ANALYSIS OF THE EFFECT OF PIEZOELECTRIC SENSOR AGEING ON INDICATED PARAMETERS

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The research examines the ageing behavior of piezoelectric pressure sensors for internal combustion engine studies while concentrating on their declining sensitivity as time progresses. Reliable measurement of in-cylinder pressure demands precise monitoring of sensor performance to support both thermodynamic analysis and evaluation of engine performance. Research experiments performed with a single-cylinder research engine (SCRE) determine how the working cycle operational parameters relate to sensor properties, especially the indicated mean effective pressure (IMEP) and polytropic coefficients of the compression/expansion phase of the engine working process. The study demonstrates that monitoring polytropic coefficients provides an efficient technique for detecting sensitivity degradation without needing continuous pressure sensor recalibration, improving both accuracy and efficiency during prolonged engine testing. The approach allows researchers to detect sensor degradation on time, which helps maintain data integrity throughout lengthy research campaigns.

Key words*: Internal Combustion Engine Indicating, Piezoelectric pressure Sensor, Quartz durability, Piezoelectric Pressure Sensor Endurance*

1. Introduction

Since the early days of internal combustion engine research and development, in-cylinder pressure indication has been a widely used and essential technique for collecting and obtaining data on various phenomena that occur during the engine operating cycle. Because of their precision, robustness, and high-frequency response, measurement chains based on piezoelectric sensors nearly became industry standards in engine research labs more than fifty years ago. The piezoelectric pressure sensors measuring chain overcomes the difficulties associated with in-cylinder pressure measurement by making many compromises. Among the issues facing the engine indication system are the high temperatures to which the pressure sensor is subjected and the extensive range of pressure values to which the sensor must retain minimum non-linearity errors. Within the engine research domain, the strategies and tactics employed to address these problems have emerged as a topic of study, creating a nearly separate field.

One of the fundamental drawbacks of a measuring chain with a piezoelectric pressure sensor is its inability to measure absolute pressure. Consequently, one of the main tasks for researchers in indication measurement data processing is to convert the measured voltage signal from the charge amplifier into an absolute pressure signal. Since indicating refers to tracking a specific parameter of the engine working process in the angular domain, an additional challenge arises in identifying and synchronizing the measurement with the working process.

The errors in positioning the measured signal in both the angular and absolute pressure domains lead to inaccuracies in thermodynamic analysis. The relative magnitude of these errors can be significant [1] and can tremendously impact determining values such as the mean indicated pressure (IMEP) [2].

The influences, whose consequences should be minimized through carefully selected measures (from sensor installation to signal processing) are numerous [3]:

- Electrical interferences originate from various sources, such as the charging/discharging process of the ignition coil and the electrical discharge process at the spark plug, as well as disturbances caused by the triboelectric effect due to vibrations of the sensor measuring cable.
- Mechanical vibrations that are transferred into the electrical signal (inevitably, due to the measuring principle of piezoelectric sensors);
- Errors in determining the gain of the charge amplifier, the angular phase of the signal, and referencing in the absolute pressure domain;
- Errors due to analogue signal discretization by an ADC with limited resolution;
- Errors in determining geometric parameters of the engine (primarily cylinder volume, compression ratio, and kinematic parameters of the crankshaft mechanism);
- Errors caused by the so-called short-term thermal shock, i.e. the sudden exposure of the sensor to high-temperature peaks during the operating cycle ([4], [5]).

Piezoelectric pressure sensor-based engine indication technology has evolved significantly throughout the decades. Most of the abovementioned issues are addressed and more or less solved with great success. Moreover, commercially available system solutions provide indispensable tools for everyday R&D tasks within the engine test laboratory by integrating all measurement chain components and supporting dedicated digital acquisition systems under the supervision of particularly tailored real-time data evaluation software solutions.

The persistent issue in R&D tasks involving engine in-cylinder indication is related to the piezoelectric pressure sensor itself, i.e., its characteristic- mainly sensitivity, which changes over time (sensor ageing). There are various root causes of the piezoelectric pressure sensor characteristic change, where the high span amplitude of the dynamic delivery of the heat flux and mechanical stresses caused by the engine in-cylinder working process are the most influential. A significant influence on the gradual change of the sensor characteristics over time can also be provoked by sensor diaphragm area sooting by the build-up of combustion residue deposits. This exceptionally can be valid for sensors with an installed heat shield in front of the pressure-sensing diaphragm, where the in-between gap, filled with combustion residues over long-term operation, in extreme cases, can influence calculated IMEP error of 10% or more [6].

The sensor "ageing" issue is negligible if the R&D task on the engine is conducted on a short-term basis, which could be measured by a few days of full working shift utilization on the testbed since the sensor ageing process is relatively slow. The sensor ageing gradients heavily depend not only on the "in-use" time but also on the nature and distribution of the engine operating point load (amplitude and frequency of the high in-cylinder pressure gradients, number and frequency of preignition and/or knock events) as well as the sensor design and type of mounting (cooled/uncooled, diameter, flush or threaded mounting). In short-term usage, regular and thorough calibration of the sensor/amplifier measurement chain on dead-weight devices is sufficient to provide accurate updates on potential sensitivity change.

However, in cases where an R&D task requires long-term engine testing, which can last for weeks, conducting a measurement chain calibration on a daily basis can be counterproductive and not the most desirable procedure to conduct so often since it requires sensor dismounting from the engine. A large number of disconnecting/connecting the sensor from the (fragile) coaxial cable and a large number of unthreading/threading the sensor in a delicate mounting hole (particularly valid for small diameter sensors) is often considered as a risk for damaging the sensor/ mounting hole or introducing of some additional factor(s) which can influence the measurement accuracy.

The ICED Laboratory at the University of Belgrade Faculty of Mechanical Engineering handles daily extensive long-term R&D in engine combustion phenomena relying heavily on in-cylinder pressure indication and derived data evaluation and analysis. To ensure data plausibility of the highest possible degree, state-of-the-art testbed technology is used and best practice rules approach is to be complemented with best possible measurement quality check tools. This led to motivation to investigate the long-term ageing of sensors and potentially find a way to monitor the sensor condition during the testing process without requiring its removal and verification on a calibration device.

2. Experimental setup

The investigation of the piezoelectric sensor ageing process and methods for early recognition of their significant sensitivity change is conducted as a part of an intensive testing and research campaign on the engine testbed at ICED. The testbed is built around a versatile Single Cylinder Research Engine (SCRE), providing a platform on which many hardware changes can be implemented with reasonable efforts. Its features are presented in Table 1.

Daily testing is conducted on a prepared test plan. The good practices at ICED resulted in introducing the engine reference state measurements as mandatory first and last steps in the daily testing batches. Thus, important engine parameters can be tracked as indicators of the testbed state in general and the engine in particular. The relevance of the measured data as test bed status indicators is ensured through careful definition of the engine operating points (OP) being tested as references.

Table 1: Engine, dynamometer and test cell main features:

Engine	SCRE AVL 5404
Type	1 cylinder, 4 stroke, SI, 4 valves per cylinder VVT;
ECU	AVL RPEMS
Fuel	Gasoline
Fuel injection system	Modular / configurable (PFI, Side DI, Central DI)
Ignition	Modular (SI, PCI)
Supercharging	External

The term ERSM implies that both engine hardware configuration and operating point settings should be identical within a test batch. Since a test batch often incorporates test plans with some engine hardware changes, defining representative reference OP with a combustion process (so-called hot reference) is challenging, considering that hardware changes influence the combustion process. Therefore, two types of references are defined as valid and representative – the Cold Reference (CR) and the Hot Reference (HR). The CR is a strictly defined OP without combustion, i.e. it is conducted as motored OP, thus minimizing the effects of even minor hardware changes on in-cylinder pressure build-up. On the contrary, the HR is a strictly defined OP with combustion, thus providing realistic operation conditions but more prone to the influence of hardware changes. It is important to mention that both references operate with the same control parameters setpoints of the engine ECU and other testbed systems that directly affect the working process of the engine, such as the intake air conditioning system, the fuel conditioning system, the exhaust gas treatment systems, and the thermal level management systems of the cylinder block and the cylinder head by strict conditioning of the engine coolant and lubricating oil.

Regarding the engine hardware setup for this research, a unique hardware configuration of a gasoline-operated SCRE is selected in such a way as to minimize the effect on the variation of a fresh charge mass and motion in the cylinder during the measurement of the reference operation points. Namely, during the experimental test batch, the intake camshaft, exhaust camshaft, intake port tumble insert and compression ratio remained the same. On the other hand, some components and engine operation modes varied within the test batch in focus, like fuel injector position (side or central), fuel injection pressure (from moderate to ultra-high), spark plug type, and spark energy and ignition coil type. However, these changes are considered irrelevant or negligible to the working process of the cold/hot reference operating point, respectively.

The measured cold references were always adjusted as follows: wide open throttle (WOT), no fuel injection, the engine speed at 2000 min^{-1}, the absolute pressure in the intake manifold of 110 kPa (slightly boosted with independent/external air supply system), and the camshafts at the reference position. The coolant and lubrication oil fully conditioned at 90°C, while intake air is conditioned at 25°C. The hot reference was measured at 2000 min^{-1} and a relatively moderate load of 12 [bar] of IMEP, with retarded ignition advance angle of 2 CA ATDC in order to minimize the probability of preignition or knock appearance as well to preserve ("keep safe") the indicating sensor as much as possible. The coolant, lubrication oil, and intake air are conditioned the same way as in the cold reference.

The analyzed in-cylinder pressure sensor was a state-of-the-art M5 threaded, uncooled piezoelectric sensor with a nominal sensitivity 20 pC/bar sensitivity range coupled to the AVL MICROIFEM Gen 4 piezo amplifier. Detailed sensor specification is deliberately omitted since the research aims not to emphasize the behavior of any sensor type or any manufacturer in particular. Moreover, the long-term experience of at ICED with the topic showed that the behavior of comparable pressure sensors (of mainly used and well-known vendors) is very similar.

3. Experimental Test Batch Dataset

The test batch in focus gathered measurements from various test plans, comprised of almost 1500 quasi-stationary operating points with a total duration (summed engine operating time) of 200 hours. Figure 1 shows how the intensity of the testing campaign varied throughout the time. The same diagram also shows the indices of the measured cold and hot reference points. A total of about 70 cold and about 70 hot references were measured. Figure 2 shows how the cumulative indicated work of the engine is built over the test campaign time. An almost linear correlation, shown in Figure 2, implies that the engine load during the test campaign was more or less constant. The engine load could be considered a general indicator of the applied thermal load to the sensor, which is, besides operation time, an important factor influencing the pressure sensor ageing process. In order to get a more detailed picture of an operation point influence, various pressure indication parameters are taken into consideration besides Indicated Mean Effective Pressure (IMEP), like PMAX (value of the maximum pressure) and AMAX (angular position of the maximum pressure). An especially significant factor influencing pressure sensor ageing is the presence and intensity of irregular combustion events (preignition, knock); thus, the Knocking Pressure Peaks (KP_PK) indicator is also considered for the analysis. The Knocking Pressure Peaks parameter delivers the absolute maximum of the rectified knock oscillations superimposed on the cylinder pressure [7].

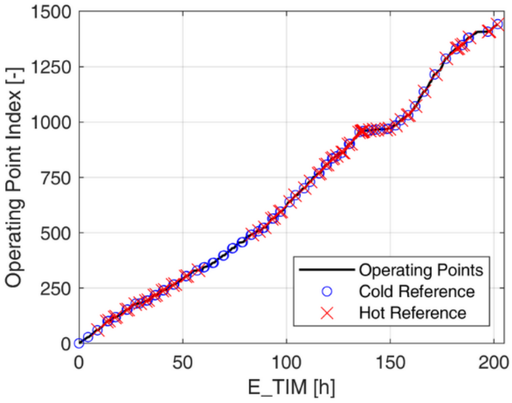

Figure 1. Number of recorded quasi-stationary operating modes with cold and hot reference indices.

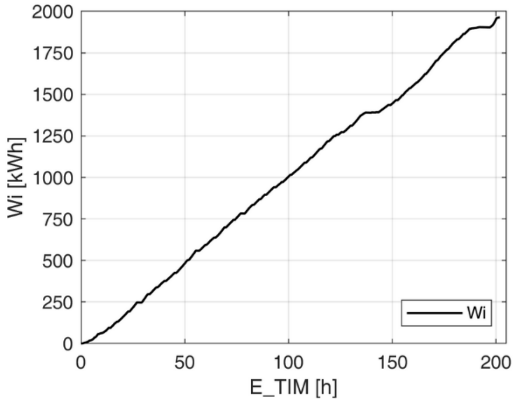

Figure 2. The cumulative indicated work achieved during the engine testing.

Figures 3 and 4 show the histograms of IMEP and the KP_PK, respectively, where the latter represents the intensity of the detonation in the combustion chamber while measuring the operating point. Additional info is that at 92% of operating points, engine speed was 2000 min^{-1} while the rest (the minority of OPs) populated testing at 1500, 3000 and 4000 min^{-1}. It can be noted from Figure 4 that the engine operation is mainly kept on an acceptable margin of the knock intensity (for the engine operation at 2000 min^{-1}). Each of the operating points is measured after a thermal stabilization of the engine is reached, where the deviation of the exhaust gas temperature less than 1°C is used as the deciding parameter.

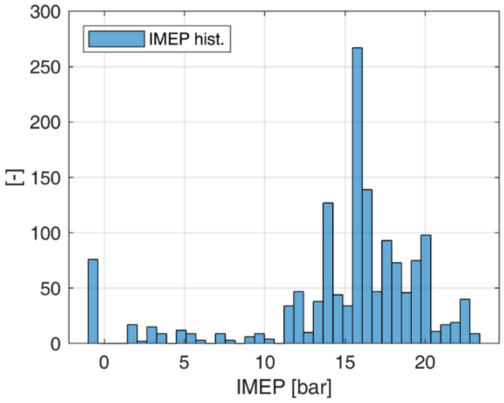

Figure 3. Distribution of values of IMEP for quasi-stationary regimes during testing.

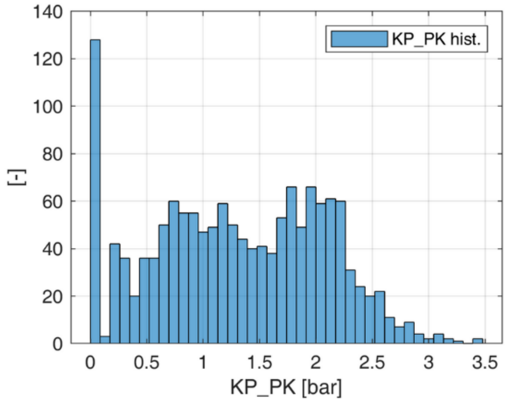

Figure 4. Distribution of KP_PK parameter values for quasi-stationary regimes during testing.

4. Experimental data evaluation

Each measurement of the operating point consists of 300 consecutive recorded cycles by the indication system (angular domain, 0.1°CA resolution). Parameters are calculated on each of the cycles and then averaged. Also, measurement includes time domain data from the test bed and engine ECU, which are evaluated in the data postprocessing phase.

Besides already mentioned indication parameters like IMEP (low and high pressure), maximum pressure value and angular position, additional focus is put on evaluating the polytropic coefficients of the compression and expansion phase of the process from the measured in-cylinder pressure curve. It is well known that both the compression and expansion phases of the engine working process can be treated as polytropic processes. Also, due to the complex nature of the heat transfer and its intensity variation during compression/expansion, the polytropic coefficient is also variable but within some commonly expected boundary values. Since the pressure sensor ages and accompanying sensitivity changes, the influence on the evaluation of the heat transfer process from the measured pressure curve becomes evident. Therefore, it is considered that the analysis of the change of the evaluated polytropic coefficients can be indicative. It should be noted that the average pressure curve was previously slightly filtered with a custom Savitzky-Golay filter [8]. All combustion-related data was analyzed using AVL Concerto software and "Catool" functions [9] for MathWorks MATLAB environment. Evaluation of the polytropic coefficients is done as follows [10]:

From the simple relation of the polytropic process

$$\frac{p_1}{P_2} = \left(\frac{V_1}{V_2}\right)^n \tag{1}$$

polytropic coefficient n can be evaluated as:

$$n = \frac{\log(p_2) - \log(p_1)}{\log(V_1) - \log(V_2)} \tag{2}$$

Indices (1,2) are related to the pressure and volume values at the boundaries of the treated angular window of the compression (or expansion) process. For the sake of having a broader picture of the polytropic coefficient change, the evaluation is conducted within a much wider angular window of [-170°CA, -5°CA] for the compression and of [5°CA, 170°CA] for the expansion phase, where 0°CA is declared as combustion phase TDC.

In order to get a smoother picture of the polytropic coefficient change, evaluation is conducted with an applied running average filter with a halfwidth of 15°CA:

$$\begin{gathered} n = \frac{\log\big(p(\alpha + hw)\big) - \log\big(p(\alpha - hw)\big)}{\log\big(V(\alpha - hw)\big) - \log\big(V(\alpha + hw)\big)} \\ \alpha_{compression} = [-170°, -5°]CA \\ \alpha_{expansion} = [5°, 170°]\ CA \end{gathered} \tag{3}$$

5. Indicated parameters for cold references

Figure 5 shows the log-log in-cylinder pressure trace for all recorded cold references. The first CR, i.e. the mode where the new sensor is installed, is marked in blue. The last CR measured within the test batch is marked in red and corresponds to a sensor that has been in use for the aforementioned period of time. The same way of marking the first and the last measured CR (and HR) is adopted on all subsequent figures. It is evident that there is a slight change in the slope of the pressure trace, i.e. the polytropic coefficient, which can be considered as a consequence of the slight sensor sensitivity and linearity drift after a certain usage period.

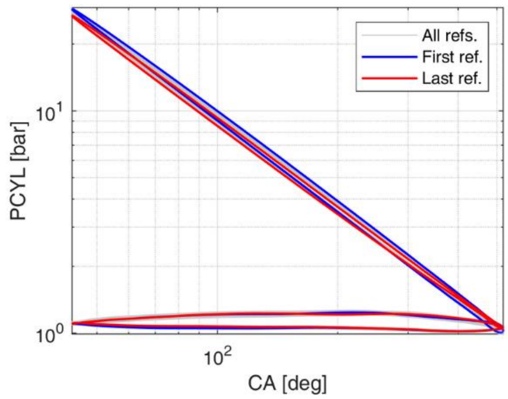

Figure 5. In-cylinder pressure with emphasized the first and the last cold ref.

Figure 6 shows details of the low-pressure part of the cycle, focusing on the beginning of the compression phase for all CR. In the low-pressure part, curve traces match consistently, i.e., there is no clear direction of pressure trace deviation over time. This implies that pressure reading deviation is neglectable over time in the area of low sensor load (both thermal and mechanical).

As the pressure sensor load rises, it is more evident that the reading deviates over time with a clear direction i.e. the influence of the changed sensor sensitivity is much more significant in the high-pressure area. Figure 7 shows the upper part of the high-pressure area of the CR cycle, where the sensitivity drop of the sensor can be clearly identified – when presented visually. The question arises whether it is possible to identify a numerical indicator that would be sufficiently indicative and whose monitoring over time would allow conclusions to be drawn about the extent to which the sensor sensitivity has changed. Therefore, an analysis was conducted on how various parameters change over time (or applied in-cylinder work) in order to spot some clear and statistically valid dependencies.

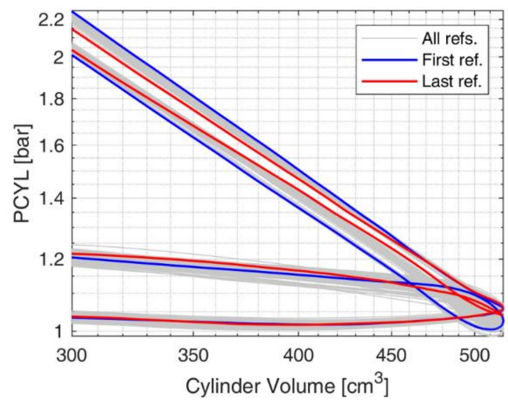

Figure 6. Low pressure part of the cycle for cold references.

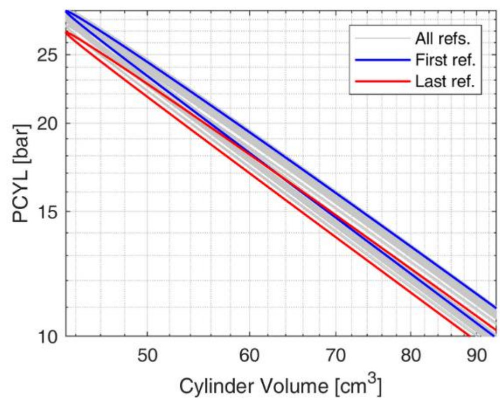

Figure 7. High pressure part of cycle for cold references.

Figure 8 shows how average cycle maximum pressure values for CR vary as a function of cumulative indicated work where continuous and almost linear drop can be observed.

Figure 9 shows the angular positions of the cycle maximum pressure value for CR regimes. A relatively small angular scatter of the data is observed, which indicates a solid reproducibility of the engine operating regime.

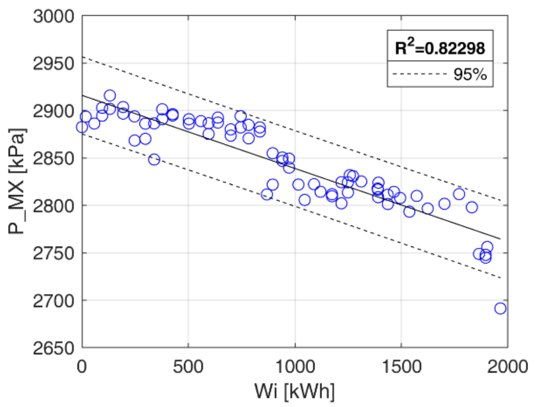

Figure 8. Cycle maximum pressure values for cold references.

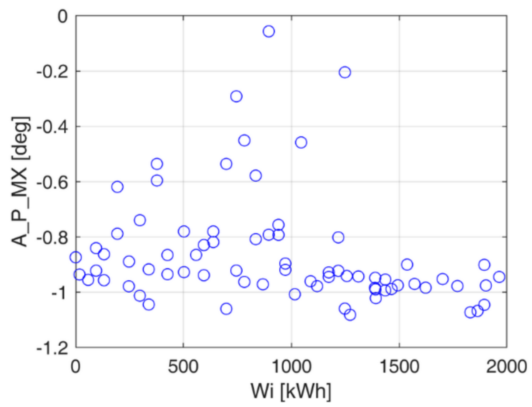

Figure 9. Angular position of the Cycle maximum pressure for cold references.

Figure 10 shows the change in the value of the maximum gradient of the pressure rise for CR as a function of the cumulative indicated work. It is noticed that there is a trend of decreasing this value as the experiment progresses, i.e., the sensor ability to respond to a rapid pressure change in the same way decreases over time. Figure 11 shows the angular position of the maximum gradient of the pressure rise for the CR, and it can be seen that the deviations of this parameter are within very narrow limits.

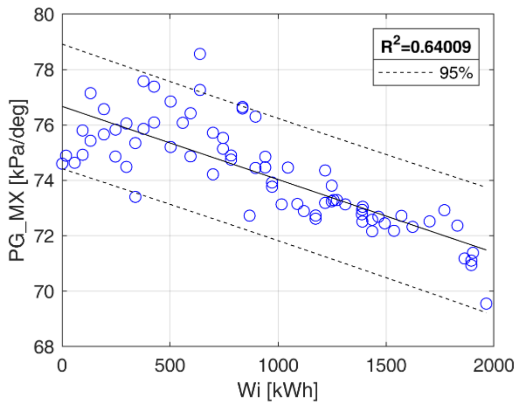

Figure 10. Maximum cycle pressure gradient values for cold references.

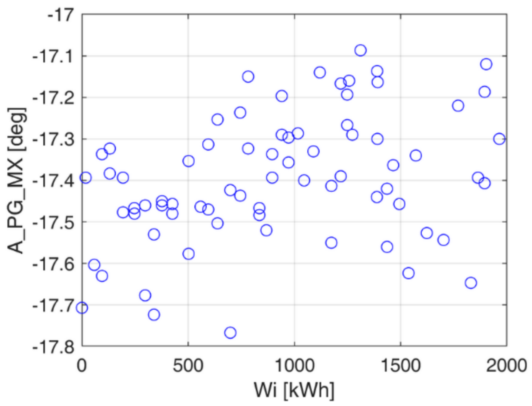

Figure 11. Angular position of maximum cycle pressure gradient for cold references.

Figure 12 shows the change of IMEP evaluated from the pressure sensor readings during cold reference measurements. The further analysis of IMEP in the low-pressure part of the cycle (IMPEL) and in the high-pressure part of the cycle (IMEPH) is shown in Figure 13 and Figure 14, respectively. The change in IMEPL is insignificant because the pressure amplitudes during the low-pressure part of the cycle are relatively small.

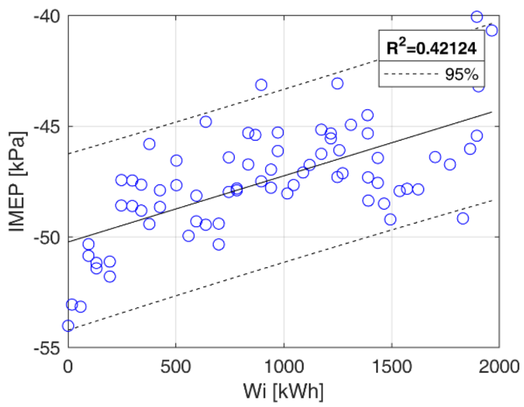

Figure 12. IMEP for cold references.

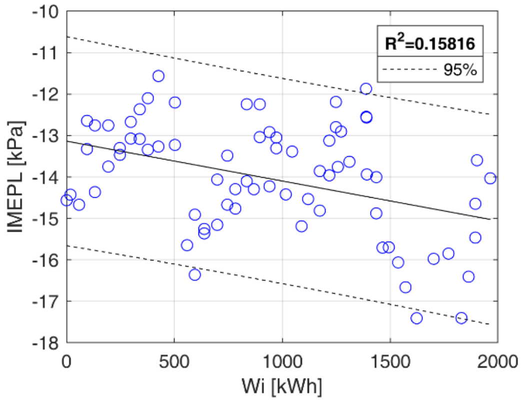

Figure 13. IMEPL for cold references.

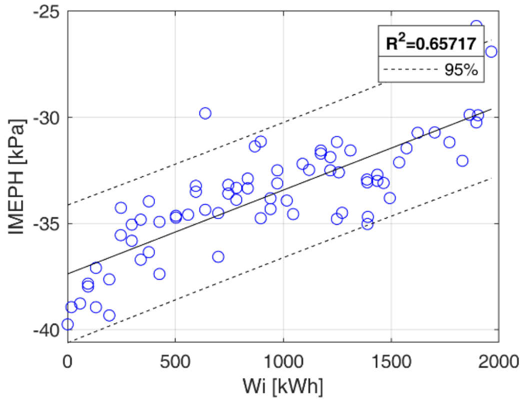

Figure 14. IMEPH for cold references.

The polytropic coefficients for cold references, calculated according to equation 3, are shown in Figure 15 and Figure 16 for the compression and expansion phases, respectively. It is evident that there is a significant drop in the value of the polytropic coefficient over time, although the in-cylinder conditions remained unchanged. This is particularly emphasized in the area at the beginning of the compression phase, where the heat transfer intensity is not so intensive. A drop is also evident in the expansion phase, particularly towards the end of the phase (before the exhaust valve opening).

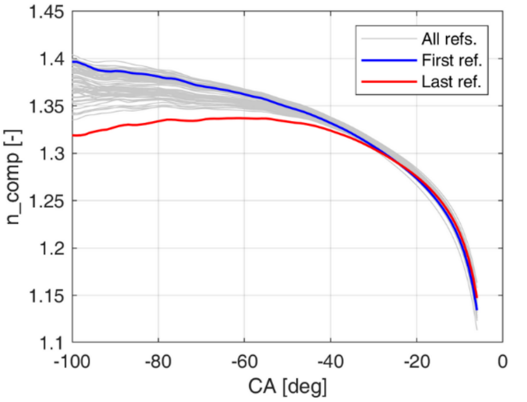

Figure 15. Polytropic coefficient during compression for cold references.

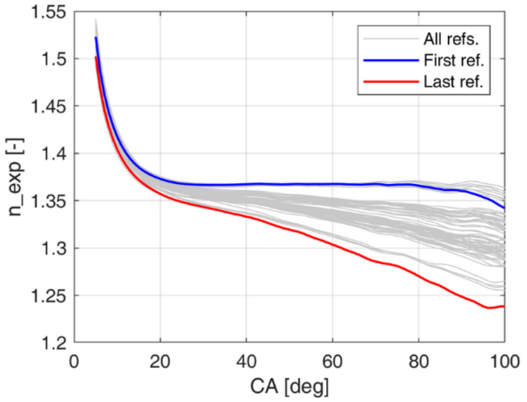

Figure 16. Polytropic coefficient during expansion for cold references.

6. Indicated parameters for hot references

Although CR are more rewarding for pressure sensor sensitivity change tracking and analysis, HR are way closer to typical test plan-defined operating points. As already mentioned, the definition of the control settings for the hot reference is devious since it has to be unique and feasible to reproduce in all hot reference measurements (which can differ in some aspects of engine hardware configuration) without compromising engine safety and operation.

Figure 17 shows log-log diagrams of the in-cylinder pressure curves for all HR measured within the test batch.

In Figure 18, the focus is on the low-pressure cycle part. A clear difference and divergence of measured pressure curves over time can be observed during the exhaust phase. In Figure 19, more focus is put on the high-pressure area of the cycle – particularly in the compression phase, keeping in mind that cycle variations on the expansion phase can be influenced by sensor ageing and variations in the combustion process, driven by engine hardware and/or control changes.

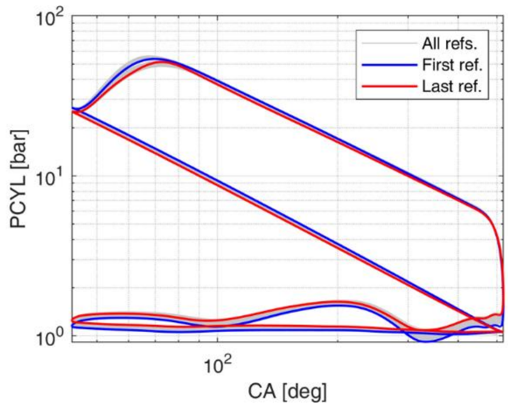

Figure 17. In-cylinder pressure with emphasized the first and the last hot reference.

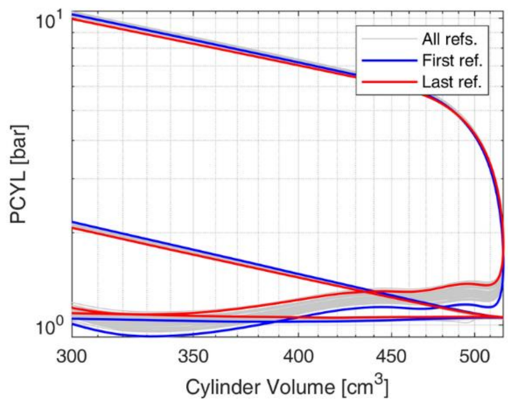

Figure 18. Low-pressure part of the cycle for hot references.

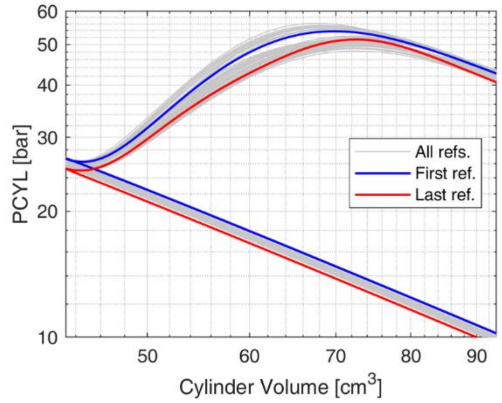

Figure 19. High-pressure part of the cycle for hot references.

Figure 20 shows the values of the maximum cycle pressure for hot reference modes. Similarly, as in cold references, a decrease in these values is observed as a consequence of the sensor ageing and sensitivity change. Figure 21 shows the angular positions of the pressure peaks, and it can be seen that the scatters are small, although the dynamics of combustion certainly influence these values.

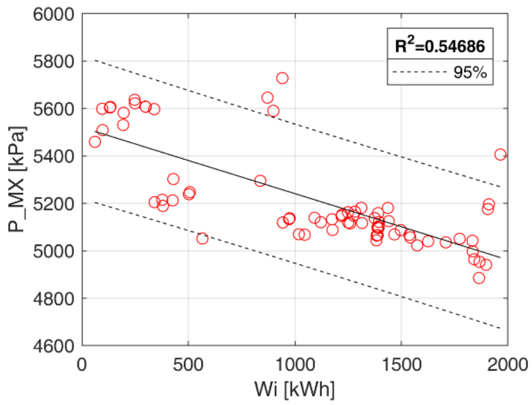

Figure 20. Cycle maximum pressure values for hot references.

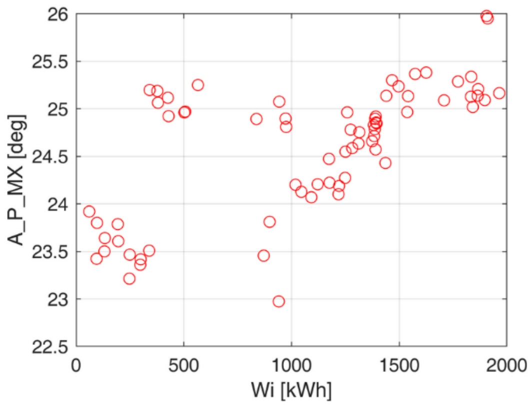

Figure 21. Angular position of the Cycle maximum pressure for hot references.

Regarding the values and angular positions of the maximum pressure gradient during the cycle for the recorded hot references, the conclusions drawn during the analysis of the cold references are further confirmed here. For almost identical cycles with combustion, the sensor loses the ability to follow the pressure change dynamics over time, which can be seen in Figure 22. The angular position of the maximum pressure gradient for combustion cycles is provided in Figure 23. A relatively small scatter of data is observed, with one outlier deliberately shown at the end of the experiment.

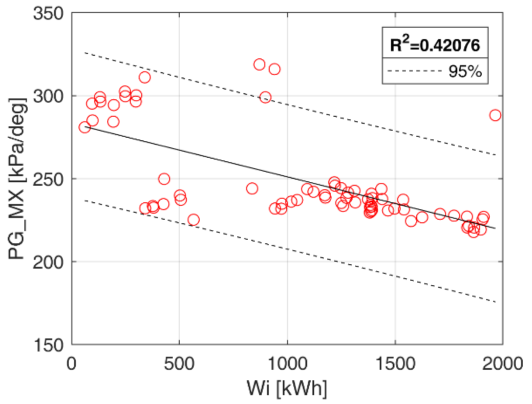

Figure 22. Maximum cycle pressure gradient values for hot references.

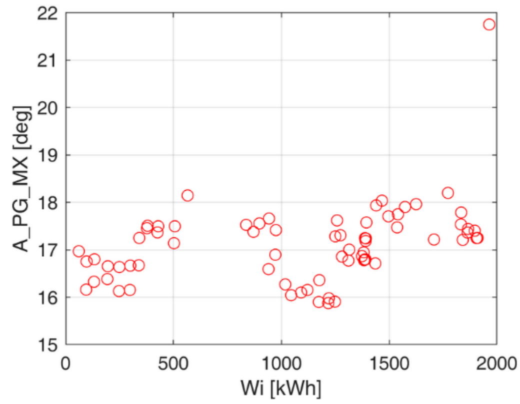

Figure 23. Angular position of maximum cycle pressure gradient for hot references.

It was observed that with the repetition of HR, the IMEP value gradually decreases, as shown in Figure 24. Despite the scatter, it is clear that the values of IMEP have a global decrease trend. It is necessary to emphasize that the presented trend appears to be opposite to the one shown in Figure 12. However, the trend is the same because the CR operating points are motored, resulting in a negative total output.

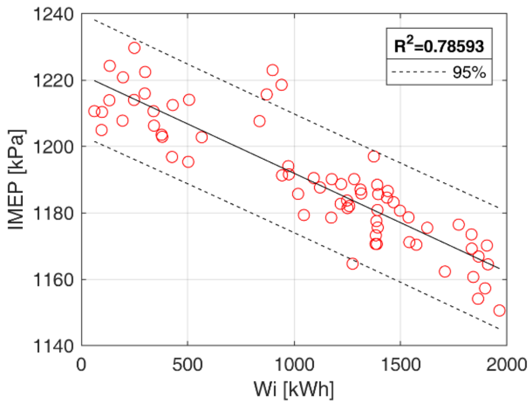

Figure 24. IMEP for hot references.

Figure 24 illustrates the essence of the pressure sensor ageing problem – although the in-cylinder conditions are unchanged, repeated reference operating point measurements indicate that the IMEP changes over time. It is important to stress that the engine is permanently monitored to detect any mechanical failures which can lead to the IMEP change (blow-by-gasses flow measurement, friction losses plausibility check,…) and that during the test batch realization in focus, neither of the mechanical issues were spotted leaving to the conclusion that the IMEP change is influenced solely by changes in pressure sensor behavior. The presented problem imposes the question of how to monitor and timely detect changes in sensor sensitivity in a way that does not compromise IMEP measurement accuracy while avoiding the necessity of frequent sensor calibration.

Going into further analysis, IMEP for the low-pressure and high-pressure parts of the cycle, IMEPL and IMEPH, are shown in Figure 25 and Figure 26, respectively. Changes in IMEPL for the low-pressure part of the cycle in CR and HR have the same trend. The pressure amplitudes in the low-pressure part of the cycle are slightly higher for the combustion cycle, which can be seen in these diagrams. Regarding IMEPH, it follows the same trend as charts showing IMEP, which is expected.

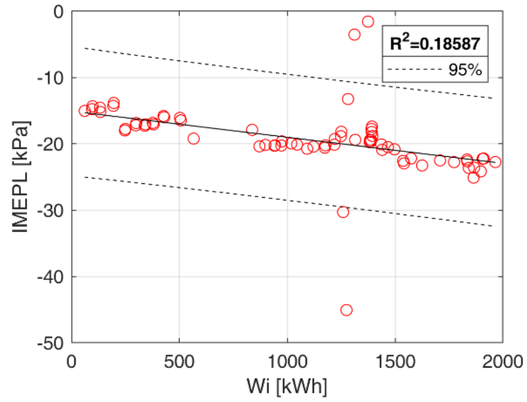

Figure 25. IMEPL for hot references.

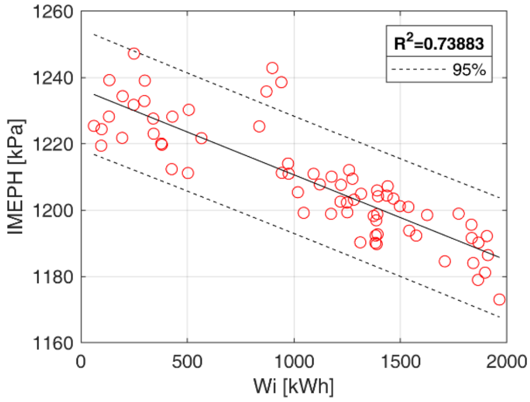

Figure 26. IMEPH for hot references.

For combustion cycles, i.e. HR, the angular ranges for evaluating the polytropic coefficient during compression and expansion are adjusted so that the influence of heat release on coefficient value change is limited, as shown in Figure 27 and Figure 28. These diagrams show how the polytropic coefficient curves migrate over time due to pressure sensor ageing. As already concluded, a drop in the sensor sensitivity influenced a false indication of more intensive heat losses and, thus, lower polytropic coefficients both in the compression and expansion phases of the process.

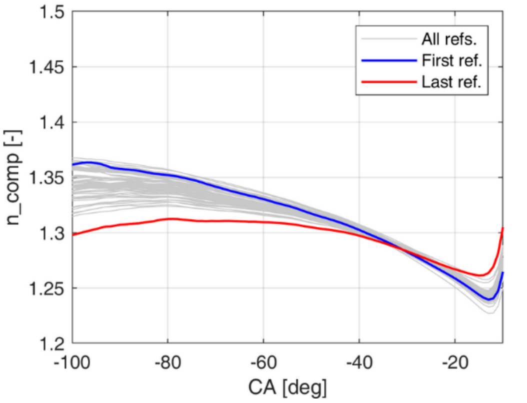

Figure 27. Polytropic coefficient during compression for HR.

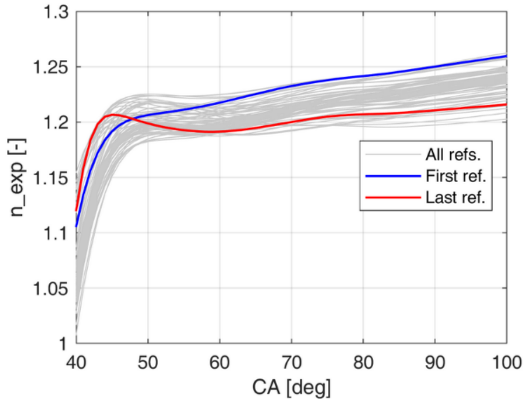

Figure 28. Polytropic coefficient during expansion for HR.

7. Conclusions

The general conclusion is that as the pressure-indicating sensor is installed, its characteristics change under engine operation over time. Assuming that incorporating the reference operating point measurements into the test plan is a common practice, it is shown that indicating parameters, evaluated from the references, can provide valuable data to identify the pressure sensor sensitivity deterioration even without frequent calibration checks.

It is a prerequisite that through the realization of the engine test campaign, the engine has an unambiguous hardware configuration of the elements that significantly influence the cylinder filling with an air/mixture so that the comparisons of pressure traces at the reference regimes are valid.

It should be noted that it is essential to know which operating regimes the sensor was exposed to between the reference operation point measurements. Operation points with higher knock intensity could drastically change the sensor characteristics in just a few engine work cycles.

The polytropic coefficient, evaluated from the measured pressure curve at the cold reference, appears to be the most promising indicator of the in-cylinder pressure sensor ageing, i.e. its sensitivity change. Cold reference operating points are significantly more straightforward to reproduce and can be accessed with high repeatability of engine work cycle thermodynamic boundary conditions. On the other side, evaluating the polytropic coefficient is simple and undemanding.

Figure 29 shows the change in the value of the polytropic coefficient for cold references as a function of the cumulative indicated work that the engine had at the crankshaft angle of 90 CA ATDC (expansion phase). It can be spotted that the trend of the polytropic coefficient change is very similar to the trend of the evaluated IMEP change of the hot reference. Moreover, when the changes of the IMEP and *n* are relativized, it can be spotted that the trend slopes of both parameters have similar values regarding percentual change.

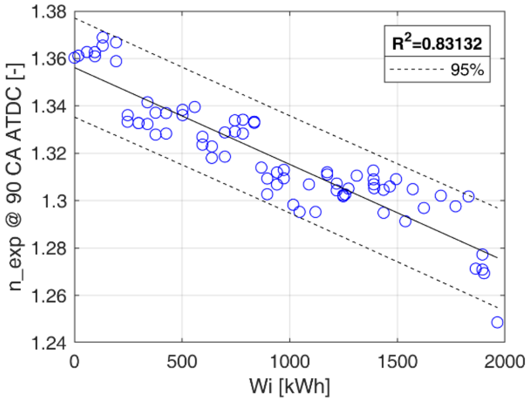

Figure 29. Polytropic coefficient values for cold references at 90 CA ATDC as a function of cumulative indicated work.

That means if the testing campaign allows some margin error in IMEP evaluation (2%, for example), a similar margin can be applied in tracking the polytropic coefficient change to indicate when the pressure sensor critical sensitivity deterioration level is reached and that the calibration of the sensor is necessary.

Nomenclature

A_P_MX	Angular position of P_MX	OP	Operating Point
A_PG_MX	Angular position of PG_MX	P_MX	Cycle Maximum Pressure
ATDC	After Top Dead Center	PCI	Pre-Chamber Ignition
CA	Crank angle	PFI	Port Fuel Injection
CR	Cold Reference	PG_MX	Cycle Maximum Pressure Gradient
DI	Direct Injection	RPEMS	Rapid Prototyping Engine Management system
HR	Hot Reference		
IMEP	Indicated Mean Effective Pressure	SCRE	Single Cylinder Research Engine
KP_PK	Knock peak	UHP	Ultra-High pressure
n_exp	Polytropic coefficient	Wi	Cumulative indicated work

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