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Original Research Article



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# STUDY ON THE INFLUENCE OF RATING CHARGE ON TEMPERATURE AND PHASE BEHAVIOR OF STABILIZED MATRIX WAX-BASED THERMAL STORAGE

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***Abstract.*** *The rating charge characteristic is crucial for the heat energy storage, particularly for low-temperature system which uses paraffin wax. The influence of different rating charge causes severe temperature fluctuation, which is undesirable for the heat system. It is affected by unstable phase transformation, reducing the heat distribution and makes the average rating charge insufficient. In this work, the fluctuation can be minimized by adding polyethylene plastic as phase stabilizer for the wax. The polyethylene is added by ratio of weight of 15% from the total mass of 134 grams. Each material is mixed in the liquid state, stirred and molded into the apparatus. The phase transition evaluation is performed, showing the mixture indicates an additional transition peak after the principal phase transformation, ranging between 15.26 °C – 19.34 °C (melting) and 11.98 °C – 9.45 °C (freezing). The steady operation makes the lowest rating variation is only 0.3 °C/min, which is obtained by the mixture of wax and polyethylene. In the same rating charge, the wax has rating variation of 2.9 °C/min, signifying the effect of unsteady melting transition. It clearly demonstrates the addition of polyethylene for the mixture promotes a better phase transformation under various rating charge, maintaining the effective temperature distribution for the heat storage.*

**Keywords:** decomposition, rating charge, hydrocarbon, melting, solidification, polymer.

## 1. Introduction

The provision of clean and sustainable energy is a global topic due to the urgency of mitigating the energy crisis. A short mitigation effort is done through reutilization of the old oil well [1]. At the same effort, various concepts of harvesting energy from different sources are developed extensively. For example, the utilization of waste is proven as a reliable solution to obtain alternative fuel and also reducing the waste issue in society [2]. The development is also supported in the technological aspect, including the research in the burner system to provide alternative thermal energy through the combustion of the alternative fuel. Thermal load is taken as one of the highest global energy consumptions. It can be solved through the utilization of solar thermal system [3]. The system is supported by heat storage device (HSD) [4], making it possible to store the excess energy production in the daytime and released it when required in the nighttime [5].

The HSD is considered as a cost-effective energy storage, since the energy can be discharged directly to thermal load [6]. It reduces significantly the need for electric energy for heating systems. The HSD works by storing the heat through the material within the system, preferably solid-liquid storage material (SLSM), which has a higher storage density [7]. One good example of solar thermal utilization is solar drying.

Alkahdery L.A. [8], studied improvement of the solar drying system which used additional heat source, implying a better drying mechanism and higher temperature within the chamber. The system can be supported using HSD to promote a continuous drying in the nighttime. It makes the improvement of alternative energy can be maximized, since it combines several power sources to drive the energy exchange within the system [9]. Thus, HSD is potentially applied in various solar thermal system, which is expected to accelerate the energy mix from solar source.

One crucial problem related with the SLSM in an HSD is poor heat exchange rate due to low conductivity. S.A. Abtahi Mehrjardi et al. [10], optimizes the HSD system using fins for accelerating the average heat transfer within the system. It shows the suitable configuration of fin spacing and angle which allows to improve the conduction and convection heat transfer within the system. W. Cui et al. [11], utilize nanoparticles and ultrasonic fields to improve the average time processing within the system. The result demonstrates a notable achievement for the time reduction of the system up to 46.5%. B. Brahma et al. [12], proposed a combined air heater system with HSD. The proposed method utilizes SLSM from paraffin wax (Pw) which has the highest solar absorption rate of about 36.56 kW. The optimization provides a better heat exchange rate for the HSD system. The high heat exchange rate leads to an acceleration of rating charge (RC) within the system. H. Hosseininaveh et al. [13], analyzed the charge/discharge cycle for Pw-based HSD using intermediate boiling fluid, indicating the melting transition was followed by various temperature increment within the system. Z. Zhang et al. [14], performed an analysis of SLSM for building, showing the high temperature fluctuation in the charge process which highly affected by the rating convective heat transfer rate from air. D.S. Mehta et al. [15], demonstrated the uneven distribution of the temperature of the finned-HSD, showing each measured zone indicates different temperature rating during charge operation. The uneven temperature distribution is unsatisfactory which causes partial energy exchange [16], difficulty for determining the charge level [17], leading to extensive measurement for setting the charge controller [18].

The variation on the temperature of SLSM in an HSD is related with the molecular movement during energy exchange. Y. Du et al. [19], highlighted this aspect for thermal-conductivity enriched SLSM material, indicating the conduction path plays critical role in the energy transfer within the high rating charge system. To promote a steady temperature distribution, using an additional binder to the SLSM is suitable [20]. The proposed method also has a better safety factor which related to the mechanical strength of the modified SLSM [21]. M. He et al. [22], developed graphene aerogel (GA) as the matrix for Pw, indicating a good affirmation of the produced modified-Pw/GA. M. Zarrinjooy Alvar et al. [23], introduces monomer for Pw through impregnation and combined with graphite powder, allowing for a reliable performance both in stability and conductivity of the produced modified-Pw.

The additional matrix for the Pw can be obtained from various material, while polyethylene (PE) comes as the most suitable candidate considering its availability and cost [24]. The PE-based matrix is favorable for SLSM which promotes a steady phase-transformation of the SLSM. T. Al-Gunaid et al. [25], employed PE-low density (LD) with Pw for phase stabilization, demonstrating an excellent mechanical strength with an excellent ratio of stored/released energy. Another PE-class (high-density/HD) was also utilized for stabilization with nano-additives, showing a satisfactory mechanical and phase behavior [26]. However, characterization is generally concentrated for mechanical evaluation, with minimum evaluation on the effect of rating charge in the temperature profile. Thus, further work is required to address the effect of rating charge on the phase-transformation behavior and charge profile of the stabilized-SLSM.

The novelty from this work is a detailed temperature profile of the stabilized-SLSM under different RC. It aims to promote a better understanding on the effect RC on phase transformation of the stabilized-SLSM. Moreover, this study employes PE-LD and linear-LD (LLD) as phase stabilizer, which considered as one major component in plastic waste [27]. Thus, the finding is expected to improve the capability of HSD and offer additional consideration for waste reutilization. The assessment is focused through evaluation using low RC (LRC), medium RC (MRC) and high RC (HRC), providing a detailed result which can be used for developing suitable RC of an HSD.

## 2. Materials and Method

This work used Pw as the SLSM, while the matrix comes from polymer PE-LD and PE-LLD. The all-raw materials were obtained from local supplier, where the Pw has an average melting temperature of 60 °C. The polymers were used sheet-based structure in order to maximizing the mixing process. The preparation of

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the sample was performed without causing any polymerization, which is the advantage of forming PE-based stabilized-SLSM (sSLSM). The sSLSM was produced following the direct melting method [28] to accommodate the solid-liquid transition between the SLSM and binders. The ratio of SLSM was 85% of its weight while the binder was set only 15%. It is aimed to maintain the total storage capacity of the mixture as recommended here [29]. Each component was melted at different temperature (80 °C for SLSM and 160 °C for LD and LLD). The molten binder was poured to the liquid SLSM, continuously stirred at the elevated temperature (140 °C) to ensure the homogeneity. A small portion of SLSM, $sSLSM_1$ (Pw/LD) and $sSLSM_2$ (Pw/LLD) were taken for thermal analyzing through calorimetry and thermogravimetric method. Then, the liquid was moved to the charge container for evaluating the temperature change under various RC (Fig. 1).

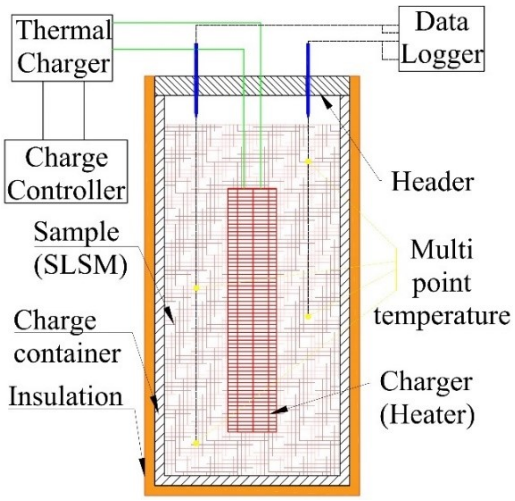



**Fig.1**. Charge evaluation for the SLSM and sSLSM

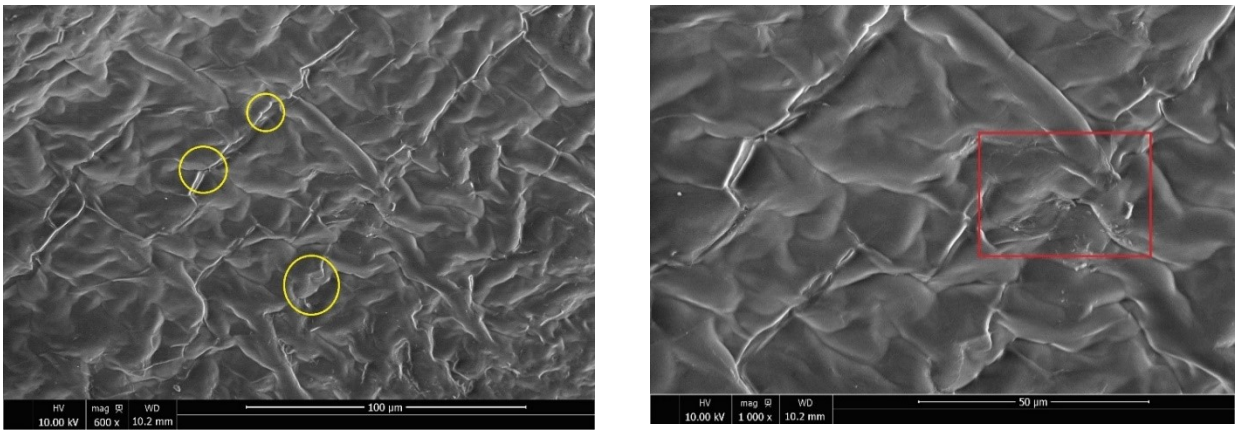
Fig. 1 shows the schematic of charge evaluation, which was adopted using temperature-history and temperature-energy method for a detailed assessment [30–32]. In this scenario, the liquid sample was placed within the charge container and four temperature sensors (K thermocouple) were located at the upper, middle (two sensor) and lower zone. The mass of sample was 134 grams, while direct contact heater (surface area of 673 $mm^2$ and diameter 9.5 mm) was placed and set precisely at the center point of the container. The charge controller was used to adjust the heating rate with three different powers: 30 Watts (LRC), 60 Watts (MRC) and 100 Watts (HRC). The charge profile then taken to determine the charge behavior for each sample.

## 3. Results and Discussions

The initial observation was taken for mapping the surface morphology using scanning electron microscope (SEM) of the SLSM to support the justification of unsteady phase behavior. The presented profile in Fig. 2a clearly signifies the effect of slow nucleation, causing wavy structure (yellow circle) where most of the solid interface stacked each other. The feature is caused by unfavorable crystallization rate which occurs in the liquid-solid transformation as the heat liberated from the SLSM [33]. It also potentially leads to void formation which causes unsuitable distribution of the solid SLSM within the tank. It can be seen notably in the Fig. 2b where some part of the surface is agglomerated (red square).

The direct decomposition is observed for the SLSM under thermogravimetric evaluation (Fig. 3). The curve indicates the evaporation of the compound occurs as a single process, which is started at temperature 220 °C until 365 °C. Contrary to that, the both sSLSM has two curves. The first curve corresponds to the decomposition of the SLSM, while the latter curve belongs to the matrix PE (LD and LLD). It indicates the sSLSM is formed as non-eutectic system, since the phase separation occurred at different temperature [34]. The higher decomposition temperature for the matrix PE makes the sSLSM more favorable in term of thermal stability, which is suitable for a higher temperature operation in HSD.

The impact of the matrix-PE within the sSLSM is observed distinctively since the temperature at this transition varies compared to the SLSM. Moreover, the melt transition for the sSLSM exhibit a longer temperature range, which is higher around 5.38 °C and 2.14 °C for $sSLSM_1$ and $sSLSM_2$, respectively. It seems the thermal behavior of PE-LD causes a longer melting transition.




a) b)

**Fig.2**. Surface profile of the SLSM at magnification (a) 100 and (b) 500

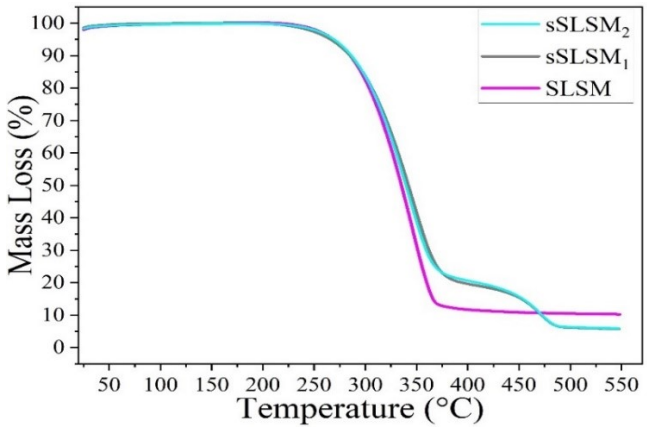
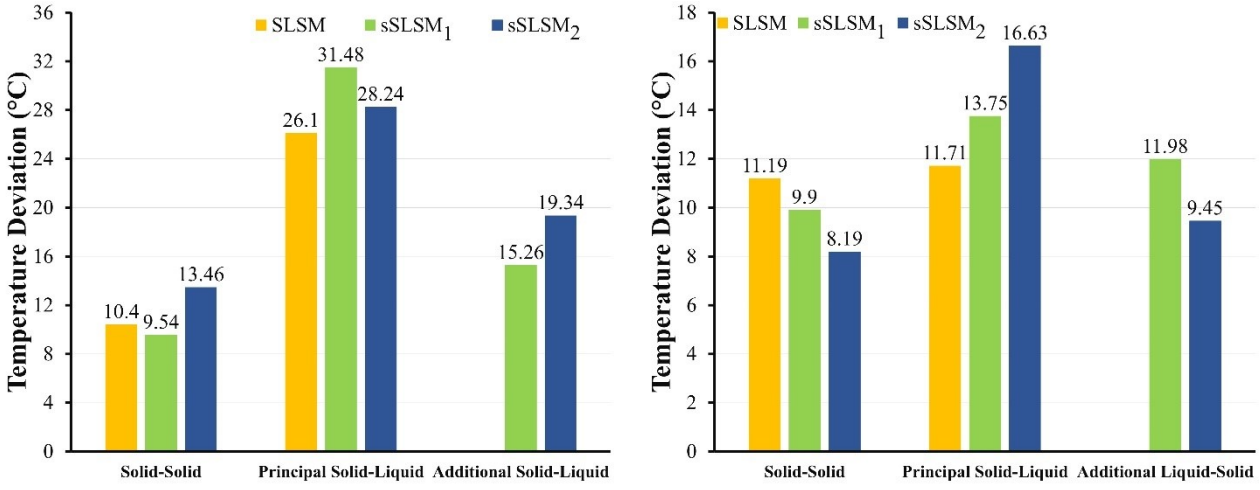



**Fig.3**. The mass loss behavior under thermal decomposition evaluation

There is one additional solid–liquid transition for the sSLSM. It occurs at temperature above 100 °C. Therefore, the physical characteristic for the sSLSM is immiscible. It makes the correspond substance melt separately. The change in thermal properties between SLSM and sSLSM can be analyzed in detail according to the its temperature transition. As seen in Fig. 4a, the SLSM has one significant characteristic which experiences solid-solid transition prior to melt. The process takes at higher temperature span, around 10.4 °C.




a) b)

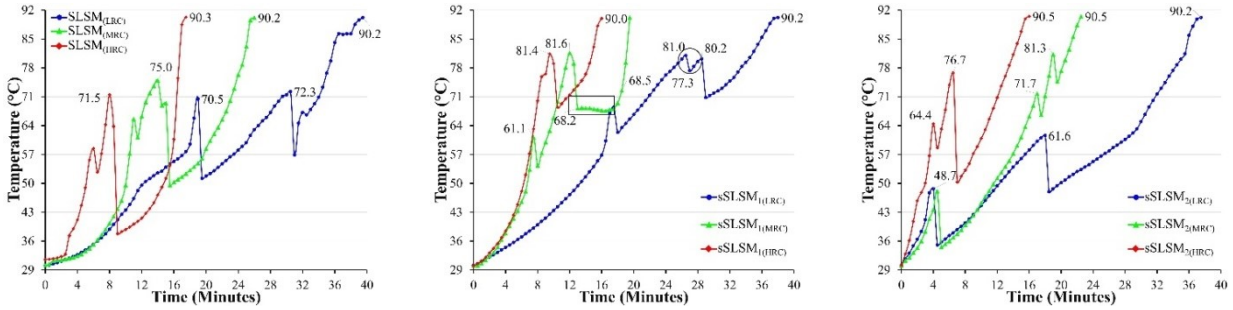
**Fig.4**. The detailed temperature transition for each sample during heating (a) and cooling (b) cycle

The impact of the matrix-PE within the sSLSM is observed distinctively since the temperature at this transition varies compared to the SLSM. Moreover, the melt transition for the sSLSM exhibit a longer temperature range, which is higher around 5.38 °C and 2.14 °C for $sSLSM_1$ and $sSLSM_2$, respectively. It seems the thermal behavior of PE-LD causes a longer melting transition. There is one additional solid–liquid transition for the sSLSM. It occurs at temperature above 100 °C. Therefore, the physical characteristic for the sSLSM is immiscible. It makes the correspond substance melt separately.

The freezing behavior for the SLSM is quite different (Fig. 4b). The main finding is shown as a shorter freezing transition. For example, the principal transition for SLSM is decreased by 55.1%. It makes the solidification occur at relatively shorter temperature range. It is also observed for the all sSLSM which indicates a shorter temperature transition during solidification. Interestingly, the solid–solid transition for SLSM and $sSLSM_1$ is increased around 0.8 °C and 0.4 °C, respectively. In contrast, the $sSLSM_2$ experiences a significant decrement for the transition which reduced about 39.2%. Each matrix has an identic pattern for the additional peak, where the temperature span reduces around 3.28 °C and 9.89 °C, respectively. Thus, the major change is caused by the interaction between the correspond matrix and SLSM (Pw).

Charge behavior is extremely important for the HSD. It indicates the ability of the storage material to absorb heat, which is critical to determine the performance of the system. The effect of charge rate causes significant change on the temperature profile. For example, charge rate of 30 Watts for SLSM (Fig. 5a) causes two step melt transition which starts at the identic temperature (around 70 °C).

The increment in charge rate makes the melt step becomes shorter at the identic temperature region. It indicates the melt transition for SLSM is delayed at higher temperature compared to its melt transition which is observed at 62.8 °C. It is the major issue for SLSM because the delayed transition reduces the heat absorption rate. Moreover, the pattern demonstrates the transition occurs as a non-isothermal behavior.




a) b) b)

**Fig.5**. The effect of RC on the temperature evolution for (a) SLSM, (b) $sSLSM_1$, and (c) $sSLSM_2$

Positive influence is observed for the all sSLSM. For $sSLSM_1$ (Fig. 5b), the melt transition still observed under 70 °C. It indicates the melting process is stabilized sufficiently. The mixture also indicates a short isothermal transition at temperature 68.2 °C (rectangular in Fig. 5b) which is highly desirable for the actual HSD. Despite the advantages, thermal disruption is observed (circle in Fig. 5b). It can be taken as the second stage transition of the composite due to low charge rate. The peak transition at higher charge rate (100 Watts) is shown at 81.4 °C, which is close to the thermal disruption temperature as occurred in low charge rate. Thus, determining a suitable charge rate is highly important to ensure a stable charge process for the HSD.

One unique charge behavior is observed for $sSLSM_2$ (Fig. 5c). It is the only sample which experiences three stages transition. Considering the temperature transition (Fig. 4), the three stages is highly related with each transition [35]. It makes the $sSLSM_2$ takes the longest duration to achieve the final temperature compared to SLSM and $sSLSM_1$. The positive influence for $sSLSM_2$ is observed at higher rate (60 Watts and 100 Watts) with a significant charge acceleration compared to SLSM. It allows the material to achieve the final temperature faster around 3.5 minutes (60 Watts) and 1.5 minutes (100 Watts). It can be assumed that $sSLSM_2$ is suitable for high charge rate system to achieve the advantages of adding matrix within the SLSM.

The detailed effect of matrix as stabilizer is shown in Fig. 6. The pure SLSM is the only sample which experiences decrement in the temperature rate between the upper and lower zone under LRC. It confirms the insufficient phase transformation of the material. Increasing the RC level leads to a higher deviation between the upper and lower zone. The highest deviation is obtained under HRC, with variation of 6.59 °C/min. As a result, the system unable estimate the precise value of the charge level due to high variation between each zone.

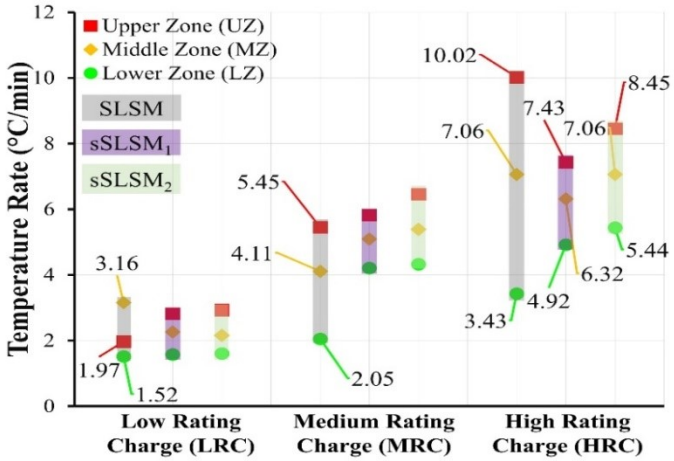



**Fig.6**. The changes in temperature rate for each zone under different RC

The effect of matrix demonstrates a better temperature rating between each zone. It has maximum temperature rate deviation of 1.24 °C/min (LRC), 2.13 °C/min, and 3.01 °C/min (HRC). It clearly demonstrates a steady phase transformation, particularly for the HRC operation. It corresponds to the plastic behavior of the matrix which maintain a suitable distribution of the liquid phase in the charge stage. Thus, the heat can be distributed effectively with minimum deviation, making the charge fluctuation can be decreased sufficiently and promoting a better estimation of charge indicator.

## 4. Conclusion

Utilization of polyethylene as matrix for SLSM (Pw) successfully promotes a steady phase transformation of the sSLSM in HSD. The matrix reduces the effect of temperature fluctuation in all RC scenario. The temperature rate deviation can be decreased up to 52.71% and 61.9% under medium and high RC. It is a direct impact on the presence of plastic behavior which increases the phase transformation characteristic of SLSM. The proposed method allows to accelerate the average temperature rate with the highest rating of 6.98 °C/min, which only deviates 3.01 °C/min between the upper and lower zone.

The surface observation of the SLSM clearly indicates the effect of insufficient phase transformation behavior. It contributes to the high deviation between each zone of the storage tank, which is disadvantageous for the operation of HSD, especially for large tank. The presence of additional matrix comes from polyethylene group is proven to reduce the drawback, minimize the temperature rate deviation, including the possibility to operate the system under high rating charge operation. Therefore, the proposed solution is suitable for developing a reliable HSD system with suitable phase transformation of the storage material.

**Conflict of interest statement.**
The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

**CRediT author statement**
Rahman R.A.: Writing – original draft, Visualization, Methodology, Data curation, Conceptualization; Sulistyo: Writing – review & editing, Validation, Supervision; Utomo M.S.K.T.S.: Formal analysis; Febriansyah I.: Investigation
The final manuscript was read and approved by all authors.

## References

1 Ismail I., Mulyanto A.T., Rahman R.A. (2022) Development of free water knock-out tank by using internal heat exchanger for heavy crude oil. *EUREKA: Physics and Engineering*, 4, 77–85. DOI: 10.21303/2461-4262.2022.002502.

.

2 Firman L.O.M., Adji R.B., Ismail, Rahman R.A. (2023) Increasing the feasibility and storage property of cellulose-based biomass by forming shape-stabilized briquette with hydrophobic compound. *Case Studies in Chemical and Environmental Engineering*, 8(April), 100443. DOI:10.1016/j.cscee.2023.100443.

3 Suyitno B.M., Rahman R.A., Sukma H., Rahmalina D. (2022) The assessment of reflector material durability for concentrated solar power based on environment exposure and accelerated aging test. *Eastern-European Journal of Enterprise Technologies*, 6(12–120), 22–29. DOI:10.15587/1729-4061.2022.265678.

4 Khademi A., Abtahi Mehrjardi S.A., Tiari S., Mazaheri K., Shafii M.B. (2022) Thermal efficiency improvement of brayton cycle in the presence of phase change material. *International Conference on Fluid Flow, Heat and Mass Transfer*, 135, 1–9. DOI:10.11159/ffhmt22.135.

5 Khademi A., Darbandi M., Behshad Shafii M., Schneider G.E. (2019) Numerical simulation of thermal energy storage process benefiting from the phase change materials concept. *AIAA Propulsion and Energy Forum and Exposition*, 2019, August, 1–9. DOI:10.2514/6.2019-4225.

6 Khademi A., Mehrjardi S.A.A., Said Z., Chamkha A.J. (2023) Heat transfer improvement in a thermal energy storage system using auxiliary fluid instead of nano-PCM in an inclined enclosure: a comparative study. *Journal of Applied and Computational Mechanics*, 9(2), 475-486. DOI:10.22055/jacm.2022.41867.3829.

7 Khademi A., Darbandi M., Schneider G.E. (2020) Numerical study to optimize the melting process of phase change material coupled with extra fluid. *AIAA Scitech 2020 Forum*, 1 Part F, 1–6. DOI:10.2514/6.2020-1932.

8 Alkahdery L.A., Yurchenko A.V., Mohammed J.A.K., Mekhtiyev A.D., Neshina Y.G. (2023) Performance improvement of solar dryer using an auxiliary heat source under different values of airflow rates. *Eurasian Physical Technical Journal*, 20(1–43), 42–50. DOI:10.31489/2023No1/42-50.

9 Usenkov R.A., Kokhanova S.Y., Trushin M.V. (2023) The use of alternative energy sources for the operation of engineering systems of detached consumers. *Eurasian Physical Technical Journal*, 20(2–44), 46–56. DOI:10.31489/2023No2/46-56.

10 Ali S., Mehrjardi A., Khademi A., Fazli M. (2024) Optimization of a thermal energy storage system enhanced with fins using generative adversarial networks method. *Thermal Science and Engineering Progress*, 49(February), 102471. DOI:10.1016/j.tsep.2024.102471.

11 Cui W., Li X., Li X., Lu L., Ma T., Wang Q. (2022) Combined effects of nanoparticles and ultrasonic field on thermal energy storage performance of phase change materials with metal foam. *Applied Energy*, 309(August 2021), 118465. DOI:10.1016/j.apenergy.2021.118465.

12 Palacio M., Ramírez C., Carmona M., Cortés C. (2022) Effect of phase-change materials in the performance of a solar air heater. *Solar Energy,* 247(April), 385–396. DOI:10.1016/j.solener.2022.10.046.

13 Hosseininaveh H., Mohammadi O., Faghiri S., Shafii M.B. (2021) A comprehensive study on the complete charging-discharging cycle of a phase change material using intermediate boiling fluid to control energy flow. *Journal of Energy Storage,* 35, 102235. DOI:10.1016/j.est.2021.102235.

14 Zhang Z., Zhang N., Yuan Y., Phelan P.E., Attia S. (2023) Thermal performance analysis of an existing building heating based on a novel active phase change heater. *Energy and Buildings*, 278, 112646. DOI:10.1016/j.enbuild.2022.112646.

15 Mehta D.S., Vaghela B., Rathod M.K., Banerjee J. (2020) Thermal performance augmentation in latent heat storage unit using spiral fin: An experimental analysis. *Journal of Energy Storage*, 31(April), 101776. DOI:10.1016/j.est.2020.101776.

16 Hashem Zadeh S.M., Ghodrat M., Ayoubi Ayoubloo K., Sedaghatizadeh N., Taylor R.A. (2022) Partial charging/discharging of bio-based latent heat energy storage enhanced with metal foam sheets. *International Communications in Heat and Mass Transfer*, 130(November 2021), 105757. DOI:10.1016/j.icheatmasstransfer.2021.105757.

17 Bastida H., De la Cruz-Loredo I., Ugalde-Loo C.E. (2023) Effective estimation of the state-of-charge of latent heat thermal energy storage for heating and cooling systems using non-linear state observers. *Applied Energy*, 331(August 2022), 120448. DOI:10.1016/j.apenergy.2022.120448.

18 Beyne W., Couvreur K., T'Jollyn I., Lecompte S., De Paepe M. (2022) Estimating the state of charge in a latent thermal energy storage heat exchanger based on inlet/outlet and surface measurements. *Applied Thermal Engineering*, 201(PB), 117806. DOI:10.1016/j.applthermaleng.2021.117806.

19 Du Y., Zhou T., Zhao C., Ding Y. (2022) Molecular dynamics simulation on thermal enhancement for carbon nano tubes (CNTs) based phase change materials (PCMs). *International Journal of Heat and Mass Transfer*, 182, 122017. DOI:10.1016/j.ijheatmasstransfer.2021.122017.

20 Gandhi M., Kumar A., Elangovan R., Meena C.S., Kulkarni K.S., Kumar A., Bhanot G., Kapoor N.R. (2020) A review on shape-stabilized phase change materials for latent energy storage in buildings. *Sustainability* (Switzerland), 12(22), 1–17. DOI:10.3390/su12229481.

21 Weng J., Huang Q., Li X., Zhang G., Ouyang D., Chen M., Yuen A.C.Y., Li A., Lee E.W.M., Yang W., Wang J., Yang X. (2022) Safety issue on PCM-based battery thermal management: Material thermal stability and system hazard mitigation. *Energy Storage Materials*, 53(September), 580–612. DOI:10.1016/j.ensm.2022.09.007.

22 He M., Xie D., Yin L., Gong K., Zhou K. (2023) Influences of reduction temperature on energy storage performance of paraffin wax/graphene aerogel composite phase change materials. *Materials Today Communications*, 34(October 2022), 105288. DOI:10.1016/j.mtcomm.2022.105288.

23 Zarrinjooy Alvar M., Abdeali G., Bahramian A.R. (2022) Influence of graphite nano powder on ethylene propylene diene monomer/paraffin wax phase change material composite: Shape stability and thermal applications. *Journal of Energy Storage*, 52(PC), 105065. DOI:10.1016/j.est.2022.105065.

24 Suyitno B.M., Anggrainy R., Plamonia N., Rahman R.A. (2023) Preliminary characterization and thermal evaluation of a direct contact cascaded immiscible inorganic salt/high-density polyethylene as moderate temperature heat storage material. *Results in Materials*, 19, 100443. DOI:10.1016/j.rinma.2023.100443.

25 Al-Gunaid T., Sobolčiak P., Chriaa I., Karkri M., Mrlik M., Ilčíková M., Sedláček T., Popelka A., Krupa I. (2023) Phase change materials designed from Tetra Pak waste and paraffin wax as unique thermal energy storage systems. *Journal of Energy Storage*, 64(October 2022). DOI:10.1016/j.est.2023.107173.

26 Mu M., McNally T. (2022) The effect of multi-walled carbon nanotubes on the thermo-physical properties of shape stabilised phase change materials for buildings based on high density polyethylene and paraffin wax. *Journal of Energy Storage*, 55(PC), 105601. DOI:10.1016/j.est.2022.105601.

27 Al-Haydari I.S., Al-Haidari H.S., Khudhur H.M.N., Jummah N.W., Al-Hamza M.A. (2021) Durability and aging characteristics of sustainable paving mixture. *International Journal of Engineering, Transactions B: Applications*, 34(8), 1865–1873. DOI:10.5829/ije.2021.34.08b.07.

28 Liu C., Xiao T., Zhao J., Liu Q., Sun W., Guo C., Ali H.M., Chen X., Rao Z., Gu Y. (2023) Polymer engineering in phase change thermal storage materials. *Renewable and Sustainable Energy Reviews*, 188, 113814. DOI:10.1016/j.rser.2023.113814.

29 Rahmalina D., Zada A.R., Soefihandini H., Ismail I., Suyitno B.M. (2023) Analysis of the thermal characteristics of the paraffin wax/high-density polyethylene (HDPE) composite as a form-stable phase change material (FSPCM) for thermal energy storage. *Eastern-European Journal of Enterprise Technologies*, 1(6 (121)), 6–13. DOI:10.15587/1729-4061.2023.273437.

30 Rolka P., Kwidzinski R., Przybylinski T., Tomaszewski A. (2021) Thermal characterization of medium-temperature phase change materials (Pcms) for thermal energy storage using the t-history method. *Materials*, 14(23). DOI:10.3390/ma14237371.

31 Firman L.O.M., Rahmalina D., Rahman R.A. (2023) Hybrid energy-temperature method (HETM): A low-cost apparatus and reliable method for estimating the thermal capacity of solid – liquid phase change material for heat storage system. *HardwareX*, 16, e00496. DOI:10.1016/j.ohx.2023.e00496.

32 Brütting M., Vidi S., Hemberger F., Ebert H.P. (2019) Dynamic T-History method - A dynamic thermal resistance for the evaluation of the enthalpy-temperature curve of phase change materials. *Thermochimica Acta*, 671(September 2018), 161–169. DOI:10.1016/j.tca.2018.10.030.

33 Yang B., Raza A., Bai F., Zhang T., Wang Z. (2019) Microstructural evolution within mushy zone during paraffin's melting and solidification. *International Journal of Heat and Mass Transfer*, 141, 769–778. DOI:10.1016/j.ijheatmasstransfer.2019.07.019.

34 Tang Y., Su D., Huang X., Alva G., Liu L., Fang G. (2016) Synthesis and thermal properties of the MA/HDPE composites with nano-additives as form-stable PCM with improved thermal conductivity. *Applied Energy*, 180, 116–129. DOI:10.1016/j.apenergy.2016.07.106.

35 Janghel D., Karagadde S., Saha S.K. (2023) Measurement of shrinkage void and identification of solid-liquid phases in phase change materials: Ultrasound-based approach and simulated predictions. *Applied Thermal Engineering*, 223(December 2022), 120048. DOI:10.1016/j.applthermaleng.2023.120048.

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