Novel Electric-Charge Thermal (NECT) Storage System for Integrated PV-Grid Liquid-Based Heating Supply Technology

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Abstract

Photovoltaic (PV) systems grow rapidly as one reliable solution to harvest solar power. The energy output of the modules can be directly used or partially stored to reduce the mismatch between supply and demand. However, storing the energy in electricity becomes one crucial factor due to the lifetime and cost of the battery. Meanwhile, typical solar water heating operates using bulk components (evacuated tube), which requires a sophisticated frame structure that increases the installation cost. In this work, the two challenges are addressed by introducing novel electric charge thermal (NECT). The model is developed as a thermal energy storage (TES) tank, which possibly stores the excess electric production from PV in the form of heat energy. The compact model of the tank operates with minimum components, while the charge operation can be monitored effectively. The temperature-specific energy performance (SEP) is plotted precisely, showing the continuous effect of phase behavior and energy level. Another crucial factor is also included in the maximum temperature output, which corresponds to the total energy percentage. The high charging rating reduces the duration, which significantly minimizes the heat losses, resulting in higher operation efficiency. The role of material within the tank and operational aspect is assessed in detail, providing a clear reference to integrate the electric-heat energy system in a better aspect.

Keywords: phase behavior, charge, metering, power rate, voltage

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1. Introduction

The key agenda for the energy transition comes from the risk of energy crisis and environmental impact. The transition faces immense technical challenges, including the development and regulation of technology, which requires considerable effort and time to achieve the goal of a mix of renewable energy [1,2]. The improvement of the method for the harvesting of renewable sources is the key to accelerating the transition [3–5]. Different solutions for solar energy harvesting are proposed, including the possibility of producing renewable heat [6] and electricity [7]. This results in astonished achievement regarding the commercial price of renewable devices, such as photovoltaic (PV), making the device applicable to supply energy on various production scales. Despite well-established renewable technology, the mismatch between supply and demand remains a major problem, especially for heat and electricity. To address the issue, energy storage is applied to balance supply and demand for the end user. The high solar radiation in the daytime is favorable for photovoltaic power production. The energy produced is partially stored through an electric battery for later use, connected to a pump for a pumped hydro system or even for electrocatalysis in a hydrogen plant [8]. An alternative storage model is also applicable for heating the heat-absorbed material (HAM) in thermal energy storage (TES).

The TES system has become one of the leading energy storage technologies in recent years [9]. It has many technical advantages, such as simplicity in the working principle, scalability, and flexibility, which meet the criteria of various heat-based energy systems [10]. The system can be integrated for power production in solar thermal plants, domestic water heaters, supporting crop production, and reducing the heating load for cold regions [11]. The system operates by physically storing heat in the HAM, which is released when necessary. The storage period can be extended for months, depending on the specific purpose. The storage capacity is enhanced by harvesting the latent heat of the HAM and combining it with sensible properties, resulting in a higher storage density.

The TES model is continuously improved to achieve a higher level of technology readiness. The improvement is generally performed for the HAM by introducing phase stabilization using a polymer or additional supporting matrix [12]. X. Li et al. synthesized a composite wax with HDPE, demonstrating a reliable solution to prevent leakage of HAM along with phase transition [13]. In terms of thermal response, solid additives are introduced to HAM as a solution for thermal enhancers [14]. M. Zhao and R. Yang added expanded graphite with a maximum ratio of 15 wt%, resulting in a suitable improvement in conductivity (up to $3.58 W \cdot m^{-1} \cdot K^{-1}$) [15]. The approach is generally taken to improve the operation ability from the HAM aspect within the TES system.

Modification is applied to the TES tank to provide sufficient energy interaction within the system. The tank basically functions as a heat exchanger, which involves fluid to perform energy transfer. B. Medjahed et al. developed a multitube heat exchanger for biobased HAM, and despite the application of numerous tubes within the system, the heat release stage was longer than the charge cycle as a result of solid HAM formation [16]. G. Feng et al. [17] numerically evaluated a novel multitube arrangement model incorporated with baffles and two HAM at different phase-change temperatures. The numerical model showed that the addition of baffles improves the charge quantity with a utilization rate of up to 85%. Another numerical analysis was conducted using crossing tubes in the TES tank, and it was concluded that the solidification rate could increase by more than 50% using the proposed model [18]. Previous works demonstrate the urgency to provide a robust solution to meet the operation of the TES tank due to the insufficient energy interaction and its relationship to the phase behavior of the HAM.

The root problem for the typical TES tank is considered as the operation of the working fluid to perform the charge cycle. It is affected by the typical energy input using a solar thermal collector to heat the working fluid before entering the TES tank [19–21]. In addition, numerous factors are involved, such as design variation, different HAMs and type of working fluid [22]. Changes in temperature operation alter the thermophysical properties of the HAM and working fluid [23], causing significant variation and challenges to maintain optimal performance of the TES system. Moreover, the variation makes the determination of the charge state relatively complex, resulting in various models, increasing the number of design considerations [24]. Charge estimation can be estimated using the temperature of the working fluid [25] and dynamic energy quantification [26], which requires the consideration of specific parameters and is highly variable from model to model.

Simplification of the TES tank is necessary and can be focused by introducing different charge methods. Alternatively, the execution of a direct electric-thermal charge concept can be considered an advisable solution [27]. The model referred to the direct use of photovoltaic electricity generation, which can be used to drive electric heaters for water heater systems, as discussed in this work [28]. The concept of TES was studied numerically by A. Szajding et al. as a viable solution to store excess electrical production from photovoltaics [29]. Y. Liang et al. studied direct charge HAM with photovoltaic energy for rural air heating, showing this option as a reliable solution with a suitable utilization ratio of around 81% with sufficient tilt angle [30]. In terms of thermo-economic assessment, this work [31] proposed an integrated photovoltaic solar thermal plant to accommodate the low temperature achievement of the TES tank.

Another technical challenge is related to the phase behavior for HAM, especially palmitic acid (PA). PA has an excellent melting enthalpy which is considerably higher than paraffin [32], beeswax [33] and inorganic salt [34]. Modification was performed for PA by forming an eutectic system and combined with graphite for excellent energy transfer [35]. However, the process significantly reduces the melting temperature and requires additional solid additive for the PA-TES. Different studies used polyvinyl butyral with carbon for the PA eutectic system, indicating significant achievements in phase stabilization [36]. Despite that, the system is designed to operate with a minimum temperature gradient, which makes different models required to accommodate the phase behavior of PA, especially for direct heating operation.

Previous studies imply the possibility of obtaining a simplified TES tank where the charge method is conducted through electric-heat conversion. However, there is still a research gap regarding the detailed temperature during charge and its relation to charge level, including how the system can be integrated into one compact model. From HEM, a suitable modification is required to adjust the phase behavior of PA and integrate it with the direct heating operation. Thus, the present work evaluates a new concept of a novel electric charge thermal (NECT) tank using the direct electric-thermal charge concept. The effect of power rating and different HAMs on the operation curve is analyzed by specific energy percentage (SEP) to indicate a clear basis for the operation behavior of the proposed tank.

2. Materials and Method

The 3D design for the NECT tank is shown in Fig. 1a. There are only three main parts for the proposed model: shell for locating the HAM, thermal charger for heating the material, and a discharge tube to release stored energy. The simplified design is desirable, as the system is more reliable for practical applications and manufacturing considerations. The shell can be made with various materials according to technical requirements and compatibility with HAM [37]. Thermal chargers are based on resistive heating that has reached the commercial stage and works with the highest electricity-heat conversion ratio [38], making it a considerably reliable and cost-effective technology. The discharged tube operates under typical shell-tube heat exchanger, where previous work [39] indicated that modification can be made by adjusting the contact ratio to enhance heat transfer. Thus, the three components have solid fundamental technical considerations to combine as a NECT tank.

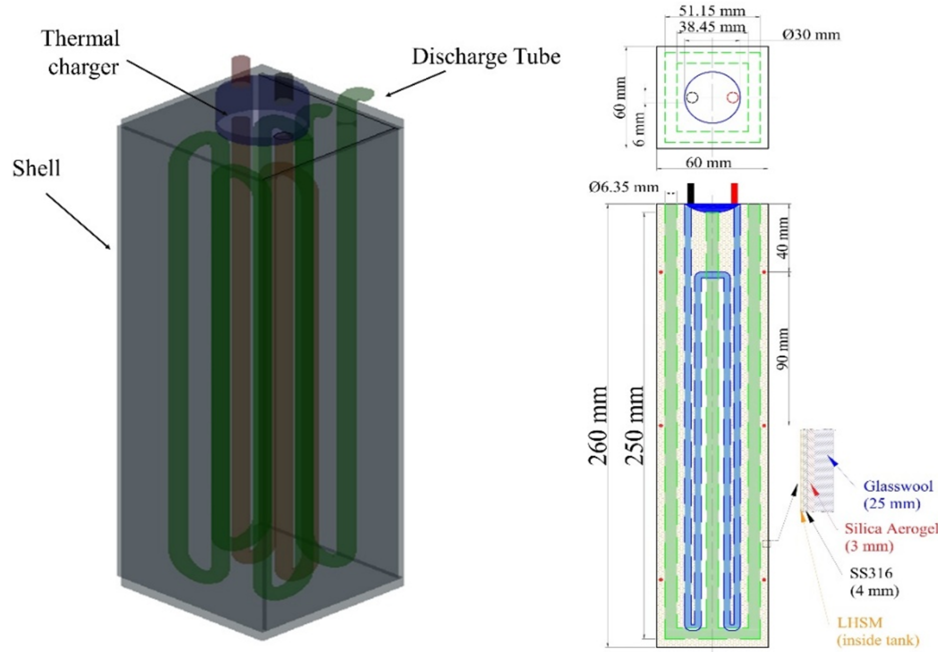

Figure 1: *The 3D model of novel electric charge thermal tank (a) and detailed dimension for evaluation (b)*

The dimension of the NECT tank in this work is presented in Fig. 1b. The thermal charger has a specific resistance of 12.2 Ω and an effective surface area of around 86.7 cm^2. The discharge tube (copper) has a thickness of 0.71 mm with eight straight passes to improve the overall heat transfer rate during the discharge stage. The shell was made of stainless steel (SS 316) considering its suitable mechanical properties and corrosion resistance. In addition, two external insulations (glasswool and silica aerogel) were added to enhance the insulation of the shell. It reduces the probability of heat loss to surrounding during the test. The aim was to reduce the potential heat loss during the charge stage. The dead volume of the shell was 842.5 cm^2. The typical HAM experience volumetric changes during the melting/solidification stage. Hence, the effective volume was around 95% of the dead volume (approximately 800 cm^2).

The operation of TES requires an energy interaction for the charge/discharge cycle [40]. Thus, an operation assessment was performed to evaluate the proposed NECT tank. As seen in Fig. 2, the charging process was relatively simple without a pumping system to heat the HAM. The NECT tank allows the charge stage to be effectively controlled and monitored using an electric metering device and a voltage regulator. In this work, the charge stage was performed using three power ratings (PR): 50 Watts (slow PR/SPR), 100 Watts (medium PR/MPR), and 150 Watts (rapid PR/RPR). It was achieved by regulating the input voltage to the heater (24.6 V for SPR, 34.8 V for MPR, and 42.6 V for RPR) with a maximum voltage variation less than 0.2 V. The total electric input for the charge process was recorded by the power meter (absolute error 1.7%), providing a specific amount of energy consumed throughout the process.

The temperature of HAM was measured at six locations within the NECT tank. The upper limit for charge was established at 100 °C. The stored heat was discharged using oil-based working fluid

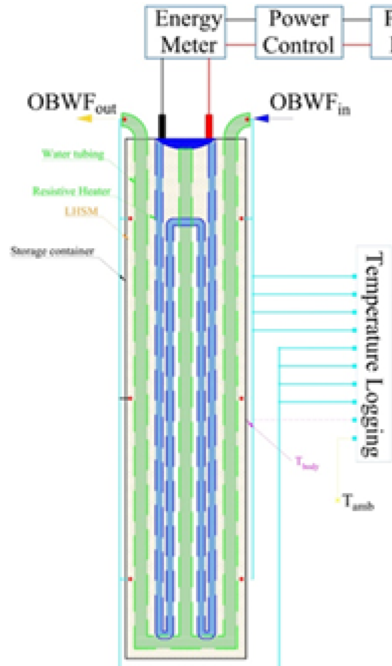

Figure 2: *Schematic model for the operation assessment of the NECT tank*

(OBWF, thermo-oil AT-400). The process was carried out by flowing the OBWF at a constant mass flow rate (20 g/s) and temperature (20 °C, ±1.5 °C). The evaluation was carried out using palmitic acid (PA) as the base HAM considering its high melting enthalpy (above 160 $J \cdot g^{-1}$). Furthermore, a modification was performed using 15 wt% polymer (LDPE/PAL and LLDPE/PALL). It was intended to improve the phase change characteristic for the HAM during the energy interaction cycle as a TES system. The detailed process of production and the structural characteristics of the HAM can be obtained from our previous work [41]. In addition, the power rating and the HAM variation were intended to provide a solid background on the interrelation between the operation assessment and storage material that simultaneously affect the performance of TES.

3. Results and Discussion

There is a clear impact on the effect of the power rating on the temperature evolution. As plotted in Fig. 3, the power rating influences the temperature increase for the HAM. The use of SPR (Fig. 3a) increases the effective temperature increase in the solid region of the HAM. It shows that the average increment varies significantly for each HAM. For example, PA reaches SEP 39.8% at temperature 60.5 °C, while at the same SEP the PAL and PALL already at temperature 69.4 °C. The deviation shows a slow heat intake that leads to partial melting within the HAM. It also affects the increase in SEP during the solid-liquid transition, where PA experiences a delayed melting stage that starts at 73 °C with 54.8% SEP while the PAL and PALL already exceeding the SEP above 60%. As a result, PA has the lowest SEP rate with only 1.08%/minutes while PAL and PALL slightly higher around 1.22%/minutes and 1.25%/minutes.

Fig. 3b shows that the increase in power rating makes the temperature evolution between PA and PAL relatively similar. The steady increase in SEP (around 20%) occurs at a closed temperature

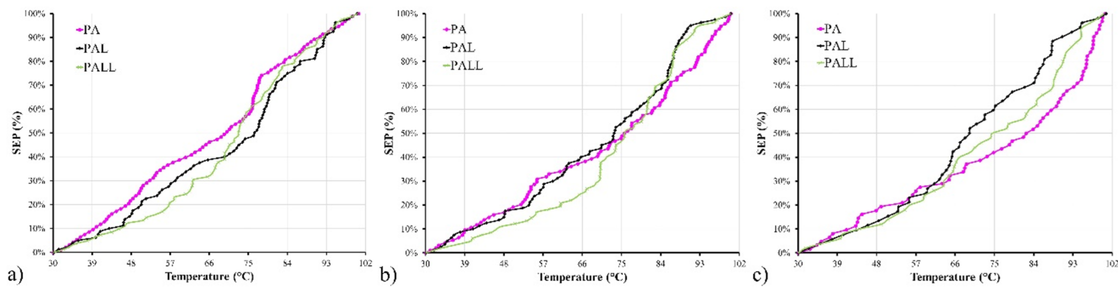

Figure 3: *The SEP versus temperature graph for the charge assessment*

at 51.9 °C (PA) and 52.3 °C (PAL). In contrast, PALL experiences a delayed transition which is observed after reaching SEP 30% at 70 °C. This implies that the transition is highly affected by the heating rate of the system to charge the HAM. Despite that, the temperature for PALL shows a steady increment, which makes the final temperature identic with PAL.

The SEP profile for RPR has a distinguishing result, particularly for PA (Fig. 3c). It has a slow temperature increase with minimum SEP rates. Compared with the previous rating, it seems that PA has the highest variation regarding the charge characteristic. It is a clear impact on the phase behavior of HAM affects the operation of the system, which makes the stable transition become advantages to ensure the effective operation. It can be observed for PA and PALL with a consistent specific rate. Despite the variation after passing the SEP 40%, both HAMs demonstrate a reliable profile that makes the curve operation preferable.

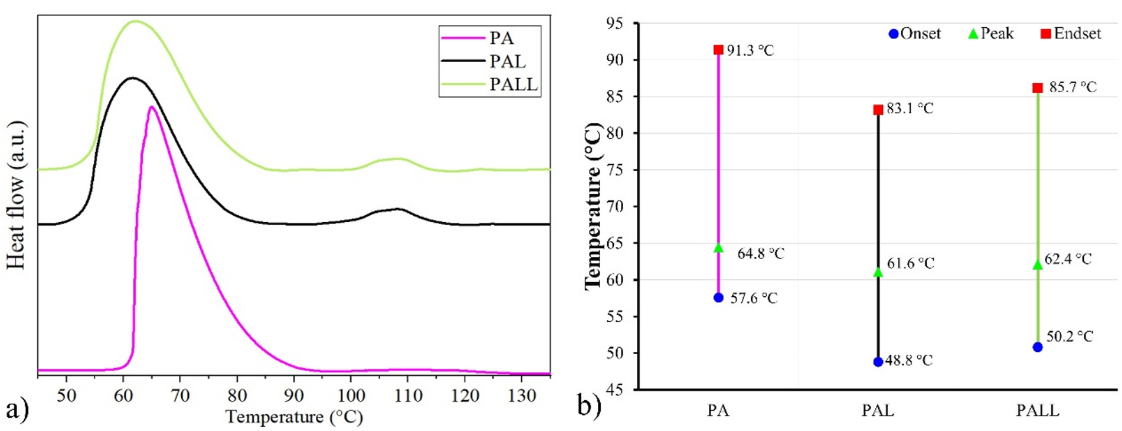

Figure 4: *Melting characteristic from DSC measurement (a) and detailed solid-liquid temperature transition (b)*

Changes in the SEP/temperature curve show a notable influence between the PA and its composite. It is also observed according to the melting characteristic from the differential scanning calorimetry (DSC) assessment (Fig. 4a). The peak indicates the solid-liquid transformation of the HAM. It shows significant changes between PA and its composite. The factor that contributes to the given phenomenon is the addition of plastic-based polymer, which has a different melting mechanism compared to that of PA. It promotes a steady phase transition, resulting in a steady melting stage, which helps to provide a better heat distribution, as observed in charge assessment (Fig. 3). Indicates a significant improvement in the transition between the onset and the maximum temperature (Fig. 4b). It reduces the deviation for the peak temperature and endset, implying that the phase transition becomes smoother. Thus, the phase behavior of the HAM also affects the operation assessment, which is justification for the use of different HAM.

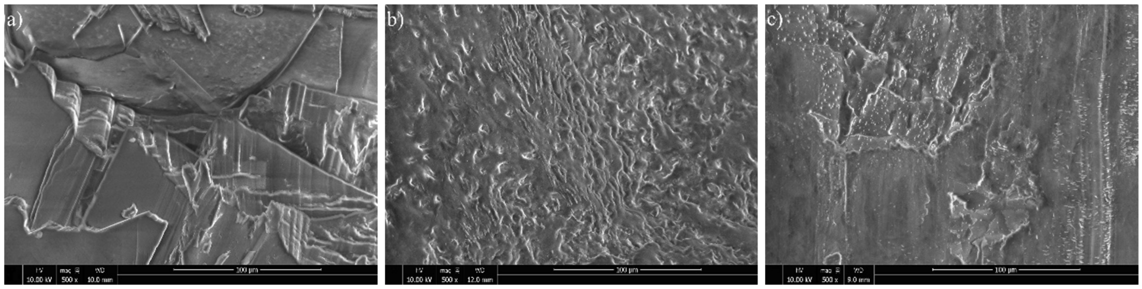

Figure 5: *Surface characteristic of the PA (a), PAL (b) and PALL (c)*

Changes in the melting mechanism can be assessed according to the SEM images presented in Fig. 5. The platelet morphology for PA (Fig. 5a) indicates the complex structure of long- and straight-chain fatty acids, resulting in a shorter melting transition before reaching its maximum peak transition temperature. Adding thermoplastic polymer provides additional physical bonding, which helps to ensure steady phase behavior. It can be observed notably between PAL (Fig. 5b) and PALL (Fig. 5c). The firm profile demonstrates that the polymer acts as a stabilizer to improve the solidification mechanism, especially for PALL (Fig. 5c), indicating the solid fraction without protuberance as appeared for PAL (Fig. 5b).

The stored heat is released to the OBWF, causing temperature elevation (Fig. 6a). The continuous interaction between the OBWF and HAM resulting in unsteady heat transfer behavior. It makes the temperature fluctuate significantly, which also corresponds to the nature of the freezing mechanism of the HAM. The maximum temperature of OBWF while using PA as HAM is 40.7 °C, which is relatively similar to that for using PAL (40.6 °C). The highest temperature output is achieved by PALL at 41.8 °C, confirming the impact of the excellent solidification mechanism to form a steady solid fraction as appeared in Fig. 5c. It is probably affected by various crystallization kinetics between PA and LLDPE, demonstrating that interaction between the two elements causes certain impact on the heat discharge performance. The high temperature gradient is observed for all HAM. It corresponds to a continuous heating stage since the designed tube arrangement circulates between the upper-lower zone that has different solidification rates. As a result, it disturbs the temperature outlet of the OBWF. The average temperature outlet for PA is 29.2 °C, and increases around 14.7% for PAL and 16.5% for PALL.

The temperature outlet of the OBWF is related to the temperature and state of the HAM within the tank. As presented in Fig. 6b, the temperature for all HAM reduces rapidly to 84 °C, and starts to slow after passing it. The short flat line in Fig. 6b demonstrates the phase transition which forms the liquid-solid interface within the tank. It affects the average heat transfer rate, making the heat absorbed insufficiently to the OBWF. The unsteady movement of the liquid fraction for PA causes the maximum discharge rate is only 0.74 °C/min, while the excellent freezing mechanism for PA and PALL able to improves the rate about 24.7%. It confirms the complex operation of the TES system, especially for using a convection heat transfer rate, since the operation is continuous affected by the multiphase region of the HAM, which leads to a different heat transfer rate as the phase of the HAM changes.

The discharge profile reveals the nature of the operation of a typical convective-based TES tank. The complex heat transfer process, which is linked to the type of working fluid, the state of the HAM, and the temperature, results in a high variation in the SEP rates. The proposed NECT tank

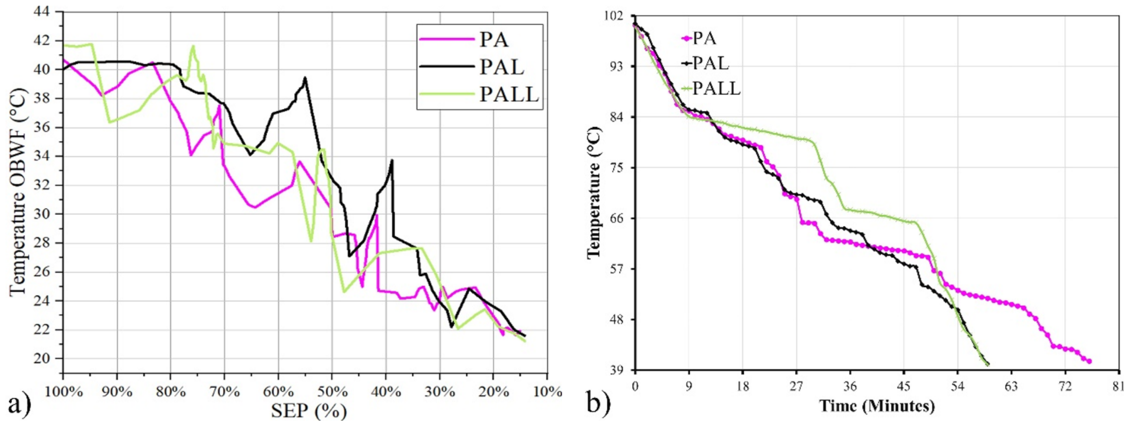

Figure 6: *Discharge profile based on temperature of OBWF (a) and HAM (b)*

uses direct electric heating that allows one to provide a uniform heating rate, potentially promotes a steady temperature increase within the tank, and helps to monitor the operation effectively. The effect of the multiphase region can be minimized by the presence of close contact between the HAM and the heat source.

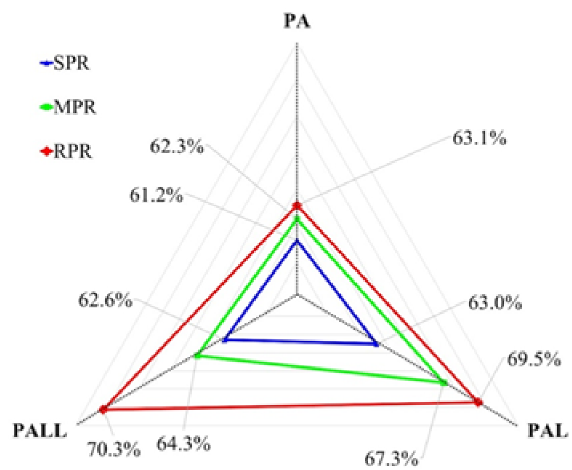

Figure 7: *The effective energy ratio for the NECT tank operation*

Fig. 7 shows the energy fraction for the NECT under different power ratings. The value is obtained by comparing the energy intake through the charge stage with the effective energy that can be harvested by the OBWF during the discharge cycle. Despite the tank being covered with insulation, some losses remain due to the charge process and the temperature difference with ambient. The usage of low power rate (SPR) can be observed, resulting in a lower effective energy ratio. Low heating rates can potentially increase the heat losses through the body of the tank and tube arrangement, making the effective energy much lower. In contrast, the rapid charge allows the system to reach maximum charge level in a shorter duration, minimizing the heat leakage to the environment, and improving the reliability of the system. In addition, the phase behavior of the HAM influences the effective energy ratio. The highest value is obtained by composite PA (PAL and PALL) as a result of the high discharge power ratio and shorter charge duration.

Eventually, the interconnection between the operation of the NECT tank and the HAM plays a crucial role, making further evaluation advisable to address this issue.

The discharge of heat with an OBWF also affects the effective energy extraction. The low conductivity of the fluid reduces the amount of heat that can be transported (Fig. 6). It proves the essential point of enhancing the conductivity of OBWF using various methods such as nanoparticles [42]. It indicates conductivity that is also essential to maintain the performance of the TES system. The method also provides positive improvement for the HAM as the higher conductivity allows the system to transfer heat in an effective manner, reducing the high variation for the charge cycle (Fig. 3). Adjustments in the operational aspect (heating rate and flowrate) eventually alter the temperature profile, which is essential to analyze by providing energy-temperature interaction for possible control automation. Moreover, various sources by combining photovoltaic energy and wind turbine as an electric source [43] are favorable to achieve smart grid system, while general back up can be supplied by low demand grid energy.

4. Conclusion

This work demonstrates the possibility of designing a simplification of the TES tank. The NECT shows that charge operation is possible using resistive heating. The process can be effectively controlled using a voltage regulator and metering device to observe the charge ratio. The present work reveals that the power rating and phase behavior of the HAM affect simultaneously the operation of the system. The minimum temperature transition is preferable to maximize the charge reading. It is also sufficient to ensure an effective discharge stage. The working fluid is effectively heated for the HAM which shows a stable freezing behavior. The combined factor results in a higher operational efficiency, showing the maximum values of 70.3%. The NECT tank is highly relevant to the development of alternative storage models for a photovoltaic system, possibly leading to a new concept to efficiently harvest electricity from the photovoltaic system.

The evaluation shows excellent innovation for applying NECT as a TES operation system. It opens up for new modifications that can be performed for future work. Modification of the heating surface is recommended to maximize the input energy from the source to the HAM and reduces potential losses. For the modified HAM, cyclic assessment and molecular simulation are essential to observe the degradation of the HAM over extended operation and its impact on the bonding between the polymer-HAM, including the possibility to assess different binder materials. In addition, an optional automation system can be developed to maintain ease of operation of the system and reduce the impact of seasonal change by combining various inputs into one integrated system. Thus, an advanced TES model can be achieved to support the energy transition.

Declaration of interest: The authors declare no conflicts of interest.

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