# CHAPTER 5

# THERMOPHYSICAL PROPERTIES AND THERMAL PERFORMANCE ANALYSIS OF MWCNT BASED ORGANIC PCMS TES SYSTEM USING T-HISTORY METHOD

The present chapter is broadly divided into three sections. The first section briefly describes the experimental setup, procedure, and empirical correlations for conducting the experiments through the T-History method. The second section evaluates the thermophysical properties and their comparisons for multiwall carbon nanotubes (MWCNT) based on capric acid, lauric acid, paraffin wax, and stearic acid nano-enhanced phase change materials (NEPCMs) using the T-History method. Furthermore, thermal performance comparisons of MWCNT-based organic NEPCMs-based TES systems have been examined and discussed in the last section.

Generally, multi-walled carbon nanotubes (MWCNT) have a regular hexagonal structure and have no functional group or other bonds. The surface modification of MWCNTs is an approach that reduces surface resistance and improves the interaction between MWCNTs and the base fluid/PCM. Therefore, the thermal conductivity of the nanofluid can be increased by surface modification of CNTs. Among the CNT types, single-walled carbon nanotubes have an almost negligible effect on the increasing thermal conductivity. As already mentioned, MWCNTs with smaller diameters have a lower contact area, leading to increased thermal resistance and decreasing thermal conductivity.

## 5.1. About T-History Method

The T-History method is a very conventional, simple, inexpensive, fast, and helpful method for measuring the thermophysical properties of any pure or additives-based materials. The standard tools such as differential scanning calorimetry (DSC) and differential thermal analysis (DTA) are limited to small material samples which need a high precision sampling of the material. (Zhang and Jiang, 1999) proposed the T-History method. Thermo-physical properties such as latent heat of fusion, specific heat (liquid/solid), and thermal conductivity (liquid/solid) of actual bulk PCM with or without additives were calculated by the T-History method without sampling steps. The lumped capacity method must fulfill the reference material (Bi<0.1). In this method, two vertical test tubes are required. The first test tube was filled with the melted PCM at a constant temperature bath higher than PCM's melting temperature. However, the second test tube was filled with distilled water as reference material. Afterward, both the test tubes were removed from the bath and cooled in the surrounding. The temperature measuring devices recorded the temperature profile of materials and surrounding test tubes.

Three areas are observed between the PCM and ambient air temperature profiles based on these temperature profiles. These areas are indicated as the liquid, liquid-solid, and solid zones. Similarly, these areas also represent the reference material for PCM. However, by putting the values in given empirical equations (Eqs.5.1-5.6), the thermo-physical properties were calculated through simple mathematical calculation.

### 5.1.1. Procedure and types of equipment used in the T-History method

Fig.5.1 shows a schematic diagram of the experimental setup. The experimental setup consists of glass test tubes, a borosilicate beaker, a hot plate magnetic stirrer and PT100 type thermocouples, a digital temperature display meter, and a stopwatch. Table

.5.1 shows the specification of the experimental instruments. Also, Table 5.2 and Table 5.3 show the accuracy of instruments and maximum uncertainties of parameters, respectively. In this experimental study, the pure and MWCNT-based PCMs/NEPCMs were filled in glass test tubes at ambient temperature. A borosilicate beaker filled with water as HTF is heated from 20°C to 80°C with the help of a hot plate magnetic stirrer. The loaded test tubes with the vol. fraction of 0, 0.01%, 0.02%, and 0.025% MWCNT-based CA, LA, PW, and SA composite PCMs have been placed in this borosilicate beaker. With the help of a PT100 coupled to a digital temperature display meter, the temperature of the TES system was recorded. Furthermore, the charging and solidification temperatures of PCMs/NEPCMs have been recorded at a time slot of every 3min and 5min. The temperature variation range of PT100 is from -200°C to 850°C. Furthermore, the vol. fraction range with 0, 0.01%, 0.02%, and 0.025% MWCNT based CA, LA, PW, and SA composite PCMs have been prepared by the one-step method. The samples of vol. fraction within the range of 0-0.025% MWCNT-based CA has been presented in Fig. 5.2.

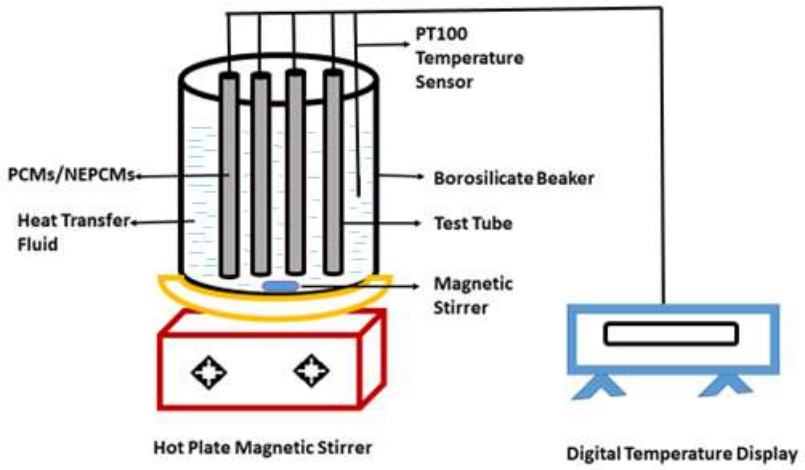


**Fig.5.1.** The schematic diagram of an experimental setup


**Fig.5.2.** Samples of MWCNT based Capric acid NEPCM

**Table 5.1:** Specification of the experimental instruments

| Parameters | Diameter (m) | Length (m) | Sp.heat capacity (kJ/kgK) | Thermal conductivity (W/mK) | Density ($kg/m^3$) |
|---|---|---|---|---|---|
| **Borosilicate breaker** | 0.145 | 0.185 | 0.8 | 1.2 | 223 |
| **Glass test tube** | 0.02 | 0.18 | 0.8 | 1.2 | 223 |

**Table 5.2:** Accuracy of Instruments

| Instrument | Value |
|---|---|
| Stopwatch | ±0.2% |
| Digital weighing machine | ±0.4% |
| Measuring flask | ±0.3% |
| Thermocouple | ±0.5°C |

**Table 5.3:** Calculated maximum uncertainties

| Parameters | Uncertainties |
|---|---|
| Temperature | ±1% |
| Mass m | ±0.8% |
| Area A | ±0.14% |
| Specific heat capacity | ±2.1% |
| Thermal conductivity | ±2.7% |
| Heat of fusion | ±3.4% |
| Heat transfer coefficient | ±1.2% |
| Heat transfer rate | ±1.6% |

### 5.1.2. Equations used for the T-History method

The specific heat capacity of solid-phase PCMs/NEPCMs is expressed by the T-History method (Zhang and Jiang, 1999);

$$c_{ps} = \frac{m_w c_{pw} + m_t c_{pt}}{m_{pcm}} \times \frac{A_3}{B_2} - \frac{m_t}{m_{pcm}} \times c_{pt} \tag{5.1}$$

The specific heat capacity of liquid phase PCMs/NEPCMs can be expressed by the T-History method (Zhang and Jiang, 1999);

$$c_{pl} = \frac{m_w c_{pw} + m_t c_{pt}}{m_{pcm}} \times \frac{A_1}{B_1} - \frac{m_t}{m_{pcm}} \times c_{pt} \tag{5.2}$$

The thermal conductivity of solid-phase PCMs/NEPCMs can be expressed by the T- History method (Zhang and Jiang, 1999);

$$k_s = \left[1 + \frac{c_{ps}}{h_{ls}} \times (T_m - T_w)\right] / 4 \left[\frac{t_f}{\rho_p R^2 h_{ls}} \times (T_m - T_w) - \frac{1}{h_w R}\right] \quad (5.3)$$

The thermal conductivity of liquid phase PCMs/NEPCMs can be expressed by the T- History method (Zhang and Jiang, 1999);

$$k_l = \left[1 + \frac{c_{pl}}{h_{ls}} \times (T_m - T_w)\right] / 4 \left[\frac{t_f}{\rho_p R^2 h_{ls}} \times (T_m - T_w) - \frac{1}{h_w R}\right] \quad (5.4)$$

The latent heat ($h_{ls}$) of the pure form of PCMs shown by the T-History method (Zhang and Jiang, 1999);

$$h_{ls} = \frac{m_w c_{pw} + m_t c_{pt}}{m_{pcm}} \times \frac{A_2}{B_1} \times (T_o - T_s) \quad (5.5)$$

The latent heat ($h_{ls}$) of NEPCMs is shown by (Zhang and Jiang, 1999);

$$h_{ls} = \frac{m_w c_{pw} + m_t c_{pt}}{m_{pcm}} \times \frac{A_2}{B_1} \times (T_o - T_s) - \frac{m_t c_{pt}}{m_{pcm}} \times (T_{f1} - T_{f2}) \quad (5.6)$$

Where $T_{f1}$ and $T_{f2}$ are the temperature ranges during the phase-change process.

### 5.1.3. Solidification profile of PCM/NEPCMs

The solidification profile of pure LA, PW, and SA phase change materials with the additive MWCNT by vol. fractions of 0.01%, 0.02% and 0.025% have been shown in Figs. 5.3(a-d). Results revealed that 0.02% vol. fraction MWCNT in CA, LA, PW, and SA composite phase change materials required 360 sec, 420sec, 600sec, and 900sec less time than LA, PW, and SA phase change materials.

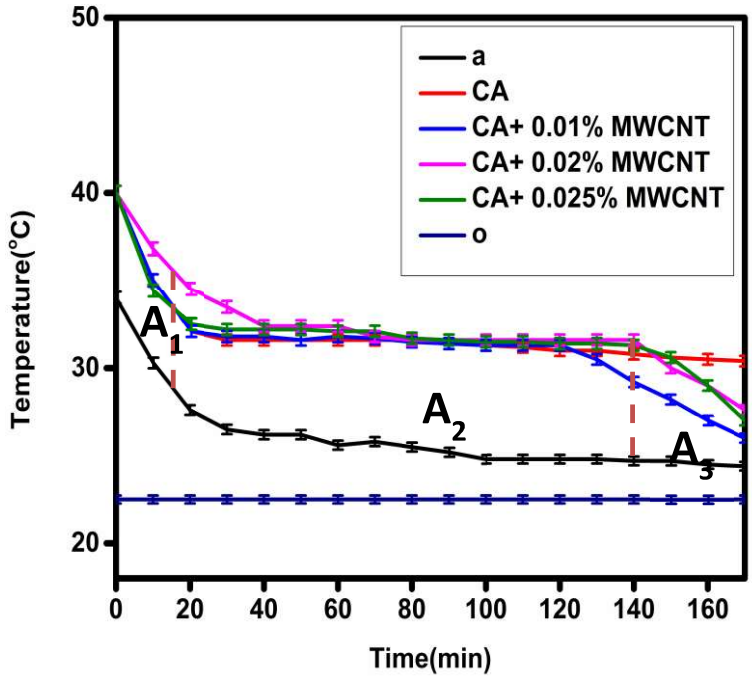


**Fig. 5.3(a).** Solidification profile of capric acid PCM/NEPCM

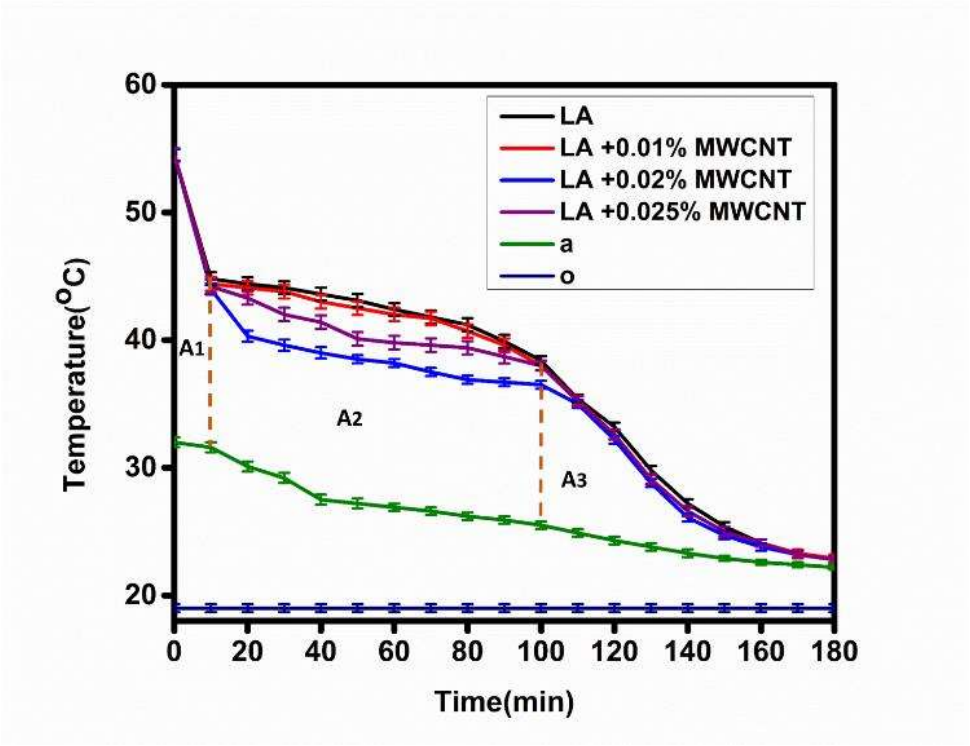


**Fig. 5.3(b).** Solidification profile of lauric acid PCM/NEPCM

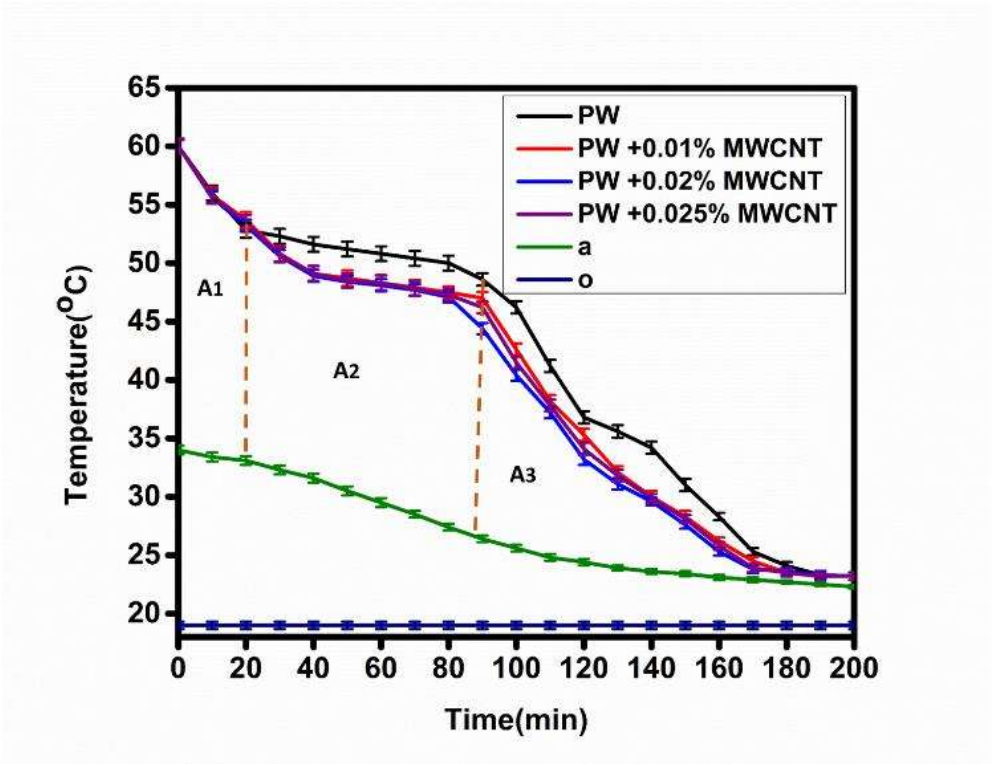


**Fig. 5.3(c).** Solidification profile of paraffin wax PCM/NEPCM

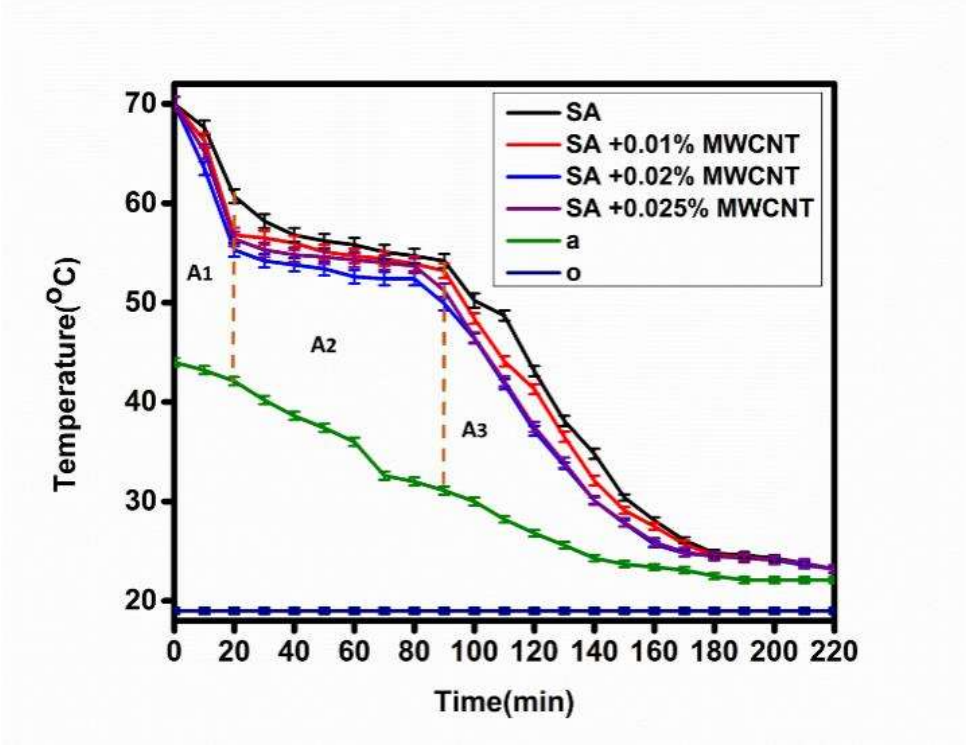


**Fig. 5.3(d).** Solidification profile of stearic acid PCM/NEPCM

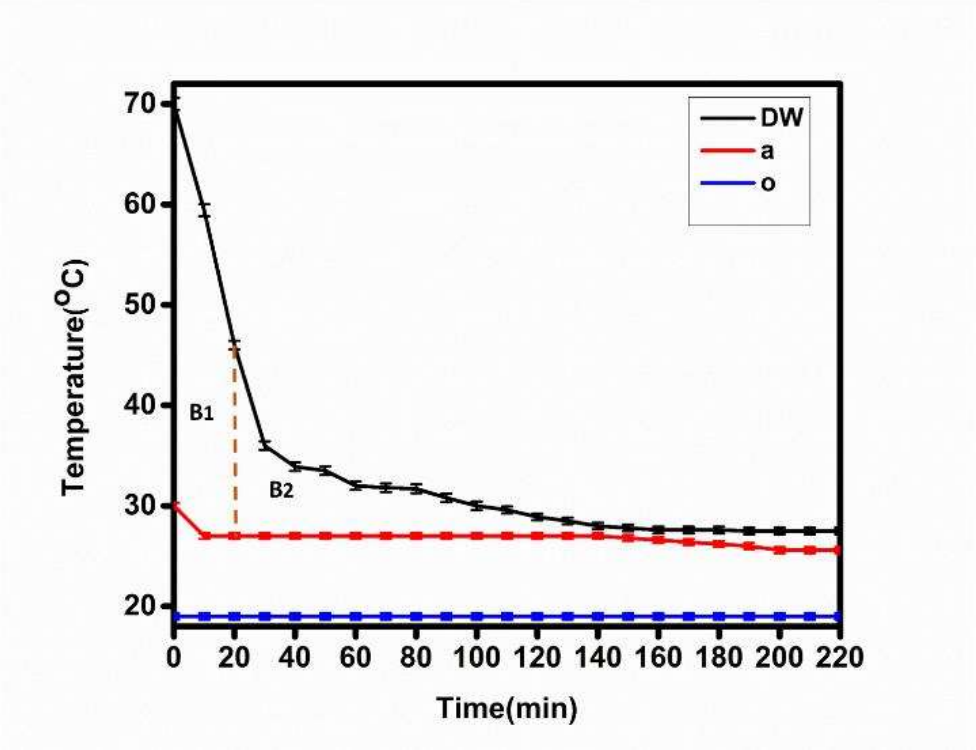


**Fig. 5.3(e).** Temperature of distilled water during the cooling process

The reason may be the reduced charging and discharging times for adding MWCNT additives in CA, LA, PW, and SA phase change materials. Also, it is generally happened due to the reduction in the heat of fusion of PCMs/NEPCMs. However, Fig. 5.3(e) represents the temperature profile during the cooling process of distilled water at ambient temperature. The temperature gradually decreases with time.

## 5.2.Variation in thermophysical properties of PCM/NEPCM

The T-History method obtained the thermophysical properties for pure CA, LA, PW, and SA phase change materials with 0.01%, 0.02%, and 0.025% MWCNT. Result revealed tremendous enhancement in the thermo-physical properties of capric acid, lauric acid, paraffin wax, and stearic acid by mixing MWCNT additives. It has been established that a heat capacity(solid-state) of 0.02% MWCNT in CA, LA, PW, and SA composite phase change materials was increased by 35.9%, 34.26%, 36.54%, and 25.86% than CA,

LA, PW, and SA phase change materials, respectively. The specific heat capacity of a material is defined as the amount of heat (J) absorbed per unit mass (kg) when its temperature rises 1 K (or 1°C), and it is measured in J/(kg K) or J/(kg °C). The heat capacity (liquid state) of 0.02% MWCNT in CA, LA, PW, and SA composite phase change materials increased by 52.85%, 15.71%, 62.57%, and 16% than CA, LA, PW, and SA phase change materials, respectively, as shown in Figs 5.4(a)-5.4(d). Furthermore, the heat capacity (liquid) of 0.02% MWCNT in PW increased by 69.74% and 48.49% to 0.02% MWCNT in LA, and SA, respectively. However, the thermal conductivity (liquid state) of 0.02% MWCNT in CA, LA, PW, and SA composite phase change materials increased by 31.29%, 36.96%, 25.77%, and 13.45% than pure CA, LA, PW, and SA phase change materials, respectively, as shown in Figs. 5.5(a-d).

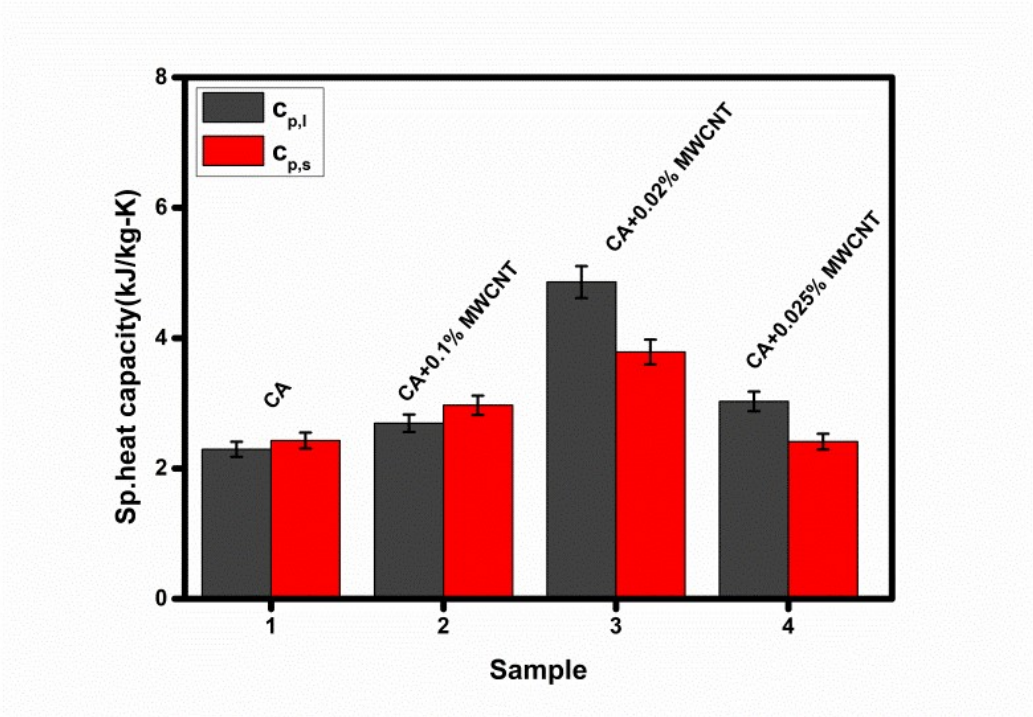


**Fig. 5.4(a).**Specific heat capacity of capric acid PCM/NEPCM

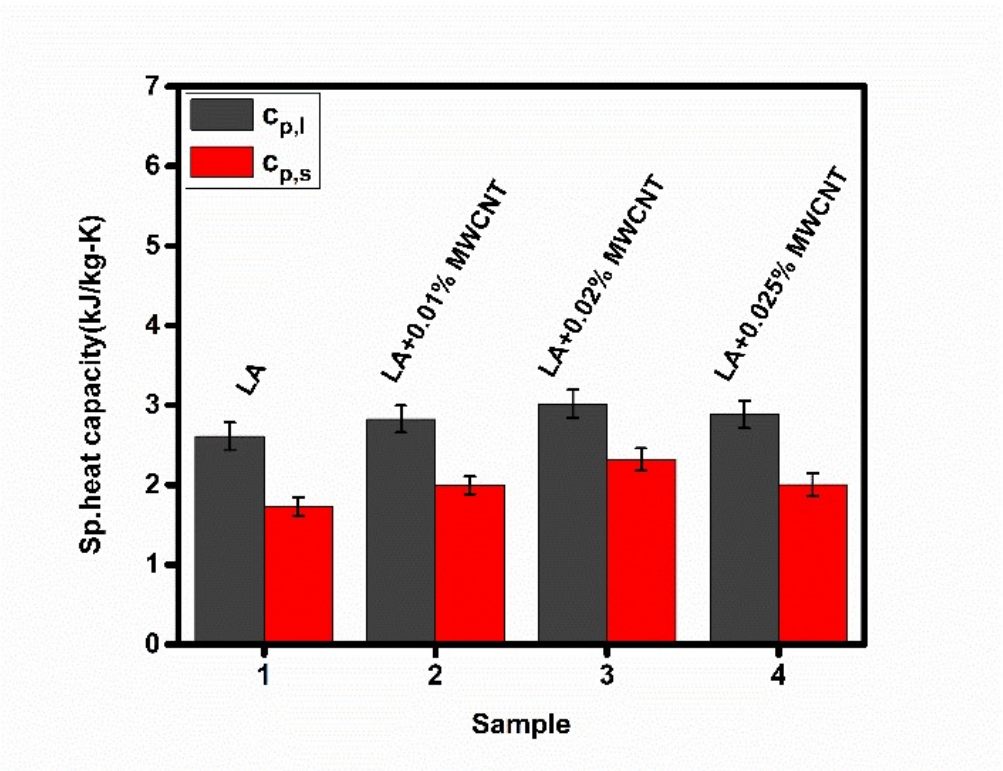


**Fig. 5.4(b).** Specific heat capacity of lauric acid PCM/NEPCM

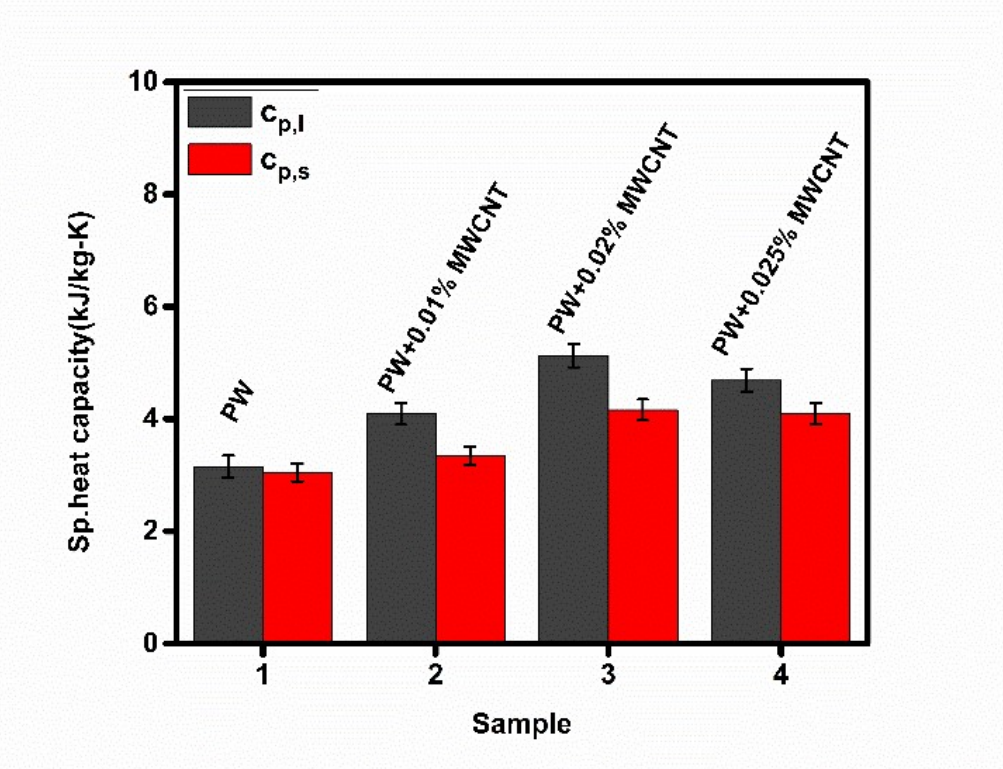


**Fig. 5.4(c).** Specific heat capacity of paraffin wax PCM/NEPCM

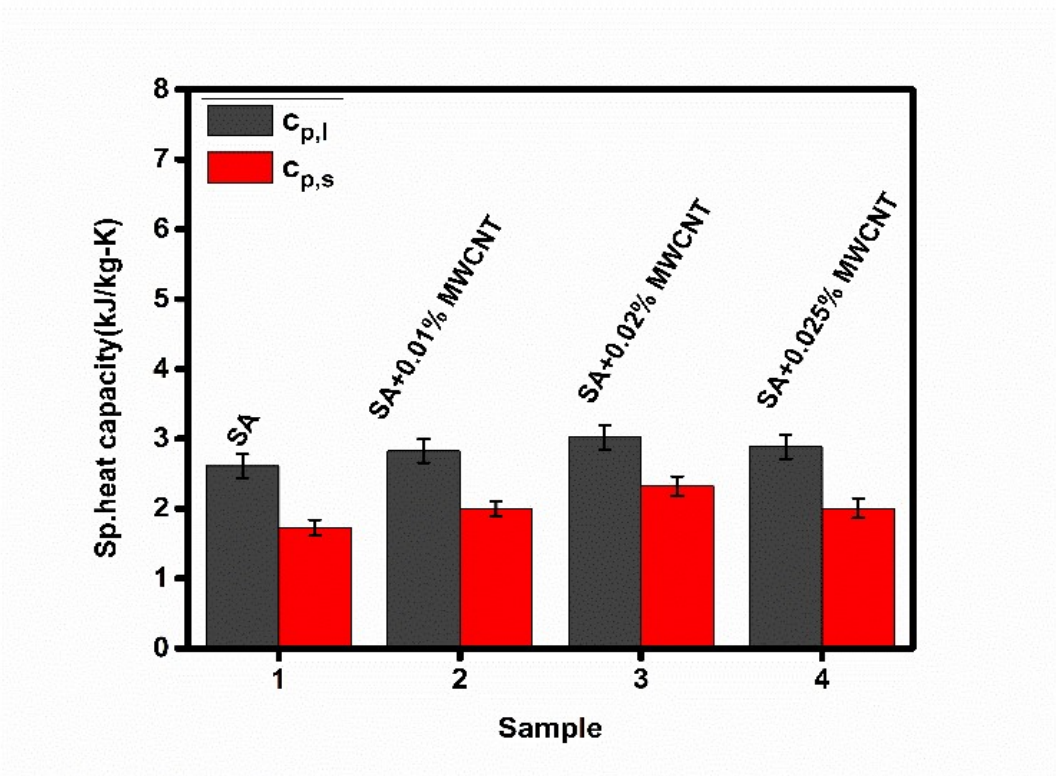


**Fig. 5.4(d).** Specific heat capacity of stearic acid PCM/NEPCM

The thermal conductivity (solid-state) of 0.02% MWCNT in CA, LA, PW, and SA composite phase change materials were increased by 14.4%, 37.8%, 24.4%, and 13.5% than CA, LA, PW, and SA phase change materials, respectively. The thermal conductivity represents the amount of heat that flows per unit time through a unit area with a temperature gradient of one degree per unit distance, expressed as the amount of heat that flows per unit time through a unit area with a temperature gradient of one degree per unit distance. Also, the thermal conductivity (liquid and solid) of 0.02% MWCNT in PW was increased by 65.56%, 110.7%, 59.63%, and 107.71% than 0.02% MWCNT in lauric acid and stearic acid, respectively.

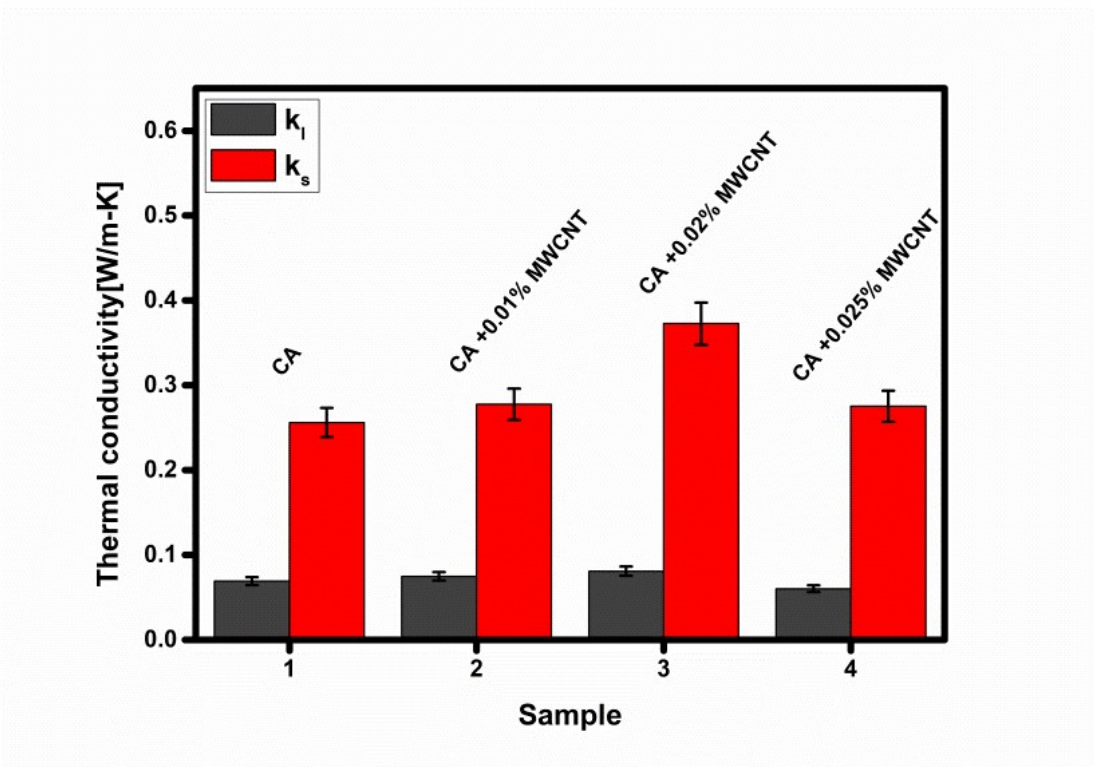


**Fig. 5.5(a).**Thermal conductivity capric acid PCM/NEPCM

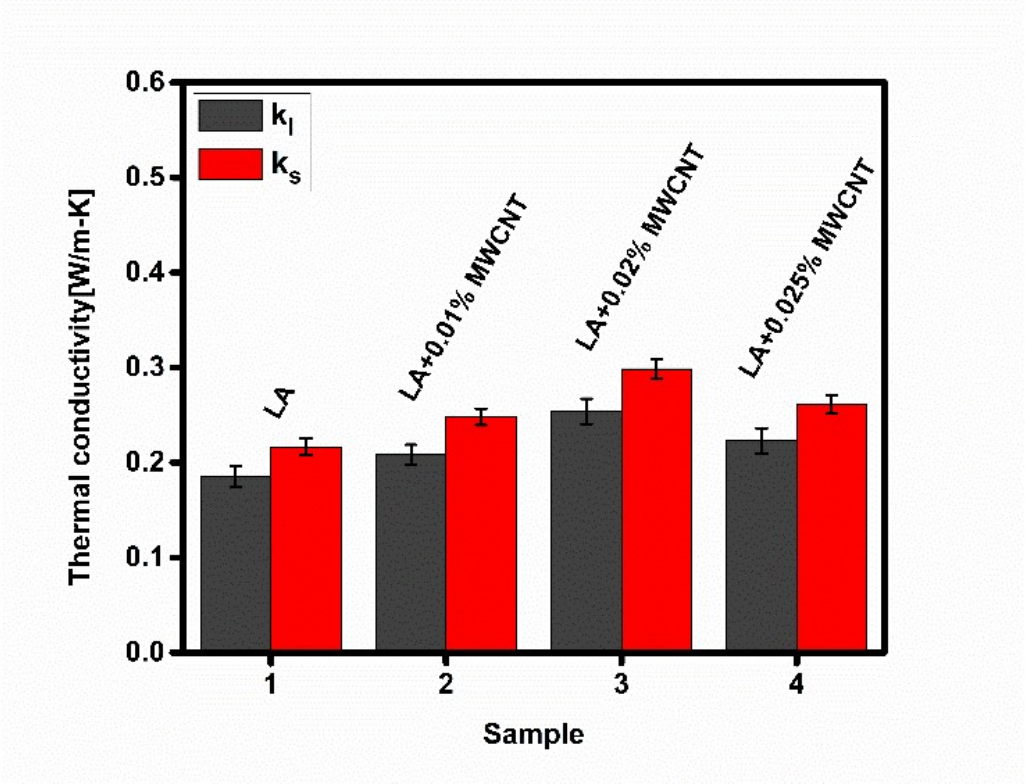


**Fig. 5.5(b).** Thermal conductivity lauric acid PCM/NEPCM

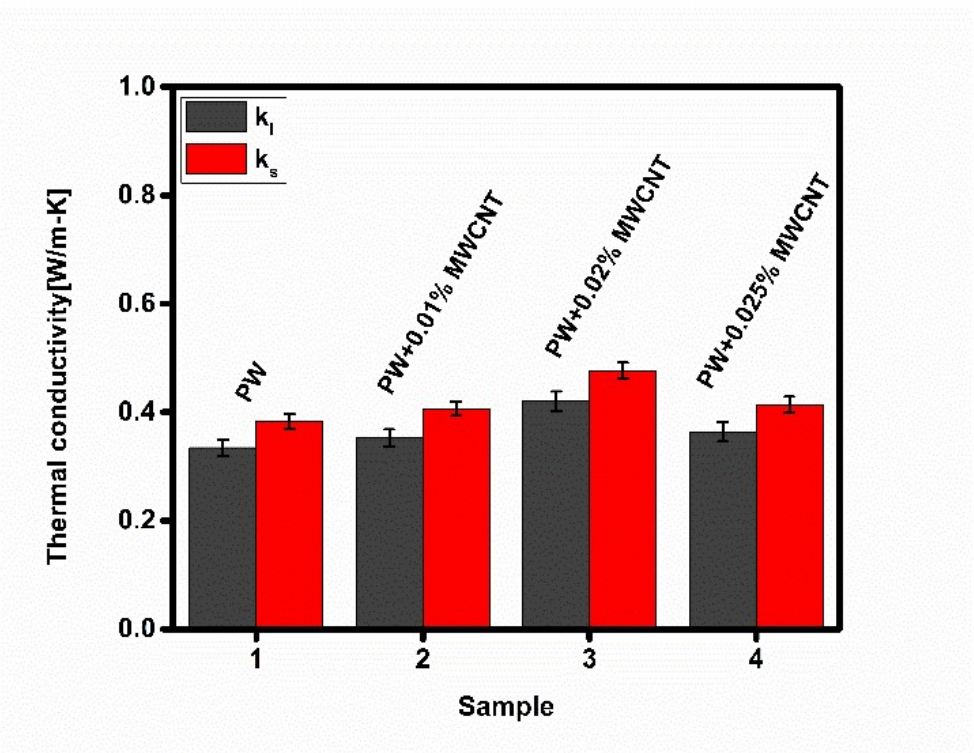


**Fig. 5.5(c).** Thermal conductivity paraffin wax PCM/NEPCM

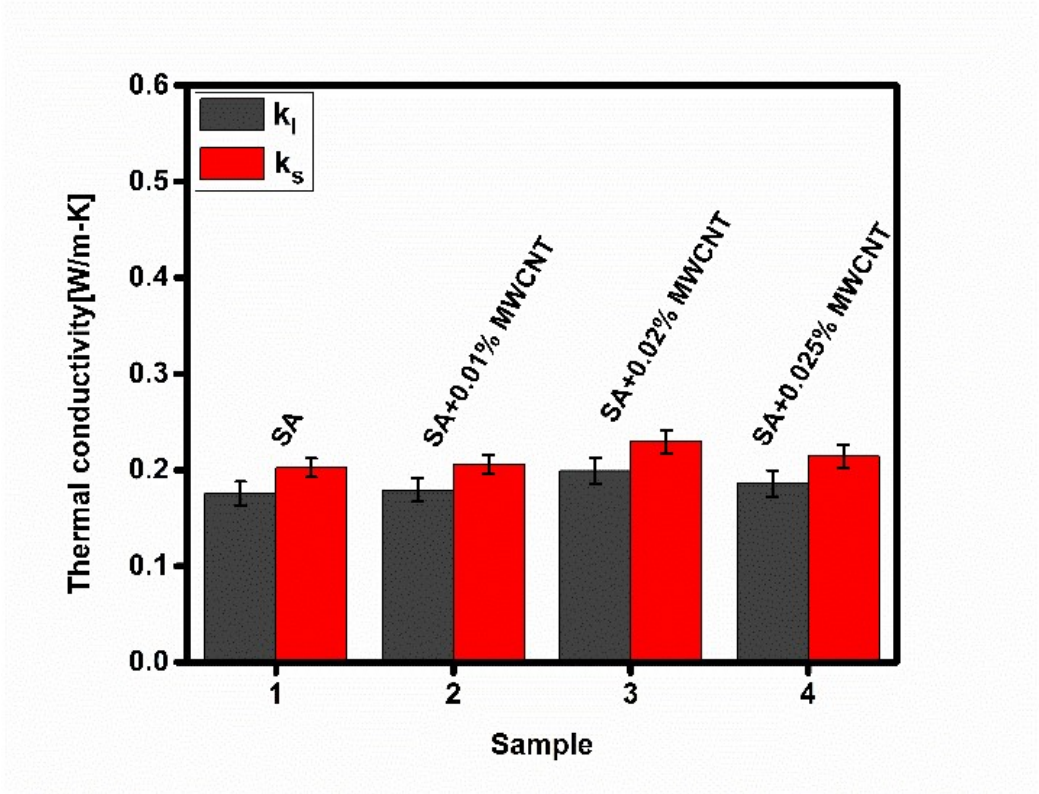


**Fig. 5.5(d).** Thermal conductivity stearic acid PCM/NEPCM

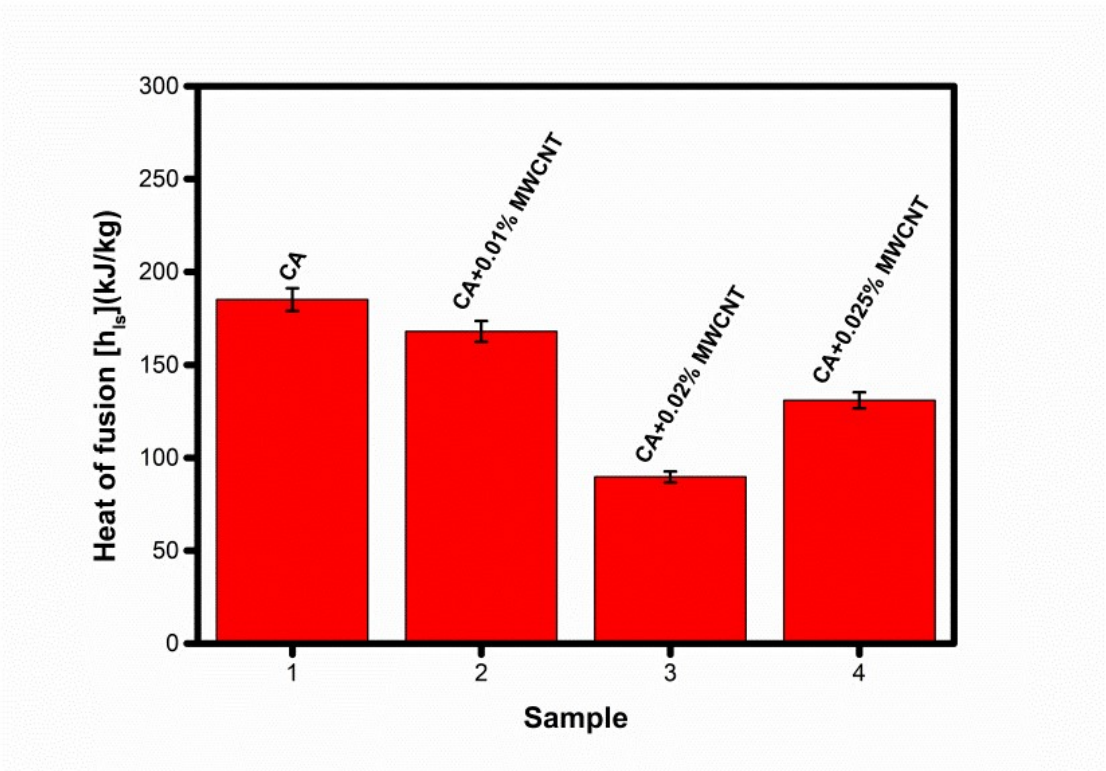


**Fig. 5.6(a).** Latent heat of capric acid PCM/NEPCM

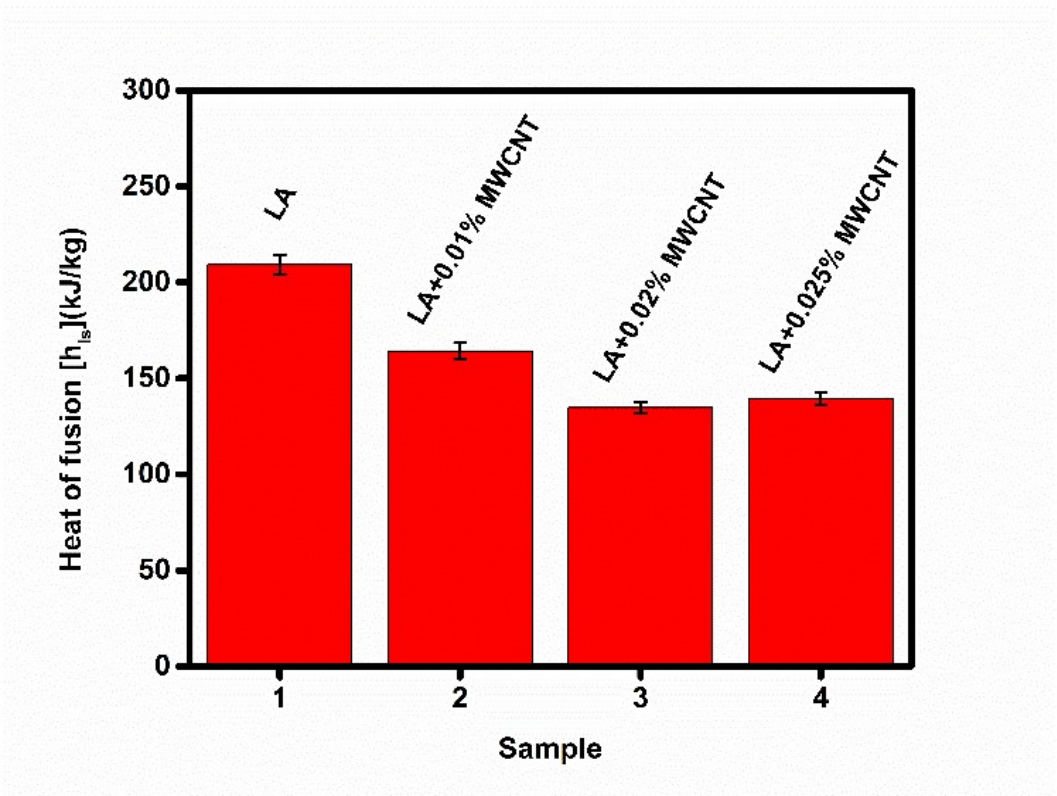


**Fig. 5.6(b).** Latent heat of lauric acid PCM/NEPCM

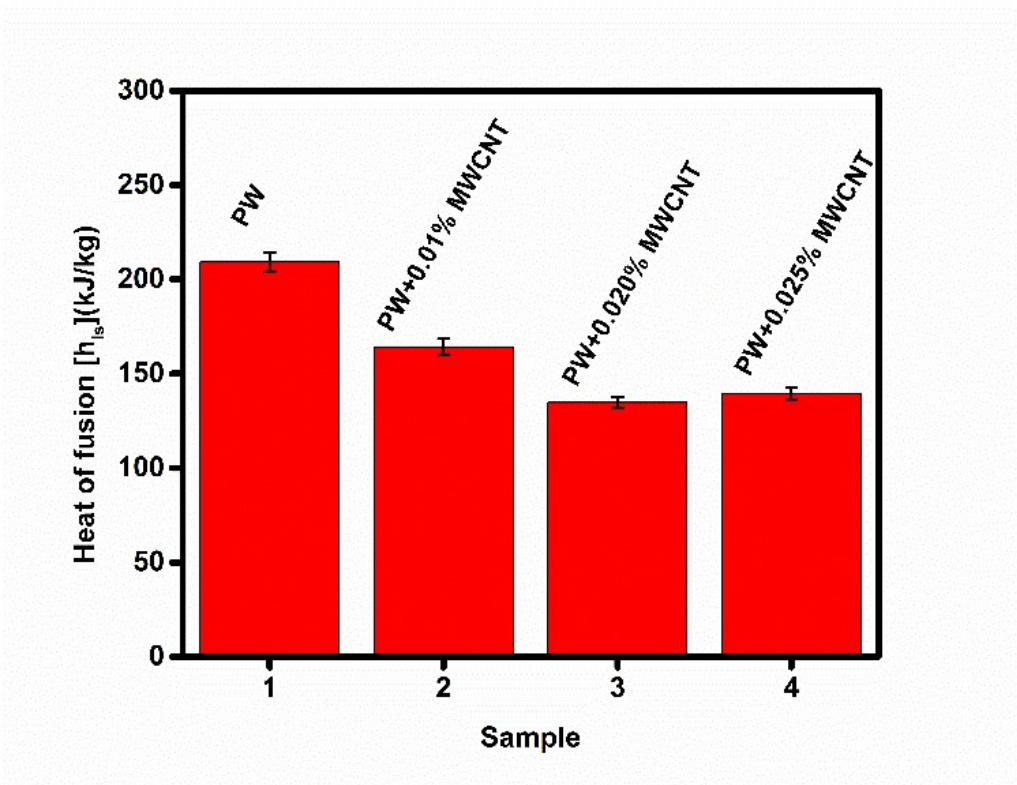


**Fig. 5.6(c).** Latent heat of paraffin wax PCM/NEPCM

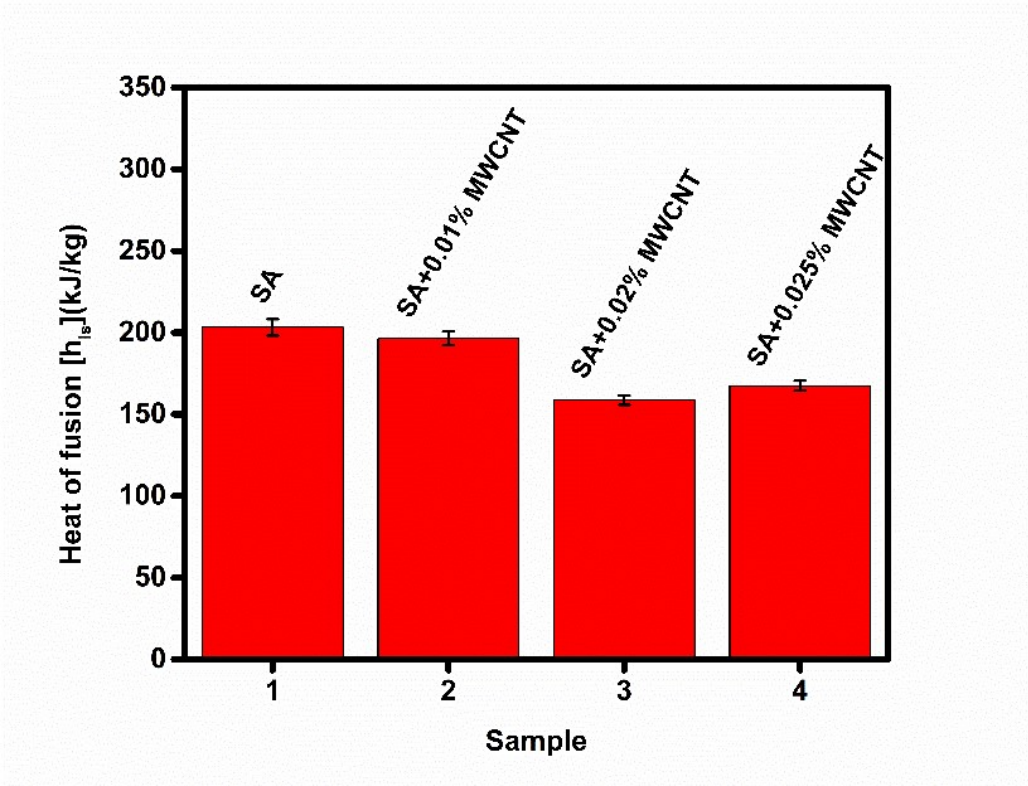


**Fig. 5.6(d).** Latent heat of stearic acid PCM/NEPCM

Furthermore, Figs. 5.6(a-d) presents the variation in the heat of fusion of pure CA, LA, PW, and SA phase change materials with 0.01%, 0.02%, and 0.025% vol. fraction MWCNT. However, the present analysis revealed that the latent heat for 0.02% MWCNT CA, LA, PW, and SA composite phase change materials were reduced by 106.5%, 8.55%, 35.95%, and 21.95% than pure CA, LA, PW, and SA phase change materials, respectively. Also, the latent heat of 0.02% MWCNT in PW was reduced by 16.49% and 18.36% than 0.02% MWCNT in LA and SA, respectively. It was observed that the vol. fraction of MWCNT varied from 0-0.02% in CA, LA, PW, and SA composite phase change materials; the thermophysical properties have improved beyond the above vol. fraction, the thermo-physical properties were decreased. It may happen due to the settlement of MWCNT particles after a vol. fraction of 0.02% in CA, LA, PW, and SA composite phase change materials.

Also, the comparative results of thermo-physical properties for 0.02% MWCNT based CA, LA, PW, and SA composite PCMs through the T-history approach and the Hot disks analyzer were presented in Table 5.4.

**Table 5.4:** Thermo-physical data obtained for 0.02% MWCNT based NEPCMs by T-history method and Hot disk analyzer

| | **Results obtained by the T-history method** | | | | **Results obtained by Hot disk analyzer** | | | |
|---|---|---|---|---|---|---|---|---|
| | CA+0.02 % MWCNT | LA+0.02% MWCNT | PW+0.02% MWCNT | SA+0.02% MWCNT | CA+0.02% MWCNT | LA+0.02% MWCNT | PW+0.02 % MWCNT | SA+0.02% MWCNT |
| **$C_{pl}$ [kJ/kg-K]** | 4.67 ±0.181 | 3.02 ±0.173 | 5.126 ±0.206 | 3.452 ±0.195 | 4.23 ±0.178 | 2.92 ±0.154 | 4.962 ±0.186 | 3.256 ±0.163 |
| **$C_{ps}$ [kJ/kg-K]** | 3.81 ±0.164 | 2.32 ±0.14 | 4.159 ±0.188 | 4.18 ±0.176 | 3.51 ±0.122 | 2.03 ±0.118 | 4.03 ±0.167 | 3.856 ±0.143 |
| **$K_l$ [W/m-K]** | 0.0808±0.011 | 0.2538 ±0.013 | 0.4202 ±0.018 | 0.199 ±0.0137 | 0.064 ±0.011 | 0.2365 ±0.009 | 0.3956 ±0.012 | 0.1652 ±0.0098 |
| **$K_s$ [W/m-K]** | 0.3726±0.011 | 0.298 ±0.009 | 0.4765 ±0.0147 | 0.2294 ±0.0121 | 0.321 ±0.012 | 0.2736 ±0.006 | 0.432 ±0.011 | 0.1986 ±0.0087 |

## 5.3. Thermal performance evaluation of TES system with MWCNT based organic PCMs

### 5.3.1. Data reduction

The following correlations were used to evaluate the thermal performance of the TES system with MWCNT-based organic PCMs.

The Liquid fraction (f) of PCMs/NEPCMs filled in TES system can be expressed (Cao et al., 2018);

$$f = \begin{cases} 0, \ if T < T_s \\ \frac{T-T_s}{T_l-T_s}, \ if T_s < T < T_l \\ 1, \ if T > T_l \end{cases} \quad (5.7)$$

The Fourier number (Fo) of pure and MWCNT based PCMs/NEPCMs can be expressed as:

$$Fo = \alpha t / l^2 \quad (5.8)$$

where thermal diffusivity, $\alpha = k/\rho c_p$

Also, the Rayleigh number (Ra)of pure and MWCNT-based PCMs/NEPCMs can be expressed (Totala et al., 2013).

$$Ra = \frac{g\rho\beta l^3 (T_W - T_m)}{\alpha\mu} \quad (5.9)$$

The Nusselt number (Nu) of pure and MWCNT based PCMs/NEPCMs filled in the TES system can be expressed as (Totala et al., 2013),

$$Nu = 0.59 \times Ra^{0.25} \quad (5.10)$$

The heat transfer coefficient (h) for a TES system filled with PCMs/NEPCMs can be expressed as:

$$h = \frac{Nu \times k}{l} \tag{5.11}$$

The heat transfer rate (Q) from water to PCMs/NEPCMs can be expressed as:

$$Q = hA(T_w - T_R) \tag{5.12}$$

where cross-section area of the tube, $A = 2\pi R \times l$

### 5.3.2. Variation in Charging profile and liquid fraction of PCM/NEPCM

The term charging of TES system indicates the temperature of PCM/NEPCM in the TES system is equal to the temperature of HTF.

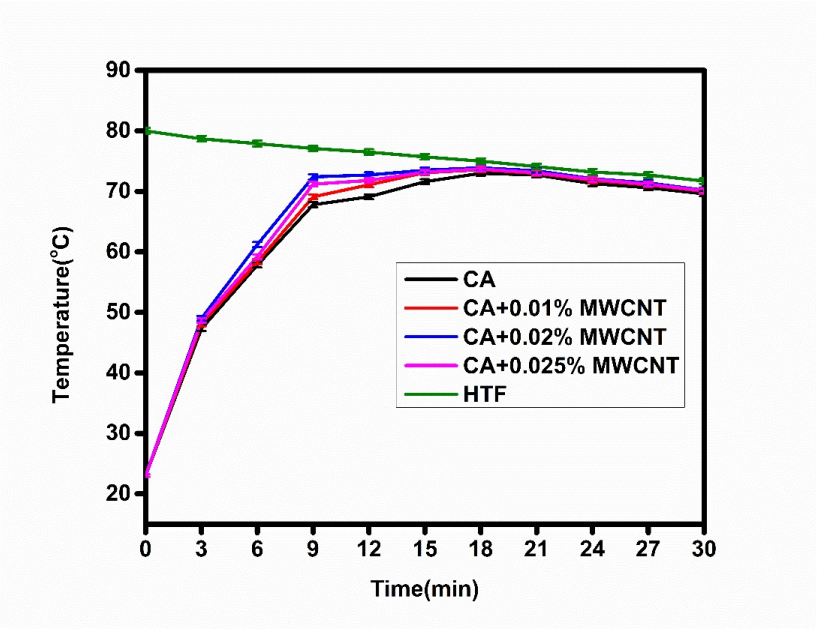


**Fig. 5.7(a).** Charging profile of capric acid PCM/NEPCM

The melting profile of pure CA, LA, PW, and SA with 0.01%, 0.02%, and 0.025% volume fractions of MWCNT have been presented in Figs. 5.7(a-d). Results revealed that 0.02% vol. fraction MWCNT-based CA, LA, PW, and SA required 360 sec, 300sec, 300sec, and 420sec less time than pure CA, LA, PW, and SA phase change materials.

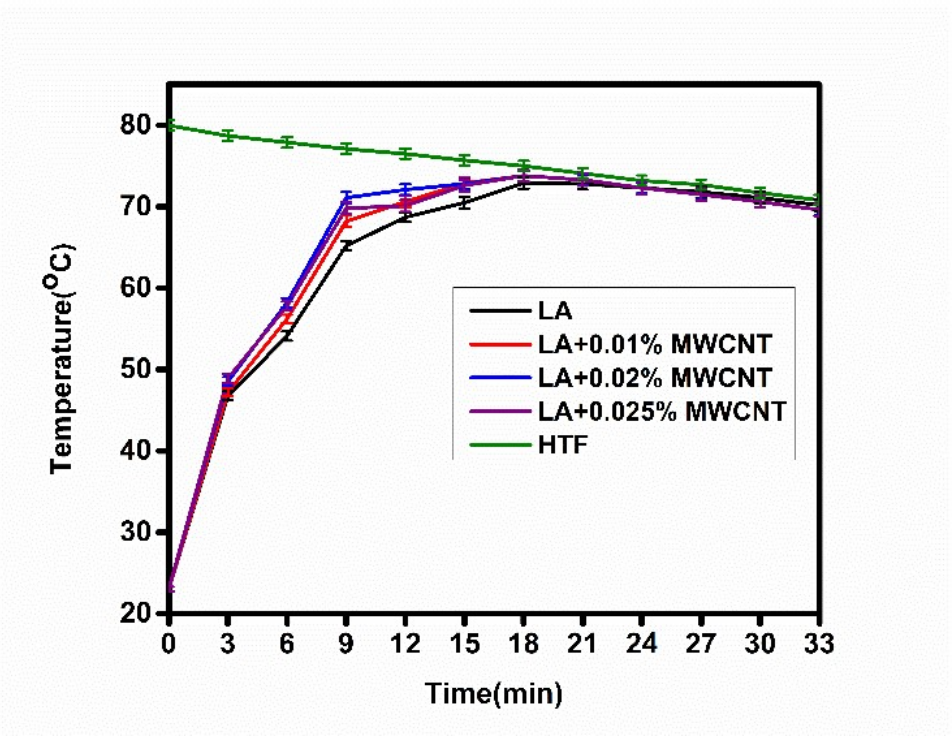


**Fig. 5.7(b).** Charging profile of lauric acid PCM/NEPCM

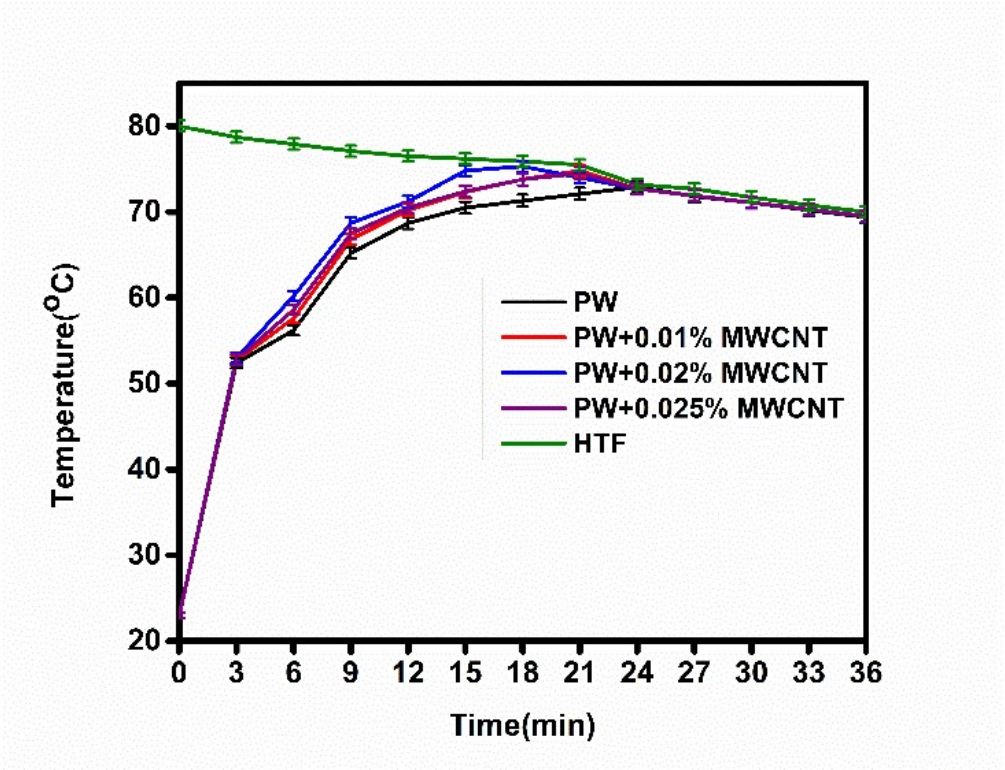


**Fig. 5.7(c).** Charging profile of paraffin wax PCM/NEPCM

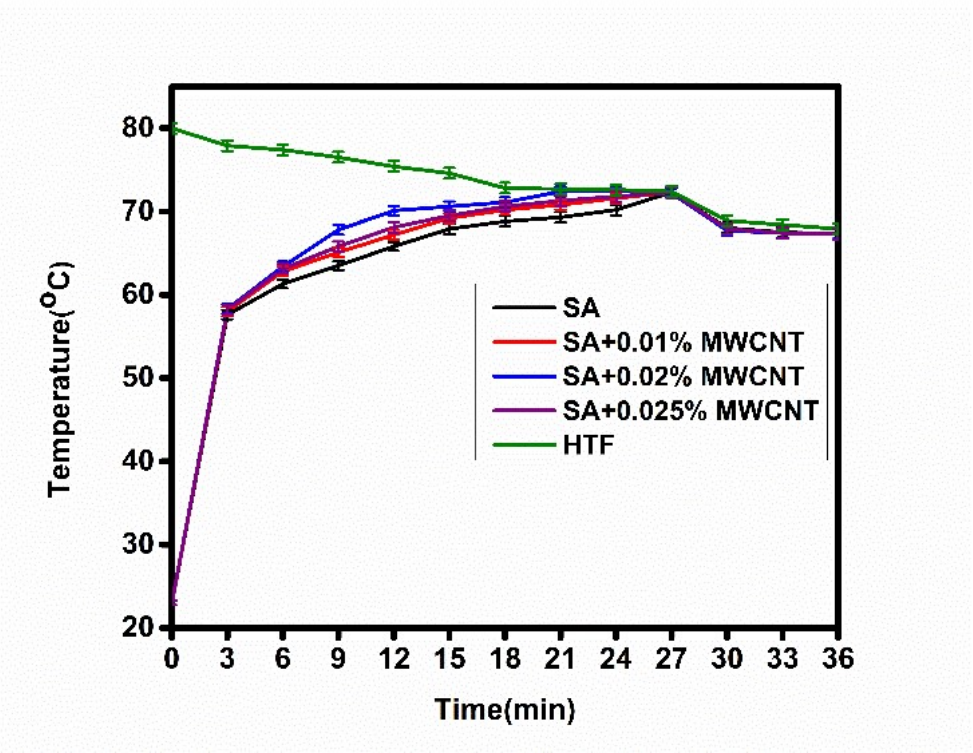


**Fig. 5.7(d).** Charging profile of stearic acid PCM/NEPCM

The liquid fraction is used to determine the PCM state (solid, liquid, or undergoing phase change). The liquid fraction ranges from 0 to 1. A liquid fraction having values 0 and 1 indicates PCM's liquid and solid states, respectively. However, a liquid fraction value between 0 and 1 indicates that PCM is in the phase change. Results revealed that the melting time of the vol. fraction 0.02% MWCNT based CA, LA, PW, and SA composite phase change materials required less time than other considered vol. fractions of MWCNT-based NEPCM. It is also observed in the variation in a liquid fraction shown in Figs. 5.8(a-d).

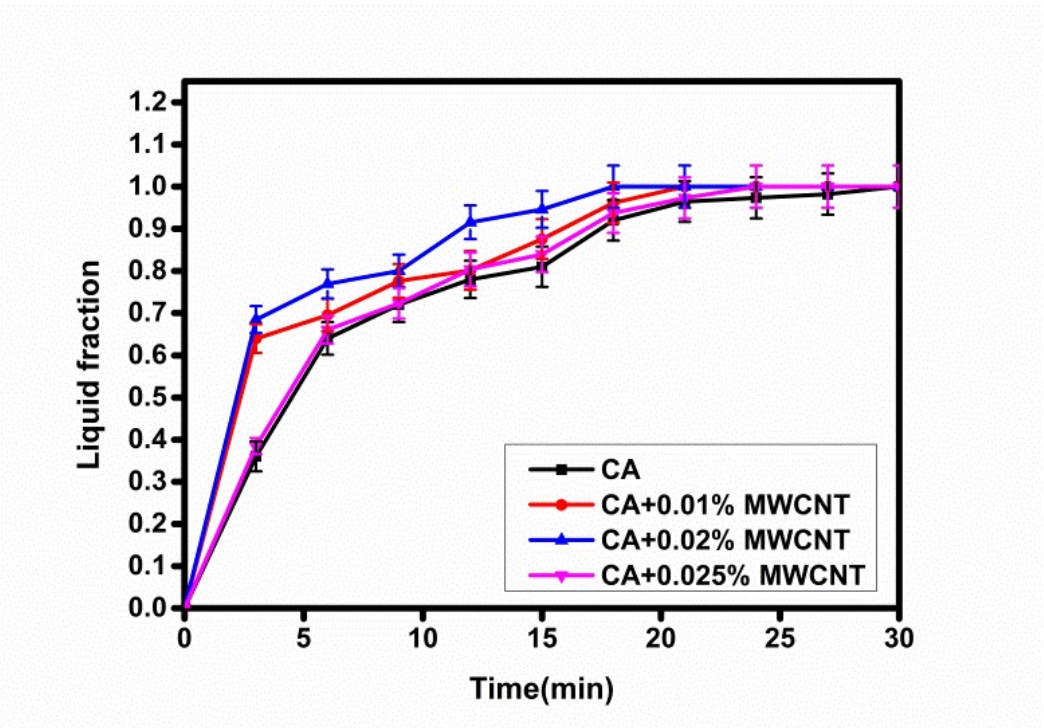


**Fig. 5.8(a).** Liquid fraction of capric acid PCM/NEPCM

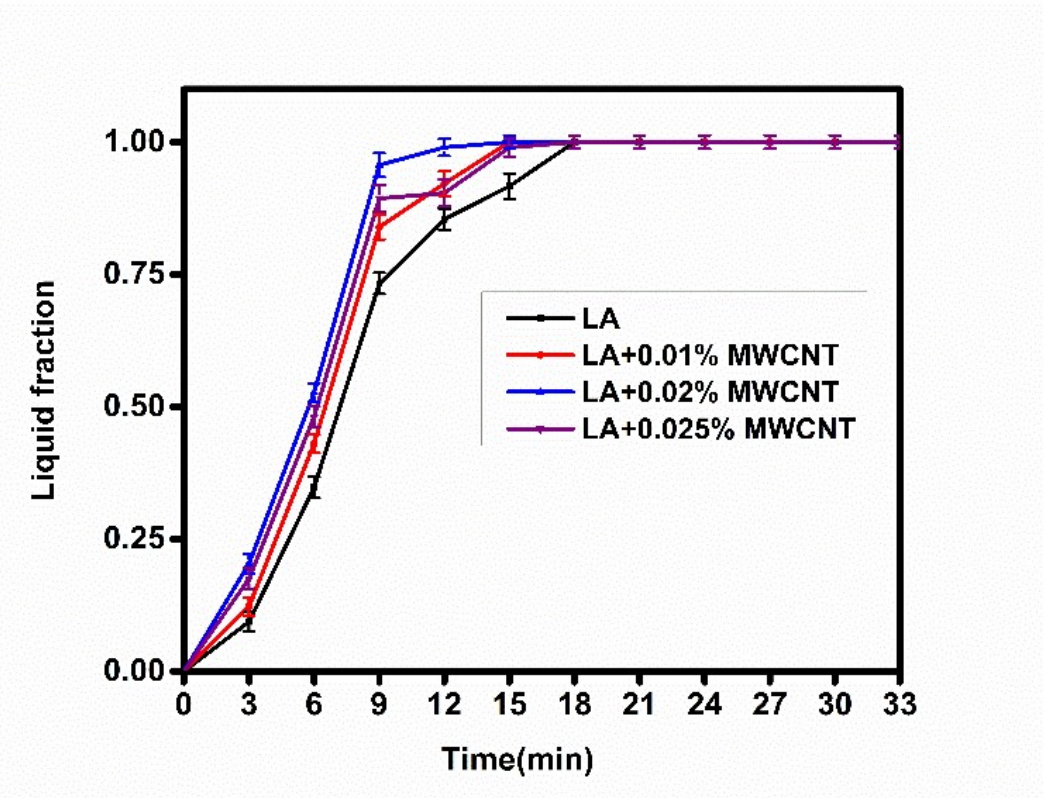


**Fig. 5.8(b).** Liquid fraction of lauric acid PCM/NEPCM

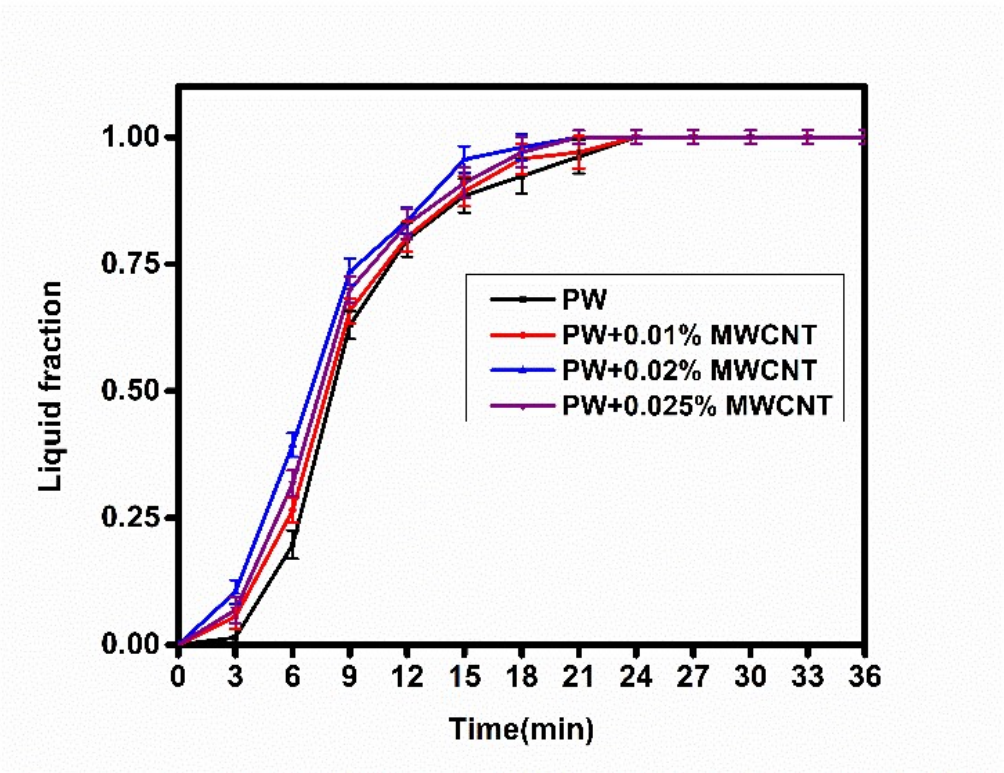


**Fig. 5.8(c).** Liquid fraction of paraffin wax PCM/NEPCM

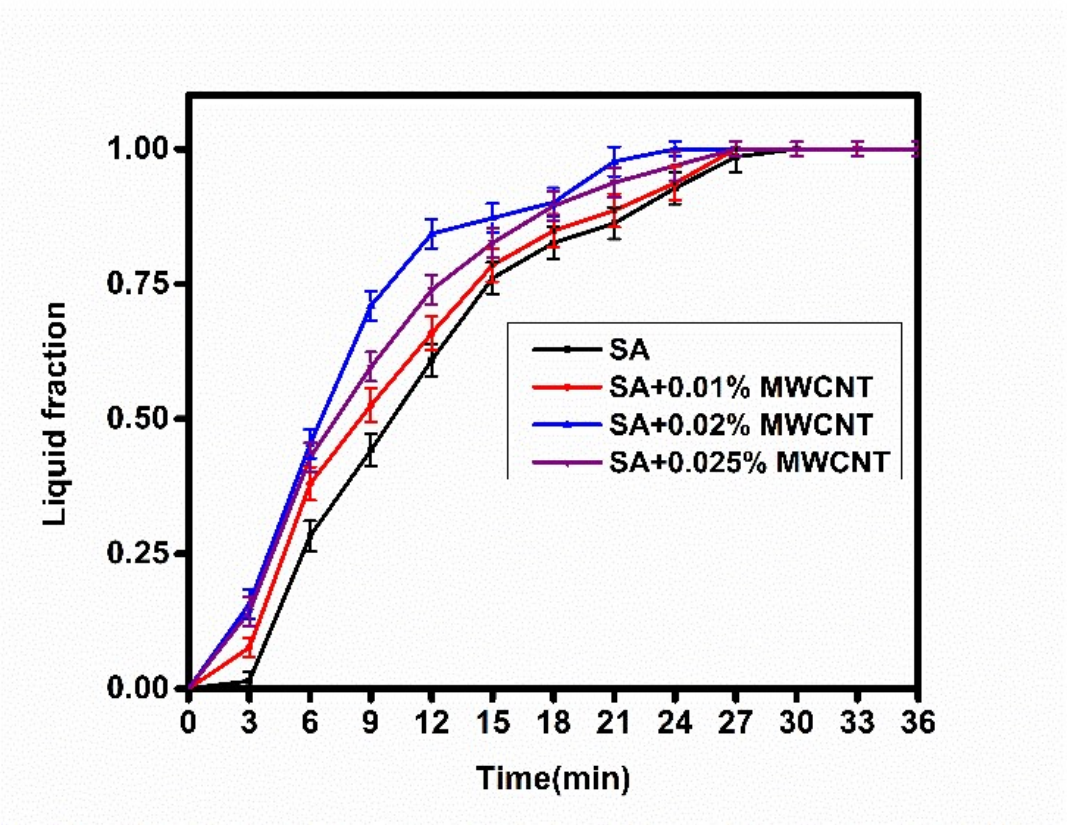


**Fig. 5.8(d).** Liquid fraction of stearic acid PCM/NEPCM

### 5.3.3. Variation in dimensionless numbers of PCM/NEPCM

Several relevant relationships between dimensionless numbers show how different factors affect the system. Dimensionless numbers predict the system's behavior. Furthermore, dimensionless numbers make it easier to solve heat transfer problems by scaling them. Variations in the Fourier number of pure and MWCNT-based CA, LA, PW, and SA composite phase change materials have been presented in Figs. 5.9(a-d). The Fourier number represents the relationship between the rate of heat conduction and the rate of heat storage in the body. It is used to describe and forecast the temperature response of materials subjected to transient conductive heating or cooling. Results revealed that the Fourier number varies from 4% to 33.3% in the case of 0.02% MWCNT in CA, LA, PW, and SA PCMs concerning pure CA, LA, PW, and SA PCMs. It happened due to a higher heat transfer rate in case of 0.02% MWCNT in CA, LA, PW, and SA composite phase change materials-based TES system than in the other samples.

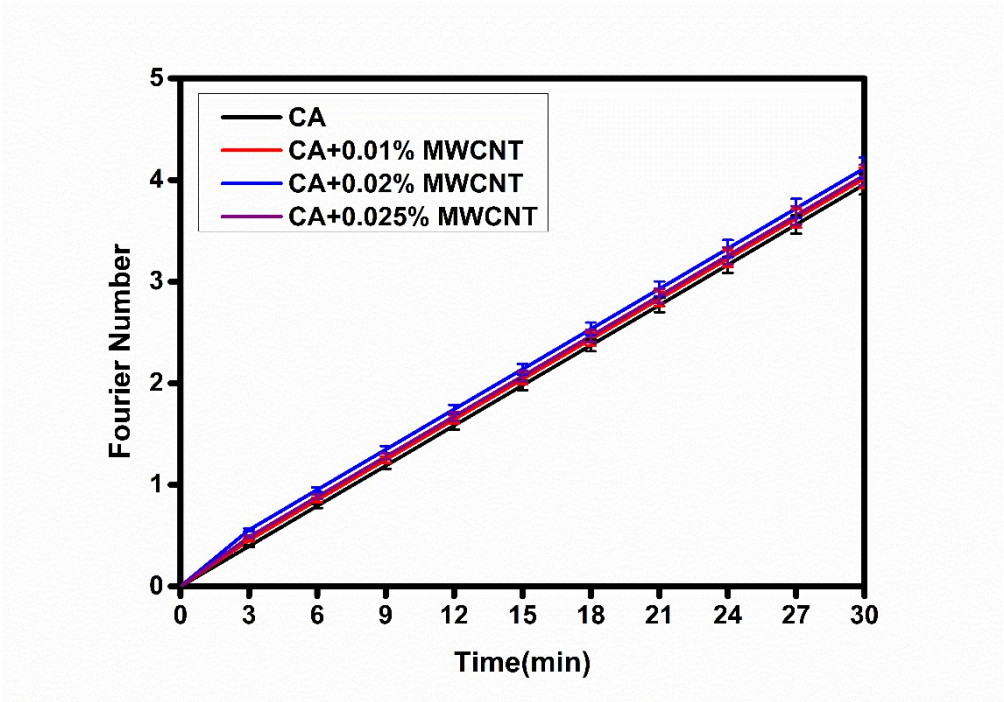


**Fig. 5.9(a).**Fourier Number of capric acid PCM/NEPCM

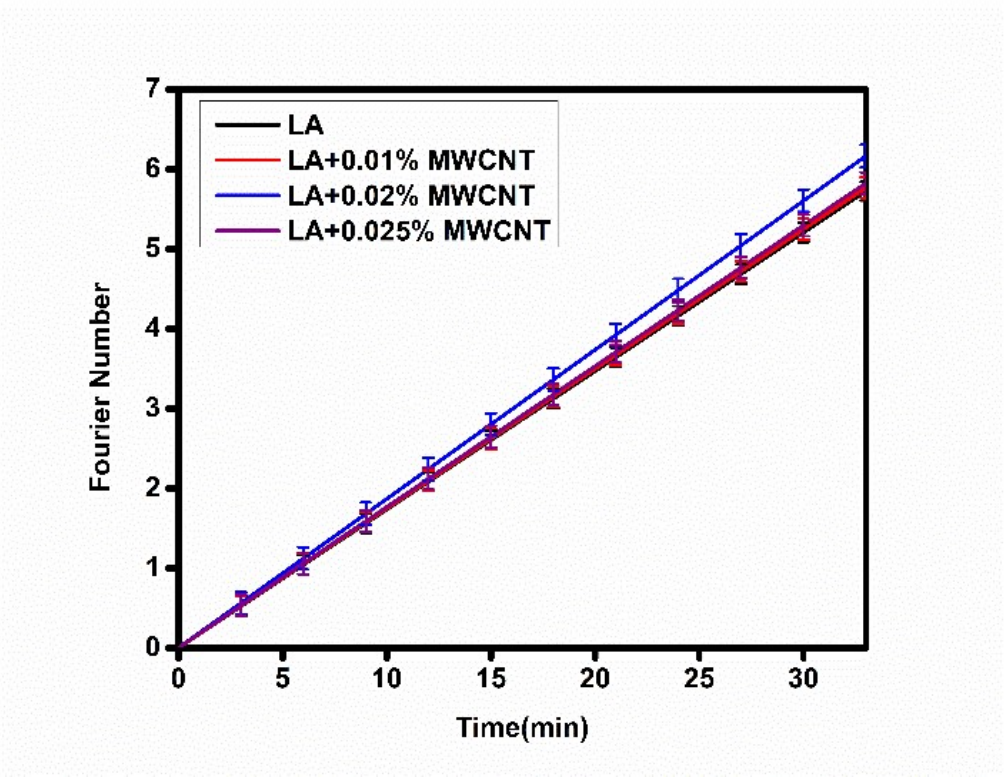


**Fig. 5.9(b).** Fourier Number of lauric acid PCM/NEPCM

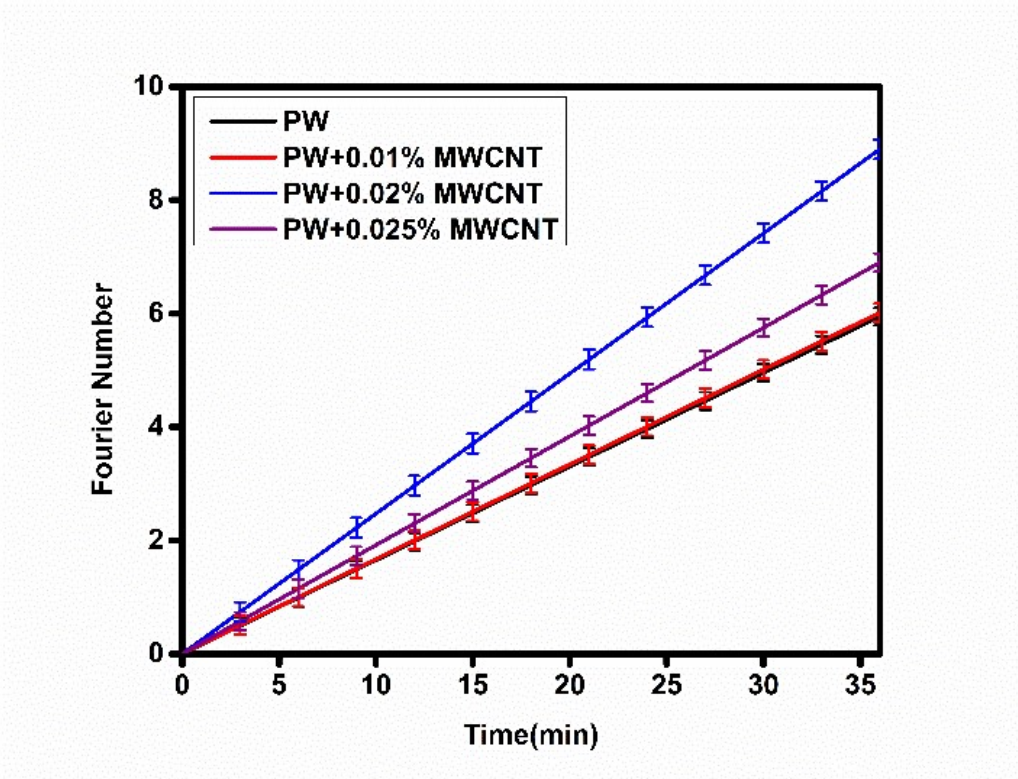


**Fig. 5.9(c).** Fourier Number of paraffin wax PCM/NEPCM

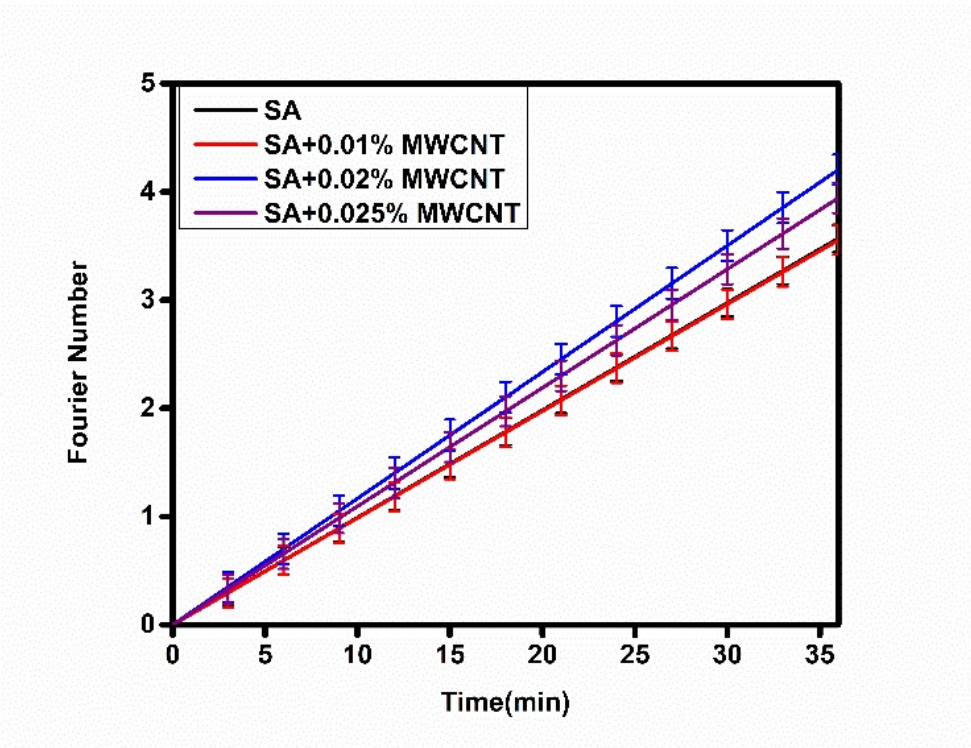


**Fig. 5.9(d).**Fourier Number of stearic acid PCM/NEPCM

However, the variation in Rayleigh number for LA, PW, and SA phase change materials with 0-0.025% MWCNT based PCMs/NEPCMs, have been presented in Figs. 5.10(a-d). Rayleigh number is a dimensionless number associated with free or natural convection. From the experimental data, the variation of the Rayleigh number shows the heat transfer process is in natural convection. However, with an increase in the vol. fraction of MWCNT from 0 to 0.02% in capric acid, lauric acid, paraffin wax, and stearic acid PCMs, the variation in Rayleigh number increases, and after then decreases. The maximum deviation of Rayleigh number of 0.02% MWCNT based CA, LA, PW, and SA composite phase change materials was increased by 60%,15.5%, 127.4%, and 27.34% than CA, LA, PW, and SA phase change materials, respectively.

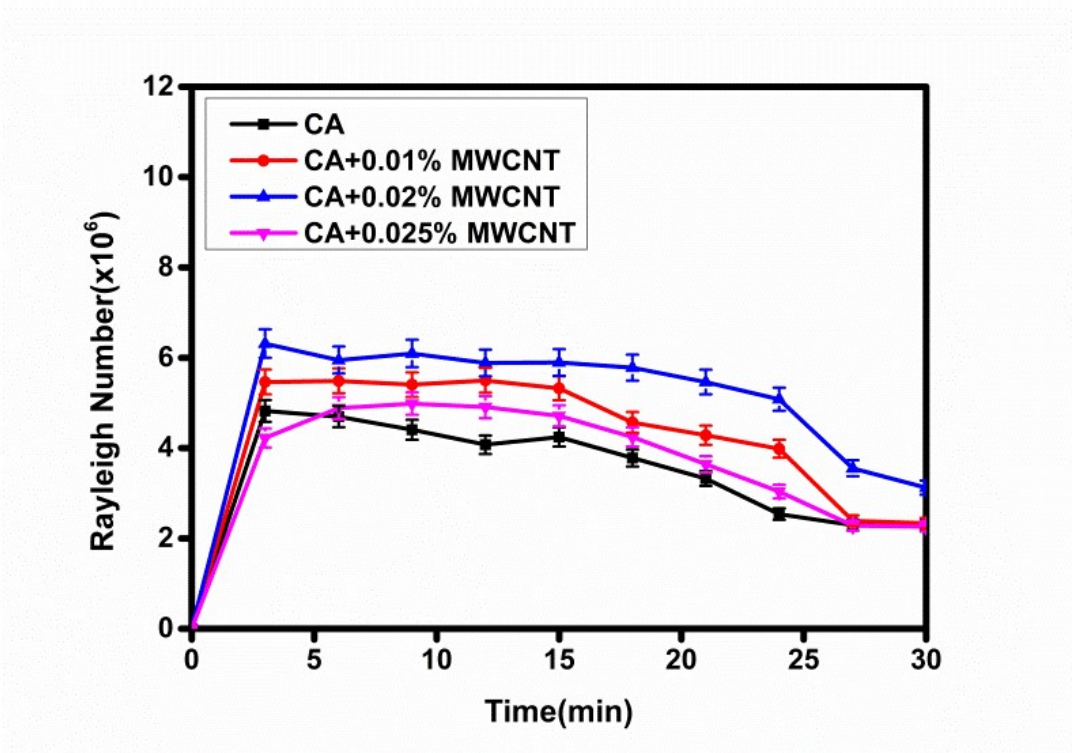


**Fig. 5.10(a).** Rayleigh Number of capric acid PCM/NEPCM

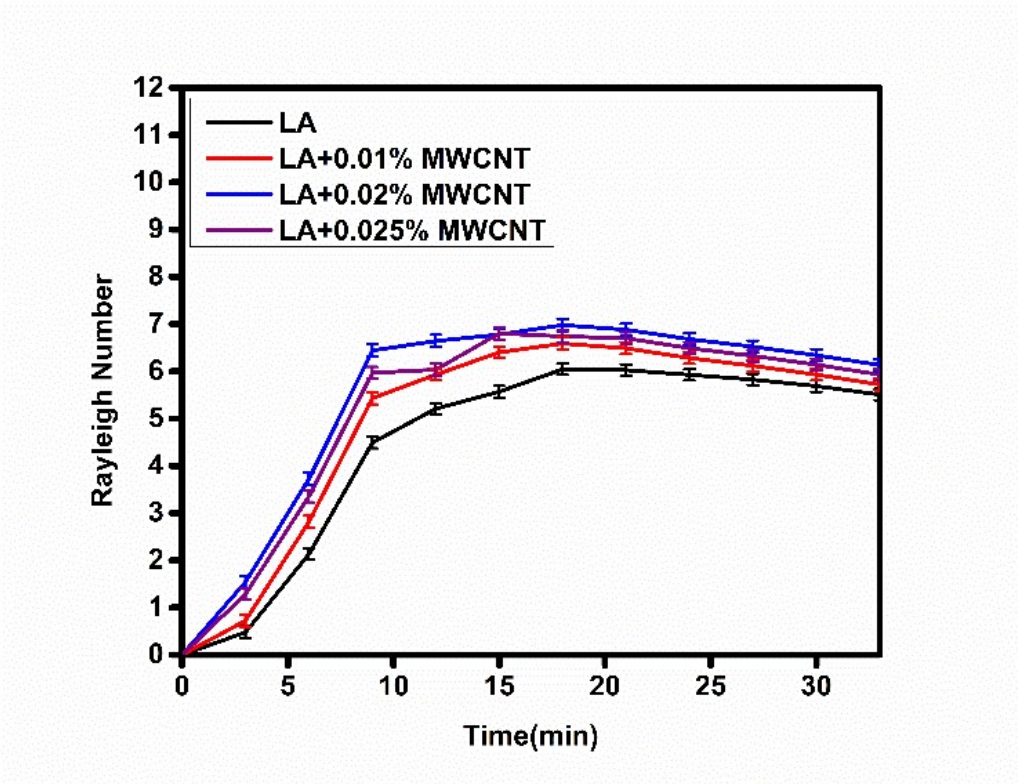


**Fig. 5.10(b).** Rayleigh Number of lauric acid PCM/NEPCM

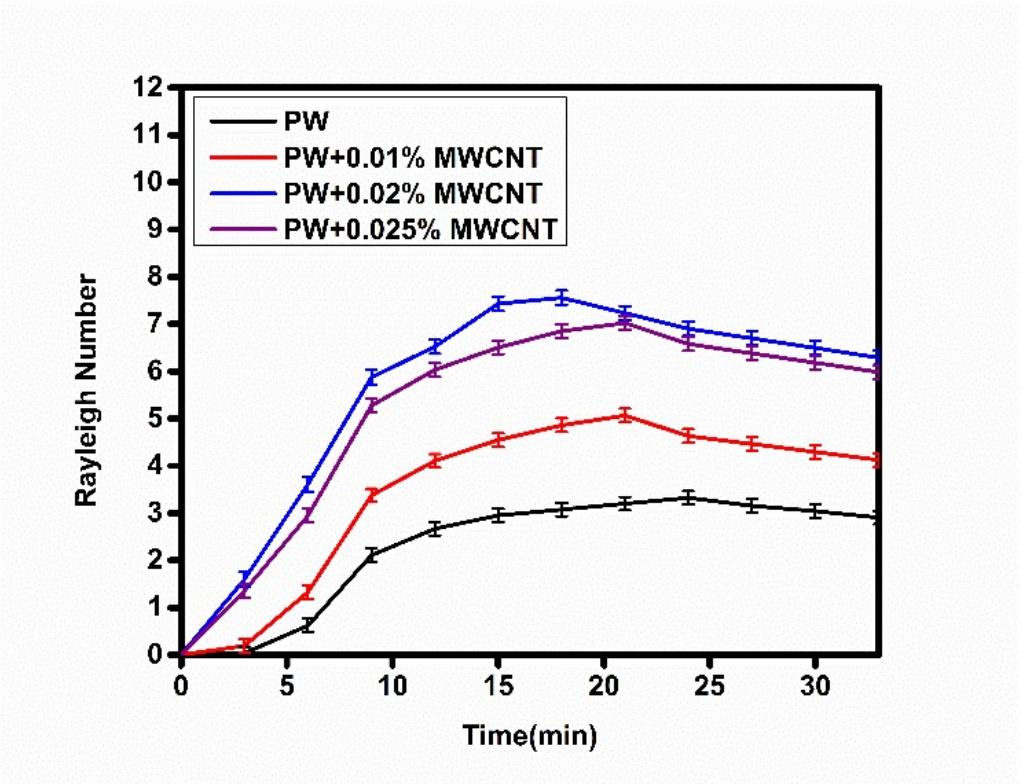


**Fig. 5.10(c).** Rayleigh Number of paraffin wax PCM/NEPCM

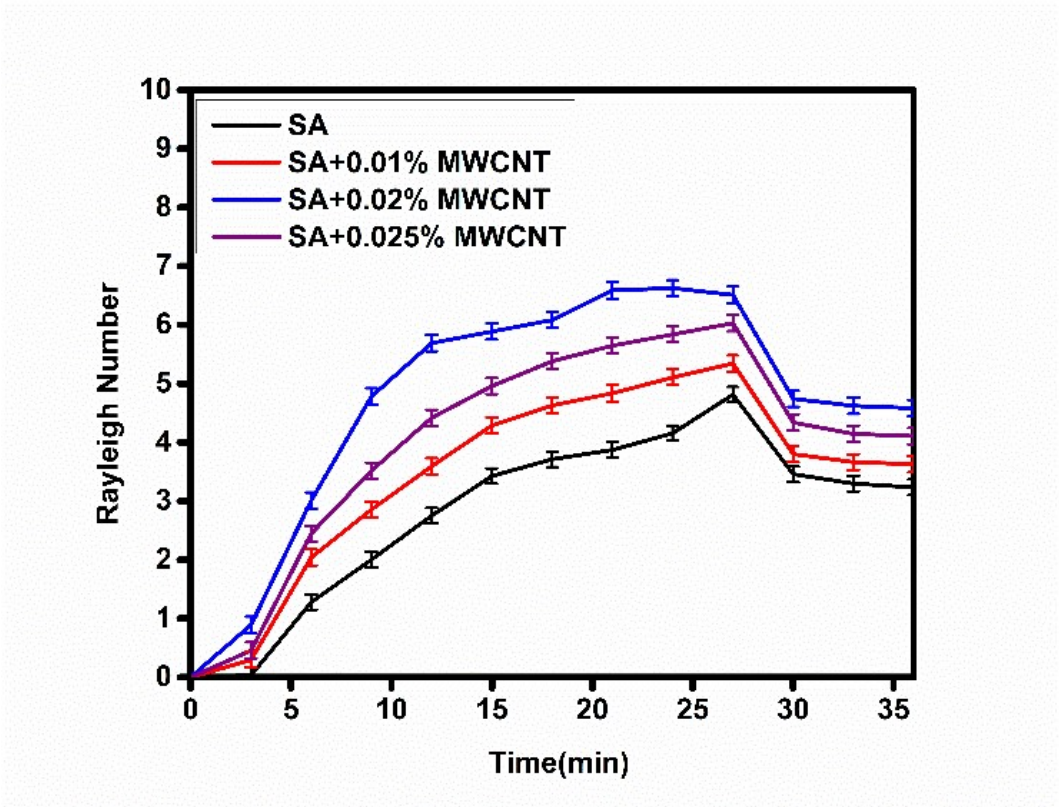


**Fig. 5.10(d).** Rayleigh Number of stearic acid PCM/NEPCM

Also, the maximum variation in Nusselt number for 0.02% MWCNT based CA, LA, PW, and SA composite phase change materials increased by 13.8%, 3.14%, 22.6%, and 8.33% than CA, LA, PW, and SA phase change materials, respectively, as presented in Figs. 5.11(a-d). The ratio of convective to conductive heat transfer across the boundary is expressed as a Nusselt number, which is a dimensionless number. From the experiments, the Nusselt number varies from 0 to 31, justified by the heat transfer across the boundary by conduction and convection processes.

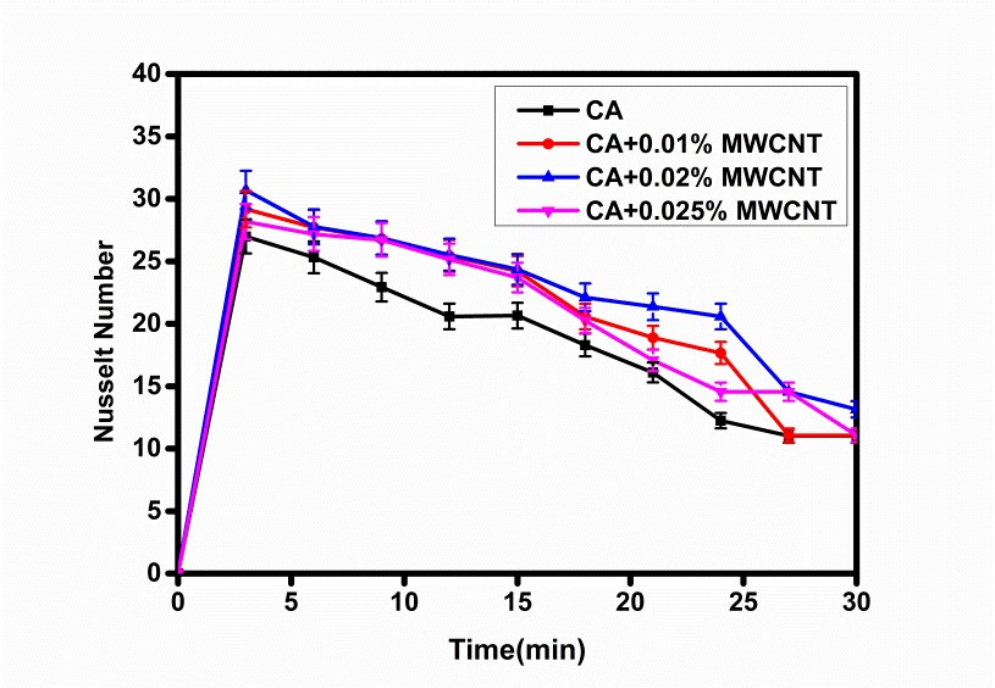


**Fig. 5.11(a).** Nusselt Number of capric acid PCM/NEPCM

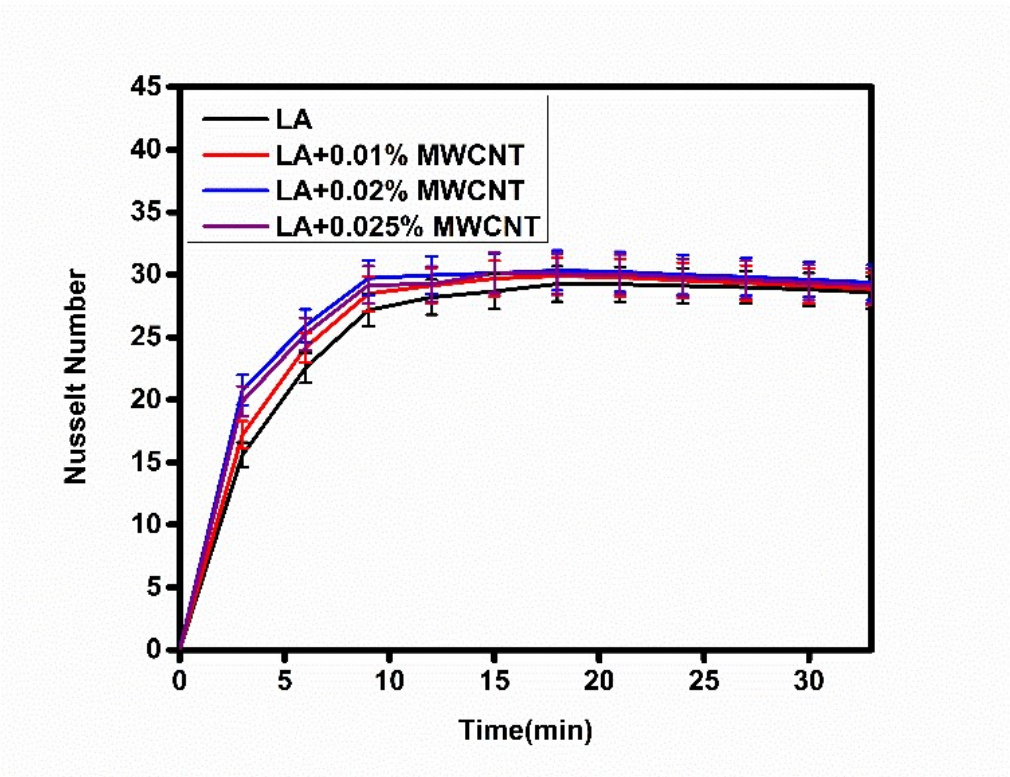


**Fig. 5.11(b).** Nusselt Number of lauric acid PCM/NEPCM

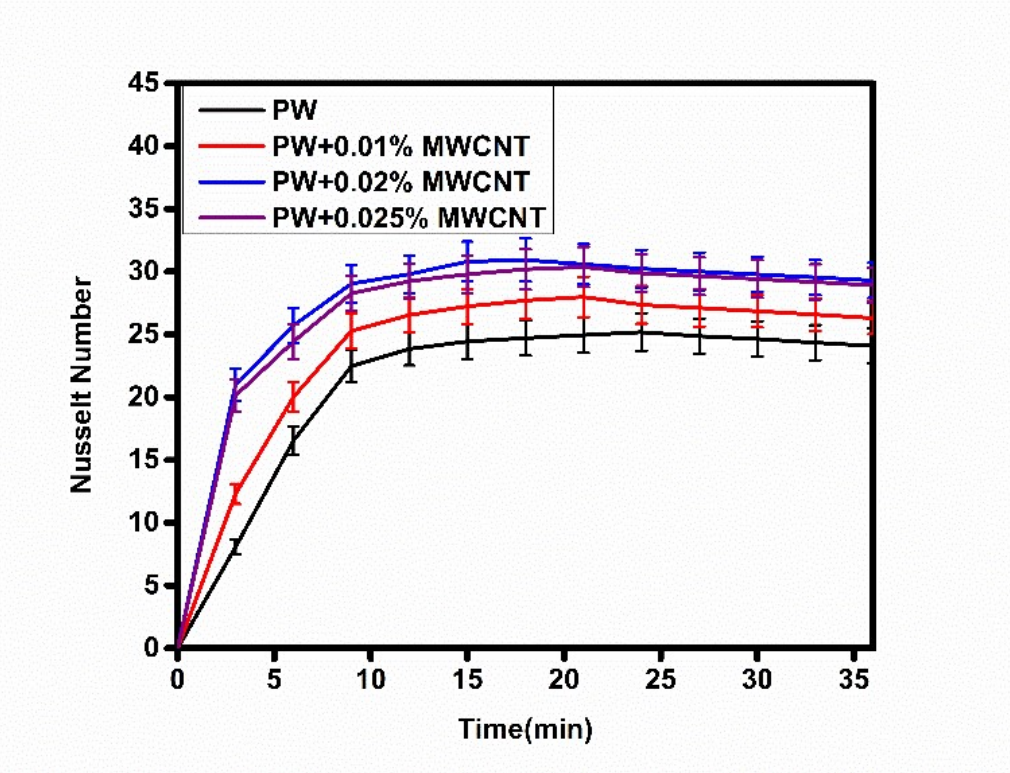


**Fig. 5.11(c).**Nusselt Number of paraffin wax PCM/NEPCM

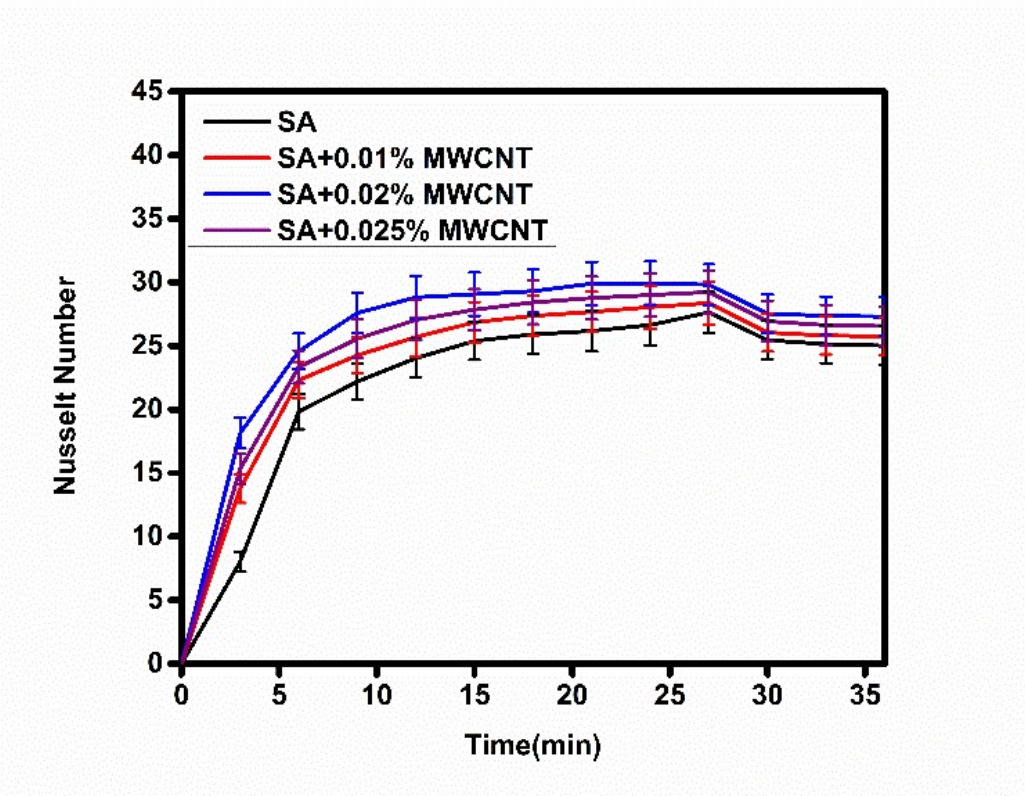


**Fig. 5.11(d).** Nusselt Number of stearic acid PCM/NEPCM

### 5.3.4. Variation in heat transfer coefficient PCM/NEPCM

Variations in the heat transfer coefficient of MWCNT in LA, PW, and SA composite PCMs have been shown in Figs. 5.12(a-d). Results revealed that 0.02% MWCNT in CA, LA, PW, and SA composite PCMs obtained 13.8%, 42.89%, and 52.8. Also, the maximum heat transfer coefficient of 0.02% MWCNT in paraffin wax increased by 62.8% and 114.9% to 0.02% MWCNT in LA and SA, respectively.

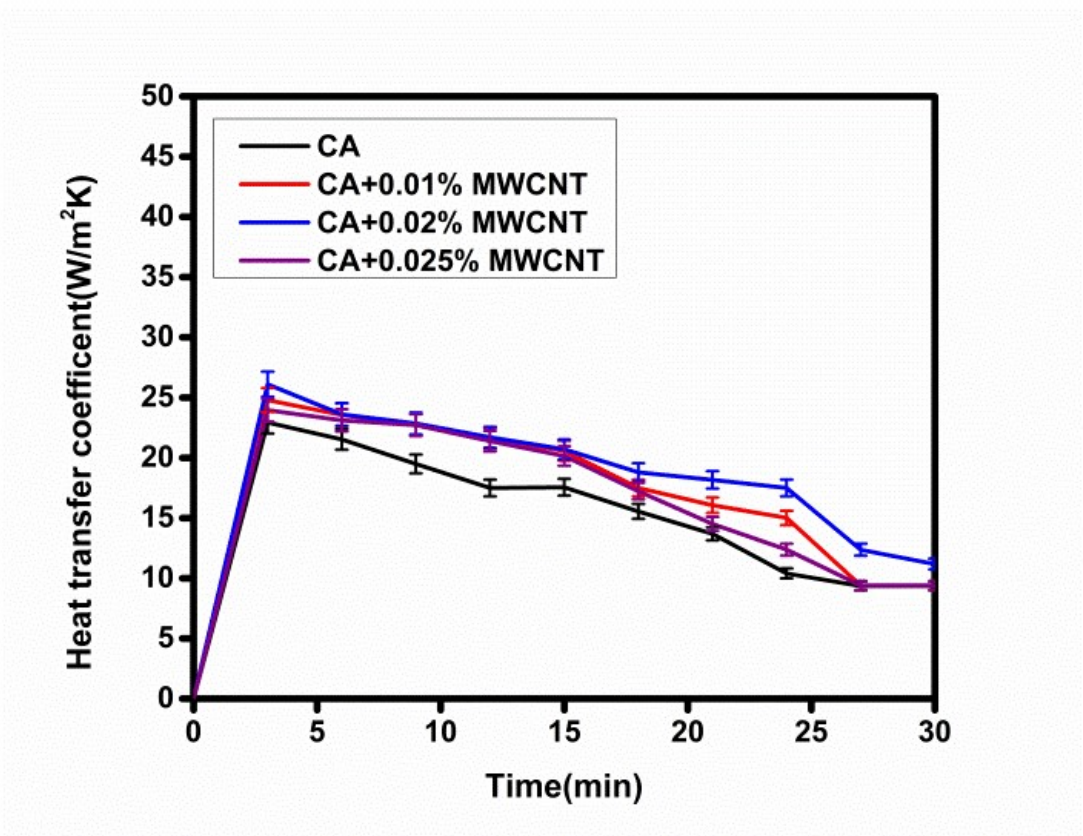


**Fig. 5.12(a).** Heat transfer coefficient of capric acid PCM/NEPCM

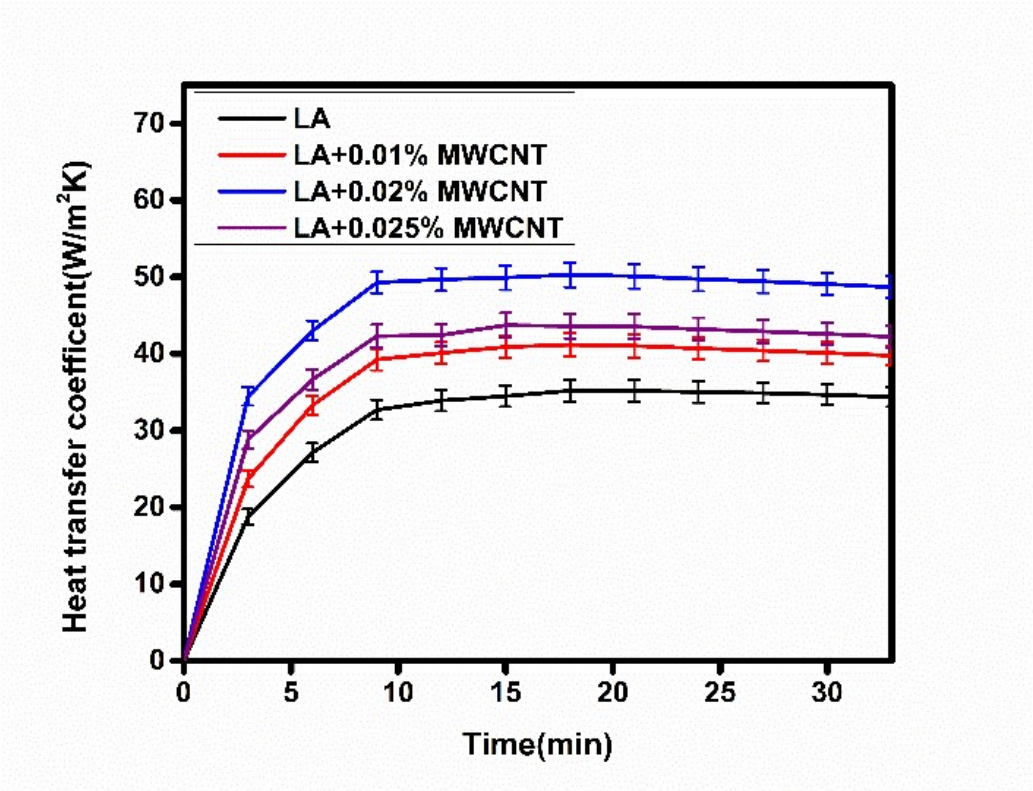


**Fig. 5.12(b).** Heat transfer coefficient of lauric acid PCM/NEPCM

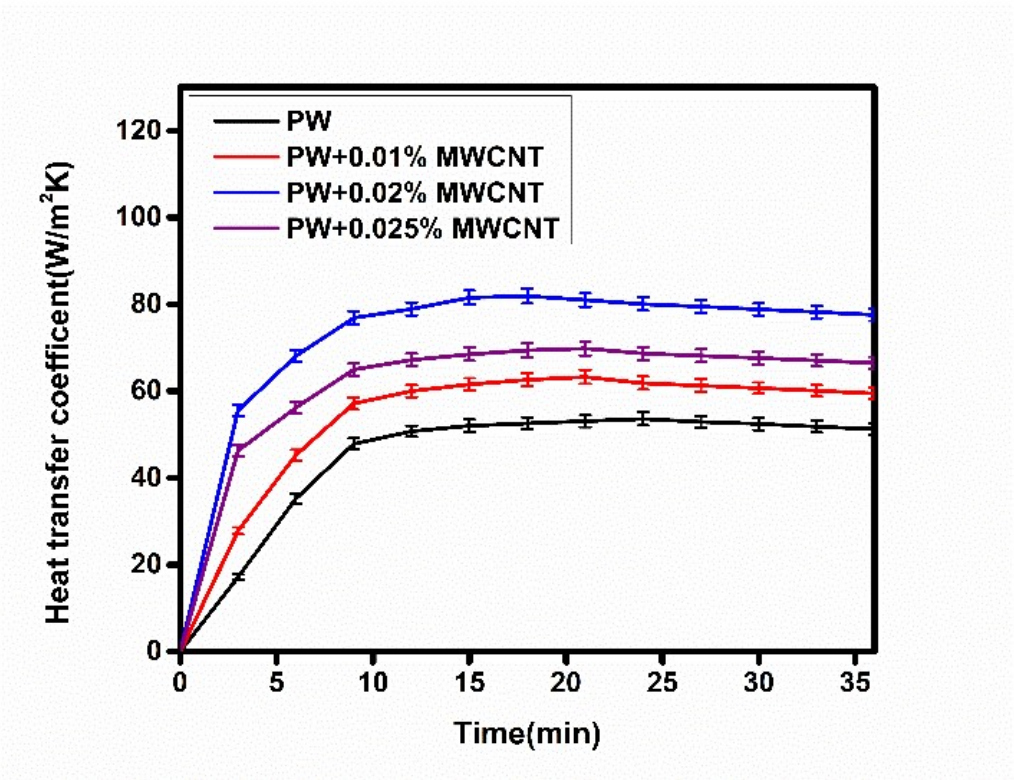


**Fig. 5.12(c).** Heat transfer coefficient of paraffin wax PCM/NEPCM

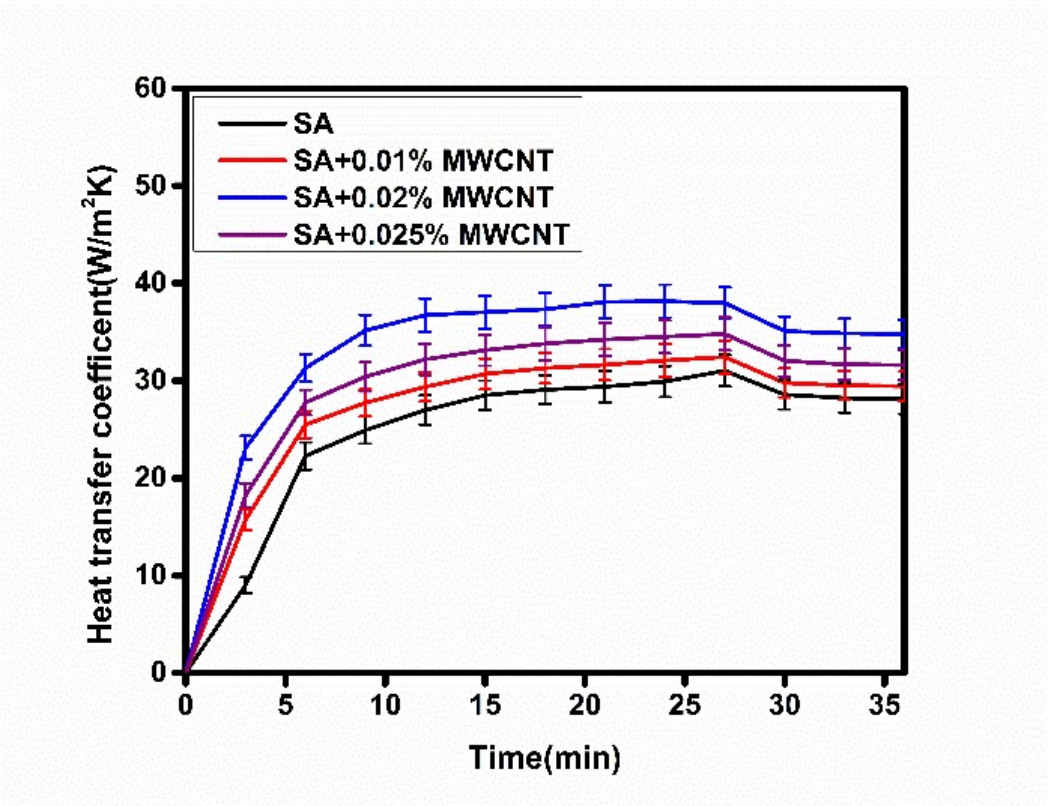


**Fig. 5.12(d).** Heat transfer coefficient of stearic acid PCM/NEPCM

### 5.3.5. Variation in the heat transfer rate of PCM/NEPCM

The variation in heat transfer rate during charging of pure PCMs such as CA, LA, PW, and SA was compared to MWCNT volume fractions of 0.01%, 0.02%, and 0.025% based on CA, LA, PW, and SA PCMs. As shown in Figs. 5.13(a-d), the heat transfer rate in MWCNT of 0.02% volume fraction based CA, LA, PW, and SA phase change materials increased by 30.97%, 61.16%, 87%, and 26.4%, respectively, with CA, LA, PW, and SA PCMs. It happened because the thermophysical characteristics (thermal conductivity and specific heat capacity) have improved as MWCNT has been added to PCMs to a certain extent. In addition, the charging time of MWCNT from 0 to 0.02% volume fraction-based PCMs is reduced due to the reduction in latent heat of fusion. Furthermore, due to the problem of MWCNT particle settling in PCMs, the heat transfer rate was decreased after adding a 0.02% vol. fraction of MWCNT-based PCMs.Also, Parafin wax with 0.02% MWCNT-based PCM shows the optimum heat transfer rate to other samples of PCMs. It is observed that the maximum heat transfer for 0.02% MWCNT in paraffin wax was 37.2% and 215%, higher than the 0.02% volume fraction of MWCNT in lauric acid and stearic acid, respectively, based on thermal energy storage.

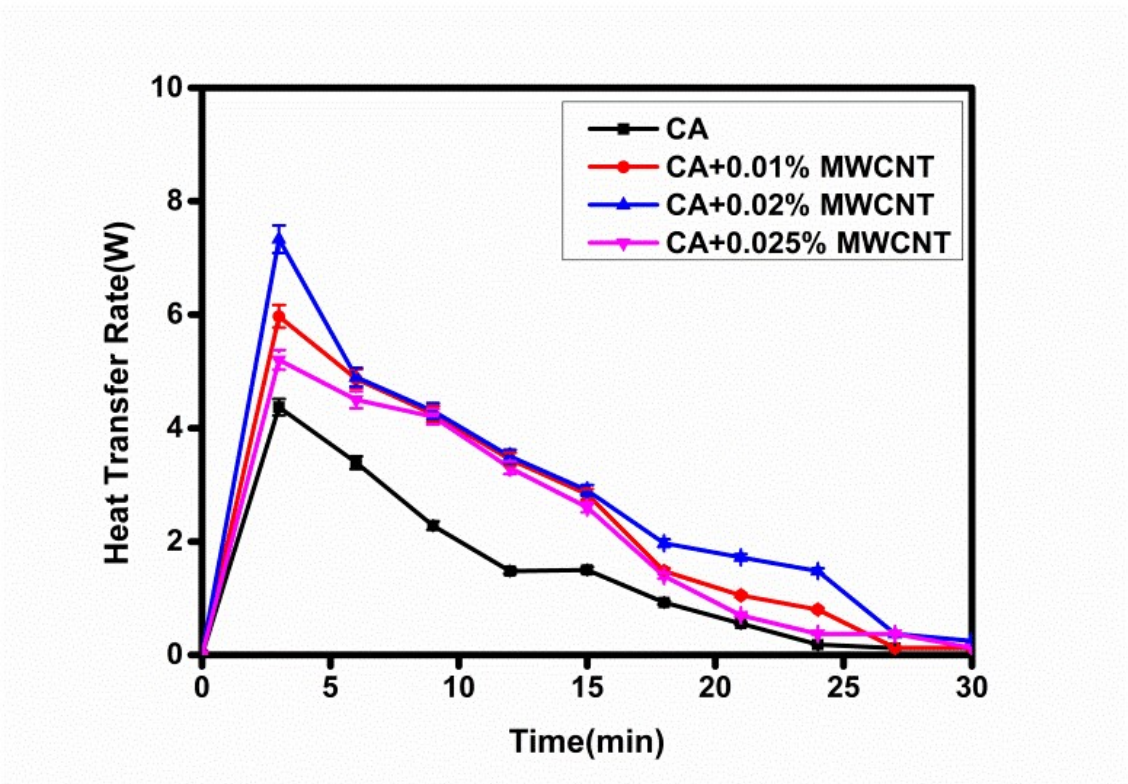


**Fig. 5.13(a).** Heat transfer rate of capric acid PCM/NEPCM

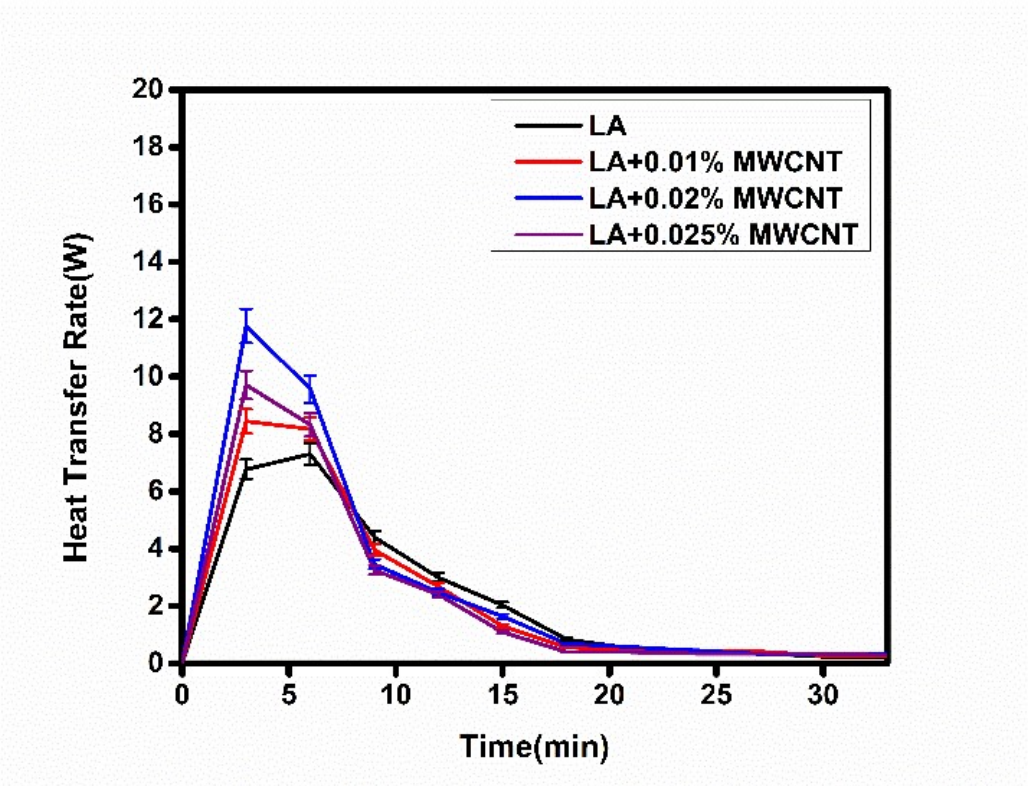


**Fig. 5.13(b).** Heat transfer rate of lauric acid PCM/NEPCM

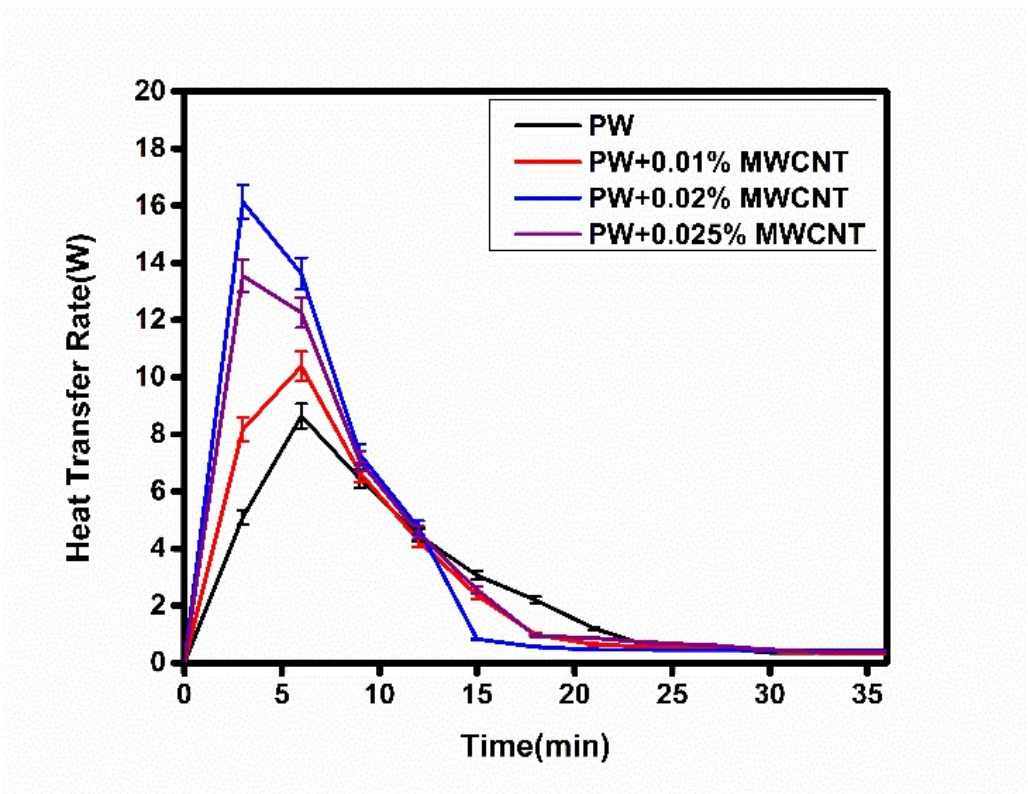


**Fig. 5.13(c).** Heat transfer rate of paraffin wax PCM/NEPCM

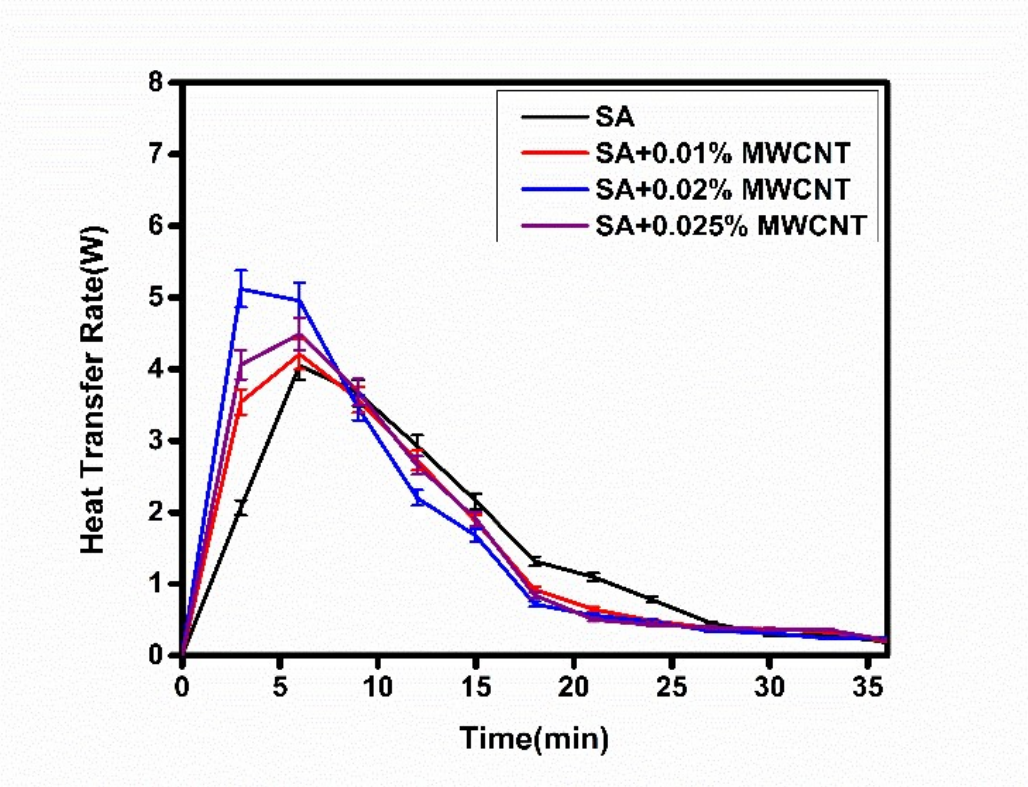


**Fig. 5.13(d).** Heat transfer rate of stearic acid PCM/NEPCM

## 5.4. Highlights

- The present experimental study revealed that 0.02% volume fraction MWCNT nano additives in CA, LA, PW, and SA composite phase change materials had shown an optimum result than pure CA, LA, PW, and SA PCMs.
- Also, 0.02% MWCNT in PW has better thermophysical parameters than 0.02% MWCNT in NEPCMs containing LA or SA phase change material-based thermal energy storage.
- Due to the reduction in the latent heat and increment in thermal conductivity with the addition of MWCNT from 0-0.02% vol. fraction based on CA, LA, PW, and SA composite phase change materials, the heat transfer rate increases.
- Experimental results revealed that the Nusselt number varies from 0 to 31, justified by conduction and convection processes' heat transfer across the boundary.
- Variation of the Rayleigh number shows the heat transfer process is in natural convection from the experimental data. Furthermore, with an increase in the vol. fraction of MWCNT from 0 to 0.02% in CA, LA, paraffin wax, and SA PCMs, the variation in Rayleigh number increases, and after then decreases.
- The melting time for the vol. fraction 0.02% MWCNT based CA, LA, PW, and SA composite phase change materials required less time than others considered vol. fractions of MWCNT-based NEPCMs.