

Heat storage technology has a critical role for a number of applications involving renewable thermal energy (such as solar water heater). The application of wax (*n*-octacosane/OCT) as a medium for storing heat brings many positive influences for the system. However, the operational curve is undesirable for the OCT-based energy storage, which makes it necessary to use a binding material. The present work employed LD-class polymer (LDPE) and linear-LDPE as binding materials for OCT. The mixture is prepared through mechanical hot stirring, which comes into two categories: SOCT1 (OCT/LD) and SOCT2 (OCT/LLD). The assessment through the calorimetry method shows an increment in transition temperature for SOCT with a value of 2.1 °C and 5.5 °C. This contributes to the variation of fusion energy for solid-liquid change for both materials, which amounted to 132.05 J/g (SOCT1) and 113.4 J/g (SOCT2). Another assessment related to its chemical and structural phase demonstrates that SOCT has an identical structure to OCT, indicating that SOCT is mixed physically. At the operational level, SOCT is more optimal than OCT according to the indicator related to charge and discharge duration for energy exchange. SOCT1 demonstrates a short plateau line as the indication of a steady transition between 65.4–67.9 °C, while SOCT2 indicates the average heating rate, which is higher than for single OCT. The heat releasing curve for SOCT1 varies at a lower value between 1.92 °C/min and 0.77 °C/min, while SOCT2 has the lowest variation, which is only 0.17 °C/min. Moreover, the self-insulation for SOCT2 has the lowest rate, which is only 0.3 °C/min. The evaluation and analysis from this work show that SOCT is reliable to increase the operational curve of OCT and can be implemented for thermal systems

Keywords: binding material, *n*-octacosane, operational energy, phase transition, energy storage

EVALUATION OF THE OPERATIONAL CURVE FOR HEAT STORAGE TECHNOLOGY USING N-OCTACOSANE/LOW-DENSITY AS A BINDING MATERIAL

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1. Introduction

Continuous efforts for improvement come with a good example in wind energy technology, which is also supported by the improvement in the research process, resulting in a significant achievement according to the energy mix that comes from renewable sources. Providing heat from waste is also suitable [1], since thermal is considered as the highest energy demand [2]. The utilization of alternative fuel, which is also supported by several concepts of innovative burner, allows it to be taken as a reliable alternative heat source, particularly for remote areas. Alternatively, it can be supplied from solar thermal technology [3].

Fig. 1, *a* shows the typical pattern of operation at the supply and demand side in a thermal system without energy storage, while Fig. 1, *b* uses a storage device. The storage

allows the stored heat to be reused in the absence of solar supply [4]. The heat storage technology is heavily dependent on the operational aspect to maintain the optimum performance during operation. Maintaining the heat exchange operation is mostly focused on the utilization of the fin heat apparatus within the system [5] and utilization of an intermediate fluid [6]. The operation of transferring the fluid is done through the utilization of a positive displacement pump, including a gerotor pump [7], which is able to withstand under high-temperature operation.

The material of heat storage technology is in the development phase to ensure effective performance [8]. Combined sensible and fusion heat for the material significantly improves the cumulative storage capacity [9]. It helps to ensure a suitable volumetric and gravimetric storage capacity. The material is obtained from organic material, which has many

technical benefits [10]. However, the transition of the material during an effective heat exchange process is heavily unfavorable, due to partial transition. It makes the binding process for the material important to stabilize the transition [11]. The binding material is taken as an advanced approach to promote a desired level for the operation of heat storage technology as it exhibits stable phase change. Eventually, it increases the effective heat exchange rate for the system.

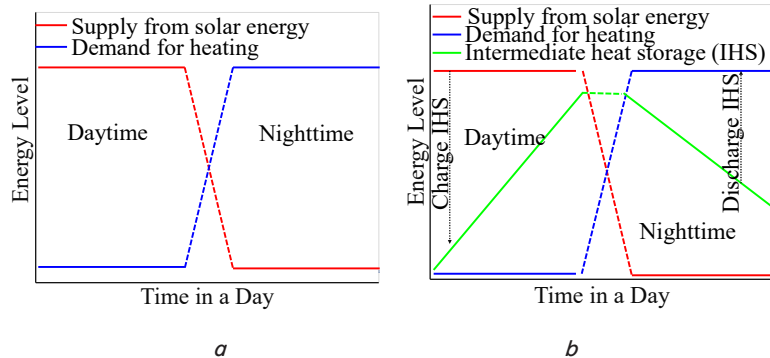


Fig. 1. Typical characteristic of thermal load:
a – without heat storage technology; b – using storage technology

The usage of binding material for the heat storage technology is extremely important, making it the most viable option to ensure effective storing and energy exchange for the system. The key problem is to find the most suitable option of the binder material. It is based on the nature characteristics of the binder material, which vary from one type to another. Research on utilizing binder material in heat storage technology is related to the development in the energy sector to support the transition and also for the improvement of heat and thermal technology. Thus, research in the given area is extremely relevant with the future direction for further development and recent trend to ensure sustainable improvement in the heat storage system.

2. Literature review and problem statement

The stabilization of the material in the heat storage device (HSD) has a crucial impact on maintaining the ideal performance of the system along with the heat transfer process. As proposed in [12], the stabilization of wax as a storage material with aerogel brings positive influences to maintain the effective charge duration, particularly through the photon-charge process. Positive outcomes can be drawn as a significant reduction in the average duration of heat update into the system. Specifically, the report in [13] utilizes a renewable source material (bio-based) as a binder for wax in HSD. The outcome is generally notable, according to the effectiveness of loading the stored heat, which is close to 100 %. However, the usage of bio-based material requires extensive processing, which is rather complex, and also the characteristics of raw materials may differ from different sources.

The modification of binder material, which comes from a monomer as the supporting structure can be considered a reliable option. The findings from [14] indicate that the swelling rate for the composite can be improved. Moreover, adding graphite contributes to the improvement of conductivity up to 120 %. A better approach is well discussed in [15] by

ensuring that the produced composite is obtained by a simple method using HDPE. The proper composition for the composite is suggested around 15 wt % to ensure suitable storage capacity. This is also supported by the consideration for large production as analyzed in [16], including the usage of graphite to accelerate the heat transfer rate. However, HDPE may be considered as a higher density compared to wax, which means that the volumetric ratio of the system may be changed distinctively [17]. Therefore, exploring another binder material, which comes from the polymer group, is extremely critical to provide a suitable composite material for thermal storing technology.

The approach to balance the density between the base material and its binder can be done using two different base PCM. As well evaluated in [18], HDPE can be combined by sugar alcohol class (D-mannitol) and also added graphite. It offers a better storage density at elevated temperatures. A better approach might be considered by introducing a different class of polymer, including low density (LD) and linear LD (LLD). The work [19] analyzes the usage of LDPE for wax and using nanofillers for building applications. The binder can work effectively to maintain the distribution of the filler. Nevertheless, the designed component is specifically proposed for building application, which has a low temperature gradient.

Another work utilizes LDPE for the thermal management of an electric battery system. The work [20] employed LDPE at a ratio of 4 wt % while the preparation is designed for high transfer rate operation. The positive influences of LDPE are also analyzed from various sources, including from packaging, which means that the binding material can be obtained from various sources [21]. Another approach is also taken by employing rubber to provide a flexible shape of the heat storage device [22]. The main attention is generally paid to using a complex composition, which makes the critical challenge still unresolved for introducing a better heat storage material.

The aforementioned paragraph explains clearly the urgency to obtain stable heat storage, using a polymer with relatively close density with the base material. The assessment on the polymer, including LLD is still required, without introducing another thermal enhancer within the system. Thus, the nature operation of the proposed approach requires further work, ensuring the effective operation of the heat storage to obtain possible operation with an LD-class polymer.

3. The aim and objectives of the study

The aim of the study is to produce a stable heat storage material using different LD-class polymers. This will help the researcher and energy engineer to explore various performance characteristics of the heat storage system with stable material. Moreover, the raw material of the LD-class polymer can be obtained from various sources, which means that the materials are widely available and ensures the readability of the material for large-scale production.

To achieve this aim, the following objectives are accomplished:

- to determine the heating and cooling profile of the base material and its composite using different LD-class polymers;

- to evaluate the impact of the composite formation according to physical and structural changes;
- to understand the cyclic ability under different discharge methods.

4. Materials and methods

The object of the study is the characteristics of OCT with different binding materials. The binding material was LD-grade polymers. OCT was paraffin, which is considered the base material for heat storage, and the binding materials were LDPE and LLDPE. The ratio of the base material was set at a higher value (85 wt %) while the binding material was set at rest. Thus, there were three sample categories in this work: OCT, SOCT₁ (OCT/LDPE) and SOCT₂ (OCT/LLDPE). The preparation of the composite was done by setting the binding material in the liquid phase separately in the oven. This was done to ensure the homogeneity of the liquid phase since the polymer has a higher transition temperature than OCT. The mixing of the liquid material was done according to the physical mixing process at the given ratio [23]. Then, the mixture was let to cool down at room temperature.

The fundamental assessment of the prepared sample was taken according to its thermal properties, chemical and phase structure. The assessment was used generally in the development of a composite for solid-liquid material in heat storage applications [24]. The thermal properties were evaluated using calorimetry to obtain the transition temperature and heat of fusion. The chemical and phase structure were assessed using infrared spectroscopy (FTIR) and x-ray diffraction (XRD) methods. According to the results, the addition of binding material can be observed in detail to analyze the performance change after using the binding material for OCT.

The material for HSD uses temperature as the main indicator. It is taken for evaluating the performance of the evaluated sample for charge and discharge. Charge assessment was taken following the energy-temperature approach [25]. In this process, the sample was heated at a constant heating rate, which was regulated by a heater controller (Fig. 2, *a*). The heater was fully covered with the evaluated samples. Thus, the sample was assumed to absorb the transferred heat from the heater without any loss. The temperature of the sample was recorded simultaneously throughout the entire process. This was done to assess the charge performance. For the discharge, two approaches were taken using air and water as cooling media. For the water, the heated sample within the container was placed in a cooling bath at 30 °C (Fig. 2, *b*). This leads to substantial temperature decrement of the sample, indicating the typical high rating discharge system. On the other hand, the slow discharge performance was evaluated based on forced air convection (Fig. 2, *c*). The inlet speed of the system was 2 m/s, allowing to observe the temperature drop at a lower rate for the system, which needs to be operated at a low discharge rate. In addition, the next evaluation was taken by locat-

ing the container at ambient temperature to determine the general heat losses. Thus, three possible discharge scenarios were obtained simultaneously from this work.

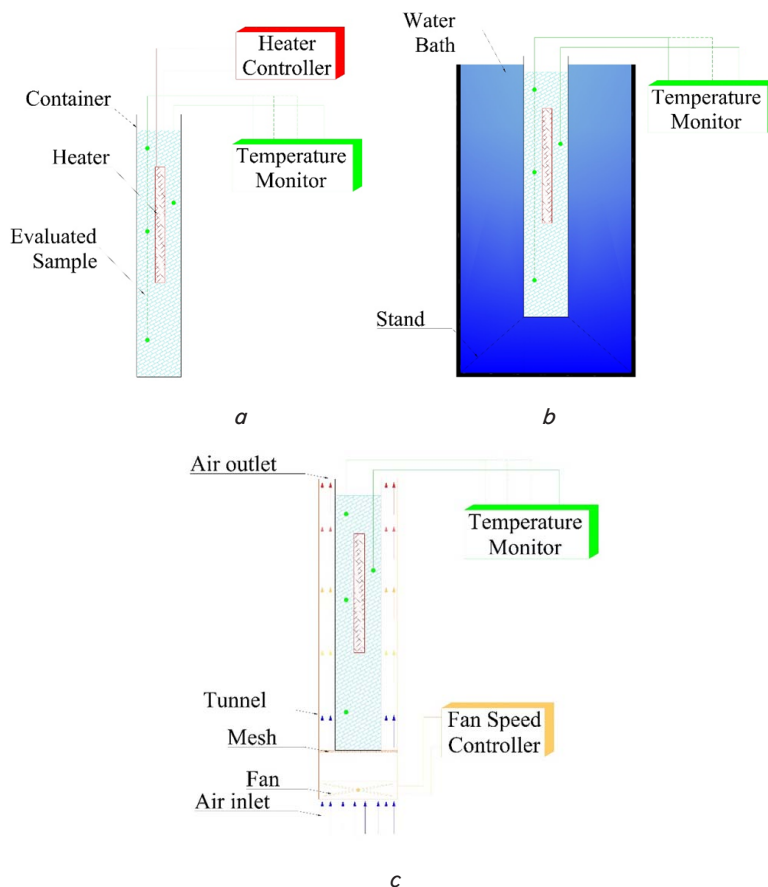


Fig. 2. Performance characterization of the evaluated sample: *a* – heating charge; *b* – water load test; *c* – forced air test

5. Results of performance characteristics of the evaluated material for heat storage technology

5.1. Results of heating and cooling characteristics between the base and its composite

The detailed heating characteristic of wax (OCT) and its composite is plotted in Fig. 3. The unique property of OCT causes two significant peaks, which can be analyzed according to the first solid transition and melting. The solid transition is found at 48.3 °C, which is much earlier compared to the principal curve that occurs at 62.8 °C. According to the plot, there is no new signal after the principal curve for OCT. An interesting result is seen for the two SOCT. First, there are significant changes in the principal curve for both composites. Also, a new peak is observed after the principal peak.

The change for SOCT results in a reduction of fusion heat. The solid-liquid fusion for OCT is achieved at 153.8 J/g, while each composite has a decrement around 21.75 J/g (SOCT₁) and 40.4 (SOCT₂). Despite that, the change in solid-liquid fusion is accompanied by a shift in the peak principal curve. Thus, the transition for SOCT₁ and SOCT₂ is 2.1 °C and 5.5 °C higher compared to OCT. It makes the clear influences for the presence of polymer for SOCT. The appearance of the third peak indicates the partial content of the polymer melt separately with the principal curve. Thus, the

melting characteristic of SOCT differs from OCT. The change is also observed for the cooling curve (Fig. 4).

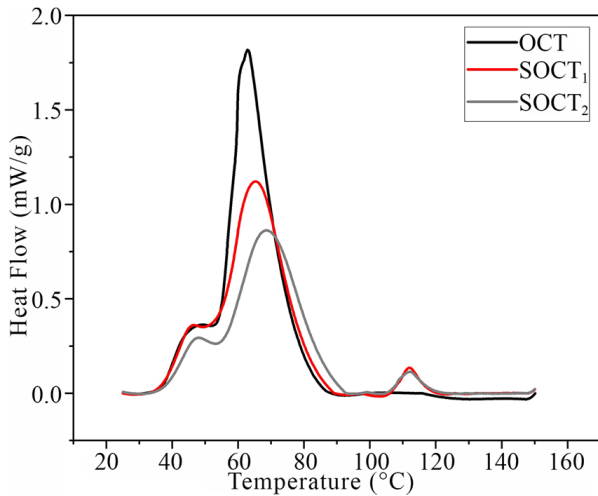


Fig. 3. Detailed heating characteristic from calorimetry profile for the base and composite

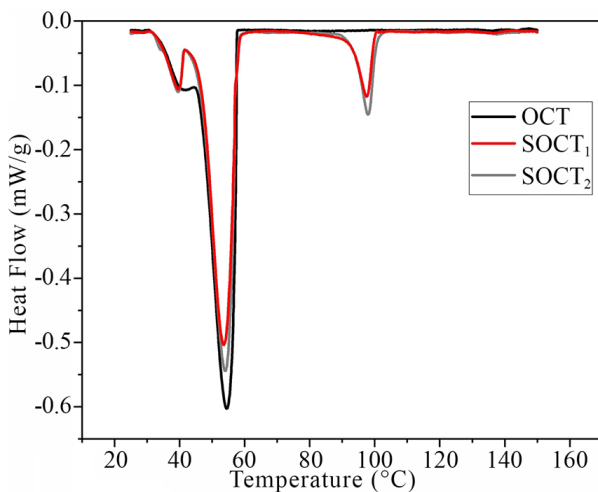


Fig. 4. Detailed cooling characteristic from calorimetry profile for the base and composites

The critical observation is drawn from Fig. 4 where the first curve of OCT is indicated by a continuous transition from the principal peak. In contrast, both SOCT confirms the initial decrement between the first and principal peak, causing a better freezing behavior according to this graph. The solidification behavior for SOCT can be concluded as a steady process, reducing the potential of the partial freezing process. Moreover, the principal curve of SOCT is relatively close to OCT, making a positive impact in the solidification process.

5. 2. Results of the impact of the composite formation according to physical and structural changes

The infrared spectrum for the sample is plotted in Fig. 5. The two-closed peak in the range of 2,950–2,800 cm^{-1} is defined as the stretching (vibrational) of $-\text{CH}_2$. The next signal is obtained around 1,475 cm^{-1} , which is taken as the deformation signal of the compound. The latter peak occurs in the fingerprint region due to rocking (vibration) of the chemical constituent within the material. The main information is

that SOCT and OCT have an exact pattern, indicating the formation of binding and base material only physically.

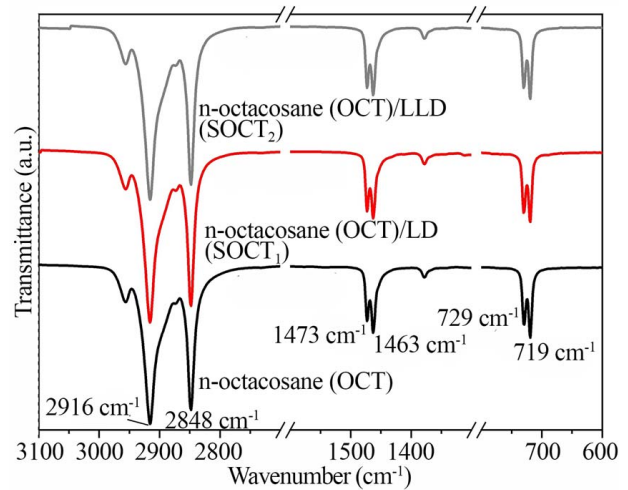


Fig. 5. Infrared spectrum for the observed base and composites

The phase characteristic is observed based on the intensity level. The pattern is plotted in Fig. 6. The main signal for all samples (OCT and SOCT) is only observed between 2θ of 20° and 25° . The peaks belong to n-octacosane (OCT) and the produced composites (n-octacosane and polymer) are identical. The signal is a highly sharp peak, indicating that the observed material has a good crystallinity. The next peak has no substantial value. Thus, the observed signal is only in the given region. The intensity results, which occur at relatively the same values between OCT and SOCT, indicating that both substances are mixed physically, strengthen the findings of the chemical spectrum according to FTIR.

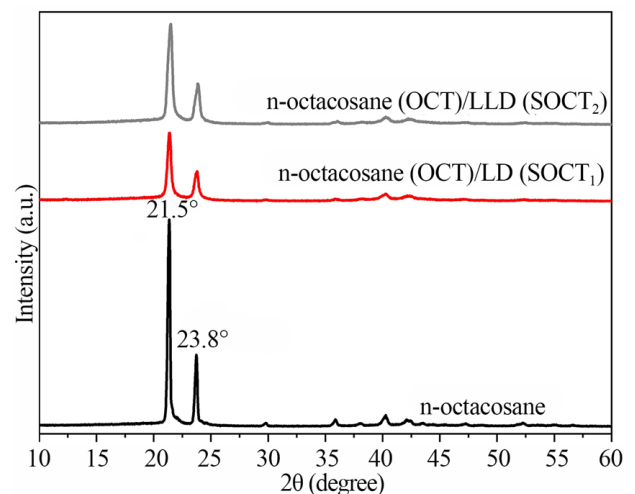
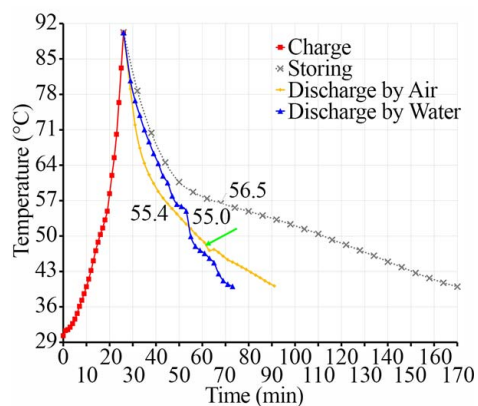


Fig. 6. Phase characteristic for the observed base and composites

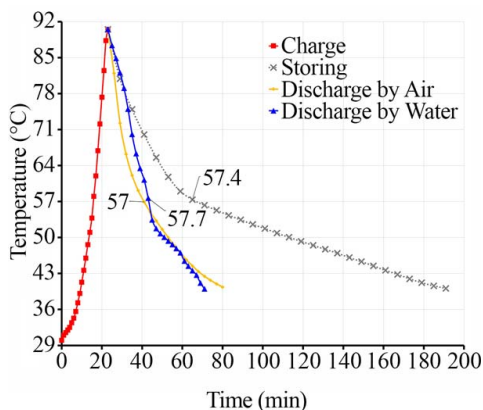
OCT (wax) is mainly derived from a saturated hydrocarbon compound. It has the identical chemical constituent of both polymers. This is the main reason why there is no substantial change for the SOCT and OCT pattern. This makes the mixture physically bonded, without altering the base chemical characteristic of the base and binding material.

5.3. Results to understand the cyclic ability under different discharge methods

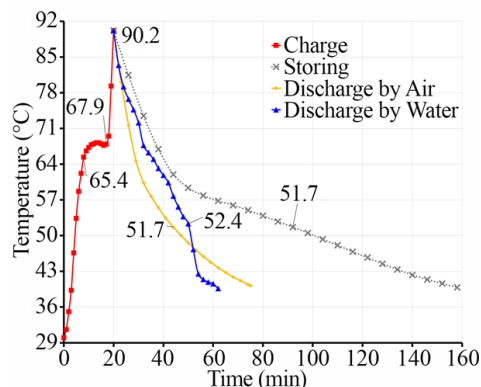
Fig. 7, *a* presents the compilation of the operational curve for OCT. The temperature intake indicates the continuous heating cycle without any indication of plateau profile. Thus, the heating process for OCT is merely as a direct phase change. The duration of the process is within 26 minutes. The ability to liberate the heat depends on the type of heat transfer mechanism. The discharge by water is done as the shorted duration, implying a suitable discharge process due to a better thermal load characteristic. The second process is done using forced air, as a result of which the process can be done within 65 minutes, which is 18 minutes longer than by water.



a



b



c

Fig. 7. Operation pattern with different discharge methods: *a* – base material; *b* – composite₁; *c* – composite₂

The key profile is observed during the storing stage. The heat is decreased rapidly before entering a temperature around 56.5 °C. The given temperature is the region with thermal disruption, which is also observed for water and forced air. This indicates that the freezing process of OCT is disrupted, causing the heat transfer rate to be decreased. It is the key point to compare the three-discharge method for observing the nature operation of the material for heat storage technology.

One interesting profile is observed for SOCT₁ (Fig. 7, *b*). The heating stage shows a short-flattened line between 65.4–67.9 °C. It can be assumed that the phase transition of the material occurs as a steady process. Despite that, SOCT₁ has a better duration than paraffin, which is faster by around 6 minutes. Also, the disruption is generally observed at a lower temperature, around 52 °C for SOCT₁ at the heat releasing stage. This can be seen clearly for the discharge by water and air. The profile implies that SOCT₁ has a better phase transition than OCT.

The operational aspect of SOCT₂ has an indication of continuous heating (Fig. 7, *c*). It is similar for the charge profile of OCT (Fig. 7, *a*). However, it has a faster charge rate by around 3 minutes, which means that the heat can be absorbed more effectively. The discharge profile has a temperature around 57 °C where the disruption occurred. As a result, the discharge duration between forced convection and water slightly differs (9 minutes). The performance demonstrates the effect of different binding materials that causes variation in the operational curve of SOCT₂. Moreover, it has the longest storing period compared to OCT and SOCT₁. Thus, the solidification mechanism under steady operation for SOCT₂ is much slower than for the two types of material for heat storage technology.

6. Discussion of the results of performance characteristics of the evaluated material for heat storage technology

The DSC signal in Fig. 3, 4 provides the essential information to understand the melting and freezing characteristics. The effect of polymer reduces the fusion of OCT, making it easier to melt and solidify. It is the critical aspect for the heat storage material to operate as it experiences phase change in the operation of the storage system [26]. The binding material, particularly for the polymer-based, reduced the potential of partial phase initiation. As a result, it maintains the effective heating/cooling cycle since the shrinkage effect can be minimized. The shrinkage effect contributes to the increment in the expansion ratio that also corresponds to the slow heating/cooling rate [27]. Therefore, the presence of binding material helps to mitigate the probability of void region within the tank.

The binding mechanism for the two substances is evaluated according to the chemical characteristic and phase profile. According to the result presented in Fig. 4, 5, there is no substantial variation for the base profile and composite. It strongly demonstrates that mixing occurs at the physical level. It is the main advantage since the nature of each material can be maintained at its fundamental level [28]. The binding material has a higher transition temperature, which protects the base material from poor phase initiation. Moreover, the physical change is clearly observed in the operational aspect for each SOCT.

The impact of unstable operation for OCT can be drawn according to the operational curve as presented in Fig. 7, *a*. The average rating for heating uptake is only 2.3 °C/min. It relates to the presence of solid transition before the melting stage for OCT (Fig. 3). Also, the severe operational aspect is observed distinctively operational during heat discharge. The average releasing rate under load is 1.92 °C/min and 0.77 °C/min for water and forced air convection, respectively. The value is decreased by more than 60 %, making it impossible to precisely set the flexibility of operation. It is the major issue that drives the utilization of various heat exchanger models within the storage system [29]. At the lowest rate, the average storing loss without any insulation for OCT is 0.35 °C/min. Thus, further insulation is required to ensure that the system is able to keep the optimum heat energy within the tank.

The detailed characteristic on the operational curve for SOCT₁ is already given in the charge profile, which indicates the short plateau line (Fig. 7, *b*). It is the most ideal condition for the heat storage system since the determination of the charge level can be set precisely [30]. This makes the positive influence from the binding material for OCT, which comes from LDPE. Also, the benefit of LDPE can be seen according to the deviation between water and forced air load, where the discharge rate decreases by 0.29 °C/min. It allows the discharge process of SOCT₁ to be managed according to the requirement, providing flexibility for various designs and operation of the thermal system. Unfortunately, the steady test for storing of SOCT₁ has a higher heat loss rate by about 0.015 °C/min than OCT. This may be caused by a rapid crystallization of LDPE, which initiates the nucleation growth for OCT as commonly found for the thermal enriched system [31].

A different operational curve is observed for SOCT₂. It has no plateau line according to the operational curve in Fig. 7, *c*. This is caused by a different melt/nucleation mechanism for LLDPE, which also influences the base material. It has a better heating rate than OCT where the average value is 2.63 °C/min. It is affected by the fusion rate for SOCT₂, which has a lower value than OCT. The key performance for SOCT₂ is achieved for the discharge rate. The deviation under thermal load for SOCT₂ was only 0.17 °C/min. This proves that SOCT₂ can be considered as the most stable cooling operation than SOCT₁ and OCT. Moreover, SOCT₂ has the lowest heat loss among the other evaluated samples where the average heat loss is only 0.3 °C/min. Thus, the presence of LLDPE substantially promotes a better self-insulation for the storage system.

The main benefit of the presence of binding material is the acceleration of the heating cycle. Both SOCT have a higher rating compared to OCT. This makes the proposed approach suitable for providing a faster charge cycle without causing a significant decrement in the volumetric capacity due to the presence of metal and thermal enhancer. A better self-insulation mechanism is achieved for SOCT₂ as LLDPE is able to maintain a slower heat loss for the storage. At the other point, the indication of plateau profile for SOCT₁ may

be considered a suitable choice for the precise charge protocol of the system.

The proposed approach for binding the base OCT (wax) with different polymers shows the substantial achievement to promote a better operational curve. However, there is another crucial issue regarding the fusion rate, which decreases as the system uses a polymer. This can be eliminated by providing a different polymer grade, which has a higher fusion rate, including the possibility for synthesizing a new polymer for the binding material of OCT in the next research. In addition, the study has limitations regarding the observation of the operational curve, which used the static process. Thus, there is still an opportunity to explore the operational behavior of the proposed material under active charge technology.

7. Conclusions

1. The addition of different LD-class polymers causes the same behavior regarding the shifting of transition temperature and decrement in heat of fusion, while minimizing the transition of the solid transition of OCT.

2. The phase characteristic between OCT and SOCT has an identical value 2θ at 21.5° and 23.8°, while the principal spectrum has the typical value according to the vibration of the main component for a hydrocarbon-based compound.

3. The highest heat loss is observed for SOCT₁, followed by OCT and SOCT₂ at 0.36 °C/min, 0.35 °C/min and 0.3 °C/min, while both SOCT have the lowest deviation of the discharge rate under thermal load, which is only 0.294 °C/min (SOCT₁) and 0.166 °C/min (SOCT₂).

Conflict of interest

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.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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