ABSTRACT

Over the last two decades, the use of renewable solar energy and industrial waste heat for electricity generation has dramatically surged. Using intermittent solar energy in place of conventional fossil fuels could introduce an energy supply-demand gap. However, the thermal energy storage (TES) system effectively bridges this gap by capturing solar energy during its availability and storing it for later use when solar energy is not available. In TES systems, phase change materials (PCMs) are widely used due to their high heat of fusion, making them an efficient and cost-effective energy storage solution. The PCMs store and release thermal energy during phase transition, depending on their melting temperature.

When considering the utilization of a PCM in a TES context, like in solar water heaters (SWHs), it becomes essential for the PCM's melting temperature to match the operational temperature of SWHs, which is around 65 °C. The contemporary PCM used for TES in SWH is paraffin, which possesses a melting temperature in the range of 50 °C to 60 °C. As a result, the maximum water temperature is limited to 60 °C, even when heat energy is supplied to the TES system at higher temperatures. Hence, an alternate PCM of choice would be OM65, with a melting temperature of 65 °C, which aligns well with the operating temperature of SWH. The OM65 PCM is a mixture of organic fatty acids with the potential to operate between 60 °C and 70 °C with good heat storage characteristics.

Nevertheless, similar to all PCMs, the OM65 possesses low thermal conductivity. In the present study, two strategies were employed and investigated to improve the thermal conductivity of the OM65 PCM. The first method is the use of highly conductive graphene nanoparticles (GNPs) at various mass fractions,

and the second method is the use of highly conductive copper wire (CW) structures with higher porosities. In the first strategy, three different weight fractions: 1 wt.%, 2 wt.%, and 3 wt.% of GNPs were dispersed in the base PCM. The resulting nanographene-enhanced PCM (NPCM) composites were named NPCM 1, NPCM 2, and NPCM 3, respectively, and they were characterized using various techniques.

The presence of GNPs in NPCM composites was confirmed through scanning electron microscope (SEM) and Raman spectroscopy. The Fourier transform infrared (FTIR) and x-ray diffraction (XRD) results showed that all three NPCM composites were chemically stable and had the same crystallinity as the base PCM. The test for thermal conductivity showed that the thermal conductivity of the PCM with 3 wt.% GNPs increased by 219.89% in the solid state and by 161.65% in the liquid state, with a 3.52% drop in latent heat capacity revealed from differential scanning calorimetry (DSC) analysis. Further, the DSC studies revealed that all the NPCM composites shared onset and peak melting temperatures similar to the base PCM. The addition of GNPs to the base PCM increased the viscosity of liquid NPCM composites, and the PCM and all NPCMs exhibited a decrease in viscosity with an increase in temperature. The density and specific heats for both solid and liquid states of PCM and NPCM composites were estimated, and the values were employed in numerical simulations.

The second method is the use of a conductive CW structure with varying porosities: 97%, 94%, and 91% with the PCM. These composites are named CW-PCM 1, CW-PCM 2, and CW-PCM 3, respectively. The effective thermal conductivity of CW structure enhanced-PCM (CW-PCM) composites was estimated, and the results indicated that decreasing the porosity of the CW structure led to a consistent and significant increase in the effective thermal conductivity of the CW-PCM composites.

Following the characterization study, numerical investigations on the melting behaviour of the PCM, NPCM, and CW-PCM composites were carried out using ANSYS-Fluent computational software by considering the temperature dependence of thermal conductivity and viscosity. The numerical study predicted a 16.67 %, 29.17%, and 37.5% reduction in melting time of NPCM 1, NPCM 2, and NPCM 3, respectively. Similarly, the melting time reduction for CW-PCM 1, CW-PCM 2, and CW-PCM 3 were approximately 13.3%, 33.33%, and 50%, respectively.

The numerical data of NPCM 3 and CW-PCM 1 composites were validated experimentally, and the results showed a positive linear relationship with a correlation coefficient of 0.99 and root means square (RMS) deviation of less than 10%, thereby indicating a satisfactory level of conformity. At higher loadings of GNPs in NPCM composites, the positive effect of increased thermal conductivity surpassed the negative effects of using nanoparticles such as increased viscosity, agglomeration and sedimentation. Increasing the GNPs beyond 3 wt.% would not significantly reduce the melting time of the PCM. Thus, it is recommended to use maximum of 3 wt.% of GNPs into PCM.

In the case of CW-PCM composites, numerical investigations were performed using effective thermal conductivity models. The results revealed a discrepancy in the liquid profile compared to the experimental study. This inconsistency may be attributed to the limitations of the effective thermal conductivity model in accurately predicting the specific liquid melting profile of CW-PCM 3. Hence, to overcome this limitation and improve the accuracy of the liquid fraction profile prediction, an actual 2-dimensional (2D) design model with local thermal non-equilibrium (LTNE) conditions can be used in numerical simulations. The K-type thermocouples are used for measuring temperature during experiments had a calibrated accuracy of ± 1.2 °C. The overall uncertainty associated with the experimental temperature measurement using thermocouples was calculated to be within ± 1.98 °C.

The numerical and experimental investigations showed that the dispersion of GNPs and incorporation of highly conductive, higher porosity CW structures into the PCM resulted in reduced melting duration. Overall, compared to the base PCM, both NPCMs and CW-PCMs exhibited higher melting rates, with NPCM 3 and CW-PCM 3 ranking the highest among them. For TES applications prioritizing faster melting rate, CW-PCM 3 could be the preferred choice despite the 9% reduction in latent heat capacity. However, applications requiring higher thermal storage capacity might benefit from other composite options. Thus, the aforementioned two thermal conductivity improvement approaches have been proven to be viable options for enhancing the heat transfer rate of PCM composites.