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METHODS TO MEASURE THERMAL DEPOLARIZATION EFFECTS IN PIEZOELECTRIC RING ELEMENTS FOR KNOCK SENSORS

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Diagnostic vibration sensors, e.g. knock sensors, use piezoelectric ceramics as the active element, whose parameters can change over time due to ambient conditions. One of the major environmental impacts on the sensor – its internal active element in particular – is that of the temperature. The knock sensor is placed directly on the device to be examined, such as the automobile engine block or the combustion engines in biogas cogeneration (CHP) units. In these units, above all, the temperature of the engine block often exceeds 100 °C. Prolonged exposure of the sensor to such conditions can damage the protective housing; more important, however, is the partial depolarization of the piezomaterial inside the sensor. We employed the frequency and the direct charge coefficient methods to determine how the temperature affects the parameters of the ring piezoelectric ceramics.

The frequency approach allows us to establish the resonance frequency and the electromechanical coefficient, facilitating partial evaluation of quality in the piezoceramics. The technique nevertheless cannot be used in deriving the relevant piezoelectric charge coefficient. If paired with the direct method, the procedure will characterize the stability of the resonance frequency and the depolarization level in the ring being tested.

In the experiment, the CeramTec's Sonox P502 material was inserted directly into the knock sensors. The stability of the resonance frequency was assessed by using an Agilent 4294a impedance analyser. Subsequently, the samples were measured via the direct method to quantify the piezoelectric charge coefficient.

The experiment yielded a comprehensive description of the impact exerted by a thermal wave on the active elements of a knock sensor; moreover, we identified convenient methods to determine the parameters of a set of samples in terms of the operational quality and suitability.

Keywords: knock sensor, piezoelectric ceramics, biogas cogeneration, thermal wave

1. Introduction

Knock sensors have traditionally been used as a standard diagnostic tool in automotive engines to monitor the ignition process and to prevent engine knocking caused by the autoignition of the mixture a root cause of which is an increased pressure and temperature. Knock can severely damage the engine or considerably reduce its service life. Progressively, diagnostic sensors have found applications also in biogas cogeneration (CHP) units, reflecting the wide expansion of the technology. The sensors, especially due to higher power outputs of CHPs, are subjected to very high thermal stresses, which affect in particular the piezoelectric element as the active part of the knock sensor [1,2,3]. This case is typical for many other diagnostics vibration sensors containing piezoelectric materials.

The actual measurement of the temperature dependence of piezoelectric materials is closely related to ceramics as described by the Curie temperature. In most such materials, a higher operating temperature can cause the increase of the actual temperature of the active element beyond its Curie point, leading to a depolarization and loss of its piezoelectric properties. Variations in ceramic parameters can occur even at temperatures below the Curie point. In these cases, a partial depolarization of the element and a decrease in the values of major coefficients can be observed. As per standard operating procedures of these sensors, the temperature in the close vicinity of the sensor must be within set limits and thus temperature does not significantly affect the active element. However, assuming a prolonged continuous operation of the CHP and the location of the sensors on the unit, thermal stresses are generated and affecting sensor's active element. In these conditions, it might be useful to describe the behaviour of the sensor over a wide temperature range, from low temperatures to ones nearing the Curie point. When mounted on a gas engine, the sensor is affected not only by the ambient temperature, which can rise due to proximity of the exhaust manifold and heat exchangers, but also the heat transfer from the engine block. In order to assess the influence of ambient conditions, measuring temperature dependences at high temperatures is crucial both in the design and subsequent usage of a sensor. The literature usually focuses on determining the Curie point, the temperature dependence of the individual coefficients, or the entire matrix of the material coefficients [4,5]. Only few articles deals with full or partial depolarization and sensor applicability when the temperature limits are exceeded. This paper reaches somewhat beyond the common interpretation of the problems, characterizing in a wider context the realistic behaviour of piezoelectric materials as active elements of diagnostic vibration sensors under difficult operating conditions. Thus, the usability of the research presented herein is not limited to knock sensors in CHPs.

2. Experiments

2.1 Knock sensors in a CHP unit: the thermal impact

In CHPs, knock sensors are mounted directly on the gas combustion engine. In terms of practical arrangement, our experiment involved two Bosch sensors on a GE Jenbacher engine, namely, a water-cooled 12-cylinder V-configured turbocharged engine (Figures 1a, 1b). The sensor consisted of a circular housing that supported an active piezoelectric ring. This element was loaded with a seismic mass embodied in a metal ring. The entire system comprising from the piezoceramics, seismic mass, and electrodes was tightened with a nut and encased in a plastic housing.

One sensor was located on one side of the engine, fixed to the first cylinder as shown in Figure 2a. The other sensor was located on the engine side with the exhaust manifold and heat exchangers and thus faced a more intensive thermal stress. Steel washers were used to mount the sensors to the engine head. Based on the measurements, we established that the exhaust manifold temperature in the vicinity of the sensor can exceed 150 °C. A detailed view of a knock sensor on the engine, together with a Fluke TI55 camera image showing the temperature distribution around the sensor, is shown in Figure 2.

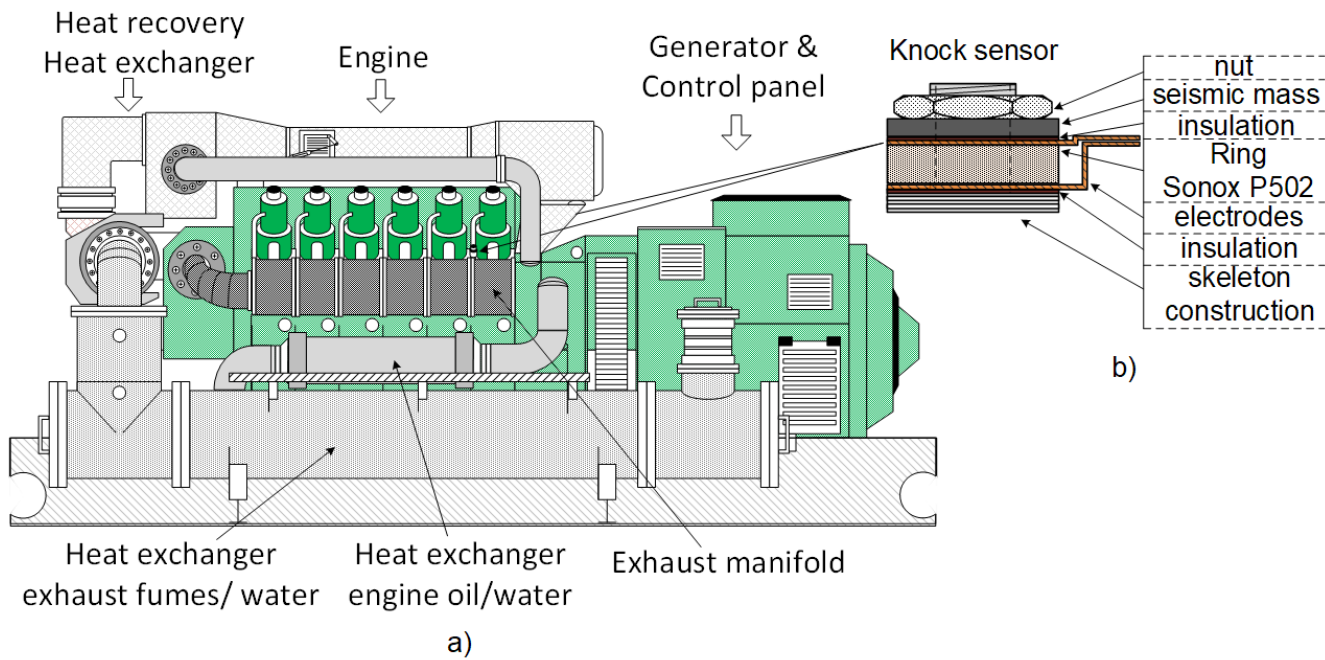


Figure 1a, b: A gas-powered, 12-cylinder, V-configured engine with cylinder head-mounted knock sensors, and a cross section through one of the sensors.

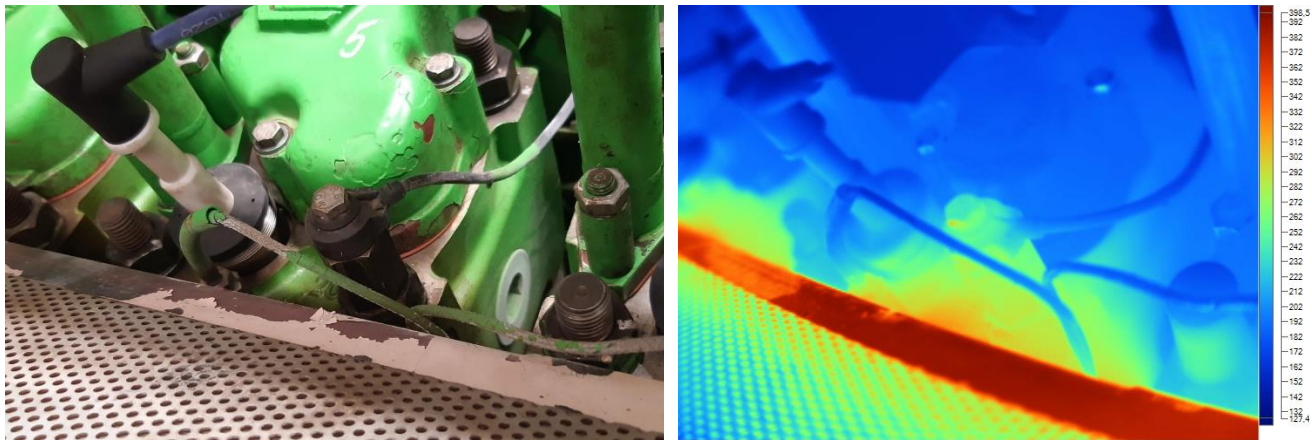


Figure 2 a, b: A knock sensor mounted on the engine (left), and a thermogram (right).

2.2 Temperature measurement in piezoelectric ceramics

2.2.1 Thermal depolarization of a piezoelectric element

When using knock sensors in a gas-powered engine operating at high temperatures, we need to define the impact of the thermal wave and to establish the basic temperature dependence of the piezoelectric element. These two steps have to be executed for practical reasons, namely, to determine the boundary temperatures below the Curie point. At these temperatures, total depolarization does not occur, but the material coefficients may irreversibly change. Before we subjected the sensor to the thermal wave, we tested the piezoelectric element in the temperature band of between 30 °C to 390 °C to obtain the Curie temperature [6,7]. The results then enabled us to carefully choose these transition temperature ranges within which the thermal wave was applied to the sensor. The experiment was not designed to completely depolarize the element, but rather to find the limit states for the examined ceramics.

2.2.2 Methods for characterizing PZT ceramics

To characterize the impact of temperature on the main material coefficients of PZT ceramics, we have to measure these coefficients correctly. In this endeavour, two standard measurement methods are available: the commonly employed frequency approach, which is described in detail within the European world standards EN50324 [8] and CEI/IEC 60483 [9], respectively, and the direct technique for measuring the piezoelectric charge coefficient [6]. The frequency method is particularly suitable for measurement of the temperature dependences and determining the Curie temperature of PZT ceramics. When determining the electrical parameters, we utilized an impedance analyser with a sufficient frequency range, as is generally recommended.

In our experiment, a following measurement setup was used. High precision temperature control was achieved with an AOIP GEMINI 700LRI temperature chamber, which features an adjustable range from 30 °C to 500 °C and an absolute stability of ± 0.05 °C. The chamber was connected over an RS422/RS232 interface to a PC with a LabVIEW application, allowing us both to monitor and set the current temperature in the chamber. The measured PZT ceramic sample was wired via four conductors to the input of an Agilent 4294A impedance analyser. This device measured the standard parameters of the PZT ceramics, including the resonant and anti-resonant frequencies, capacitance at 1 kHz, and a loss factor $\tan \delta$. The acquired data were then read through an application in LabVIEW. Using the input parameters and geometrical dimensions of the PZT ceramic sample, we can compute some material coefficients, such as the electromechanical coefficient in Eq.1:

$$k_{eff}^2 = \frac{f_a^2 - f_r^2}{f_a^2}, \quad (1)$$

where k_{eff} is effective electromechanical coupling factor (-), f_r denotes the resonance frequency (Hz), and f_a is the anti-resonant frequency (Hz).

After determining the temperature dependence, we simulated the impact of the thermal wave on the element. The setup for this simulation included placing the knock sensor on an aluminium rod that had been fixed with a heat conductive paste to the heated surface of a Hotplate Cimarec plate, Figure 3. All of the samples were ring-shaped and had an outer diameter of 22 mm, inner diameter of 14.3 mm, and a thickness of 3 mm. The PZT rings were thickness-polarized. As for the hot plate, we set the temperature to 370 °C, a value above the Curie point (see Figure 4). The aluminium rod, simulating the engine head, with the knock sensor was placed outside of the hot plate for sufficient amount of time to reach a thermal equilibrium. At the start of experiment, the rod with the sensor was placed on the hotplate and the ceramics properties were sampled at set time intervals, monitoring the change of the properties as the thermal wave propagated through the sensor. Both the frequency and the direct charge coefficient methods were used.

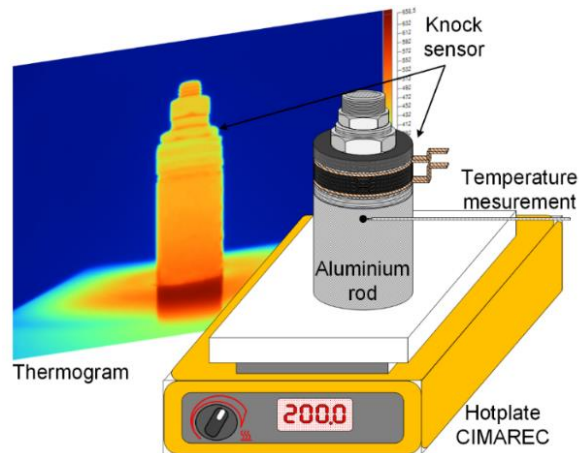


Figure 3: A knock sensor thermogram at the thermal wave-based partial depolarization.

The direct approach measures the sample-generated charge by loading the sample with a force of known magnitude. The ring-shaped sample was placed between a force transducer and shaker, and connected to two electrodes. The element was then excited with a harmonic signal of the frequency of 110 Hz, generated by B&K 4809 shaker, while the force was monitored by Kistler 9205. The maximum force was 0.25 N. The output of the PZT element and the force transducer were connected to the NI 9234 vibration module through a B&K 2647A charge amplifier. To display the data and to compute the charge coefficient, we created a LabVIEW application [6]. The charge coefficient, d_{33} , was computed according to Eq. 2:

$$d_{33} = \frac{U_{PZT}}{\frac{U_{sensor}}{K_{sensor} \cdot k_{q-sensor}} K_q}, \quad (2)$$

where d_{33} is the piezoelectric charge coefficient ($C \cdot N^{-1}$); U_{PZT} denotes the output voltage of the piezoelectric element, (V); U_{sensor} stands for the output voltage of the force sensor, (V); K_q represents the sensitivity of the charge amplifier of the PZT element, ($mV \cdot pC^{-1}$); k_{sensor} is the sensor's sensitivity, ($pC \cdot N^{-1}$); and $k_{q-sensor}$ denotes the sensitivity of the charge amplifier on the sensor.

3. Result and discussion

3.1.1 Frequency and direct methods to measure the thermal impact on the ceramics

To assess the effect of the thermal wave to the samples, we first determined the standard parameters in all of the samples. These parameters included the impedance and phase characteristics, established through the frequency method, and the values of the piezoelectric charge coefficient, which were obtained via the direct approach. From the resonant frequencies we computed the effective electromechanical coefficient to indicate it graphically for the second oscillation mode.

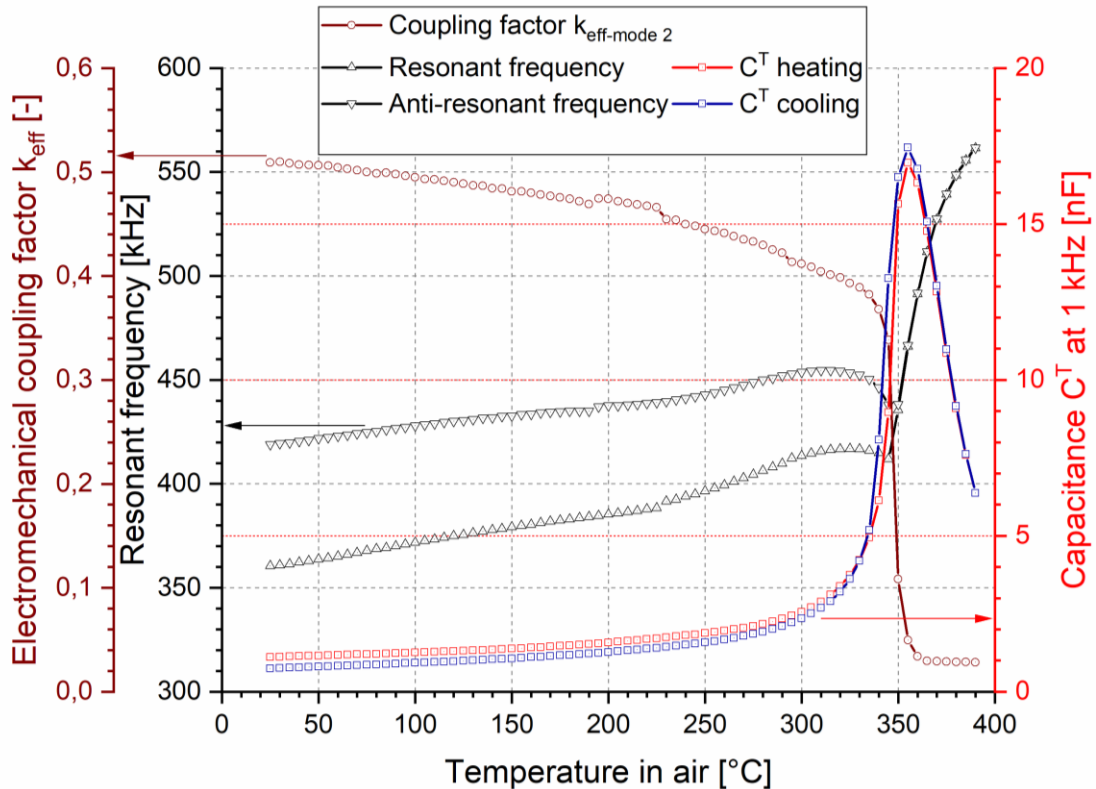


Figure 4: Determining the Curie point based on measurement of the temperature dependences of the capacitance C^T at 1 kHz, electromechanical coefficient k_{eff} in the second oscillation mode, and resonant and anti-resonant frequencies.

The Curie temperature is determined by measuring the temperature dependence of the C^T free capacitance at 1 kHz, as shown in Figure 4, which also displays the patterns of the resonant frequencies and the effective electromechanical coefficient. The patterns of the resonant and anti-resonant frequencies expose the correlation of the two frequencies when approaching the Curie point, seen in the associated jump decrease of the k_{eff} value. This is caused by a phase transition to a cubic crystal structure and a subsequent loss of the piezoelectric effect in the material. A noticeable increase in both resonant values occurs up to 320 °C and a significant decrease of the impedance of the resonant frequencies can be observed when the phase transition is approached. The piezoelectric ring was measured individually, i.e., without the knock sensor assembly, and was left to operate at each preset temperature for 15 minutes to stabilize the thermal conditions. The detailed phase transition is visualized in Figure 5, exhibiting the impedance dependence of the ring in the second oscillation mode. The maximum impedance value corresponds to the anti-resonant frequency of the converter.

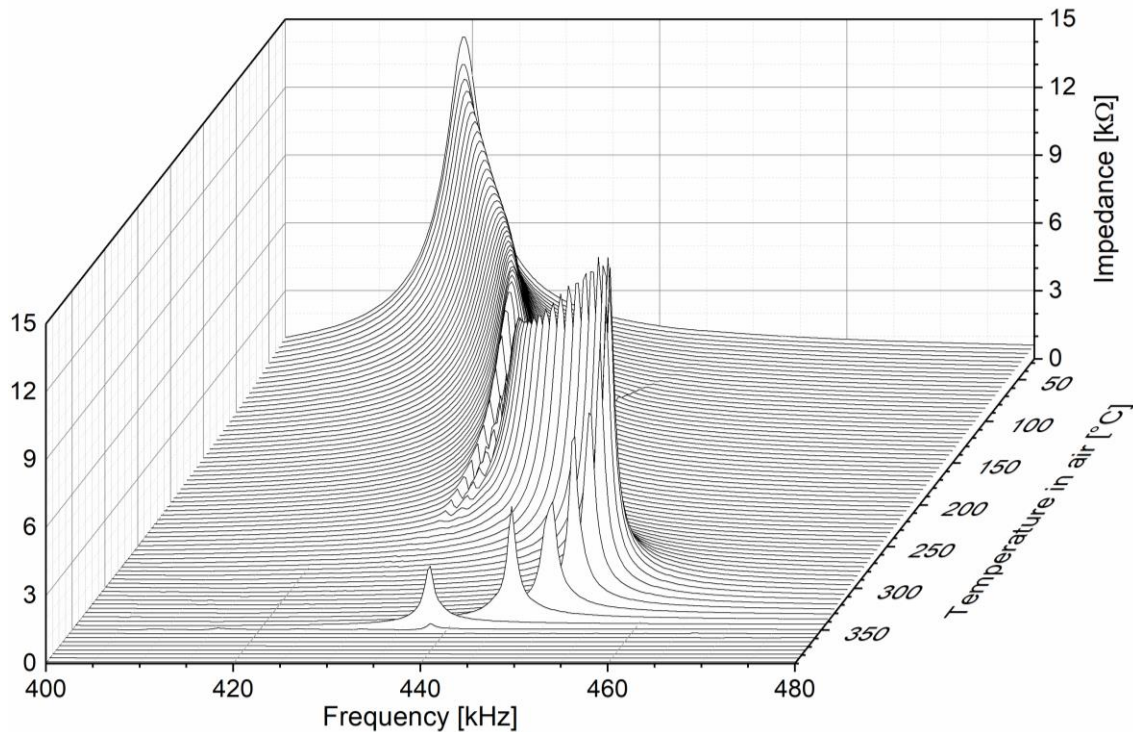


Figure 5: The temperature dependence of the impedance patterns of the second oscillation mode for the piezoelectric ring.

3.1.2 Partial depolarization of the piezoelectric ring

We expected that the amount of degradation of the standard parameters of the piezoelectric ring are correlated to the duration of the exposure to the temperatures close to the Curie temperature. To test this hypothesis, the sample was put a hot plate pre-heated to the Curie temperature of the ceramics. In Tab. 1, six samples are presented that were progressively depolarized for a period between 30 seconds and 12 minutes. The depolarization degree was evaluated via the frequency method and then expressed through the values of free capacitance, C^T ; resonant and anti-resonant frequencies, f_r and f_a , respectively; impedances for the resonances f_r and f_a ; and effective electromechanical coefficient, k_{eff} . To verify the outcomes of the measurement, we established for every samples, by the direct method, the charge coefficient d_{33} before and after depolarization. The element heating time corresponds to the depolarization degree, as is obvious also from the impedance characteristics patterns in Fig. 6. Assuming a relevant heating time, the piezoelectric material's structure takes a cubic form and loses its piezoelectric values.

Table 1: The values obtained after a partial depolarization of the piezoelectric rings.

Sample	C^T	f_r	$Z(f_r)$	f_a	$Z(f_a)$	$k_{\text{eff}} 2^{\text{mode}}$	d_{33}
Ring	[pF]	[kHz]	[Ω]	[kHz]	[Ω]	[-]	[$\text{pC}\cdot\text{N}^{-1}$]
no.01	1112.9	358.50	19.92	417.50	14692.18	0.51	408
no.01 - 30 sec	1054.3	365.50	42.61	402.75	7838.34	0.42	329
no.02	1078.6	360.00	29.89	414.75	13542.47	0.50	384
no.02 - 1 min	956,5	368.00	75.95	394.50	5480.06	0.36	284
no.03	1090.5	361.00	26.57	419.00	14114.98	0.51	411
no.03 - 1 min 30 sec	906.2	361.75	169.89	394.50	3683.67	0.40	297
no.04	1099.9	359.25	23.99	417.25	13959.41	0.51	403
no.04 - 2 m	765.4	374.25	406.85	381.00	874.48	0.19	141
no.05	1111.3	362.00	24.74	420.50	13840.74	0.51	391
no.05 - 6 min	758.0	373.75	406.04	382.25	934.35	0.21	20
no.06	1064.7	356.25	27.17	409.75	14267.31	0.49	396
no.06 - 12 min	696.9	368.25	651.00	372.50	668.69	0.15	17

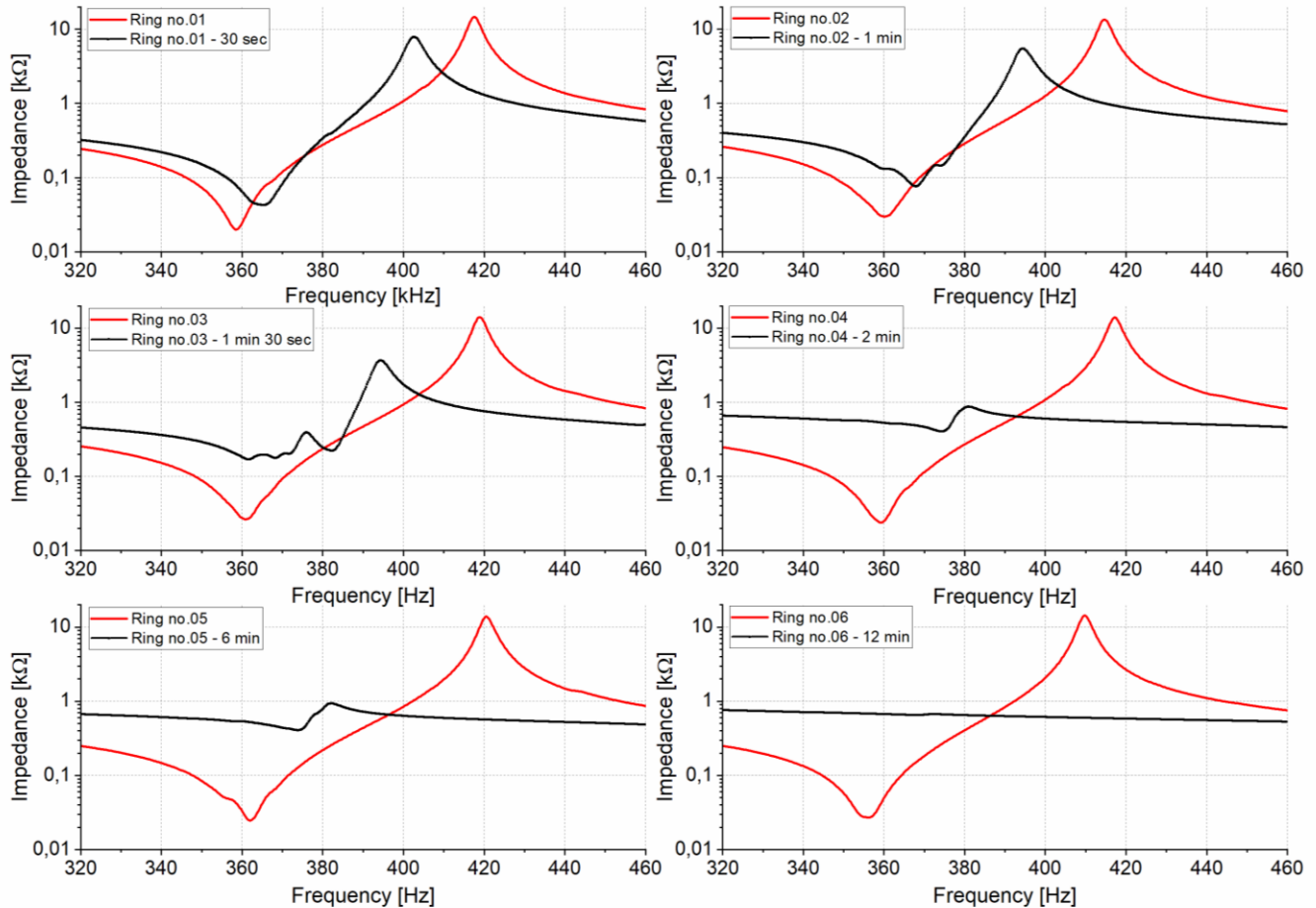


Figure 6: The degrees of depolarization in the individual elements, related to the heating time.

4. Conclusion

When knock sensors are employed to detect vibration in gas engines that operate in biogas cogeneration units, a temperature higher than the sensor operating one can usually be detected in the sensors vicinity. We carried out an experiment that characterized the impact of high temperatures on the

parameters of the piezoelectric element integrated in the knock sensor. First of all, we measured the temperature dependence of the main coefficients of the piezoceramics to establish the Curie point at around 350 °C. The evaluation showed that the established coefficients had begun to decrease markedly already at the temperature of 300 °C. If the sensor is mounted, e.g., in the vicinity of an exhaust manifold could reduce the resulting value of k_{eff} by 10%. Significant depolarization occurs only near the Curie point. The critical factors include the preset temperature and, the time during which the element is subjected to the higher temperature. A continuous decrease in most of the material coefficients can be observed, affecting the service life and parameters of active piezoelectric elements used in heavy duty diagnostics vibration sensors.

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