.

The Project was carried out through installing the CR system first on one, and then on all propulsion engines on the icebreaker Ymer. Installation on all the propulsion engines on the Ymer was a prerequisite for running performance tests under operation during one ice-breaking season.

Since the tests on the Ymer turned out well, the Swedish Maritime Administration intends to also rebuild the engines on her sister vessels Atle and Frej. Since, in that case, there is a finished system on the market, it is proposed that the remodelling of Atle and Frej take place in the following years.

The new technology will be applicable to other marine engines. The partners have an opportunity here to show that development in maritime innovations is advancing, and that they are taking responsibility for the maritime shipping of the future. Swedish Maritime Administration vessels are, in this context, an excellent test platform.

3. The Common-Rail system

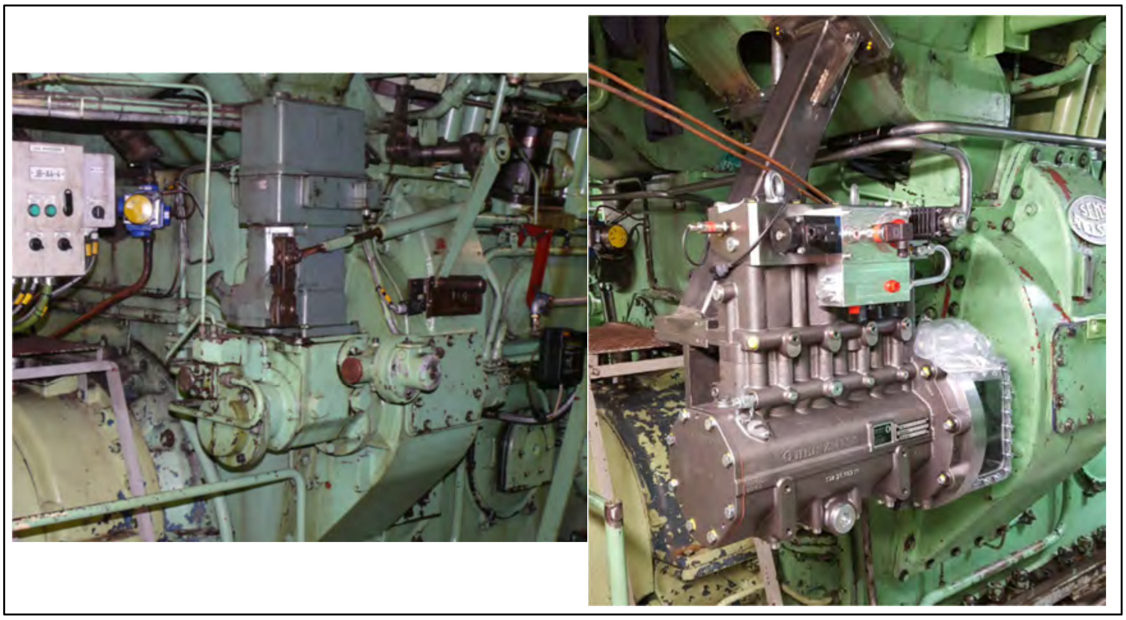
Ymer is, like all Atle-Class Icebreakers, equipped with five diesel-electric main propulsion engines and four auxiliary gen-sets in the engine room as well as one auxiliary backup generator above sea level.

Picture 1: View into the engine room; Overview main engines Pielstick PC 2-2 (V12)

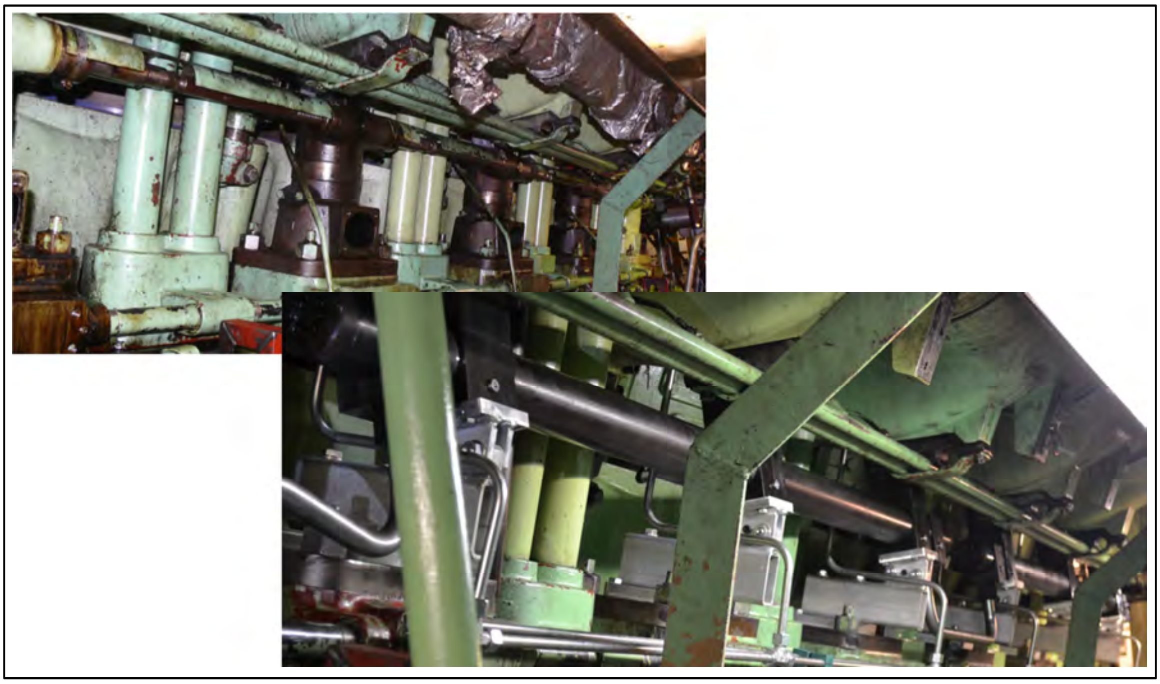
The ship was built as the 3rd ship in the fleet in 1977 but due to good maintenance and consequent investments in upgrades of the ships automation systems the vessel is in an outstanding condition. The complete ship alarm and automation system was upgraded with the software PRAXIS so many engine parameters are already monitored in the engineering control room and the data is accessible throughout the complete vessel as network and electronic communication is already implemented. The main engines however have been maintained properly during service but never been upgraded. So from the mechanical point of view the injection and speed governor system is technology from the late 70th. Originally the engines are equipped with a Pump-Pipe-Nozzle System (PPN) and a hydraulic governor. The speed is fixed at 485 RPM.

When the SMA ordered HZM engineers for a first engine survey the working principle and functionality of the system was investigated in depth using all the original technical documentation available. However for the design of parts like the fuel-rail and the injector the base of information from the original documentation is too poor and additional measurements were taken directly on the engine as well as on parts sent to HEINZMANN in Germany for closer analysis.

One of the challenges and a major concern with the project was the feared high tolerance that the old engine was built to. The pipes, connections and especially the alignment of the components has been a huge challenge. For installing the Speed Sensing Unit (SSU), a complex system of sensors, changes directly on the engine housing had been necessary. Due to too high tolerances between the housing parts it was inevitable to restrain the crank shaft lid with additional centering pins.
Heinzmann and all the staff involved have done their utmost to find solutions that have led in good results.

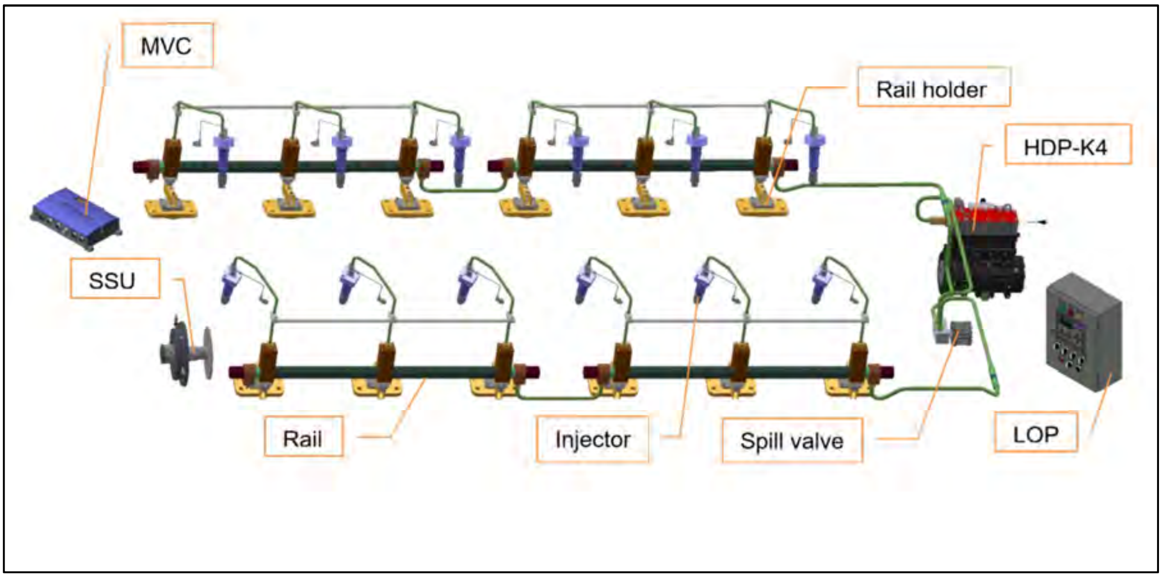


Picture 2: Original governor (left) replaced by HDP-K4 Common-Rail-Fuel-Pump (right)



Picture 3: Engine equipped with original injection pumps (left); New Rail-mounts and fuel-rail (right)

Finally, the system layout could be determined and transferred into CAD to a full model what the new and modified components would look like.



Picture 4: Full 3D-Model including all relevant mechanical components

The installation on the engine replaces the old injection system completely removing all injection pumps from the engine and replacing them with a single high-pressure common-rail-pump (CR-Pump). The fuel is distributed from the CR-Pump to the left and right bank fuel-rails. The fuel-rails are mounted onto rail holders that accept the original bolt pattern from the old injection pumps. The fuel is further distributed from the rails through the injection pipe to the electronically controlled fuel injector.

To regulate the engine speed, the rail-pressure and the sequential injection is controlled via an HEINZMANN MVC01-20. The electronical speed measurement on the engine is done with a pick-up sensor on the crankshaft and an index sensor on the camshaft. During the operation the MVC01 does all important data processing and measurements stand-alone. So even in the event of a communication loss to the engineering the engine can still be operated from a Local Operation Panel without any restrictions.
For remote operation from the engineering control room a communication base is established between the ECU and the ships monitoring system PRAXIS. All vital parameters are controllable directly via PRAXIS during normal service.

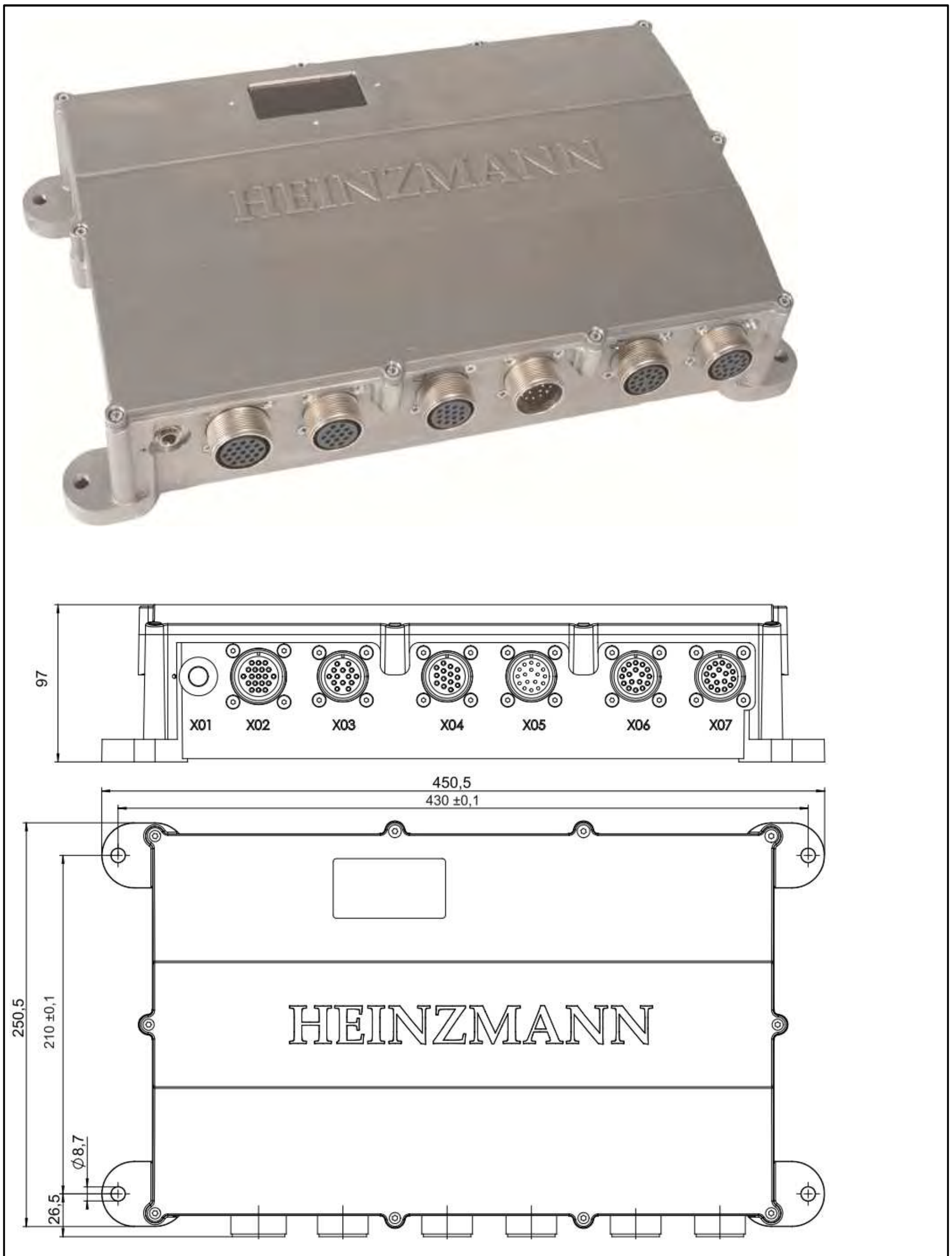
With the components developed to directly fit on the engine the installation and commissioning could be carried out without removing larger parts from the engine. After the commissioning the engine injection system is digitally controlled like on a state-of-the-art engine with full remote control of all vital parameters as well as extended diagnosis functionality but with only a fraction of the cost and ships down-time compared to the exchange of the ships main engines.

Less moving parts also make the system easier to maintain and save cost in labor. As a side effect combustion becomes a lot smoother with an impact on vibration and wear, ultimately easing the load on the complete ship structure.

4. Electronic Control System for Common Rail engine

Common Rail fuel injection system is a state-of-the-art fuel system fully controlled by electronic. An Engine Control Unit (ECU) controls a fuel injectors as well as a High Pressure fuel pump. The ECU collects information from different sensors installed on engine. The information from sensors enables optimising of engine performance depending on power demand, engine operation state and environmental conditions. Additionally, ECU provides enhanced monitoring functionality and reports the errors to the high-level monitoring system.

For the Wärtsila-Pielstick PC 2.2 the Heinzmann ECU “Dardanos I” MVC01-20 is used.



Picture 5: MVC01-20

MVC01-20. Technical data.

General

- Rated voltage — 24VDC
- Min. voltage — 18VDC
- Max. voltage — 32VDC
- Output voltage for injector solenoids — 24V or 48V
- Ambient temperature — -40°C to +80°C
- Vibration — max. 9g at 64 to 2000Hz
- Protection grade — IP65

Inputs and outputs

- CR Injectors outputs (solenoid valve drives, I_{boost} max. 25A): 20
- High-pressure pump outputs (max. 2,5A): 2
- Analogue outputs (0-25mA/0-5V): 2
- Digital (binary) outputs (+24V, max. 3A): 6
- Speed inputs (for Hall type pick-up sensors): 3
- Analogue inputs (0-25mA /0-5V): 4

Interfaces

- 1x RS232 communication for service and calibration
- 2x CAN bus

MVC01-20 is mounted near to the respective engine.

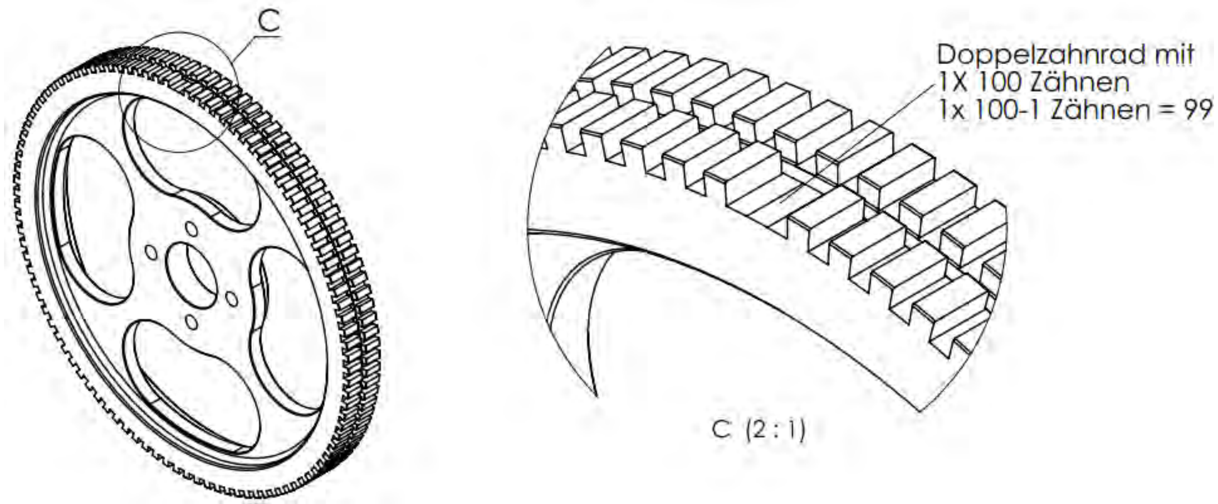
Picture 6: MVC01-20

As CR an electronic controlled system, certain sensors are required for its operation. Following ECU sensors are installed:

- Engine speed/position sensor 1 (main)
- Engine speed/position sensor 2 (backup)
- Cam Index

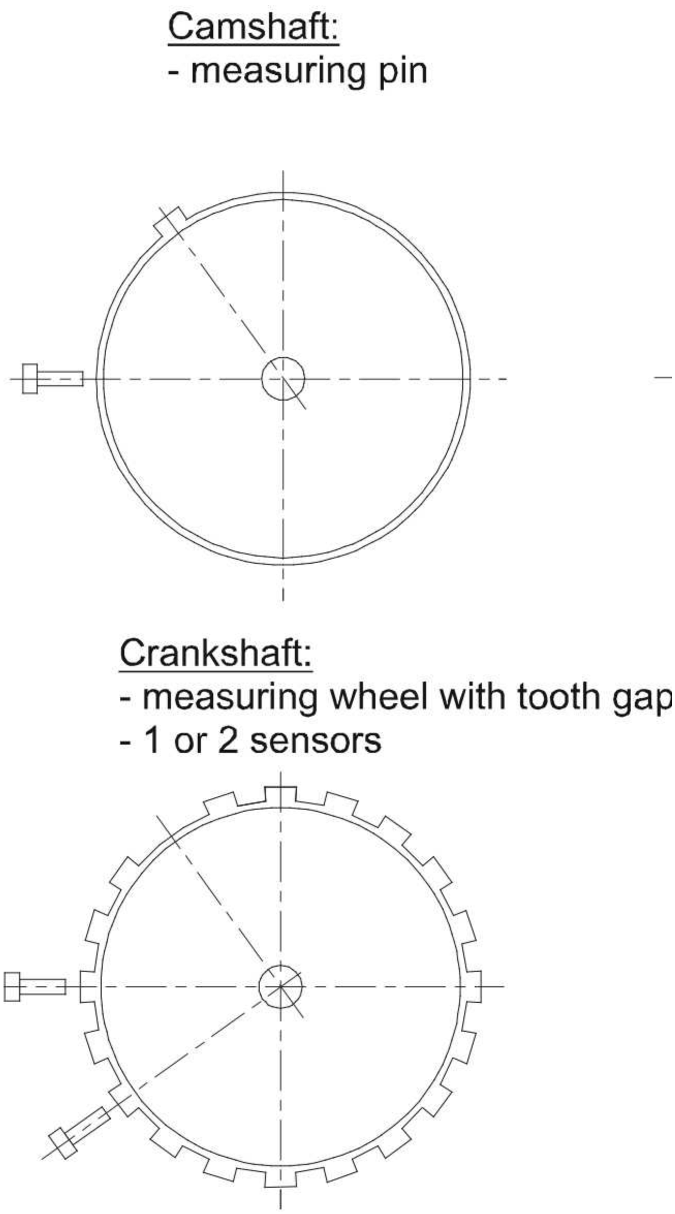
- Rail pressure sensor
- Fuel temperature
- Boost pressure Bank A
- Charge air temperature Bank A
- Boost pressure Bank B
- Charge air temperature Bank B

Measuring of engine speed/position.
For CR system the fuel should be injected at exact piston stroke and at optimal angular position of crank shaft. Therefore a precise measuring of engine speed and position is essential for engine operation. The measuring of engine speed/position occurs by means of special measuring wheel and two pick-up sensors.



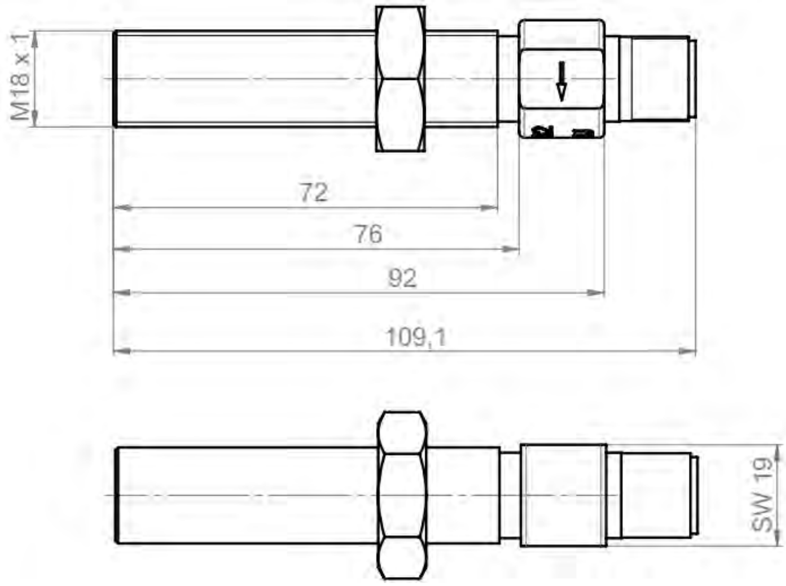
Picture 7: Measuring wheel

The measuring wheel has a double rim with 100 rectangular teeth each. For determination of angular position one tooth is removed from front rim, so-called 100-1 arrangement. The position of this missed tooth (gap) is pre-programmed in the ECU, so when the gap is detected the ECU recognises the exact angular position of crank shaft. The gap is used for verification of tooth detection. Comparing the number of teeth registered per one revolution to the stored number the ECU can detect that all teeth have been captured by pick-up sensor. Otherwise a synchronisation error arises.
As a four-stroke working cycle completes in two revolutions of crank shaft, a measurement wheel mounted on crank shaft would be detected twice during working cycle. Therefore, an additional phase sensor at cam shaft is required.

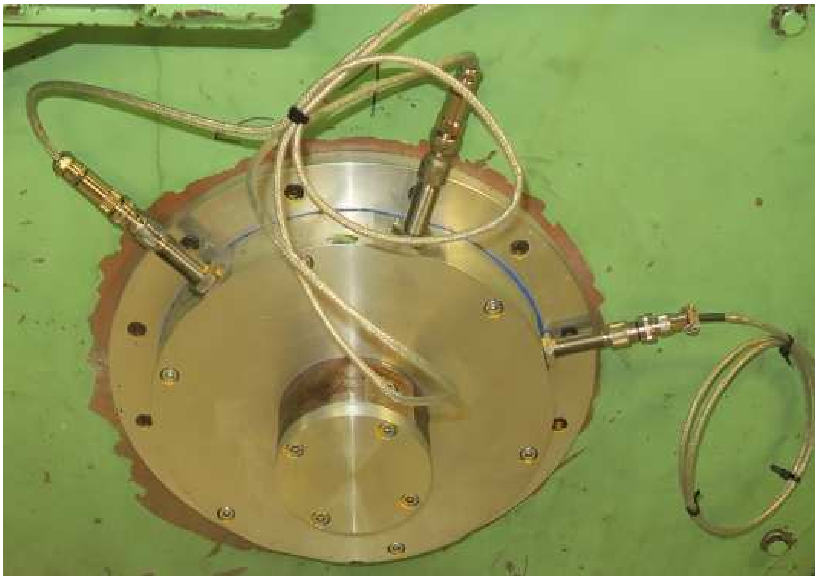


Picture 8: Measuring method speed/position

Second pick-up sensor is installed for a safety backup, in case first sensor fails.
For pick-up 1, pick-up 2 as well for Cam Index (Phase) the Hall-type sensor HIA32-76, HZM Part-No.: 600-00-060-02 is used. The pick-up 1 and pick-up 2 sensors are mounted in the SSU (Speed sensing unit).



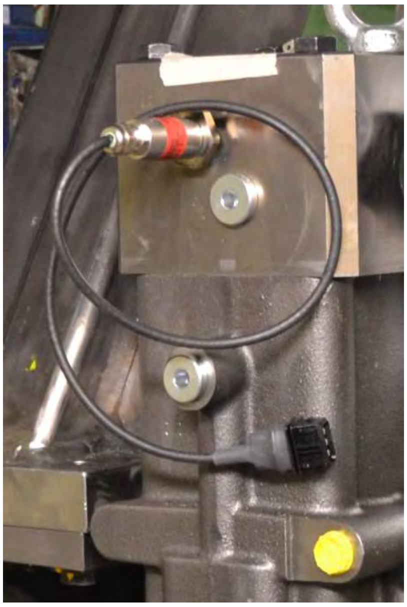
Picture 9: HIA32-76



Picture 10: SSU with Pick-up sensors

Picture 11: Cam Index sensor

Rail pressure sensor.
Rail pressure sensor HZM-No.: 600-00-137-00 with a measuring range 0-2000 bar is mounted in the High-pressure pump (K4). This sensor is essential for an engine operation. The sensor value is used for controlling of Fuel metering unit at K4 pump and therefor a pressure in fuel rail as well as for calculation of opening duration of fuel injectors.



Picture 12: Rail pressure sensor

Fuel temperature sensor.
Fuel temperature sensor HZM-No.: 600-00-053-00 is mounted at pressure control unit at inlet of each High-pressure pump. Sensor value is used in the ECU for calculation of temperature dependant fuel quantity correction as well as for monitoring of fuel feed temperature.

Fuel pressure sensor.
Fuel pressure sensor HZM-No.: 010-80-096-12 with measuring range 0-16 bar is mounted at pressure control unit at inlet of each High-pressure pump. One additional fuel pressure sensor is installed at the outlet of a fuel booster pump. Sensor value is used in monitoring system for monitoring of fuel feed pressure and differential pressure.

Picture 13: Fuel pressure sensor at K4 pump

Picture 14: Fuel pressure sensor at booster pump

Boost pressure sensors.
Two charge air pressure sensors HZM-No.: 600-00-092-00 with measuring range 0-4bar installed per engine. The sensors are mounted at the engine front, parallel to mechanical gages. Sensors 1 and 2 are connected with inlet manifold Bank A and Bank B respectively. Sensor values are used in ECU to calculate a boost pressure dependant fuel limitation, which reduces a smoke emission.

Picture 15: Boost pressure sensor

Charge air temperature sensor.
Two charge air temperature sensors HZM-No.: 600-00-061-00 installed per engine. The sensors are mounted in inlet manifolds after intercooler, one at Bank A and one at Bank B. Sensor values are used for charge air dependent reduction, which prevent too high combustion temperatures and formation of NOx.

Picture 16: Charge air temperature sensor

Emergency Shutdown System (ESS)
An independent safety system for engine protection is provided. The ESS shut down the engine in emergency cases if engine control and monitoring system fails. ESS has its own sensors:

- Engine speed
- Lubrication oil pressure
- Coolant pressure

Once a critical error is being detected ESS triggers an engine switch-off. ESS has two independent ways to stop the engine:

- Send command to ECU to stop a fuel injection.
- Relief the rail pressure by opening a spill valve in a High-pressure system.

Engine switch-off can be activated manually by pressing an emergency shutdown buttons. The ESS is the independent safety system. The hardware base for ESS is the digital control unit DC8.
DC8 technical data:
Power supply

- Redundant supply 2 × 24 V DC (Rated), 18…32V (admissible range)

Inputs / Outputs

- 8 × Digital inputs, (6 isolated);
- 1 × Analogue input, isolated 0…22,7 mA
- 1 × Analogue input, isolates 0..5V / 0..10V
- 3 × Analogue inputs 0..5V/0..10V/0-22,7mA
- 2 × Speed inputs
- 2 × Temperature inputs
- 5 × Digital outputs (3 isolated)
- 1 × Analogue output 0..22mA
- 1 × PWM output

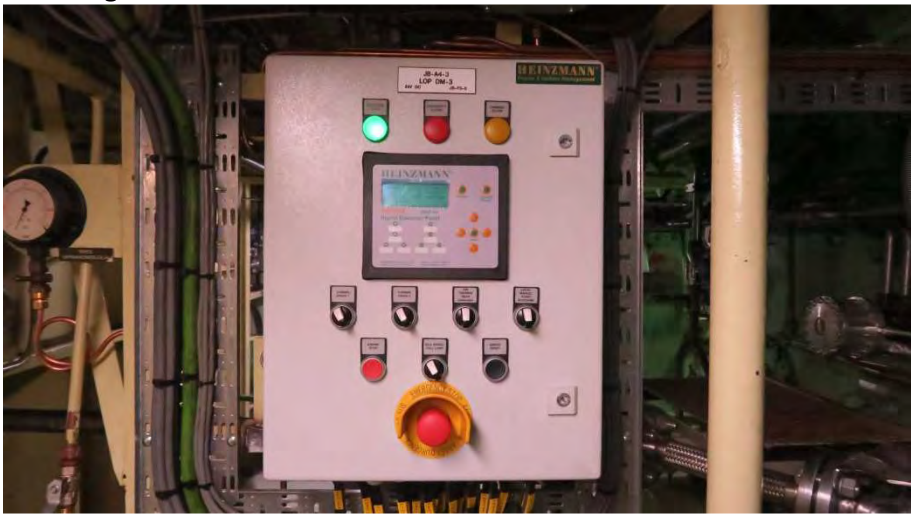
Communication

- 1 × CAN

Local Operating Panel

Local operating panel (LOP) is placed in the immediate vicinity of each engine. The LOP enables to operate the engine from the machine room. The LOP has following controls and indicators on its front:

- Switch “Turbine drain 1”
- Switch “Turbine drain 2”
- Switch “Air turning gear “Close”/”Open”
- Switch “Local manual start blocking”
- Switch “Idle speed/full speed”
- Push button “Error reset”
- Push button “Engine stop”
- Switch “Emergency stop”
- Green light indicator “Governor ready”
- Red light indicator “Emergency alarm”
- Yellow light indicator “ Common alarm”



Picture 17: Local Operating Panel

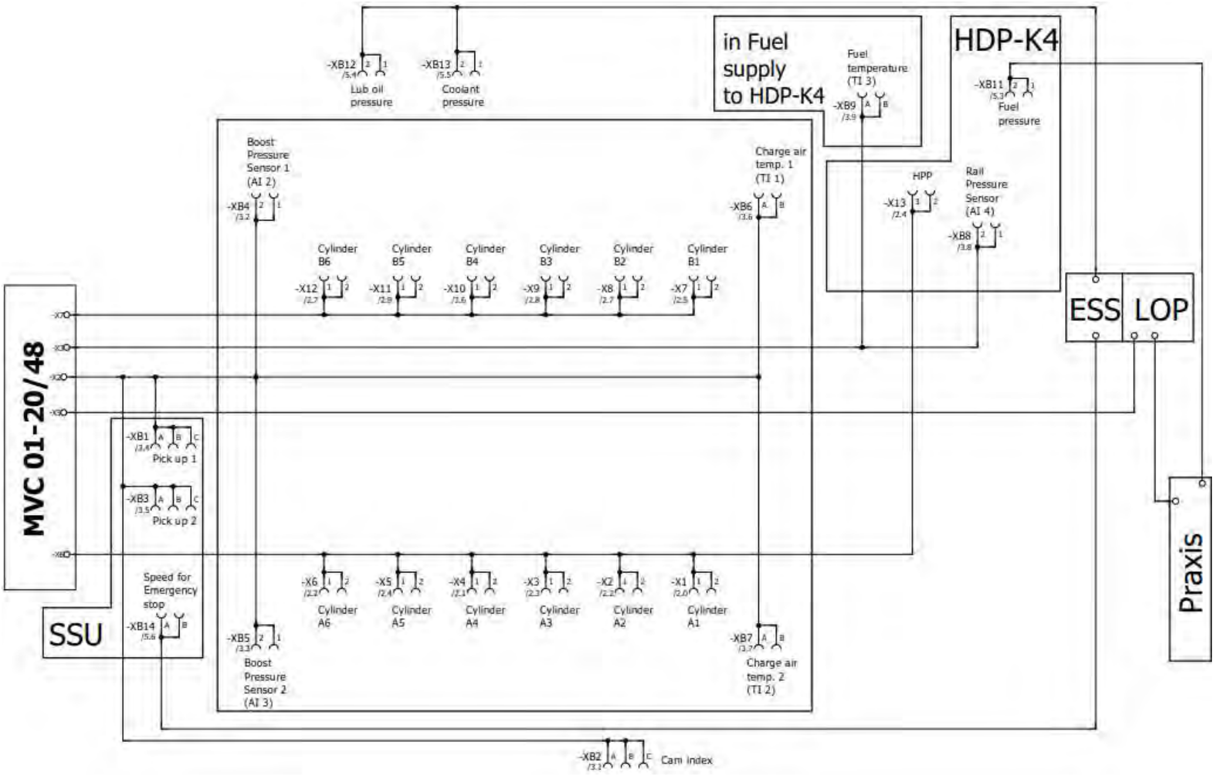
The LOP also includes a HMI, which primary functions are:

- Indication of the operating conditions of diesel engine (engine speed, rail pressure, fuel quantity, errors etc.)
- Display and adjustment of parameters of the engine ECU.

The ESS controller is mounted in the LOP cabinet.

Cable harness.

All controllers, sensors as well as actuators are connected together by means of factory-made cable harness.



Picture 18: Cable harness

Monitoring system “PRAXIS”

Communication with High-level monitoring system „Praxis“

Icebreaker “YMER” is equipped with comprehensive monitoring system. Since CR is an electronic controlled system it is possible to integrate its monitoring functionality into “Praxis” system. The ECU communicates to Praxis via CAN/Modbus Gateway. CAN telegrams from the ECU are being converted to Modbus RTU for Praxis and vice versa.

The ECU can detect appr. 300 errors. They are divided in two groups: common errors and critical errors. If one or several common errors arise the engine can still run, however with some restrictions. If critical error arises, then engine stops immediately. The presence of common and critical errors in the ECU is transferred to Praxis via communication bus.

Besides the error statuses in the ECU and Praxis exchange a number of sensor values and measurements.

From the ECU to Praxis:

- Rail pressure
- Fuel temperature
- Fuel consumption
- Charge air temperature Bank A
- Charge air temperature Bank B
- Boost pressure Bank A
- Boost pressure Bank B

From PRAXIS to MVC:

- Cooling water temperature
- Exhaust gas temperature after cyl. 1…12

Commissioning

After mechanical installation has been completed the CR system was optimised to reach the best engine performance with a fixed speed.

- Rail pressure control circuit has been carefully adjusted to provide best governing quality at any operational conditions.
- Optimization of engine speed governor stability circuit. A basic PID governor for engine speed control has been adjusted. A 3D PID map has been applied over whole speed and load range.
- Multiple injections (pilot and main) have been applied to reduce the NOx emission and mechanical stress.
- 3D map for begin of injection has been applied in order to reduce the fuel consumption and NOx emission.
- 3D map for rail pressure setpoint has been applied in order to reduce smoke and NOx emission and optimize the fuel consumption.

During a see trial the engine performance and emissions were measured based on guidelines MARPOL NTC 2008.

Green Drive

Originally, the main engines operated at constant speed (485rpm) independent of a demanded power. A CR system in conjunction with PROTACON propulsion drive control system provided an opportunity to implement an engine operation with variable speed. The main idea of variable speed is the fact, that a mechanical losses in diesel engine are in direct ration to the engine speed. Providing of demanded power at lower rpm will reduce the mechanical losses and therefore improve a fuel consumption of entire engine. Additionally, the higher load at low rpm normally improves in-cylinder combustion and increase turbocharger performance. This, in turn makes positive impact on engine efficiency. Considering the reasons above the engine operation with variable speed were baptized “GreenDrive”.

For implementing of GreenDrive a 2D curve “drive power over engine speed” has been programmed in PROTACON system. A speed set-point signal 4-20ma connected to MVC. At first, the optimal combinations of begin of injection and the rail pressure have been found at each single load point. Based on these preliminary measurements the 3D maps for begin of injection and rail pressure have been programmed. Then the engine has been run many times over the whole operating range to verify and where necessary optimise the mapping. Though engines are slightly different, we succeeded to unify an ECU parameter sets (calibration) for all five main engines. When the engine performance and emissions were measured anew with GreenDrive and fixed speed. The measurements proved lower fuel consumption with GreenDrive without impairing the NOx and soot emission.

5. Results from field tests

During a test period over two winter seasons from 2016 onwards comprehensive measurements regarding the evaluation criteria were taken under realistic harsh operating conditions.

Received results:

Soot: No visible smoke under all operating conditions. Smoke number < 0,4 FSN

NOx: After turbocharger retrofit on a level of IMO Tier 1

HC: No significant reduction. HC was already low. Mainly caused by lube oil.

Fuel saving: > 11 % in total related to the typical operating profile (including effects from turbocharger retrofit and variable speed operation).

Lube oil saving: 50 %; mainly due to variable speed mode.

Reduction of noise and vibration: 30 % due to cylinder balancing and multiple injection.

Reduction of soot deposits in the exhaust duct: Existing deposits disappeared after a while completely.

6. Conclusions

This challenging project has clearly shown that even old Diesel engines have a good potential to improve the main operating criteria regarding performance, fuel consumption and emissions with a fuel system retrofit to Common Rail. Especially under variable load conditions a remarkable fuel saving can be achieved. Further the converted engines show a clear reduction regarding harmful and climate relevant emissions. Improvements were also seen in the transient behaviour especially under harsh operating conditions with very dynamic load profiles. Improvements can be achieved also on the comfort side regarding vibration and noise. In addition, the maintenance efforts can be reduced significantly.
For an engine retrofit with Common Rail it is recommended to retrofit the turbocharger also. This will benefit in a clear additional fuel saving as part of a complete retrofit solution in emission levels in the range of IMO Tier 1 without exhaust gas after-treatment.
Compared to an engine replacement the retrofit of the engines fuel injection system and combined with a turbo charger upgrade is a very cost effective alternative with sufficient potential to meet performance, fuel consumption and emission targets.

7. Final remarks

HEINZMANN want to express that the very good cooperation and the support from customer side was highly appreciated. Particularly the responsible project manager and the entire crew have always shown big interest and a high level competence during the project phase and contributed their part to the very good success of this engine retrofit.

The main targets of the given specifications were met regarding to smoke emission and fuel consumption. NOx emissions were reduced mainly by a turbocharger retrofit. Due to the injection quantity balancing and the injection characteristics the combustion process is more smooth now resulting in lower vibration, lower noise and lower load on the engine components leading to lower wear and increased service intervals and lifetime.

During the test period over several years the Common Rail retrofit solution matured to a highly reliable and efficient state of the art fuel system for the PC 2.2 engine.

The well adapted HEINZMANN Common Rail system is ready now to be installed on the sister vessels of the YMER. HEINZMANN is looking forward to the further cooperation with the Swedish Marine Administration even with new innovative engine control solutions.

8. Appendix / Final test Reports

Complete final test reports for all 5 engines are attached.

The final measurements were performed mid of December 2017 after completion of the commissioning works for all engines.

Up to now the converted engines are operated over two winter seasons.

IB Ymer

Conversion of the fuel injection system on the Main Engine 1 (ME1)

Emission Test Report

1 Application

Ship	
Name of ship	YMER
Homeport	Luleå - Sweden
Type of ship	Icebreaker

2 Engine information

Engine	S.E.M.T. – Pielstick	
Manufacturer	Wärtsilä	
Engine type	12PC2.2V	
Engine family	PC	
Serial number	370	
Main engine number on board	ME1	
Rated speed [rpm]	485	
Electronic injection control	No:	Yes: ☑
Variable injection time	No:	Yes: ☑
Bore	400 mm	
Stroke	460 mm	
Cylinder number and configuration	No.: 12	V: ☑ In-line:

3 Engine family information

Engine family/engine group information (common specifications)		
Combustion cycle	2-stroke	4-stroke ☑
Cooling medium	Water	
Method of aspiration	turbo charged (ABB304)	
Fuel type to be used on board	Diesel fuel oil DM grade ISO 8217:2005	
Combustion chamber	Open combustion chamber	
Fuel system type	Common rail system	

4 Test cell information

Gaseous components analyser	
Manufacturer	Testo SE & Co. KGaA
Model	testo 350 MARITIME
Serial no.	60378450
Order no.	0632351050504
Date of calibration	04/2017
Probe location	Approx. 3 meter behind turbochargers in the very centre of exhaust pipe

Inlet fuel oil flow meter	
Manufacturer	Emerson electric Co.
Sensor	Micro motion Flow Meter F050S F50S172C2FMEZZZZ
Serial No.	14393357
Transmitter	Micro Motion Transmitter 2700R 2700R12AFMEZZX
Serial No.	3836062
Date of calibration	
Probe location	In the fuel oil supply line to the engine
Return fuel oil flow meter	
Manufacturer	Emerson electric Co.
Sensor	Micro motion Flow Meter F050S F50S172C2FMEZZZZ
Serial No.	14397846
Transmitter	Micro Motion Transmitter 2700R 2700R12AFMEZZX
Serial No.	3837120
Date of calibration	
Probe location	In the fuel oil return line from the engine

Engine power measurement	
Manufacturer	Protacon Marine
Model	IB Ymer, Propulsion control
Probe location	Armature current of propulsion generators resp. propeller motors

5 Fuel characteristics

Fuel type		
Manufacturer	ST1 Refinery AB, Göteborg, Sweden	
Product name	Gasoil E10	
Specification	2012-02-28 Utg:2	
Sample ID	173115	
fuel properties (Extract from Test report dated 2016-06-29)		
Property	Test Method	Results
Cetane index	SS-EN ISO 4264	51,8
Density at 15°C	SS-EN ISO 12185	0,8485 kg/l
Gross heat of combustion	SS 15 51 38	45,57 MJ/kg
Viscosity at 40°C	SS-EN ISO 3104	3,663 mm^2/s
Sulphur	SS-EN ISO 20846	277 mg/kg

6 Converting of exhaust gas emission concentrations

Exhaust mass flow

$$q_{mew} = q_{mf} \cdot (1 + \lambda \cdot 14{,}545)$$

where:

q_{mf} – fuel oil mass flow, kg/h
λ – excess air factor: kg dry air/(kg fuel · A/F_{st})
14,545 – stoichiometric air to fuel ratio for diesel (A/F_{st}=1)

Excess air factor

$$\lambda = \frac{20{,}95}{20{,}95 - O_2\%}$$

where:

20,95 - concentration of O_2 in the inlet air, %
O_2% - concentration of O_2 in the exhaust gas, %

Humidity of intake air

$$H_a = \frac{6.22 \cdot p_a \cdot R_a}{p_b - 0.01 \cdot R_a \cdot p_a}$$

(9) §5.12.3 NTC2008

where:

R_a – relative humidity of the intake air, %
P_b – total barometric pressure, kPa
p_a – saturation vapour pressure of intake air, kPa

$$p_a = (4.856884 + 0.2660089 \cdot t_a + 0.01688919 \cdot t_a^2 - 7.477123 \cdot 10^{-5} \cdot t_a^3 + 8.10525 \cdot 10^{-6} \cdot t_a^4 - 3.115221 \cdot 10^{-8} \cdot t_a^5) \cdot \frac{101.32}{760}$$

(10) §5.12.3 NTC2008

with:

t_a – temperature of intake air, °C

Humidity correction factor for NOx

$$k_{hd} = \frac{1}{1 - 0.012 \cdot (H_a - 10.71) - 0.00275 \cdot (T_a - 298) + 0.00285 \cdot (T_{SC} - T_{SCRef})}$$

(17) §5.12.4 NTC2008

where:

T_{SC} – temperature of the charge air, °C
T_{SCRef} – temperature of the charge air at each mode point corresponding to a seawater temperature of 25°C, °C
H_a – humidity of the intake air at the inlet to the air filter in g water per kg dry air
T_a – temperature of the air at the inlet to the air filter in °K

To take the humidity in the charge air into account, the following consideration is added:

H_{SC} – humidity of the charge air, g water per kg dry air in which:

$$H_{SC} = \frac{6.22 \cdot p_{SC} \cdot 100}{p_c - p_{SC}}$$

where:

p_{SC} – saturation vapour pressure of the charge air, kPa

p_c – charge air pressure, kPa

However if $H_a \geq H_{SC}$, then H_{SC} shall be used in place of H_a in formula for k_{hd}

NOx emission mass flow rate

$$q_{mNOx} = u_{NOx} \cdot c_{NOx} \cdot q_{mew} \cdot k_{hd}$$

(18) §5.12.5 NTC2008

where:

q_{mNOx} – NOx emission mass flow rate, g/h

u_{NOx} – ratio between density of NOx and density of exhaust gas = 0,001586, (see Table 5 §5.12.5 NTC2008)

c_{NOx} – concentration of NOx in the raw exhaust gas, ppm, wet

q_{mew} – exhaust mass flow, kg/h, wet

k_{hd} – NOx humidity correction factor

Average weighted NOx emission

$$NOx = \frac{\sum_{i=1}^{n}(q_{mNOx} \cdot W_{Fi})}{\sum_{i=1}^{n}(P_i \cdot W_{Fi})}$$

(19) §5.12.6.1 NTC2008

where:

$P = P_{Gen}/0{,}95$

and

q_{mNOx} – NOx mass mass flow, g/h

W_{Fi} – Weighting factor of individual mode

P_{Gen} – measured power of propulsion generator of the individual mode, kW

0,95 – efficiency factor of propulsion generator

7 Engine test data

7.1 Constant speed operation

Table 1 – Constant speed operation

Mode point	1	2	3	4
Time at beginning of mode	19:02	17:18	17:08	17:25
Date	10.05.2017	10.05.2017	10.05.2017	10.05.2017
Power, %	25	50	75	100
Measured data				
Generator power P_{Gen}, kW	879	1740	2613	3454
Engine speed n, rpm	485	485	485	485
Fuel oil flow, kg/h	218,2	392,5	557,7	766,4
Emission concentrations in the exhaust gas				
O_2,%	16,82	15,73	15,12	14,01
NO_x, ppm	341	522	810	835
Calculated data				
Engine power, kW	923	1827	2744	3627
Excess air factor λ	5,073	4,013	3,593	3,019
exhaust mass flow q_{mew}, kg/h	16317,33	23304,71	29707,11	34417,07
Humidity of intake air H_a, g/kg	3,3168	3,3168	3,3168	3,3168
NOx correction factor k_{hd}	0,89334	0,90276	0,92125	0,94001
NO_x emission mass flow rate q_{mNOx}, g/h	7883,59	17417,75	35158,28	42844,61
Weighting factor according to E2 test cycle (ISO 8178)	0,15	0,15	0,5	0,2
Average weighted NOx emission, g/kWh	11,93			
Additional engine test data				
Efficiency/SFOC, g/kWh	236	215	203	211
Injection timing, °BTDC	7,5	6,4	8,1	6,0
Charge air pressure Bank A, bar rel.	0,24	0,62	1,02	1,31
Charge air pressure Bank B, bar rel.	0,24	0,62	1,03	1,36
Charge air temperature Bank A, °C	30,5	36,4	38,6	41
Charge air temperature Bank B, °C	33	40	43,7	48,7
Reference temperature of charge air T_{SCRef}, °C [1)]	40	50	60	70
Pressure in the fuel rail, bar	800	932	1103	1197
Average exhaust gas	251	295	322	394

temperature, °C				

Table 1 (continued)

Environmental conditions [2)]				
Temperature of intake air, °C	4	4	4	4
Relative humidity of intake air, %	65	65	65	65
Total barometric pressure, kPa	101,1	101,1	101,1	101,1

1) estimation, as manufacturer specification not available

2) for Lulea / Kallax (CustomWeather Inc.)

7.2 Variable speed operation

Table 2 – variable speed operation

Mode point	1	2	3	4
Time at beginning of mode	18:50	18:10	16:59	17:25
Date	10.05.2017	10.05.2017	10.05.2017	10.05.2017
Power, %	25	50	75	100
Measured data				
Generator power P_{Gen}, kW	879	1739	2613	3454
Engine speed n, rpm	360	365	452	485
Fuel oil flow, kg/h	206,7	389,4	558,2	766,4
Emission concentrations in the exhaust gas				
O_2,%	16,21	14,61	14,94	14,01
NO_x, ppm	470	638	768	835
Calculated data				
Engine power, kW	923	1826	2744	3627
Excess air factor λ	4,420	3,304	3,486	3,019
exhaust mass flow q_{mew}, kg/h	13494,71	19105,03	28859,94	34417,07
Humidity of intake air H_a, g/kg	3,3168	3,3168	3,3168	3,3168
NOx correction factor k_{hd}	0,89448	0,90603	1,02515	0,94001
NO_x emission mass flow rate q_{mNOx}, g/h	8997,77	17515,13	36036,84	42844,61
Weighting factor according to E2 test cycle (ISO 8178)	0,15	0,15	0,5	0,2
Average weighted NOx emission, g/kWh	12,18			
Additional engine test data				
Efficiency/SFOC, g/kWh	224	213	203	211
Injection timing, °BTDC	3,8	1,6	n.a.	6,0
Charge air pressure Bank A, bar rel.	0,19	0,55	n.a.	1,31
Charge air pressure Bank B, bar rel.	0,19	0,56	n.a.	1,36
Charge air temperature Bank A, °C	30	35	n.a.	41
Charge air temperature Bank B, °C	32	37	n.a.	48,7
Reference temperature of charge air T_{SCRef}, °C [1)]	40	50	60	70
Pressure in the fuel rail, bar	680	733	n.a.	1197
Average exhaust gas temperature, °C	252	331	n.a.	394

Table 2 (continued)

Environmental conditions [2]				
Temperature of intake air, °C	4	4	4	4
Relative humidity of intake air, %	65	65	65	65
Total barometric pressure, kPa	101,1	101,1	101,1	101,1

1) estimation, as manufacturer specification not available

2) for Lulea / Kallax (CustomWeather Inc.)

8 NOx emission limit

The NOx emission limit is calculated according to §3.2 (Tier I) of Regulation 13, MARPOL ANNEX VI.

Total weighted emission of NO_2 should be within the following limits:

$45 \bullet n^{(-0,2)}$, g/kWh,

where n = rated engine speed (crankshaft revolution per minute).

Manufacturer	S.E.M.T. – Pielstick (Wärtsilä)
Engine type	12PC2.2V
Engine family	PC
Rated speed [rpm]	485
Tier I NOx emission limit	13,06 g/kWh

9 Test results

The results of the emission tests conducted according to §§4-6 for the engine described in §§1-3 under conditions prevailing at the time of the test run §7 are presented at the table 3.

Table 3 – Emission test results

Total weighted emission of NO_x	Results
Tier I limit (§8)	13,06 g/kWh
Constant speed operation (§7.1)	11,93 g/kWh
Variable speed operation (§7.2)	12,18 g/kWh

Schönau, 18 December 2017

Vasily Leytes
Project engineer EFI

Walter Burow
Chief technology officer

IB Ymer

Conversion of the fuel injection system on the Main Engine 2 (ME2) Emission Test Report

1 Application

Ship	
Name of ship	YMER
Homeport	Luleå - Sweden
Type of ship	Icebreaker

2 Engine information

Engine	S.E.M.T. – Pielstick		
Manufacturer	Wärtsilä		
Engine type	12PC2.2V		
Engine family	PC		
Serial number	367		
Main engine number on board	ME2		
Rated speed, rpm	485		
Rated power, bhp	5000 (3677 kW)		
Electronic injection control	No:	Yes: ☑	
Variable injection time	No:	Yes: ☑	
Bore	400 mm		
Stroke	460 mm		
Cylinder number and configuration	No.: 12	V: ☑	In-line:

3 Engine family information

Engine family/engine group information (common specifications)		
Combustion cycle	2-stroke	4-stroke ☑
Cooling medium	Water	
Method of aspiration	turbo charged (ABB304)	
Fuel type to be used on board	Diesel fuel oil DM grade ISO 8217:2005	
Combustion chamber	Open combustion chamber	
Fuel system type	Common rail system	

4 Test cell information

Gaseous components analyser	
Manufacturer	Testo SE & Co. KGaA
Model	testo 350 MARITIME
Serial no.	60378450
Order no.	0632351050504
Date of calibration	04/2017
Probe location	Approx. 3 meter behind turbochargers in the very centre of exhaust pipe

Inlet fuel oil flow meter	
Manufacturer	Emerson electric Co.
Sensor	Micro motion Flow Meter F050S F50S172C2FMEZZZZ
Serial No.	14393357
Transmitter	Micro Motion Transmitter 2700R 2700R12AFMEZZX
Serial No.	3836062
Date of calibration	
Probe location	In the fuel oil supply line to the engine
Return fuel oil flow meter	
Manufacturer	Emerson electric Co.
Sensor	Micro motion Flow Meter F050S F50S172C2FMEZZZZ
Serial No.	14397846
Transmitter	Micro Motion Transmitter 2700R 2700R12AFMEZZX
Serial No.	3837120
Date of calibration	
Probe location	In the fuel oil return line from the engine

Engine power measurement	
Manufacturer	Protacon Marine
Model	IB Ymer, Propulsion control
Probe location	Armature current of propulsion generators resp. propeller motors

5 Fuel characteristics

Fuel type		
Manufacturer	ST1 Refinery AB, Göteborg, Sweden	
Product name	Gasoil E10	
Specification	2012-02-28 Utg:2	
Sample ID	173115	
fuel properties (Extract from Test report dated 2016-06-29)		
Property	Test Method	Results
Cetane index	SS-EN ISO 4264	51,8
Density at 15°C	SS-EN ISO 12185	0,8485 kg/l
Gross heat of combustion	SS 15 51 38	45,57 MJ/kg
Viscosity at 40°C	SS-EN ISO 3104	3,663 mm^2/s
Sulphur	SS-EN ISO 20846	277 mg/kg

6 Converting of exhaust gas emission concentrations

Exhaust mass flow

$$q_{mew} = q_{mf} \cdot (1 + \lambda \cdot 14{,}545)$$

where:

q_{mf} – fuel oil mass flow, kg/h
λ – excess air factor: kg dry air/(kg fuel · A/F_{st})
14,545 – stoichiometric air to fuel ratio for diesel (A/F_{st}=1)

Excess air factor

$$\lambda = \frac{20{,}95}{20{,}95 - O_2\%}$$

where:

20,95 - concentration of O_2 in the inlet air, %
O_2% - concentration of O_2 in the exhaust gas, %

Humidity of intake air

$$H_a = \frac{6.22 \cdot p_a \cdot R_a}{p_b - 0.01 \cdot R_a \cdot p_a}$$

(9) §5.12.3 NTC2008

where:

R_a – relative humidity of the intake air, %
P_b – total barometric pressure, kPa
p_a – saturation vapour pressure of intake air, kPa

$$p_a = (4.856884 + 0.2660089 \cdot t_a + 0.01688919 \cdot t_a^2 - 7.477123 \cdot 10^{-5} \cdot t_a^3 + 8.10525 \cdot 10^{-6} \cdot t_a^4 - 3.115221 \cdot 10^{-8} \cdot t_a^5) \cdot \frac{101.32}{760}$$

(10) §5.12.3 NTC2008

with:

t_a – temperature of intake air, °C

humidity correction factor for NOx

$$k_{hd} = \frac{1}{1 - 0.012 \cdot (H_a - 10.71) - 0.00275 \cdot (T_a - 298) + 0.00285 \cdot (T_{SC} - T_{SCRef})}$$

(17) §5.12.4 NTC2008

where:

T_{SC} – temperature of the charge air, °C
T_{SCRef} – temperature of the charge air at each mode point corresponding to a seawater temperature of 25°C, °C
H_a – humidity of the intake air at the inlet to the air filter in g water per kg dry air
T_a – temperature of the air at the inlet to the air filter in °K

To take the humidity in the charge air into account, the following consideration is added:

H_{SC} – humidity of the charge air, g water per kg dry air in which:

$$H_{SC} = \frac{6.22 \cdot p_{SC} \cdot 100}{p_c - p_{SC}}$$

where:

p_{SC} – saturation vapour pressure of the charge air, kPa

p_c – charge air pressure, kPa

However if $H_a \geq H_{SC}$, then H_{SC} shall be used in place of H_a in formula for k_{hd}

NOx emission mass flow rate

$$q_{mNOx} = u_{NOx} \cdot c_{NOx} \cdot q_{mew} \cdot k_{hd}$$

(18) §5.12.5 NTC2008

where:

q_{mNOx} – NOx emission mass flow rate, g/h

u_{NOx} – ratio between density of NOx and density of exhaust gas = 0,001586, (see Table 5 §5.12.5 NTC2008)

c_{NOx} – concentration of NOx in the raw exhaust gas, ppm, wet

q_{mew} – exhaust mass flow, kg/h, wet

k_{hd} – NOx humidity correction factor

Average weighted NOx emission

$$NOx = \frac{\sum_{i=1}^{n}(q_{mNOx} \cdot W_{Fi})}{\sum_{i=1}^{n}(P_i \cdot W_{Fi})}$$

(19) §5.12.6.1 NTC2008

where:

$P = P_{Gen}/0,95$

and

q_{mNOx} – NOx mass mass flow, g/h

W_{Fi} – Weighting factor of individual mode

P_{Gen} – measured power of propulsion generator of the individual mode, kW

0,95 – efficiency factor of propulsion generator

7 Engine test data

7.1 Constant speed operation

Table 1 – Constant speed operation

Mode point	1	2	3	4
Time at beginning of mode	10:04	09:42	09:36	09:20
Date	11.05.2017	11.05.2017	11.05.2017	11.05.2017
Power, %	25	50	75	100
Measured data				
Generator power P_{Gen}, kW	869	1747	2621	3422
Engine speed n, rpm	485	485	485	485
Fuel oil flow, kg/h	218,05	396,5	566,7	756
Emission concentrations in the exhaust gas				
O_2,%	16,86	15,82	15,24	14,46
NO_x, ppm	352	548	804	862
Calculated data				
Engine power, kW	912,45	1834,35	2752,05	3593,1
Excess air factor λ	5,12	4,08	3,67	3,23
exhaust mass flow q_{mew}, kg/h	16463,45	23948,27	30809,00	36251,63
Humidity of intake air H_a, g/kg	2,7786	2,7786	2,7786	2,7786
NOx correction factor k_{hd}	0,88279	0,89632	0,91502	0,93451
NO_x emission mass flow rate q_{mNOx}, g/h	8113,771	18656,054	35947,272	46315,172
Weighting factor according to E2 test cycle (ISO 8178)	0,15	0,15	0,5	0,2
Average weighted NOx emission, g/kWh	12,47			
Additional engine test data				
Efficiency/SFOC, g/kWh	239	216	206	210
Injection timing, °BTDC	7,5	6,31	8	6,6
Charge air pressure Bank A, bar rel.	0,24	0,63	1,06	1,42
Charge air pressure Bank B, bar rel.	0,25	0,66	1,07	1,53
Charge air temperature Bank A, °C	31	35	37	39
Charge air temperature Bank B, °C	31	36	37	42
Reference temperature of charge air T_{SCRef}, °C [1)]	40	50	60	70
Pressure in the fuel rail, bar	800	938	1104	1198
Average exhaust gas	248	295	321	358

Co-financed by the Connecting Europe Facility of the European Union

temperature, °C				

Table 1 (continued)

Environmental conditions [2]				
Temperature of intake air, °C	2	2	2	2
Relative humidity of intake air, %	62	62	62	62
Total barometric pressure, kPa	101,4	101,4	101,4	101,4

1) estimation, as manufacturer specification not available

2) for Lulea / Kallax (CustomWeather Inc.)

7.2 Variable speed operation

Table 2 – variable speed operation

Mode point	1	2	3	4
Time at beginning of mode	09:59	09:47	09:28	09:20
Date	11.05.2017	11.05.2017	11.05.2017	11.05.2017
Power, %	25	50	75	100
Measured data				
Generator power P_{Gen}, kW	869	1747	2621	3422
Engine speed n, rpm	360	365	452	485
Fuel oil flow, kg/h	206,9	396,7	567	756
Emission concentrations in the exhaust gas				
O_2,%	16,21	14,62	15,07	14,46
NO_x, ppm	503	674	778	862
Calculated data				
Engine power, kW	912,45	1834,35	2752,05	3593,1
Excess air factor λ	4,42	3,31	3,56	3,23
exhaust mass flow q_{mew}, kg/h	13507,77	19493,31	29950,50	36251,63
Humidity of intake air H_a, g/kg	2,7786	2,7786	2,7786	2,7786
NOx correction factor k_{hd}	0,88279	0,89632	0,91502	0,93451
NO_x emission mass flow rate q_{mNOx}, g/h	9512,849	18677,145	33815,506	46315,172
Weighting factor according to E2 test cycle (ISO 8178)	0,15	0,15	0,5	0,2
Average weighted NOx emission, g/kWh	12,13			
Additional engine test data				
Efficiency/SFOC, g/kWh	227	216	206	210
Injection timing, °BTDC	3,8	1	7,6	6,6
Charge air pressure Bank A, bar rel.	0,19	0,58	1,07	1,42
Charge air pressure Bank B, bar rel.	0,2	0,59	1,07	1,53
Charge air temperature Bank A, °C	31	36	37	39
Charge air temperature Bank B, °C	31	35	42	42
Reference temperature of charge air T_{SCRef}, °C [1)]	40	50	60	70
Pressure in the fuel rail, bar	680	735	950	1198
Average exhaust gas temperature, °C	255	332	331	358

Table 2 (continued)

Environmental conditions [2)]				
Temperature of intake air, °C	2	2	2	2
Relative humidity of intake air, %	62	62	62	62
Total barometric pressure, kPa	101,4	101,4	101,4	101,4

1) estimation, as manufacturer specification not available

2) for Lulea / Kallax (CustomWeather Inc.)

8 NOx emission limit

The NOx emission limit is calculated according to §3.2 (Tier I) of Regulation 13, MARPOL ANNEX VI.

Total weighted emission of NO_2 should be within the following limits:

$45 \bullet n^{(-0,2)}$, g/kWh,

where n = rated engine speed (crankshaft revolution per minute).

Manufacturer	S.E.M.T. – Pielstick (Wärtsilä)
Engine type	12PC2.2V
Engine family	PC
Rated speed [rpm]	485
Tier I NOx emission limit	13,06 g/kWh

9 Test results

The results of the emission tests conducted according to §§4-6 for the engine described in §§1-3 under conditions prevailing at the time of the test run §7 are presented at the table 3.

Table 3 – Emission test results

Total weighted emission of NO_x	Results
Tier I limit (§8)	13,06 g/kWh
Constant speed operation (§7.1)	12,47 g/kWh
Variable speed operation (§7.2)	12,13 g/kWh

Schönau, 18 December 2017

Vasily Leytes
Project engineer EFI

Walter Burow
Chief technology officer

IB Ymer

Conversion of the fuel injection system

on the Main Engine 3 (ME3)

Emission Test Report

1 Application

Ship	
Name of ship	YMER
Homeport	Luleå - Sweden
Type of ship	Icebreaker

2 Engine information

Engine	S.E.M.T. – Pielstick		
Manufacturer	Wärtsilä		
Engine type	12PC2.2V		
Engine family	PC		
Serial number	368		
Main engine number on board	ME3		
Rated speed, rpm	485		
Rated power, bhp	5000 (3677 kW)		
Electronic injection control	No:	Yes: ☑	
Variable injection time	No:	Yes: ☑	
Bore	400 mm		
Stroke	460 mm		
Cylinder number and configuration	No.: 12	V: ☑	In-line:

3 Engine family information

Engine family/engine group information (common specifications)		
Combustion cycle	2-stroke	4-stroke ☑
Cooling medium	Water	
Method of aspiration	turbo charged (ABB304)	
Fuel type to be used on board	Diesel fuel oil DM grade ISO 8217:2005	
Combustion chamber	Open combustion chamber	
Fuel system type	Common rail system	

4 Test cell information

Gaseous components analyser	
Manufacturer	Testo SE & Co. KGaA
Model	testo 350 MARITIME
Serial no.	60378450
Order no.	0632351050504
Date of calibration	04/2017
Probe location	Approx. 3 meter behind turbochargers in the very centre of exhaust pipe

Inlet fuel oil flow meter	
Manufacturer	Emerson electric Co.
Sensor	Micro motion Flow Meter F050S F50S172C2FMEZZZZ
Serial No.	14393357
Transmitter	Micro Motion Transmitter 2700R 2700R12AFMEZZX
Serial No.	3836062
Date of calibration	
Probe location	In the fuel oil supply line to the engine
Return fuel oil flow meter	
Manufacturer	Emerson electric Co.
Sensor	Micro motion Flow Meter F050S F50S172C2FMEZZZZ
Serial No.	14397846
Transmitter	Micro Motion Transmitter 2700R 2700R12AFMEZZX
Serial No.	3837120
Date of calibration	
Probe location	In the fuel oil return line from the engine

Engine power measurement	
Manufacturer	Protacon Marine
Model	IB Ymer, Propulsion control
Probe location	Armature current of propulsion generators resp. propeller motors

5 Fuel characteristics

Fuel type		
Manufacturer	ST1 Refinery AB, Göteborg, Sweden	
Product name	Gasoil E10	
Specification	2012-02-28 Utg:2	
Sample ID	173115	
fuel properties (Extract from Test report dated 2016-06-29)		
Property	Test Method	Results
Cetane index	SS-EN ISO 4264	51,8
Density at 15°C	SS-EN ISO 12185	0,8485 kg/l
Gross heat of combustion	SS 15 51 38	45,57 MJ/kg
Viscosity at 40°C	SS-EN ISO 3104	3,663 mm^2/s
Sulphur	SS-EN ISO 20846	277 mg/kg

6 Converting of exhaust gas emission concentrations

Exhaust mass flow

$$q_{mew} = q_{mf} \cdot (1 + \lambda \cdot 14{,}545)$$

where:

q_{mf} – fuel oil mass flow, kg/h
λ – excess air factor: kg dry air/(kg fuel · A/F_{st})
14,545 – stoichiometric air to fuel ratio for diesel (A/F_{st}=1)

Excess air factor

$$\lambda = \frac{20{,}95}{20{,}95 - O_2\%}$$

where:

20,95 - concentration of O_2 in the inlet air, %
O_2% - concentration of O_2 in the exhaust gas, %

Humidity of intake air

$$H_a = \frac{6.22 \cdot p_a \cdot R_a}{p_b - 0.01 \cdot R_a \cdot p_a}$$

(9) §5.12.3 NTC2008

where:

R_a – relative humidity of the intake air, %
P_b – total barometric pressure, kPa
p_a – saturation vapour pressure of intake air, kPa

$$p_a = (4.856884 + 0.2660089 \cdot t_a + 0.01688919 \cdot t_a^2 - 7.477123 \cdot 10^{-5} \cdot t_a^3 + 8.10525 \cdot 10^{-6} \cdot t_a^4 - 3.115221 \cdot 10^{-8} \cdot t_a^5) \cdot \frac{101.32}{760}$$

(10) §5.12.3 NTC2008

with:

t_a – temperature of intake air, °C

humidity correction factor for NOx

$$k_{hd} = \frac{1}{1 - 0.012 \cdot (H_a - 10.71) - 0.00275 \cdot (T_a - 298) + 0.00285 \cdot (T_{SC} - T_{SCRef})}$$

(17) §5.12.4 NTC2008

where:

T_{SC} – temperature of the charge air, °C
T_{SCRef} – temperature of the charge air at each mode point corresponding to a seawater temperature of 25°C, °C
H_a – humidity of the intake air at the inlet to the air filter in g water per kg dry air
T_a – temperature of the air at the inlet to the air filter in °K

To take the humidity in the charge air into account, the following consideration is added:

H_{SC} – humidity of the charge air, g water per kg dry air in which:

$$H_{SC} = \frac{6.22 \cdot p_{SC} \cdot 100}{p_c - p_{SC}}$$

where:

p_{SC} – saturation vapour pressure of the charge air, kPa

p_c – charge air pressure, kPa

However if $H_a \geq H_{SC}$, then H_{SC} shall be used in place of H_a in formula for k_{hd}

NOx emission mass flow rate

$$q_{mNOx} = u_{NOx} \cdot c_{NOx} \cdot q_{mew} \cdot k_{hd}$$

(18) §5.12.5 NTC2008

where:

q_{mNOx} – NOx emission mass flow rate, g/h

u_{NOx} – ratio between density of NOx and density of exhaust gas = 0,001586, (see Table 5 §5.12.5 NTC2008)

c_{NOx} – concentration of NOx in the raw exhaust gas, ppm, wet

q_{mew} – exhaust mass flow, kg/h, wet

k_{hd} – NOx humidity correction factor

Average weighted NOx emission

$$NOx = \frac{\sum_{i=1}^{n}(q_{mNOx} \cdot W_{Fi})}{\sum_{i=1}^{n}(P_i \cdot W_{Fi})}$$

(19) §5.12.6.1 NTC2008

where:

$P = P_{Gen}/0,95$

and

q_{mNOx} – NOx mass mass flow, g/h

W_{Fi} – Weighting factor of individual mode

P_{Gen} – measured power of propulsion generator of the individual mode, kW

0,95 – efficiency factor of propulsion generator

7 Engine test data

7.1 Constant speed operation

Table 1 – Constant speed operation

Mode point	1	2	3	4
Time at beginning of mode	18:45	19:15	19:40	19:45
Date	21.10.2017	21.10.2017	21.10.2017	21.10.2017
Power, %	25	50	75	100
Measured data				
Generator power P_{Gen}, kW	871	1746	2621	3451
Engine speed n, rpm	485	485	485	485
Fuel oil flow, kg/h	222,8	400,7	574,4	785
Emission concentrations in the exhaust gas				
O_2,%	16,8	15,78	15,40	14,49
NO_x, ppm	388	580	690	738
Calculated data				
Engine power, kW	914,55	1833,3	2752,05	3623,55
Excess air factor λ	5,05	4,05	3,77	3,24
exhaust mass flow q_{mew}, kg/h	16582,10	24017,80	32111,31	37813,40
Humidity of intake air H_a, g/kg	3,5583	3,5583	3,5583	3,5583
NOx correction factor k_{hd}	0,89014	0,90390	0,93026	0,94276
NO_x emission mass flow rate q_{mNOx}, g/h	9083,057	19970,239	32689,904	41725,743
Weighting factor according to E2 test cycle (ISO 8178)	0,15	0,15	0,5	0,2
Average weighted NOx emission, g/kWh	11,56			
Additional engine test data				
Efficiency/SFOC, g/kWh	244	219	209	217
Injection timing, °BTDC	8,3	6,3	6,3	4,8
Charge air pressure Bank A, bar rel.	0,23	0,58	1,06	1,47
Charge air pressure Bank B, bar rel.	0,23	0,58	1,06	1,48
Charge air temperature Bank A, °C	32	35	34	39
Charge air temperature Bank B, °C	31	36	37	44
Reference temperature of charge air T_{SCRef}, °C [1)]	40	50	60	70
Pressure in the fuel rail, bar	805	964	1120	1200
Average exhaust gas	242	282	314	370

temperature, °C				

Table 1 (continued)

Environmental conditions 2)				
Temperature of intake air, °C	2	2	2	2
Relative humidity of intake air, %	80	80	80	80
Total barometric pressure, kPa	102,3	102,3	102,3	102,3

1) estimation, as manufacturer specification not available

2) for Lulea / Kallax (CustomWeather Inc.)

7.2 Variable speed operation

Table 2 – variable speed operation

Mode point	1	2	3	4
Time at beginning of mode	18:30	19:00	19:30	19:45
Date	21.10.2017	21.10.2017	21.10.2017	21.10.2017
Power, %	25	50	75	100
Measured data				
Generator power P_{Gen}, kW	871	1746	2621	3451
Engine speed n, rpm	360	365	452	485
Fuel oil flow, kg/h	209	398,6	568,2	785
Emission concentrations in the exhaust gas				
O_2,%	16,17	14,70	15,11	14,49
NO_x, ppm	490	656	732	738
Calculated data				
Engine power, kW	914,55	1833,3	2752,05	3623,55
Excess air factor λ	4,38	3,35	3,59	3,24
exhaust mass flow q_{mew}, kg/h	13532,43	19832,28	30215,57	37813,40
Humidity of intake air H_a, g/kg	3,5583	3,5583	3,5583	3,5583
NOx correction factor k_{hd}	0,89240	0,90390	0,92780	0,94276
NO_x emission mass flow rate q_{mNOx}, g/h	9385,033	18650,845	32546,059	41725,743
Weighting factor according to E2 test cycle (ISO 8178)	0,15	0,15	0,5	0,2
Average weighted NOx emission, g/kWh	11,47			
Additional engine test data				
Efficiency/SFOC, g/kWh	228,5	217	206	217
Injection timing, °BTDC	4	1	7,6	4,8
Charge air pressure Bank A, bar rel.	0,17	0,56	1,01	1,47
Charge air pressure Bank B, bar rel.	0,17	0,56	1,02	1,48
Charge air temperature Bank A, °C	30	35	35	39
Charge air temperature Bank B, °C	30	36	37	44
Reference temperature of charge air T_{SCRef}, °C $^{1)}$	40	50	60	70
Pressure in the fuel rail, bar	684	733	952	1200
Average exhaust gas temperature, °C	238	321	320	370

Co-financed by the Connecting Europe Facility of the European Union

Table 2 (continued)

Environmental conditions [2]				
Temperature of intake air, °C	2	2	2	2
Relative humidity of intake air, %	80	80	80	80
Total barometric pressure, kPa	102,3	102,3	102,3	102,3

1) estimation, as manufacturer specification not available

2) for Lulea / Kallax (CustomWeather Inc.)

8 NOx emission limit

The NOx emission limit is calculated according to §3.2 (Tier I) of Regulation 13, MARPOL ANNEX VI.

Total weighted emission of NO_2 should be within the following limits:

$45 \bullet n^{(-0,2)}$, g/kWh,

where n = rated engine speed (crankshaft revolution per minute).

Manufacturer	S.E.M.T. – Pielstick (Wärtsilä)
Engine type	12PC2.2V
Engine family	PC
Rated speed [rpm]	485
Tier I NOx emission limit	13,06 g/kWh

9 Test results

The results of the emission tests conducted according to §§4-6 for the engine described in §§1-3 under conditions prevailing at the time of the test run §7 are presented at the table 3.

Table 3 – Emission test results

Total weighted emission of NO_x	Results
Tier I limit (§8)	13,06 g/kWh
Constant speed operation (§7.1)	11,56 g/kWh
Variable speed operation (§7.2)	11,47 g/kWh

Schönau, 18 December 2017

Vasily Leytes
Project engineer EFI

Walter Burow
Chief technology officer

IB Ymer

Conversion of the fuel injection system on the Main Engine 4 (ME4)

Emission Test Report

1 Application

Ship	
Name of ship	YMER
Homeport	Luleå - Sweden
Type of ship	Icebreaker

2 Engine information

Engine	S.E.M.T. – Pielstick	
Manufacturer	Wärtsilä	
Engine type	12PC2.2V	
Engine family	PC	
Serial number	369	
Main engine number on board	ME4	
Rated speed, rpm	485	
Rated power, bhp	5000 (3677 kW)	
Electronic injection control	No:	Yes: ☑
Variable injection time	No:	Yes: ☑
Bore	400 mm	
Stroke	460 mm	
Cylinder number and configuration	No.: 12	V: ☑ In-line:

3 Engine family information

Engine family/engine group information (common specifications)		
Combustion cycle	2-stroke	4-stroke ☑
Cooling medium	Water	
Method of aspiration	turbo charged (ABB304)	
Fuel type to be used on board	Diesel fuel oil DM grade ISO 8217:2005	
Combustion chamber	Open combustion chamber	
Fuel system type	Common rail system	

4 Test cell information

Gaseous components analyser	
Manufacturer	Testo SE & Co. KGaA
Model	testo 350 MARITIME
Serial no.	60378450
Order no.	0632351050504
Date of calibration	04/2017
Probe location	Approx. 3 meter behind turbochargers in the very centre of exhaust pipe

Inlet fuel oil flow meter	
Manufacturer	Emerson electric Co.
Sensor	Micro motion Flow Meter F050S F50S172C2FMEZZZZ
Serial No.	14393357
Transmitter	Micro Motion Transmitter 2700R 2700R12AFMEZZX
Serial No.	3836062
Date of calibration	
Probe location	In the fuel oil supply line to the engine
Return fuel oil flow meter	
Manufacturer	Emerson electric Co.
Sensor	Micro motion Flow Meter F050S F50S172C2FMEZZZZ
Serial No.	14397846
Transmitter	Micro Motion Transmitter 2700R 2700R12AFMEZZX
Serial No.	3837120
Date of calibration	
Probe location	In the fuel oil return line from the engine

Engine power measurement	
Manufacturer	Protacon Marine
Model	IB Ymer, Propulsion control
Probe location	Armature current of propulsion generators resp. propeller motors

5 Fuel characteristics

Fuel type		
Manufacturer	ST1 Refinery AB, Göteborg, Sweden	
Product name	Gasoil E10	
Specification	2012-02-28 Utg:2	
Sample ID	173115	
fuel properties (Extract from Test report dated 2016-06-29)		
Property	Test Method	Results
Cetane index	SS-EN ISO 4264	51,8
Density at 15°C	SS-EN ISO 12185	0,8485 kg/l
Gross heat of combustion	SS 15 51 38	45,57 MJ/kg
Viscosity at 40°C	SS-EN ISO 3104	3,663 mm^2/s
Sulphur	SS-EN ISO 20846	277 mg/kg

6 Converting of exhaust gas emission concentrations

Exhaust mass flow

$$q_{mew} = q_{mf} \cdot (1 + \lambda \cdot 14{,}545)$$

where:

q_{mf} – fuel oil mass flow, kg/h
λ – excess air factor: kg dry air/(kg fuel · A/F_{st})
14,545 – stoichiometric air to fuel ratio for diesel (A/F_{st}=1)

Excess air factor

$$\lambda = \frac{20{,}95}{20{,}95 - O_2\%}$$

where:

20,95 - concentration of O_2 in the inlet air, %
O_2% - concentration of O_2 in the exhaust gas, %

Humidity of intake air

$$H_a = \frac{6.22 \cdot p_a \cdot R_a}{p_b - 0.01 \cdot R_a \cdot p_a}$$

(9) §5.12.3 NTC2008

where:

R_a – relative humidity of the intake air, %
P_b – total barometric pressure, kPa
p_a – saturation vapour pressure of intake air, kPa

$$p_a = (4.856884 + 0.2660089 \cdot t_a + 0.01688919 \cdot t_a^2 - 7.477123 \cdot 10^{-5} \cdot t_a^3 + 8.10525 \cdot 10^{-6} \cdot t_a^4 - 3.115221 \cdot 10^{-8} \cdot t_a^5) \cdot \frac{101.32}{760}$$

(10) §5.12.3 NTC2008

with:

t_a – temperature of intake air, °C

humidity correction factor for NOx

$$k_{hd} = \frac{1}{1 - 0.012 \cdot (H_a - 10.71) - 0.00275 \cdot (T_a - 298) + 0.00285 \cdot (T_{SC} - T_{SCRef})}$$

(17) §5.12.4 NTC2008

where:

T_{SC} – temperature of the charge air, °C
T_{SCRef} – temperature of the charge air at each mode point corresponding to a seawater temperature of 25°C, °C
H_a – humidity of the intake air at the inlet to the air filter in g water per kg dry air
T_a – temperature of the air at the inlet to the air filter in °K

To take the humidity in the charge air into account, the following consideration is added:

H_{SC} – humidity of the charge air, g water per kg dry air in which:

$$H_{SC} = \frac{6.22 \cdot p_{SC} \cdot 100}{p_c - p_{SC}}$$

where:

p_{SC} – saturation vapour pressure of the charge air, kPa
p_c – charge air pressure, kPa

However if $H_a \geq H_{SC}$, then H_{SC} shall be used in place of H_a in formula for k_{hd}

NOx emission mass flow rate

$$q_{mNOx} = u_{NOx} \cdot c_{NOx} \cdot q_{mew} \cdot k_{hd}$$

(18) §5.12.5 NTC2008

where:

q_{mNOx} – NOx emission mass flow rate, g/h
u_{NOx} – ratio between density of NOx and density of exhaust gas = 0,001586, (see Table 5 §5.12.5 NTC2008)
c_{NOx} – concentration of NOx in the raw exhaust gas, ppm, wet
q_{mew} – exhaust mass flow, kg/h, wet
k_{hd} – NOx humidity correction factor

Average weighted NOx emission

$$NOx = \frac{\sum_{i=1}^{n}(q_{mNOx} \cdot W_{Fi})}{\sum_{i=1}^{n}(P_i \cdot W_{Fi})}$$

(19) §5.12.6.1 NTC2008

where:

$P = P_{Gen}/0{,}95$

and

q_{mNOx} – NOx mass mass flow, g/h
W_{Fi} – Weighting factor of individual mode
P_{Gen} – measured power of propulsion generator of the individual mode, kW
0,95 – efficiency factor of propulsion generator

7 Engine test data

7.1 Constant speed operation

Table 1 – Constant speed operation

Mode point	1	2	3	4
Time at beginning of mode	13:17	12:55	12:48	12:33
Date	10.05.2017	10.05.2017	10.05.2017	10.05.2017
Power, %	25	50	75	100
Measured data				
Generator power P_{Gen}, kW	870	1756	2621	3447
Engine speed n, rpm	485	485	485	485
Fuel oil flow, kg/h	221,6	404,45	583,5	804
Emission concentrations in the exhaust gas				
O_2,%	16,71	15,69	15,22	13,83
NO_x, ppm	374	551	715	786
Calculated data				
Engine power, kW	913,5	1843,8	2752,05	3619,35
Excess air factor λ	4,94	3,98	3,66	2,94
exhaust mass flow q_{mew}, kg/h	16147,41	23834,70	31613,66	35213,14
Humidity of intake air H_a, g/kg	3,0604	3,0604	3,0604	3,0604
NOx correction factor k_{hd}	0,87142	0,89248	0,90866	0,92446
NO_x emission mass flow rate q_{mNOx}, g/h	8346,535	18589,268	32574,978	40580,527
Weighting factor according to E2 test cycle (ISO 8178)	0,15	0,15	0,5	0,2
Average weighted NOx emission, g/kWh	11,32			
Additional engine test data				
Efficiency/SFOC, g/kWh	243	219	212	222
Injection timing, °BTDC	7,6	6,3	6,3	4,8
Charge air pressure Bank A, bar rel.	0,25	0,66	1,14	1,44
Charge air pressure Bank B, bar rel.	0,26	0,65	1,15	1,46
Charge air temperature Bank A, °C	39,3	39,8	42,8	47,6
Charge air temperature Bank B, °C	40	40	43,8	46,2
Reference temperature of charge air T_{SCRef}, °C 1)	40	50	60	70
Pressure in the fuel rail, bar	800	958	1125	1200
Average exhaust gas	253	297	327	407

Co-financed by the Connecting Europe Facility of the European Union

temperature, °C				

Table 1 (continued)

Environmental conditions [2]				
Temperature of intake air, °C	4	4	4	4
Relative humidity of intake air, %	60	60	60	60
Total barometric pressure, kPa	101,1	101,1	101,1	101,1

1) estimation, as manufacturer specification not available

2) for Lulea / Kallax (CustomWeather Inc.)

7.2 Variable speed operation

Table 2 – variable speed operation

Mode point	1	2	3	4
Time at beginning of mode	13:11	13:03	12:42	12:33
Date, DD.MM.YYYY	10.05.2017	10.05.2017	10.05.2017	10.05.2017
Power, %	25	50	75	100
Measured data				
Generator power P_{Gen}, kW	870	1756	2621	3447
Engine speed n, rpm	360	366	453	485
Fuel oil flow, kg/h	209,87	405,2	575,3	804
Emission concentrations in the exhaust gas				
O_2,%	16,00	14,55	15,01	13,83
NO_x, ppm	535	670	769	786
Calculated data				
Engine power, kW	913,5	1843,8	2752,05	3619,35
Excess air factor λ	4,23	3,27	3,53	2,94
exhaust mass flow q_{mew}, kg/h	13129,29	19697,64	30087,78	35213,14
Humidity of intake air H_a, g/kg	3,0604	3,0604	3,0604	3,0604
NOx correction factor k_{hd}	0,86991	0,89044	0,90960	0,92446
NO_x emission mass flow rate q_{mNOx}, g/h	9691,080	18637,904	33378,737	40580,527
Weighting factor according to E2 test cycle (ISO 8178)	0,15	0,15	0,5	0,2
Average weighted NOx emission, g/kWh	11,56			
Additional engine test data				
Efficiency/SFOC, g/kWh	230	220	209	222
Injection timing, °BTDC	3,8	1,4	7,7	4,8
Charge air pressure Bank A, bar rel.	0,19	0,61	1,10	1,44
Charge air pressure Bank B, bar rel.	0,19	0,61	1,11	1,46
Charge air temperature Bank A, °C	40	40,7	42,4	47,6
Charge air temperature Bank B, °C	42,6	41,1	42,8	46,2
Reference temperature of charge air T_{SCRef}, °C [1)]	40	50	60	70
Pressure in the fuel rail, bar	682	740	952	1200
Average exhaust gas temperature, °C	259	341	334	407

Table 2 (continued)

Environmental conditions [2)]				
Temperature of intake air, °C	4	4	4	4
Relative humidity of intake air, %	60	60	60	60
Total barometric pressure, kPa	101,1	101,1	101,1	101,1

1) estimation, as manufacturer specification not available

2) for Lulea / Kallax (CustomWeather Inc.)

8 NOx emission limit

The NOx emission limit is calculated according to §3.2 (Tier I) of Regulation 13, MARPOL ANNEX VI.

Total weighted emission of NO_2 should be within the following limits:

$45 \bullet n^{(-0,2)}$, g/kWh,

where n = rated engine speed (crankshaft revolution per minute).

Manufacturer	S.E.M.T. – Pielstick (Wärtsilä)
Engine type	12PC2.2V
Engine family	PC
Rated speed [rpm]	485
Tier I NOx emission limit	13,06 g/kWh

9 Test results

The results of the emission tests conducted according to §§4-6 for the engine described in §§1-3 under conditions prevailing at the time of the test run §7 are presented at the table 3.

Table 3 – Emission test results

Total weighted emission of NO_x	Results
Tier I limit (§8)	13,06 g/kWh
Constant speed operation (§7.1)	11,32 g/kWh
Variable speed operation (§7.2)	11,56 g/kWh

Schönau, 18 December 2017

Vasily Leytes
Project engineer EFI

Walter Burow
Chief technology officer

IB Ymer

Conversion of the fuel injection system

on the Main Engine 5 (ME5)

Emission Test Report

1 Application

Ship	
Name of ship	YMER
Homeport	Luleå - Sweden
Type of ship	Icebreaker

2 Engine information

Engine	S.E.M.T. – Pielstick		
Manufacturer	Wärtsilä		
Engine type	12PC2.2V		
Engine family	PC		
Serial number			
Main engine number on board	ME5		
Rated speed, rpm	485		
Rated power, bhp	5000 (3677 kW)		
Electronic injection control	No:	Yes: ☑	
Variable injection time	No:	Yes: ☑	
Bore			400 mm
Stroke			460 mm
Cylinder number and configuration	No.: 12	V: ☑	In-line:

3 Engine family information

Engine family/engine group information (common specifications)		
Combustion cycle	2-stroke	4-stroke ☑
Cooling medium	Water	
Method of aspiration	turbo charged (ABB304)	
Fuel type to be used on board	Diesel fuel oil DM grade ISO 8217:2005	
Combustion chamber	Open combustion chamber	
Fuel system type	Common rail system	

4 Test cell information

Gaseous components analyser	
Manufacturer	Testo SE & Co. KGaA
Model	testo 350 MARITIME
Serial no.	60378450
Order no.	0632351050504
Date of calibration	04/2017
Probe location	Approx. 3 meter behind turbochargers in the very centre of exhaust pipe

Inlet fuel oil flow meter	
Manufacturer	Emerson electric Co.
Sensor	Micro motion Flow Meter F050S F50S172C2FMEZZZZ
Serial No.	14393357
Transmitter	Micro Motion Transmitter 2700R 2700R12AFMEZZX
Serial No.	3836062
Date of calibration	
Probe location	In the fuel oil supply line to the engine
Return fuel oil flow meter	
Manufacturer	Emerson electric Co.
Sensor	Micro motion Flow Meter F050S F50S172C2FMEZZZZ
Serial No.	14397846
Transmitter	Micro Motion Transmitter 2700R 2700R12AFMEZZX
Serial No.	3837120
Date of calibration	
Probe location	In the fuel oil return line from the engine

Engine power measurement	
Manufacturer	Protacon Marine
Model	IB Ymer, Propulsion control
Probe location	Armature current of propulsion generators resp. propeller motors

5 Fuel characteristics

Fuel type		
Manufacturer	ST1 Refinery AB, Göteborg, Sweden	
Product name	Gasoil E10	
Specification	2012-02-28 Utg:2	
Sample ID	173115	
fuel properties (Extract from Test report dated 2016-06-29)		
Property	Test Method	Results
Cetane index	SS-EN ISO 4264	51,8
Density at 15°C	SS-EN ISO 12185	0,8485 kg/l
Gross heat of combustion	SS 15 51 38	45,57 MJ/kg
Viscosity at 40°C	SS-EN ISO 3104	3,663 mm^2/s
Sulphur	SS-EN ISO 20846	277 mg/kg

6 Converting of exhaust gas emission concentrations

Exhaust mass flow

$$q_{mew} = q_{mf} \cdot (1 + \lambda \cdot 14{,}545)$$

where:

q_{mf} – fuel oil mass flow, kg/h
λ – excess air factor: kg dry air/(kg fuel · A/F_{st})
14,545 – stoichiometric air to fuel ratio for diesel (A/F_{st}=1)

Excess air factor

$$\lambda = \frac{20{,}95}{20{,}95 - O_2\%}$$

where:

20,95 - concentration of O_2 in the inlet air, %
O_2% - concentration of O_2 in the exhaust gas, %

Humidity of intake air

$$H_a = \frac{6.22 \cdot p_a \cdot R_a}{p_b - 0.01 \cdot R_a \cdot p_a}$$

(9) §5.12.3 NTC2008

where:

R_a – relative humidity of the intake air, %
P_b – total barometric pressure, kPa
p_a – saturation vapour pressure of intake air, kPa

$$p_a = (4.856884 + 0.2660089 \cdot t_a + 0.01688919 \cdot t_a^2 - 7.477123 \cdot 10^{-5} \cdot t_a^3 + 8.10525 \cdot 10^{-6} \cdot t_a^4 - 3.115221 \cdot 10^{-8} \cdot t_a^5) \cdot \frac{101.32}{760}$$

(10) §5.12.3 NTC2008

with:

t_a – temperature of intake air, °C

humidity correction factor for NOx

$$k_{hd} = \frac{1}{1 - 0.012 \cdot (H_a - 10.71) - 0.00275 \cdot (T_a - 298) + 0.00285 \cdot (T_{SC} - T_{SCRef})}$$

(17) §5.12.4 NTC2008

where:

T_{SC} – temperature of the charge air, °C
T_{SCRef} – temperature of the charge air at each mode point corresponding to a seawater temperature of 25°C, °C
H_a – humidity of the intake air at the inlet to the air filter in g water per kg dry air
T_a – temperature of the air at the inlet to the air filter in °K

To take the humidity in the charge air into account, the following consideration is added:

H_{SC} – humidity of the charge air, g water per kg dry air in which:

$$H_{SC} = \frac{6.22 \cdot p_{SC} \cdot 100}{p_c - p_{SC}}$$

where:

p_{SC} – saturation vapour pressure of the charge air, kPa

p_c – charge air pressure, kPa

However if $H_a \geq H_{SC}$, then H_{SC} shall be used in place of H_a in formula for k_{hd}

NOx emission mass flow rate

$$q_{mNOx} = u_{NOx} \cdot c_{NOx} \cdot q_{mew} \cdot k_{hd}$$

(18) §5.12.5 NTC2008

where:

q_{mNOx} – NOx emission mass flow rate, g/h

u_{NOx} – ratio between density of NOx and density of exhaust gas = 0,001586, (see Table 5 §5.12.5 NTC2008)

c_{NOx} – concentration of NOx in the raw exhaust gas, ppm, wet

q_{mew} – exhaust mass flow, kg/h, wet

k_{hd} – NOx humidity correction factor

Average weighted NOx emission

$$NOx = \frac{\sum_{i=1}^{n}(q_{mNOx} \cdot W_{Fi})}{\sum_{i=1}^{n}(P_i \cdot W_{Fi})}$$

(19) §5.12.6.1 NTC2008

where:

$P = P_{Gen}/0,95$

and

q_{mNOx} – NOx mass mass flow, g/h

W_{Fi} – Weighting factor of individual mode

P_{Gen} – measured power of propulsion generator of the individual mode, kW

0,95 – efficiency factor of propulsion generator

7 Engine test data

7.1 Constant speed operation

Table 1 – Constant speed operation

Mode point	1	2	3	4
Time at beginning of mode	16:56	17:10	18:05	18:20
Date	09.05.2017	09.05.2017	09.05.2017	09.05.2017
Power, %	25	50	75	100
Measured data				
Generator power P_{Gen}, kW	875	1746	2620	3450
Engine speed n, rpm	485	485	485	485
Fuel oil flow, kg/h	221	404,4	583,6	803,3
Emission concentrations in the exhaust gas				
O_2,%	16,69	15,58	15,12	14,08
NO_x, ppm	444	590	784	802
Calculated data				
Engine power, kW	918,75	1833,3	2751,00	3622,5
Excess air factor λ	4,92	3,90	3,59	3,05
exhaust mass flow q_{mew}, kg/h	16029,13	23351,86	31086,74	36433,54
Humidity of intake air H_a, g/kg	3,0513	3,0513	3,0513	3,0513
NOx correction factor k_{hd}	0,89353	0,90018	0,91760	0,93471
NO_x emission mass flow rate q_{mNOx}, g/h	10085,658	19669,985	35468,755	43316,607
Weighting factor according to E2 test cycle (ISO 8178)	0,15	0,15	0,5	0,2
Average weighted NOx emission, g/kWh	12,28			
Additional engine test data				
Efficiency/SFOC, g/kWh	241	221	212	222
Injection timing, °BTDC	8	5	5	3,8
Charge air pressure Bank A, bar rel.	0,22	0,63	1,11	1,45
Charge air pressure Bank B, bar rel.	0,22	0,64	1,12	1,54
Charge air temperature Bank A, °C	29,7	36,4	39	42
Charge air temperature Bank B, °C	29,3	38	41	45
Reference temperature of charge air T_{SCRef}, °C [1)]	40	50	60	70
Pressure in the fuel rail, bar	800	940	1145	1200
Average exhaust gas	246	294	322	388

temperature, °C				

Table 1 (continued)

Environmental conditions [2)]				
Temperature of intake air, °C	4	4	4	4
Relative humidity of intake air, %	60	60	60	60
Total barometric pressure, kPa	101,4	101,4	101,4	101,4

1) estimation, as manufacturer specification not available

2) for Lulea / Kallax (CustomWeather Inc.)

7.2 Variable speed operation

Table 2 – variable speed operation

Mode point	1	2	3	4
Time at beginning of mode	16:45	17:24	17:55	18:20
Date, DD.MM.YYYY	09.05.2017	09.05.2017	09.05.2017	09.05.2017
Power, %	25	50	75	100
Measured data				
Generator power P_{Gen}, kW	874	1747	2615	3450
Engine speed n, rpm	360	365	452	485
Fuel oil flow, kg/h	213,8	401,4	576,6	803,3
Emission concentrations in the exhaust gas				
O_2,%	15,91	14,44	14,87	14,08
NO_x, ppm	528	755	817	802
Calculated data				
Engine power, kW	917,7	1834,35	2745,75	3622,5
Excess air factor λ	4,16	3,22	3,45	3,05
exhaust mass flow q_{mew}, kg/h	13140,12	19189,99	29474,67	36433,54
Humidity of intake air H_a, g/kg	3,0513	3,0513	3,0513	3,0513
NOx correction factor k_{hd}	0,89948	0,89879	0,92000	0,93471
NO_x emission mass flow rate q_{mNOx}, g/h	9897,595	20653,050	35136,863	43316,607
Weighting factor according to E2 test cycle (ISO 8178)	0,15	0,15	0,5	0,2
Average weighted NOx emission, g/kWh	12,28			
Additional engine test data				
Efficiency/SFOC, g/kWh	233	219	210	222
Injection timing, °BTDC	2,2	0,5	6,3	3,8
Charge air pressure Bank A, bar rel.	0,18	0,58	1,07	1,45
Charge air pressure Bank B, bar rel.	0,18	0,58	1,08	1,54
Charge air temperature Bank A, °C	27,4	37	38	42
Charge air temperature Bank B, °C	26,7	39	40	45
Reference temperature of charge air T_{SCRef}, °C [1)]	40	50	60	70
Pressure in the fuel rail, bar	680	735	950	1200
Average exhaust gas temperature, °C	244	337	328	388

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Table 2 (continued)

Environmental conditions [2]				
Temperature of intake air, °C	4	4	4	4
Relative humidity of intake air, %	60	60	60	60
Total barometric pressure, kPa	101,4	101,4	101,4	101,4

1) estimation, as manufacturer specification not available

2) for Lulea / Kallax (CustomWeather Inc.)

8 NOx emission limit

The NOx emission limit is calculated according to §3.2 (Tier I) of Regulation 13, MARPOL ANNEX VI.

Total weighted emission of NO_2 should be within the following limits:

$45 \bullet n^{(-0,2)}$, g/kWh,

where n = rated engine speed (crankshaft revolution per minute).

Manufacturer	S.E.M.T. – Pielstick (Wärtsilä)
Engine type	12PC2.2V
Engine family	PC
Rated speed [rpm]	485
Tier I NOx emission limit	13,06 g/kWh

9 Test results

The results of the emission tests conducted according to §§4-6 for the engine described in §§1-3 under conditions prevailing at the time of the test run §7 are presented at the table 3.

Table 3 – Emission test results

Total weighted emission of NO_x	Results
Tier I limit (§8)	13,06 g/kWh
Constant speed operation (§7.1)	12,28 g/kWh
Variable speed operation (§7.2)	12,28 g/kWh

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Vasily Leytes
Project engineer EFI

Walter Burow
Chief technology officer