

## THERMAL STABILITY ANALYSIS OF ORGANIC PHASE CHANGE MATERIAL

Hamza Ayaz<sup>a\*</sup>, José Lara Cruz<sup>a</sup>, Jorge Salgado-Beceiro<sup>b</sup>, Magnus Rotan<sup>b</sup>, Ragnhild Sæterli<sup>b</sup>,  
Fride Vullum-Bruer<sup>b</sup>, Alexis Sevault<sup>b</sup> and Jean-Pierre Bedecarrats<sup>a</sup>

<sup>a</sup> Université de Pau et des Pays de l'Adour, E2S UPPA, LaTEP, Laboratoire de Thermique, Énergétique et Procédés, 64000 Pau, France

<sup>b</sup> SINTEF Energy Research, Postboks 4761 Torgarden, 7465 Trondheim, Norway.

\*Corresponding Author: hamza.ayaz@univ-pau.fr

### ABSTRACT

Thermal batteries that use phase change material to store/retrieve thermal energy are becoming increasingly essential in the energy sector to reduce supply/demand issues and improve overall system performance. The primary barriers to the broad acceptance of these thermal batteries are their high initial cost and long payback time. As a result, it is critical to search for thermal battery materials that are stable and have a longer lifespan. A systematic technique is necessary for analyzing the stability of thermal battery materials. However, there is no standard approach available in the open literature for examining the stability analysis of phase change materials (PCMs) used as thermal battery materials. To generalize the process for stability investigation plenty of experiments are required with different groups of PCMs. This study provides the first set of results that will help to compose a general process for the stability investigation of organic phase change. The methodology involves thermal cycling (the impact of the phase change process on the thermal properties). Decanoic acid, a commercially available organic PCM, was chosen for this study. The impact of different parameters (cooling rate, sample volume) on decanoic acid during thermal cycling was examined. The results show that varying cooling/heating rates and volumes have no meaningful effect on the sample thermal properties (melting temperature and phase change enthalpy obtained from DSC). The highest variation in thermal characteristics during 1500 thermal cycles was 11.13% for the latent heat of fusion. The stability investigation of the organic PCM can be performed with the findings of this study.

### 1 INTRODUCTION

Thermal energy storage technology is getting more attention in recent times due to the energy crises and focus on sustainable energy sources. The technology is utilized as a thermal battery that bridges the thermal energy supply and demand difference by storing the excess amount at peak time and utilizes it later. The technology can be integrated into conventional systems which can augment the overall performance of the existing system. The primary steps for all the thermal energy storage technologies are charging, storing, and discharging the energy. Based on how to store thermal energy, different mechanisms exist that include sensible heat storage, latent heat storage, and thermochemical heat storage (Ayaz et al., 2021). Among the different types of thermal energy storage (TES) latent heat energy storage is getting more attention due to phase transition in a narrow temperature range and high storage density. Latent heat storage utilizes Phase change materials (PCMs) that are used as thermal battery materials. The PCM stores thermal energy by solid-liquid phase transition at a specific phase change equilibrium temperature. During charging, heat is transferred to the PCM and, as a result, phase transition occurs, and the energy is stored. Whereas the energy is retrieved in the discharging process. The PCM can be divided into two main groups based on the chemical structure which are organic (carbon-based) and inorganic (for example: metallic and salt hydrates) PCM. Detailed literature is available on the utilization of PCM for different applications (Ismail et al., 2022).

Alkane, ester, fatty acid, and fatty alcohol are among the many materials that collectively make up organic phase change materials (PCMs). Fatty acid possesses suitable characteristics including high latent heat, low degree of supercooling, no phase segregation, and a wide range of phase change equilibrium temperature that makes them interesting for different applications. Decanoic acid is widely utilized in the building sector and for the thermal management of lithium-ion batteries (Liu et al., 2022; Zhao et al., 2023). The stability investigation of decanoic acid becomes more important for the mass implementation of this potential PCM. The stability investigation includes cyclic stability tests (accelerated thermal cycling where the PCM is subjected to a continuous phase change process) and the impact of temperature on thermal properties reliability. The thermal stability of the decanoic acid is studied by different research groups. Martín et al. (Martín et al., 2019) performed accelerated thermal cycling for decanoic acid for a total of 2000 thermal cycles. The accelerated thermal cycling is completed in a thermocycler where the volume of the PCM utilized was 0.5 ml. The temperature profile employed consists of a temperature range from 18 to 40 °C with a heating rate of 5 °C/s, whereas the cooling rate was 4 °C/s. The result did not show much variation in the thermal properties, after 2000 thermal cycles the phase change equilibrium temperature was the same and the latent heat of fusion changed from 150 J/g to 151 J/g.

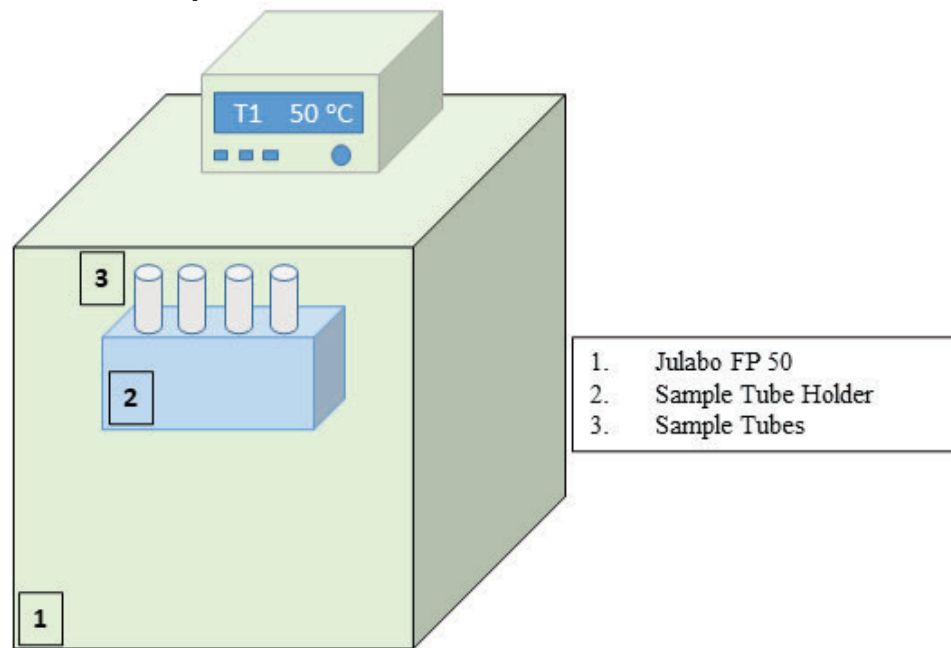
Majó et al., 2021 performed a thermal cycling test of decanoic acid for 1000 thermal cycles for a temperature range of 15 to 70 °C at 0.5 °C/min. The result shows a degradation of the decanoic acid which is represented in terms of the thermal properties variation. The variation in the latent heat of fusion was more pronounced with a reduction of 6 J/g after 1000 thermal cycles. The performance of PCM plays a key role in the widespread implementation of latent heat thermal energy storage. The selection criteria for a PCM involve the phase change equilibrium temperature, energy density, and stability. The stability of the PCM includes thermal stability which is related to the reliability of the thermal properties and chemical stability which is linked to the chemical profile of the PCM (Miró et al., 2016). The life span of a PCM is examined in an accelerated thermal cycling test. The reliability of the thermal properties is investigated after performing accelerated thermal cycling (repetition of phase change process). Different approaches are available in the literature for performing accelerated thermal cycling tests for PCM. A technical review of 18 different experimental setups utilized for accelerated thermal cycling is summarized (Rathgeber et al., 2020) and the result shows that scattered data is available regarding accelerated thermal cycling. Among all the experimental setups the different parameters which include the amount of PCM (0.5 ml to 154 l), the heating/cooling rates (0.05 to 50 °C/min), and cycles performed each day (1 to 140) were summarized. The thermal properties of the PCM are investigated with differential scanning calorimetry (DSC). The DSC analysis gives detailed information about the phase change equilibrium temperature and phase change enthalpy. Plenty of authors studied the stability of PCM and unanimously agreed that the PCM should be investigated for thermal and chemical stability. Stability investigation of the PCM shows the effective lifetime of a PCM. The thermal stability of the PCM includes thermal properties reliability for the phase change process (thermal cycling). However, to the best of our knowledge, there is no standard procedure describing general guidelines for stability tests. Furthermore, although decanoic acid with different volume and cooling/heating rates was utilized in the open literature for accelerated thermal cycling, the impact of these parameters in the degradation process is not deeply investigated. In this work, the accelerated thermal cycling experiment is performed in a separate cooling bath where the impact of different cooling rates and different volumes are investigated. After inspecting the different parameters for accelerated thermal cycling an experiment of 1500 thermal cycles was performed. The thermal properties variations are presented. In general, this study is part of a project where the aim is to conclude a general methodology for the stability investigation of the organic PCM. The result of this paper will help to compose the general methodology for the stability investigation.

## 2 MATERIALS AND METHODOLOGY

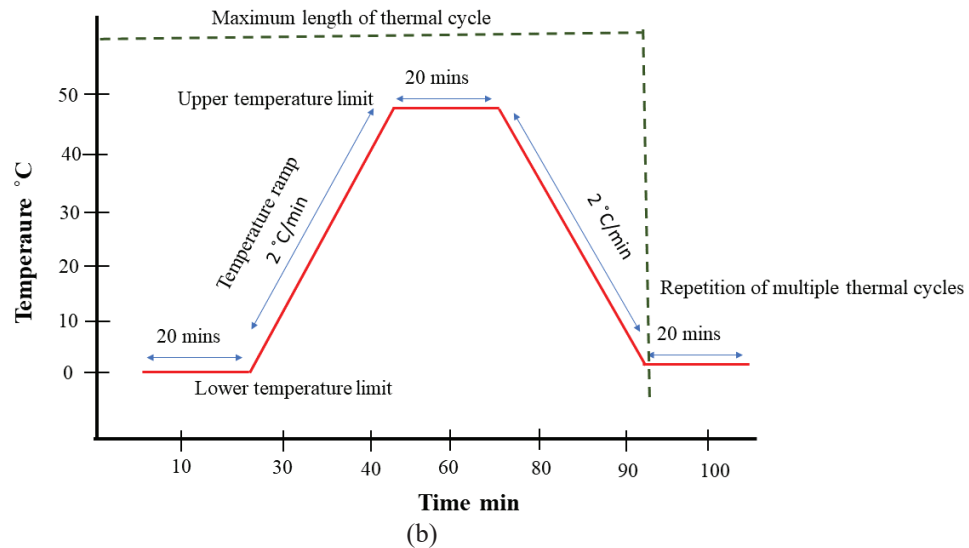
Decanoic acid which is also known as capric acid is a medium-chain fatty acid that consists of 10 carbons, 20 hydrogens, and 2 oxygen ( $C_{10}H_{20}O_2$ ). Decanoic acid has a phase change equilibrium temperature of nearly 30 °C (Sigma aldrich, n.d.). It has a white crystalline texture at room temperature. It was procured from Sigma Aldrich with a purity of 98%. In this work, the decanoic acid was utilized without further purification or additives.

### 2.1 Accelerated thermal cycling

The accelerated thermal cycling experiment was conducted in a refrigerated heating/cooling device (Julabo FP 50). A thermal cycle program was fed into the machine. The refrigerated heating/cooling device and thermal cycle program utilized are shown in Figure 1. The upper and lower limit of the temperature was set to 0 °C and 50 °C. The temperature ramps utilized in this work are 0.5, 1, and 2 °C/min. Initially, the temperature of the machine was set to 0 °C for 20 mins to have a better thermal equilibrium with the PCM sample. This step was followed by a temperature ramp where the temperature was changed to 50 °C. Once the temperature was achieved, the device was maintained at this temperature for 20 mins. Afterward, the reverse cycle starts and is finished when the initial temperature of the cycle is achieved. These steps represent one thermal cycle and for multiple thermal cycles, this procedure is repeated. During the accelerated thermal cycling experiments, first the impact of different cooling/heating (0.5, 1, and 2 °C/min) and volume (5.6 ml and 56 ml) was performed. The maximum thermal cycles performed to investigate the impact of these parameters were 50 cycles. This experiment was performed to investigate whether the different parameters selected have any influence on the thermal stability of the PCM. After performing the first set of experiments, a long-term accelerated thermal cycling of the decanoic acid was done. The long-term accelerated thermal cycling was performed for 1500 thermal cycles.



(a)



**Figure 1:** (a) Refrigerated heating/cooling device, (b) Thermal cycle program utilized

## 2.2 Differential scanning calorimetry (DSC) for decanoic acid

Using a Differential Scanning Calorimeter (DSC) (MICRO-DSC7-EVO, SETARAM), a standard approach was performed to acquire the thermal characteristics of the PCM. Comprehensive data regarding the PCM's thermal characteristics can be obtained from the thermograph obtained with the DSC (Quant et al., 2021). The ideal DSC thermograph is shown in Figure 2. The exothermic curve shows the energy retrieval process from the PCM which starts at the  $T_{\text{onset(S)}}$  phase change equilibrium temperature (liquid to solid) and finishes at  $T_{\text{endset(S)}}$ . The  $T_{\text{onset(S)}}$  is an important value because it represents the starting of a phase transition. The integration of the area under the curve which starts from the  $T_{\text{onset(S)}}$  to the  $T_{\text{endset(S)}}$  is the amount of energy retrieved  $\Delta_{\text{fus}}H$  and vice versa for the reverse process. Most of the PCM has a degree of supercooling which is the difference between the onset solid-liquid phase change equilibrium temperature and onset crystallization temperature. Hence, with an ideal PCM thermograph the degree of supercooling is zero where the thermograph of the real PCMs looks slightly different from the one presented. The DSC thermograph gives detailed information about the phase change process of a PCM. For better DSC analysis, a smaller amount of sample and a lower cooling/heating rate are selected to have a better thermal equilibrium within the DSC cell. The temperature program employed for the DSC covers a temperature range of 0–60 °C with a linear ramp of 0.5 °C/min and the amount of sample utilized was 10  $\mu\text{l}$ . DSC was used to examine the thermal characteristics of the PCM samples from the accelerated thermal cycling. Four thermal cycles were completed in the DSC for every test. Among four thermal cycles, the first cycle was carried out to complete the preparation of the sample, the initial melting ensuring good contact between the PCM and the bottom of the cell. The phase change temperature and phase change enthalpy average thermal characteristics of the three thermal cycles are reported with uncertainty of  $\pm 0.2$  °C and  $\pm 1.3\%$ , respectively. The uncertainty was computed by analyzing distilled water using DSC and contrasting it with the sample's standard data.

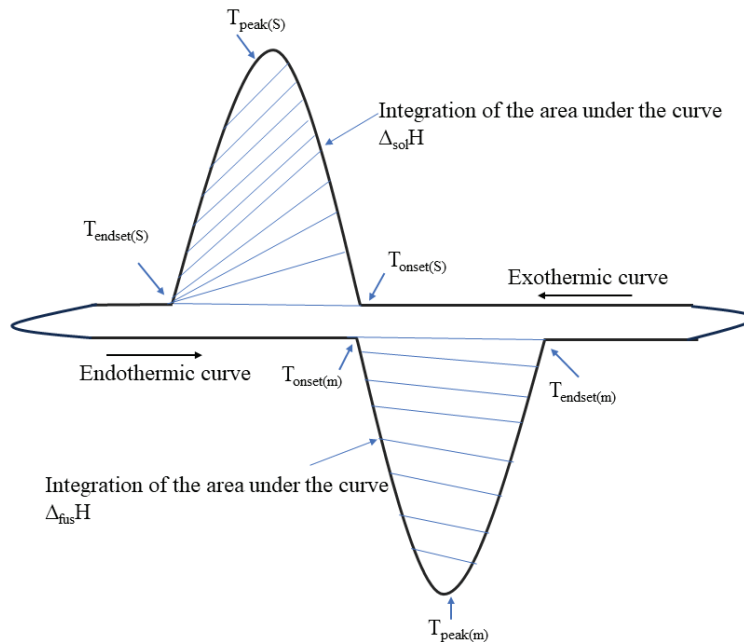
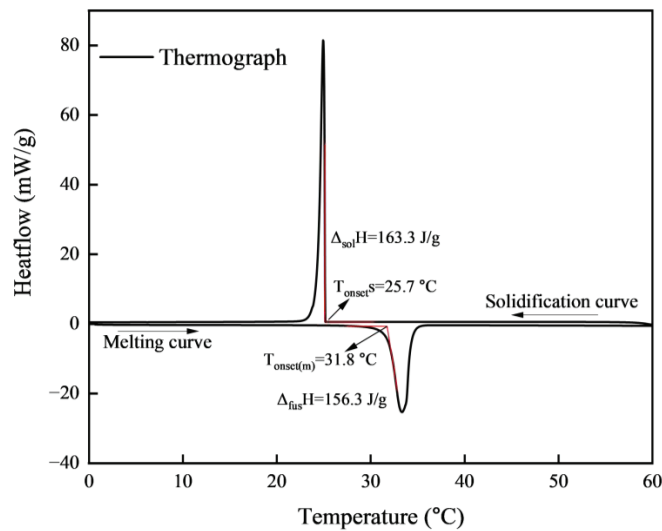


Figure 2: Ideal thermograph of a PCM

### 3 RESULT AND DISCUSSION

#### 3.1 DSC characterization of decanoic acid

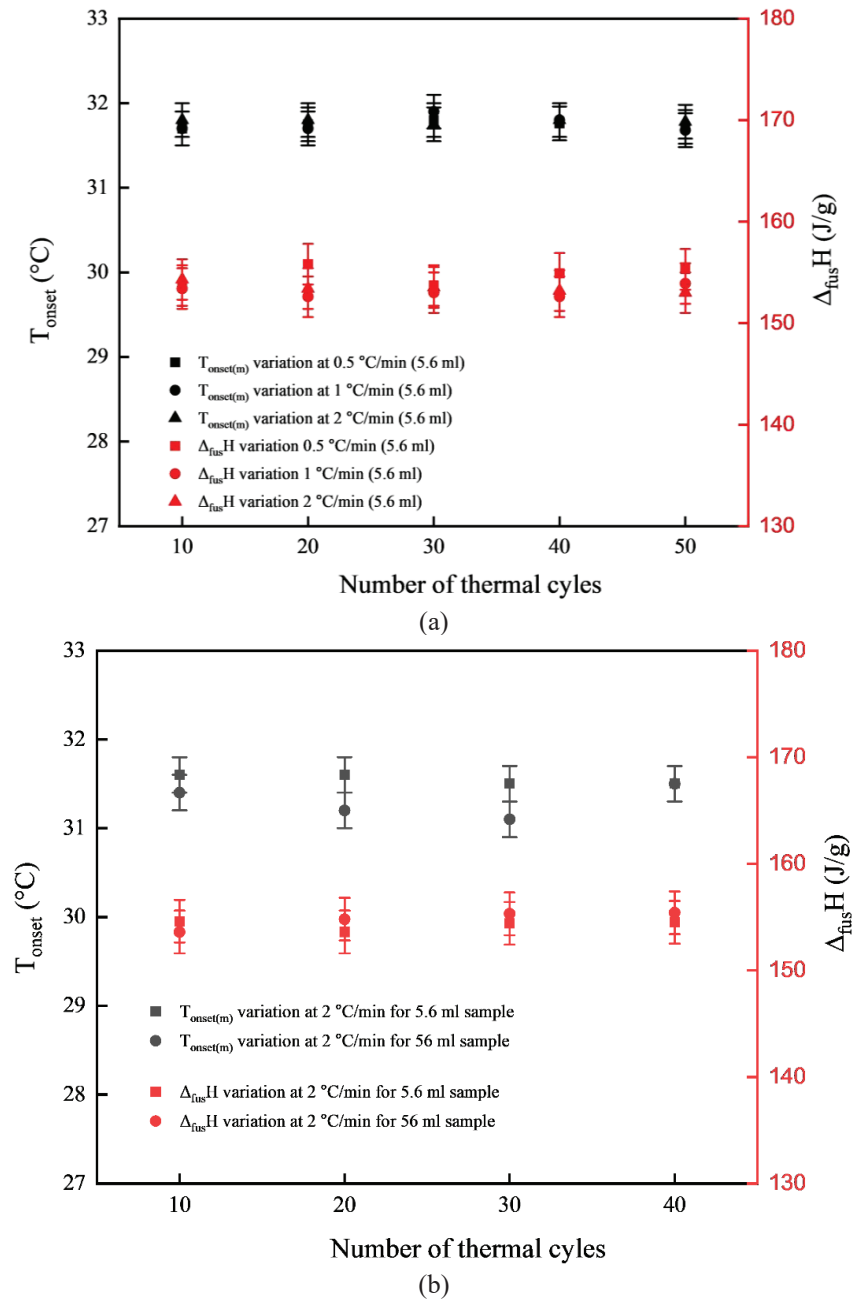
The thermograph that shows the melting and solidification process of decanoic acid is shown in Figure 3. This DSC analysis was performed for pure decanoic acid before accelerated thermal cycling. The melting curve shows the phase transition from solid to liquid. For each DSC experiment, four thermal cycles were performed in the DSC for better repeatability of the results. As already mentioned, the first cycle helped the sample to have better contact with the cell. The average thermal properties for the remaining three cycles are presented for discussion. The phase change equilibrium temperature, which represent the onset phase transition temperature during the melting process, is  $T_{\text{onset}(m)}=31.8\pm 0.2\text{ }^{\circ}\text{C}$  and the energy associated with the phase change is  $\Delta_{\text{fus}}H=156\pm 2\text{ J/g}$ . The  $T_{\text{onset}(m)}$  is measured from the slope of the thermograph which is shown by the red lines in the Figure 3, whereas the phase change enthalpy is the area under the thermograph. The reverse process which represents the solidification of the PCM is presented too. The solidification process shows the phase transition from solid to liquid which initiates at  $T_{\text{onset}(s)}=25.7\pm 0.2\text{ }^{\circ}\text{C}$  and the latent heat of solidification  $\Delta_{\text{sol}}H=163\pm 2\text{ J/g}$ . The difference between the  $T_{\text{onset}(m)}$  and  $T_{\text{onset}(s)}$  is  $6.1\pm 0.2\text{ }^{\circ}\text{C}$  and it is explained by the supercooling of decanoic acid. The supercooling has an erratic behavior that cannot be determined by carrying out just a few experiments. In a supercooled PCM, the temperature is below the liquid-solid equilibrium temperature (melting temperature), but the PCM does not crystallize. To calculate accurately the degree of supercooling plenty of experiments must be performed with different volumes. Therefore in this study, the degree of supercooling is not considered. The results for the decanoic acid are in good agreement with the data reported in the open literature (Cárdenas-Ramírez et al., 2021; Sarafoji et al., 2022).



**Figure 3:** DSC thermograph of decanoic acid

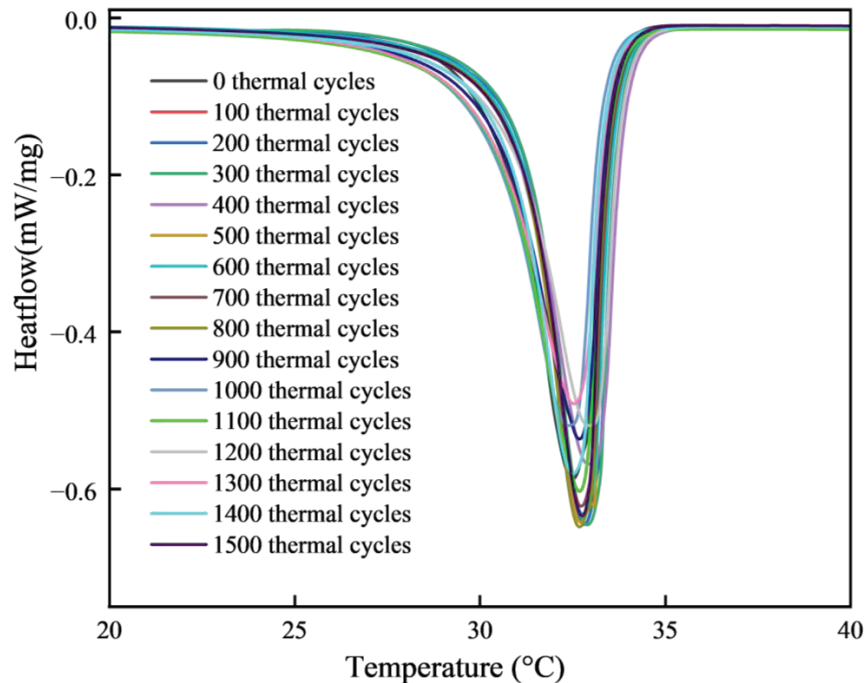
### 3.2 Accelerated thermal cycling of decanoic acid

Accelerated thermal cycling is utilized for the cyclic stability test of PCM. In the open literature, different cooling rates and volumes are utilized in the experimental setup employed for the cyclic stability test of decanoic acid, but those studies didn't analyze in depth the impact of those parameters on the degradation process of the PCM. This study investigated the impact of different cooling rates and volumes on the stability of the PCM subjected to refrigerator heating/cooling device. The results of different cooling/heating rates (0.5, 1, and 2 °C/min) with a 5.6 ml volume are shown in Figure 4 (a), whereas the different volumes of PCM utilized for thermal cycling at 2 °C/min are shown in Figure 4 (b). In general, Figure 4 shows the evolution of the thermal properties of the PCM as a function of the number of cycles at different cooling rates and for different volumes of PCM. The results presented are deduced by analyzing the decanoic acid sample after each 10 thermal cycles completed. The 50 thermal cycles performed for the cooling rates 0.5, 1, and 2 °C/min with a volume of 5.6 ml showed that the variation in the thermal properties is not significant. The points with the uncertainty bars overlap from which the PCM seems to have stable thermal properties at different cooling. In addition, the results of different sample sizes (5.6 and 56 ml) have the same tendency where the thermal properties didn't vary. Based on the results it was deduced that the higher cooling rate (2 °C/min) and a small amount of PCM (5.6 ml) will be utilized for long-term stability investigation of decanoic acid. This choice is due to the fact that none of these parameters seems to change the results of these first stability tests, and utilizing a small sample size with a higher cooling/heating will help to perform accelerated thermal cycling more promptly.



**Figure 4:** (a) Impact of different cooling rates during thermal cycling, (b) impact of different volumes during thermal cycling

The long-term stability investigation of the decanoic acid was performed for 1500 thermal cycles. The thermographs that represent the melting process for 1500 thermal cycles are presented in Figure 5. From the thermographs, the thermal properties variation can be calculated. Based on the thermal properties reliability the life span of the PCM could be decided. In Figure 5 the crystallization peaks are not presented for discussion due to the supercooling of the samples, that is not analyzed in this work. The melting process which is not influenced by the supercooling phenomenon is considered to present the thermal properties of the decanoic acid. The variation in the thermal properties can be seen in Figure 5, where we observe different areas under the curve which represent the latent heat of fusion for decanoic acid and a slight difference in the phase change equilibrium temperature (determined by the onset).



**Figure 5:** DSC thermograph of decanoic acid for 1500 thermal cycles

The thermal properties variation for 1500 thermal cycles are shown in Figure 6. The two important parameters  $T_{\text{onset}(m)}$  and  $\Delta_{\text{fus}}H$  of the PCM are presented for the 1500 thermal cycle. The  $T_{\text{onset}(m)}$  and  $\Delta_{\text{fus}}H$  for the PCM were investigated after every 100 thermal cycles performed. The variation in  $T_{\text{onset}(m)}$  after 1500 thermal cycles was 3.14% whereas for  $\Delta_{\text{fus}}H$  it was 10.45%. The variation in the thermal properties started after 100 thermal cycles for the latent heat of fusion. The maximum variation in the latent heat of fusion and phase change equilibrium temperature was 11.13% and 5.82% respectively. The result shows a degradation for the decanoic acid that has a significant impact on the latent heat of fusion. In terms of phase change equilibrium temperature, the change after 1500 thermal cycles is not as much as the latent heat of fusion. The maximum change in the  $T_{\text{onset}(m)}$  is 5.82%, but after 1500 thermal cycles the change is 3.14% which means it was a fluctuation but not a permanent variation. The results are compared to previous accelerated thermal cycling performed for decanoic acid which are presented in table 1. The result of Martin et al. (Martin et al., 2019) where the accelerated thermal cycling is performed with a small amount of 0.5 ml volume of PCM does not show any degradation. This may be due to the fact that the small sample will not have enough free convection within the sample and a very high cooling/heating rate may have failed to trigger the degradation. In the study of (Majó et al., 2021), on the other hand, the authors used a lower cooling/heating rate on a PCM sample whose volume is not mentioned, and they observed a degradation on the decanoic acid. In our study, we have performed accelerated thermal cycling with 5.6 ml which shows a significant degradation. From the comparison, it is concluded that the degradation of PCM might not be observed with very small volume and high cooling/heating. The reduction in the latent heat of fusion shows that the decanoic acid degraded. However, the DSC analysis does not give information on thermal degradation mechanism of the PCM. Quant et al., 2021 studied the binary mixture of urea and sodium



nitrate. The result showed the variation in thermal properties is linked to the decomposition of urea which produces byproducts such as biuret and cyanuric acid. In future work, the author wants to perform other characterization to investigate the mechanism of degradation for capric acid. Hence this study will be followed by further characterization techniques where the aim is to search for a mechanism for how the thermal properties of the decanoic acid change with the phase change process.

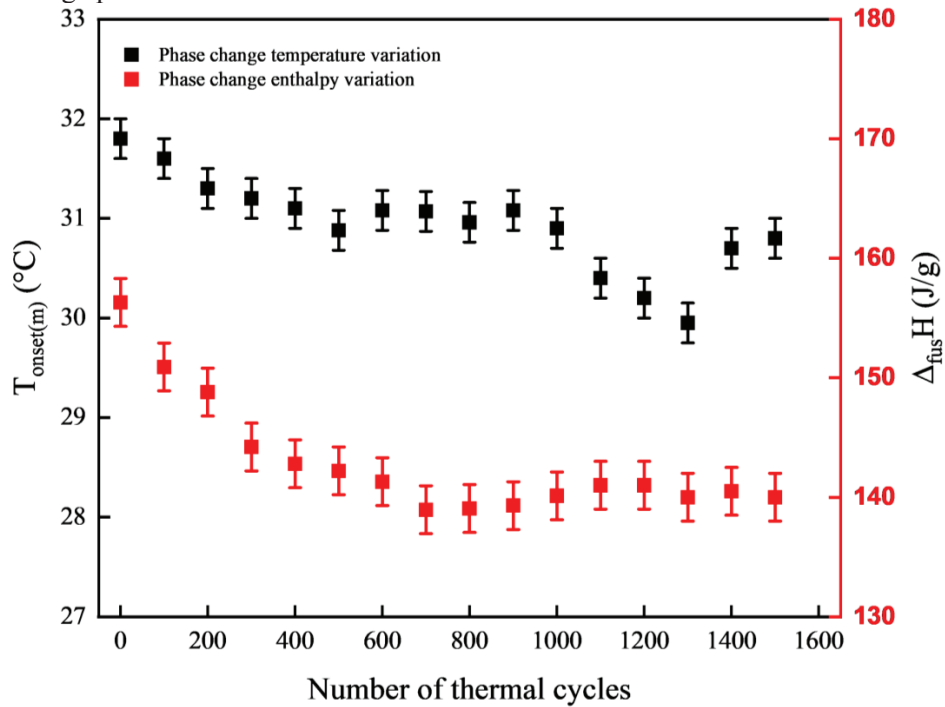


Figure 6: Thermal properties variation of decanoic acid for 1500 thermal cycles

Table 1: Comparison of the results with open literature data for decanoic acid

PCM	Decanoic acid (Martín et al., 2019)	Decanoic acid (Majó et al., 2021)	Decanoic acid [This study]
Cooling/Heating rate (°C/min)	240/ 300	0.5	2
Volume of sample (ml)	0.5	-	5.6
Device utilized	Thermocycler (Bioer Gene Q T-18)	Thermal bath	Refrigerated cooling/heating device (Julabo FP 50)
Number of thermal cycles	2000	1000	1500
T <sub>onset(m)</sub> (°C) initial	31.5	32.3±0.0	31.8±0.2
T <sub>onset(m)</sub> (°C) final	31.5	31.8±0.0	30.8±0.2
ΔH <sub>fus</sub> (J/g) initial	150	159±1	156.3±2

$\Delta H_{\text{fus}}$ (J/g) final	151	153±1	140±2
-------------------------------------	-----	-------	-------

#### 4 CONCLUSION

This work aims to perform a stability analysis of organic PCM (decanoic acid) and investigate the thermal properties reliability. Firstly, DSC analysis of the decanoic acid was performed and the results were in good agreement with data in the open literature. For the long-term stability investigation of the decanoic acid, a refrigerated cooling/heating device was utilized. The impact of different cooling rates and volumes of the PCM sample were investigated. The results did not show much variation due to the different cooling rates and volumes. For the long-term thermal cycling experiment, a cooling rate of 2 °C/min with a PCM sample size of 5.6 ml was chosen. The accelerated thermal cycling was performed for 1500 thermal cycles. The results show a maximum variation of 11.13% for the phase change enthalpy and 5.82% for the phase change equilibrium temperature. The maximum change in the  $T_{\text{onset(m)}}$  is 5.82%, but after 1500 thermal cycles the change is 3.14% which means it was a fluctuation but not a permanent variation. The degradation of the decanoic acid is best highlighted by the changes in the latent heat of fusion compared to any variation in the phase change equilibrium temperature. The methodology suggested will help other researchers select the different parameters involved in the accelerated thermal cycling utilized for the stability investigation of organic PCMs. In this work, DSC analysis was performed which gives detailed information on thermal properties but does not give insight into how the thermal properties are changed. In the future, the goal will be to identify why the thermal properties have changed with the phase change process. This work will be followed by performing other characterization techniques (FT-IR, NMR, and GC) that can give more information about the mechanism of variation in the thermal properties of decanoic acid.

#### NOMENCLATURE

$T_{\text{onset}}$  Phase change equilibrium temperature  
 $\Delta_{\text{fus}}H$  latent heat of fusion  
 $\Delta_{\text{sol}}H$  latent heat of solidification

#### Subscript

m melting process  
sol solidification process

#### REFERENCES

- Ayaz, H., Chinnasamy, V., Yong, J., & Cho, H. (2021). Review of technologies and recent advances in low-temperature sorption thermal storage systems. In *Energies* (Vol. 14, Issue 19). MDPI. <https://doi.org/10.3390/en14196052>
- Cárdenas-Ramírez, C., Gómez, M. A., & Jaramillo, F. (2021). Comprehensive analysis of the thermal properties of capric-myristic, lauric-myristic and palmitic-stearic acids and their shape-stabilization in an inorganic support. *Journal of Energy Storage*, 34. <https://doi.org/10.1016/j.est.2020.102015>
- Ismail, K. A. R., Lino, F. A. M., Machado, P. L. O., Teggarr, M., Arıçı, M., Alves, T. A., & Teles, M. P. R. (2022). New potential applications of phase change materials: A review. *Journal of Energy Storage*, 53, 105202. <https://doi.org/10.1016/J.EST.2022.105202>
- Liu, L., Hammami, N., Trovalet, L., Bigot, D., Habas, J. P., & Malet-Damour, B. (2022). Description of phase change materials (PCMs) used in buildings under various climates: A review. *Journal of Energy Storage*, 56, 105760. <https://doi.org/10.1016/J.EST.2022.105760>

- Majó, M., Sánchez, R., Barcelona, P., García, J., Fernández, A. I., & Barreneche, C. (2021). Degradation of fatty acid phase-change materials (PCM): New approach for its characterization. *Molecules*, 26(4). <https://doi.org/10.3390/molecules26040982>
- Martín, M., Villalba, A., Inés Fernández, A., & Barreneche, C. (2019). Development of new nano-enhanced phase change materials (NEPCM) to improve energy efficiency in buildings: Lab-scale characterization. *Energy and Buildings*, 192, 75–83. <https://doi.org/10.1016/J.ENBUILD.2019.03.029>
- Miró, L., Barreneche, C., Ferrer, G., Solé, A., Martorell, I., & Cabeza, L. F. (2016). Health hazard, cycling and thermal stability as key parameters when selecting a suitable phase change material (PCM). *Thermochimica Acta*, 627–629, 39–47. <https://doi.org/https://doi.org/10.1016/j.tca.2016.01.014>
- Quant, L., Diarce, G., Bouzas, L., Bédécarrats, J.-P., & García-Romero, A. (2021). Long-term assessment of the thermal stability of sodium nitrate-urea eutectic phase change material. *Solar Energy Materials and Solar Cells*, 230, 111261. <https://doi.org/https://doi.org/10.1016/j.solmat.2021.111261>
- Rathgeber, C., Hiebler, S., Bayón, R., Cabeza, L. F., Zsembinszki, G., Englmaier, G., Dannemand, M., Diarce, G., Fellmann, O., Ravotti, R., Groulx, D., Kheirabadi, A. C., Gschwander, S., Höhle, S., König-Haagen, A., Beaupere, N., & Zalewski, L. (2020). Experimental devices to investigate the long-term stability of phase change materials under application conditions. *Applied Sciences (Switzerland)*, 10(22), 1–30. <https://doi.org/10.3390/app10227968>
- Sarfoji, P., Mariappan, V., Anish, R., Karthikeyan, K., & Kalidoss, P. (2022). Characterization and thermal properties of Lauryl alcohol – Capric acid with CuO and TiO<sub>2</sub> nanoparticles as phase change material for cold storage system. *Materials Letters*, 316. <https://doi.org/10.1016/j.matlet.2022.132052>
- Sigma aldrich. (n.d.). *Capric acid (Sigma aldrich)*. Retrieved January 17, 2024, from <https://www.sigmaaldrich.com/FR/fr/product/sigma/c1875>
- Zhao, Y., Lin, X., Hu, M., Xu, L., Ding, J., & Ding, Y. (2023). Development and investigation of form-stable and cyclable decanoic acid-based composite phase change materials for efficient battery thermal management. *Journal of Power Sources*, 558, 232615. <https://doi.org/10.1016/J.JPOWSOUR.2022.232615>

## ACKNOWLEDGEMENT

This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska Curie Actions, Grant Agreement No. 945416 and was carried out through the research project KSP PCM-STORE (308847) supported by the Research Council of Norway and industry partners. PCM-STORE aims at building knowledge of novel PCM technologies for thermal energy storage systems.