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ORIGINAL ARTICLE

Assessment of PCM-container interfacial heat transfer using a hot/cold probe technique

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Abstract

A novel technique for assessing heat transfer characteristics of salt-based phase change materials (PCM) was proposed here. The method is based on solution to inverse heat conduction problem. Nanoparticles (Graphite, Graphene, and multi wall carbon nanotube [MWCNT]) were dispersed in the PCM (KNO_3) to assess their respective influence on heat transfer in the PCM. Graphite added PCM offered highest heat flow values and heating rates, while the pure salt-PCM offered the least. The probe material had a significant influence on the heat transfer rates at the PCM-probe interface.

KEYWORDS
nanoparticles, PCM, thermal energy storage

1 | INTRODUCTION

In recent years, thermal energy storage (TES) systems have received considerable attention for their impact on cost-effectiveness and sustainability of concentrated solar thermal power (CSP) plants. The development of high energy phase change materials (PCMs) is crucial in the effective inclusion of TES systems in CSP plants. Researchers have used many characterization techniques such as differential scanning calorimetry, T-history method, etc to analyze the suitability of PCMs. Phase transition temperature, latent heat of fusion, specific heat capacity, thermal conductivity, etc are the major functions that define the suitability of a PCM for TES applications. These characterization techniques have certain inherent limitations such as small sample size in DSC and the need for a reference material in the T-history method. These limitations have been discussed in detail in the literature.[1,2]

Recently a computer-aided cooling curve method was introduced by Sudheer and Prabhu.[1] This method analyses the solidification path of PCMs while the sample cools. It falls short in obtaining information about phase transitions during the heating of the PCM sample.

Here, a novel technique based on solving an inverse heat conduction problem is proposed. A metallic probe instrumented with thermocouples is brought in contact with the PCM, and the heat transfer at the probe surface is estimated. This perspective is different from the conventional PCM characterization studies. It offers a better insight of ability of PCMs to receive heat compared with that attained from the computer aided cooling curve analysis (CACCA) technique where only the release of thermal energy is analyzed. In other words, this method assesses both the charging and discharging of thermal energy in a TES system.

The PCM used here is potassium nitrate salt (KNO_3) which melts at 335°C. Graphene, graphite, and MWCNT nanoparticles were dispersed into the salt-PCM to assess their influence on the heat transfer characteristics of the PCM.

2 | EXPERIMENTAL

In the current study, the salt-PCM (KNO_3) was mixed with the nanoparticles separately to study their respective effects on the TES parameters. The nanoparticles used were MWCNT (OD > 50 nm, ID 5-15 nm, and length 10-20 μm), graphite (400 nm and 50 μm), and graphene (thickness 1-5 nm) The nanoparticles were procured from Chengdu Organic Chemical Co Ltd, Chinese Academy of Sciences, and from Reinste Nanoventures, Delhi. The PCM mass was fixed at 1 kg for every trial into which the particle additives weighing 0.1% of the PCM weight were added. Nanoparticles were dispersed into the pulverized salt-PCM by thorough manual mixing.

Cylindrical probes of length 60 mm and diameter 12 mm (L/D of 5) were prepared of copper and stainless steel (SS) (type 304). The schematic sketch of the probe is shown in Figure 1. Axial holes of diameter 1 mm were drilled to the midplane of the probe to locate thermocouples during the experiment. Two series of experiments were performed. First, a probe at room

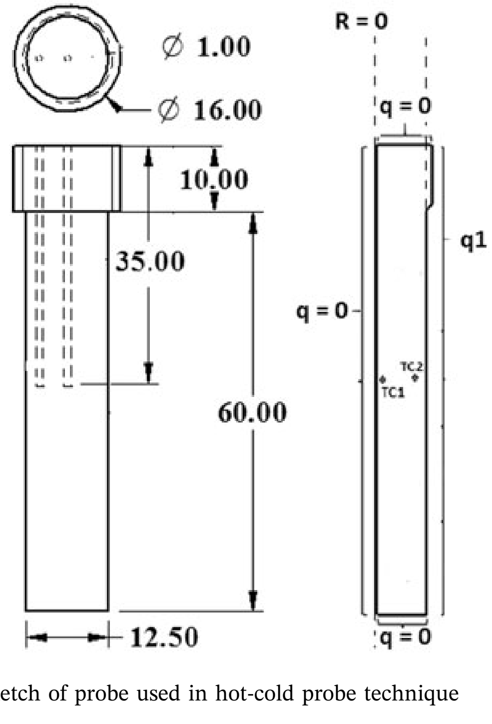

FIGURE 1 Schematic sketch of probe used in hot-cold probe technique

temperature (cold probe) was immersed into a pool of molten PCM held at 360°C. 1 kg of PCM was used in every experiment. This was followed by immersion of a hot probe (at 570°C) into finely pulverized PCM (at room temperature).

The probes were instrumented with two thermocouples of 1 mm diameter each. The probe temperature histories of probes were recorded in both the cases using a DAQ NI9213 device, and were processed to compute the heat flux transients at the probe-PCM interface. Figure 1 shows a 2D model of the probe. This model was used to estimate the unknown heat flux transient ($q1$) using a TmmFe inverse solver (Thermet Solutions Pvt. Ltd., Bangalore, India).

The model was meshed with 1-side graded four-nodded quadrilateral elements, resulting in 448 elements on discretization. Thermophysical properties such as thermal conductivity, specific heat, and density of probe materials (Cu and SS304) were used as input to the model. The boundary surfaces represented by $q = 0$ indicate insulated boundary condition. The temperatures measured by the near-surface thermocouples were assigned to locations TC (1), and TC (2), shown in the model.

3 | THEORETICAL BACKGROUND

The solution to inverse heat conduction (IHC) problem is used when the direct measurement of surface temperature and heat flux cannot be done using the conventional methods.

In the current study, a one-dimensional IHC problem was solved where the temperature data recorded from locations within the probe is used to analyze heat conduction within the probe and, the subsequent heat flux transients at the probe-PCM interface. A nonlinear estimation technique [5] was used here.

The one-dimensional transient heat conduction equation in cylindrical coordinates given below was solved inversely.

$$\rho \mathrm{Cp}\frac{\partial T}{\partial t} = \frac{k}{r}\frac{\partial\left(r\frac{\partial T}{\partial r}\right)}{\partial r} \tag{1}$$

where,

k is the thermal conductivity of the probe material, W/m·K

ρ is the density of the probe material, kg/m^3

C_p is the specific heat capacity of the material, J/kg·K

In this inverse technique, the surface heat flux density is estimated from the knowledge of measured temperatures inside the probe. This is done by minimizing function,

$$F(q) = \sum_{i=1}^{\mathrm{mr}} \left(T_{n+1} - Y_{n+1}\right)^2 \tag{2}$$

where, $\boldsymbol{r}$ is the number of future time temperatures $(n) + 1$, and $\boldsymbol{m} = \frac{\Delta\theta}{\Delta t}$. $\Delta\theta$ and Δt are the time steps for heat flux and temperatures, respectively, Y_{n+i} and T_{n+i} are measured and calculated temperatures, respectively, at locations near to the surface where the boundary condition is unknown.

Applying the condition $\frac{\partial F}{\partial q} = 0$ on Equation (2) for minimization, the correction for the heat flux (Δq) at each iteration step is estimated. This procedure is continued until the ratio $(\frac{\Delta q}{q})$ becomes less than 0.001 (convergence limit). This procedure simultaneously yields the

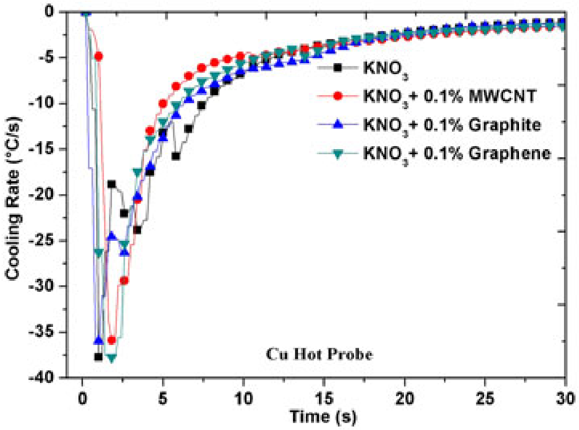

FIGURE 2 Cooling rate curve of Cu hot probe when immersed in various PCM composites. PCM, phase change materials [Color figure can be viewed at wileyonlinelibrary.com]

temperature of the specimen surface in contact with the PCM and the interfacial heat flux. The mathematical details of the inverse heat conduction problem are given in the references.[3,4]

4 | RESULTS AND DISCUSSION

The performance of nano PCMs during charging and discharging of thermal energy was assessed by analyzing the temperature gradients within a cylindrical metallic probe which is brought in contact with the PCM. The probe-PCM control experiment is a stand-in for a container-PCM unit in a TES system. The influence of thermophysical properties of the container material over the effectiveness of TES systems, along with modified PCMs was analyzed here. Copper and SS were chosen as they are industrially used in storing salt-PCMs.

Both the sets of experiments were performed, and the respective thermal history was obtained. A typical cooling rate and heating rate curves of Cu probe are shown in Figure 2 and in Figure 3 respectively.

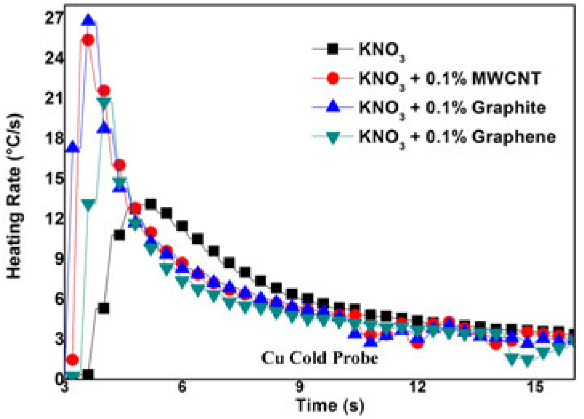

FIGURE 3 Heating rate curve of Cu cold probe when immersed in various PCM composites. PCM, phase change materials [Color figure can be viewed at wileyonlinelibrary.com]

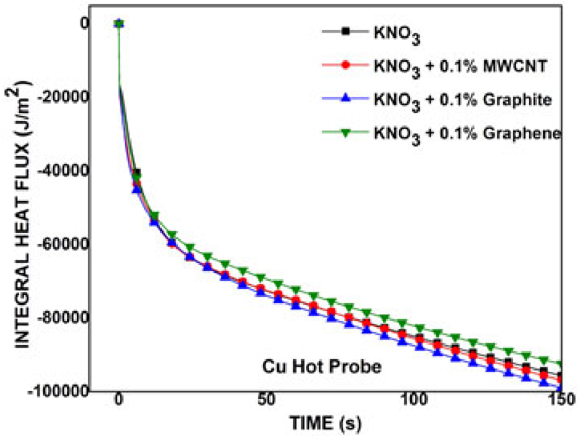

FIGURE 4 Integral heat flux curve of Cu hot probe when immersed in various PCM composites. PCM, phase change materials [Color figure can be viewed at wileyonlinelibrary.com]

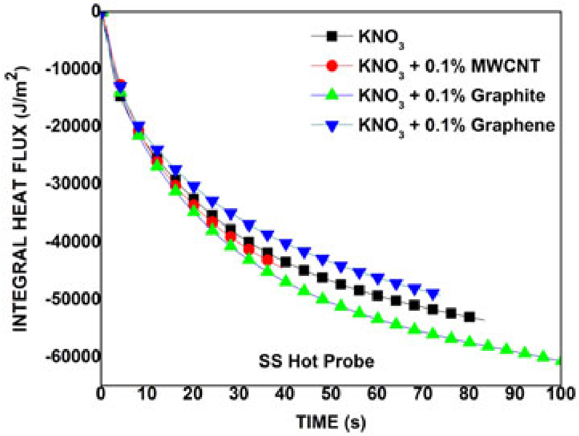

FIGURE 5 Integral heat flux curve of SS hot probe when immersed in various PCM composites. PCM, phase change materials; SS, stainless steel [Color figure can be viewed at wileyonlinelibrary.com]

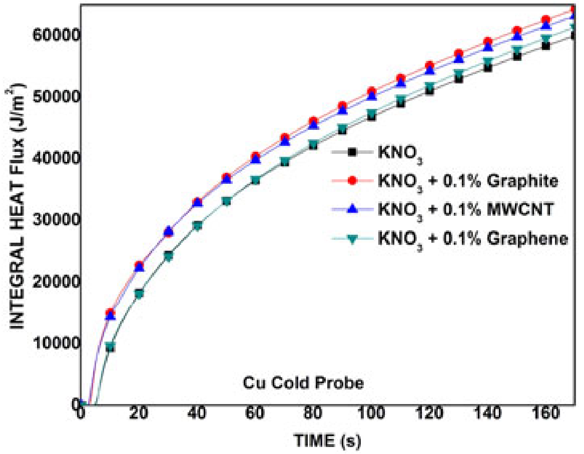

FIGURE 6 Integral heat flux curve of Cu cold probe when immersed in various PCM composites. PCM, phase change materials [Color figure can be viewed at wileyonlinelibrary.com]

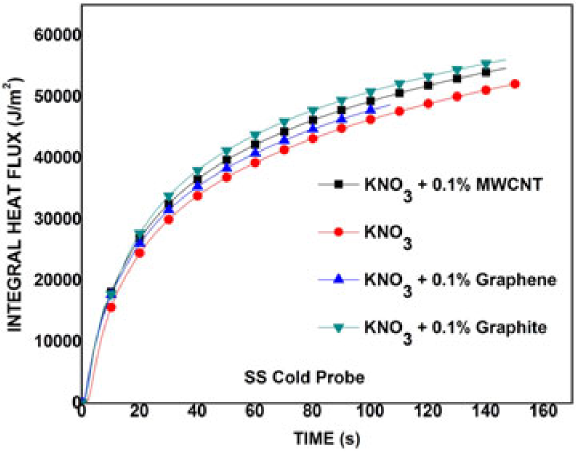

FIGURE 7 Integral heat flux curve of SS cold probe when immersed in various PCM composites. PCM, phase change materials; SS, stainless steel [Color figure can be viewed at wileyonlinelibrary.com]

Heat flux at the probe surface (probe-PCM interface) was estimated. The integral heat flow curves of both hot and cold probes are shown in Figures 4–7.

In a cold Cu probe, higher peak heating rates were observed when immersed in molten nano-PCMs compared with that in molten KNO_3 (pure PCM). As shown in Figure 3, the highest heating rates were observed when the probe was immersed into nano-PCM with graphite nanoparticle additives. Pure PCM offered the least heating rates. The substantial increase in the heating rates is attributed to the significant decrease in the solidification time of the PCM samples on addition of graphite nanoparticles as observed by Sudheer and Prabhu.[6] PCM with graphite additives offered an increase in heating rates by 116%, while MWCNT and graphene added PCM offered an increase of 100% and 65%, respectively.

The increase in peak heating rates observed in an SS probe on nanoparticle addition is less compared to that observed in a Cu probe. It indicates that a container material with superior thermophysical properties offers an easy path for heat transfer offering higher heat transfer rates.

On the contrary, in hot probe experiments, the cooling rates were not affected by the addition of nanoparticles. Both Cu and SS probes showed negligible increase in the cooling rates when immersed in nano salt-PCM. On contact with the hot probe surface, a thin layer of PCM would melt instantly. As salt-PCMs have a negative coefficient of thermal expansion, an air gap is developed at the probe-PCM interface. These air gaps can considerably reduce the charging rates of PCM. Another cause for this is the formation of oxide layers at the probe surface. Oxide layers form on the probe surface as the probes were raised to temperatures above 500°C. The formation of an oxide layer on the probe surface would increase thermal contact resistance retarding the heat transfer rates at the probe-PCM interface.

Integral heat flow curves were plotted. In cold probe experiments, the PCM with graphite additives offered the highest heat flow values over a period of time into both the Cu and SS probes. As the graphite added PCM had the lowest solidification time[6] they offered thermal energy absorption at higher rates. In a span of 100 seconds, Cu probe absorbed 9% more heat energy from graphite added PCM compared to that from the pure PCM.

The differences in the heat flux across the probe-PCM interface were more prominent in cold probe experiments with SS probes. SS probes have higher thermal energy storage capacity compared with that of a Cu probe of the same volume. Although the rates of heat absorption is less as mentioned above, the total heat flow into an SS probe is more compared to that in a Cu probe.

A similar trend was observed in hot probe experiments where the difference in the integral heat flow curves were more prominent in SS probe compared to that in a Cu probe, with graphite added PCM offering highest integral heat flux values followed by MWCNT and graphene added PCM, and the pure PCM.

Heat flux curves indicate that the initial rates of heat transfer into the probes (cold probe) is very much influenced by the thermophysical properties of the probe material. The probe material does have a crucial influence on the energy exchange between the HT fluids and the PCM. Cu with higher thermal conductivity and thermal diffusivity offered higher rates of heat transfer initially, which diminished with time. In contrast, SS with higher heat capacity and lower thermal diffusivity and conductivity offered more heat transfer over the large period of time. Both heat capacity and thermal diffusivity play a pivotal role in the selection of container material for PCM storage.

Thermal cycling had a deleterious effect on the integral heat flow curves. Thermal cycling affected the performance of graphite added PCM the most, and the graphene added PCM was affected the least. Graphite nanoparticles were found to agglomerate to a maximum extent on thermal cycling.

5 | CONCLUSION

The following conclusions were drawn from the present investigation:

- The proposed hot-cold probe technique is suitable for assessment of heat transfer characteristics at the PCM-container interface.
- Cu probe offered higher heating rates compared with SS probes, indicating that the container material with superior thermophysical properties offer an easy path for heat transfer.
- The addition of nanoparticles enhanced the heat flow at the probe-PCM interface. Graphite added PCM offered highest heat flow at the probe-PCM interface as observed in integral heat flow curves.
- Integral Heat flow curves indicate that thermophysical properties such as specific heat capacity and thermal diffusivity property play a significant role in the selection of container materials for PCM storage.

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