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Experimental characterisation of a novel phase change material heat storage unit for state-of-charge estimation

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ABSTRACT

Energy storage methods will be a critical part of the future energy supply system, as demand is increased by electrification of domestic heat and take-up of renewable generation increases the variability of supply. Domestic storage units are likely to be key to this transition, and this paper will present investigations into a unit for storage of domestic heat. A phase change material (PCM) heat storage unit has been developed that has the potential to provide effective heat storage facility in a domestic capacity. Effective control and use of the storage units is dependent on accurate state-of-charge (SoC) estimation, tools for which are being developed and supported by data presented in this paper. A novel test bed has been developed in order to acquire data for this purpose. The rig is situated in a temperature-controlled chamber which enables charge and discharge tests at a range of ambient temperatures. Automated control of the rig is also available, which allows for repeatable tests to be carried out to gather data for model development.

Keywords: *Characterisation, phase change material, thermal energy storage, state-of-charge*

1. INTRODUCTION

Thermal energy storage (TES) will be key to the net-zero energy transition. This paper presents initial outcomes of a major project that aims to provide solutions for advanced storage that will have significant impact on electricity grid operation as part of the wider the decarbonisation of domestic heat.

Domestic heating constitutes a major portion of overall energy demand, making up 64.4% of energy consumption in EU households in 2021 [1]; this demand has traditionally been met by the use of gas boilers to provide space heating and hot water. Decarbonisation of this system will be critical to meeting climate change targets such as net-zero. A potential solution is to electrify domestic heat by using heat pumps; this is an attractive option given the high coefficients-of-performance available. However, widespread electrification will present a major new demand on the supply of electricity, with significant variations in the demand both in the short and long term. A parallel challenge is that the ongoing take-up for renewable energy generation means that the supply of electricity itself is becoming more variable [2]. In light of these issues, energy storage will likely be required in order to stabilise the demand for electricity and to manage the peaks and troughs in its supply [3].

Access-level TES, where heat is stored at the point-of-access in a domestic setting, offers a series of benefits. In this system, TES units would allow users to store heat generated by their domestic heat pump when supply is greater than demand, and access the energy in the stores when demand outstrips supply. This would enable users to take advantage of variable-price tariffs without compromising their access to heat when required, and would reduce the overall strain on the electricity supply.

This paper presents a novel phase change material (PCM) storage unit – developed at the University of Loughborough – that could be incorporated as part of a domestic TES system. Following a technical presentation of the device, a new experimental rig that has been developed to test and characterise the technology will be presented. Initial findings from experimental work carried out on the rig will then be presented, followed by discussions of the results and ideas for future work.

2. PCM STORAGE UNITS

Thermal energy can be stored by melting a solid PCM, where energy can be stored in the latent heat of melting by holding the material in its transitioned phase. The energy can then be recovered by allowing the PCM to re-solidify. PCM devices have a high energy storage density (compared to sensible heat TES), and have the benefit of releasing the majority of stored heat at a consistent temperature (the crystallisation point of the PCM). In addition, relatively large amounts of thermal

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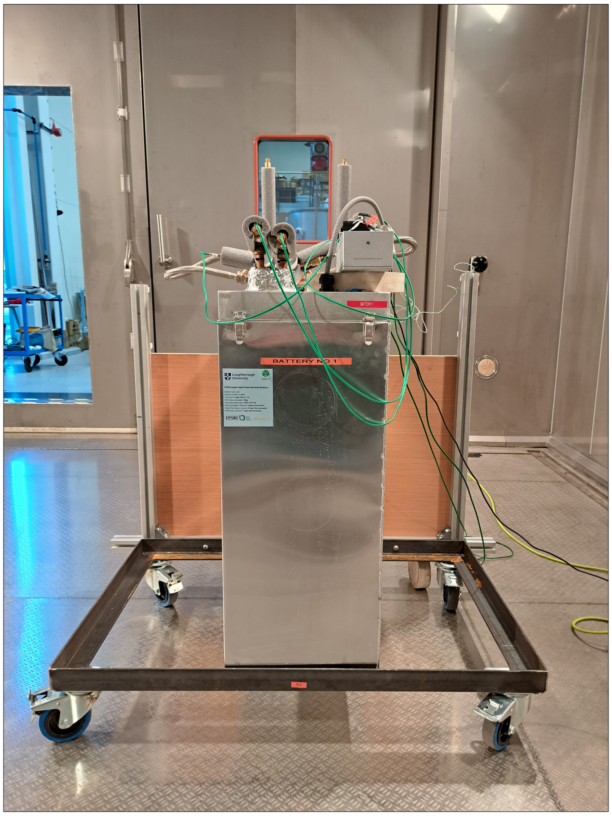

Figure 1 The latest-generation PCM unit

energy can be stored at relatively low temperatures, which reduces the loss of energy in a standing charged unit. A performance analysis on a previous version of the unit presented in this paper can be found in [4].

The key parameters controlling the state-of-charge (SoC) of the unit presented in this paper are the inlet and outlet water temperatures, and the flow rate through the heat exchanger. If it is assumed that energy losses are small relative to these heat transfer rates, these parameters will determine the rate at which energy can be transferred to the PCM via the heat exchanger.

The PCM itself is a commercial material called CrodaTherm^{TM} 53; it has a melting temperature of 53^{o}C, a latent heat of melting of 226kJ/kg and a latent heat of crystallisation of -225kJ/kg. The test units are each fitted with six thermocouples; three within the PCM, labelled T1, T2, T3, and three on the surface of the inner wall (an outer insulating case comprising a Polyisocyanurate layer is also used to reduce heat loss), labelled T4, T5 and T6. T5 was fixed to the upper side of the internal wall of the cell, T4 and T6 were hung loose on each side of the cell in the air gap between the external and internal walls. The overall dimensions of the unit are 900x600x320mm. The units can be operated singly or in groups (these can be set for use in series or in parallel). The nominal capacity of each unit is 4.5kWh.

3. EXPERIMENTAL RIG

The LVV is a state-of-the-art facility at the University of Sheffield for verification and validation testing. It contains three environmentally-controlled chambers, which are ideal for developing a controlled testing environment for the testing of TES technology.

The rig was developed with the aim of providing a basis for testing the PCM units in a fully controlled environment. This would then allow for specific tests to be designed targeting the investigation of key behaviours of the units, such as their ability to hold thermal energy over a standing period.

Two storage tanks are used to store hot and cold water respectively, with heating and cooling energy provided by a Huber Unistat 510. Flow control valves were installed to ensure that either the hot or cold tank was in operation depending on whether the rig was in heating or cooling mode. Valving was also designed to ensure that, while the water flowed in the same direction on the outer side of the rig, it could be reversed through the PCM unit. Hot water was provided to the top of the heat exchanger when charging the unit, and cold water was supplied to the bottom of the exchanger when discharging the unit; this was to avoid pressure build-ups due to expansion or contraction in melting or solidification of the PCM. A schematic illustrating the operation of the LVV rig is given in Figure 4.

The key benefit of this rig is that it can be used to control the main conditions for charging and discharging the PCM units. The inlet temperature is controlled by the Huber, the flow rate is actively controlled by feeding back meter data to the pump, and the ambient temperature can be set in the environmental chamber. Furthermore, the rig will enable controlled and automated testing that replicates the conditions seen in real-world environments, including part-charging, part-discharging and varying ambient temperatures. As a result, the performance of the storage device could be characterised in a far more detailed way than had previously been possible, supporting the development of advanced SoC methods.

4. EXPERIMENTAL TESTING AND RESULTS

An experimental programme is presented in this paper to demonstrate the capabilities of the rig at the LVV. This represents an initial test phase, focusing on standing losses in the units, with further tests planned to investigate part-charging and -discharging and the effect of ambient temperature on performance. The data recorded in this initial phase will allow for the development of models for the standing charge loss of the units.

The recorded data for each test comprised the time stamps, the flow rate through the rig and a series of temperature measurements. These included the environmental chamber temperature, the hot and cold water tank

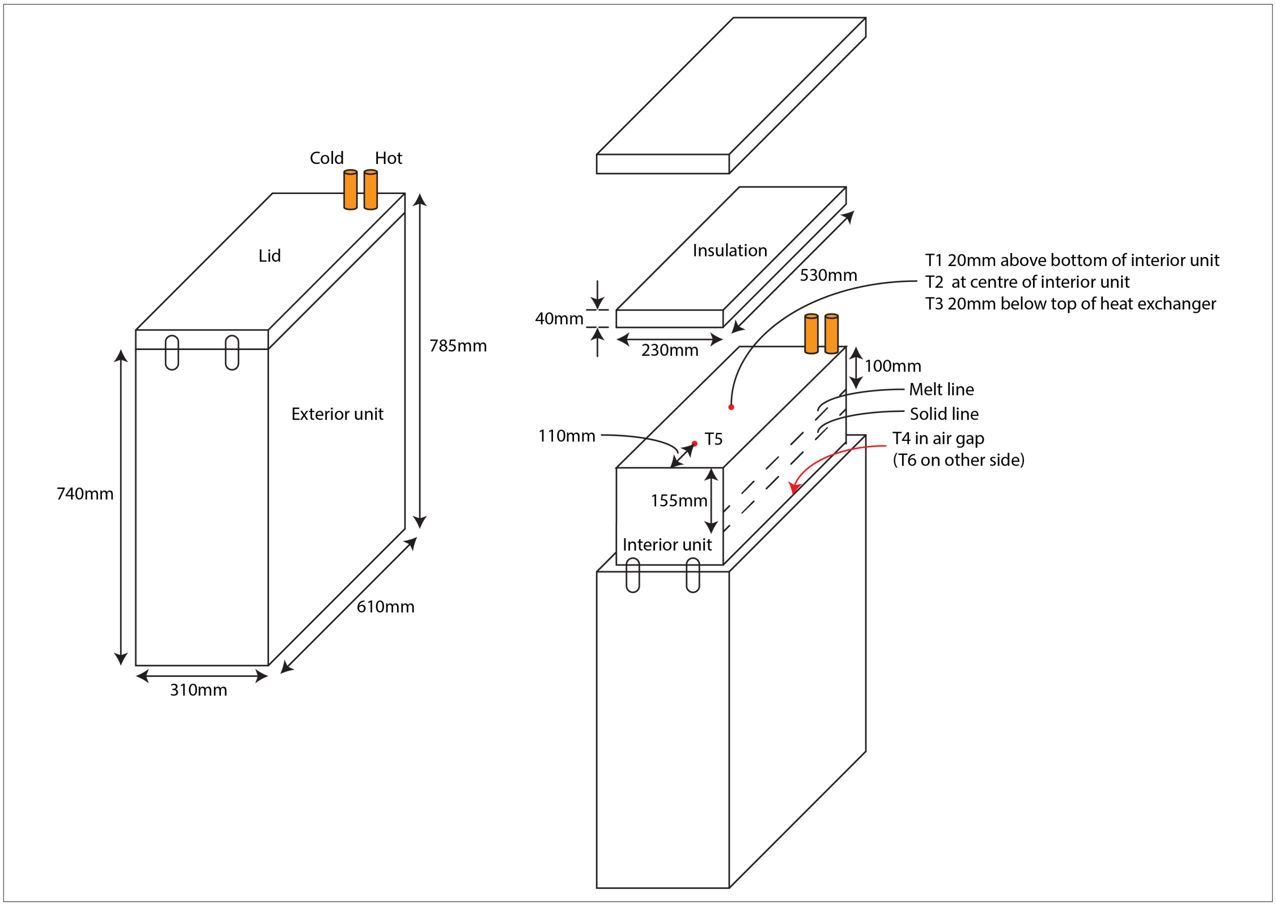

Figure 2 A sketch of the PCM assembly, including locations of internal thermocouples

temperatures, the inlet and outlet temperatures at the Huber heat exchanger, the inlet and outlet temperatures to the PCM unit both at the unit and on the rig side, and the unit thermocouples described in Section 2. The measurements were recorded at a sampling rate of 0.5Hz.

Experiments were designed to quantify the standing loss in time for a single PCM unit. The unit was fully charged, and then disconnected from the heat supply. The unit was then left to stand for a period of time before it was fully discharged. The difference between the energy stored in the unit and the energy recovered in the discharge phase constituted the standing loss, which could then be estimated as a function of standing period by carrying out multiple experiments over a range of standing periods.

For these experiments, the unit was considered 'fully charged' when all temperature measurements had reached a steady value around the charging temperature. Conversely, the unit was considered 'fully *dis*charged' when all temperature measurements had reached a steady value around the *dis*charging temperature. For all tests, the unit was charged to 70°C and discharged to 20°C. The experiments carried out are summarised in Table 1.

Upgrades were carried out on the test rig throughout the gathering of data for this paper. From Test 3 onwards, active flow control was added to the rig. During these tests, issues were identified with maintaining a steady temperature in charging and discharging. An immersion heater was added to the hot water tank for Test 4 onwards in order to help maintain the supply of hot water in charging cycles. From Test 7 onwards, additional heat metering was added to the water circuit and a mixing circuit was added to the cold water tank; these upgrades were also intended to help maintain steady supply temperatures in charging and discharging cycles (the charging time was reduced for Test 8 onwards as a result of these upgrades).

The charge and discharge cycles for Test 4 are illustrated in Figures 5 and 6 respectively. These figures show the temporary failure of steady heat supply at around 45 minutes; this issue was resolved as discussed above by modifications to the rig. It can be seen in Figure 5 that a steady state for all measured temperatures could be reached in around 3–3.5 hours on the charge cycle; this time was reduced following upgrades to the rig to around 2.5–3 hours. On the discharge cycle, the steady state could not be reached for all measured temperatures within working hours, as can be seen in Figure 6. At

Table 1. Description of tests carried out

Test no.	Charge time (hrs)	Standing period (hrs)	Discharge time (hrs)	Target flow rate (l/min)
1[a]	01:00:00	14:48:00	04:24:08	No control applied
2[a]	01:00:00	00:03:00	01:58:00	No control applied
3	03:30:00	18:37:00	07:58:00	12
4	03:18:00	19:10:00	06:30:00	5
5	03:17:00	116:26:00	04:39:00	5
6[b]	03:30:00	163:55:42	05:22:14	5
7	02:43:00	18:53:00	07:07:00	5
8	02:45:00	69:27:00	04:53:00	5
9	03:00:00	44:00:00	04:00:00	5
10	02:46:00	91:58:00	04:00:00	5
11	02:40:00	00:30:00	03:30:00	5

[a] Flow ‘wrong’ way through PCM (hot water supplied to the bottom of the unit, cold water supplied to the top)
[b] Rig upgrades carried out during standing period. Brief initial discharge wrong flow direction

Figure 3 The experimental rig at the LVV

the end of the recorded cycle, T5 and T6 were still discharging; however, it can be seen that at this point the water circuit had reached a stable point, so no further useful heat was being extracted.

The charge profiles for the tests are plotted in Figure 7. Similar initial profiles can be observed for Tests 1 and 2, with a peak charging power of around 14kW. However, a sawtooth profile can be observed in the data from Test 1 – this was due to the internal temperature of the Huber reaching a safety limit. This limit was raised so that it did not impact on following tests. From Test 3 onwards, the flow was reversed to the correct direction through the PCM unit resulting in a new charging profile – this allowed for a higher peak charging power of around 17kW to be reached. For Tests 2 onwards, it can be seen that the heat supply temporarily fails at around 45 minutes – this was due to the supply of preheated water from the hot water tank failing (possibly due to a short circuit through the tank) and the Huber not being able to meet the heat demand quickly enough. This issue was resolved by the upgrades implemented from Test 7 onwards.

Figure 7 shows the discharge power for each test. This shows significant variation between tests, which is not surprising given the varying charging periods and standing periods between the tests. Tests 3 and 4 have similar discharge profiles to each other – this makes sense given that the test conditions were similar for these tests (see Table 1). As with the charge profiles, in Tests 3 and 4 there is a period in which the cold supply fails before the Huber could begin supplying cold water to the PCM unit. This issue was also resolved by the upgrades implemented from Test 7 onwards.

The energy stored in the PCM unit during a charge cycle was calculated using the flow rate and temperature difference across the unit; the same process was followed for the energy recovered during discharging. A minimum power of 0.5kW was set when calculating these values; this meant that the charge and discharge power curves

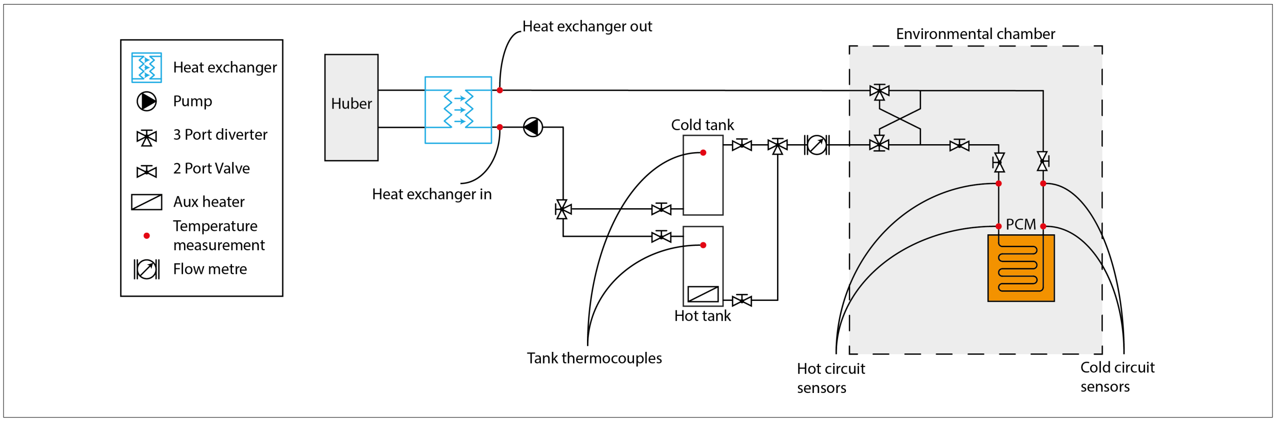

Figure 4 A schematic diagram of the rig at the LVV

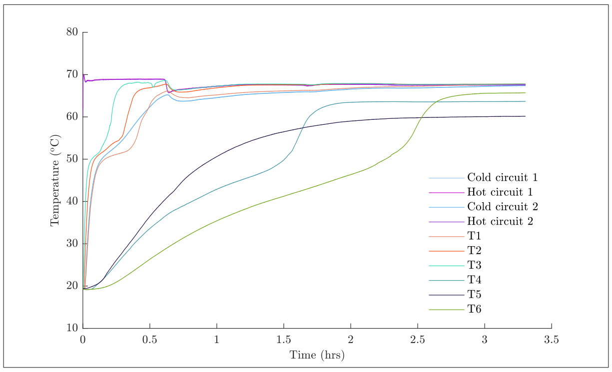

Figure 5 The measured temperatures during the charge cycle for Test 4

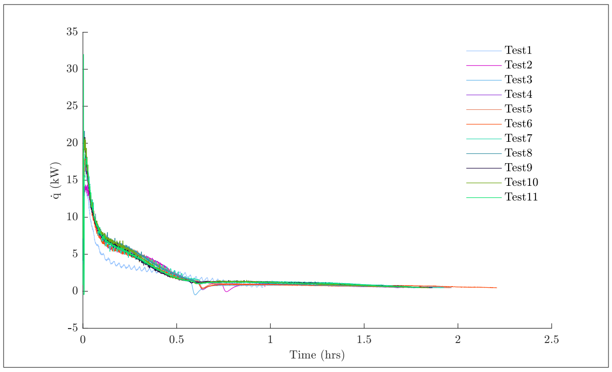

Figure 7 The charging power over time for each test

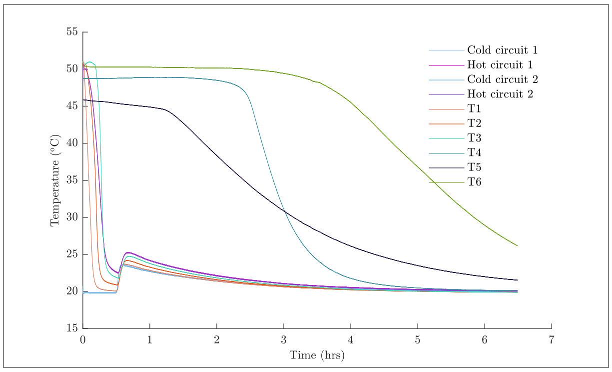

Figure 6 The measured temperatures during the discharge cycle for Test 4

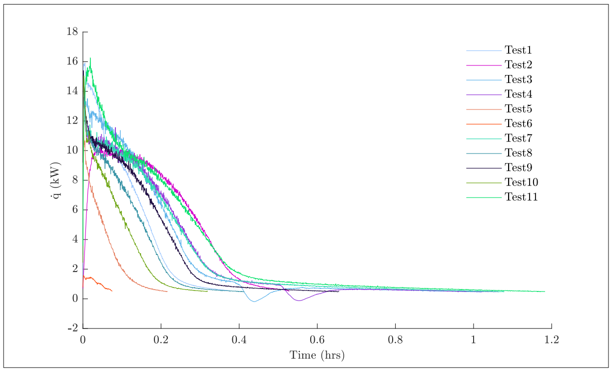

Figure 8 The discharging power over time for each test

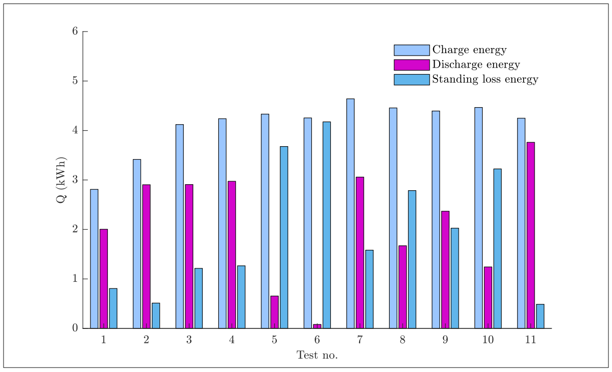

Figure 9 The energy stored for each test compared to the discharge energy and standing losses

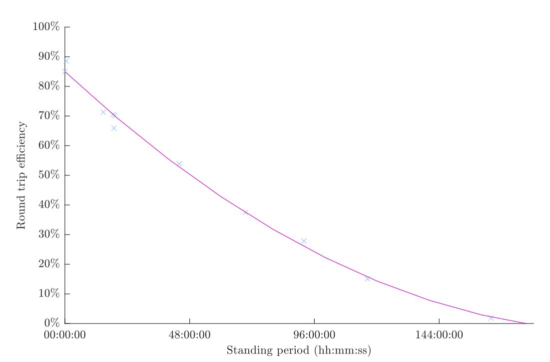

Figure 10 The round trip efficiency for the PCM unit with second-order polynomial line of best fit added

were only counted towards the stored or discharged energy totals when they were above this threshold. The standing loss could then be calculated from the difference between the two; these results are plotted in Figure 9.

It can be seen that from Test 3 onwards, for which the unit was fully charged, the stored energy was around 4–4.5kWh (the nominal capacity of the unit). It is also clear that for tests with a short standing period (Tests 1–4), a high proportion of the stored energy could be recovered in discharging. For longer-duration tests (Tests 5 and 6), the standing losses were much more significant.

The round trip efficiency can be easily calculated by dividing the discharged energy by the stored energy. Round trip efficiency would be expected to have a maximum value near 100% in the absence of any charge or discharge inefficiencies, and would be expected to decline as the standing period increases and the standing losses increase. The relationship between round trip efficiency and standing period is plotted in Figure 10. It can be seen that, as expected, the round trip efficiency steady decreases with standing period. The maximum efficiency appears to be around 85–90%; the relationship between efficiency and standing period closely fits a second-order polynomial.

5. DISCUSSIONS AND FUTURE WORK

The results of the tests carried out in this research both validate the design specifications of the PCM unit, and provide promise as to its suitability for domestic TES. The unit can be readily charged to its nominal storage capacity of 4.5kWh in a relatively short time period of a few hours. The apparent round trip efficiency is promising, with a maximum value of 85–90% and good performance over several hours.

A few limitations were identified in the rig during these tests: initially it was difficult to achieve the charging temperature of 70°C. Further to this, maintaining a steady charge and discharge temperature was also difficult in the first few tests. These issues were overcome by modifying the use of the Huber in the rig. An enduring challenge in utilising the rig is that fast switching between charge and discharge modes is limited by the time taken to change the internal temperature of the Huber, allowing it to provide water to the unit at the correct temperature.

The data presented in this paper provide a good starting point for the development of an SoC estimation tool. A regression model fitted to the data in Figure 10 would allow for a controller to estimate the SoC of the unit given a known amount of stored energy. However, significantly more data would be required to traina more comrehensive model than is currently available; still more data would then be required to validate its predictions.

Future tests will be key to developing a comprehensive SoC estimation tool. A series of part charging tests will be required to enable a controller to estimate the available stored energy following a given charging period. Furthermore, the impact of ambient temperature on both the stored energy during charging and the standing loss energy should be quantified. The ambient temperature was not controlled during the tests presented here, but could be set to a range of temperatures in future. Finally, the PCM units are intended to be deployed in a modular layout to enable storage capacity to be scaled as appropriate. Therefore, the performance of the units should be assessed in groups, as well as in isolation.

6. CONCLUSIONS

The aims of this paper were to demonstrate a novel PCM TES unit for domestic use. An experimental rig was constructed to test and characterise the unit, and the test results were set out in this paper. The unit contained 45kg of PCM with a nominal storage capacity of 4.5kWh – this was demonstrated to be an accurate estimate of available storage. The unit was instrumented with six thermocouples, and further measurements on the experimental rig allowed for accurate measurement of charging and discharging power, from which the stored and recovered energy could be calculated.

The tests carried out allowed for estimates of the round trip efficiency to be made given a particular standing period. The maximum efficiency, for an immediate charge and discharge, was around 85–90%. The efficiency reduced (approximately) quadratically with standing period, but remained high for durations of up to 24 hours, at which point the round trip efficiency would be expected to be around 70% – this indicates that the unit would be highly effective for medium-term storage applications. Furthermore, higher efficiencies could be achieved by focusing operations of the store around the melting point of the PCM; this would reduce sensible heat losses from the unit.

Further work is planned to expand on these results, in particular investigating the behaviour of the storage devices during part-charge and part-discharge tests and the effect of ambient temperature on the performance of the units. These tests would then allow for development of an effective SoC estimation tool.

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