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Article

Alternative Sensing for State-of-Charge Estimation of Latent Heat Thermal Energy Storage

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Abstract: Thermal energy storage (TES) is likely to play a significant role in the decarbonisation of domestic heat, allowing consumers to shift their energy consumption away from peak demand periods and reducing overall strain on the grid. Phase change materials (PCMs) are a promising option for TES, in which energy can be stored in the latent heat of the melting of the PCM; these offer greater storage densities than sensible heat TES and have the benefit of releasing stored heat at a consistent temperature (the crystallisation temperature of the PCM). One of the key difficulties for PCM-based TES is state of charge (SoC) estimation (the estimation of the proportion of energy stored in the TES unit up to its maximum capacity), particularly during idle periods while the unit is storing heat. SoC estimation is key to the implementation of TES, as it enables the effective control of the units. The use of a resonator within the PCM for SoC estimation could potentially provide a global estimate of the SoC, since the resonator passes through the full depth of the PCM in the unit. The SoC could be inferred by measuring the vibrational response of the resonator under excitation, which varies depending on the melt state of the PCM. This paper presents findings from a test rig investigating this proposal, including discussions on the features required from the resonator response for SoC inference.

Keywords: phase change material; thermal energy storage; state of charge; resonator

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1. Introduction

In order to meet Net Zero, a range of sectors of the UK economy require rapid decarbonisation [1]. Domestic heating contributes significantly to household energy demand, with space heating and hot water provision making up 63.5% and 14.9% of energy consumption respectively in EU households in 2022 [2]. Demand-side interventions will be key to the decarbonisation of domestic heating, with thermal energy storage (TES) likely to play a significant role. The use of energy storage technologies would allow consumers to shift their energy consumption away from peak times, reducing overall strain on the grid [3,4].

Phase change materials (PCMs) are a promising technological option for TES, where thermal energy can be stored in the latent heat of melting of the PCM. PCM-based TES devices offer higher energy storage densities than traditional TES technologies, such as hot water tanks, and they also have the benefit of releasing heat at a consistent temperature (the crystallisation temperature of the PCM) [5].

One of the key difficulties in operating PCM-based TES units is accurate estimation of the state of charge (SoC). During charging or discharging, the SoC can usually be estimated relatively easily, based on the charging/discharging rate of the unit; however, measuring the SoC during idle periods while the unit is storing heat can be considerably more challenging [6].

Generally, the SoC is measured using temperature sensors embedded within the PCM [7,8]. However, these sensors can typically only measure the temperature in their immediate vicinity, which is not always accurately representative of the overall SoC of the unit, as heat is dissipated unevenly throughout the PCM. This can cause particular issues if only one temperature sensor is used, which will only be able to measure the temperature in a small area of the PCM; if multiple sensors are deployed then they can be used to build a more accurate estimation of the overall melt state of the unit; however, this then introduces problems related to recording large volumes of data and costs related to the implementation of multiple sensors.

An alternative sensing method is presented in this paper: using a resonator within the PCM. In the proposed resonator-based SoC estimation, the SoC is inferred from measurements of the resonator's vibrational response under excitation, which would be expected to vary based on the melt state of the PCM. This could provide a more global estimate of the SoC, since the resonator would pass through more of the actual PCM than a discrete number of temperature sensors.

The inspiration for this method of SoC estimation was drawn from the use of resonators to determine fluid viscosity [9]; this investigation used a tuning fork resonator to accurately track the density and viscosity of drilling fluid. The proposed transfer of this technology to SoC estimation for PCMs seems viable, given the significant changes observable in a PCM state during charging, discharging and standing periods compared to small changes in viscosity or density in other applications. Other analogous measurement techniques that use vibrational signals include ultrasound responses for battery state-of-health measurement [10], use of Lamb waves in submerged structures [11] and ultrasonic pitch-catch [12]. Alternative methods for SoC measurement include use of the coefficient of expansion of the PCM to determine its melt state [13] and advanced temperature measurement techniques [6]. A comprehensive review of SoC measurement techniques can be found in [7].

The outcomes of this investigation provide evidence for the potential of resonator-based SoC sensing. The findings could motivate future research to develop optimal data processing and to directly evaluate the technological benefits of the method against competing methods for SoC estimation.

The following section of this paper covers the overall philosophy and methodology for resonator-based SoC measurement, followed by a description of the experimental work carried out. This is succeeded by an analysis of the gathered data, focusing on methods to infer the SoC of the PCM from the data. Discussions on the applicability of the methods are then presented alongside comparisons to other technological solutions and suggestions for future work.

2. Methodology

In this investigation, a resonator beam was attached to the base of a TES unit (as depicted in Figure 1), and its vibrational response was used as an indirect measure of the SoC. When a PCM state changes from solid to liquid, the effective stiffness of the resonator is significantly reduced, while the damping increases since the liquid PCM is expected to dissipate vibrational energy. This stiffness change can be observed as a shift in the frequency and amplitude response of the beam; the change in damping causes a less sharp peak for the charged case. This is shown—qualitatively—in Figure 2.

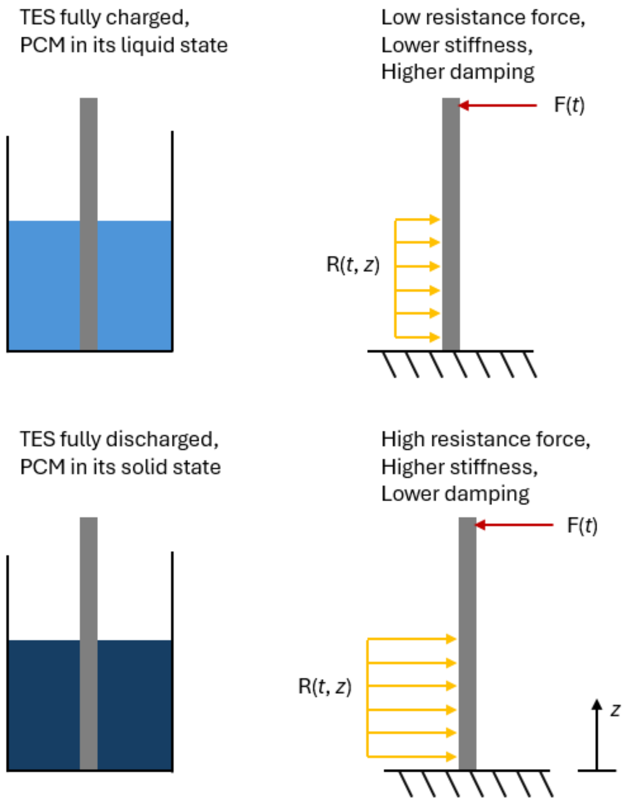

Figure 1. Diagrammatic depiction of the PCM resonator device, with excitation forces given in crimson and resistive forces due to the PCM given in amber.

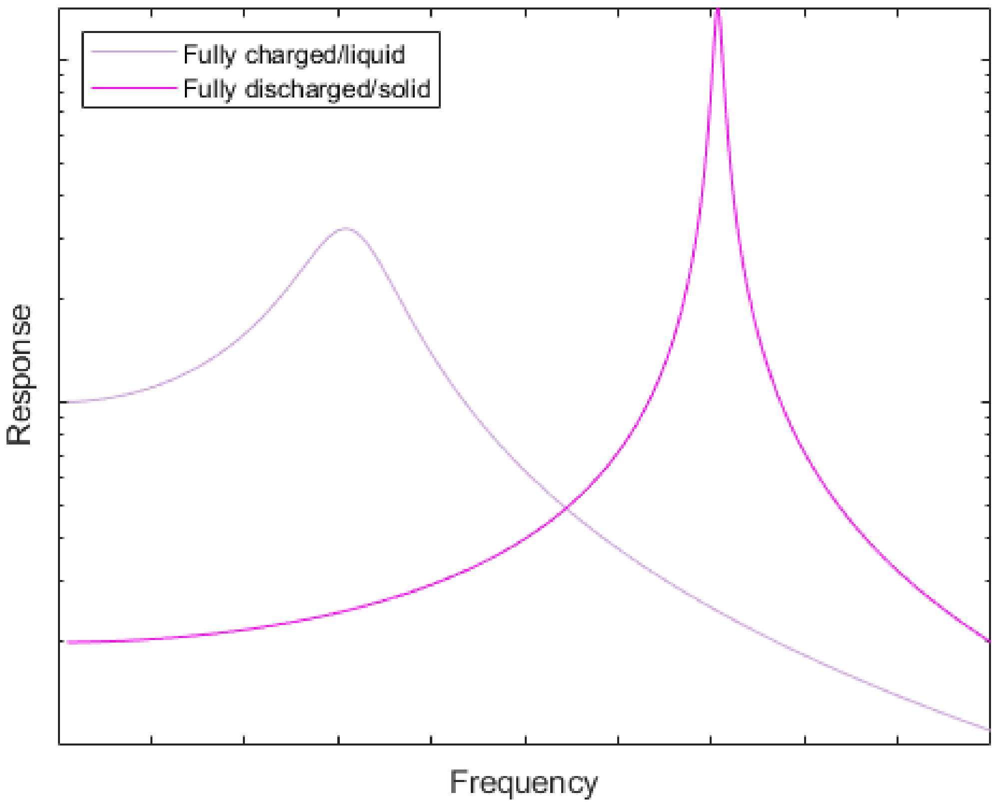

Figure 2. Illustrative example of the change in response expected for a PCM resonator in charged and discharged conditions.

While it is possible to anticipate the frequency response of the resonator for fully charged or discharged cases, when the PCM is entirely liquid or solid respectively, it is more difficult to foresee the response of the resonator during the phase transition. During this transition, the resonator may be surrounded by liquid PCM in some regions and solid PCM in others, or it may experience a 'mushy zone' [14]. In this case, the melt state of the PCM would be expected to vary in space, depending on the manner in which the phase transition is taking place (during charging, discharging or some more complex mode of operation); this would cause the resistance force, R, to vary with z, potentially causing non-linearity in the response of the resonator and its response to excitation. The assumption made prior to testing (and to be verified in the following investigations) was that the response would sit somewhere between the two states exhibited in Figure 2 and would correlate directly with the SoC of the PCM.

The frequency response (Figure 2) illustrates that exciting the beam at a frequency sufficiently below its first fundamental frequency (at a frequency lower than the peak value of the response) when the TES material is solid would enable SoC estimation through measurement of the response amplitude (which would be expected to correlate directly with the SoC and provide a significant, measurable modal displacement). Ensuring that measurement and excitation are carried out at a frequency below the lowest value for the first fundamental frequency of the resonator also ensures that any complications caused by multiple modes of the resonator changing order are avoided and removes the potential for any bi-directionality in the relationship between the response amplitude and the SoC.

Alternatively, measurement of the first natural frequency itself could also be used to estimate the SoC; however, this would add a signal processing and mathematical estimation burden, and it could be vulnerable to the problem of mode crossing. The resonator-based approach would offer a practical and cost-effective alternative for SoC estimation, eliminating the need for many internal temperature sensors while providing continuous SoC tracking regardless of the operational state of the TES unit.

It should be noted that this paper is mainly concerned with liquid–solid PCMs and does not consider solid–solid PCMs, although this may constitute an area for future research in resonator applications. Furthermore, the PCM used in this study (CrodaTherm 53™) exhibits little hysteresis around the phase change, so complex behaviours related to this were ignored [15]. Other more complex PCM behaviours, such as supercooling or superheating, were not considered significant, due to the slow speed of the heating and cooling in the investigations.

3. Experimental Work

To demonstrate the practical applicability of the introduced resonator-based SoC measurement method, a simple experimental setup was constructed to simulate the operation of a TES unit in a controlled laboratory environment, as illustrated in Figure 3.

The PCM used was a commercial material called CrodaTherm 53™ manufactured by Croda, Snaith, UK, which has a phase change temperature of 53 °C. It was poured into a transparent, polypropylene beaker, which enabled visual observation of the material state transitions during testing. The beaker was located in an environmental chamber using rubber pads to reduce vibration from other sources. The environmental chamber enabled setting of the operating temperature during testing; this was monitored with an additional thermocouple placed inside the chamber.

A steel beam (3 mm diameter, 100 mm length) was fixed and sealed at the enclosure base with an elastic connection component to prevent any leakage issue in the liquid state. A PCB Piezotronics ICP Model 352C22 accelerometer manufactured by PCB Piezotronics in

Depew, NY, USA of sensitivity 50 mV/g was fixed on the free tip of the beam to record the vibrational response.

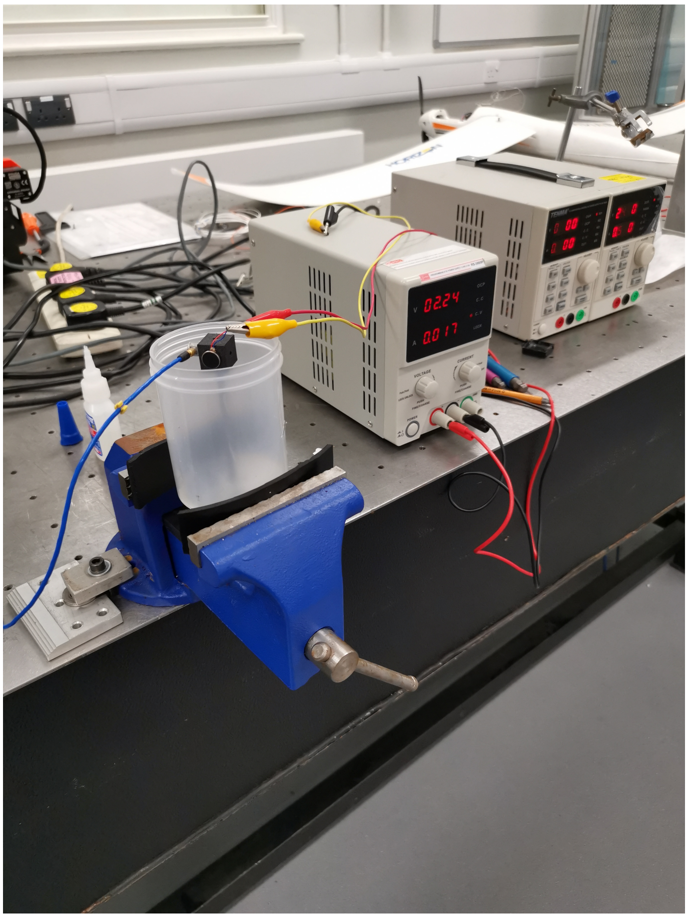

Figure 3. The beaker (held in a vice) with resonator installed set up for initial testing without PCM. The resonator had a cuboid mounting at its top end to which the rotating mass (front face) and accelerometer (left face) were attached. The motor drive can be seen to the right of the beaker on the workbench.

To determine the range in the first fundamental frequency of the resonator (in order to determine a suitable excitation bandwidth for testing), impact tests were performed in both the liquid and solid states of the material. Thirteen repeat tests were carried out when the PCM was in its solid, discharged, state; 22 repeats were used when the PCM was in its liquid, charged, state. The average frequency-domain responses were computed via discrete Fourier transform; the results are shown in Figure 4. It can be seen from the graph that an excitation frequency smaller than 40 Hz would effectively provide excitation for amplitude-based SoC measurement. In order to track the first fundamental frequency for frequency-based SoC monitoring, a bandwidth covering up to 300 Hz would be appropriate. It should be noted that the recorded data are presented in Volts, which was simply the direct recorded output of the accelerometers.

Comparing the results presented in Figure 4 with what was predicted in Figure 2, a few observations can be made. Firstly, it is clear that, as expected, the first fundamental frequency (represented by the peak amplitude for each set of results) significantly reduced when the PCM was in its charged, liquid state. However, the predicted impact of increased damping for the charged state was not observable. This was because the response amplitude for the discharged state was necessarily lower, due to the change in boundary conditions: the resonator was effectively fixed up to the height of the solid PCM. Finally, a 'split peak' was observable for the charged condition; some apparent resonance could also be seen around these frequencies (40–50 Hz) for the discharged condition. The causes for this would include the contributions of the beaker or its mounting to the response, or the fact that the resonator itself may have coincident natural frequencies in this range of the spectrum. Given that the resonator was of circular cross-section, the latter is highly likely as the rotational symmetry around its longitudinal axis would cause an infinite number of fundamental modes to exist, which might be slightly offset by the resonator's interactions with the PCM around its cross-section. The use of a rectangular cross-section resonator would eliminate this behaviour, meaning that split peaks in the response using a resonator of this type could be attributed with confidence to external sources of vibration such as the response of the beaker.

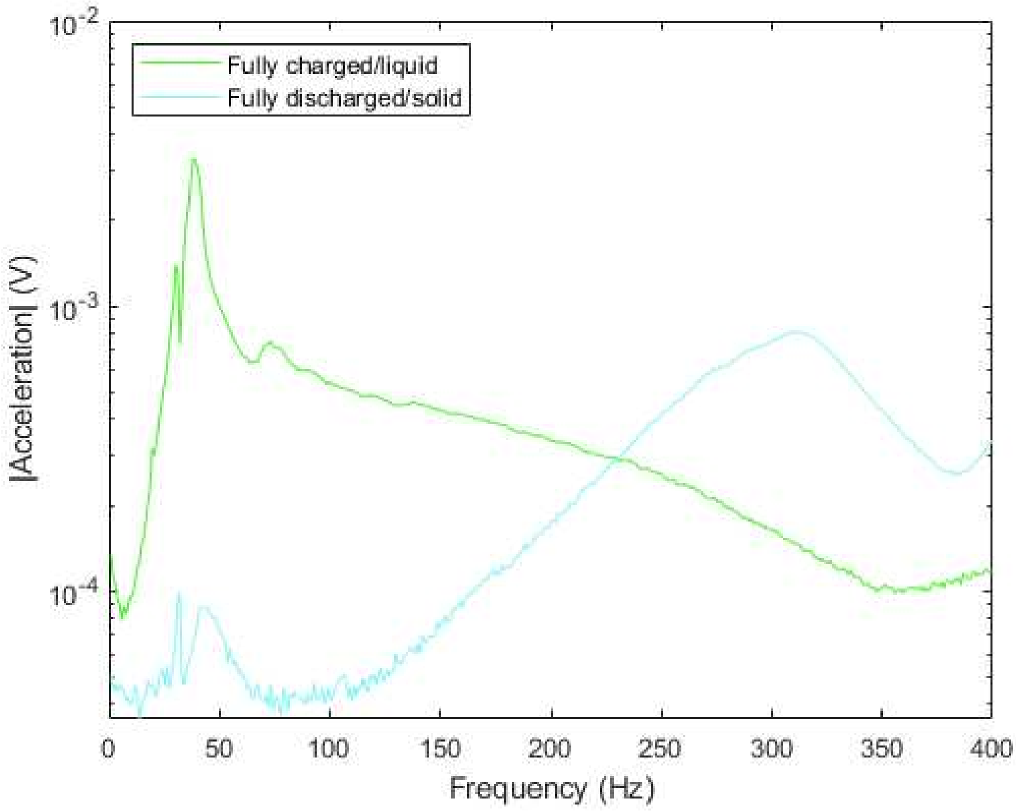

Figure 4. The resonator's response to tap testing with the PCM in its fully charged and discharged states.

Excitation was provided using a rotating mass actuator mounted near the free tip of the beam. The rotating mass used was a Seeed Studio Mini Vibration Motor, and it was driven using a benchtop power supply. Prior to testing, the motor was driven up to its maximum voltage in order to determine its maximum frequency range with no PCM in the container. For these pre-tests, the motor was driven at a range of voltages up to its maximum power, providing a stepped-sine excitation to the resonator. The tests were carried out at a range of temperatures, in order to determine if this had an effect on the operation of the motor, and the recorded accelerometer data were converted to the frequency domain using the fast Fourier transform. Welch's method of averaging, in which the data are split into multiple windows, enabling an average signal to be estimated, was used to reduce the noise on the signal [16]. These spectral results are plotted in Figure 5, which shows that the maximum excitable frequency was around 160 Hz, although this maximum frequency varied depending on temperature: it appeared that the motor could reach higher frequencies at cooler temperatures, which was assumed to be for mechanical reasons, enabling the motor to run more freely in these conditions. This meant that a frequency-based SoC estimation method could not be investigated using this motor, as the first fundamental frequency could not be excited when the PCM was fully discharged and in its solid state. Therefore, the amplitude-based method was pursued and is presented in this paper. This issue could be overcome in future testing by using a lower-stiffness resonator or by adding mass to the current resonator, either of which would reduce its first fundamental frequency.

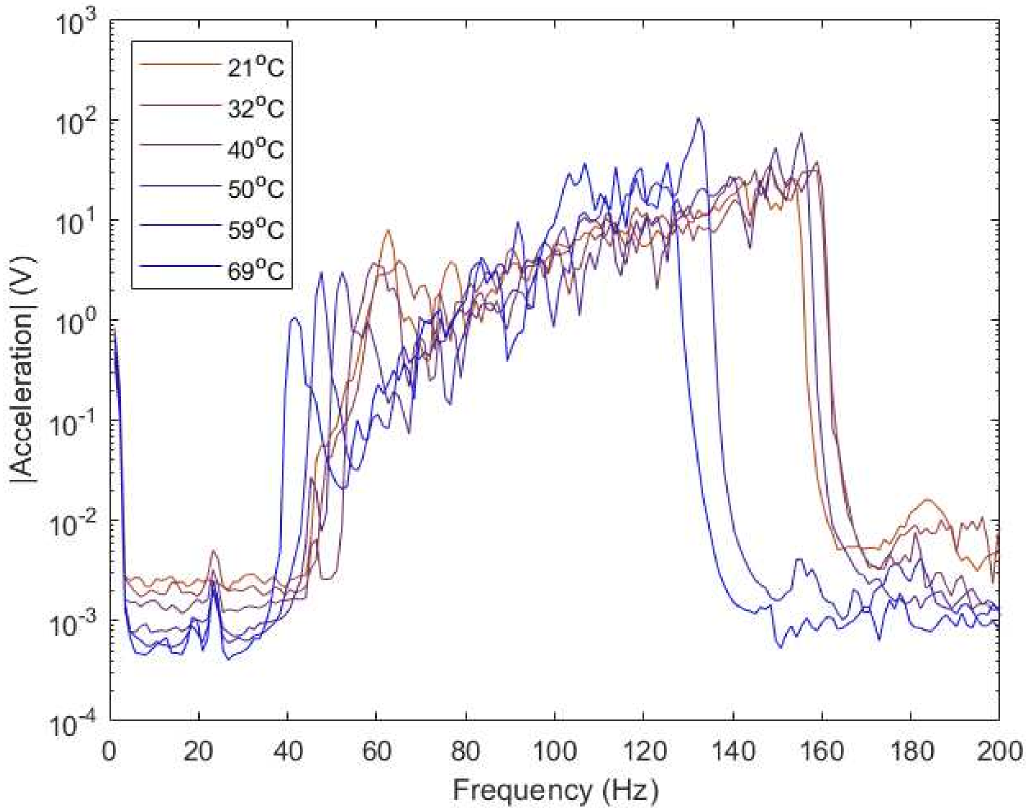

Figure 5. The resonator's response to rotating mass excitation over its full frequency range for varying temperatures.

The tests were initiated when the PCM was in a liquid state after being fully charged to 70 °C. The temperature was incrementally reduced during testing to a fully solid (discharged) state. Each test was carried out when the oven had reached its set temperature and held this temperature for ten minutes (to allow the PCM to acclimatise). The settling time was determined by trying to introduce a set time of significant length without compromising the ability to carry out the tests within one working day. The test points are summarised in Table 1. For each test point, the rotating mass was driven at 1.2 V, resulting in an excitation frequency of around 30 Hz, which was sufficiently below the minimum value for the first fundamental frequency of the resonator. As discussed in the Methodology section, it was therefore anticipated that exciting this frequency would result in a steady variation in the response as the melt state of the PCM developed. The test duration for these tests was ten seconds, and five repeat measurements were taken at a 1.5 kHz sampling rate.

Tests to monitor the progression of SoC—as measured using a resonator—during a charge cycle will be carried out in future investigations. However, PCM cooling was considered to be of the most significant interest, given that the SoC can be more readily measured using temperature-based methods during charge cycles and that PCM charging would usually be expected to be carried out during overnight periods (enabling full charges to be carried out at low cost).

Table 1. Summary of tests carried out (time of measurement refers to the time of day).

Test No.	Oven Set Temperature (°C)	Measured Oven Temperature (°C)	Time of Measurement
1	70	67	12:15
2	60	59	12:40
3	59	59	13:00
4	58	56	13:20
5	57	54	13:30
6	56	54	13:40
7	55	53	13:55
8	54	53	14:05
9	53	52	14:15
10	52	51	14:25
11	51	50	14:35
12	50	49	14:45
13	40	39	15:05
14	30	30	15:20
15	20	20	15:40

4. Results and Analysis

A picture was taken of the PCM during each test in order to attempt to qualitatively determine its melt state and SoC; these images are shown in Figure 6. The images are not easily interrogable as the plastic beaker was not fully transparent, but it can be seen that during solidification the PCM appears to have formed a ring shape (Figure 7) in its solid state around the resonator, before fully solidifying (Figure 8). It is likely that the heat transfer through the PCM, having moved from one test point to another, would take significantly longer than the ten minutes allowed, as the formation of the solid ring shows that the temperature was clearly not distributed evenly throughout the PCM. This is an inherent issue with this setup, and it could be rectified in future research by using a heat exchanger submerged in the PCM rather than an oven to improve the heat transfer rate when charging and discharging the PCM, or by allowing the PCM to self-discharge to ambient conditions from its charged condition and tracking the temperatures within the PCM.

The raw accelerometer data recorded from the first repeat of these tests are plotted in Figure 9. This figure shows a clear dependency between signal amplitude and the melt state of the PCM, which was incrementally cooled from test to test. The acceleration amplitude gradually decreased as the temperature reduced and the PCM transferred into its solid state.

There are also some clear unexpected results to note. Firstly, for many tests the amplitude of the signal seemed to reduce during the test period. This could be explained by the fact that the resonator required some time to reach steady-state vibrations and that the observed reduction in amplitude was due to a decaying transient excitation at the beginning of the test. Secondly, the average amplitude of the signal did not always reduce steadily between tests; for example, Test 5 had a much lower amplitude than Tests 4 and 6. Potential explanations for this phenomenon include 'unsteady' phase changes between tests (see Figure 6), inaccurate control of the temperature of the environmental chamber or temporary solidification of the PCM around the resonator. The explanations for these behaviours are currently hypothetical in nature, which is a motive for further research to make a more informed commentary on the matter.

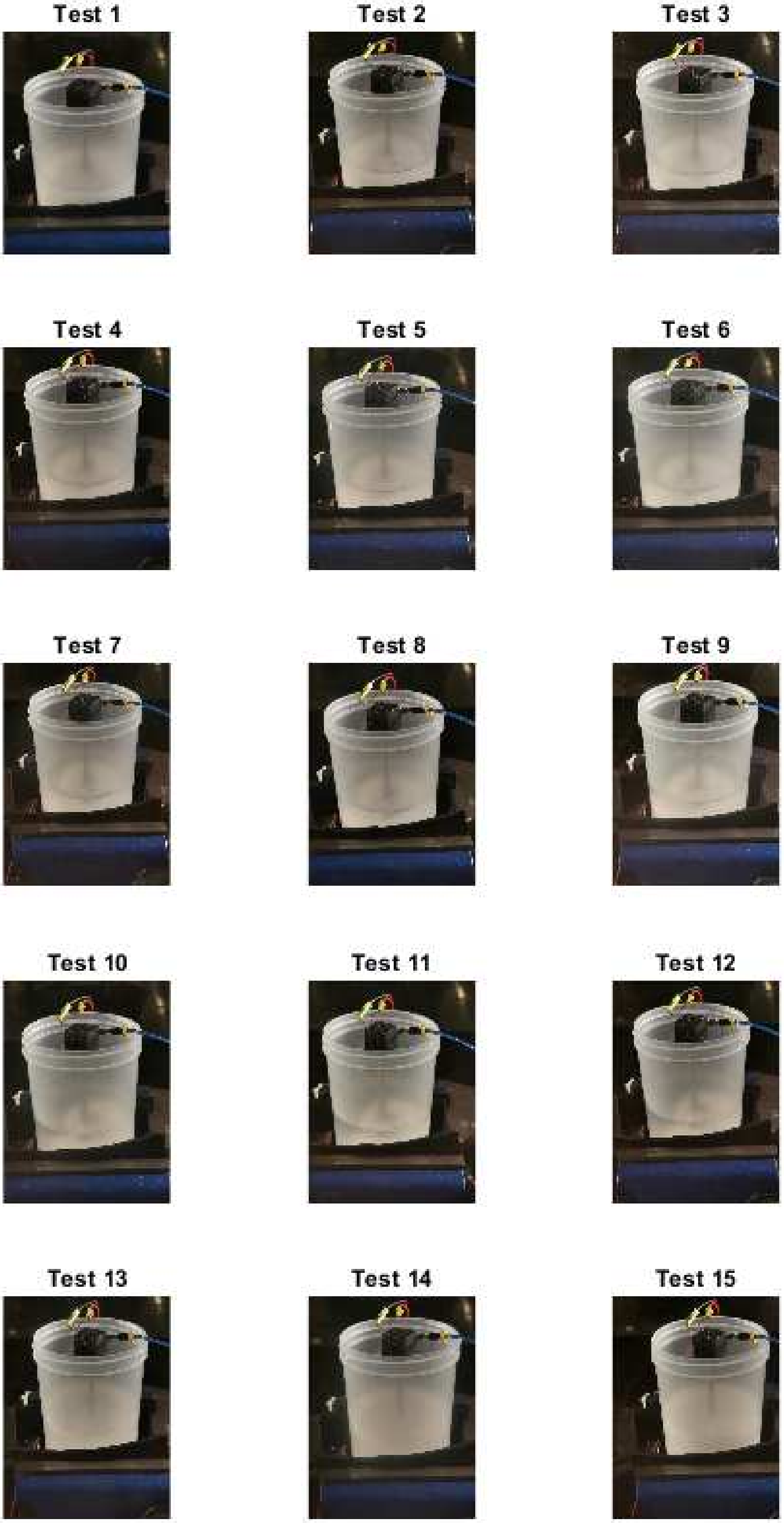

Figure 6. The PCM pictured during each test.

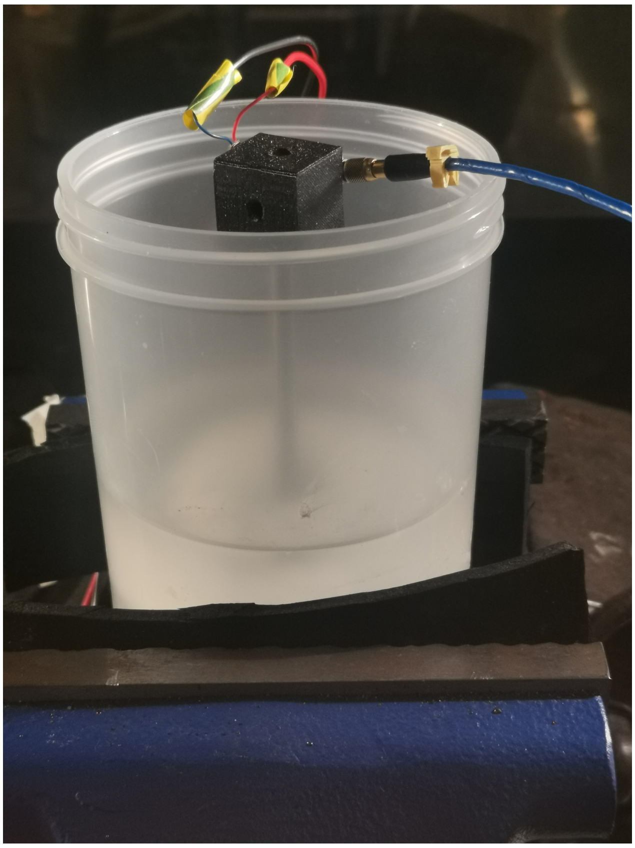

Figure 7. The PCM pictured with a ring formed during Test 4.

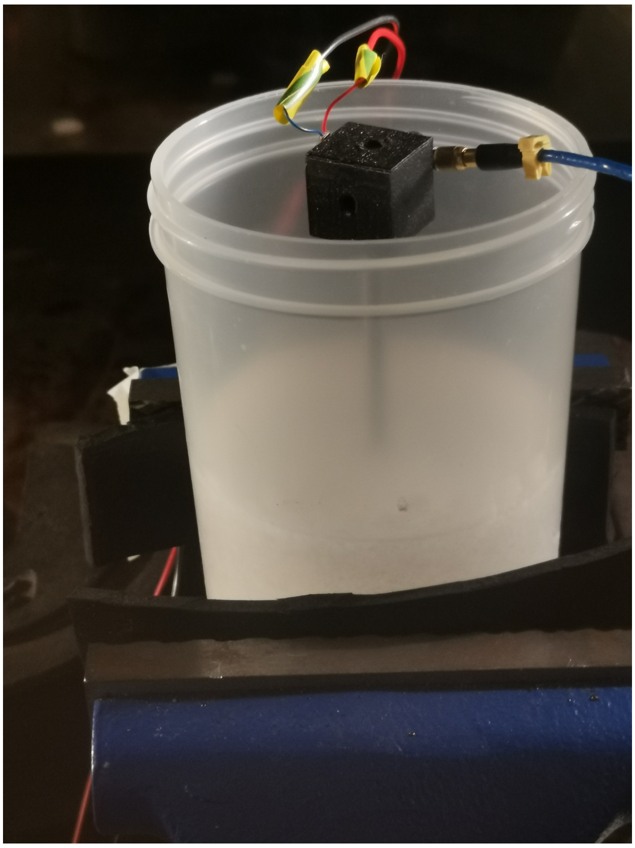

Figure 8. The PCM pictured dully solidified during the final test.

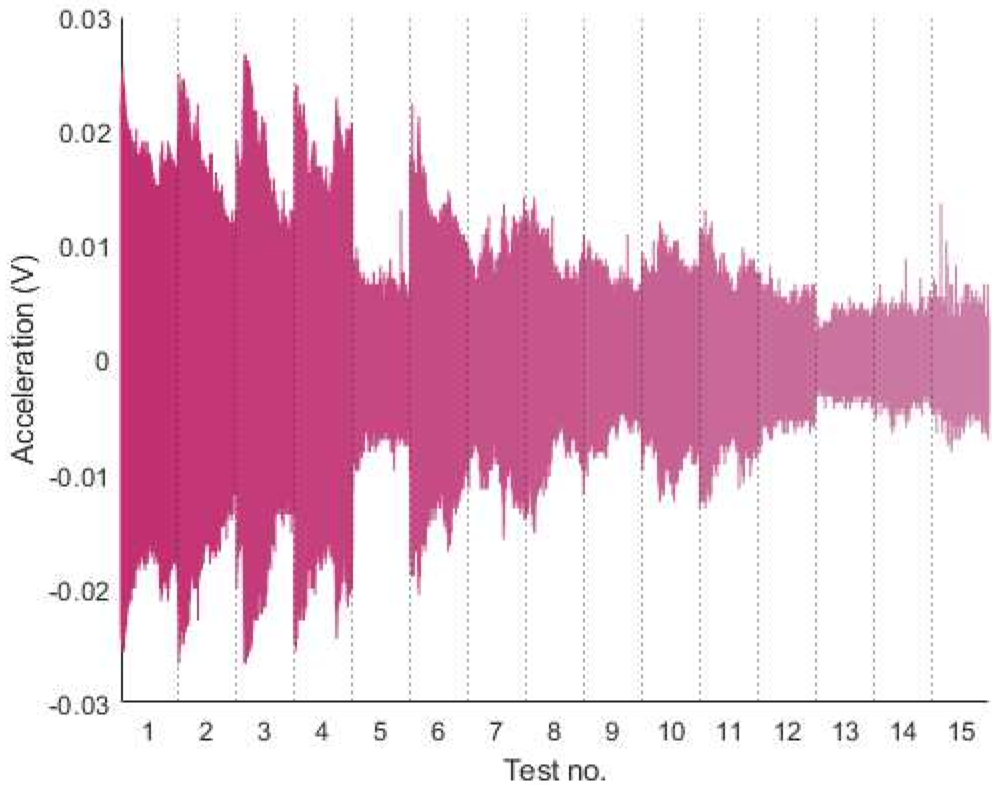

Figure 9. The recorded response data from the accelerometer for the first repeat over all tests during solidification of the PCM.

Two features were extracted from these data for use as SoC indicators: the amplitude and the root mean square (RMS) of the signal for each test. The amplitude was evaluated for each test point by taking an average of the MATLAB R2024b 'Envelope' function for each test, which tracks the amplitude of the waveform over time; the function was utilised on its default settings [17]. The features were recorded for each repeat test, then averaged across repeats to provide an overall datapoint for each test; these results are plotted—with uncertainty bounds—against the measured oven temperature in Figure 10. This figure shows that the two presented features, amplitude and RMS, of the time-domain signal had good variation with the PCM temperature, which is correlated closely with the SoC for TES systems. However, as was noted in the analysis of Figure 9, the relationship between the features and the oven temperature was not strictly consistent, with the datapoint for Test 4 (56 °C) sitting significantly above the curve. These variations from the overall trend could be initially assumed to have been aleatory in nature, since there was signifiant variability in the physical phase transition process, meaning that longer test periods would have reduced their effects as any unbiased noise was averaged out, but this assumption would require further research to validate. The variability of the results in this section of the graph is also indicated by the relatively wide uncertainty bounds observable in Figure 10.

A reasonable level of sensitivity can be seen for both features around the crystallisation temperature of the PCM (53 °C). This is highly promising for the technology, as measurement of the SoC using temperature in this region is extremely difficult. At temperatures above this range, the features are highly sensitive to temperature, while below 50 °C the features show very little sensitivity. This is thought to be due to the ambient temperature having little impact on the response of the resonator once the PCM was fully solidified, meaning that the technology would not act as a good SoC sensor below the phase change temperature.

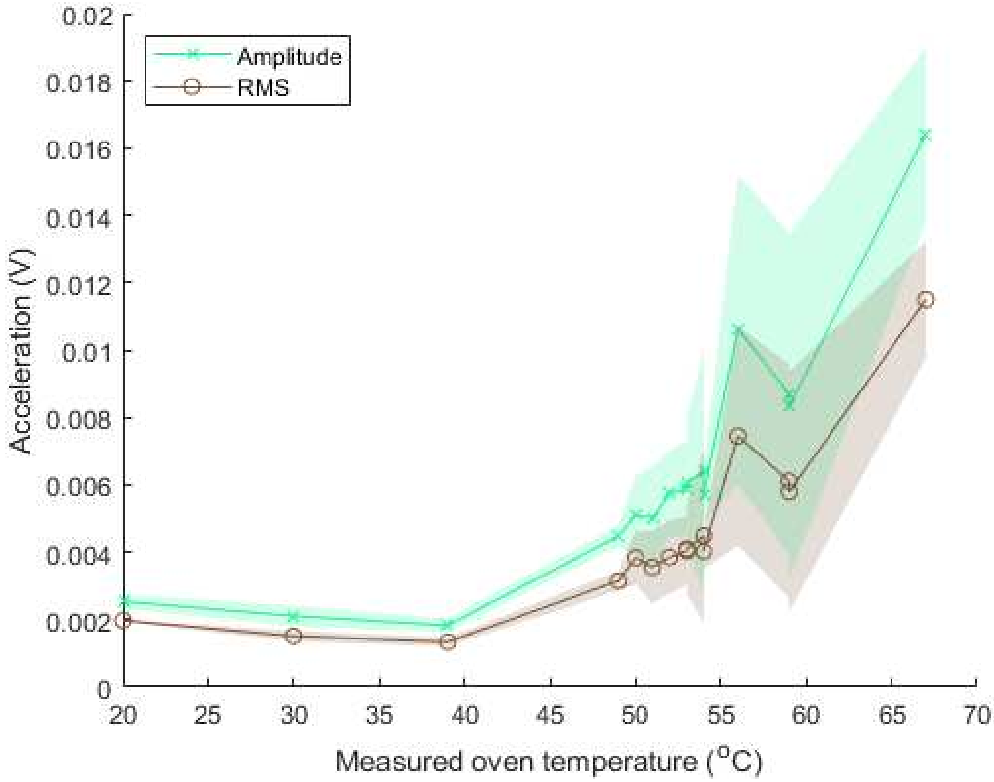

Figure 10. The extracted features for SoC estimation plotted against measured oven temperature with shaded areas indicating ±1 standard deviation.

5. Discussion and Future Work

The results published in this paper provide an excellent indication of the potential of resonator-based methods for SoC estimation of PCM TES systems. The results presented here serve as a strong proof of concept for the technique.

A particular strength of the method is the apparent sensitivity the resonator showed in the phase transition region of the cooling process, with a difference of 46% in the amplitude and RMS values between Tests 2 and 12 (see Figure 10). This can be contrasted with temperature-based methods, where measured PCM temperature will be close to constant for the duration of the phase transition, making the SoC extremely difficult in a key operating area for PCM-based TES [18].

It should be stated that these results were derived using small quantities of data from only one sensor (the accelerometer mounted on the resonator), whereas equivalent results derived from temperature-based methods would require multiple sensors and greater physical understanding of the characteristics of the phase transition. Furthermore, the sampling rate required for carrying out amplitude-based SoC measurement could be significantly reduced in future testing if low excitation frequencies are required (although higher sampling rates—such as the 1.5 kHz utilised in this study—may still be required for frequency-based methodologies). Given that the methods followed are due significant further development, these are extremely promising findings, indicating that future SoC sensing for PCM-based TES could be carried out very cheaply and simply with little computational burden.

However, significant further work is required to strengthen the case for this technology; this is detailed in this section with reference back to the testing where relevant. The initial plan for these experiments was to carry out back-to-back tests at each temperature setting to enable amplitude-based SoC inference, as was discussed in this paper, and frequency-based inference. This second method would have used a stepped power signal to vary the frequency of the rotating mass actuator and to determine the first fundamental frequency of the resonator throughout the tests. However, as was shown in Figure 5, it was not possible to achieve a high enough frequency to excite the first fundamental frequency of the resonator when the PCM was fully discharged. This issue could be alleviated in future tests by using a different actuator, or by using a resonator with lower stiffness (or with greater mass).

Future testing work should include measures for improving the quality of the data; this would include reducing noise on the measurements and making greater provision for temperature settling. Noise reduction could be carried out relatively easily by increasing the test duration or the number of repeat measurements—this would allow for increased averaging over the length of the test. The quantity of data recorded could be managed by reducing the sampling rate if required. In terms of temperature settling, future rigs should provide better visual analysis of the PCM as well as in situ temperature measurements; this would enable a more appropriate assessment of temperature stabilisation than simply applying a set waiting time, as was done in these tests. Use of temperature sensors in the PCM would also allow for the mapping of temperature to the SoC of the material, which would be a useful comparator against which the resonator-based methods could be assessed. An improved design of experiments may also yield clearer results: for example, where the TES is heated to its maximum temperature, then allowed to cool naturally while monitoring ambient temperature, PCM internal temperature and resonator features. It would also provide valuable insight to assess the use of the resonator for SoC measurement during charging of the PCM; this was not investigated in the current work because the idle period between charging and discharging was identified as most relevant for SoC measurement by this method (by comparison, inferring the SoC during charging and discharging processes from the measured charge/discharge power is a relatively straightforward process).

An in-depth comparison of resonator-based SoC sensing against other established methods will be key to establishing its effectiveness beyond pure feasibility studies. The main method against which resonators should be assessed would be temperature measurement, as mentioned above. However, other measurement techniques including PCM level measurement and vessel pressure should also be investigated for evaluation [7].

Finally, a test rig investigating a PCM-based TES device that uses a heat exchanger submerged in the PCM for charging the TES unit (rather than an oven), is required. This is a more realistic operating case representing a more complex extension of the simpler cases using laboratory scale vessels and equipment. The use of heat exchangers in applicable PCM-based TES technology has been demonstrated in a range of products [19,20], and reflects the case where a PCM-based TES unit could be incorporated into a domestic heating circuit. A foreseeable difficulty in integrating a resonator-based SoC system into a TES unit with a heat exchanger is that space will have to be provided within the unit for both the resonator and the heat exchanger, which may result in the requirement for complex heat exchanger design.

6. Conclusions

This paper presents results from a novel SoC sensing technique for PCM-based TES using a resonator embedded within the PCM. A basic rig was developed to investigate the technology, where a small amount of CrodaTherm 53™ was poured into a plastic beaker containing a steel resonator bar fixed to its base. The beaker was then placed in a controlled-temperature oven for charging and discharging, with the temperature monitored using a separate thermocouple during testing. During the tests, the amplitude of the resonator excited at low frequencies was found to correlate well with the independent temperature monitor, indicating its potential as an effective SoC sensor; in particular, the sensitivity to temperature around the phase change point (with a measured difference of 46% in the amplitude and RMS values during the phase transition) was very promising, since SoC measurement using traditional measurement techniques is often difficult around the phase change. Use of this technology could lead to simpler, cheaper and more effective SoC measurement for PCM-based TES systems, significantly aiding with the efficiency of their operation. Significant further work is required to develop the methodology offered in this paper; however, the results presented here show a strong indication of the potential impact of current and future research into resonator-based SoC estimation methods.

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