Pressure Sensor for State of Charge Measurements in Latent Thermal Energy Storage (P-SOC)

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ABSTRACT

In thermal energy storage systems that undergo latent energy change, the state of the charge of the system is a critical piece of information required for optimal operation of the thermal energy battery (i.e., the amount of latent energy left in the thermal battery, such as is 25%, 50%, or 85%). In sensible energy storage, inexpensive thermocouples are often used but do not describe the latent energy change well because the energy transfer happens at a constant temperature. The state of charge (SOC) measurement technique developed in this paper uses the well-known physics principle of $Pv = nRT$ by measuring the pressure changes in an airtight tank outfitted with an expansion vessel. The method can be applied to determine the latent thermal energy storage SOC for phase change material (PCM) in thermal storage applications. This paper first outlines derivation of the mathematics for a simple system without an expansion vessel. The paper next introduces the experimental apparatus and heat loss experiment that quantifies the effect of ambient temperatures on SOC experiments. The results indicate that the model is correct for the working principle of the sensor and notes the linear relationship between the system pressure and the SOC of the PCM. The low cost of pressure sensors (<$200) when compared with the cost of high-accuracy flow meters (>$1,000) and temperature sensors (>$50) that use energy balance methods per local measurement suggests this sensor is an economical way to measure SOC globally and is the new state-of-the-art sensor for SOC determination. Furthermore, energy based SOC measurement have increasing uncertainty for two reasons, as they leave the initial condition of a known temperature in the liquid or solid state and during periods of partial charge the heat loss or gained from ambient is often significant during periods of low use or system downtime.

1. INTRODUCTION

Accurate monitoring of the state of charge (SOC) in a phase change material (PCM)-based thermal storage system is critical for efficient energy management. The pressure-based SOC (P-SOC) sensor has emerged as a promising solution because of its high accuracy, up to 0.25%, better than that of a temperature sensor, while also providing a global rather than local measurement. The sensor will be priced much lower, only about 10%–20% of the cost of a high-accuracy flow meter (which offers 0.5% to 1% accuracy). The P-SOC measures the SOC globally from one point instead of measuring locally, found with temperature measurements inside the PCM store. The P-SOC will be easy to install on PCM enclosures (e.g., tanks) and will not be misled by subcooling because it indirectly reads the amount of PCM that has changed phase. The latter can be a significant issue for salt hydrates and is also found in organic PCMs to some extent. Local temperature sensors in the PCM cannot determine if the PCM has been subcooled; we hypothesize that the P-SOC can infer the onset and extent of subcooling based on historic data.

Attempts in the literature can be found to reduce the burden of measurement by applying models. Beyne et al., in a 2022 work, measured the inlet, outlet, and surface temperatures of the storage to determine a model of the SOC that was compared with a finite volume model (Beyne et al., 2022). They concluded that an estimator to determine SOC was applicable when there were negligible heat losses and small temperature differences between the interior and surface of the storage. The deviations from the finite volume model were 0.5% in the heat transfer fluid, 3.9% in the

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heat exchanger metal, and 0.6% for the PCM. The definition of SOC in this work means the energy stored in the PCM (Barz et al., 2018; Rösler & Brüggemann, 2011; Scharinger-Urschitz et al., 2020; Thiem et al., 2017), which is independent of heat exchanger material. This paper claims high accuracy but is compared with simulation instead of experimental data. The limits of the estimator compared with the simulation are near 10% because the PCM is reaching the fully charged state. Another recent work on estimating the SOC was conducted by Bastida et al. (2023), who introduced a nonlinear state observer, or a one-dimensional (1D) model of the system that required three measurement inputs (mass flow rate, inlet temperature, and outlet temperature). The SOC estimation of the errors by root mean square error and mean absolute error were 4.6% and 3.62%, respectively, when compared with experimental measurements. Serpentine, fin and tube, in counter, and parallel flow were discussed. Bastida et al. note that an accurate 1D dynamic model is required for use of this method. This work will show that the propagated error in measurements can grow to 22% when SOC is determined from the cumulative energy transfer—even with calibrated thermocouples and a 0.5% accurate flow meter.

Moreover, individual barometric sensors are used for ice storage (Griffin, n.d.). The system includes a polyethylene tank and a spiral-wound heat exchanger. The tank freezes solid, and the pressure transmitters monitor the change in water level created by the forming ice. The pressure difference between the atmosphere and the water column above the ice is read. The accuracy of this device is not reported in the following reference (Griffin, n.d.). Similarly, this project aims to use a pressure-based measurement to determine the SOC—this time, in a closed system, including an expansion tank.

In previous work, the authors tested the SOC in a heat flux meter apparatus (Rendall et al., 2022) and found a correlation between the readings on a bed of haptic resistive sensors (pressure plates) in a flexible plastic bag. This was later deemed the “constant pressure case,” owing to the plates providing a consistent 1.4 psi of pressure with a changing volume case as the plastic bag slightly expanded to have more contact with the haptic sensors, which changed the resistive reading in a mostly linear fashion for the case of liquid expansion. The volume fraction of the PCM to the heat exchanger fluid and metal was about the same in a parallel and serpentine flow heat exchanger. Hysteresis was noticed in this work owing to the bag changing its contact area with the haptic sensor.

The P-SOC sensor is an improved version of the aforementioned pressure sensors. The sensor will be global, will not require expensive flow meters, and will have an onboard database for the properties of many PCMs. The inputs into the design include PCM material properties (e.g., solid and liquid density and latent heat of fusion), the mass of PCM in the system, an estimate of the air above the PCM, and an indication if the air space above the PCM changes temperature significantly. The goal is ±2% accuracy at all times during charge/discharge.

This paper lays out the working principal mathematically, examines initial data from a test rig that is described in detail, and compares the instrumentation uncertainty of the experimental setup to that of the mathematical model. As of the date of this submission, only ±11.4% accuracy has been achieved using the mathematical model, although a coefficient of determination (R^2) of 0.996 was achieved when fitting the pressure to the SOC during the melting process. This suggests the experiment had high precision, and an additional term, linear in nature, may be required in the mathematical model calculation or experimental data analysis to increase the accuracy. Two potential reasons for the linear offset are discussed later in this paper.

2. MATHEMATICAL MODEL

We derived the relationship between SOC and pressure change from State 1 to State 2 (Δ_{SOC}) for the simplest case (**Error! Reference source not found.**). The working principal for the derivation is that the change in volume of the liquid to solid will have a corresponding change in volume of air, which is modeled by $Pv = nRT$. The following physical variables are measurable and accounted for in empirical equations for a real system. The Δ_SOC can be determined by equations (1) or (2).

The change in state of charge for the case that includes both solid and liquid phases is:

$$\Delta_{SOC} = \frac{\rho_S \rho_L}{m_{PCM}(\rho_S - \rho_L)} \frac{[V_1 \Delta P - m_a R(T_2 - T_1)]}{P_1 + \Delta P} \quad (1)$$

where $\Delta P = P_2 - P_1$ is the pressure change from State 1 to State 2, which can be measured by the pressure sensor; m_a is the mass of the air; and R is the universal gas constant for air. The ratio $\frac{\rho_S \rho_L}{m_{PCM}(\rho_S - \rho_L)}$ accounts for the properties of the PCM and the mass of PCM placed in the container. The ratio $\frac{[V_1 \Delta P - m_a R(T_2 - T_1)]}{P_1 + \Delta P}$ accounts for the impact of the change in properties of the PCM from the liquid to solid state, or vice versa, by changing pressure ΔP between the two states. The change in temperature difference of the air, $m_a R(T_2 - T_1)$, is expected to have a maximum impact of 10% on the reading and be accounted for empirically.

On the other hand, Δ_{SOC} can also be expressed based on the amount of PCM in the liquid or solid state and the amount of heat gained or released (ΔQ) through the heat exchanger. Then, Δ_{SOC} is equal to ΔQ divided by the total energy that can be stored, $m_{PCM} H_{LF}$.

$$\Delta SOC = \frac{\Delta Q}{m_{PCM} H_{LF}} = M_S/(M_L + M_S) \quad (2)$$

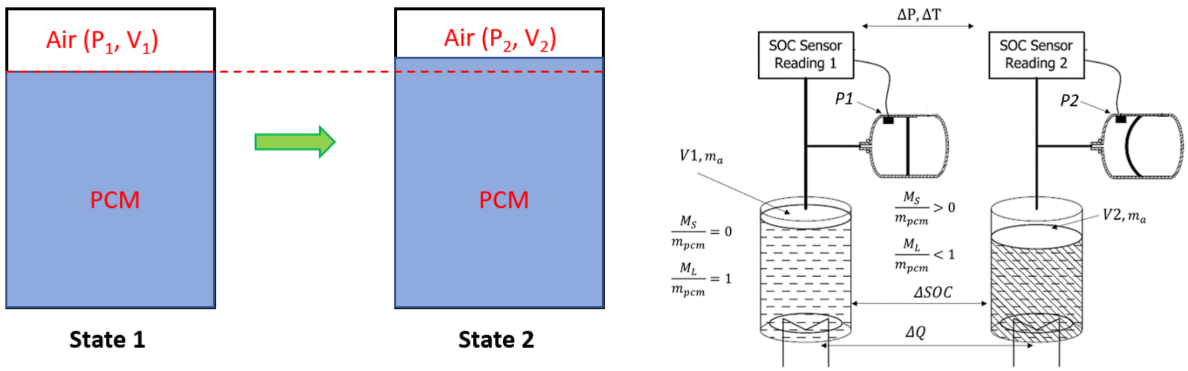

Figure 1: Simplest case of PCM expansion in closed container (left). Configuration and description of system with expansion vessel to allow inexpensive containers (low wall strength) to be used with PCM (right).

With equations (1) and (2) in hand, the researcher can develop an experiment to verify the relationship in equation (1) to that of equation (2). The actual technology can be better described by Error! Reference source not found., which includes expansion tanks to ensure the vessel does not undergo undo stresses. Specifically, any inelastic deformation of the container or the expansion tank diaphragm will cause offset error in the sensor owing to permanently increased the container volume.

3. EXPERIMENTAL SETUP

The experimental setup shown in Figure 2 mirrors **Error! Reference source not found.** but includes additional sensors for verification of the amount of energy entering or leaving the system. A heat loss experiment was conducted to determine the impact of ambient temperature on the state of charge because heat can be lost or gained from the environment during a test. The setup includes the following sensors: T1—inlet water temperature, T2—air above PCM temperature, T3—outlet water temperature, T4—PCM temperature, FM—flow meter, and P1—pressure sensor.

The equipment includes an expansion vessel, four solenoids to control flow (S1 to S4), hot and cold water baths, two flat plate heat exchangers, a pump, a filter, and a shell and tube heat exchanger for holding the PCM (shell side) (Figure 2). An additional pressure gauge on the opposite side of the expansion tank was set to 10 psi for the data shared in this paper.

The operation of the system was to discharge the PCM (freeze) by opening S1 and S2 while having S2 and S4 closed. The setpoints on the baths were 11°C above and below the PCM phase change temperature of 18°C. The PCM properties are as follows: liquid density, 950 kg/m^3; solid density, 860 kg/m^3; specific heat, ~1.60 J/g·K; melting point, 18°C (onset T, 15°C; complete T, 19.5°C); freezing point, 14.5°C; and latent heat, 170 J/g. The digital scanning calorimetry curve of the PCM is shown in **Error! Reference source not found.**.

The instrument uncertainty with additional properties of the system can be found in **Table 1**.

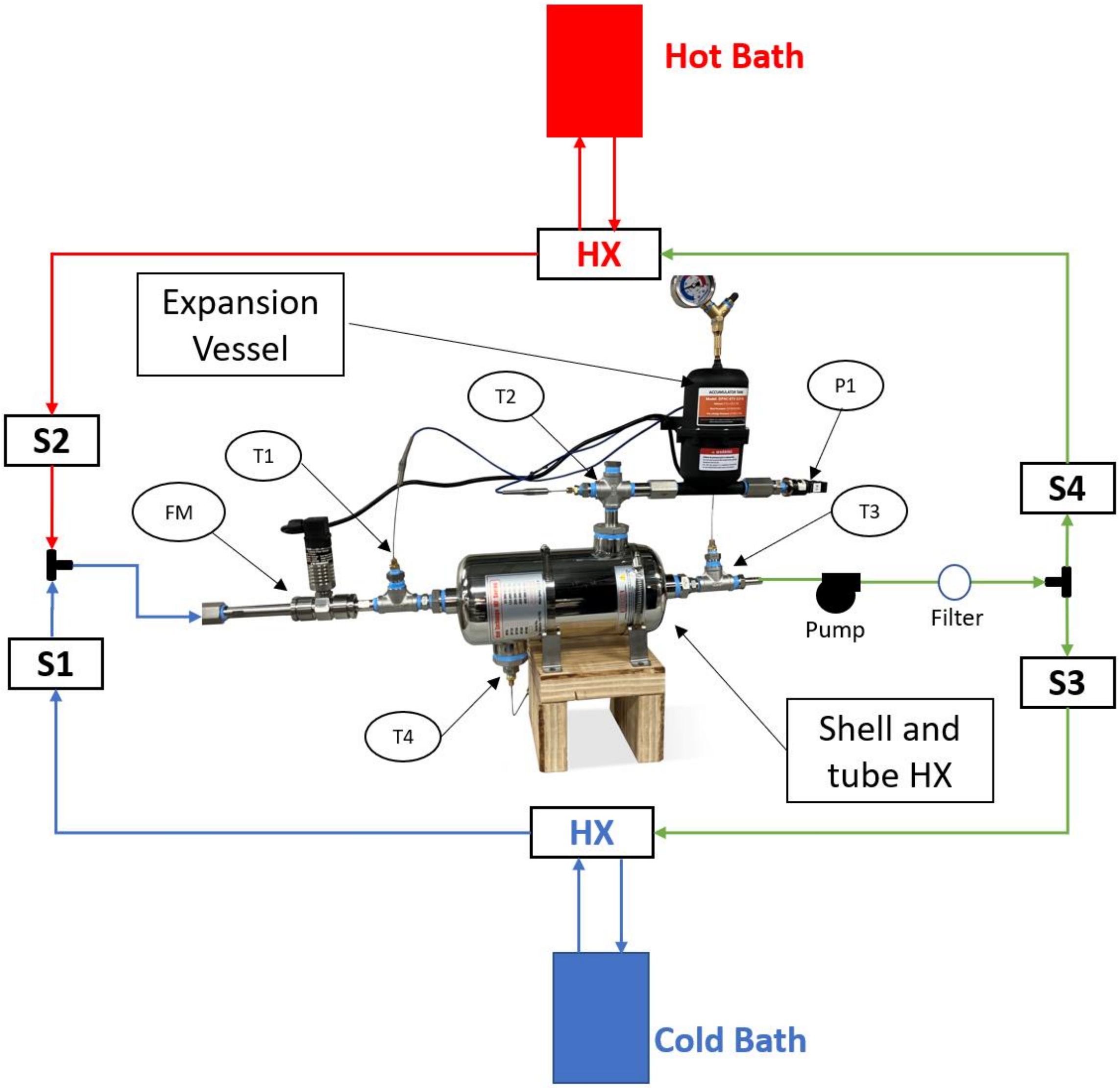

Figure 2**:** Experimental test rig picture, instrumentation labels, and piping diagram.
(HX = heat exchanger)

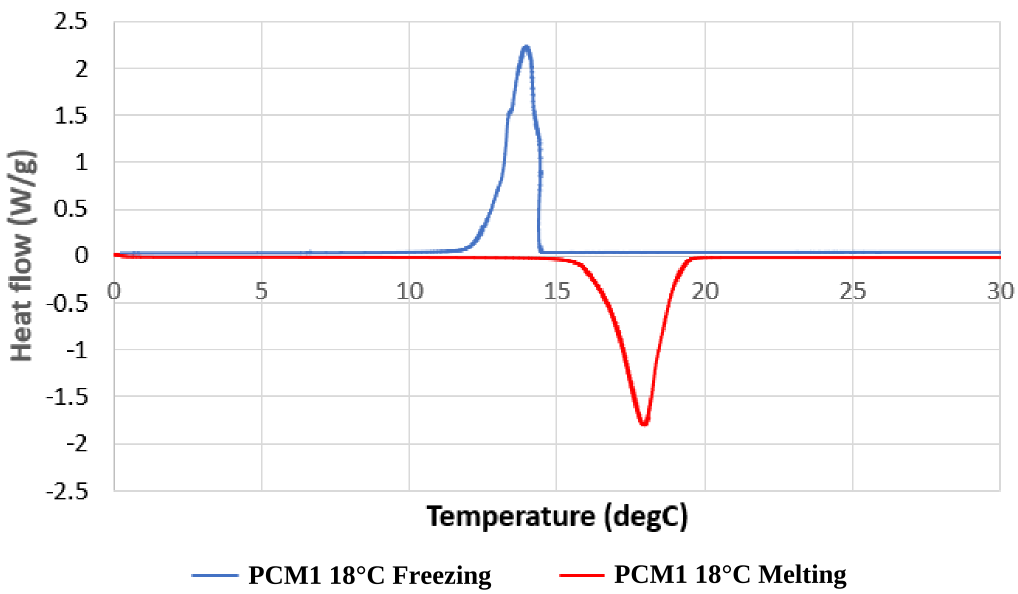

Figure 3: Digital scanning calorimetry results for PCM used.

Table 1: Instrument uncertainty, setpoints of critical equipment, and propagated uncertainty

Measurement type	Uncertainty
Type T thermocouple	0.3 °C
Flow rate	±0.5% full scale, 0.012 gal/min
Pressure sensor	1%
Heat loss	0.27 W/K
Sample rate and data averaging	1 sample/second averaged into 60 samples
Flow rate variation with standard deviation	1.0095 GPM ± 0.004 GPM
Hot bath setpoint	29°C
Cold bath setpoint	7°C
Expansion tank charge pressure	10 psig
Initial pressure	0 psig
Final pressure	4 psig
Uncertainty in energy balance SOC	Negligible to ±11.4% with increasing SOC
Uncertainty in pressure-based SOC measurement	±10% at SOC >20%, ±20% at SOC <20%,

3.1 Estimation of Heat Loss

To estimate the heat losses in the system, we used Newton's law of cooling, where the system was allowed to cool down until it reached ambient temperature from an elevated temperature. Using the heating loop, the system from 40°C was allowed to cool with water inside the storage medium of the heat exchanger, and the temperature difference between the system and ambient is recorded, as shown in Figure 4.

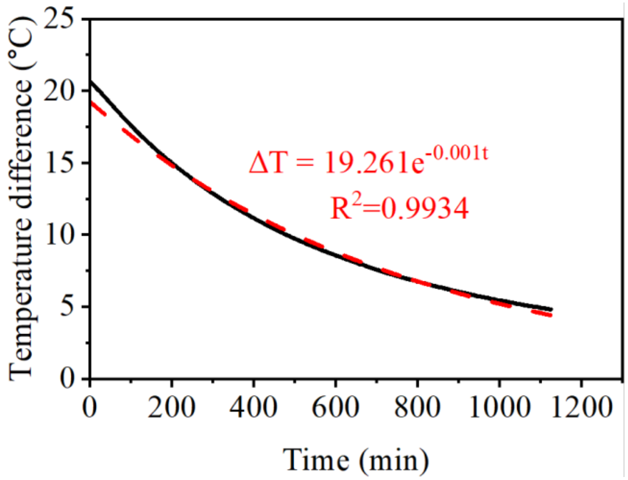

Figure 4: Plot of temperature difference as a function of time to estimate the heat loss to ambient for the system.

The rate of heat loss from the system to the surroundings can be described as

$$\Delta T = \Delta T_o e^{-\frac{t}{\tau}} \tag{3}$$

$$\tau = \frac{mc_p}{UA} \tag{4}$$

where ΔT is the temperature difference between the system and the surroundings measured in Celsius, ΔT_o is the temperature difference at time 0, t is the total time the system interacts with the environment in seconds, and τ is the time constant measured in seconds. The time constant can be further defined using equation (4), where mc_p is the lumped total thermal capacitance (J/K) of the heat exchanger and water inside the storage medium, U is the overall heat transfer coefficient (W/m^2-K), and A is the total surface area of the TES system interacting with the environment measured in square meters. In this study, the rate of heat loss of the system (UA) from equation (4) is 0.27 W/K. This heat loss/gain was subtracted or added to the energy balance for the SOC measurement.

4. RESULTS

The relationship between pressure in the air volume above the PCM that is in contact with the expansion tank diaphragm is close to linear (Figure 5). The linearity is within 0.4% of a 1 to 1 ratio. The phase change process happens over 16 min, and each data point represents the average pressure for each minute. The data were sampled each second and were averaged.

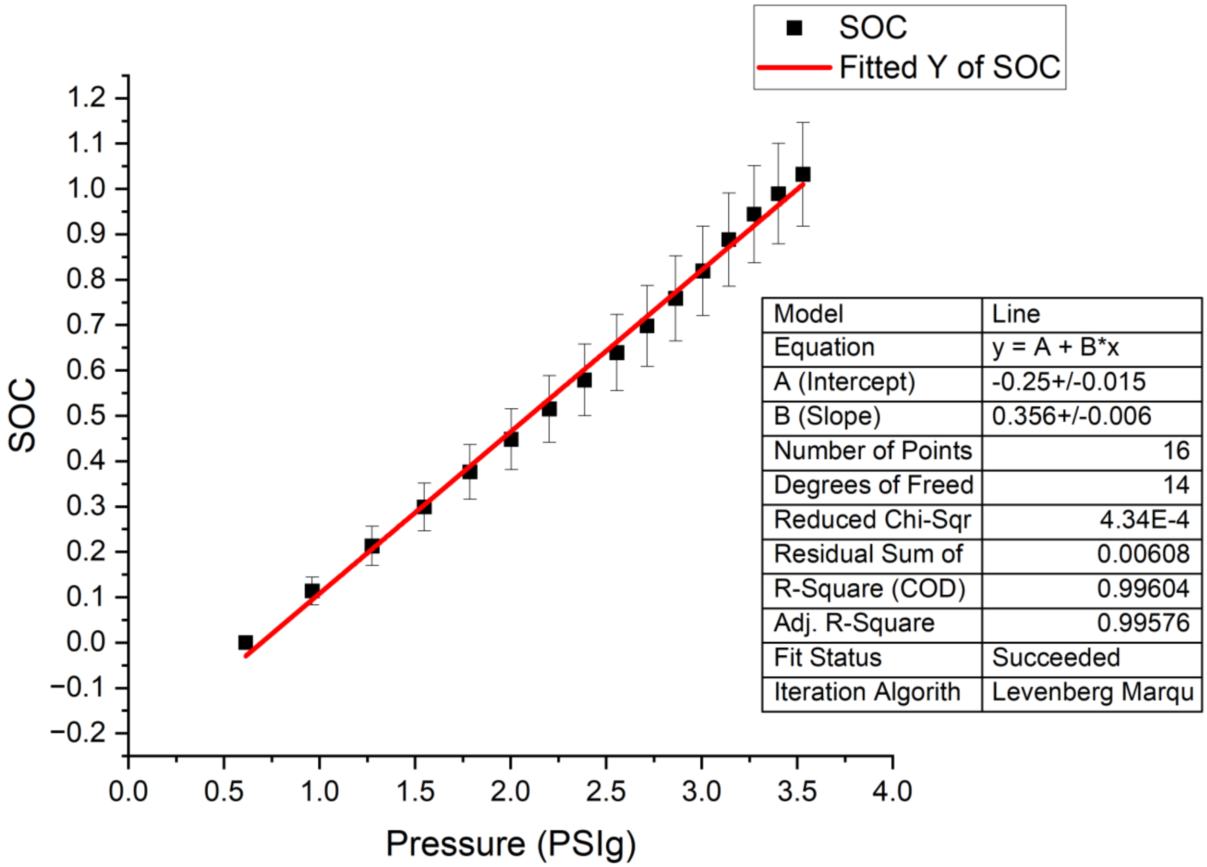

Figure 5: Linear relationship between pressure and SOC during the melting process with the instrument propagated error.

The high linearity suggests basic physics is captured well by the pressure sensor. The low reduced chi-square indicates that a linear model is correct, and there is a possibility of oversampling the data. The instrument uncertainty was propagated in the Engineering Equation Solver software; because the energy balance-based SOCs rely on previous states, the uncertainty becomes large near the SOC of unity. Since the pressure-based method was verified against the energy balance calculation, the error in the energy balance calculation resulted in an increasing uncertainty in the relationship between pressure and SOC. This is the major issues with energy flow-based measurements as the uncertainty can quickly become much larger in time. Furthermore, many real systems will sit without charging or discharging while losing or gaining heat from the ambient. This will not result in an energy change being measured by the sensors in the fluid line but would be captured by a pressure-based measurement as the PCM is changing from solid to liquid or vice-versa.

Thirteen data points were used to determine the SOC by equation (1) and are plotted against energy-based SOC (Figure 6). The first two data points were not used because the effect of sensible energy change was present; the SOC above 1 (SOC = 1.06) was also not used, although the fit was good in this region.

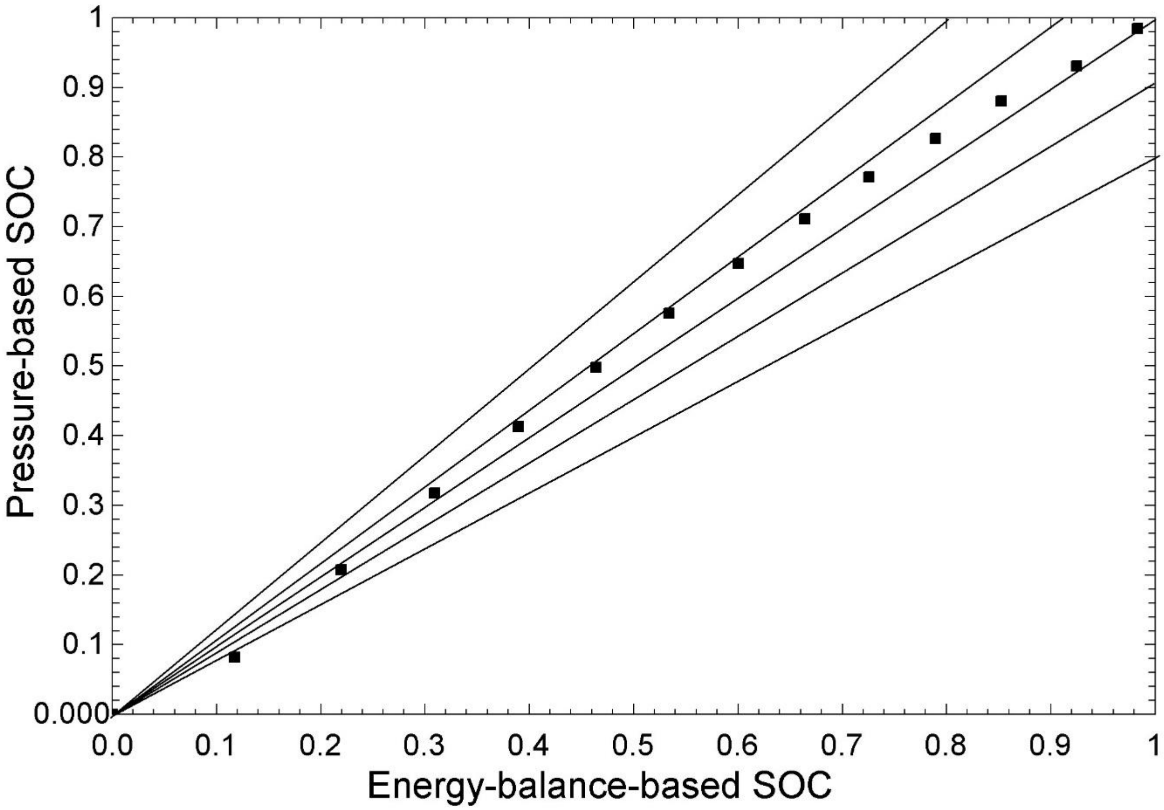

Figure 6: Energy-based SOC vs. pressure-based SOC with ±10 and ±20% agreement lines.

5. DISCUSSION

The low cost of the pressure sensor and low range of pressure in which it works suggest commercial viability. Although there is significant error at low SOC with the pressure-based PCM calculation, future experiments will allow for better quantification of the 0 SOC point, the PCM temperature, and the effect of the initial pressure setting of the expansion tank on the accuracy at low pressures. The high linearity, simple mathematic relationship, low total pressure, and initial pressure required for developing a reading (e.g., high signal-to-noise ratio) suggest this sensor will accurately describe the SOC. The pressure swing to allow for high accuracy is estimated at ±1.5 psig based on the data in this paper with a 2% full scale accuracy rated pressure sensor. For reference, 1.5 psig is 3.5 ft water column, which suggests any container that can hold 3.5 ft of water will be applicable for this sensor if the container is sealed.

When the temperature difference in the air is low, (e.g., data use in this paper were <0.5°C), the relationship the mathematic derivation results in a form of the change reduces to SOC = C1 × (1 − C2/x) + last SOC (e.g., inverse proportional) where C1 represents material properties, C2 represents initial conditions, and x is the new pressure when charging. The relationship between pressure and SOC was found to be linear proportional in this paper owing to the arbitrary decision that 1 is liquid and 0 is solid. It is easy to conceptualize 1 as charged and 0 as discharged from the point of view of the PCM. Thus, we suggest that for heating applications, 1 is liquid and 0 is solid, whereas in cooling applications, 1 is solid and 0 is liquid. In systems where PCM handles both cooling and heating, the decision of which phase is SOC = 1 is once again arbitrary.

The effect of sensible energy change when determining at what point SOC was an offset up to 7% since logging data at 1 min intervals the SOC changed up to 14% in the first minute. Furthermore, the lack of additional temperature sensors in the PCM bulk made determining the properties of the PCM difficult, and potential thermal lag of the system presented challenges for establishing the exact point of 0 SOC in the reduced data.

When going over the initial setpoint of the expansion tank, the diaphragm inverted, causing a drop in pressure. Thus, the setpoint of the expansion tank should be above that of the maximum expected pressure in the system. To decrease uncertainty in low SOCs, the initial setpoint of the expansion tank should be as close as possible to the maximum pressure expected.

Although these tests were conducted with organic PCMs, inorganic PCMs that subcool (e.g., do not change phase when below the freezing point) can be monitored with this system, as well. Currently, temperature sensors in the PCM cannot indicate subcooling until after the subcooling stops and an unexpected increase in temperature is noticed. It is hypothesized that this sensor will notice the subcooling when a temperature sensor is included in the PCM. Also, PCM degradation in the ability to store energy owing to phase separation of PCMs can be determined by this sensor as a reduction in total pressure over time.

6. CONCLUSION

This paper studied the mathematical derivation of a pressure-based state of charge sensor for phase change materials from first principals. A follow-up experimental test rig proved the linearity between the pressure measurement and the state of charge while maintaining a low pressure change. These initial findings of the P-SOC suggest a bright future for the sensor because it is global, is low cost, and shows high linearity. Additional experimental work will reduce the uncertainty and offset errors. Also, additional features for the sensor have been identified for PCMs that separate in phase. The model performed well at higher SOC, and the issues at low SOC are likely caused by the initial setpoint of the expansion tank pressure being too high (e.g., 3 times that of the pressure at SOC = 1).

The benefits of the new sensor are:

1) Lower cost than other sensors or sensor combinations at higher accuracy potential.
2) The uncertainty due to heat loss or gain from the system is negligible.
3) The sensor is a global measurement of SOC instead of local.
4) Scaling of the sensor for larger systems is simple and robust.
5) Although initial settings are important, the uncertainty in the reading will not expand in time given all components do not inelastically deform.

The low cost of pressure sensors (<$200) when compared with the cost of high-accuracy flow meters (>$1,000) and temperature sensors (>$50) that use energy balance methods per local measurement suggests this sensor is an economical way to measure SOC globally and is the new state-of-the-art sensor for SOC determination. Furthermore, energy based SOC measurement have increasing uncertainty for two reasons, as they leave the initial condition of a known temperature in the liquid or solid state and during periods of partial charge the heat loss or gained from ambient is often significant during periods of low use or system downtime. Scaling the device for larger systems is done by sizing the expansion tank to ensure low-pressure changes during the freeze and melt cycles, and the authors propose this technology as the new state-of-the-art sensor for SOC determination.

NOMENCLATURE

A	total surface area of the TES	(m^2)
e	exponential function	(–)
E	energy	(kJ)
H_{LF}	latent heat of fusion	(kJ/kg)
l	liquid	(–)
m_a	total mass of air	(kg)
mc_p	total thermal capacitance	(J/K)
M_L	mass liquid	(kg)
m_{pcm}	total mass of PCM	(kg)
M_S	mass solid	(kg)
P	pressure	(psig)
Q	heating or cooling power	(W)
s	solid	(–)

SOC	state of charge (latent)	(–)
T	temperature	(°C)
t	time	(s)
U	heat transfer coefficient	(W/m^2-K)
V	volume	(m^3)
Δ	change in state	(–)
ρ	density	(kg/m^3)
τ	time constant	(1/s)

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