

# Clarification of the Supercooling and Heat Storage Efficiency Calculation Formula for Shape-Stabilized Phase Change Materials

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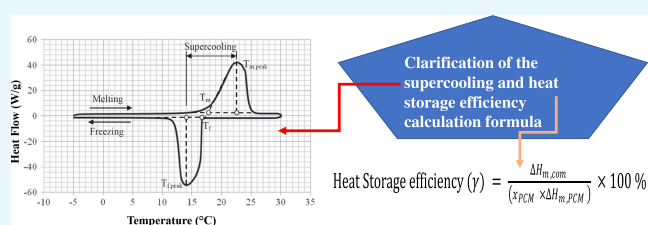
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**ABSTRACT:** It is essential to determine the heat storage efficiency of shape-stabilized phase change materials (ss-PCMs). In two published articles, the formula for heat storage efficiency is presented using two distinct equations. Using the two equations, the calculated values for heat storage efficiency revealed significant discrepancies. The outcomes cannot be compared. The evaluation of heat storage efficiency has a substantial impact on the practical application of PCMs and serves as a performance benchmark for the PCM samples that have been tested. In this paper, the correct equations for calculating the efficiency of heat storage are presented. Furthermore, it is essential to note that the methods used to calculate the supercooling value are not straightforward. Consequently, this paper clarified the correct formula and/or method for determining the supercooling value and heat storage efficiency of ss-PCMs.



## INTRODUCTION

Recently, in the field of renewable energy, phase change materials (PCMs) have attracted great interest.<sup>1</sup> In particular, shape-stabilized PCMs (ss-PCMs) have been studied by several research groups to reduce two PCM disadvantages, i.e., leakage and low thermal conductivity. Much of the published literature uses the following equations for the evolution of the newly developed ss-PCMs.<sup>1–4</sup> The ability of shape-stabilized phase change materials to store heat is crucial to understand. To the best of our knowledge, only two published articles have used the heat storage efficiency formula; in those two, a different formula or equation was used in each instance. Despite using both equations to calculate the heat storage efficiency, the results showed a significant discrepancy. For an ss-PCM, the following four equations—*R*: impregnation ratio (eq 1), *E*: impregnation efficiency (eq 2), thermal storage capability (eq 3), and storage efficiency (eq 5)—have a strong relationship and/or correlation with one another; that is, when the value of the impregnation ratio is high, the heat storage efficiency is also high. Accordingly, a high latent heat value, thermal storage capability, and storage efficiency must be attained if a system can hold or be impregnated with a lot of liquid polymers. Performance analysis of the PCM can be done using the solutions of the following equations (eqs 1–3). Moreover, these figures are necessary for the calculation of eqs 4 and 5 of the heat storage efficiency (Tables 1 and 2).

It is important to highlight the supercooling issue, which is one of the drawbacks and impacts all PCM types. The practical

applications of PCM are significantly constrained by larger values of supercooling. The process for determining the supercooling value has been given below.

$$R = \frac{H_{M,com}}{H_{M,PCM}} \times 100\% \quad (1)$$

$$E = \frac{H_{M,com} + H_{F,com}}{H_{M,PCM} + H_{F,PCM}} \times 100\% \quad (2)$$

$$\varphi = \frac{\frac{H_{M,com} + H_{F,com}}{R}}{H_{M,PCM} + H_{F,PCM}} \times 100\% \quad (3)$$

where *R* is the impregnation ratio, *E* is the impregnation efficiency, and  $\varphi$  is the thermal storage capability.

$H_{M,PCM}$  and  $H_{F,PCM}$  are melting and freezing latent heat of PCMs, respectively (i.e., poly(ethylene glycol) (PEG), paraffin, lauric acid (LA), etc.);  $H_{M,com}$  and  $H_{F,com}$  are the melting and freezing phase change enthalpies, respectively; and com (composite) = PCM + matrix.

It is important to note that  $\gamma$  is the efficiency of heat storage (eqs 4 and 5), which is an important parameter for evaluating

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**Table 1.** Data Adapted from Mitran et al.<sup>6</sup> and the Heat Storage Efficiency ( $\gamma$ ) Values were Calcd Using eqs 4 and 5<sup>a</sup>

samples	$T_f$	$T_m$	$H_f$ (J/g)	$H_m$ (J/g)	$\Delta T$	R (%)	E (%)	$\varphi$	$X_{\text{PCM}}$	eq 4	eq 5
LA	41	42.7	163.4	166	1.7				1	100.0	1.6
LA1-MCM	39.1	40.1	30.2	34.9	1	21.02	15.42	94.00	0.5	42.1	13.5
LA2-SBA	41.1	41.7	62.6	73.7	0.6	44.40	32.28	93.20	0.67	66.3	15.1
LA4-MCF1	41.3	42.4	110.3	110.5	1.1	66.57	52.29	100.70	0.8	83.2	0.2

<sup>a</sup> $\varphi$ : thermal storage capability [eq 3];  $X_{\text{PCM}}$ : polymer weight fraction in PCM.

**Table 2.** Data Adapted from Qian et al.<sup>7</sup> and the Heat Storage Efficiency ( $\gamma$ ) Values were Calcd Using eqs 4 and 5

samples	$T_f$	$T_m$	$H_f$ (J/g)	$H_m$ (J/g)	$\Delta T$	R (%)	E (%)	$\varphi$	$X_{\text{PCM}}$	eq 4	eq 5
PEG PCM	38.5	60.51	164.6	180.3	22.01				1	100.0	
ss-PCM1	38.63	59.21	46.1	51.5	20.58	28.56	28.30	99.07	0.3	95.2	10.5
ss-PCM2	39.21	58.86	64.1	70.2	19.65	38.94	38.94	100.01	0.4	97.3	8.7
ss-PCM3	40.54	59.16	80.3	88.4	18.62	49.03	48.91	99.76	0.5	98.1	9.2

PCM activity. However, most of the fabricated ss-PCMs did not provide the energy storage efficiency value in the literature,<sup>2–10</sup> most likely because of the two different types of equations and the outcomes being different. Using a calculation for heat storage efficiency that is flawed affects the findings and recommendations of the published paper. From a scientific perspective, the question of which equation is accurate must be resolved. Mitran et al.<sup>6</sup> and Qian et al.<sup>7</sup> have reported two different equations for heat storage efficiency, as shown below

$$\text{heat storage efficiency}(\gamma) = \frac{\Delta H_{m, \text{com}}}{(x_{\text{PCM}} \times \Delta H_{m, \text{PCM}})} \times 100\% \quad (4)$$

[ref 6]

$$\text{heat storage efficiency}(\gamma) = \left(1 - \frac{H_{F, \text{com}}}{H_{M, \text{com}}}\right) \times 100\% \quad (5)$$

[ref 7]

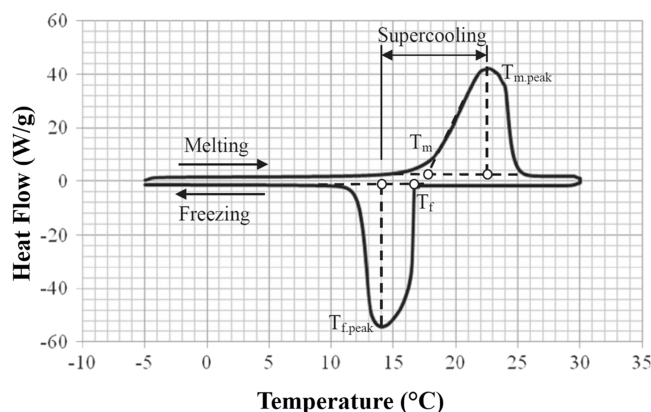
where  $X_{\text{PCM}}$  is the polymer weight fraction in PCMs.

Using the two equations presented above to calculate heat storage efficiency, the first equation yields high values, while the second equation yields low values. For the calculations of the heat storage efficiency percentage (Tables 1 and 2), it appears that eq 4 is acceptable and/or reasonable. For a new PCM, the heat storage efficiency value should not be 0.2% when it exhibits quite high latent heat values (Table 1). In fact, it was proved in eq 5 that its source reference is not correct. The detailed explanation is discussed below. Moreover, the values derived from eq 5 were abysmal. Such a low value has not previously been reported in the literature studies.

Qian et al.<sup>7</sup> made use of eq 5 for the first time. In this paper, Qian et al. cited reference number 54, which indicates that eq 5 was derived from and/or the original source was reference number 54. Reference 54 refers to “Yu et al. [54]” and his article “Microencapsulation of *n*-octadecane phase change material with calcium carbonate shell for enhancement of thermal conductivity and serving durability,” was published in 2014 in the journal Appl. Energy, 114, 632–643. Nevertheless, our cross-checking revealed that the aforementioned statement was false because eq 5 was not discussed in the article of Appl. Energy 2014, 114, which is cited as 54. In addition, the same authors published PCM-related articles in the same year<sup>1</sup> without including the heat storage efficiency value and without

indicating that the equation they had previously employed was incorrect.

**Supercooling.** The PCMs based on inorganic salts and salt hydrates are among the most promising PCMs based on organic, inorganic, and eutectic saltwater solutions because of their low cost, widespread availability, and high energy storage capacity. Inorganic PCMs are not suitable for practical applications due to phase separation and supercooling issues that have not yet been resolved. Suppressing the degree of subcooling in PCMs is crucial for latent heat energy storage because the thermal energy released during solidification is used as useful energy for PCMs and the solidification temperature controls the quality of the released heat.<sup>11,12</sup> It has been reported that the supercooling value can be calculated using the equation  $T = T_m - T_f$ , which is dependent on the peak temperature (Figure 1). On the other hand, Beupere et



**Figure 1.** DSC melting and freezing curves of the pure hexadecane at a scanning rate of 5 °C/min and the characteristic temperatures  $T_m$ ,  $T_{m, \text{peak}}$ ,  $T_f$ , and  $T_{f, \text{peak}}$ .<sup>8</sup>

al.<sup>9</sup> measured the supercooling value using the onset temperature (Figure 2). However, supercooling utilizes the initial temperature to display relatively smaller values. To compile a table of supercooling values, a note about the onset and maximum temperatures must be included. Since the supercooling value is 6.2 when measured using the onset temperature (Figure 2), but it is 9.0 when measured using the difference in peak temperature for the same material. Finally, we can claim that the supercooling value based on the process shown in Figure 1 is accurate.

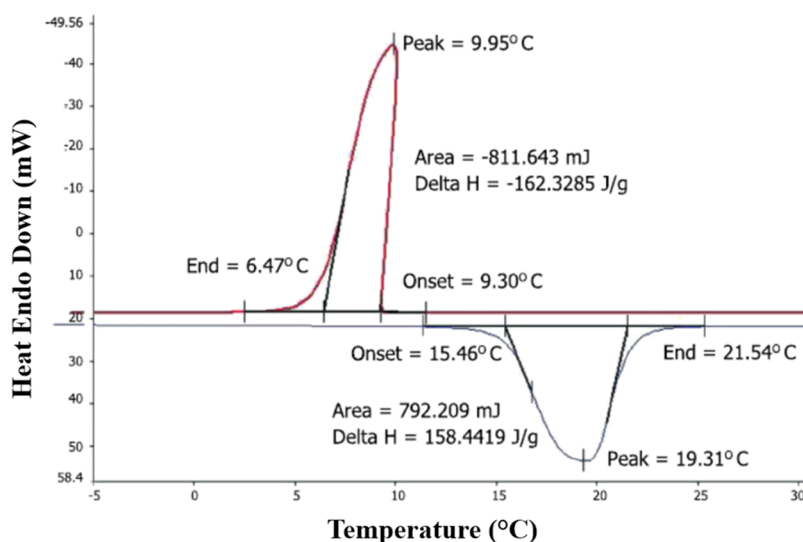


Figure 2. Differential scanning calorimetry thermogram of caprylic acid.<sup>9</sup>

## CONCLUSIONS

It is essential to evaluate the outcomes of eqs 1, 2, 3, and 5 to characterize newly generated ss-PCMs. Without the results of these parameters derived from the correct equation, it will be difficult to comprehend the capability and/or practical applications. In addition to evaluating these equations, it is also necessary to characterize supercooling. If the equation is accurate, anyone can use it as a research tool, thereby reducing confusion. By calculating the efficiency values of several PCMs in this study, the correct equation was determined with absolute certainty. The values of supercooling were also calculated using Figures 1 and 2, and it was determined that the method depicted in Figure 1 is adequate.

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## Notes

The authors declare no competing financial interest.

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