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Latent Heat Validation of Phase Change Material using T-History Method

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ABSTRACT

Phase change material (PCM) is a material that will absorb and release heat over a specified timeframe and it functions as a cooling technique to reduce temperature of the photovoltaic panels. The T-history method is a technique used to measure the thermal diffusivity of a material by subjecting a sample to a sudden temperature change. This project proposed PCM36 as a cooling method for PV temperature reduction and the expected result for this study is to meet the data from manufacturer with a small different percentage. T-history is introduced to validate the PCM36 latent heat capacity and melting point and thus compare it with the manufacturer data. The manufacturer data's latent heat capacity and melting point are 220 J/g and 36 ˚C, respectively. Based on the result obtained, the latent heat capacity from T-history is 217.891 J/g and is 0.9591% different compared with the manufacturer data. On the other hand, the melting point based on the T-history curve is in the range of 36 ˚C-38 ˚C, which is similar to the manufacturer data.

1. Introduction

The sun's abundant and easily accessible resources make it a highly promising option for thorough exploration [1]. Solar energy systems prove to be highly useful for both preheating and cooling applications, as well as electricity generation [2]. Different technologies, such as photovoltaic systems, can be employed to capture solar energy [3]. The photovoltaic system functions akin to a typical flat plate solar collector by absorbing sunlight and converting it into electricity [4]. Therefore, cooling techniques are required such as phase change material for the purpose of cooling down the PV in order to enhance its efficiency.

Phase change materials are effective and useful because they melt and solidify at specific temperatures, and thus making them appropriate to control the temperature in a wide range of applications [5]. PCMs are extensively utilized in solar applications and building and HVAC systems to

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lower energy consumption [6]. Paraffin waxes are widely used as phase change materials (PCMs) for thermal management in electronics due to their substantial heat of fusion per unit weight, elevated melting point, and reliable cycling performance [7]. Additionally, they offer non-corrosive and chemically inert properties [7].

There are multiple approaches available to validate the properties of the PCM, which are conventional calorimetry methods, differential thermal analysis (DTA) and differential scanning calorimetry (DSC) [8]. Through the DTA and DSC approaches that have been extensively developed, an extremely small number of samples with the range of 1-10mg are allowed to be tested. The obtained results from DTA may be inadequate for accurately predicting the performance of bulk material for DTA and DSC approaches [9]. The advantages and disadvantages of T-history method are listed in Table 1 below.

Table 1
Advantages and disadvantages of T-history method

Advantages	Disadvantages
Simple and cheap laboratory equipment	Long measurement time
Relatively large test samples (typically dozens of grams)	Substantial effort required to ensure accurate measurement results

Yinping and Yi [8] proposed a T-history approach that enables simultaneous testing of multiple PCMs for their melting point, degree of supercooling, fusion heat, specific heat, and thermal conductivity. According to Gopinathan *et al.,* [9] the T-history approach is more appropriate to analyse a larger sample, as it can provide a more realistic representation of PCM performance in practical applications. On the other hand, I, Theresa and Velraj [10] found that T-history offers a superior characterization of PCM compared to DSC analysis, especially for low-temperature PCM. Besides that, Omaraa *et al.,* [11] presented that the T-history approach can measure the thermophysical properties of PCM at high temperatures. In the temperature range of 0°C to 100°C, water is commonly employed as the standard reference material for the testing sample [12,13]. A few researchers using T-hisory method for the validating of thermal properties of PCM are briefly summarized in Table 2.

Table 2
Literature review

PCM	Manufacturer's Data / Literature		Experimental Data		Reference
	Specific Heat capacity, (solid/liquid)	Heat of fusion (kJ/kg)	Specific Heat capacity, (solid/liquid)	Heat of fusion (kJ/kg)	
RT 28 HC	2	250	1.95/2.38	242.004	[10]
Coconut oil	2.25/3.29	72	2.385/2.42	71.15	[10]
Sodium acetate	2.11/3.68	263	2.26/3.74	245	[14]
Paraffin	-	156.8	5.11/2.19	135	[14]
Lauric acid	1.8/2.38	183	2.81/2.14	186	[14]
PCM 34	-/0.56	150	0.215/2.581	151	[15]
RT18	2	260	2.54/5.68	264.32	[13]
Paraffin	-	141.08	4.77/6.6	151.65	[12]
Beeswax	-	138.18	4.86/8.45	148.71	[12]

This project uses PCM36 as the phase change material. Thus, the latent heat capacity and the melting point of the PCM36 is validated using T-history method. T-history is a reliable and precise approach for measuring PCM's latent heat capacity and melting point [14]. This approach involves heating the PCM sample at a temperature over the PCM melting point until it melts, then cooling it down and monitoring the temperature changes over time. The T-history data collected through this procedure can be used to determine the melting point and latent heat of the PCM [15].

By validating PCM using the T-history approach is necessary to ensure that the experimental result aligns with the manufacturer's data. By conducting the T-history testing, any variations between the actual behavior of the PCM and the manufacturer's provided data can be identified and evaluated. This comparison is essential for verifying the accuracy and reliability of the manufacturer's claims regarding the PCM's properties and performance. It allows for a comprehensive assessment of PCM's suitability for specific applications and ensures that the information provided by the manufacturer is trustworthy and can be used for further analysis and decision-making. In a nutshell, validating PCM using the T-history method and thus comparing the results with the manufacturer data can provide valuable information about the material's thermal properties and help ensure it performs optimally in specific applications.

2. Methodology

2.1 Sample Preparation

Before launching the validation process, preparing the requisite materials and apparatus is imperative. Table 3 shows the list of materials and apparatus needed for this project.

Table 3
List of material and apparatus for T-history method

Experiment	Material	Apparatus
T-history method (To validate the latent heat and melting point of PCM 36)	PCM36 Water	Glass tube Beaker Retort Stand and Clamp Snowrex BBA 600 Balances Elma-Ultrasonic S 60 (H) Thermocouple Type K PicoLog TC-08 Laptop-Data Acquisition

Using material samples with appropriate diameters and measurements for testing is essential. The volume for the PCM36 and water used in the T-history approach (Figure 1) will depend on the measurement of the glass tube used. By referring to the experiment conducted by Gopinathan *et al.,* [9], the measurement of the glass tube used is 180, and the PCM and water required volume is around 25.4g and 15.4g, respectively.

Since the size of the glass tube which only available in the chemical lab is 150mm, thus the volume for PCM36 and water need to be calculated by using the Eq. (1). The measurement of the glass tube filled is 112.5mm, and the volume for water to be filled in the glass tube is 35cm^3. Since the density for both PCM36 and water is different, to find the mass of the PCM36 required to achieve similar volume with water is determined by using Eq. (2), all the findings are summarized in Table 4. Figure 2 shows the volume of PCM36 needed in this project.

$$\frac{Length\ of\ test\ tube\ filled}{Length\ of\ test\ tube} = \frac{Length\ of\ test\ tube\ filled\ (new)}{Length\ of\ test\ tube\ (new)} \tag{1}$$

$$Mass\ of\ PCM\ required\ (kg) = Volumn\ for\ water\ (m^3) \times\ density\ of\ PCM \tag{2}$$

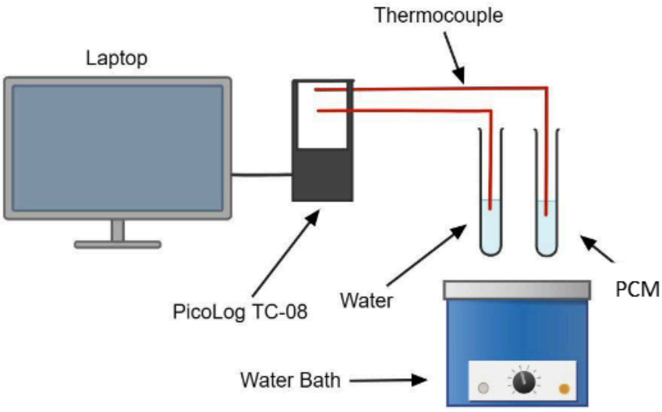


Fig. 1. Schematic diagram of T-history method

Table 4
Volume and dimensions for PCM36 and water

Material	Density (kg/m^3)	Mass required (g)	Volume (cm^3)	Measurement of the glass tube (mm)	Measurement of the glass tube filled (mm)
PCM36	827.51	29	35	150	112.5
Water	997	35	35	150	112.5

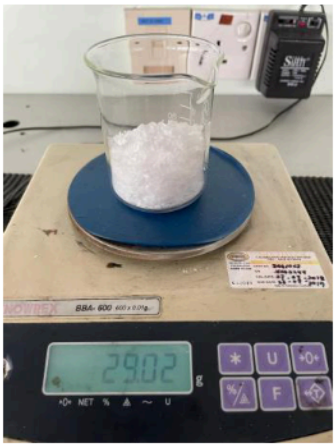


Fig. 2. Volume of PCM36

2.2 Experiment Part

The PCM36 is in a solid state in the initial stage. Water act as the reference material with known thermal properties. The utilization of water as a reference material holds significance due to its well-established specific heat and latent heat of fusion values. These known properties of water are instrumental in calibrating the T-history approach, enabling precise measurement of the thermal properties of the phase change material (PCM). By referencing against water, the accuracy of the measurements can be ensured and the reliability of the results can be enhanced. In the T-history approach, the PCM36 and water are heated to a temperature higher than the melting point T_0, where $T_0 > T_l$ (T_l was the phase-transition temperature) [7]. The heating process uses the Elma-Ultrasonic S 60 (H). Figure 3 shows the melting process to make the PCM36 change to the liquid stage from the solid stage.

Fig. 3. Melt the PCM into the liquid stage

The T-history approach is initiated by placing the glass tubes vertically at a constant temperature bath. The purpose of this method is to monitor and record the temperature changes experienced by the sample over time. Both glass tubes are then removed from the hot water tank and allowed to cool to ambient temperature, T_a [16]. For this project, the ambient temperature,T_a is 24.56°C. The positioning of the thermocouple is crucial for temperature detection. It impedes solidification growth while the thermocouple is fully embedded [17,18]. The solidification growth occurs due to the thermal sensing element of the thermocouple accumulating heat. Therefore, the thermocouple is placed at a depth of 35mm inside the PCM36 and position symmetrically along the axis of the glass tube, initially surrounded by water. Figure 4 shows the experimental setup for the cooling process at ambient temperature (Ta=24.56°C).

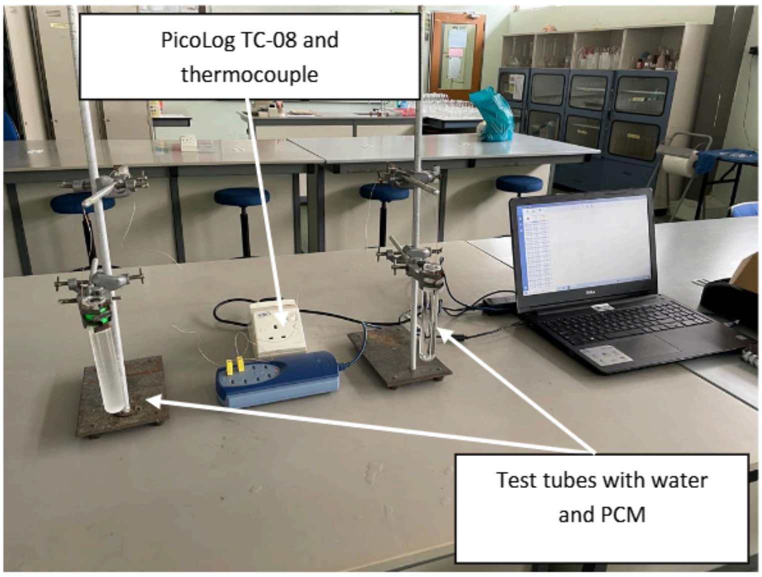


Fig. 4. Experiment setup

The temperatures of the glass tubes and the surrounding atmosphere are measured simultaneously, and resulting T-history curves, depicting the variations in temperature over time for both PCM36 and reference material, are obtained. The T-history curves are analyzed to assess the behavior of the PCM36 and the reference material under the given conditions. Figure 5 shows the cooling curve for both PCM and reference material [19].

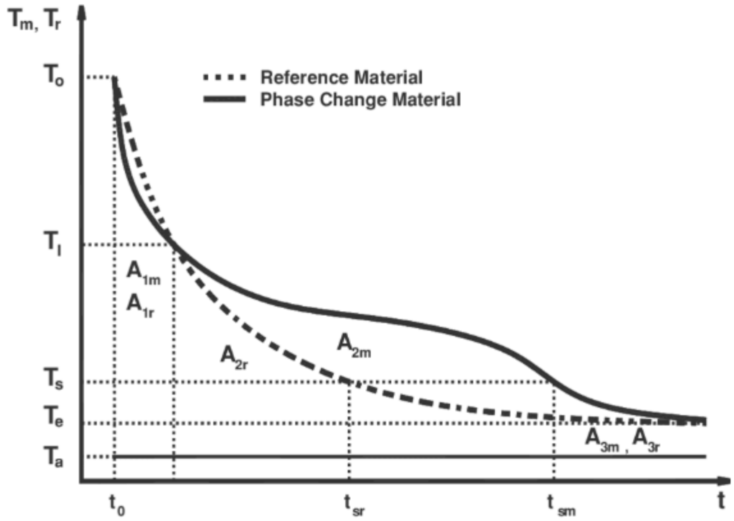


Fig. 5. Cooling curve for PCM and reference material [20]

2.3 Calculation Part
2.3.1 Cooling cycle

The data from the Excel file is then converted into a graph, and the graph is divided into three behaviours that are liquid, phase change, and solid. The area under the graph from these three behaviours is then calculated to determine thermal properties. Table 5 shows the equation for PCM and water to determine the area under the graph.

Table 5
Equations to determine the area under the graph

Material	Behaviour	Temperature range	Time range	Equation
PCM36	Liquid	T_o- T_{m1}	t_o- t_{m1}	$A_1 = \int_{to}^{tm1} (T_{PCM}(t) - T_a)\, dt$
	Phase Change	T_{m1}- T_{m2}	t_{m1}- t_{m2}	$A_2 = \int_{tm1}^{tm2} (T_{PCM}(t) - T_a)\, dt$
	Solid	T_{m2}- T_{m3}	t_{m2}- t_{m3}	$A_3 = \int_{tm2}^{tm3} (T_{PCM}(t) - T_a)\, dt$
Water	Liquid	T_o- T_{m1}	t_o- t_{r1}	$A_1{}' = \int_{to}^{tr1} (T_r(t) - T_a)\, dt$
	Liquid	T_{m1}- T_{m2}	T_{r1}- t_{r2}	$A_2{}' = \int_{tr1}^{tr2} (T_r(t) - T_a)\, dt$

where T_{m1} represents melting or freezing temperature for PCM36, T_o represents the maximum temperature reached by the sample, T_{m2} represent the temperature for solidus or freezing, and T_{m3} represent the solidification end temperature reached by the sample.

2.3.2 Thermophysical properties analysis

The temperature measurements recorded over time are plotted, resulting in the generation of cooling curves. The analysis of these curves aids in determining the freezing and solidification temperatures, the phase change region, the latent heat of fusion, and specific heat capacity. These values can be determined using the empirical relation described in this section. The freezing and solidification cycles provide valuable insights into the loading and unloading of thermal energy in practical applications involving PCM. The mathematical model of the energy equations presented by Hong *et al.,* [13] is employed to calculate the latent heat and specific heat capacity.

Zhang *et al.,* [20], Khudhair and Farid [21], Tabares-Velasco *et al.,* [22], and Bony and Citherlet [23] provide the energy equations, specifically the modified T-history method, for the organic PCM in its liquid, phase change, and solid behaviour. These equations are utilized to calculate the thermophysical properties of the selected PCM, taking into account the known properties of the distilled water and the glass tube. The energy equation of the PCM is shown in Eq. (3) to Eq. (5).

$$(m_t c_{p,t} + m_p c_{p,l})(T_0 - T_s) = hA_c A_1 \tag{3}$$

$$m_p H_m = hA_c A_2 \tag{4}$$

$$(m_t c_{p,t} + m_p c_{p,s})(T_S - T_r) = hA_c A_3 \tag{5}$$

where m_t represents the weight of the glass tube, $c_{p,t}$ represents the mean specific heat of the glass tube material, m_p represent the weight of the PCM36, $c_{p,l}$ represent the mean specific heat of PCM36 in liquid behaviour, $c_{p,s}$ represent the mean specific heat of PCM in solid behaviour, h represents the convective heat transfer coefficient, H_m is the latent heat of fusion of the PCM36, T_i represent the sample temperature, A_c represent the area of the tube with PCM36 and water when convection occurs, and A_x represents the area under the curve for PCM36.

In fact using the Eq. (6), the natural convective heat-transfer coefficient of air outside a tube, *h* can be obtained. Eq. (6) and Eq. (7) present the energy equations for the water.

$$(m_t c_{p,t} + m_w c_{p,w})(T_0 - T_s) = hA_c A_1{}' \tag{6}$$

$$(m_t c_{p,t} + m_w c_{p,w})(T_s - T_r) = hA_c A_2{}' \tag{7}$$

where m_w represents the weight of the water, $c_{p,w}$ represents the mean specific heat of the water, and $A_x{}'$ represent the area under the curve for water.

The Biot number calculation is performed to verify the uniform heat distribution within the sample. Furthermore, a detailed analysis is conducted to determine the specific heat, latent heat, and thermal conductivity calculation of the PCM. The Biot number was defined as the Eq. (8).

$$B_i = \frac{hr}{2k} \tag{8}$$

where *r* represents the radius of the glass tube, *k* represents the thermal conductivity of the PCM, and *h* represent the atmospheric free convection heat transfer coefficient.

Thus, the mean specific heat of PCM36 in both liquid and solid behavious can be written as Eq. (9) and Eq. (10), respectively. With the supercooling, the latent heat of fusion for PCM36 can be calculated by using the Eq. (11).

$$c_{p,l} = \frac{m_t c_{p,t} + m_w c_{p,w}}{m_{pcm}} \frac{A_1}{A_1{}'} - \frac{m_{t,pcm}}{m_{pcm}} c_{p,t} \tag{9}$$

$$c_{p,s} = \frac{m_t c_{p,t} + m_w c_{p,w}}{m_{pcm}} \frac{A_3}{A_2{}'} - \frac{m_{t,pcm}}{m_{pcm}} c_{p,t} \tag{10}$$

$$H_m = \frac{m_w c_{p,w} + m_t c_{p,t}}{m_{pcm}} \frac{A_2}{A_1'} (T_0 - T_s) \tag{11}$$

For PCM36 without supercooling, the expressions for $c_{p,l}$ and $c_{p,s}$ will remain the same as Eq. (9) and Eq. (10), but the heat of fusion will be rewritten as Eq. (12).

$$H_m = \frac{m_w c_{p,w} + m_t c_{p,t}}{m_{pcm}} \frac{A_2}{A_1'} (T_0 - T_{m1}) - \frac{m_t c_{p,t} (T_{m1} - T_{m2})}{m_{pcm}} \tag{12}$$

3. Results and Discussion

The T-history method determines a material's specific heat and latent heat capacity under test. It involves comparing the heat release behaviour of PCM36 with water. By analysing the duration and heat release patterns, a calculation can be performed to quantify the specific heat and latent heat capacity of the PCM36. The T-history curve that obtained in this project is shown in Figure 6 below. The specific values for the x-axis and y-axis are shown in Table 6 below.

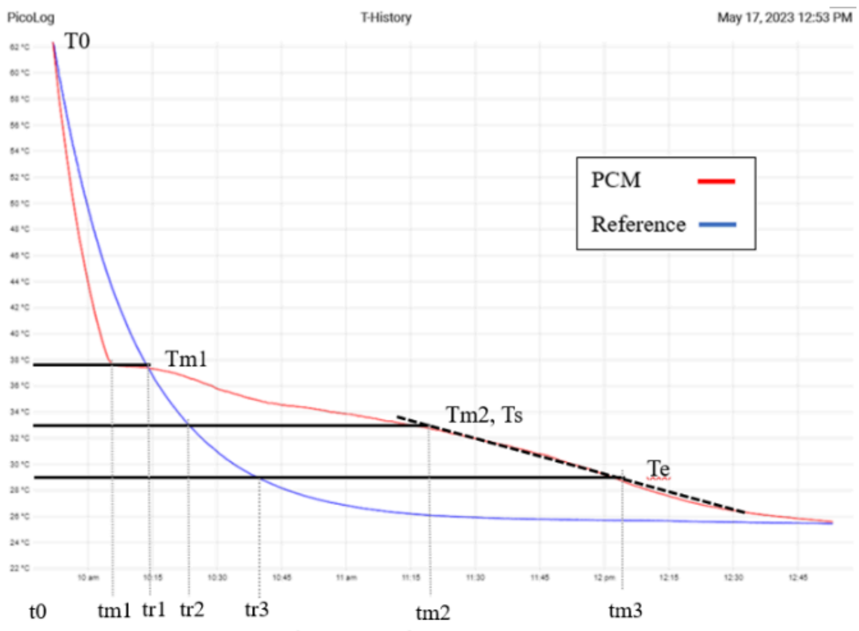


Fig. 6. T-history curve for this project

Table 6
Specific values for temperature (T) and time (t)

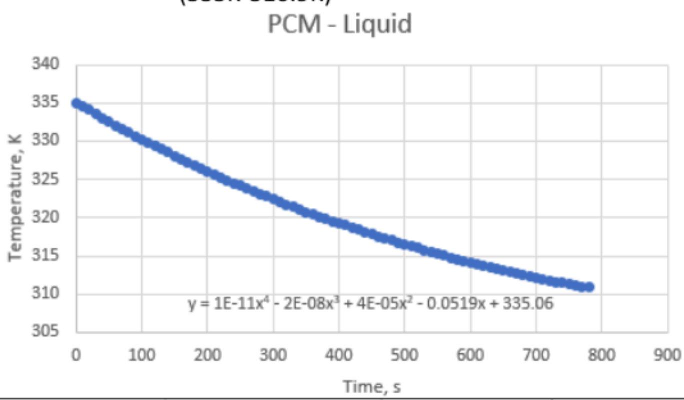
Temperature, (T)		Value, (°C)	Time, (t)		Value, (s)
T0	Initial Temperature for PCM36 and water	62	t0	Initial time for PCM36 and water	0
Tm1	Temperature of solidification for PCM36	37.9	tm1	Solidification starting time for PCM36	0.178
Tm2	Temperature when the solidification process end for PCM36	33	tm2	Solidification ending time for PCM36	4.96
Ts	Similar to the temperature of phase change ending of PCM36	33	tm3	End time for PCM36	7.77
Te	Temperature end for PCM36 and water	29	tr1	Time for water parallel with the solidification starting time for PCM36	1.88
			tr2	Time of water parallel to the solidification ending time for PCM36	2.83

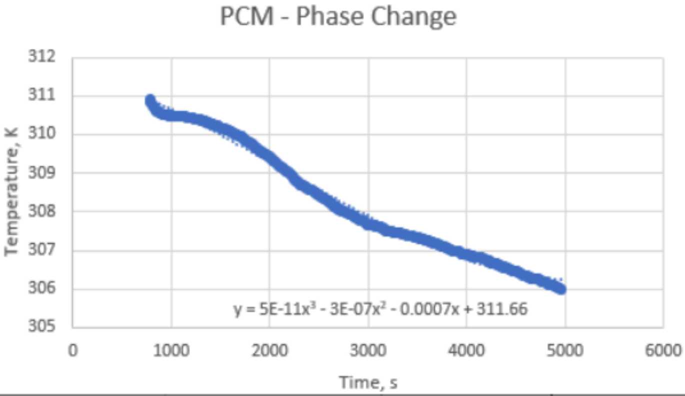
3.1 Calculation Part
3.1.1 Cooling cycle

The area under the graph from these three behaviours is then calculated to determine thermal properties. Table 7 shows the area under the graph for PCM36 and water.

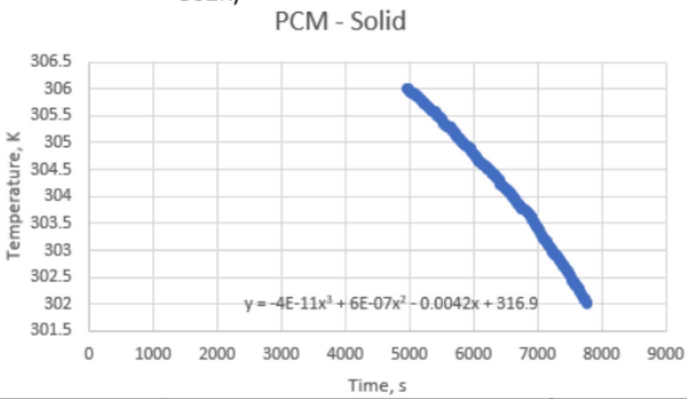
Table 7
Area under the graph for PCM36 and water

Material	State of substance	Temperature range	Time range	Results	Equation
PCM36	Liquid	62°C-37.9°C (335K-310.9K)	0- 780s	18516.06	$y = 1E\text{-}11x^4 - 2E\text{-}08x^3 + 4E\text{-}05x^2 - 0.0519x + 335.06$
PCM36	Phase Change	37.9°C-33°C (310.9K-306K)	780- 4960s	45946.3	$y = 5E\text{-}11x^3 - 3E\text{-}07x^2 - 0.0007x + 311.66$

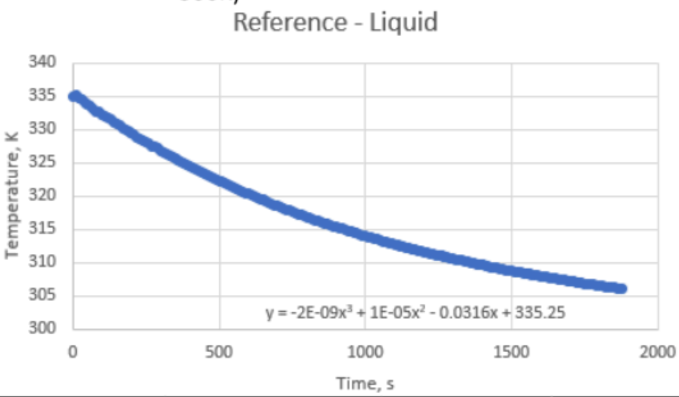




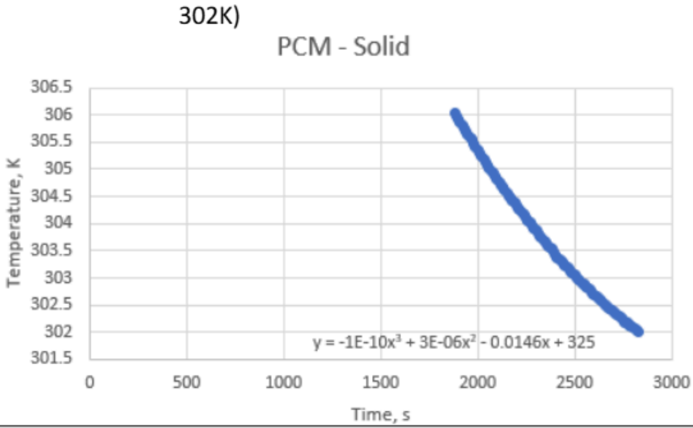
PCM36	Solid	33°C-29°C (306K-302K)	4960- 7770s	18243.89	$y = -4E-11x^3 + 6E-07x^2 - 0.0042x + 316.9$



Water	Liquid	62°C-33°C (335K-306K)	0- 1880s	30916.59	$y = -2E-09x^3 + 1E-05x^2 - 0.0316x + 335.25$



Water	Liquid	33°C-29°C (306K-302K)	1880-2830s	8133.4	$y = -1E-10x^3 + 3E-06x^2 - 0.0146x + 325$



3.1.2 Thermophysical properties analysis

In fact using the Eq. (6), the natural convective heat-transfer coefficient of air outside a tube, *h* can be obtained. To evaluate the thermal properties of PCM36, the Biot number must be determined to determine whether the temperature distribution is uniform or lumped capacitance method can be used. Biot number can be obtained from Eq. (8) after determining the *h* value. Eq. (9) and Eq. (10) will be used to evaluate the latent heat of fusion for PCM36 at liquid and solid behaviour. For PCM36 without supercooling will be evaluated by Eq. (12). All these thermophysical properties analysis are based on the data of dimension and properties shown in Table 8 below. All the thermophysical properties finding will be summarised in Table 9.

Table 8
Dimension and properties

Properties	Value	Unit
Diameter of glass tube, D	0.024	m
Measurement of glass tube, L	0.15	m
Convective area, A_c	0.00984	m^2
Weight of glass tube,m_t	0.042	Kg
Weight of PCM, m_{pcm}	0.029	Kg
Weight of water, m_w	0.035	Kg
Weight of glass tube filled with PCM, $m_{t, pcm}$	0.071	Kg
Weight of glass tube containing of water, $m_{t,w}$	0.077	Kg
Specific heat of water, $C_{p,w}$	4181 [24]	J/kgK
Specific heat of tube, $C_{p,t}$	830 [25]	J/kgK

Table 9
Thermophysical properties

Properties	Value	Unit
Natural heat transfer coefficient, h	11.9153	W/m^2K
Biot number	0.2979	-
Specific heat of PCM36 in liquid behaviour, $C_{p,l}$	2539.943279	J/kgK
Specific heat of PCM36 in solid behaviour, $C_{p,s}$	12812.94468	J/kgK
Latent heat of fusion of PCM36, H_m	217.891	J/g
Percent Error, %	0.9591	J%

3.2 Discussion

This project aims to validate the PCM36 melting point and latent heat capacity with the manufacturer's data. The thermal properties of PCM36 from manufacturer is shown in Table 10 below.

Table 10
Dimension and properties

Properties	Value
Melting point	36°C
Heat of fusion	220 J/g
Specific gravity	0.83
Thermal conductivity	0.24 W/mk
Thermal cycling	Multiple more than 10000 cycles

Based on the observation of this experiment, the freezing point of the PCM36 is in the range of 36°C to 38°C, which is similar to the melting point given by the manufacturer's data. The latent heat of fusion obtained by the T-history is 217.891 J/g, while the data given by the manufacturer is 220 J/g. Thus, the latent heat of PCM is considered close to the data, which only gives a 0.9591% difference.

In the previous paper, the Biot number less than 0.1 is recommended. The natural heat transfer coefficient,h recommended to achieve this about 5 to 6 W/m^2K [9]. But the Biot number for this project is 0.2979. Several variables can cause the difference, such as the dimension of the glass tube and the natural heat transfer coefficient, h. The natural heat transfer coefficient achieved in this project is 11.9153 W/m^2K which is higher than the recommended value. On the other hand, due to the limitation of the glass tube, the glass tube available for this project has a dimension of 0.024m, but the previous paper used a 0.0104mm diameter [9].

4. Conclusions

Validating PCM using the T-history approach is necessary to ensure that the experimental result aligns with the manufacturer's data. By conducting the T-history testing, any variations between the actual behavior of the PCM and the manufacturer's provided data can be identified and evaluated.

Although the Biot number for this project is 0.2979, higher than the recommended value. This is due to the dimensions of the glass tube used and the natural heat transfer coefficient. But while comparing the melting point, PCM36 is within the range of 36°C to 38°C, which achieved the same melting point given by the manufacturer's data. According to the latent heat of fusion, the result obtained from the T-history is 217.891 J/g, which achieved a 0.9591% difference compared with the manufacturer's data. In short, the T-history approach has successfully validated the melting point and latent heat of fusion with deviation less than 1% from the manufacturer's data.

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References

[1] Rosli, Mohd Afzanizam Mohd, Danial Shafiq Mohd Zaki, Fatiha Abdul Rahman, Suhaila Sepeai, Nurfaizey Abdul Hamid, and Muhammad Zaid Nawam. "F-Chart Method for Design Domestic Hot Water Heating Systemin Ayer Keroh Melaka." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 56, no. 1 (2019): 59-67.

[2] Sachit, F. A., Noreffendy Tamaldin, M. A. M. Rosli, S. Misha, and A. L. Abdullah. "Current progress on flat-plate water collector design in photovoltaic thermal (PV/T) systems: A Review." *Journal of Advanced Research in Dynamical and Control Systems* 10, no. 4 (2018): 680-689.

[3] Rosli, Mohd Afzanizam Mohd, Yew Wai Loon, Muhammad Zaid Nawam, Suhaimi Misha, Aiman Roslizar, Faridah Hussain, Nurfaizey Abdul Hamid, Zainal Arifin, and Safarudin Gazali Herawan. "Validation Study of Photovoltaic Thermal Nanofluid Based Coolant Using Computational Fluid Dynamics Approach." *CFD Letters* 13, no. 3 (2021): 58-71. https://doi.org/10.37934/cfdl.13.3.5871

[4] Rosli, Mohamad Afzanizam Bin Mohd, Sohif Mat, Kamaruzzaman Sopian, Mohd Yusof Sulaiman, Elias Ilias Salleh, and Mohd Khairul Anuar Sharif. "Thermal performance on unglazed photovoltaic thermal polymer collector." *Advanced Materials Research* 911 (2014): 238-242. https://doi.org/10.4028/www.scientific.net/AMR.911.238

[5] Cargill. "Bioindustrial." *Cargill*. Accessed July 20, 2023.

[6] Advance Cooling Technologies. "Phase Change Material (PCM) Selection." *Advance Cooling Technologies*. Accessed June 21, 2023.

[7] Jančík, Petr, Michal Schmirler, Tomáš Hyhlík, Adam Bláha, Pavel Sláma, Jakub Devera, and Jan Kouba. "Experimental investigation and modelling of a laboratory-scale latent heat storage with cylindrical PCM capsules." *Scientific Reports* 11, no. 1 (2021): 1-15. https://doi.org/10.1038/s41598-021-02705-1

[8] Yinping, Zhang, and Jiang Yi. "A simple method, the-history method, of determining the heat of fusion, specific heat and thermal conductivity of phase-change materials." *Measurement Science and Technology* 10, no. 3 (1999): 201. https://doi.org/10.1088/0957-0233/10/3/015

[9] Gopinathan, Arun, Jaroslav Jerz, Jaroslav Kováčik, Behzad Sadeghi, and Pasquale Cavaliere. "Implementation of T-history method to determine the thermophysical properties of the phase change materials." *Thermochimica Acta* 723 (2023): 179485. https://doi.org/10.1016/j.tca.2023.179485

[10] Theresa, Lovelyn, and R. Velraj. "Thermophysical characterization and comparison of PCMs using DSC and T-History experimental setup." *Materials Research Express* 6, no. 12 (2019): 125527. https://doi.org/10.1088/2053-1591/ab5aae

[11] Omaraa, Ehsan, Wasim Saman, Frank Bruno, and Ming Liu. "Modified T-history method for measuring thermophysical properties of phase change materials at high temperature." In *AIP conference proceedings*, vol. 1850, no. 1. AIP Publishing, 2017. https://doi.org/10.1063/1.4984441

[12] Kapica, Paulina, Jarosław Karwacki, and Sebastian Bykuć. "The use of the T-history method to estimate thermal capacity and latent heat for RT15 and RT18 materials." In *E3S Web of Conferences*, vol. 70, p. 01008. EDP Sciences, 2018. https://doi.org/10.1051/e3sconf/20187001008

[13] Hong, Hiki, Sun Kuk Kim, and Yong-Shik Kim. "Accuracy improvement of T-history method for measuring heat of fusion of various materials." *International Journal of Refrigeration* 27, no. 4 (2004): 360-366. https://doi.org/10.1016/j.ijrefrig.2003.12.006

[14] Jansone, Dace, Mikelis Dzikevics, and Ivars Veidenbergs. "Determination of thermophysical properties of phase change materials using T-History method." *Energy Procedia* 147 (2018): 488-494. https://doi.org/10.1016/j.egypro.2018.07.057

[15] D'Avignon, Katherine, and Michaël Kummert. "Assessment of T-history method variants to obtain enthalpy–temperature curves for phase change materials with significant subcooling." *Journal of Thermal Science and Engineering Applications* 7, no. 4 (2015): 041015. https://doi.org/10.1115/1.4031220

[16] Xie, Jingchao, Yue Li, Weilun Wang, Song Pan, Na Cui, and Jiaping Liu. "Comments on thermal physical properties testing methods of phase change materials." *Advances in Mechanical Engineering* 5 (2013): 695762. https://doi.org/10.1155/2013/695762

[17] Safari, A., R. Saidur, F. A. Sulaiman, Yan Xu, and Joe Dong. "A review on supercooling of Phase Change Materials in thermal energy storage systems." *Renewable and Sustainable Energy Reviews* 70 (2017): 905-919. https://doi.org/10.1016/j.rser.2016.11.272

[18] Garg, Hari Prakash, Subhash C. Mullick, and Vijay K. Bhargava. *Solar thermal energy storage*. Springer Science & Business Media, 2012.

[19] Kravvaritis, E. D., K. A. Antonopoulos, and C. Tzivanidis. "Improvements to the measurement of the thermal properties of phase change materials." *Measurement Science and Technology* 21, no. 4 (2010): 045103. https://doi.org/10.1088/0957-0233/21/4/045103

[20] Zhang, Yongyichuan, Xuelai Zhang, Xiaofeng Xu, and Mengyao Lu. "Derivation of thermal properties of phase change materials based on T-history method." *Journal of Energy Storage* 27 (2020): 101062. https://doi.org/10.1016/j.est.2019.101062

[21] Khudhair, Amar M., and Mohammed M. Farid. "A review on energy conservation in building applications with thermal storage by latent heat using phase change materials." *Energy Conversion and Management* 45, no. 2 (2004): 263-275. https://doi.org/10.1016/S0196-8904(03)00131-6

[22] Tabares-Velasco, Paulo Cesar, Craig Christensen, and Marcus Bianchi. "Verification and validation of EnergyPlus phase change material model for opaque wall assemblies." *Building and Environment* 54 (2012): 186-196. https://doi.org/10.1016/j.buildenv.2012.02.019

[23] Bony, Jacques, and Stéphane Citherlet. "Numerical model and experimental validation of heat storage with phase change materials." *Energy and Buildings* 39, no. 10 (2007): 1065-1072. https://doi.org/10.1016/j.enbuild.2006.10.017

[24] The Engineering ToolBox. "Water - Specific Heat vs. Temperature." *The Engineering ToolBox*. Accessed Jun 22, 2023.

[25] Schott. "Produkteigenschaften, Borosilikatglas BOROFLOAT® – Thermische." *Schott*. Accessed Jun 22, 2023.