



Acoustic condition monitoring of coffee beans, during the roasting process

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ABSTRACT

The research results presented here deal with the acoustic condition monitoring of coffee beans during the roasting process. In particular, the question was investigated whether the current state (roasting level) of the coffee beans during the roasting process can be detected by acoustic monitoring. To answer this question, an experiment was carried out with a sample drum roaster (Hottop KN-8828B- 2K+) in which the airborne sound pressure was recorded for five different roasting methods and then examined. The methods used differed in the inner temperature of the roaster when the coffee beans were inserted (75°C, 100°C, 150°C, 175°C, 200°C). The recording of the roasting processes has been made by two microphones placed in front of the drum, with each process being repeated five times. To enable a comparison between the different processes, five points at which the coffee beans had reached a certain temperature were determined for each grating. Five sequences of equal length were then cut from each recording, with the determined time points serving as the starting value of the sequence.

First, the differences in the spectral composition of the signals in the first and second crack were investigated and compared with those in other past publications. Furthermore, the comparison of the behavior as a function of the throw-in temperature has been investigated. For most of the processes analysed, the sound pressure levels can be clearly separated as a function of the bean temperature. In conclusion, it was shown that sound analysis can be used to determine the proportion of cracked beans.

1. Introduction

During the roasting process, profound changes occur in the coffee bean. These are manifested by an increase in volume (50–80%), changes in color and structure, weight reduction (burn-in, 11–20%) and in the formation of the typical coffee aroma, which the raw bean lacks (Belitz et al., 2008). The specific mass, which describes the ratio of density and volume of a body, is also reduced on average by approx. 56%. The roasting process can be divided into the following four main phases: drying (approx. 100 °C), decomposition (approx. 150 °C) and full roasting (approx. 200 °C).

At approx. 50°C (bean temperature), the first changes occur in the tissue layers of the bean as a result of evaporating water and denaturing proteins; when 100°C is exceeded, thermal decomposition of the organic portion of the bean begins. This is indicated by the onset of browning of the bean, as a result of smoldering. From about 150°C, gases such as CO₂, CO and water vapour develop inside the bean, increasing the internal pressure and thus also the volume of the bean, until the bean bursts between 180°C and 200°C. This causes the coffee groove to burst.

During this process, the coffee groove of the bean bursts open with an audible cracking sound, marking the beginning of the decomposition phase (Belitz et al., 2008). This cracking is also referred to as the "first crack" (Wilson, 2014). The roasting process can be monitored using various techniques based mainly on detecting the color, volume, temperature or weight loss of the beans (Shan et al., 2015). In the subsequent and final phase, full roasting, roasting time and temperature with caramel formation determine the flavor characteristics of the coffee, with the water content dropping to 1.5–3.5%. During coffee roasting, various alerts can be used to individualize the final phase. They are represented, for example, by the temperature in the roasting camera, by the color of the coffee beans and by the crackling of the bean, which produces a typical sound. This acoustic alarm is often used by roasting professionals to determine the degree of roasting of the coffee. During coffee roasting, different alarms can be used to individualize the final stage (Magrini & Melchiorre, 2018). The acoustic signal of the crack can be a resource for process control and can be used for an optimization process of the whole system. After a review of the proposals for the control of coffee bean roasting using crack noise detection, the paper presents some considerations for measurements on roasting machines.

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Abbreviations

RoR	rate-of-rise
AUC	area-Under-the-Curve
t_{RD}	process duration
RD	Roast development
FFT	Fast Fourier Transformation

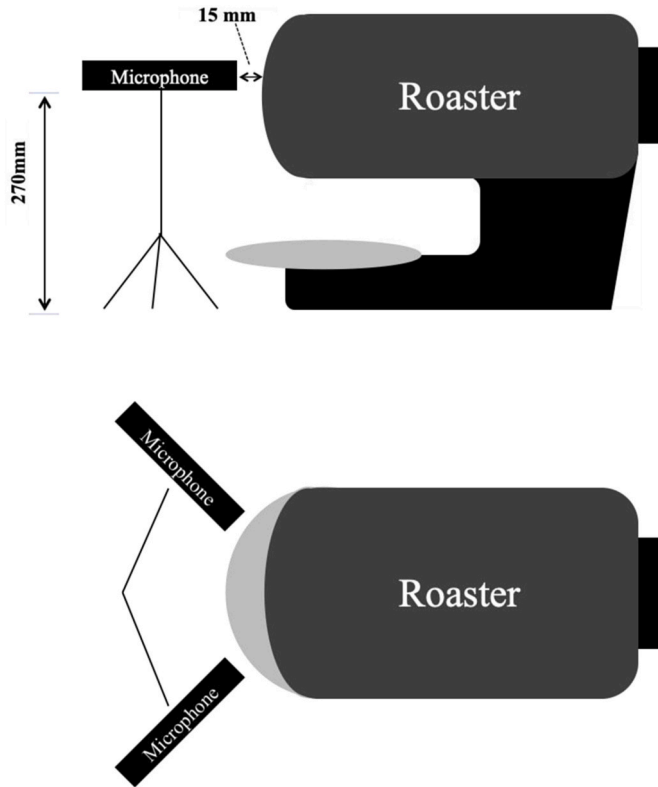


Fig. 1. Sketch of the side view (top) and top view (bottom) of the roaster and microphones.

Moreover, the results of the measurements will help to develop a better control of the process and allow the automatic process control, the timely detection of potential process defects in the roasting machines, the provision of additional information related to the individual roasting batch, the combination of the noise information with color, time, temperature, energy consumed, etc (Magrini & Melchiorre, 2018).

2. State of the art

Previously known work in the field of acoustic monitoring of the roasting process has focused exclusively on determining the frequency range of the acoustic signals in the first or second crack. Magrini (Magrini & Melchiorre, 2018) pursued the approach that a sound detector should register the cracking of the coffee beans and stop the roasting at the right time. This is to be automated and optimized on the basis of the known crack sound spectrum. Accordingly, the investigations determined by Magrini can be summarized in the two determined spectra during the first and the second crack. In these investigations, the noise known as the first crack is characterized primarily by components in the comparatively high frequency range between 6.0 kHz and 15.0 kHz, and the second crack by lower components between 1.0 and 2.0 kHz. In contrast, Wilson's studies (Wilson, 2014; Wilson &



Fig. 2. Photographic side view of the roaster (source: author).

Wochner, 2016), conducted on a comparatively small roaster, show that the first crack is louder than the second crack (by 15% in peak acoustic precision), the dominant frequency of the first crack is significantly lower than that of the second crack (by a factor of almost 19), and the events of the second crack proceed at a higher rate (by a factor of about 5) than the events of the first crack. Winjaya et al., (Winjaya, 2017) investigated the identification of cracking sound during coffee roasting using neural network. The experimental results show that by using Voice Activity Detection equipped with Fast Fourier Transform algorithm, the first and second cracking sounds can be detected.

The objectives of the work presented here were therefore, on the one hand, to test the statements on the spectral composition of the noises for the first and second crack for the plant and grades used here. In addition, however, the main part of the investigations was aimed at testing the extent to which the roasting state of the beans can be determined acoustically independently of the roasting curve set (throw-in temperature). For this purpose, experience with acoustic monitoring of various applications in the field of agricultural and biosystem processes was used, e.g. Siebald et al. (2017), Müller-Blenke et al. (2018), and Siebald et al. (2020).

3. Material and methods

In particular, the test assembly, the used coffee roaster, the measurement equipment and the test procedure are described below.

3.1. Test assembly

Fig. 1 shows the basic setup of the experiment. Two microphones of the type PCB-378B02 (PCB Piezotronics, New York, USA) were positioned at the front at the height of the roasting drum axis and at a distance of 15 mm from the roasting chamber lid.

3.2. Coffee roaster KN-8828B-2K+

The used Hottop KN-8828B-2K + coffee roaster (Chang YUE Industrial Corp., Tainan, Taiwan), s. Fig. 2 is a drum roaster for home use or sample roasting, with a capacity of up to 300 g of coffee beans, although the recommended amount is 250 g per roast (Rebels). The coffee beans are continuously moved in the roasting drum by rotation to allow for even roasting and to prevent the coffee beans from burning. Through a window on the front of the drum, the coffee beans can be inspected during the roasting process. During roasting, the temperature

supply can be manually regulated in the range of 0–100 in steps and the fan strength can also be adjusted in steps from 0 to 10. The manually created curves can be stored in one of the three available digital memory locations on the roaster and used as an automatically running program for subsequent roasts.

The roaster can be filled quickly and without much heat loss through a filling hatch, making it possible to select a very accurate starting temperature and achieve more precise roasting. Through an integrated USB port at the roaster, it can be connected to a computer and controlled by means of software from the company Artisan. This software is also used in large commercial roasters and allows the curves obtained with the home roaster to be transferred to large roasters.

With the program, the roasting curve can be controlled by accessing the fan and temperature supply. In addition, the software allows you to record and save the temperature curve during the process. The temperature of the roaster, as well as the surface temperature of the coffee beans are displayed, which are measured by two built-in thermometers. Furthermore, information on roasting, such as the "burn-in" or the type of bean, can be added afterwards and constantly determined variables, such as Roast Development Time or the Rate of Rise, can be viewed. Burn-in is the weight loss of the coffee beans caused by the evaporating water during roasting (Fischer, 2005, p. 43). The burn-in depends on the green coffee used and is usually between 16% and 20%. The burn-in is the ratio of the mass loss of the beans during the whole roasting process to the mass of the green beans. The "Roast Development" is calculated as the quotient of two process times, namely the time from the start of the first crack to the end of the roasting process divided by the total time of the roasting process. This quotient provides information about the condition of the bean and allows it to be compared. Roast development is usually between 15% and 25%. (Barista Institute n.d.) The Rate of Rise describes the temporal course of the temperature increase during roasting. For inexperienced users, it is possible to use the roaster's automatic mode to determine the degree of roasting of the coffee beans. It is possible to set the maximum duration of roasting (8–25 min) or the target bean temperature (80–220 °C). Furthermore, the Hottop KN-8828B-2K + has a large external cooling system, which is important for the flavor development of the coffee. This roaster is well suited for the acoustic investigations in that the operating noise is comparatively low and thus the measurements of the noise generated by the beans are less disturbed (Roast Rebels).

3.3. Coffee beans

The coffee beans used for roasting were "washed" organic coffee beans of the Arabica variety from Ethiopia.

To prevent moisture exchange with the environment, the coffee beans were delivered and stored in a resealable plastic bag.

3.4. Measurement equipment

Microphones from the manufacturer PCB were used to record the acoustic signals of the coffee beans. These consist of the PCB-377B02 microphone capsule and the PCB-426E01 preamplifier and are calibrated as a system. The nominal diameter of the microphone is $\frac{1}{2}$ ", designed for free field application and the sensitivity is 50 mV/Pa with a dynamic range of >135 dB in a frequency range between 3.75Hz and 20,000Hz.

An 8-channel measuring instrument, imc CS-3008-N (IMC Test & Measurement GmbH, Berlin, Germany), was used for data acquisition. The measuring instrument is controlled using the imc STUDIO or imc DEVICES software (IMC Test & Measurement GmbH, Berlin, Germany). The imc STUDIO software provides access to the Online FAMOS tool, which allows to analyze the recorded signals in real time.

The imc FAMOS (IMC Test & Measurement GmbH, Berlin, Germany) application is used for the analysis, evaluation and documentation of measurement results, with a variety of fast display options for the

Table 1

Measuring points and the corresponding bean temperature in °C.

Measuring point	Bean temperature [°C]
P1	100
P2	125
P3	150
P4	175
P5	200

measured values. The roaster is controlled with the Artisan software.

This is a 64 bit open-source software. It allows control, recording, analysis and evaluation of roasting process and roasting profiles of an extensive number of supported coffee roasters. The option of automatically generating various roasting metrics can help in making decisions that affect the resulting coffee flavor. For analysis, the program calculates, for example, the Rate-of-Rise (RoR), which indicates the temperature rise of the coffee bean per unit time, or the Area-Under-the-Curve (AUC), which can provide information on how much energy the coffee beans absorbed/received during roasting, and records various statistics and reports (Luther, 2016).

3.5. Test procedure

At the beginning, the roaster was examined in its settings and possibilities and familiarized with the procedure of roasting as well as the characteristics of the process and at the same time the setting of the acoustic measuring equipment was carried out.

3.5.1. Characterization of the roasting processes

The roasting curves used for the experiment differ in the temperature of the roaster when the coffee beans are thrown in and in the process duration. The process duration t_{RD} was selected on the basis of the time-based Roast Development (RD) and with the determination of the time to first crack.

All other operating parameters remain unchanged. In the investigations, a RD of 22% was applied. The start of the first crack was determined acoustically during the process and the process time was calculated using an Excel tool in order to achieve the specified roast development. The final mass was determined experimentally after the process and the burn-in was calculated from this. After roasting, the coffee beans were weighed again to document the weight loss and to calculate the burn-in. In addition, the time of onset of first crack was determined. These data were used to characterize the different roasting processes.

3.5.2. Sound analysis - representation of the roasting process in principle

The data recorded with the measuring system were first evaluated and displayed in the time domain in order to describe the course of the sound level during the roasting process in principle. The level was calculated using a moving average. In particular, this data can be used to determine the time for the first and second crack. By means of the Fourier analysis the time data were spectrally analysed. In particular the spectrum in the "first" and "second" crack was considered. The settings of the FFT were Window width of 500 number of lines, hanning-window, overlap of 90% and arithmetic averaging.

3.5.3. Comparison of the methods

For the experiment, the coffee beans were portioned into 25 samples of 250g each and placed in transparent, resealable cups, with a filling volume of 400 ml, in order to minimize moisture exchange with the environment. In the process curves of the different methods, the time points of the bean temperatures listed in Table 1 were used for the comparison of the airborne sound pressure.

Using the Artisan software, the five time points at which the coffee beans possessed the sought temperature were determined for each roast.

Table 2
Injection Temperature and process time for the different test procedures.

Procedure	Injection temperature [°C]	Average total process time [s]
A	75	965.0
B	100	844.2
C	150	709.0
D	175	674.2
E	200	606.8

Each of the time points was set as the starting value for a 5 s section. For the comparison, it was possible to generate in imc FAMOS the average values of the time sections and export them in an Excel format. The 250 values obtained were then clearly presented in an Excel spreadsheet and the average value from the two microphones was calculated for each measurement point.

4. Results and discussion

4.1. Characterization of the roasting processes

Table 2 shows the temperature of the roaster when the coffee beans are inserted and the corresponding process duration of the roasting curves used.

Fig. 3 shows the corresponding temperature curves of the various roasting processes. After the beans have been inserted at a comparatively low temperature, the process temperature therefore initially drops significantly before rising continuously as a result of further heating of the roaster.

In Table 3 the characteristics and results of the recorded roasts, and average and standard deviation for each process in comparison are listed. It shows that, despite almost identical roast development, the results of the processes differ, as expected, with regard to the time of first crack, process time, weight loss and burn-in: the process time shortens with increasing feed temperature and the time of first crack occurs earlier.

The weight loss of the coffee beans decreases with increasing throw-in temperature, resulting in a lower burn-in.

Fig. 4 shows a comparison of the average rate-of-rise of the five methods between the selected measuring points. This indicates the temperature rise per time in °C/min and is calculated by the time interval of the measuring points and the temperature difference of the measuring points, which is always 25 °C in this case.

Fig. 5 graphically compares the course of the mean values of burn-in and roasting time of the different processes. The blue bars reflect the process duration and refer to the left axis, while the red line shows the course of the burn-in and refers to the right axis. Fig. 6 shows the exemplary roasted sample of each process in comparison.

4.2. Acoustic analysis - Characterisation of the roasting processes in principle

The uniform circulation of the coffee beans in the drum produces a permanent rustling sound. In the course of roasting, an audible change

Table 3
Overview roasting processes, begin time of first crack, process time, roast development, end mass and burn-in value

Procedure	Average standard deviation	First Crack [s]	Process time [s]	Roast Development [%]	Final Mass [g]	Burn-in [%]
A	Ø	755.0	965.0	21.76	200.6	19.76
	σ	20.3	22.4	0.39	1.1	0.46
B	Ø	656.8	844.2	22.17	204.0	18.40
	σ	12.0	16.5	0.11	0.3	0.11
C	Ø	551.4	709.0	22.17	210.1	15.97
	σ	19.7	26.2	0.22	0.7	0.26
D	Ø	525.6	674.2	22.04	211.4	15.42
	σ	22.1	28.3	0.10	2.1	0.83
E	Ø	473.4	606.8	21.98	212.9	14.82
	σ	10.1	12.8	0.03	1.0	0.39

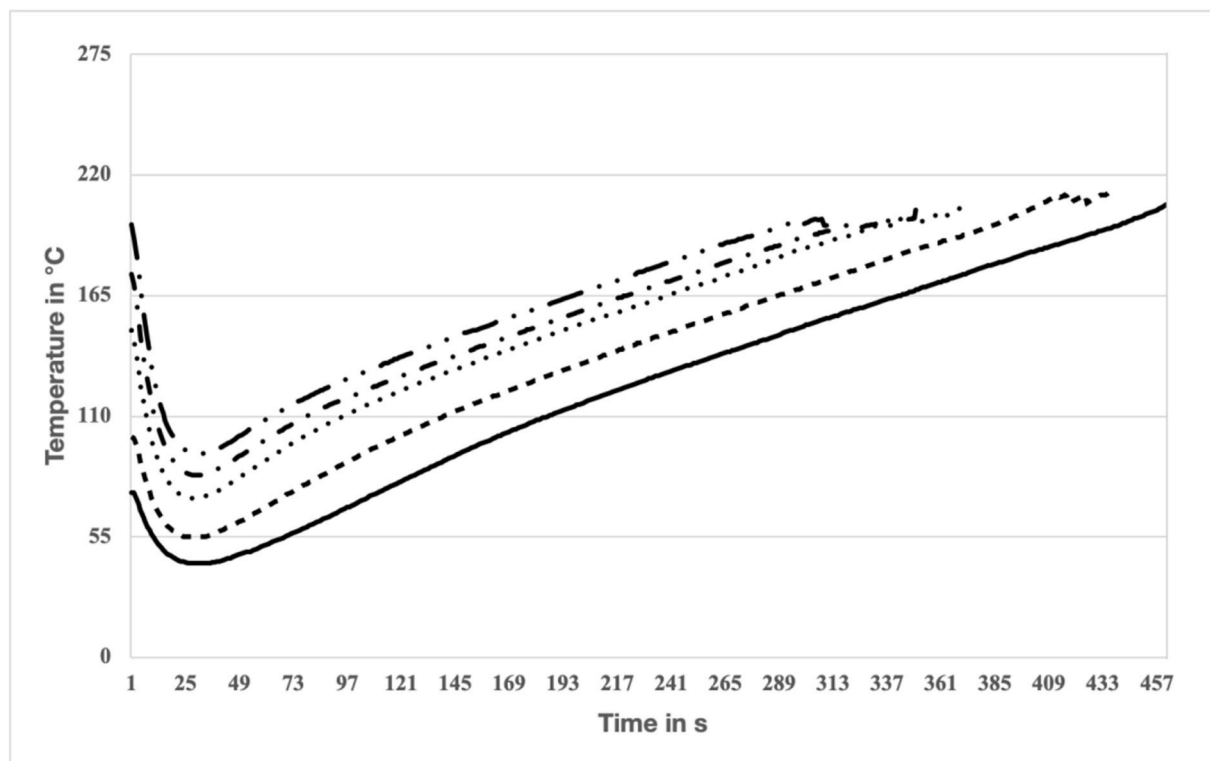


Fig. 3. Temperature curves of the various roasting processes: Throw-in temperatures 75 °C (solid), 100 °C (dashed), 150 °C (dotted), 175 °C (dashed-dotted), and 200 °C (dasheddouble-dotted).

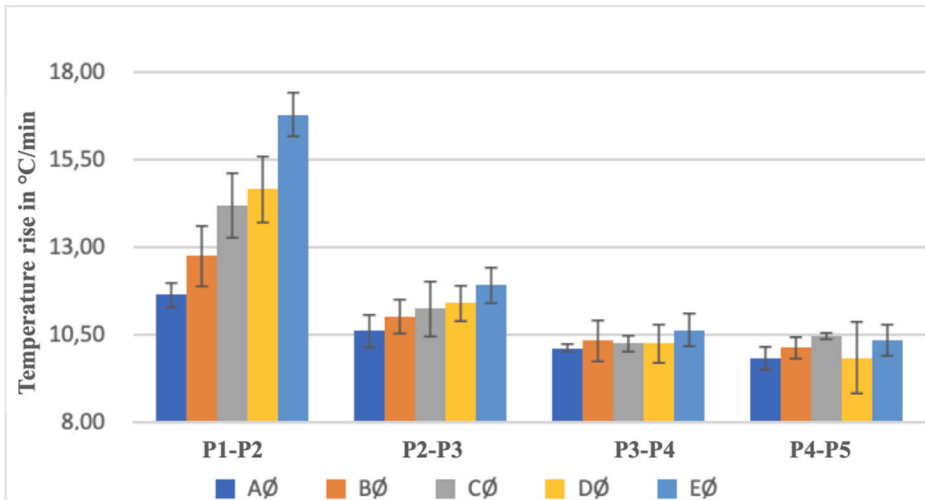


Fig. 4. Average temperature rise of the processes in comparison.

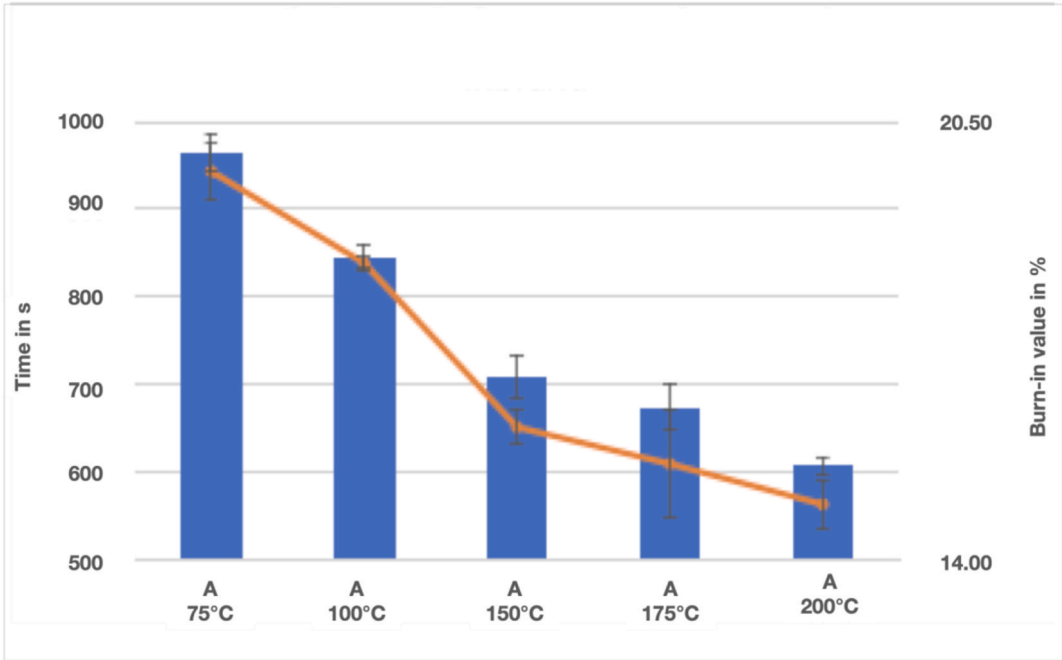


Fig. 5. Correlation between process time (bars) and the burn-in value (solid line).

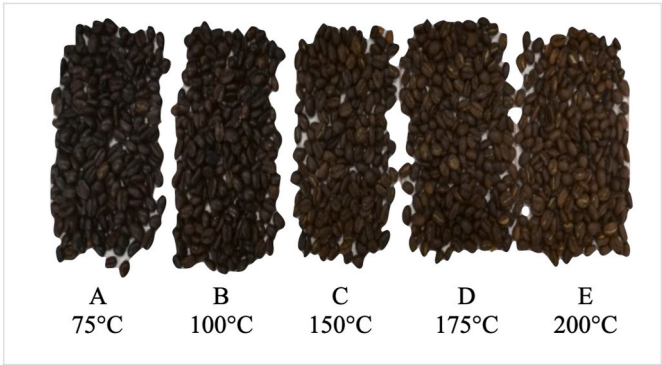


Fig. 6. Photographic representation of the roasting results for the different test procedures with the corresponding injection temperatures.

in the rustling can be detected. Fig. 7 shows the high-pass filtered (cutoff frequency of 5Hz) time signal (top) and the corresponding short-time rms value (bottom) of the airborne sound signal over the duration of one roasting, exemplified for the first process. The time signal shows a tapering of the course until the occurrence of the first crack (approx. 750s). The level curve (bottom) shows a clear decrease in the overall volume as roasting progresses and an increase in the region of the first crack (approx. 750–850s).

Corresponding spectra at three selected time points (around 50, 250 and 450s) in the area before the first crack can be seen comparatively in Fig. 8. The reduction of the sound pressure level over the course of the process (Fig. 7) corresponds to a reduction of the amplitudes in the individual frequencies more or less over the entire frequency range considered. In addition to a change in the overall sound level, the curves also show a change in the dominant frequencies or frequency ranges of the sounds. However, the reduction is more pronounced in the higher frequency range, about 5.0–9.0 kHz. The initially high, in comparison

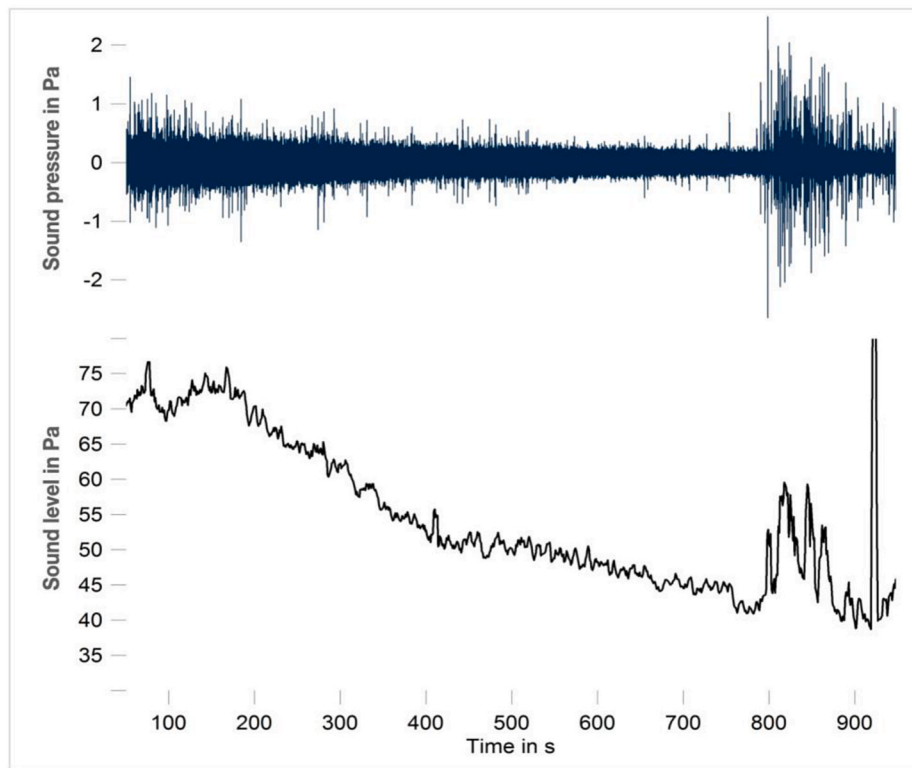


Fig. 7. Roasting curve, sound signal of microphone 1 (top) and level curve (bottom).

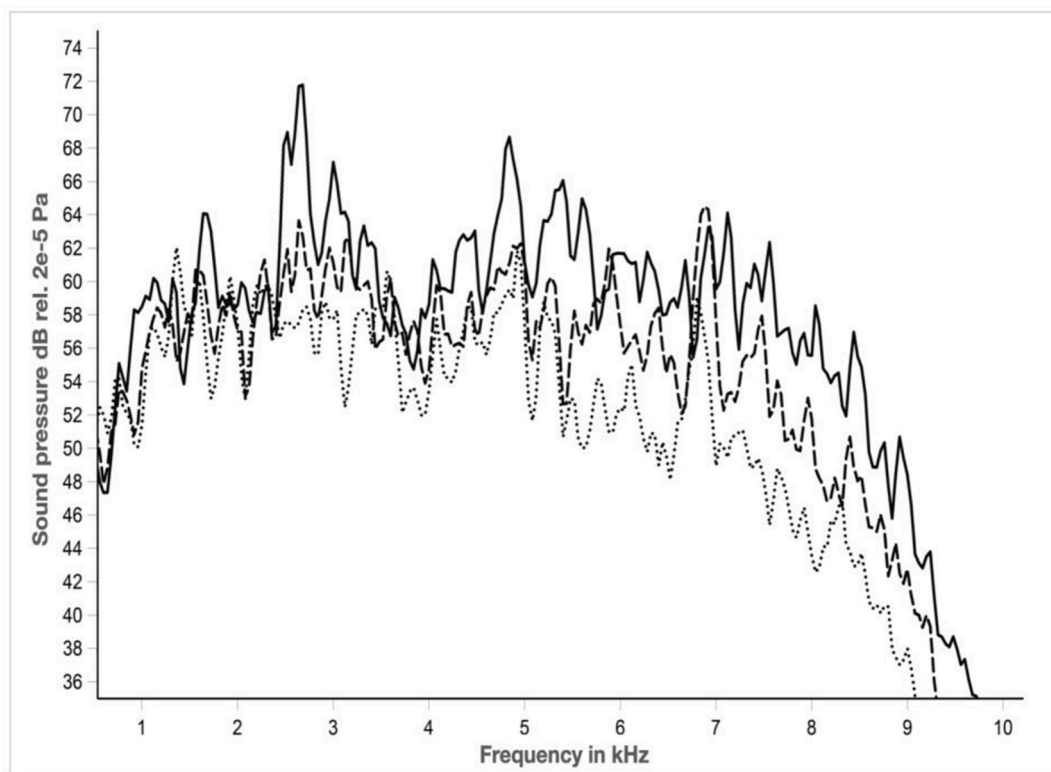


Fig. 8. Short time spectra at time points 50 (solid), 250 (stroked) and 450s (dotted) in the region before the first crack.

somewhat clanging rustling, develops into a lower and duller rustling. At the beginning of the coffee roasting process, the coffee begins to dry. Green coffee usually has a moisture content of around 10–12%. This is

essential to maintain its quality. During the drying process, the water content begins to evaporate, which leads to the development of vapour in the beans. As a result, the volume and internal pressure of the beans

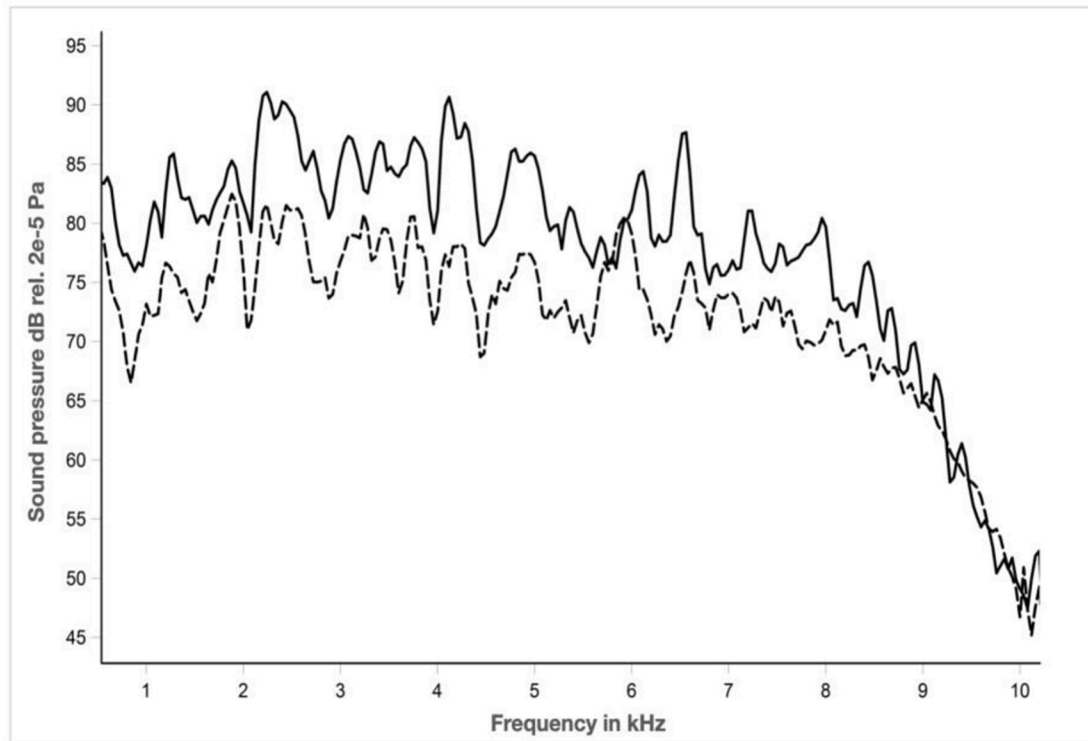


Fig. 9. Spectra of the airborne sound signal in the first crack (solid) compared to the one in the second crack (dashed).

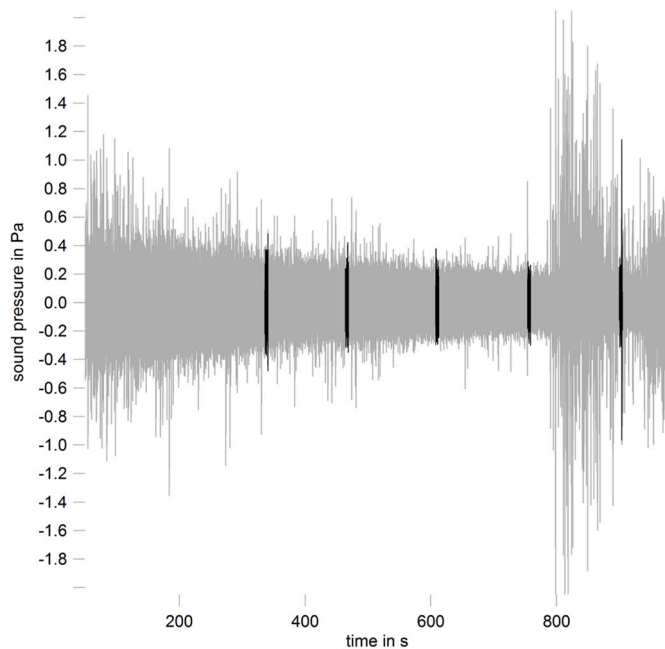


Fig. 10. Time signal of the air borne sound with highlighted selected measuring points.

increase. At this stage, the coffee beans lose density. Acoustically, the water vapour inside the bean has a dampening effect, and it is also to be expected that the larger, more homogeneous beans with a smoother surface will produce less contact-related noise.

4.3. Sound analysis - comparison of behavior in first and second crack

The sound in the first and second crack are also different, whereby

the characteristic course of the two curves is very comparable. The sound in the first crack has amplitudes that are approx. 5–10 dB higher than those in the second crack up to approx. 9 kHz, see Fig. 9. These results correspond quite well with those of Wilson et al. First of all with regard to the sound pressure level insofar as here, too, the first crack is described as louder than the second crack. With regard to the frequency weighting, it is the case that in the investigations that are the subject of this publication, the rather low frequency range (approx. 2.0–4.5 kHz) dominates in the first crack. This dominance is much less pronounced in the second crack.

4.4. Acoustic analysis - comparison of the behavior as a function of the insert temperature

In order to investigate whether the degree of bean roasting correlates with the acoustic signals, the acoustic signals at the same bean temperatures were compared for the different processes. The gray curve in Fig. 10 shows the course of the acoustic pressure of a roasting process. Within the curve, the sections resulting from the selected measuring points are highlighted in black.

The rms value and the corresponding standard deviation of the airborne sound signal at the individual measuring points (bean temperature) for the various methods are shown comparatively in Fig. 11. The courses of the sound pressure level as a function of the bean temperature are not unambiguous for methods A and B, but are clearly separable for the others. The standard deviation is in the range of approx. 10%. Up to approx. 150 °C, initially only the water physically bound in the coffee evaporates. From a temperature of 130 °C–140 °C, the bean begins to change colour and there is an increase in volume. This part of the roasting process therefore includes the endothermic processes. From 180 °C, the exothermic processes begin: CO_2 and hairline cracks form in the bean, which can extend into the interior of the bean. These hairline cracks and the bursting of the bean, the so-called "first crack", reduce the pressure inside the bean. (Fischer, 2005; Hamatschek, 2016). As the injection temperatures of processes A and B are below or both in the lower range of these temperature ranges, which are

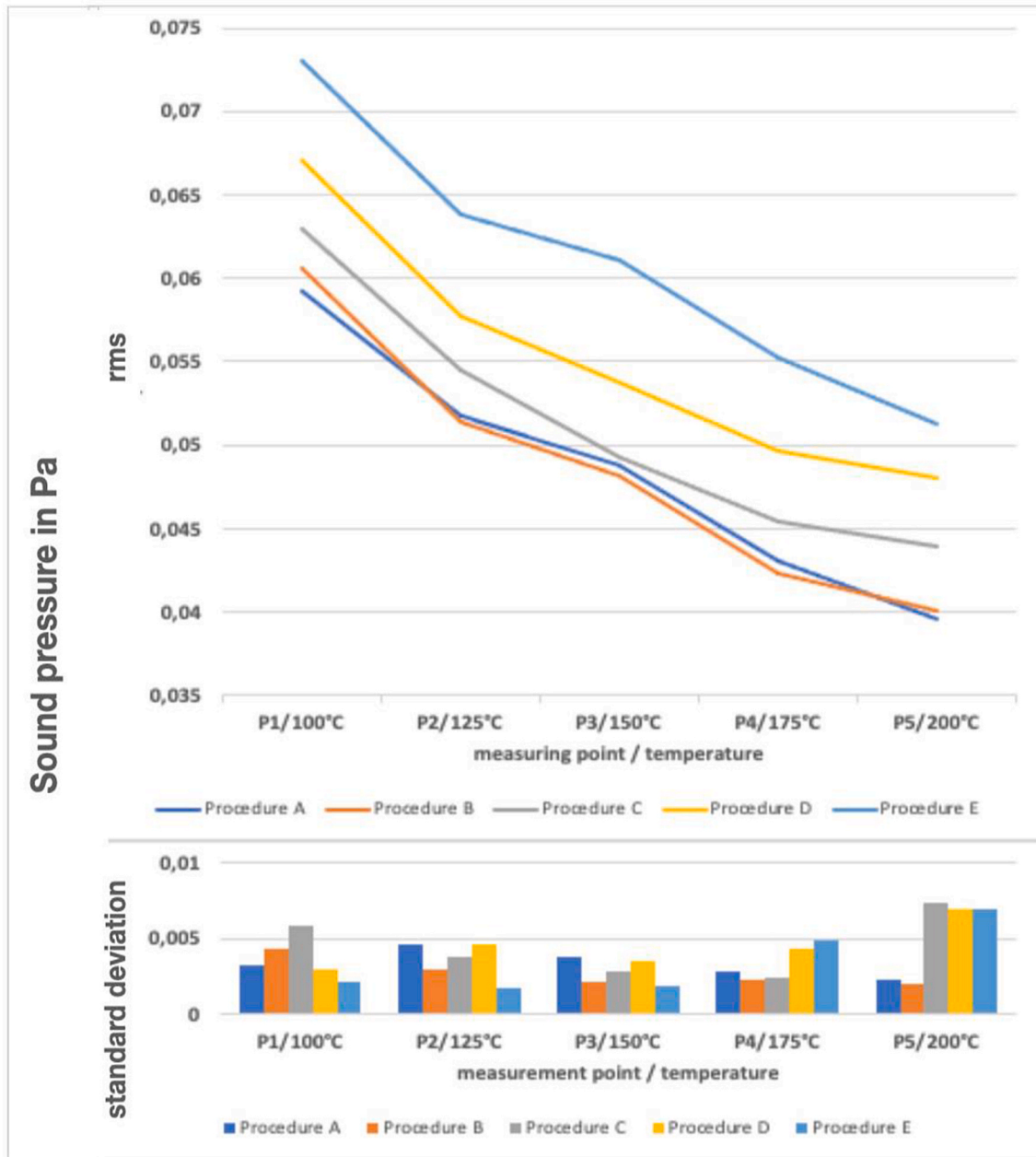


Fig. 11. RMS value (top) and standard deviation (bottom) of the airborne sound signal at the individual measuring points (bean temperature) for methods A (blue), B (orange), C (gray), D (yellow) and E (light blue) in comparison. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

significant for the roasting process, the roasting process is carried out at a comparable speed in all phases. The acoustic phenomena are therefore also comparable. In processes C - E, on the other hand, the phases are passed through at very different speeds.

The correlation between the realized burn-in of the beans (method A E) and the sound pressure level at the measuring point 200 °C can be seen in Fig. 12. A continuous increase of the sound pressure level with the increase of the burn-in is detectable.

4.5. Sound analysis - determination of the proportion of cracked beans

By detecting the individual cracking noises, it is possible to determine the proportion of beans that have already cracked at any one time. In practice, however, the beans crack at the same time, which usually generates a correspondingly louder noise, and the cracking beans are

located at different positions in the drum, which results in different measured volumes due to the distance from the microphone. The latter effect can be taken into account by averaging the signals, the simultaneous occurrence of cracks can be taken into account by looking at the relative signals or by a corresponding normalization. Therefore, with the calculation of a cumulative normalised moving average of the sound pressure in the area of the first crack. Fig. 13 shows accordingly the cumulative sound pressure level (normalised) in the area of the first crack for process A (solid curve) and process E (dashed curve). Marking lines illustrate the points in time when 0.25, 0.50 and 0.75 of the maximum total sound level is reached in the different methods. These points then indicate successively when 25%, 50% and 75% of the beans have been cracked. This would make it possible to automatically determine the gradient of the total sound pressure curve after the start of the first crack and then set the end time of roasting according to the

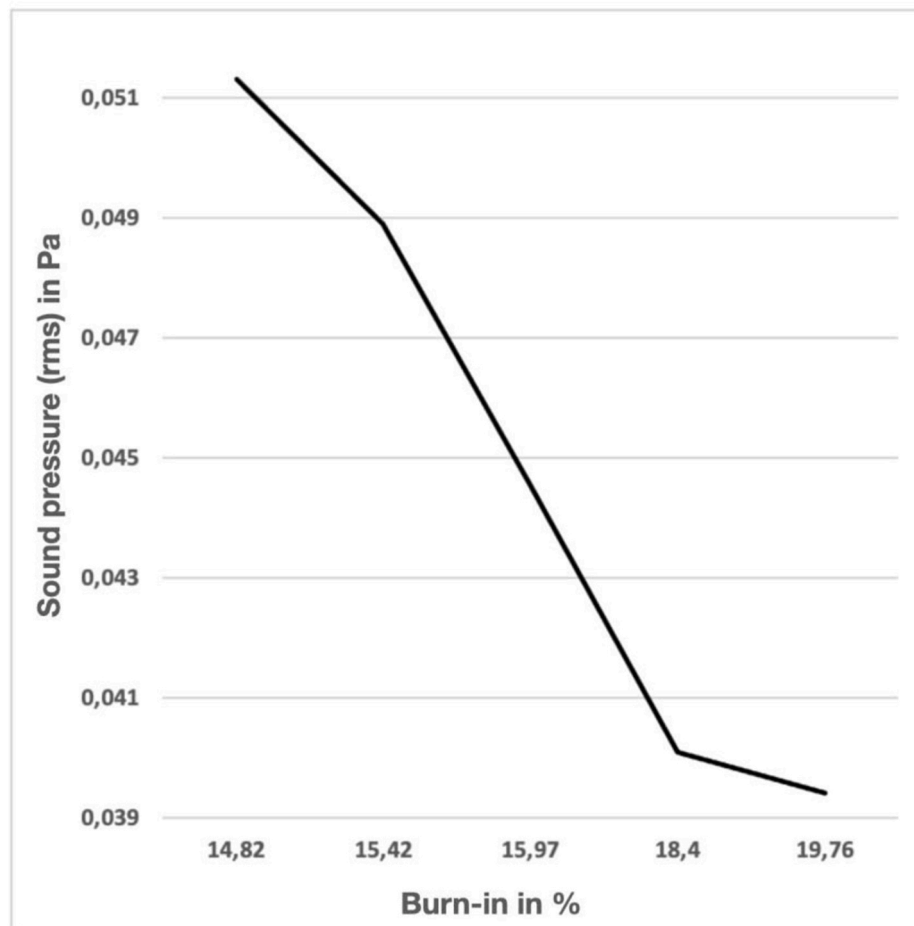


Fig. 12. RMS value of the airborne sound signal at the measuring point 200 °C above the burn-in value especially the different procedures A - E, 14.82 % (A); 15.42 % (B); 15.97 % (C); 18.40 % (D) and 19.76 % (E).

desired number of beans.

This is shown here as an example for the first crack; a transfer to the second crack is of course also possible.

The various processes now differ not only in terms of a different process time until a defined burn-in is reached, but also in terms of a different roasting time within the first crack. Therefore, although the curves for all processes are similar in principle, the longer or shorter process time results in a change in the maximum slope of the curve. Thus, in the future it would be possible with an acoustic measurement to predict the further course already at the beginning of the first crack and thus to select the ejection time exactly depending on the roasting target.

5. Summary and outlook

The experiment carried out deals with the question "Is it possible to make a statement about the current state of the coffee beans, in particular the degree of roasting, with the help of acoustic analysis of the roasting process?". A drum roaster (Hottop KN-8828B-2K+) was used for the investigations, which allows the observed events and characteristics to be transferred to larger, industrially used roasters. Five different processes were investigated, differing mainly in their different throw-in temperatures. For the different roasting processes, the beginning of the first crack, the process time, the roast development, the final mass and the burn-in were documented. The acoustic signals were recorded with microphones placed not far from the drum lid. The spectral composition of the signals as a function of the progress of the roasting process was analysed and presented. In particular, differences in the spectrum for the first and second crack were worked out and

compared with results already available in the literature from other roasting environments. The correlation between the burn-in achieved and the corresponding noise generated by the beans in the rotating drum was analysed and worked out based on the investigations for the different roasting processes. Furthermore, it was possible to show with the investigations that by means of an acoustic measurement not only the beginning and the end of the first or second crack can be determined, but rather it is possible to determine the proportion of already cracked beans at any time. In addition, it is possible to predict the proportion of cracked beans in advance for the further course of time. Both the correlation between burn-in and acoustics and the determination of beans cracked per time offer enormous potential for using acoustic evaluation in industrial coffee roasting and thus contributing to process optimization or even automation. Further investigations would have to be carried out on the basis of the data presented here to check the reproducibility of the statements on the one hand and the transferability to other roasters on the other. In particular, common methods used in practice should also be analysed with regard to acoustic monitoring. In the future, these results should be verified on a larger industrially applicable roaster. In addition, different batches of coffee beans and different varieties would have to be investigated. Further experiments could focus on a correlation between sound and aroma development. This aspect was not investigated in the present work.

CRedit authorship contribution statement

Hubertus Siebald: Writing – original draft, Validation, Supervision, Project administration, Formal analysis, Conceptualization. **Morten**

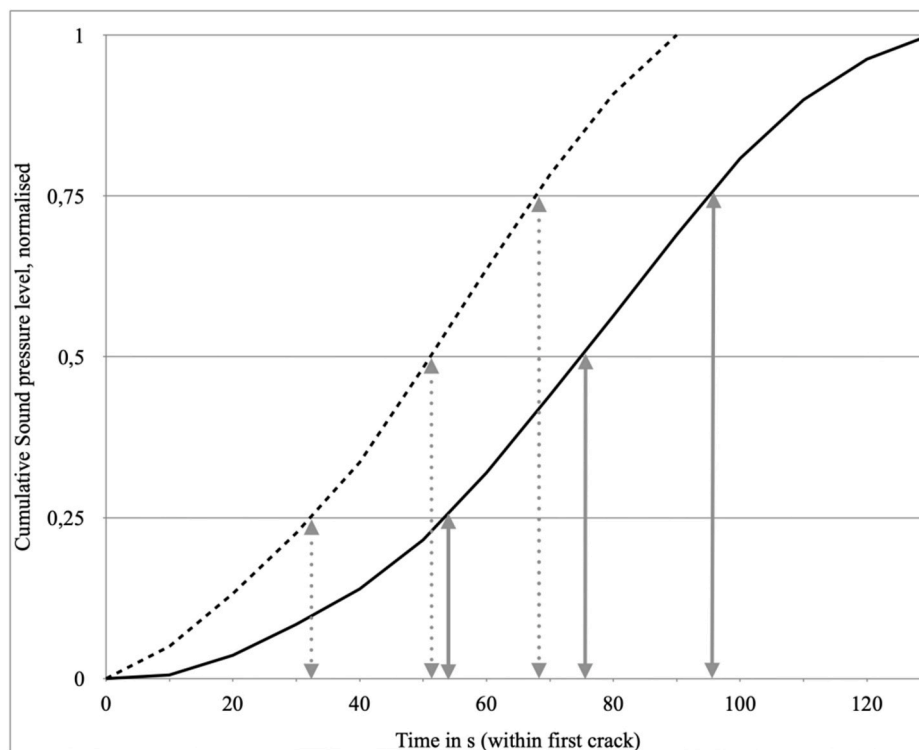


Fig. 13. Cumulative sound pressure level (normalised) in the area of the first crack for process A (solid curve) and process E (dashed curve). Marking lines to illustrate the points in time when 0.25, 0.50 and 0.75 of the maximum total sound level is reached in the different methods.

Möller: Data curation, Conceptualization. **Finn Lenz:** Data curation, Conceptualization. **Sascha Kirchner:** Methodology, Formal analysis. **Oliver Hensel:** Validation, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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