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Towards the digital engine: benefits and integration of the OMT Intelligent Injection System

Digitalization & Connectivity

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This paper has been presented and published at the 30th CIMAC World Congress 2023 in Busan, Korea. The CIMAC Congress is held every three years, each time in a different member country. The Congress program 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 themes of the 2023 event included Digitalization & Connectivity for different applications, System Integration & Hybridization, Electrification & Fuel Cells Development, Emission Reduction Technologies, Conventional and New Fuels, Dual Fuel Engines, Lubricants, Product Development of Gas and Diesel Engines, Components & Tribology, Turbochargers, Controls & Automation, Engine Thermondynamis, Simulation Technologies as well as Basic Research & Advanced Engineering.

ABSTRACT

Artificial intelligence provides powerful ways of learning, controlling and optimising processes through data analytics. Its application to engine management promises to deliver better performance over the entire lifetime of its components and to minimise downtime, through continuous monitoring and condition-based maintenance. However, in order to reach such goals, the engine components need to evolve to generate enough data about their condition for the artificial intelligence to learn from and, consequently, act upon.

This paper explains how a common rail fuel injector was made capable of continuously providing information about its operation in service, how this was used to estimate the impact of injector malfunction on engine performance and emissions, and how such knowledge opened up the possibility to compensate via software the deviations of the hardware over time, thereby providing tangible operation cost savings whilst ensuring compliance with emission regulations.

The first challenge encountered along this path was the addition of instrumentation to the injector to make it capable of detecting key information about its operation. This required the development and integration in the injector design of a low-cost sensor, and the definition of advanced artificial intelligence algorithms aimed at extracting value added data from the sensor signal. Both topics are presented and discussed, showing how a wall deformation signal is used to reconstruct a model of the actual injection rate curve.

A suitable system architecture was developed for the purposes of collecting the data from the injector sensor, transmitting them to a local processing unit where they are analysed and kept in short term storage, calculating key performance indicators and alarms and presenting them to the operators, and transmitting key injector data to a remote cloud storage. Its features are introduced and discussed, paying particular attention to the topic of virtualisation of the on-board processing unit for easier integration in engine-wide or ship-wide monitoring systems, thereby avoiding hardware redundancy and the issues this entails.

The intelligent injector was then mounted on a medium-speed single cylinder research engine and operated in both diesel and dual fuel modes. Engine performance and emissions were recorded, first looking for the optimal operating points, and then simulating deviations in injector performance. Correlations between engine and injector behaviour were analysed and modelled, providing a way to estimate the cost of operating the engine with worn injectors and, as a result, the benefits of applying dedicated recovery actions suggested by the system.

1 INTRODUCTION

The goal to significantly reduce greenhouse gas emissions of the shipping industry is driving an evolution that foresees the use of carbon neutral fuels, such as methanol, ammonia, and even hydrogen, in large internal combustion engines [1].

Compared to operating a ship with conventional fuels, the adoption of new fuels will lead to an increase in OPEX due to their higher production price. It follows that maximisation of engine performance over its entire lifespan, as well as maximisation of component lifetime, become even more crucial to ensure competitive operation of the vessel [2].

In this respect digital technologies offer many ways of ensuring process optimisation and maximisation of component lifetime. In recent years, extensive instrumentation of the engine and its subcomponents has made available a large quantity of data, which can be analysed by artificial intelligence (AI) algorithms to extract meaningful insight that can be used for applications of condition monitoring, adaptive control and predictive maintenance [3] -[7].

Fuel injection equipment operation significantly affects engine performance, and the use of fuels which are more complex to manage due to their unfavourable physical properties and the need for pilot ignition [8] makes the injection system, and the injector in particular, one of the most critical elements for achieving operational efficiency. It follows that, to keep OPEX to the minimum throughout the vessel lifespan, it seems beneficial to implement strategies for continuously monitoring the operation of the fuel injection system, in order to be able to compensate drifts, predict faults and minimise maintenance costs.

For this reason, an injector monitoring system was developed by OMT and first presented at the CIMAC 2019 congress [9]. The system was continuously improved [10] and tested on a single cylinder engine so as to be able to quantify the effect of fuel injector performance drifts on engine consumption and emissions [11].

The benefits that such injection monitoring system can provide for the operator were further investigated in [12] where engine performance prediction algorithms using data generated by the injector monitoring system were compared with data measured with an indication system using an in-cylinder combustion pressure sensor. It illustrated that injector operation data can be beneficially employed to improve predictions of engine performance parameters usually acquired with an indication system. The combination of indication and injector monitoring systems would allow backup functionality and mutual condition monitoring.

In this work, a further step in demonstrating the benefits that digitalisation can offer in terms of continuous process monitoring and optimisation was taken, by focusing on the possibility of detecting hardware anomalies and failures and estimating their effect on engine performance. The potential for compensating such deviations was also investigated, and quantitative benefits were calculated, providing concrete evidence that supports the adoption of digitalisation as a key element to maintain operational competitivity.

2 INTELLIGENT INJECTION SYSTEM

An injector monitoring system must be able to continuously record and analyse the characteristics of the injection generated at each cycle. The difficulty, however, is that the injection rate on the engine can only be measured indirectly. Therefore, a model of the injection rate must be derived from other measurement data.

Considering that any sensor and the related conditioning electronics that are added to the injector contribute to increase its cost, to remain competitive and provide a solution that maximised the value for the customer it was decided to follow an approach to injector performance monitoring that minimised the cost of the instrumentation hardware. Advanced software techniques that made use of artificial intelligence were then developed and implemented to compensate the deviations and nonlinearities of the simplified (but cheaper) hardware.

The system and all its features were presented and discussed in detail in [9]-[12] and is briefly described here for ease of reference.

2.1 Instrumented injector

As injection rate cannot be measured directly on the injector mounted on the engine, another signal had to be identified from which an injection rate model could be reconstructed. It was decided to use for this purpose a signal related to the pressure in the control volume, i.e. in the small gap between needle (in yellow in Figure 1) and orifice plate (dark grey), because this pressure is modulated by the control valve to switch the injector needle position from closed to open and vice versa and, as such, is affected by movements of both control valve piston (red in Figure 1) and injector needle.

To keep cost down and ensure robustness, a custom sensor was developed and integrated in the orifice plate body, so that a deflection of the orifice plate wall under the influence of control volume pressure and of the force applied to it by the needle would result in a deflection of the purple elastic element and the consequent generation of a force applied to the light-blue piezoelectric elements, which converted it into a charge signal.

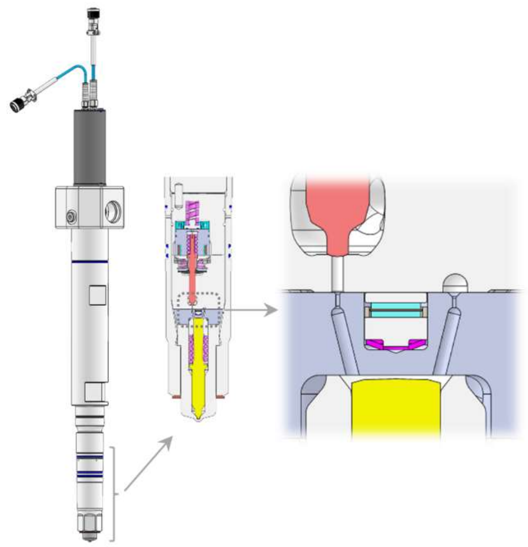

Figure 1. Instrumented injector (left) and detail of custom sensor (right).

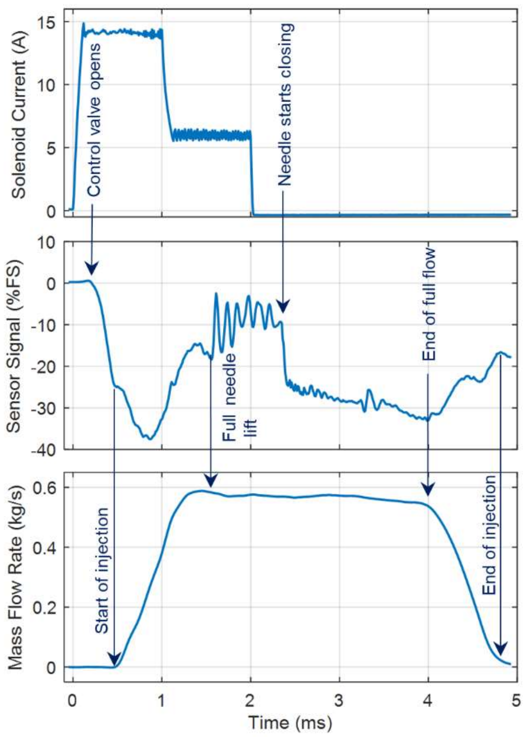

Figure 2. Experimental signals measured on the injector test rig.

By measuring the deformation of a wall of the orifice plate, no additional fuel channels needed to be drilled, resulting in robustness (no risk of leakages), simplicity, miniaturisation and reduced cost.

The signal obtained with this basic but functional sensor had high signal to noise ratio and contained the information required to reconstruct the key characteristics of the injection event, as shown in Figure 2.

As shown in [10], the gain of these embedded sensors varied from piece to piece, so that individual calibration needed to be performed before comparing the signals generated by two sensors. However, as each sensor primarily serves the purpose of monitoring the change of injection characteristics of the same injector over time, such variability did not create any practical limitations for this purpose.

On the other hand, the algorithms that performed the recognition of the significant time events that characterise an injection had to be developed in a way that such part to part variability did not represent an impediment to correct estimation of such value added data (VAD).

Hence, artificial intelligence algorithms and, in particular, feed forward neural networks, were used [11] to recognise the significant patterns in the sensor signal that identify the time event sought. This approach avoided the need to define specific thresholds that would inevitably be at risk of needing redefinition in case a new hardware variant did not comply with the general trend, causing the algorithm to fail.

Conversely, with these methods it was possible to calculate the main VAD with very high accuracy, as shown in Table 1.

Table 1. Accuracy of VAD calculation algorithms.

Regression VAD	2σ accuracy
SVO – Start of valve opening	12.1 μs
SOI – Start of injection	21.0 μs
SFIR – Start of full injection rate	90.0 μs
SNFS – Start of needle full stroke	27.6 μs
ENFS – End of needle full stroke	21.4 μs
EFIR – End of full injection rate	140.0 μs
EOI – End of injection	31.6 μs
Classification VAD	**Accuracy**
IsBallistic	100%

2.2 System architecture

Besides the instrumented injector, further elements were developed to make up the whole injection system data infrastructure that makes it possible to derive valuable insight from the signals recorded in the injector.

Figure 3 reports the complete logical architecture of the intelligent injection system. It was defined on three levels to offer modularity and ease of integration with third party systems at the desired level, as well as to provide a stand-alone vertical solution for edge to cloud.

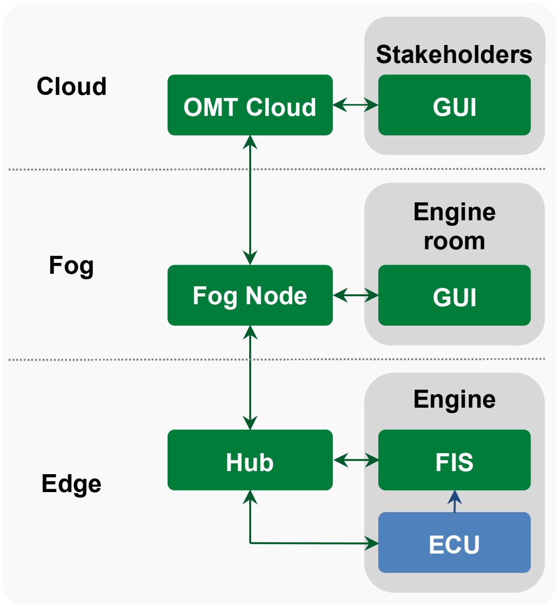

Figure 3. Architecture of the intelligent injection system.

Smart fuel injection system (FIS) components, such as the injectors, generate operation data through embedded sensors, and communicate them on a bus orchestrated by the data hub. The hub also works as a communication gateway by providing CAN and Ethernet interfaces that enable data exchange with the engine control unit (ECU) and with the data processing unit (Fog Node), respectively.

The Fog Node, or edge gateway, is at the heart of the system. It receives sensor data from the field, analyses them to extract value added data, and stores them in its internal database. It also calculates key performance indicators by analysing time histories of VADs and it compares them to initial characterisation data, to detect deviations from standard conditions and triggering warnings and alarms.

The Fog Node also exposes a web based graphical user interface, so that injection system operation data can be accessed via the on-board LAN even when internet connection is absent. When the internet connection is active, the machine can transfer all the stored data to a cloud server on shore, so that it can be used to develop and improve residual lifetime estimation algorithms which can then backpropagate their predictions towards the ship, to inform the crew that a specific component is reaching the end of its service life.

The cloud structure was designed with a set of access permits so that unauthorised data access is prevented, while authorised stakeholders can access data relevant to their needs, but that are otherwise made anonymous so that individual IPRs associated to the data are protected.

2.3 System interfacing and integration

In the case of integration with other intelligent systems on the engine, a subset of the proposed architecture can be supplied to the system integrator, and interfaces can be provided both at cloud and fog level, with and without graphical user interface.

In order to facilitate integration, the Fog Node can be provided as a containerised image, so that it can run directly on a ship datacentre, without requiring the installation of a dedicated computer. The container technology is proven and it is widely used to run proprietary software of different vendors on the same physical machine, allowing ease of integration and maintenance while ensuring proprietary data protection and secure execution.

Secure data exchange with other third-party subsystems is implemented through the use of MQTT [13], a standard, lightweight protocol especially developed for machine-to-machine communication. It is based on a publish/subscribe model that allows authorised subscribers to receive newly published data on a specific topic whenever it is made available. In this way, it is possible to regulate the type and amount of data that each subscriber is entitled to receive according to the specific license acquired.

Hence, the intelligent injection system here described can be easily integrated in a digital vessel environment which foresees a single data centre that runs all the containerised software modules of each vendor, and is ready to communicate in a standard and secure way with third party software to share the relevant insight to contribute to overall optimisation of ship operations.

3 FAULT SIMULATION

The injector monitoring system described in the previous chapter aims to provide to the operators insight into potential anomalies so as to enable them to take recovery actions aimed at minimising impact on operation costs.

In order to estimate the impact of a malfunctioning injector on engine consumption and emissions, a first set of anomalies was artificially generated by acting on the software that controls the injection system to vary injection timing, duration and pressure.

The effect of such variations was studied measuring engine performance and emissions, allowing to quantify, for example, the consumption penalty resulting from a delayed injection timing, as reported in detail in [11].

Besides the obvious effects on engine performance of an injector malfunction when operating in diesel mode, in the present work, the analysis was extended to take into account also engine operation with premixed natural gas-air mixture that is compression ignited via a small quantity of pilot diesel fuel delivered by the main injector (diesel-gas dual fuel combustion concept). Also in this case, the effect of a variation of the pilot injection mass was studied by varying control software parameters.

Conversely, other possible injector anomalies, such as clogged nozzle holes or control orifices, cannot be simulated by altering the injection system software parameters. As a result, a specific set of hardware parts was designed and built to generate injector operation anomalies typical of worn hardware parts and to estimate their effect on engine performance.

For this study, artificially worn components were built to simulate two possible anomalies: (i) clogged nozzle spray hole, due to carbon deposits, and (ii) partially clogged control volume feed (Z) orifice, due to dirt in the fuel, the characteristics of which are shown in Table 2 and compared to the baseline (unworn) case.

Table 2. Characteristics of baseline and artificially worn hardware.

ID	Anomaly	Q_{100}	Q_Z
BASE	Baseline	100%	100%
FAULT1	Fully clogged spray hole	87.5%	100%
FAULT2	Partially clogged Z-hole	100%	69.8%

3.1 Pilot injection mass drift

The effect of a drift in pilot injection mass was investigated on the test rig, seeking the correlation between injection duration (ID) and injected mass, which is shown in Figure 4, and was found to be very strong for all hardware versions here considered. Furthermore, in the small injection region the curves of baseline and clogged spray hole resulted superimposed, because the very low needle lift causes most of the pressure drop to occur between needle and seat.

This implies that the injection duration measured by the monitoring system can be used to detect, to a large extent, even small variations in injected mass, the effect of which on engine performance is reported and discussed in section 4.1.

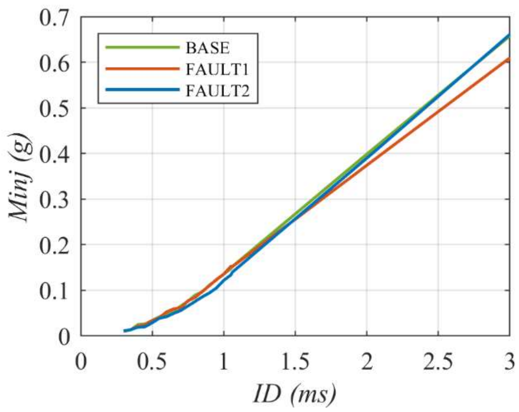

Figure 4. Correlation between injection duration and injected mass for the three hardware variants.

3.2 Fully clogged spray hole

Figure 5 shows the effect of a clogged spray hole on the injection rate profile. Compared to the baseline case, the reduced nozzle flow area results in a lower maximum mass flow rate and in a slightly delayed end of injection. The figure also reports a comparison of the signals generated by the monitoring sensor in both cases.

Analysing the monitoring signals with the artificial intelligence algorithms previously described it was possible to calculate the VAD related to the two cases, and compare them. As shown in Table 3, the monitoring system correctly detects a significant increase in injection duration partly due to late departure of the needle from its top position (ΔENFS) and mainly due to a longer time needed to complete the closing stroke (ΔEOI). The other variations are comparable with the sampling resolution (0.01 ms), indicating no significant change.

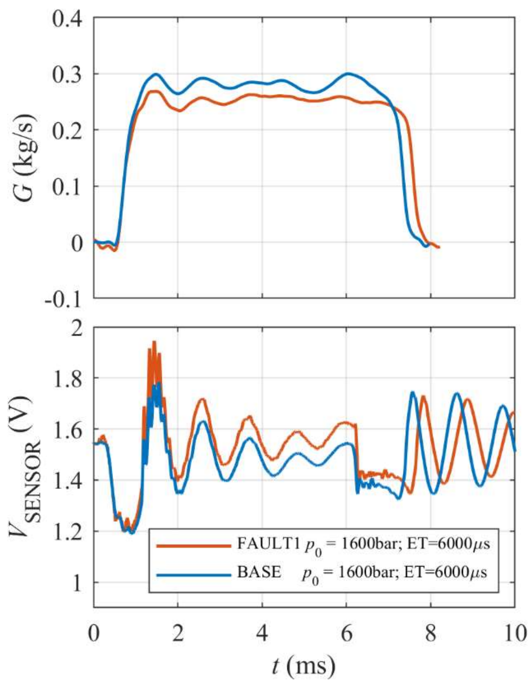

Figure 5. Effect of a clogged spray hole on injection rate (top) and on the monitoring signal (bottom).

Table 3. Effect of clogged nozzle hole on injector VAD (timing variation with respect to baseline hardware – 1600 bar - 6000 μs - 750 rpm).

VAD	Timing variation (ms)	Timing variation (°CA)
ΔSOI	-0.01	-0.04
ΔSNFS	0.01	0.04
ΔENFS	0.05	0.22
ΔEOI	0.22	0.99

While the time instants indicated in Table 1 could be detected directly by pattern recognition on the signal generated by the monitoring sensor, in order to detect the reduction in mass flow rate it was necessary to analyse the amplitude of the oscillations recorded after the end of injection. These are caused by water hammer effect during injector closing and, as such, are related to the injection flow rate when the injector was fully open.

Before comparing amplitudes, the signals were scaled to compensate for different sensor gain, aiming to obtain equal values of the initial voltage drop between SVO and SOI events.

Figure 6 shows the differences in amplitude of the residual oscillations obtained when operating the injector with the two different nozzles. The ratio of the amplitudes resulted in flow rate ratio of 0.87 (worn vs unworn), which is very close to the real value reported in Table 2.

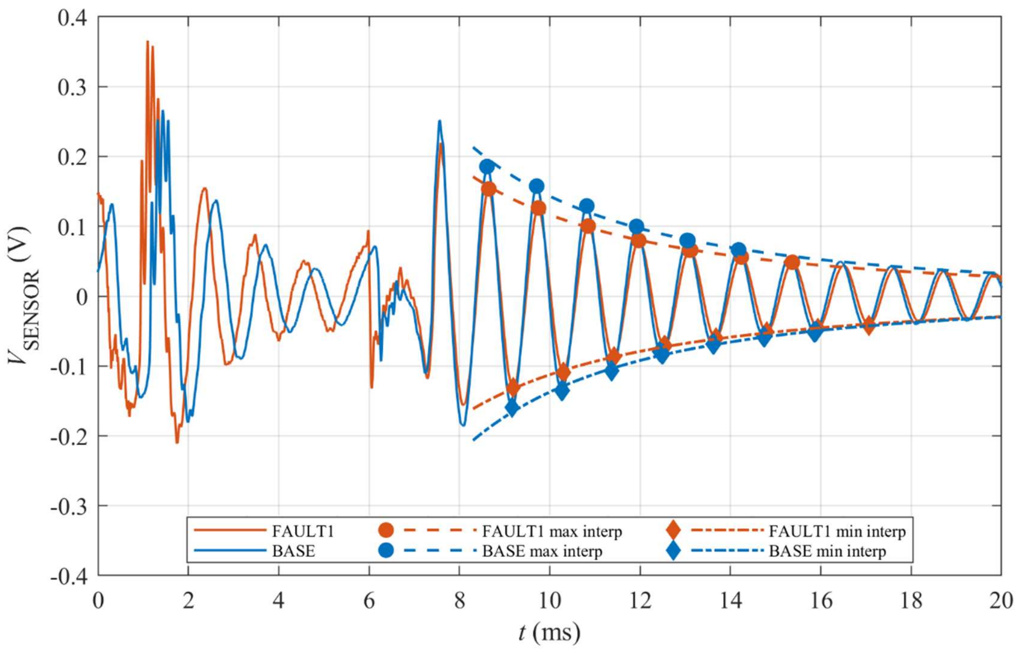

Figure 6. Visualisation of different oscillation amplitude resulting from different injection flow rate values (clogged vs. new nozzle). Time scales adjusted to synchronise signals on the first oscillation.

3.3 Partially clogged Z-hole

The dynamics of the injector is controlled via the calibration of two small orifices identified with the letters Z and A that connect the control volume with the supply and discharge lines, respectively. These are visible in the enlargement of Figure 1, with the orifice A located on the left of the custom sensor, directly below the control valve, and the orifice Z located to the right of the sensor.

The Z hole is responsible for refilling the control volume to cause injector closing, and its size affects injector closing speed. This hole is only a few tenths of millimetre in diameter and, as such, is prone to getting clogged with impurities present in the fuel, resulting in a modification of the injection rate shape.

Figure 7 shows the effect of a partial clogging of the Z-hole on the injection rate profile. Compared to the baseline case, the reduced orifice flow area results in a delayed end of injection.

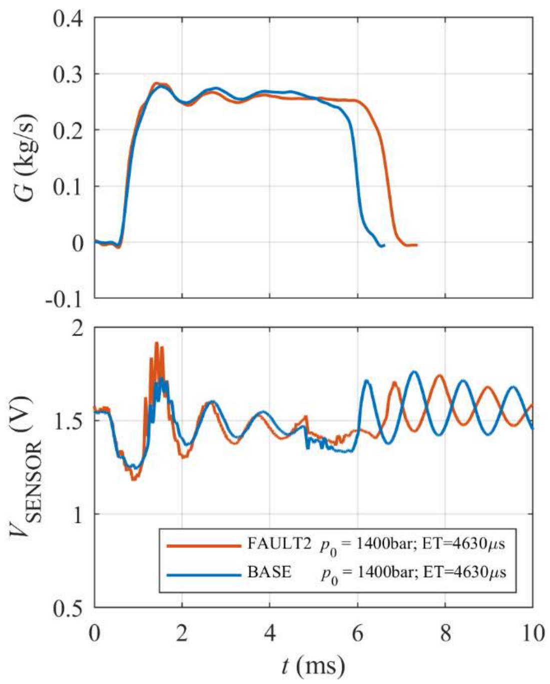

Figure 7. Effect of a partially clogged Z-hole on injection rate (top) and on the monitoring signal (bottom).

Also in this case, the data collected by the monitoring system allowed to estimate the entity of the increased end of injection delay, as reported in Table 4. No significant effect was detected on the other VAD. These findings, obtained using only the monitoring signal, were well in accordance with the data measured on the injection test rig, and therefore useful for effectively monitoring injector operation on the engine (where the injection flow rate signal is not available).

Table 4. Effect of partially clogged Z-hole on injector VAD (timing variation with respect to baseline hardware – 1400 bar - 4630 µs - 750 rpm).

VAD	Timing variation (ms)	Timing variation (°CA)
ΔSOI	-0.01	-0.04
ΔSNFS	0.02	0.08
ΔENFS	0.03	0.13
ΔEOI	0.59	2.66

4 ENGINE TESTS

To evaluate the capabilities of the intelligent injection system in an engine environment, tests on a single-cylinder research engine (SCE) were carried out at the Large Engines Competence Center (LEC), pursuing the following specific objectives:

- Investigate the impact of worn injection hardware (e.g. drift, clogged nozzle hole and partially clogged feed hole on the orifice plate) on engine performance and examine potential compensation measures, cf. section 4.1 and 4.2.
- Investigate the application of the intelligent injection system as an alternative or as a useful addition to an indication system for the purposes of combustion control and condition monitoring, cf. section 4.3.

While the former topic focuses mostly on the injection system itself, the latter considers the injection system as an integral part of an engine combustion control system, thereby exploiting the opportunities arising from real-time connectivity of engine subsystems.

The engine tests were performed on a medium-speed, four-stroke SCE with a displacement of 15.7 dm^3, key specifications of which are listed in Table 5. The main mechanical setup consisted of the research engine whose crankshaft is connected to a dynamometer. This assembly was mounted on a rigid, air-suspended base frame as illustrated in Figure 8. The fuel injector with its rotationally symmetrical spray hole layout was mounted in a central position on the cylinder head. Nozzle flow rate and spray targeting were designed to match with the desired engine power output and the employed piston bowl shape, respectively.

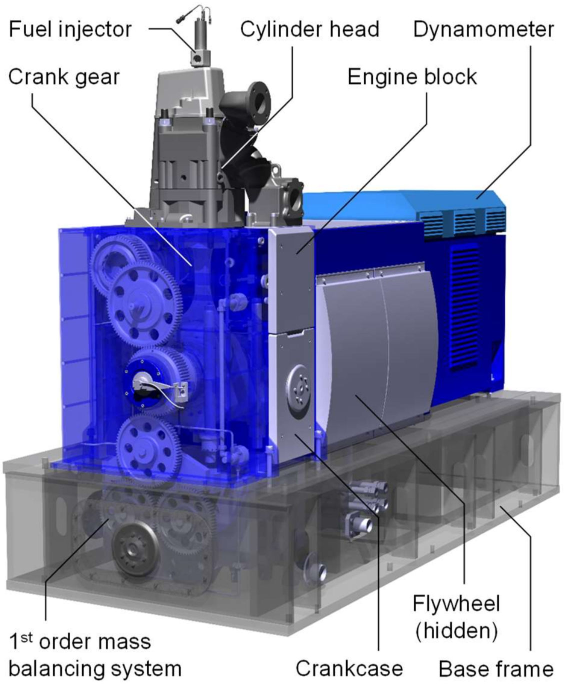

Figure 8. Mechanical setup of the single-cylinder research engine.

Table 5. Technical specifications of the single-cylinder research engine.

Rated speed	1050 min^{-1}
Bore	250 mm
Stroke	320 mm
Displacement	15.71 dm^3
Conrod length	590 mm
Compression ratio	17:1
Number of inlet/exhaust valves	2/2

To enable engine operation at defined and reproducible operating conditions, extensive external conditioning systems were used for coolant, lubricating oil, charge air, ambient air and fuel. To simulate the presence of a turbocharger, charge air pressure in the intake manifold was generated by an external compressor and back pressure in the exhaust pipe was controlled by a flap. High-pressure diesel fuel supply on the SCE was achieved with help of an external Hammelmann HDP 24 pump which delivers rail pressures of up to 3500 bar and includes a high-pressure fuel accumulator. For diesel-gas dual fuel operation, a port fuel injection valve serves for low pressure natural gas admission.

The intelligent diesel fuel injector was operated via a user-configurable electronic control unit (ECU). With this setup, all relevant ECU parameters acting on the control valve (e.g., start of current and energizing time) could be adjusted, monitored and recorded via an interface to the test bed automation system. A second interface enabled a bi-directional communication between the intelligent injector and the test bed automation system, thereby facilitating e.g., the acquisition of injection system VAD and other SCE data synchronously when a measurement was taken.

For the presented SCE investigations, steady-state operating points were set precisely before corresponding measurements were triggered. State-of-the-art time- and crank angle-based measurement systems served to record all relevant measurands from the engine itself and from its periphery. Several key result parameters were based on further processing of the data, e.g., by means of cylinder pressure trace analysis. Testing was focused on engine speed and load combinations relevant for power generation (constant speed) and ship propulsion (propeller law). For these applications, a rated speed of 750 min^{-1} and a rated SCE BMEP of 20.3 bar were chosen. Further details about the engine operating strategies will be outlined along with the specific investigations presented in the subsections below.

4.1 Impact of pilot injection mass variation on engine performance

To investigate the impact of the pilot diesel fuel injection mass on engine performance, the SCE was operated in diesel-gas dual fuel mode at its nominal BMEP and with an energetic diesel fraction of 1% (representing the share of energy introduced to the combustion chamber by the pilot diesel fuel).

Originating from this baseline operating point, pilot fuel quantity (and thereby energetic diesel fraction) was slightly varied. Since combustion stability in diesel-gas operation is an issue, combustion phasing of the baseline operating point was chosen so that stable engine operation is still achieved, even when combustion phasing is further delayed, e.g., due to a decrease in pilot fuel mass. Key results of the study are presented in Table 6.

Table 6. Effects of pilot injection mass on engine performance.

Energetic diesel fraction	BSFC (g/kWh)	BSNO$_x$ (g/kWh)
1% (baseline)	199.5	5.7
0.6%	204.2	2.7
1.4%	196.7	8.6

Even though the variation is limited to ±0.4% points of the total pilot fuel energy input, the effects on overall fuel consumption (diesel equivalent) and NO_x emissions are significant, and can be explained as follows.

With less pilot fuel mass injected, the main combustion process is slower and thermodynamically less efficient (and vice versa). Furthermore, with less pilot fuel mass injected, the premixed combustion peak is smaller and the main combustion process slower, both leading to lower NO_x emissions (and vice versa). This can be visualised also looking at the heat release rate (HRR) recorded in the different operating conditions reported in Table 6, which is shown in Figure 9.

It follows that, in order to use the main injector for reliably igniting the main fuel when the engine operates in diesel-gas mode, it is necessary to accurately control the pilot quantity to very tight tolerances. This can be achieved when all the components are new but, once they start wearing out, drifts are unavoidable. In this case, the intelligent injection system can help the ECU in keeping the pilot quantity under control by continuously recording pilot injection timing and duration.

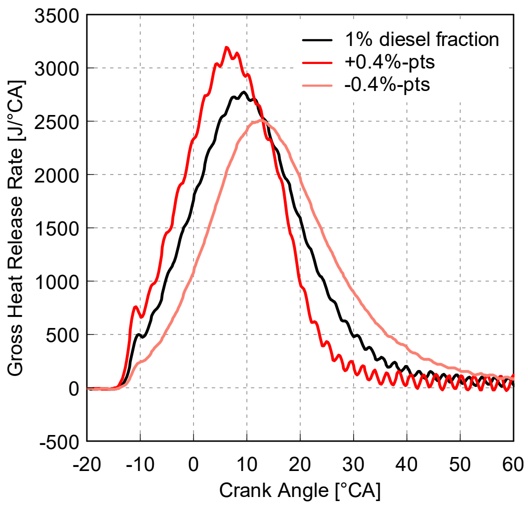

Figure 9. Gross heat release rate curves obtained with different energetic diesel fractions in diesel-gas operation.

4.2 Impact of injector wear on engine performance in diesel mode and corresponding wear compensation measures

To investigate the impact of artificially worn components of the intelligent injector on engine performance and to evaluate potential wear compensation measures, a dedicated measurement plan was developed and carried out on the SCE. First, selected application-relevant diesel fuel operating points were investigated on the SCE with unworn injection hardware to provide a baseline. In a second step, each of the artificially worn injection hardware variants was employed on the SCE and studied by means of three specific scenarios, which are outlined in detail below. All scenarios have in common that engine speed, rail pressure, charge air pressure and temperature as well as exhaust manifold pressure were kept constant at the level of the corresponding baseline operating point. With the latter three parameters in particular, this procedure is based on an initial approximation in which the impact of a single wear-affected cylinder on the turbocharger behaviour on a MCE is considered small.

1. To achieve a direct assessment of the impact of an investigated wear phenomenon on engine performance, the injector settings in terms of start of current (SoC) and duration of current (DoC) of the solenoid valve were kept constant. Thereby, BMEP, excess air ratio and combustion phasing (MFB50%) could deviate from the corresponding baseline operating point and were considered results.

2. To investigate engine performance when the original cylinder load is restored by means of an adapted injection duration, the DoC was adjusted to match the baseline BMEP.

3. To study engine performance when both the original cylinder load and combustion phasing are restored, DoC as well as SoC were adjusted to match the baseline BMEP and MFB50%.

Figure 10 illustrates key SCE results plotted over the three operation scenarios for both the clogged nozzle hole as well as the partially clogged orifice plate feed hole hardware variants. The corresponding baseline results obtained with the unworn hardware are indicated by the dashed lines. For this particular study, the SCE was operated at nominal BMEP (20.3 bar), nominal speed (750 min^{-1}) and a rail pressure of 1400 bar. The operating point was chosen as a representative example due to the significance of high load operation in the duty cycles of large engines and due to the high impact of changes in brake-specific fuel consumption (BSFC) on absolute fuel consumption (and related costs). The baseline settings such as the injection SoC were chosen in a way that a low BSFC and low engine-out soot emissions were achieved, while NO_x emissions were comparatively high (assuming a corresponding exhaust gas aftertreatment system to be in place on a related production engine).

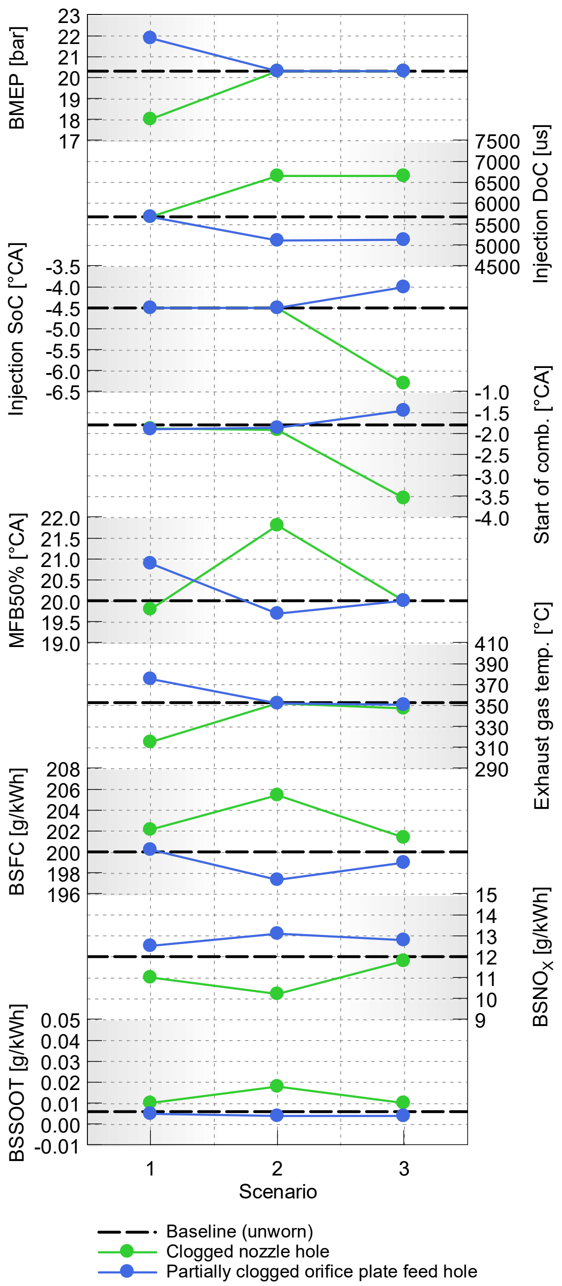

Figure 10. Key engine results obtained with the baseline configuration (unworn injection hardware) as well as with the artificially worn hardware variants.

With the clogged nozzle hole, it can be found that the achieved BMEP as well as the exhaust gas temperature decrease significantly when both SoC and DoC are taken over from the baseline investigation (scenario 1), while start of combustion and MFB50% practically do not change. This can be explained by nozzle's reduced flow rate, which leads to a smaller injected fuel mass per cycle when the baseline injection duration is maintained.

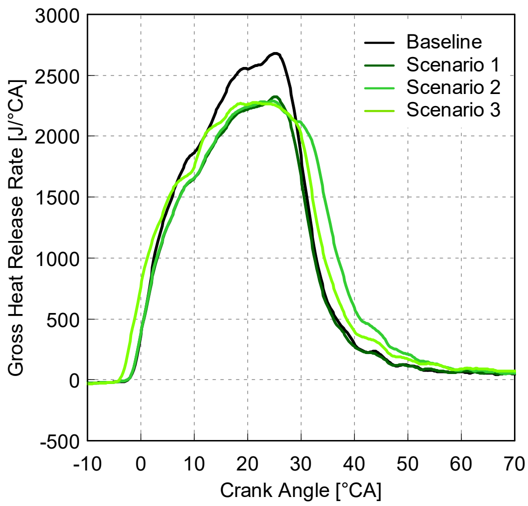

Figure 11. Gross heat release rate curves obtained with the baseline (black) and with the clogged nozzle hole (green) configurations.

The behaviour is further described by means of the corresponding heat release rate curve in Figure 11. It illustrates that while start and end of combustion are practically the same and the overall shape of the heat release rate curve is very similar compared to the baseline, the peak heat release rate is considerably smaller. Due to the change in engine power output, brake-specific results are not directly comparable to the baseline and will thus not be further discussed.

In scenario 2, the baseline BMEP and, consequently, the exhaust gas temperature is restored by adjusting the injection DoC, thereby increasing the injected fuel mass per cycle. While the start of combustion remains practically at baseline level, the MFB50% is retarded, as explained by the corresponding HRR curve in Figure 11. Compared to the baseline, the longer and thus thermodynamically less favourable combustion process leads to a penalty of approximately 5.5 g/kWh in BSFC. Concerning emissions, the overall slower combustion process is beneficial in terms of NO_x, but leads to an increase in soot.

In scenario 3, both BMEP and MFB50% are maintained at baseline levels through adjustment of injection DoC and SoC, which in turn also leads to practically the same NO_x and soot emissions as with the baseline combustion process. A small penalty of approximately 1.5 g/kWh in BSFC remains, however, due to the inferior shape of the HRR curve.

With the artificially partially clogged Z-hole on the orifice plate, as shown in Figure 7 and Table 4, the injector closes considerably slower compared to the baseline injector configuration. As illustrated in Figure 10, in scenario 1, this injection behaviour leads to an increase in BMEP due to a larger injected fuel mass.

Based on the corresponding HRR curves in Figure 12, it can be found that while the impact of the changed injector opening behaviour with the artificially worn hardware seems to be small (the rising edge of the HRR curve is hardly affected), the slower needle closing results in a significant longer combustion process, which increases cylinder load and shifts MFB50% further away from top dead centre compared to the baseline.

Therefore, in contrast to SCE operation with the clogged nozzle hole, in scenario 2 the injection DoC needs to be decreased to restore the nominal BMEP level and the corresponding exhaust gas temperature. This in turn leads to a slight advance in MFB50%, increase in NO_x emissions and decrease in BSFC compared to the baseline, while the soot emissions are hardly affected.

Adjustment of SoC and DoC in scenario 3 to match the baseline BMEP and MFB50% finally leads to approaching the NO_x and BSFC results achieved with the baseline configuration (small differences remain, which could likely be eliminated by further adjustment of the injection timing). Overall, the impact of the partially clogged feed hole on the orifice plate was found to be smaller than that of the clogged nozzle hole and the anomaly can be practically fully compensated since only the end of injection is delayed, while the nominal nozzle flow rate is not changed.

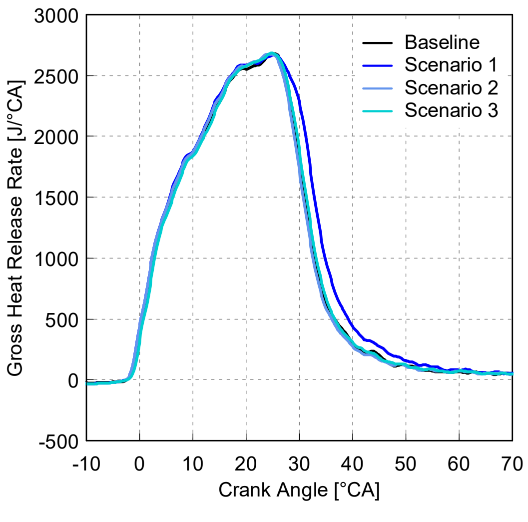

Figure 12. Gross heat release rate curves obtained with the baseline (black) and with the partially clogged orifice plate Z-hole (blue) configurations.

While not presented in detail in this publication, SCE testing at other baseline operating points (i.e., part load operation for both marine and power generation applications) revealed a similar impact of the investigated injection hardware variants on combustion behaviour and thus on engine performance.

In summary, the SCE results illustrate that the investigated wear phenomena have a significant impact on engine performance. Undesirable consequences such as penalties in BSFC can be compensated to a large extent, in particular if not only BMEP but also combustion phasing can be adjusted to match with the baseline values.

The intelligent injector is a key tool to enable such an advanced wear compensation strategy. Making use of the VAD that the system calculates for every injection cycle it would be possible to control both injected fuel mass and phasing of the injection process, thereby achieving the best possible combustion process for any given wear status.

Further enhancement could be achieved by a corresponding real-time capable model that predicts combustion parameters based on injection system VAD and engine parameters readily available on production engines, an approach that will be outlined in detail in section 4.3.

4.3 Prediction of combustion parameters based on the intelligent injection system

Besides the usage for purposes such as stand-alone wear and drift compensation as outlined in section 4.2, great potential lays also in employing the intelligent injector in synergy with other digital systems in ICEs. An option closely related to the topic of combustion control is to use the intelligent injection system as an alternative to costly and delicate indication systems.

To this end, it was investigated how accurate key combustion parameters usually obtained with an indication system (Figure 13b) can be predicted with help of a data-driven model that uses a combination of injection system VAD (Figure 13a) and standard engine parameters (Figure 13c) as features. The latter is expected to be readily available in production engines, thus enabling a later implementation of the concept in series application. The study was published in detail in [12], the key approaches and results are summarized below.

A comprehensive SCE measurement database for the modelling study was established synergistically with engine performance testing for diesel marine propulsion and power generation application scenarios.

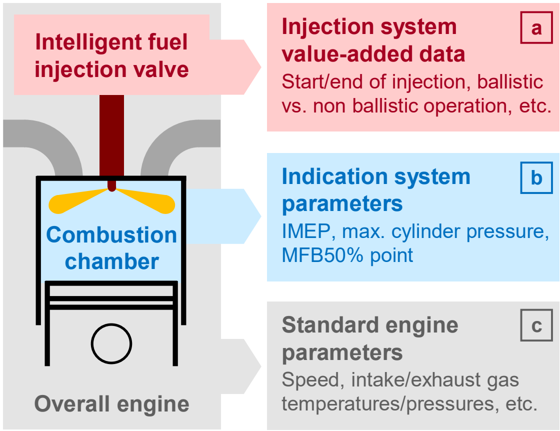

Figure 13. Intelligent fuel injector, combustion chamber, overall engine and corresponding measured and/or modelled parameters (based on [12]).

Within this database, the investigated SCE BMEPs and speeds range from 1.8 to 20.3 bar and 348 to 1000 min^{-1}, respectively. It furthermore includes variations of key engine operating parameters such as excess air ratio, injection timing and rail pressure.

A total of 715 measurements (247 engine operating points with up to 3 repetitions each) were acquired and provide the basis for data-driven modelling of IMEP, maximum cylinder pressure and 50% fuel mass fraction burned point (model targets) with help of supervised ML approaches. Two different scenarios, A and B, were considered:

A. Both injection system VAD and standard engine parameters serve as model input features. Thereby, the concept is to fully exploit both the available information from the intelligent fuel injector as well as standard measurement data readily available from production engines.

B. Only the standard engine parameters serve as model input features. Through comparison of the results from to scenarios A and B, a deeper understanding of the benefits of the information obtained with the intelligent injector can be generated.

Several ML methods were compared based on a dedicated data splitting and model training strategy, see [12]. Separate training was conducted for each of the model targets and scenarios (using identical data splits). Throughout, a kernel ridge regression approach was found to achieve the best predictive performance. These models were therefore further assessed based on a test data set that was not used during model training, the results of which are illustrated in Figure 14. The outcomes show that when both standard engine data and intelligent injection system VAD are considered as model features (scenario A), the model targets can be predicted with a high accuracy that would be acceptable for combustion control purposes (cf. [12]). The advantage over standard engine parameters as features only (scenario B) is not very pronounced but could likely gain importance if model training also considers worn injection equipment, whose characteristics are not inherent to the standard engine data. While the modelling results in Figure 14 rely on a database that was created with unworn injection components only, the inclusion of wear phenomena in the presented data-driven approach is currently under investigation.

Besides employing the intelligent injection system as an alternative to an indication system, there is also an application case conceivable in which both systems are in place, in particular to obtain a backup functionality of the combustion control system as well as to allow for mutual condition monitoring of the indication system and the intelligent injector.

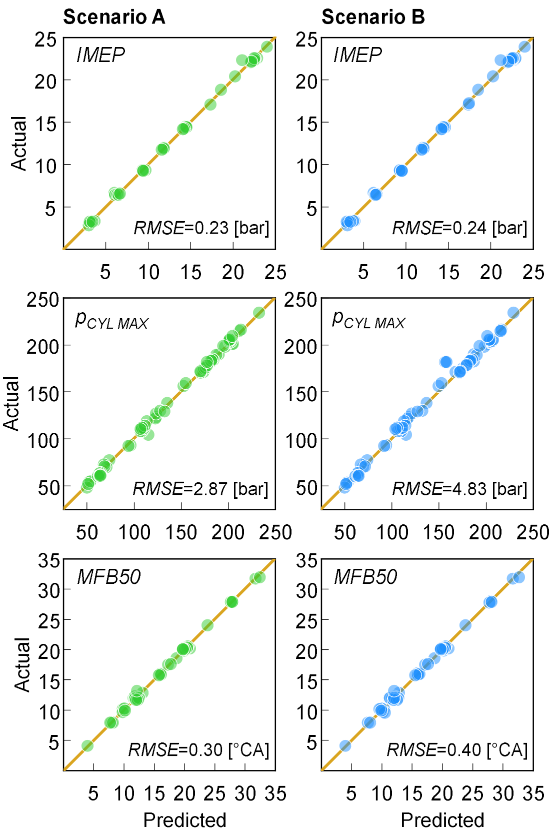

Figure 14. Modelling results for the unseen test data for all target parameter (based on [12]).

Specifically for the latter purpose, suitable approaches for diagnosis will be required to identify the source of error in case that the two systems do not deliver consistent results and therefore indicate an unwanted condition (e.g., wear or failure) on one or both of them.

Overall, advanced data-driven modelling of combustion parameters based on injection system VAD and standard engine parameters opens up several promising avenues towards advanced combustion control and condition monitoring approaches. For series engine application, the consideration of injector wear in the model building process (currently under investigation) will likely be key to ensure a high prediction accuracy throughout an injector's lifetime.

5 VALUE CREATION

The anomalies that were studied in the present work represent a subset of typical failures that do occur when operating marine engines in the field but that are not usually detected immediately as they happen.

The intelligent injection system proved capable of characterising injector behaviour and thus identifying and quantifying the deviations due to the simulated anomalies. With the help of the SCE, it was possible to quantify the effect on engine operation of the improper functioning of the injector. This enabled calculating the resulting impact on OPEX according to the scenarios outlined in section 4.2

Analysing, for example, the case of the clogged spray hole, and considering an engine with unit power of 600 kW/cylinder, a fuel cost of 570 $/t, and a yearly utilization of 6000 h, this anomaly would result in the additional fuel expenses detailed in Table 7.

Table 7. OPEX impact of a clogged spray hole.

Scenario	Δ fuel burnt daily	Δ daily cost	Δ yearly cost
2	78.5 kg	43.9 $	10,987 $
3	19.4 kg	10.9 $	2,722 $
Saving	*59.1 kg*	*33.0 $*	*8,265 $*

In scenario 2, which represents the typical case of a MCE in which cylinders are balanced with the exhaust gas temperature signal, the anomaly would cause the control system to increase injection duration to recover the expected cylinder power, resulting in an additional daily consumption of 78.5 kg of fuel without the user even noticing that something went wrong.

In scenario 3, the presence of the intelligent injection system enables the control unit to know that one injector is malfunctioning and especially how it deviates from the expected behaviour, so that an adequate choice of injection start and duration can minimise as much as possible the effects of the anomaly. In such case, the daily increase in fuel usage is limited to 19.4 kg, resulting in a saving of 59.1 kg/day of fuel, for an expected yearly saving of 8,265 $ for a single anomaly of this kind.

The intelligent injection system also allows the engine operator to visualise such figures, enabling him/her to take additional actions, such as planning dedicated maintenance, that can fully recover injector operation.

Furthermore, in engines that operate without indication system, the intelligent injection system can improve the prediction accuracy of engine operation parameters, as shown in 4.3. This combines the benefits of identifying the injection system defects and quantifying the effects on engine performance with the OPEX savings of not having to maintain and periodically replace the combustion pressure sensors.

Dual fuel engines can also greatly benefit from a monitoring system that can detect changes in pilot injection characteristics and inform the ECU so that appropriate compensations can be put in place. According to the results reported in Table 6, a reduction of 0.4% points in diesel energy fraction can increase BSFC by 4.7 g/kWh.

Considering the same engine size and yearly utilisation previously used for calculating the impact of a clogged spray hole, and considering a natural gas price of 1000 $/t, such single drift on a single injector would cause a yearly increase in fuel costs of 16,925 $, as shown in Table 8.

Considering that this drift is likely to occur on more than one injector, it becomes evident that significant savings can be made with an intelligent injection system connected to an engine ECU that implements pilot injection drift compensation techniques.

Table 8. OPEX impact of pilot injection drift.

Δ Energy fraction	Δ fuel burnt daily	Δ daily cost	Δ yearly cost
-0.4% points	67.7 kg	67.7 $	16,925 $
+0.4% points	-40.3 kg	-40.3 $	-10,075 $

Table 8 also shows that a drift in the opposite direction (i.e., pilot injection quantity increase over time) actually leads to fuel savings. However, as shown in Table 6, this comes at the expense of a 51% increase in NO_x emissions. In the case that the settings of the initial engine operating point were chosen to obtain best possible engine performance at a specific NO_x emission limit, such a large deviation in NO_x would be unacceptable. Hence, compensation of pilot injection drifts does not only bring financial savings but also helps ensuring emission legislation compliance.

The progressive adoption of synthetic fuels such as methanol and ammonia is expected to bring an even stronger focus on pilot injection control, as the price of such molecules will be higher than those from fossil origin, and so maximisation of engine efficiency is predicted to gain even more importance.

The data models reported here are based on the specific engine used for our investigations. While they cannot be directly adopted as-is for other engines, the approach followed can be rolled out to other models and tuned accordingly for each specific model.

6 CONCLUSIONS

While, in other industries (e.g. aviation), digitalisation is firmly established as a way to ensure reliable operation and process optimisation, the marine industry often still sees it as a sure source of cost and unsure source of benefits. Digitalisation is employed on ships, but its potential is by far not fully exploited, especially because the introduction of digitalisation occurred largely bottom-up by the initiative of individual vendors, rather than by a top-down demand of system integrators.

The present paper aimed to provide quantitative results that would demonstrate the tangible benefits for the engine operator that could be achieved when adding continuous monitoring capabilities to common rail fuel injectors and using the resulting insight for compensating component wear, thereby keeping engine efficiency to the maximum achievable in any given condition.

The OMT intelligent injection system was shown to be capable to provide the value added data needed to characterise injector operation with both unworn and worn hardware. The modelling methodology developed and detailed in previous works was then applied here to correlate injector drifts to changes in engine performance and emissions, and how these could be partially compensated adopting different strategies.

This made it possible to estimate concrete cost savings that could be expected when operating the engine with the knowledge of the injection system status, demonstrating the benefits that can be reaped when the systems evolve towards the creation of a “digital engine”.

In particular, due to the strong correlation between engine performance and pilot injection characteristics, the ability of the intelligent injection system to detect even slight variations of the pilot shot makes it ideal for implementing closed loop control strategies in engines operating with synthetic fuels.

7 DEFINITIONS, ACRONYMS, ABBREVIATIONS

AI: Artificial Intelligence

BMEP: Brake Mean Effective Pressure

BSFC: Brake Specific Fuel Consumption

$BSNO_x$: Brake Specific Nitrogen Oxides

CAN: Controller Area Network

DoC: Duration of Current

ECU: Engine Control Unit

FIS: Fuel Injection System

GUI: Graphical User Interface

HRR: Heat Release Rate

ID: Injection Duration

IMEP: Indicated Mean Effective Pressure

IPR: Intellectual Property Right

LAN: Local Area Network

MCE: Multi Cylinder Engine

ML: Machine Learning

MFB50%: (Point of) 50% of Mass Fraction Burnt

OPEX: Operational Expenditure

Q100: Nozzle flow rate with 100 bar pressure drop

Q_Z: Static flow rate of the control volume feed orifice

SCE: Single Cylinder Engine

SoC: Start of Current

VAD: Value Added Data

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