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Ship Engine In-Service Performance Management, Using a State-of-Art Model-Based Assessment Methodology

09 System Integration & Optimization

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The Congress programme centres around the presentation of Technical papers on engine research and development, application engineering on the original equipment side and engine operation and maintenance on the end-user side. The topics of the 2016 event covered Product Development of gas and diesel engines, Fuel Injection, Turbochargers, Components & Tribology, Controls & Automation, Exhaust Gas Aftertreatment, Basic Research & Advanced Engineering, System Integration & Optimization, Fuels & Lubricants, as well as Users' Aspects for marine and land-based applications.

ABSTRACT

Retaining and improving the performance and efficiency of shipboard power plants, as well as performing condition monitoring towards efficient fault diagnosis and asset management, requires Monitoring (measuring) and Evaluation (benchmarking).

On the monitoring side, any in-service measurements may occasionally prove to be untrustworthy, taking into account sensor and recording accuracy issues. Performance evaluation and fault diagnosis rely on dependable and accurate benchmark/reference, against which measurements can be compared.

The core of the novel methodology, presented in this paper, involves the use of a thermodynamic simulation model for each specific shipboard engine. This model is tuned to be an exact replica of the actual engine in operation, reflecting the physical relationships of all primary parameters (temperatures, pressures, rpm) and resultant values (torque, fuel consumption, emissions etc.). Once tuning is performed, the model predicts engine performance as influenced by ambient conditions, load, speed and fuel, at any operating point. Based on the premise that the operating envelope of the engine is known, a great number of simulations are performed a-priori, for combinations of all possible engine settings, ambient conditions and fuels. Thus an engine performance hyper-map (Engine Hyper Cube) is generated. This hyper-map database can provide the “expected” values of performance parameters at any engine operating condition. These “expected” values are then compared to the “measured” values offering diagnostics based on the residual differences between the two.

Euronav Shipping Company has installed Engine Hyper Cube models, as produced by Propulsion Analytics, for seven Suezmax tankers (sister ships). The ships’ main engines have various measuring and data acquisition systems installed onboard, with the Engine Hyper Cube methodology capable of working with any such system and/or sensor. To ascertain the accuracy of the methodology and the predictive potential, a single blind validation was performed where the engine settings from service performance reports for some years in the past, were input into the Engine Hyper Cube software. Any observed swing in residuals (measured-expected) in the timeline, were then compared with the known engine maintenance events. The results indicated recognizable shift in performance, following maintenance events in the ship’s records, confirming the validity and accuracy of the Engine Hyper Cube methodology.

Another case is presented, where a fuel injection problem was investigated. An in-depth analysis using measured cylinder pressure diagrams compared with pressure trace predictions and the use of heat release analysis pinpointed the cylinder with fuel injection issues.

The methodology also allows the shipping company to perform optimization studies (e.g., VIT optimization) as well as execute a number of ‘what-if’ scenarios for examining how the vessel engine performs in regimes it had not operated in the past. One such case is also presented. The shipping company is using these methodologies and technologies for monitoring and evaluation, aiming at optimum vessel operation.

INTRODUCTION

In today's shipping industry, issues like condition-based maintenance, asset management and energy efficiency are increasingly gaining the attention of ship owners and operators. This leads to the operation of ships under advanced supervision and monitoring in order to improve reliability, economy and safety. In addition to the above, stricter environmental regulatory frameworks and fluctuating oil prices are becoming the norm in which ship owners are called to operate their vessel power plants, often in conditions outside their "usual" envelope.

Diagnostics and prognostics are two important aspects of a Condition Based Maintenance program. One approach for machinery diagnostics is using Model-Based methods, which involve physics specific explicit mathematical models of the monitored machine, producing predictions which are compared with measured data.

Mathematical model based fault detection and diagnosis methods rely on the concepts of analytical redundancy. In contrast with physical redundancy, when measurements from parallel sensors are compared to each other, now sensors measurements are compared to the model predictions and thus residuals can be generated. These residuals are evaluated to arrive at fault detection, isolation and identification. Model-based approaches can be more effective than other model-free approaches, provided a correct and accurate model can be built. However, as stated in [1], explicit mathematical modeling may not be feasible for complex systems. For example, in space applications the complexity of analytical models for liquid-propellant rocket engines as well as the required robustness and reaction speed issues, means that model–based methods are paid limited attention for real-time fault detection, but have potential for fault isolation [2].

Comprehensive thermo-fluid dynamic models within performance monitoring systems are already used for aero- and power gas turbines [3]. Further, semi-physical models of combustion engines, in conjunction with neural networks for the detection and diagnosis of different engine faults increasingly appear in the automotive industry [4]. Several systems are available for marine engine assessment and diagnosis, based on cylinder pressure measurements, subsequently performing heat release calculations, using the results for statistical and trend analysis as well as comparison to some reference. The evaluation leading to fault detection, may be from a combination of analytical, machine learning and human expert methods, for example [5], [6].

The use of a detailed engine process simulation model to produce "nominal" reference performance predictions, which were then compared with actual shipboard engine measured data to evaluate the engine's performance, was reported in [7]. Finally, an overall exposition of the recent trends in maritime condition monitoring, can be found in [8].

As a response to these issues, and following what other industries, (e.g., power, aerospace and lately automotive) are doing, the shipping industry is nowadays very actively entering the era of asset performance management and condition monitoring. The two pillars that are essential for this, are those of monitoring (i.e., measuring) and benchmarking (i.e., comparing with a reference), both equally important towards the end result (Figure 1).

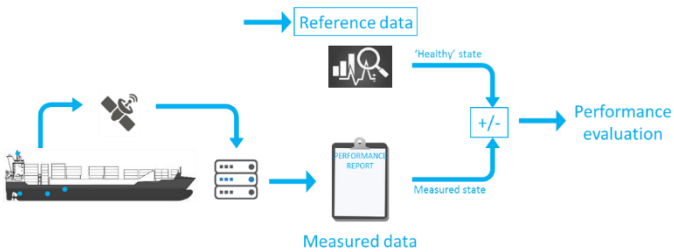


Figure 1 Performance evaluation procedure.

On the monitoring side, the evolution of smart sensors and data acquisition systems, along with advanced ship to shore telecommunications provide a solid basis for the primary source of information needed. However, lack of data is not typically the issue here. In practice, any in-service measurements may occasionally prove to be untrustworthy, taking into account fidelity of sensors and recording issues. In any case, shipboard automatic data acquisition systems often result in a flood of transmitted information in need to be filtered and processed, in order to obtain any useful results. Beyond condition monitoring, the performance evaluation and diagnostics, depend on reliable benchmarking reference for the actual operating conditions. The engine process simulation-based novel methodology, presented in this paper can provide such "dynamic" reference.

ENGINE HYPER CUBE

A comprehensive engine process simulation model is a complex software application intended to be used by experts with adequate hardware resources, usually in the context of engine design. The usage of such a model for shipboard engine performance management and assessment, as reported in [7], may be acceptable for research applications under controlled conditions and with specialized training of the end-users. However for broad field deployment, onboard many ships and onshore in shipping companies, at various locations and on various hardware platforms, any performance assessment methodology would require high robustness and tolerance in faulty input, fast response, modest computational resources, ability to be used by non-experts. The running of a complex simulation algorithm cannot readily comply with the above requirements. For deployment of such methodology in conjunction with existing engine management systems, other approaches must be examined.

The difference between the two specific application areas of engine simulation codes referred above, namely “new engine design” and “existing engine management” is that in the latter the engine type and operational envelope are already fixed and known. Thus, the various operational states can be established a-priori, (i.e. range of rpm, load, fuel quality, ambient pressure, temperature etc. parameters) hence the possible input data sets for running the simulation are distinct. If the range of each of these parameters is discretized in adequately small partition intervals, then their n-fold Cartesian product will be an n-dimensional array of sets of input for running the engine model. For predicting the performance of an existing engine, the simulation code can run a-priori for an adequate number of times to cover the whole operating envelope. Each input data set (each operating condition) is then linked to an output set. The number of runs is established by considering the required granularity of results. The results of the runs can be stored in a relational database. This database can then be considered a hypermap of engine performance. The required number of runs may turn out to be quite large for an adequate coverage of the operating envelope of the engine. If the simulation code is optimised for a very large number of runs and sufficient computing resources can be aggregated, then even hundreds of thousands of runs can be performed in a reasonable total run time. The hypermap creation process can therefore be performed off-line prior to and without interacting with any subsequent process of engine diagnosis and management, which shall only use the end product of the first process, namely the hypermap database. The hypermap database and related application has all the attributes of robustness, fast response, ease of use, transportability, as required for serial deployment in the field. Multivariate interpolation can then be used within this hypermap database to locate the expected engine performance at any freely selected operating point and any condition and thus obtain accurate “dynamic” reference for engine performance assessment. This reference is then used in conjunction with actual engine measurements so as to create residuals and further to operate on residuals with proper rule-sets, to arrive at diagnosis and actionable items, which is the final output of true value to the end-user. This engine performance hypermap application presented in this paper is the Engine Hyper Cube, developed by Propulsion Analytics.

Based on a detailed thermodynamics-based simulation model (THERMO-S), the multidimensional performance hypermap custom-produced for each vessel is generated and delivered to the ship owners/operators. The THERMO-S model is tuned to be an exact replica of each actual engine in operation, reflecting the physical relationships of all primary parameters (temperatures, pressures, rpm) and resultant values (torque, fuel consumption, emissions etc.). Once tuning is performed, the model can predict engine performance as influenced by ambient conditions, load, speed and fuel, at any operating point. Thus, a great number of simulations are performed a-priori, as detailed above, to generate an engine performance hyper-map (Engine Hyper Cube), which can provide the ‘healthy’ state at any engine operating condition in a split second.

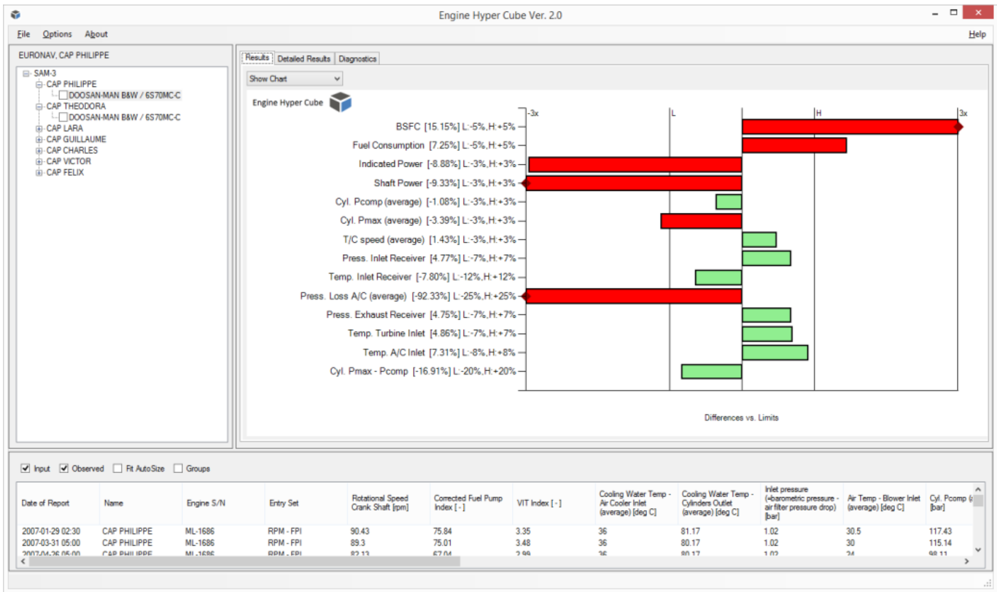
The number of simulation runs to produce the Engine Hyper Cube was optimized to around 1 Million. The simulation model is tailored for the execution and automation of this large number of runs, so that they can be performed a-priori in computer clusters or supercomputers within a reasonable time. Each Engine Hyper Cube database produced is about 400MB. It is easy to install in any platform and in actual use the interpolation is very fast (around 1 second), very stable, without any of the problems or issues associated with running a simulation algorithm. In back-to-back comparison, the interpolation in the dense cloud of results provides the same accuracy within 0.5% of the full simulation algorithm.

The application can compare any incoming engine monitoring (actual performance) data to the Engine Hyper Cube output at the same operating conditions (expected performance), and reliably:

- diagnose engine faults, resolving between sensor or engine process problems
- determine fuel consumption, emissions and assess engine performance parameters,
- predict developing faults, towards condition-based maintenance
- estimate complete performance/emissions, under any other engine operating conditions (what-if scenario)

The Engine Hyper Cube can work with any measurement and data acquisition system already installed on-board and complements any approach followed by the ship owner/operator.

Figure 2 below, shows two sample screen shots from the use of the Engine Hyper Cube software, presenting the deviations from the healthy state for a number of measured parameters (as extracted from a ‘standard’ performance report) as well as a detailed diagnostics view. As can be seen, the Engine Hyper Cube software, diagnoses and presents the user with possible sensor/measurement issues as well as possible engine faults for a given performance report, suggesting further actions and check points.



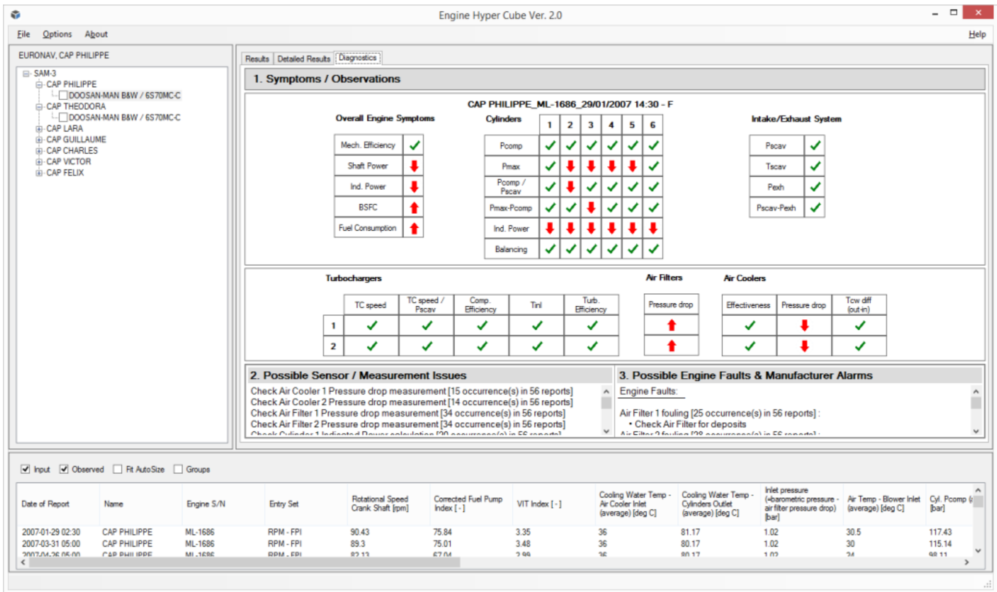


Figure 2 Engine Hyper Cube software.

APPLICATION IN EURONAV

ENGINE SETUP AND CALIBRATION

The Fleet Energy Management Department of Euronav Ship Management (Hellas) Ltd was responsible for the supervision of the Engine Hyper Cube deployment within the company. Seven sister vessels of Euronav Ship Management (Hellas) Ltd equipped with the MAN B&W 6S70MC-C7 engine were chosen to serve as a first fleet for the Engine Hyper Cube application, namely the CAP THEODORA, CAP PHILIPPE, CAP VICTOR, CAP FELIX, CAP GUILLAUME, CAP LARA and CAP CHARLES crude oil tankers. The installed main engine is a typical 6-cylinder two-stroke marine diesel engine of 17,000 kW equipped with two turbochargers and with an electronic Variable Injection Timing (VIT) system. It should be noted that although the vessels are considered as "sister ships with nominally same main engine", the accuracy of the Engine Hyper Cube application can be achieved if the “specific engine” model (THERMO-S) is properly set up and calibrated separately for each different engine. In nominally "same" engines, even small differences (e.g. 1 extra shim in compression, or 2° CA difference in valve timing) or not-so-minor differences (e.g. different nozzle ring in turbocharger turbine) must be suitably accounted for in modelling, for the proper construction of the Engine Hyper Cube.

The thermodynamic process simulation code THERMO-S considers the engine at a high level of detail, therefore an assemblage of geometric and performance data were needed to build up and calibrate the model of the engine for each vessel. Most data were provided by Euronav Fleet Energy Management Department, as follows:

- Geometry Data obtained from the engine's Instruction Manual
- Turbocharger data
- Shop Test / Sea Trials Results
- Performance Reports from ship operation

Some engine geometric data were not available (e.g. the compression ratio, valve timing and lift etc.); these had to be calculated using past experience and trial/error simulation procedures. For each engine, the above data set was firstly analyzed for consistency and accuracy, then filtered and inserted in the THERMO-S simulator to setup the specific engine model.

The next step was to calibrate the model i.e. the submodels and constants in order to match the engine performance data from the Shop Tests. The available load points (typically at 25%, 50%, 75%, 90%, 100% and 110% load) measured during the Shop Tests of each engine were simulated. The results were compared to the respective measured data in order to check the engine model's accuracy in predicting the engine performance.

As an example, referring to the above engine load points, the following bar-chart (Figure 3) presents the percentage differences between measured and expected values of the main performance parameters for the Shop Tests of the CAP THEODORA vessel:

$$\mathrm{D}(\%) = \frac{Measured - Calculated}{Measured} * 100\%$$

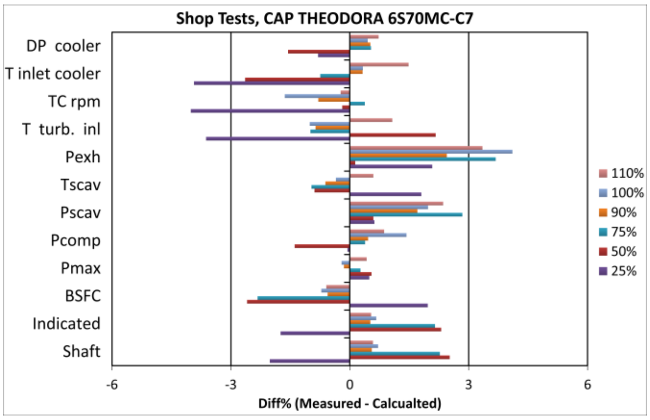


Figure 3 Shop Test Calibration with THERMO-S for CAP THEODORA vessel.

As can be observed, for all performance parameters, the maximum absolute difference between measured and calculated values is lower than 3% in almost all cases. As a conclusion, the simulation predictions for the Shop Test points are considered successful and the specific engine model effective and well calibrated.

The specific model for each one of the seven engines was subsequently verified using the Sea Trials. In almost all cases, all the engine's performance parameters were found to have a maximum absolute difference between measured and calculated values lower than 3%.

After the model for each engine was completed, the Engine Hyper Cube performance maps for all seven engines were produced with the simulator, as explained in the previous section. These hypermaps cover the engine operation from 10% to 110% of load for a range of external conditions. The produced Engine Hyper Cube databases were installed in the servers of the Shipping Company so that they could be used by their Fleet Energy Management Department, as well as by the vessels' superintendent engineers.

PERFORMANCE ANALYSIS FOR CAP THEODORA

Initial validation of Engine Hyper Cube

A number of performance reports for the year 2014 corresponding to actual operating points in-service of the CAP THEODORA vessel, were analyzed using the Engine Hyper Cube software. Engine parameters such as Indicated Power, Shaft Power, Maximum Pressure, Compression Pressure, Specific Fuel Consumption, Turbocharger Speed, Inlet Receiver Pressure and Temperature etc. were calculated and compared with the available measured data. After processing of the results, some important conclusions were drawn, as follows:

- Two distinct time periods could be observed (Figure 4). In the first time period, from January to May of 2014, significant deviations could be found (5% to 25%) of the measured data from those calculated by Engine Hyper Cube for the indicated and shaft power, maximum and compression pressure. At the same time, though, the turbocharger speed and compressor delivery temperature, scavenge pressure and temperature, exhaust gas pressure and temperature were matched within acceptable limits. This possibly indicated a faulty measurement for these four parameters probably due to measuring instrumentation or post processing procedure (e.g. TDC correction in pressure diagram).
- In the second time period from June to December 2014 (Figure 4), a sudden increase in the exhaust gas and turbocharger's characteristics (i.e. exhaust gas temperature, scavenge and exhaust receiver pressure etc.) as well as in the compression pressure P_{comp} could be observed, but not a proportional increase in the maximum pressure P_{max}, which led to a lower P_{max}-P_{comp} pressure rise as can be seen in Figure 4. This might indicate a possible problem with the combustion process (i.e. problematic injection system/process or poor quality of used fuel). Further, during the initial processing it was noticed that the Fuel Pump Index (FPI), needed to produce a certain amount of torque deviated significantly from what was expected from Shop Tests or Sea Trials (Figure 5), which could also indicate a problem with the combustion process. The

FPI is an index which indicates the amount of required fuel to maintain the desired engine speed. Finally an increase in the measured Brake Specific Fuel Consumption (BSFC) was also noticed, which although it could be due to erroneous measurement of fuel consumption or engine power, it could also originate from a combustion process problem.

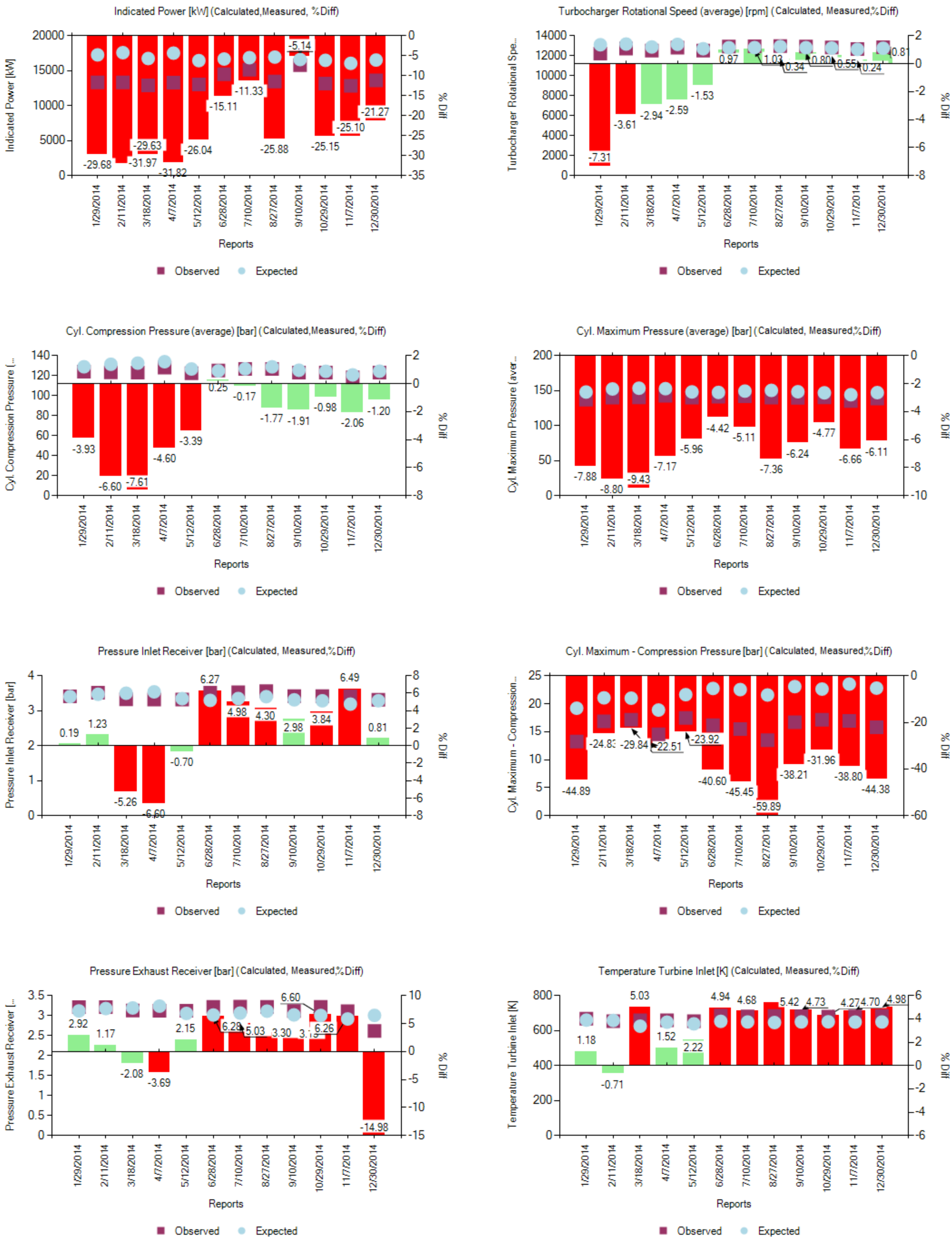


Figure 4 Vessel CAP THEODORA Engine Hyper Cube results for operating points of 2014.

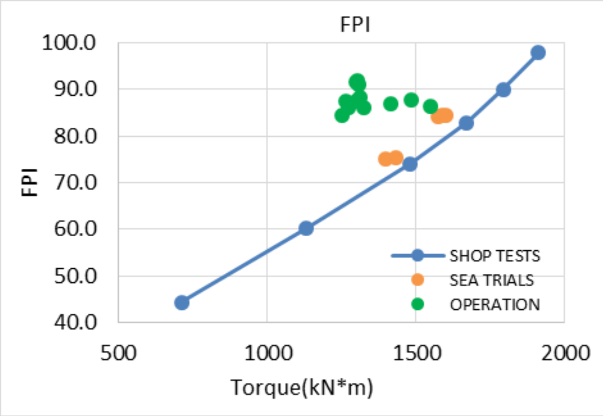


Figure 5 Fuel Pump Index vs. engine torque (operation 2014).

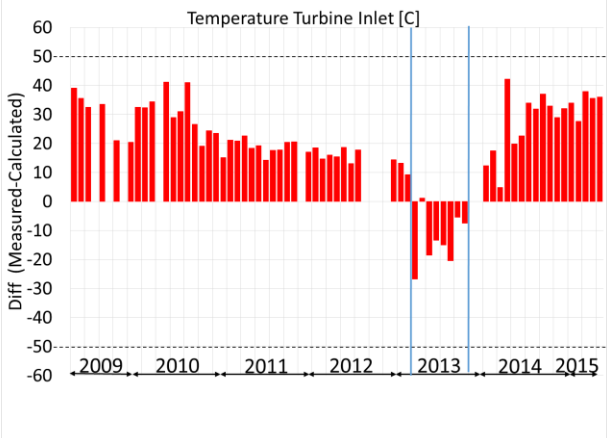


Figure 6 Exhaust gas temperature residuals.

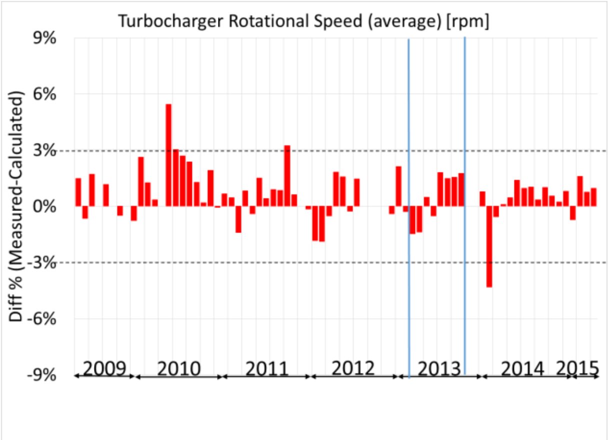


Figure 7 Turbocharger rotational speed residuals.

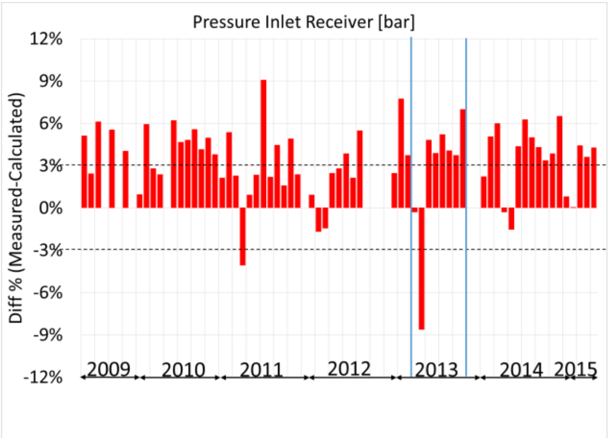


Figure 8 Pressure at inlet receiver residuals.

Extended validation of Engine Hyper Cube

Since the injection system issue identified above was important, Euronav called for the use of the Engine Hyper Cube software to examine the available performance reports for some years in the past, to ascertain the accuracy of the methodology and the predictive capability. Thus, the engine settings of all past instances (performance reports) were input into the Engine Hyper Cube, to carry out a single blind validation. For all the thermodynamic parameters of the engine, a timeline with the residuals (measured-calculated) was produced.

Any swing in residuals in the timeline, were then compared with the known engine maintenance events and periods with consecutive values above acceptable limits were sought. For each of these periods these residuals were also examined in contraposition with those of other parameters, which are thermo-dynamically related. In that way it could be identified if these changes were due to measurement / sensor errors or corresponded to an engine or process fault. Using the above methodology, some issues with measurement or sensors errors were identified, as presented hereafter.

During the period of Feb. to Sep. 2013, a sudden drop in the Exhaust Gas temperature residuals (measured – calculated) was observed, as shown in Figure 6. Other thermodynamic parameters, as shown in Figure 7 and Figure 8, did not follow this observed trend. Here, the T/C speed and P_{scav} residuals showed no change in comparison with previous operating points. If $T_{exhaust}$ was indeed significantly reduced, then the T/C speed, P_{comp} and P_{scav} would have also been significantly reduced. Finally, as can be seen in Figure 9 the measured absolute value of Turbine inlet temperature was quite lower than normal for this specific time period. Thus, it could be inferred that the “alarm” was caused by an erroneous exhaust gas temperature measurement and did not reflect a change in the engine’s condition. Such inferences are produced by the diagnostic rule set of the Engine Hyper Cube application.

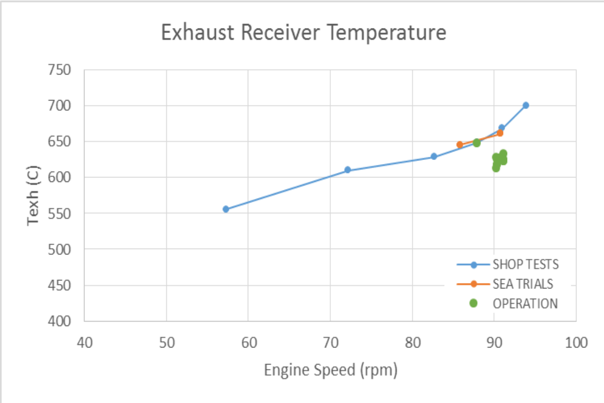


Figure 9 Exhaust gas temperature vs. engine speed.

Throughout the period of investigation (Feb. 2009 – Apr. 2015), the compression pressure (Figure 10) appeared to be normal (within +/- 3 bar), while maximum pressure (Figure 11) seemed to be gradually reducing and after a point was constantly well below 5 bar. The pressure rise P_{max}-P_{comp} residual (measured-calculated), throughout the whole period was also lower than expected. Its behavior could be grouped into three distinct time periods as shown in Figure 12. During the first period (red dotted points and lines) a declining trend can be seen. In the second period (green dotted points and lines) a more rapid decline is observed. Finally, after Dec. 2013, there seemed to be a reversal of the trend (blue dotted points and lines), which was further investigated.

Figure 13 shows a more focused view at the pressure rise residual, depicting the second period in green, clearly showing the degrading performance trend (green dotted line) reaching a peak residual larger than -9 bar and an average (green solid line) around -8 bar. In the third period, after Dec 2013, even though still not corrected, there is a clear reversal of both the average (blue solid line) and the trend (blue dotted line), denoting an event, which –assuming that the overall behavior was due to a faulty injection system- was attributed to a possible overhaul event. Indeed, following this study Euronav confirmed that in November 2013 there was a dry docking of the vessel, where the major engine components were overhauled, thus validating the outcome of the Engine Hyper Cube application.

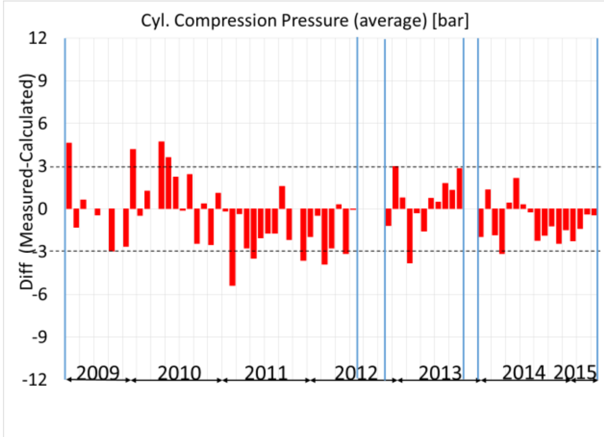


Figure 10 Cylinder compression pressure residuals.

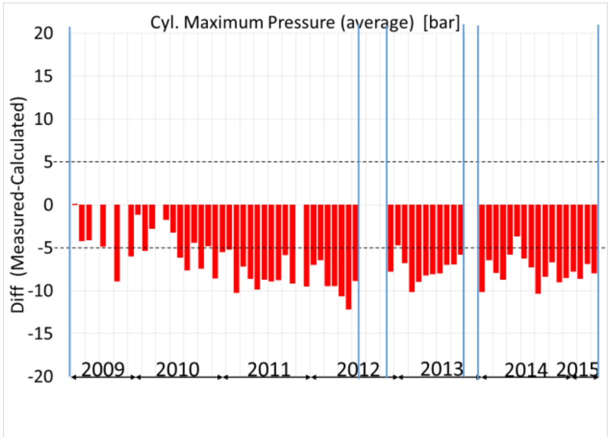


Figure 11 Cylinder maximum pressure residuals.

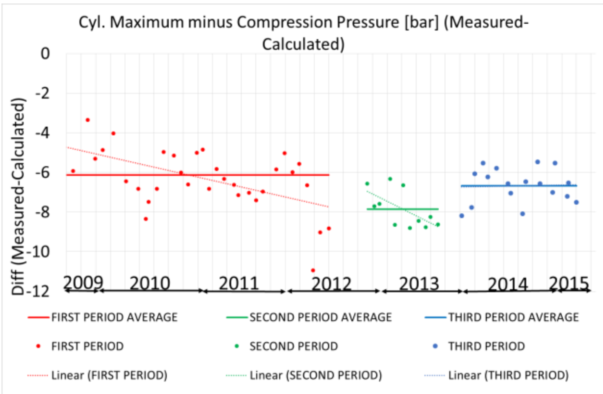


Figure 12 Cylinder pressure rise residuals (2009-2015).

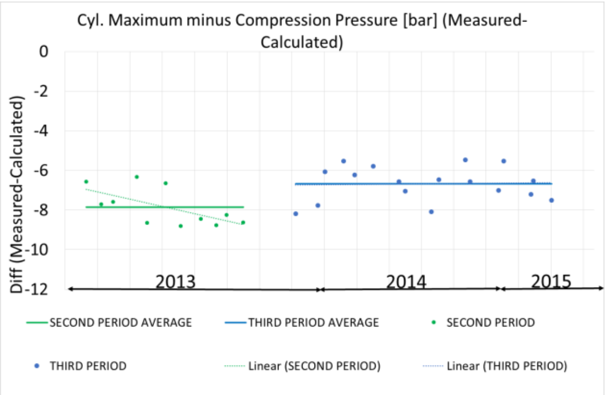


Figure 13 Cylinder pressure rise residuals (2013-2015).

The results shown so far reflected the average values between cylinders of the thermodynamic parameters. To isolate the cause of the pressure rise problem to one or more specific cylinders, the pressure rise behavior per cylinder was examined. The overall observations as described for Figure 12, applied here as well, for cylinders 1, 2, 4 and 5. Cylinders 3 and 6 seemed to show a different behavior, since the average value after Dec 2013 (period 3) was lower than the one in period 2. Among all cylinders, cylinder 4 seemed to be the best performing one throughout the period investigated (i.e. having the lowest decrease of pressure rise). Figure 14 to Figure 15 show the pressure rise residual, diagrams per cylinder, indicatively for cylinders 1 and 4. This set of diagrams depicts the whole period (Feb. 2009 – Apr. 2015) split in to the three time periods previously mentioned.

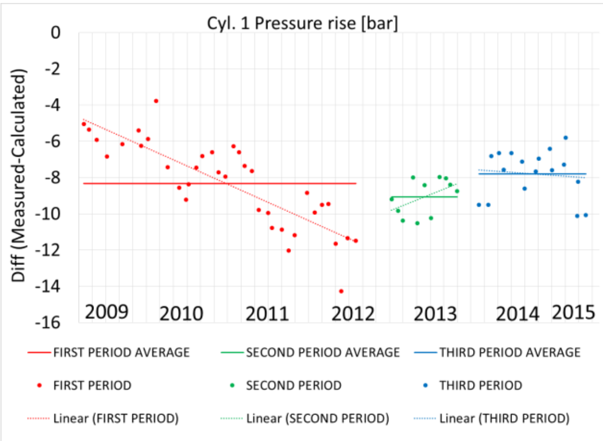


Figure 14 Cylinder 1 pressure rise residuals (2009-2015).

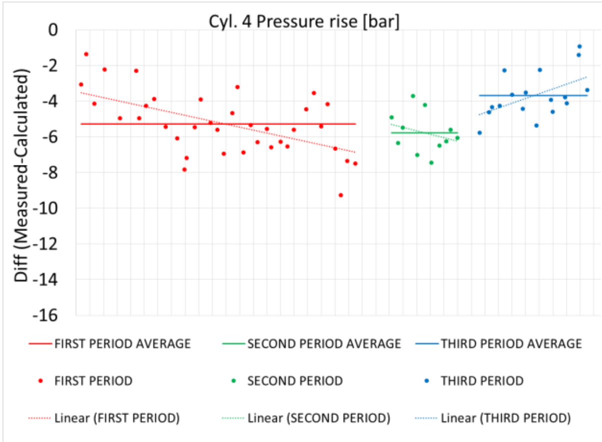


Figure 15 Cylinder 4 pressure rise residuals (2009-2015).

In-depth Analysis

Following the above historical data analysis, a deeper investigation was made to validate the finding of faulty injection system. A detailed study for the condition of the engine cylinders using the full thermodynamic model (i.e., THERMO-S) was performed for one operating point (7 April 2015). For this operating point, measured pressure diagrams using a LEMAG PREMET-C on-board system were available at Euronav. Plotting the pressure diagrams of all cylinders, produced by THERMO-S, against the ones produced by PREMET-C could lead to important conclusions about the individual performance of the cylinders. In addition, a Heat Release Rate (HRR) analysis has been conducted using the THERMO-S HRR utility, to analyze the actual combustion rate of each cylinder.

By observing the above mentioned diagrams, two distinguished groups of cylinders could be isolated: On the one hand, cylinder 4 Pressure and HRR diagrams were quite close to the calculated ones, while on the other hand significant differences between the measured and calculated Pressure diagrams and HRR diagrams were spotted in cylinders 1, 2, 3, and 5. Cylinder 6 behavior was in between the two groups. For the sake of brevity the pressure and HRR diagrams of only cylinder 4 is presented here against the respective diagrams of cylinder 1.

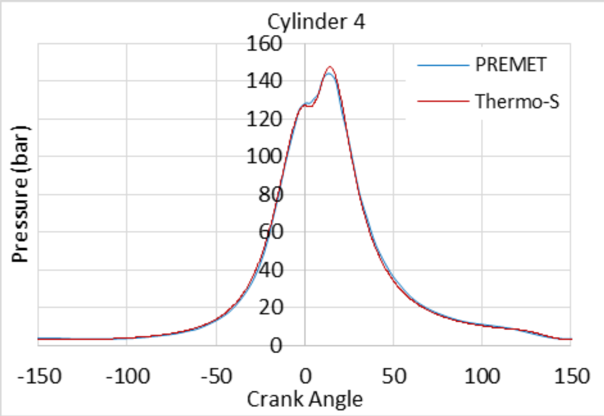


Figure 16 Cylinder 4 pressure diagram comparison.

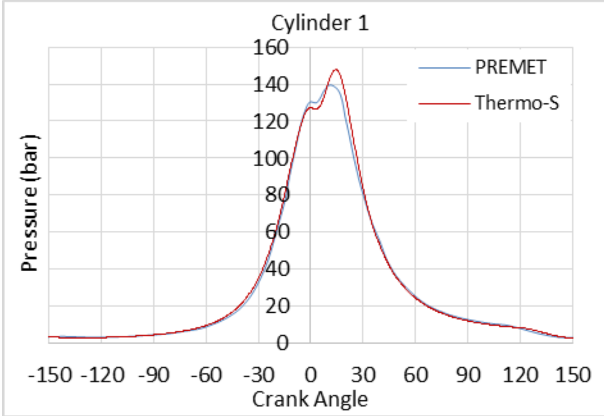


Figure 17 Cylinder 1 pressure diagram comparison.

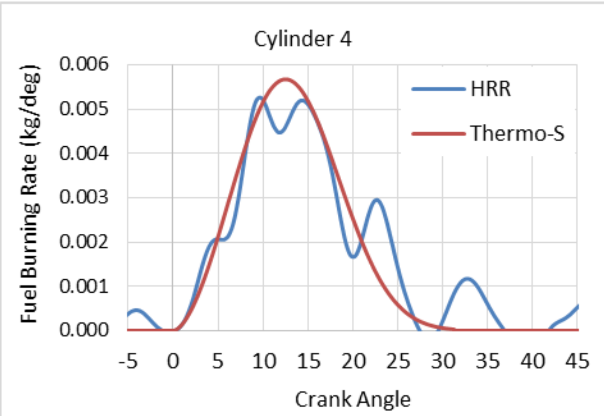


Figure 18 Cylinder 4 Fuel Burning Rate comparison.

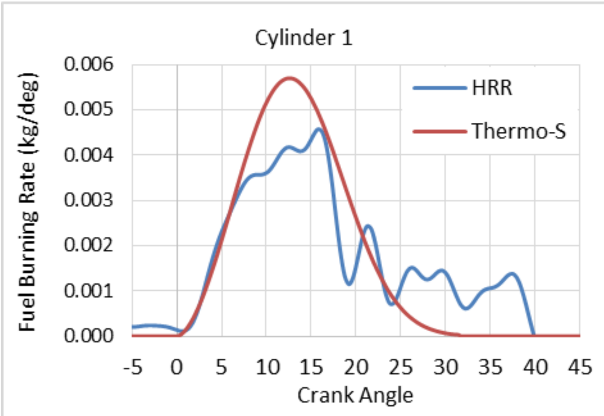


Figure 19 Cylinder 1 Fuel Burning Rate comparison.

By observing Figure 16 and Figure 17, it can be seen that the compression pressure, maximum pressure and crank angle at maximum pressure for cylinder 4 are reasonable, while the compression pressure of cylinder 1 is higher than expected, the maximum pressure is lower than expected and the crank angle at maximum pressure is lower than expected. Further, in Figure 18 and Figure 19 it can be seen that in cylinder 4 the Fuel Burning Rate (FBR) is quite close to the calculated one. Instead, in cylinder 1, while the injection timing and start of combustion matches perfectly and the combustion starts developing according to what is expected, there is not enough fuel injected to maintain the high combustion rate after 7 deg. CA, thus the FBR decreases i.e. energy is released more slowly and high P_{max} cannot be achieved.

Finally, it was decided to use the THERMO-S model as a “fault simulator”, as follows. For this study it was assumed that the decrease in P_{max} was due to a lower combustion rate. In detail, the combustion model was changed so as to produce a (lower) combustion rate similar to the one derived from the measured pressure diagram, as can be seen in the right hand side of Figure 21 below, which depicts indicatively the results for cylinder 1. It should be noted that this change was imposed only for cylinders 1, 2, 3 and 5, while the original combustion model was not changed for cylinders 4 and 6 because they did not exhibit large differences in the combustion rate.

As can be observed from the right hand side pressure diagrams, the pressure diagram derived with the lower combustion rate is almost identical with the measured one. The overall performance results with the original and also with the lower combustion rate, are presented in the following table:

Table 1

	Original			Lower combustion rate		
Parameter	Measured Value	Calculated Value	Δ (Diff.)	Measured Value	Calculated Value	Δ (Diff.)
Indicated Power [kW]	15913	16427	-514	15913	16145	-232
Shaft Power [kW]	14918	15446	-528	14918	15164	-246
P_{comp} [bar]	129.67	127.17	2.51	129.67	129.46	0.21
P_{max} [bar]	142.04	147.87	-5.83	142.04	144.19	-2.15
TC_RPM [rpm]	12910	12605	305.00	12910	12737	173.40
$T_{\_turb\_in}$ [K]	673.1	660.1	13.0	673.1	661.0	12.1
Pressure Rise [bar]	12.37	20.71	-8.34	12.37	14.72	-2.36

From the above table it can be observed that the assumption of lower combustion rate results in calculated values which are much closer to the measured values for all main thermodynamic parameters, i.e. compression pressure, maximum pressure, pressure rise, shaft power and T/C speed. Therefore, it was safely assumed that the lower combustion rate is a credible explanation of the originally observed reduction of maximum pressure and is in accordance with the indications and first-level conclusions derived with the Engine Hyper Cube software.

Due to the injection system fault spotted above, the engine produces lower Indicated Power and consumes higher amount of fuel. The engine Power loss due to the lower combustion rate is calculated as the difference between the calculated value denoting the healthy state (15446kW) and the measured value denoting the faulty state (15164kW). This power loss was equal to 282kW (=15446 - 15164kW), which when multiplied by the typical specific fuel consumption of ~180 g/kWh, gives ~50 kg/h or 1.2 tons per day increased fuel consumption due to the power loss caused by the lower combustion rate.

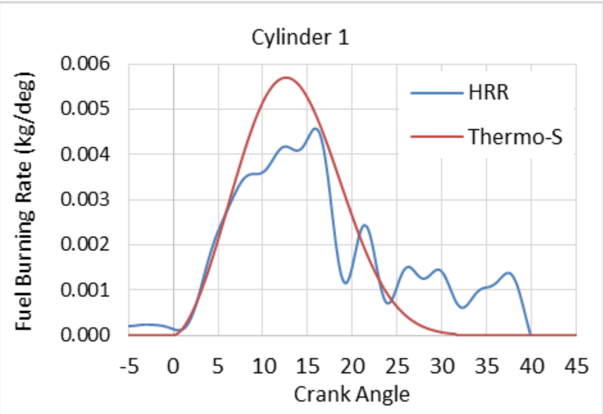


Figure 20 Cylinder 1 Fuel Burning Rate comparison (original calculation).

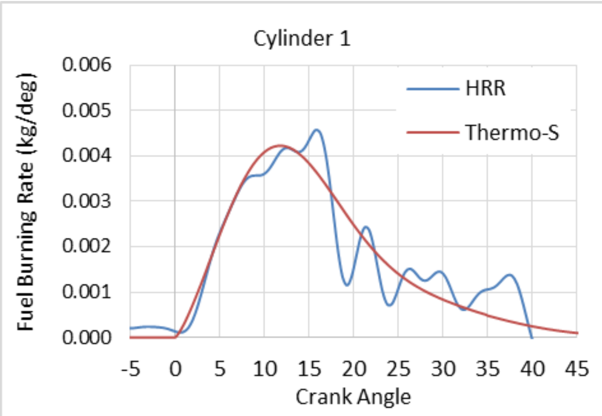


Figure 21 Cylinder 1 Fuel Burning Rate comparison (reduced combustion rate).

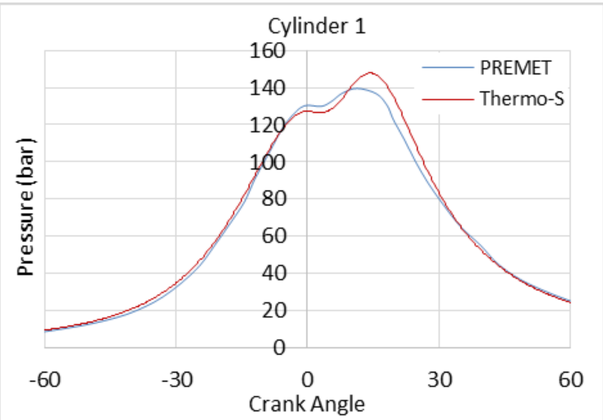


Figure 22 Cylinder 1 pressure diagram comparison (original calculation).

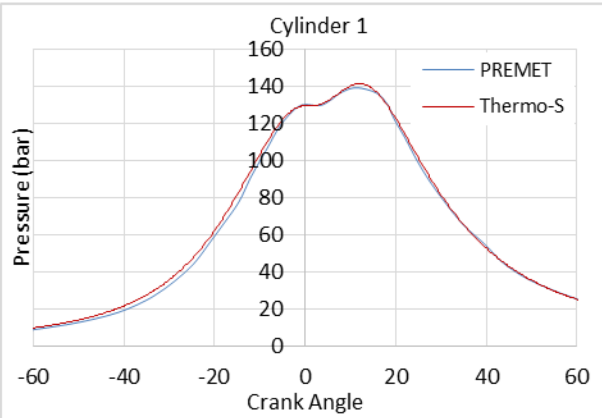


Figure 23 Cylinder 1 pressure diagram comparison (reduced combustion rate).

WHAT-IF SCENARIO

Since the Engine Hyper Cube database is created by running the specific engine model for all possible engine settings and operating points, the Engine Hyper Cube software can also act as an engine simulator. This allows the shipping company to perform various optimization studies, as well as execute a number of 'what-if' scenarios for examining how the vessel engine performs within regimes it had not operated in the past or under different settings.

A typical example of this possibility is an exercise that was performed in order to assess the impact of lowering the cooling water temperature at air cooler inlet on engine specific fuel consumption. The motivation was a related service letter from the engine manufacturer where it was mentioned that for both the central cooling water system and the seawater cooling system, by reducing the setpoint on the 3-way water temperature control valve, the result would be an approx. 0.7-1.0 g/kWh lower fuel oil consumption per 10°C lower cooling water temperature.

It use decided to select one of the 7 vessels (CAP GUILLAUME) of Euronav and to run Engine Hyper Cube for 4 operating points (from 50% to 100% load), for 4 different values of engine room air Temperature (at inlet blower) and for 5 different values of the cooling water temperature at air cooler inlet from 10°C to 36°C. The target was to assess the reduction in engine SFOC.

An indicative part of the results of this exercise is presented in Figure 24 and Figure 25 below, for 2 different values of engine room air Temperature (i.e. 10 and 40°C). It can be observed that by setting the cooling water temperature at air cooler inlet at 10°C the reduction of SFOC depends highly on the engine load and for this specific engine can be up to 1.1 g/kWh. There is also a small effect of engine room temperature i.e. the maximum benefit can be achieved at low engine room temperatures.

According to the above mentioned service letter, the shipping company can expect 1.8 to 2.6 g/kWh BSFC reduction when reducing the cooling water setpoint from 36 to 10°C. By using the Engine Hyper Cube application it was found that this result is not achievable for the specific engine, probably due to its size (larger reductions are achievable for larger size engines); instead a maximum reduction of 1.1 g/kWh can be expected. This is an engine-specific information that can be used by the shipping company to decide on the operating strategy for this specific issue.

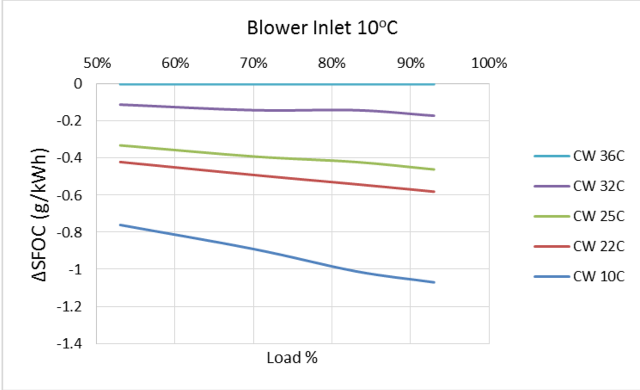


Figure 24 SFOC reduction for 10 °C engine room temperature.

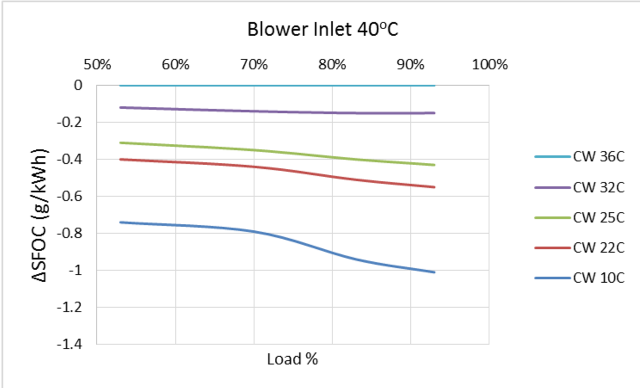


Figure 25 SFOC reduction for 40 °C engine room temperature.

CONCLUSIONS

The Engine Hyper Cube database and relevant software, by Propulsion Analytics, is a multidimensional hypermap of engine performance for all possible combinations of engine set points, throughout its load and speed range, for various fuel oil characteristics and any outside conditions. Before delivery to the shipping company, the Engine Hyper Cube database for each engine, whether propulsion or gen-set, is built up separately using an engine process simulation software, which is configurable to any engine type.

At the start of deployment of Engine Hyper Cube in the fleet of EURONAV a single blind validation was performed to ascertain the accuracy of the methodology and the predictive potential. The results indicated recognizable shift in performance, at dates which were subsequently confirmed to be after maintenance events in the ship's records, thus confirming the validity and accuracy of the Engine Hyper Cube methodology.

After installation, the Engine Hyper Cube software can compare in real time the "measured/observed" values from any data acquisition system to the "calculated/healthy" values under the same conditions.

The Engine Hyper Cube software provides "expected" values for all engine operating parameters, including fuel consumption and torque, which are difficult to measure with accuracy, as well as engine internal parameters like pressures and temperatures, which are practically impossible to measure in service. The software detects abnormal behavior based on the residuals between "measured" to "expected" data, which can be due to observation or recording error, sensor malfunctions, or actual component degradation and engine problems, resolving between measurement or engine process issues. Therefore, any under-performance is not judged by comparison to pre-set thresholds from tables or average performance curves, but from expected values, generated in real time, for the actual operating conditions of the specific engine.

On one vessel, the resulting warnings for exhaust gas temperature and indicated power, were diagnosed to being caused by issues in the measurement process and sensors. In another instance, the diagnosed issues with the injection system were confirmed by the in-depth analysis of per-cylinder data.

The methodology implemented in the Engine Hyper Cube software and the relevant applications and cases presented in this paper, confirm the validity and usefulness of applying engine process models, as a means to generate a dynamic reference state for the engines, thus allowing the shipping company to benefit from rapid and dependable diagnosis of faults as well as suitable optimization of the engine's operation. The Engine Hyper Cube gives warning notifications, fault diagnosis and actionable items, historical trends as well as reliable "what-if" predictions. It saves all instances and provides histograms, allowing trends to be detected and developing problems to be pin-pointed. The software can be used continuously on any platform onboard or onshore as needed, for multiple instances and various engines, ships and fleets.

NOMENCLATURE

BSFC	:	Brake specific fuel consumption
CA	:	Crank angle
FBR	:	Fuel burning rate
FPI	:	Fuel pump index
HRR	:	Heat release rate
P	:	Pressure
rpm	:	Revolutions per minute
SFOC	:	Specific fuel oil consumption
T	:	Temperature
TDC	:	Top dead center
T/C	:	Turbocharger
VIT	:	Variable injection timing

Subscripts

comp	:	compression
exhaust	:	exhaust receiver
max	:	maximum
scav	:	scavenge receiver
turb inl	:	turbine inlet

REFERENCES

[1] Jardine K.S., Lin, D., Banjevic, D., "A review on machinery diagnostics and prognostics implementing condition-based maintenance". J. Mechanical Systems and Signal Processing, 20(2006). p.1483-1510.

[2] Wu, J. "Liquid-propellant rocket engines health monitoring- A survey". Acta Astronautica, 56 (2005) 347-356

[3] Petek, J., Hamilton P., "Performance Monitoring for Gas Turbines", Orbit, Vol. 25, No.1, (2005) p.64-74,

[4] Kimmich,F., Schwarte, A., Ishermann, R., "Fault detection for modern Diesel engines using signal-and process model-based methods. J. Control Engineering Practice 13 (2005) p.189-203

[5] Mohr, H., Teichmann, R., Mayrhofer, N., Pfister, C., Johansen,R., "Permanent Diagnosis and Optimisation of Large-Bore Marine Engine Operation with expert based AVL/EPOS", 26th CIMAC Congress, Paper No. 214, Bergen, 2010.

[6] Using Big Data for engine Preventive Maintenance and Reduction of Life Cycle costs-MOL Starts Demonstration of Next-Generation Condition Based Engine Monitoring System: News Release, cms.molpower.com, 08/10/2015

[7] Kyrtatos, N., Tzanos, E., Coustas, J., Vastarouchas, D., Rizos, E., "Shipboard Engine Performance Assessment by Comparing Actual Measured Data to Nominal Values Produced by Detailed Engine Simulation, 26th CIMAC Congress, Paper No.75, Bergen, 2010.

[8] Knutsen, K-E, Manno, G., Vartdal B-J, "Beyond Condition Monitoring in the Maritime Industry" Position Paper 6, Strategic R&I, DNV-GL, 2014.