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Original Research Paper

Paraffin core-polymer shell micro-encapsulated phase change materials and expanded graphite particles as an enhanced energy storage medium in heat exchangers

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ABSTRACT

The Micro-Encapsulated Phase Change Materials (MEPCMs) with the melting point temperature of 28 °C was used as an energy storage medium to control the thermal behaviour of a heat exchanger. The NEPCM particles were mixed with Expanded Graphite (EG) microparticles to improve the heat transfer rate in the heat exchanger. The MEPCM particles are made of paraffin cores with a particle average size of 45 μm. The paraffin core of the particles can undergo a solid/liquid phase change and store a tremendous amount of thermal energy due to the latent heat of phase change. The heat exchanger is a copper pipe radiator with aluminium fins confined in either a bed of MEPCMs or a composite mixture of MEPCMs + Expanded Graphite (EG) microparticles. The thermophysical properties of MEPCMs and MEPCM + EG were measured. The outcomes show 132% enhancement in thermal conductivity and a 28% decrease in the sensible specific heat of the MEPCM + EG composite with the weight ratio of 70% MEPCM and 30% EG compared to pure MEPCM. The charging and discharging behaviour of heat exchanger for various flow rates and two cases of MEPCM and MEPCM + EG were studied experimentally. The results reveal that using EG notably enhances the heat transfer and capability of the heat exchanger during the charging and discharging process. Using MEPCM + EG reduces the temperature drop at the heat exchanger outlet about 15 °C compared to the case of pure MEPCM.

1. Introduction

In recent years, the use of renewable energy has become an important subject. The crisis, due to shortages of petroleum, electricity, and other natural resources, has also caused an economic shock. Therefore, many of the sudden economic downturns are due to energy problems. In order to prevent the energy crisis, energy saving has become an urgent priority. Energy storage systems are known as a potential research route. The use of renewable energy is particularly widespread not only due to the reduction of energy consumption but also to reduce environmental damages. Nowadays, thermal energy storage has been utilized in various applications such as textiles, building materials, refrigerants, healthcare, and aerospace.

The principle of thermal energy storage using phase change material (PCM) is to use the latent heat of phase change (liquid/solid) to store thermal energy. In the phase transition process, a large amount of energy can be stored and released, which adds considerable feasibility to practical applications. PCMs can be categorized into two types of organic and inorganic materials. Organic PCMs can be classified as paraffin and non-paraffin [1]. Most organic phase change materials are non-corrosive and chemically stable and compatible with building materials, with high latent heat and low vapour pressure per unit weight. However, despite extensive research to increase the heat transfer rate, they still do not change their low thermal conductivity, substantial volume changes during phase change and flammability.

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Inorganic materials (salt brine compounds and metals) are relatively inexpensive and non-flammable compared to organic materials and have high latent heat and high thermal conductivity per unit volume. However, they are corrosive to most metals, with problems of decomposition and local cooling, which may affect their phase change properties. Therefore, to overcome the above problems, a microencapsulated PCM is born. The main advantages of the microcapsule PCM are as follows: (1) increasing the heat transfer area, and (2) reducing the reactivity of the PCM to the external environment and controlling the substantial volume change of the raw material due to the phase change.

The literature review on the thermal energy storage of PCMs shows that the low thermal conductivity of PCMs significantly decreases the efficiency of thermal energy storage/release to satisfy the need for thermal energy recovery. For instance, Longeon et al. [2] explored the thermal energy storage/release of a coaxial PCM heat exchanger, in which the shell side was filled with paraffin. There was a laminar flow inside the tube. The results show that the energy of PCM cannot efficiently be transferred to the water, and the flow in the tube is not efficient. The outcomes indicated that the efficiency of the heat exchanger was 15% during energy release and 26% during energy storage. Mahdi et al. [3] utilized a combination of nano-additives and fins to enhance the response time of solidification in a triplex-tube heat exchanger. Results show that using fins and nano-additives reduces the solidification time. Considering a fixed weight of fins and nanoparticles, the efficiency of using fin with no nano-additives is better than using fins and nano-additives. Parsazadeh and Duan [4] theoretically investigated the effect of using fins and nano additives to enhance the response time of a shell and tube phase change unit. The outcomes revealed that using alumina nanoparticles deteriorated the charging response time of the enrgy storage unit. Gasia et al. [5] employed the idea of pumping the liquid PCM in the PCM side of a heat exchanger to use the aid of forced convection and enhance the thermal energy recovery of the heat exchanger. The results show 56.4% on the effectiveness, 66% on the heat transfer rates, and 65.3% on the melting period. However, the phase change material was water and using other types of PCMs has the practical problems of PCM leakage, environmental hazards, and pumping limitation. Finck et al. [6] and Junker et al. [7] studied the dynamic response of the building energy system with thermal energy storage [6] and energy flexibility [7]. Using a thermal energy system, covering the response need of a building heating system can improve the thermal management and flexibility building energy management.

These recent studies [2–5] show that much efforts and progress has been made to improve the time response of thermal energy storage/release in heat exchangers. However, problems such as leakage, packaging, flexibility, and the low thermal conductivity of PCMs are still demanding future researches. A novel way to reduce the leakage and packaging problems and increase the flexibility of thermal energy storage systems is using microencapsulation.

Gharsallaoui et al. [8] pointed out that microencapsulation is a method that can encapsulate tiny particles or drops in a matrix (regardless of whether the matrix is uniform), and can produce many tiny capsules of practical value. Sarier and Onder [9] divided microencapsulation into chemical and physical processes. Su et al. [10] prepared a double-shell microcapsule PCM with a melting point of 24 °C. Their experimental outcome shows that two-layer microcapsule PCM can prevent penetration compared to the single layer. In order to ensure proper heat storage, the optimal mass ratio of the outer shell to the inner layer is 3 to 1.

The micro capsulation techniques for phase change materials have been investigated in many recent studies, and many researchers have successfully encapsulated phase change materials. For example, Döğüşcü et al. [11] prepared Micro Encapsule PCMs (MEPCMs) with n-alkane eutectics core and polystyrene as the shell. Leng et al. [12] synthesized a high-temperature energy storage MEPCM using chloride salt as core and diatomites as the shell. Zhang et al. [13] utilized paraffin as core and melamine-formaldehyde resin as the shell, which was enhanced by graphene oxide nanosheets. Magnetic MEPCMs with n-octadecane core and modified with Fe_3O_4 also have been synthesized benefiting phase change advantages and magnetic properties [14].

The encapsulation of PCMs and preparation of a stable MEPCMs have been subject of several recent patents [15,16]. There are also several recent patents that they have embedded MEPCMs in flexible matrixes and synthesized flexible composite phase change material [17,18]. Moreover, some of the encapsulation techniques and application of MEPCMs are reviewed in several recent excellent studies [12,19–21]. Zhou et al. [22] employed MEPCMs in the roof of a building for thermal storage purpose. The paraffin core MEPCMs were filled in aluminum honeycomb boards and mounted at the roof a building. The outcomes show that using MEPCM can shift the energy peak load of the building, but also it had the drawback of a slightly raising the indoor heat gain. The MEPCMs were properly phase changed to a solid state during the night times to be prepared for cooling of the building in the day. The MEPCMs are also utilized in wood floors for energy storage in buildings [23].

Zhang et al. [24] dispersed MEPCMs into a fluid such as water and synthesized a microcapsule PCM slurry. They revealed that utilizing a MEPCM slurry in a refrigeration or air conditioning cycle results in the rise of energy efficiency and reduction in the amount of required refrigerant. Diaconu et al. [25] used a commercial MEPCM (product of CIBA Chemicals-UK) with a mass fraction of 45% as a heat transfer medium for air conditioning applications. The results showed that this system as an alternative to high-temperature energy storage ensures cooling requirements when energy supply is insufficient.

Ho et al. [26] attached a layer of MEPCM to the back of a photovoltaic module to enhance the temperature control and power generation efficiency of photovoltaic modules. The results showed that the presence of the microcapsule layer significantly improved the heat and electricity performance of the photovoltaic module. Ho et al. [27] investigated the forced thermal convection performance of MEPCM slurry in a tube subject to constant heat flux. The results showed that the presence of microcapsules enhances the convection heat transfer in the entrance regions of the tube. Also, at a concentration of 10% suspension, the increase of convection depends on the flow rate, heating power and the amount of phase change material. Compared with the pure water, the local heat transfer coefficient increased by 42% at a flow rate of 12.5 cm^3/min. Sabbah et al. [28] studied the heat transfer characteristics of a slurry of 10 μm diameter MEPCMs at a concentration between 0% and 20% in a tube subject to constant heat flux. The wall temperature distribution, the inlet and outlet temperatures of the fluid were measured experimentally, and the corresponding heat transfer coefficients were investigated. The results showed that the effect of parameters is very significant. More than 50% enhancement in the heat transfer coefficient and more than 40% enhancement on tube wall temperature were observed.

Ho et al. [29] investigated the thermal energy storage characteristics of a packed bed of MEPCMs in an air-filled enclosure. The phase change core of MEPCMs was made of n-octadecane with melting temperature of 24 °C. The bed of MEPCMs was modelled as a porous medium, and the flow and heat transfer of air in the space between the MEPCM particles was calculated. The results show that the phase change of microcapsule cores increases the unsteady duration of heat transfer in the enclosure. Fang et al. [30] conducted an experimental study on the thermal characteristics of microencapsulated phase change composite cylinders. The thermal performance of MEPCM composite samples were investigated for thermal energy storage applications. The results revealed that the temperature distribution was more uniform in the presence of additives.

The MEPCMs the same as most of the phase change materials have a low thermal conductivity. The low thermal conductivity of MEPCMs reduces the heat transfer rate and increases the required time of the charging/discharging process. The thermal conductivity of MEPCMs can be enhanced using high thermal conductive particles as additives [31], embedding MEPCMs in metal foams [32] or increasing the contact surface of MEPCM beds [33]. Wang et a. [31] utilized flake graphite (FG), expanded graphite (EG) and graphite nanosheets (GNS) to enhance the heat transfer of MEPCMs. The outcomes show significant thermal conductivity enhancement of MEPCMs by using graphite as the matrix.

Saeed et al. [34] experimentally investigated the performance of thermal energy storage in a vessel for load-shifting purposes. The heat storage vessel was a plate-type heat exchanger unit with water as the working fluid and a phase change material (PCM) as the energy storage medium. Wu et al. [35] proposed an experimental investigation to study the feasibility of an EG paraffin phase change material heat exchanger, which operates as a condenser in an instant air-source heat-pump water-heater. They studied the temperature distribution and volume expansion of an EG-paraffin heat exchanger. The heat exchanger was tested under different inlet water flow rates. The results showed that the volume expansion rate of a 16 L EGPHE was 6.25% at 76 °C. Also, When the inlet flow rate increased, the hot water volume increment rate decreased.

The present study aims to study the capability and performance of MEPCMs and MEPCM enhanced with Expanded Graphite (EG) as an energy storage medium. The charging and discharging process of heat exchanger confined in a bed of MEPCMs + EG for various flow rates of water is addressed. The contribution of the present study is utilizing a composite of MEPCMs as a thermal storage medium and EG microparticles as a thermal enhancement matrix for heat exchanger applications. Employing MEPCMs + EG does not reduce the flexibility of MEPCMs packaging. A composite of MEPCMs + EG can easily fill the complex geometry of heat exchanger fins with no leakage problem with the advantage of enhanced energy storage response time.

2. Experimental setup

The present study aims to investigate the charging and discharging energy storage performance of MEPCMs in a heat exchanger. The heat exchanger is placed in an acrylic box, and the box is filled with MEPCMs. The hot or cold water can flow in the heat exchanger to charge or discharge the bed of MEPCMs around the heat exchanger.

In order to study the energy storage performance of MEPCMs in the heat exchanger, an experimental setup is built. The experimental setup consists of two isothermal bathes, pumps, insulated plastic pipes, measurement systems, and a test module. Fig. 1 depicts the schematic diagram of the experimental setup. The test module consists of a finned heat exchanger confined in a bed of MEPCMs or MEPCMs + EG. A three-dimensional view of the heat exchanger is illustrated in Fig. 2 (a). Fig. 2(b) depicts the actual photo of the heat exchanger enclosed in the acrylic box. The geometrical details of the heat exchanger are given in Fig. 2(a).

The distance between the fins F_p is 5 mm. The fins are made of aluminium and welded continuously on copper tubes. The heat exchanger is placed in an acrylic box, which later this box will be filled by a compact bed of MEPCMs or MEPCMs/EG to confined the heat exchanger. The acrylic box is a cube of 25.5 cm length, 25.0 cm width, and 9.0 cm height. There are two drilled holes in the side of the box for inlet and outlet of the heat exchanger. After filling with MEPCM/EG, the acrylic box will be well covered and insulated by a layer of insulation cotton to prevent heat losses.

MEPCMs in the present study are made of paraffin cores and polymer shells with an average size of 45 μm and a melting point of 28 °C. Details of MEPCMs are shown in Table 1. It is well-known that the thermal conductivity of polymers and most of phase change materials, including paraffin is very low. Thus, EG with high thermal conductivity can be mixed with MEPCMs to provide a composite of MEPCM/EG as a thermal storage medium with enhanced thermal conductivity. The properties of utilized EG are summarized in Table 2. Fig. 3 (a) and (b) depict the samples of MEPCMs + EGs, respectively.

The experiments are performed for two cases of the acrylic box filled with pure MEPCMs or filled with a composite mixture with the weight composition of 70% MEPCMs and 30% EG. In the case of the composite mixture of MEPCMs + EG a ball mill (12 balls and 3 h of stirring) is used to mix the MEPMCs and EGs well.

Considering the diagram of the experimental setup, depicted in Fig. 1, there are two isothermal bathes, one with a low isothermal temperature of 10 °C, and the other one with a high isothermal temperature of 50 °C. By using some valves, it is possible to control the flow of the hot water and the cold water through the heat exchanger. The water flow may charge or discharge the MEPCMs

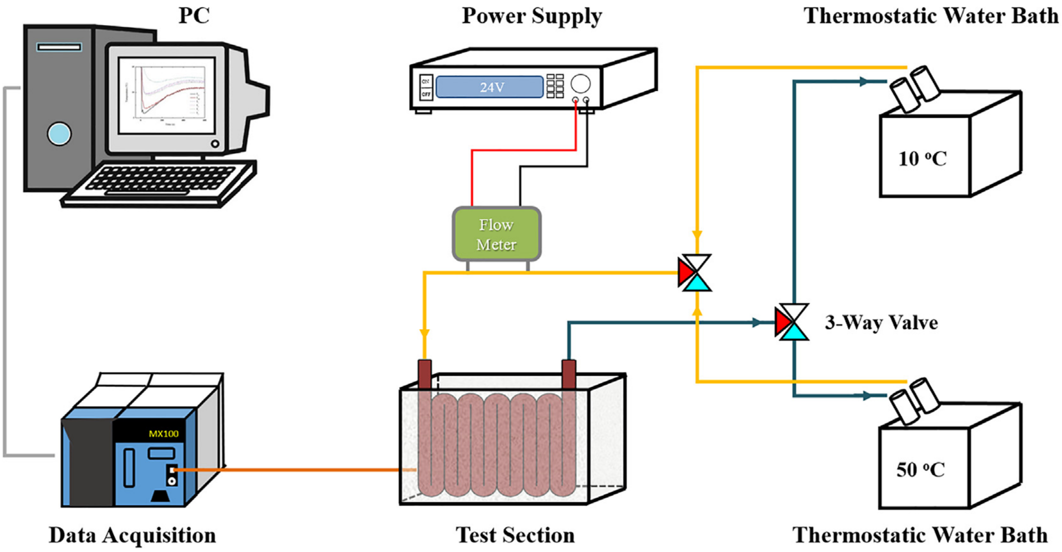


Fig. 1. Schematic diagram of experimental equipment.

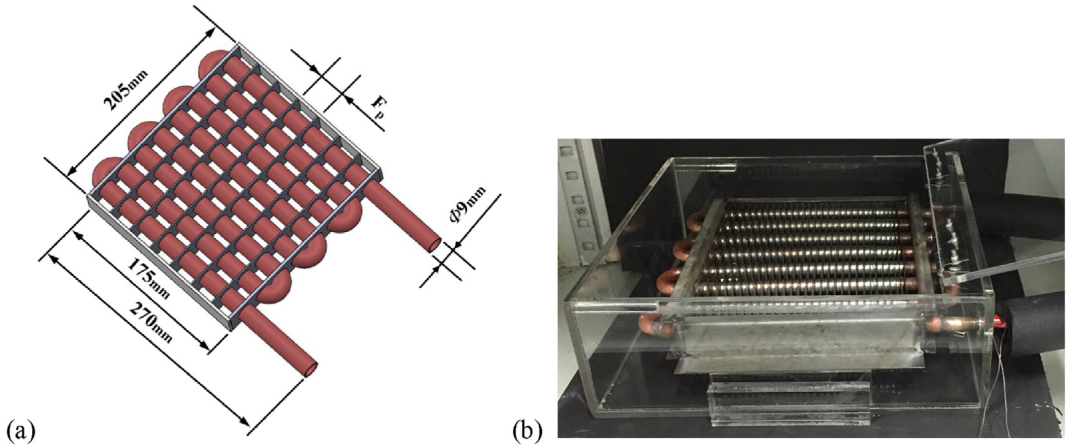


Fig. 2. The heat exchanger utilized for the test section; (a) A three-dimensional view of the geometric model of the heat exchanger, (b) The actual photo of the heat exchanger F_p = 5 mm.

Table 1
Microcapsule phase change material properties [37].

Property	Value
Appearance	White to slightly off-white color
Form	Dry Powder (≥97% Solids)
Capsule Structure	85–90 wt% PCM 10–15 wt% polymer shell
Core Material	Paraffin
Particle Size (Mean)	15–30 μm
Melting Point	28 °C
Latent Heat	180–190 J/g
Temperature Stability	Extremely stable – less than 1% leakage when heated to 250 °C
Thermal Cycling	Multiple
Density	452.6 (kg/m^3)

depending on the temperature of the fluid inside the heat exchanger.

The measurement system in this experiment consists of a data accusation system, a data storage module, an ultrasonic flowmeter, and several t-type thermocouples. The flowmeter measures the flow rate of water flowing through the heat exchanger. A thermocouple was placed inside the plastic pipe just before the entrance of the heat exchanger and sealed. Another thermocouple was placed inside the plastic pipe just after the heat exchanger outlet and sealed. These thermocouples measure the inlet and outlet temperatures of the heat exchanger. The placement of thermocouples inside the pipes allows direct measurement of the flow temperature and avoids the errors of attaching the thermocouples to the walls of copper pipes.

Table 2
Expanded Graphite Properties [38] and EG + MEPCM.

Property	Value
Type	G36C-300–85
Appearance	Black Powder
Material	Carbon Graphite
Particle Size (Mean)	45 μm
Fixed Carbon (%)	85.3
Ash (%)	12.5
Volatile Matter (%)	2.2
Moisture (%)	0.22
Density	560.8 kg/m^3
Thermal conductivity enhancement of EG + MEPCM composite $(k_{MEPCM+EG}- k_{MEPCM})/(k_{MEPCM})$	132%
Sensible specific heat $(C_{MEPCM+EG}- C_{MEPCM})/(C_{MEPCM})$	−28%
30% EG + 70% MEPCM	485.1 kg/m^3

The experiments are performed in two stages: the charging experiments and the discharging experiments. In the charging experiment, initially the MEPCMs are cold, and the paraffin cores are frozen. Flowing hot water in heat exchanger increases of the temperature of the heat exchanger pipes, and MEPCMs absorb a

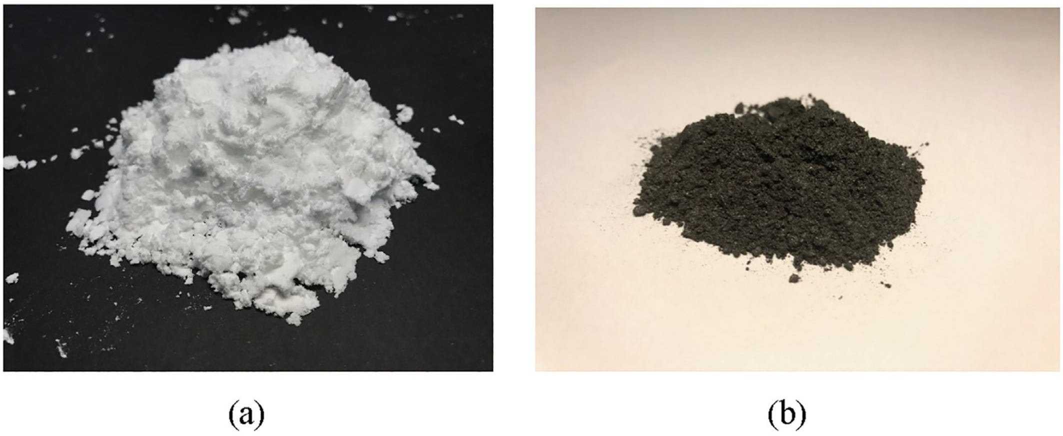


Fig. 3. (a) Micro-encapsulated phase change material, (b) Expanded graphite (EG).

significant amount of heat and phase change to a hot liquid. As described, the charging process commences by flowing hot water into the heat exchanger. However, before the charging stage, the cold water with the temperature of 10 °C was flowing in the heat exchanger for at least 30 min, and the steady outlet temperature was monitored to ensure that the MEPCM bed is uniformly in the cold discharged frozen state. Then, the charging stage was commenced by changing of the control valves to quickly shift the cold water into a bypass loop and allowing 50 °C hot water flow in the heat exchanger.

The discharging experiment is roughly similar to the charging experiment, and usually, it was performed following the charging experiment. In this case, before commencing of the discharging experiment, the uniform fully charged bed of MEPCMs was ensured by flowing 50 °C hot water in the heat exchanger and monitoring the outlet temperature. Then, the discharging experiment was initiated by a sudden change of the direction of 10 °C cold water into the heat exchanger and transferring the hot water to a bypass loop. The charging and discharging experiments were repeated for various water flow rates, and the outlet temperatures were monitored with the time interval of 2 records per second.

3. Thermophysical properties

This section firstly presents the thermophysical properties measurement results of composite microcapsule phase change materials. The thermophysical properties include density, heat transfer coefficient, and DSC measurement. The specific heat is calculated from DSC data. Following Ho et al. [27], the effect of convection heat transfer in MEPCMs bed was neglected, and the microcapsule PCM is considered as a simple uniform substance.

The bulk density of MEPCM/EG composite was evaluated using the density of its components. The capsule shell is a polymer, the PCM is sealed inside, and when the phase change reaction occurs, the density does not change as a function of temperature and considered as a constant. The measured density of the MEPCM was 452.6 kg/m^3; the measured density of EG was 560.8 kg/m^3. Considering 70% MEPCM and 30% EG, the density of the MEPCM/EG composite was calculated as 485.1 kg/m^3.

The thermal conductivity of MEPCMs and MEPCM + EG was measured using KD2-Pro probe. Fig. 4 shows the measured thermal conductivity as a function of temperature. The phase change point is 28 °C. This figure shows that the thermal conductivity outside the phase change range decreases slightly with increasing the temperature. However, the thermal conductivity changes drastically in the phase change range due to the phase change process. In the phase change range, the microcapsule PCM will absorb a large amount of latent heat, so that, the temperature difference in contact with the KD2-Pro probe remains small. Therefore, KD2-Pro overestimates the thermal conductivity in the phase change region. The thermal conductivity coefficients for the pure MEPCM and the composite MEPCM + EG are 0.22 W/m K and 0.51 W/m K, respectively. It is clear that the presence of EG particles significantly increased the thermal conductivity coefficient of the composite.

Following McHugh et al. [36], the specific heat of MEPCM and MEPCM + EG are measured using DSC curves. The specific heat of MEPCM and MEPCM + EG, including the phase change effects, were calculated as 25 kJ/kg K, and 18 kJ/kg K, respectively. The presence of EG microparticles increases the thermal conductivity about 132% and decreases the sensible specific heat of the composite by 28%.

Fig. 5 shows DSC curves of MEPCM (Pure) and MEPCM + EG (Composite) for two cases of cooling and heating and various values of heat flow. The peak area of the bell curve is the latent heat of the MEPCM, and the peak temperature is the melting point temperature of the microcapsule phase change material. When the MEPCM is subjected to the cooling measurement, there are two peaks in the solidification curve. One of them is the homogeneous nuclear condensation of the same molecule, and the other is the heterogeneous nuclear condensation of different molecules. It should be noted that the solidification temperature is lower than the melting temperature.

4. Results and discussion

4.1. The effect of heat storage time

The thermal energy can be stored using the latent heat of phase change in the paraffin core of microencapsulated particles. Therefore, the flow of high-temperature water in the heat exchanger can melt down the paraffin core of MEPCMs and store a significant amount of energy in MEPCM bed. However, as the heat transfer in MEPCM bed occurs due to the conduction mechanism, a considerable amount of time is required to melt down all of MECPM cores.

Here, at the beginning of the experiment, the required time to fully charge the MEPCM bed is studied. As pure MEPCM without EG has the lowest thermal conductivity, the case of pure MEPCM is selected as the worst charging case. The middle range flow rate

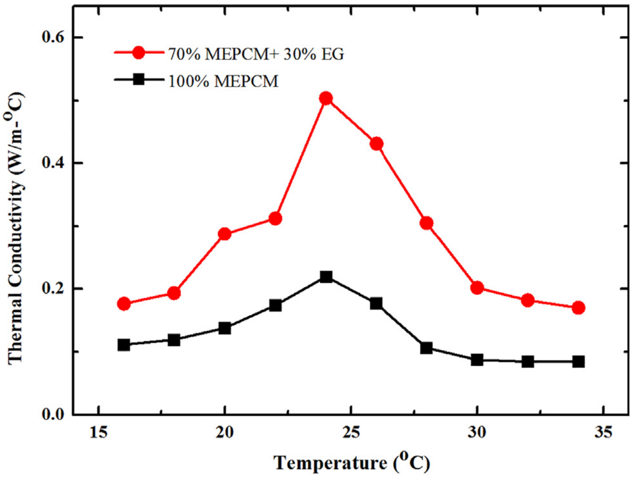


Fig. 4. Thermal conductivity coefficient as a function of temperature for MEPCM and MEPCM + EG.

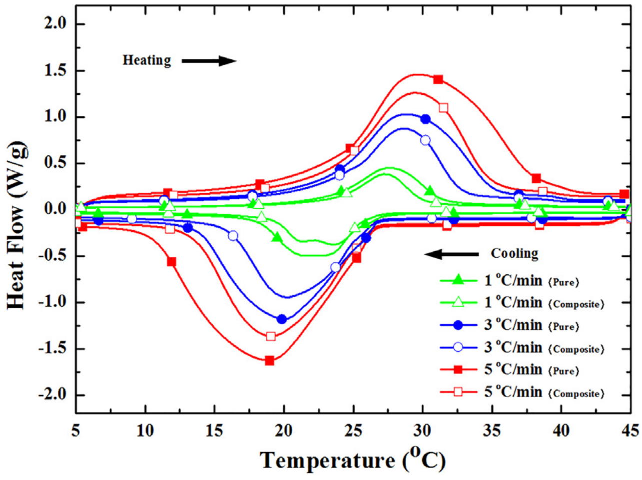


Fig. 5. Shows DSC heat curves of pure MEPCMs and MEPCM + EG composite under different heating and cooling rates.

of 45L/h is also adopted for the flow rate of water. Four cases of half an hour, one hour, three hours, and 13 h are selected for charging time of MEPCM bed. Then, the discharging process commenced by entering the cold water with a temperature of 10 °C. The temperature outlet as a function of time is plotted in Fig. 6 for the time interval of the 1,800 s. As seen, the thermal behaviour of discharge of the heat exchanger is almost independent of the charging time. Hence, it can be concluded that at least 30 min of charging time is adequate for fully charging of the heat exchanger.

4.2. Effect of flow rate

Fig. 7 shows the outlet temperature of the heat exchanger filled with MEPCM for various volume rates of hot water. This is the energy storage case, in which the hot water with the hot temperature of 50 °C flows into the heat exchanger. Before the charging process, the cold water with the cold temperature of 10 °C was circulating in the heat exchanger. Then, suddenly, the cold flow bypassed, and the hot water commenced to flow into the heat exchanger. Fig. 7(a) depicts the outlet temperature at the initial times. As seen, although the 50 °C hot water has entered in the heat exchanger, the outlet is fixed at 10 °C for several seconds. This is since the heat exchanger initially is filled with cold water, and entering the hot weater pushes the cold water toward the heat exchanger outlet. Therefore, there is a delay in hot water to reach the outlet. This delay is proportional to the length of copper pipes in the heat exchanger and the inverse of flow rate (liquid velocity). As seen in Fig. 7, an increase in the flow rate decreases the delay of reaching the hot water to the outlet. By the increase of the flow rate, the liquid moves in the pipes faster, and consequently, it reaches the outlet in a shorter time. It should be mentioned that the delay is not only due to the required time to hot water reaches to the outlet. The sensible heat of heat exchanger also contributes to this delay. For instance, for the water with the flow rate of 15 L/h about 40 s is required to the temperature of outlet start raising. This time is only about 10 s for the water with a flow rate of 95 L/h.

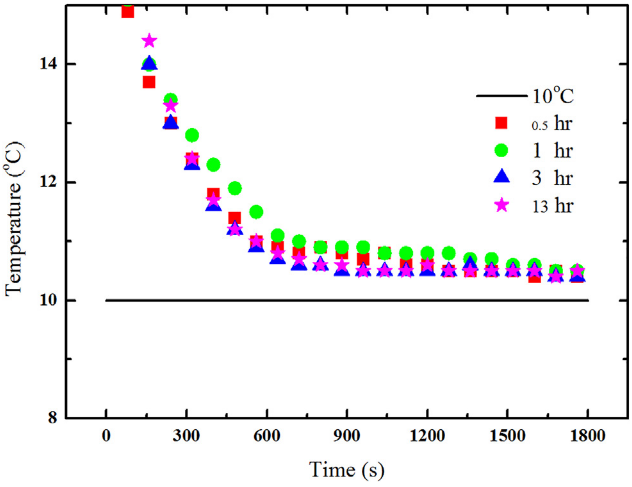


Fig. 6. The outlet temperature of heat exchanger filled with MEPCM as a function of time during the discharging process for various charging durations.

Fig. 7(b) shows the outlet temperature up to 1,800 s. This figure shows that most of the curves have reached a steady outlet temperature at the 1,200 s. Fig. 7(a) demonstrates that MEPCM tends to prevent the temperature rise in the flow outlet by absorbing a sufficient amount of energy from the hot water. Thus, considering the moderate flow rate of 45 L/h, 60 s time is required to outlet temperature reaches 40 °C. By the increase of the flow rate, the temperature raises faster since a larger amount of water can provide more energy to be stored in the MEPCMs. At times higher than the 1200 s the outlet temperature is constant and close to the inlet temperature of 50 °C.

In the case of high flow rates, mostly higher than 65 L/h, the charging curves are very close together in the initial and steady times. Thus, it can be concluded that in these cases, the hot water can provide a sufficient amount of energy to be stored in MEPCMs, but the MEPCMs are unable to absorb the provided energy adequately. Therefore, the heat transfer is limited by the thermal absorption capability of MEPCMs. In contrast, the meagre flow rate of 15 L/h shows slightly abnormal behaviour. This is due to the low volume rate of water. In this case, water flows in the pipe very slowly, and the charging of MEPCMs is limited by the amount of the energy that hot water can provide. So, PCMs are charged very slowly. After a very long time, in which the outlet reaches to a steady situation, a small difference between the inlet and outlet temperatures can be observed. This difference is notable in the cases of water with low flow rates. This difference is due to heat

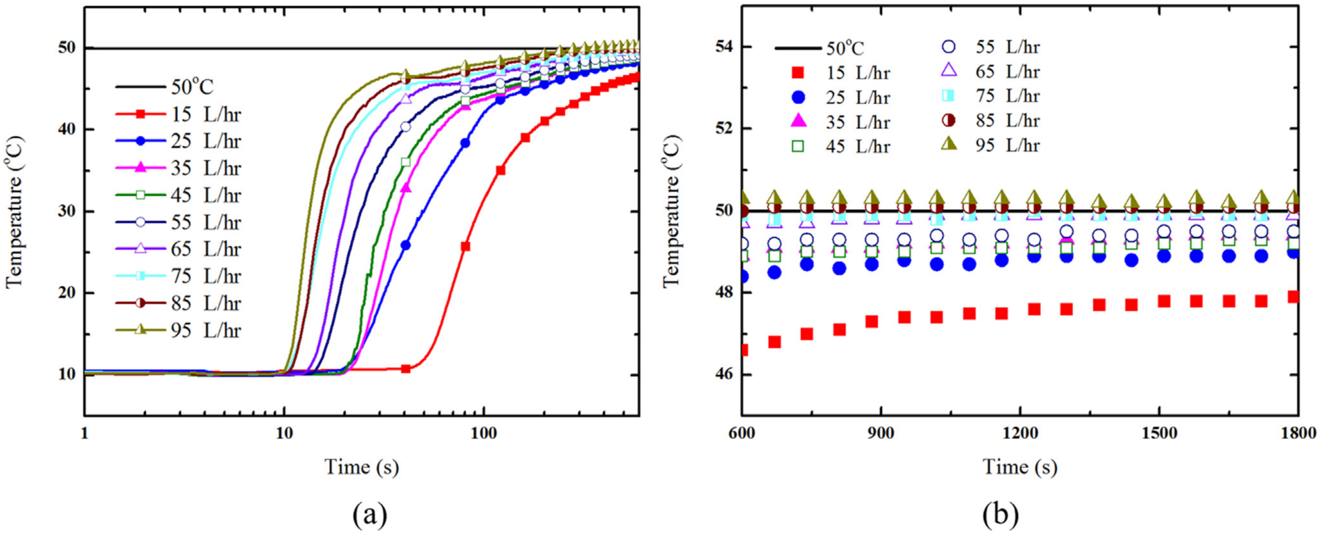
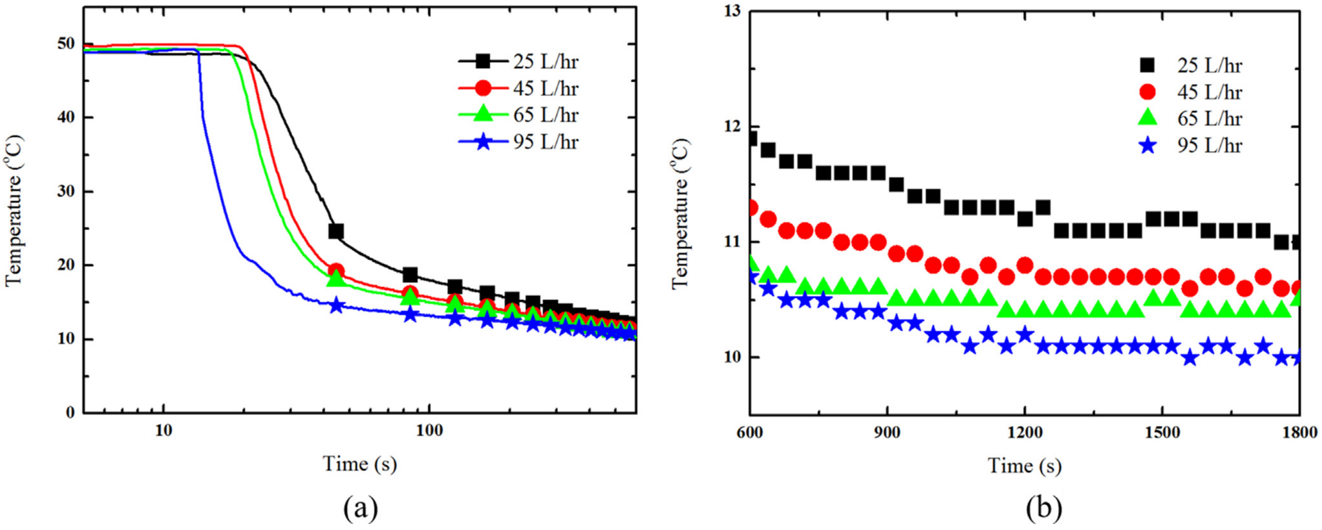


Fig. 7. Outlet temperature of heat exchanger filled with MEPCM for various flow rates in the case of energy storage; (a) Initial states, (b) Steady state.

losses of the experiment at the long pipes, metal gate values, and the heat exchanger insulation.

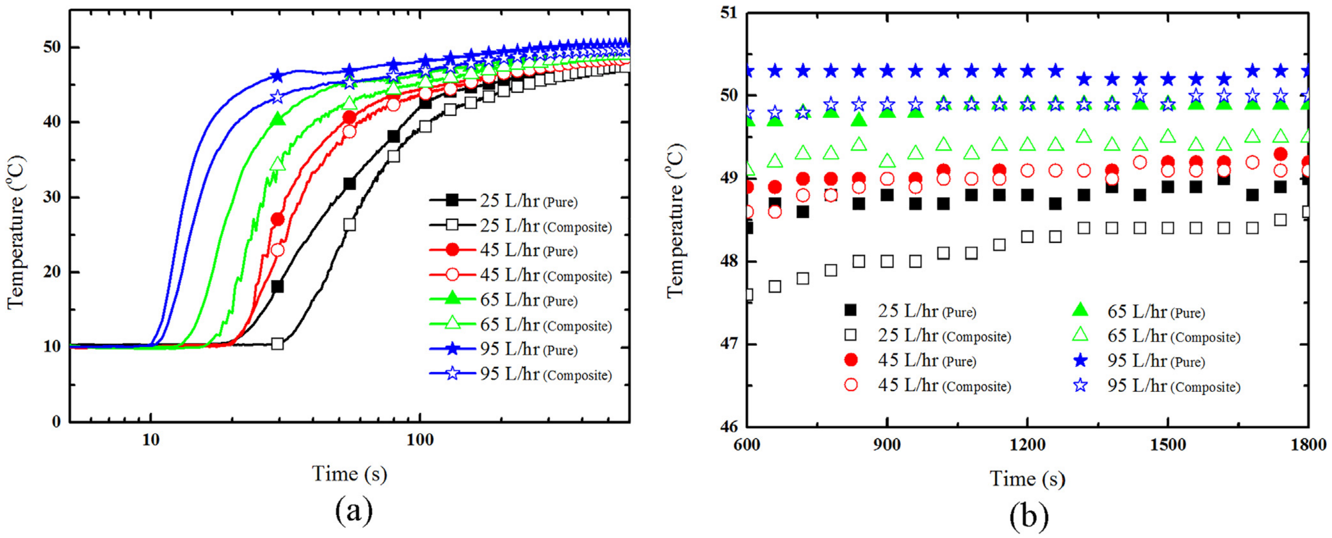
Fig. 8 shows the outlet temperature of the heat exchanger during the discharge process for various flow rates. Before discharge, 50 °C hot water was flowing in the heat exchanger. Then suddenly, the hot water bypassed and the cold water with a temperature of 10 °C has entered the heat exchanger. Thus, similar to the results of Fig. 7, there is a delay to cold water reaches to the outlet. Fig. 8(a) depicts the outlet temperature for initial times in logarithmic time scale. As expected, the higher the flow rate, the sooner cold water rehashes the outlet. As it was observed in the charging process of Fig. 7(b), the low flow rate of 25 L/h leaves the heat exchanger with a temperature difference about 2 °C, i.e., the outlet temperature of 48 °C.

In Fig. 8(a) is also clear when the cold water reaches the outlet, the outlet temperature drops notably. At this stage, the sensible heat of heat exchanger pipes and MEPCMs next to the pipes play a significant role by quickly release heat and warming the water flow. So, at this stage, the heat transfer process is dominated by the heat absorption potential of the water in the pipe. The higher the flow rate, the faster the temperature drop. The outlet temperature of the low flow rate of 25 L/h drops smoothly. This is because the amount of water moving in the heat exchanger is small, and the heat exchanger warms the water quickly. So, the water cannot carry a significant amount of energy out of the heat exchanger. After about 100 s, all of the outlet temperature curves converge together; this is when the latent heat of MEPCMs dominates the heat transfer process. In this stage, the outlet temperature is mostly controlled by the heat transfer capacity of heat exchangers. The lower the flow rate, the higher outlet temperature. The steady outlet temperature in Fig. 8(b) shows that the steady cold temperature of 24 L/h leaves the heat exchangers with a temperature about 11.5 °C, which is about 1.5 °C temperature difference from cold inlet temperature. This is due to the heat losses in the metal valve connections, long pipes, and insulation of heat exchangers. It is clear that the increase of flow rate to 95 L/h decreases to outlet temperature to about 10 °C.



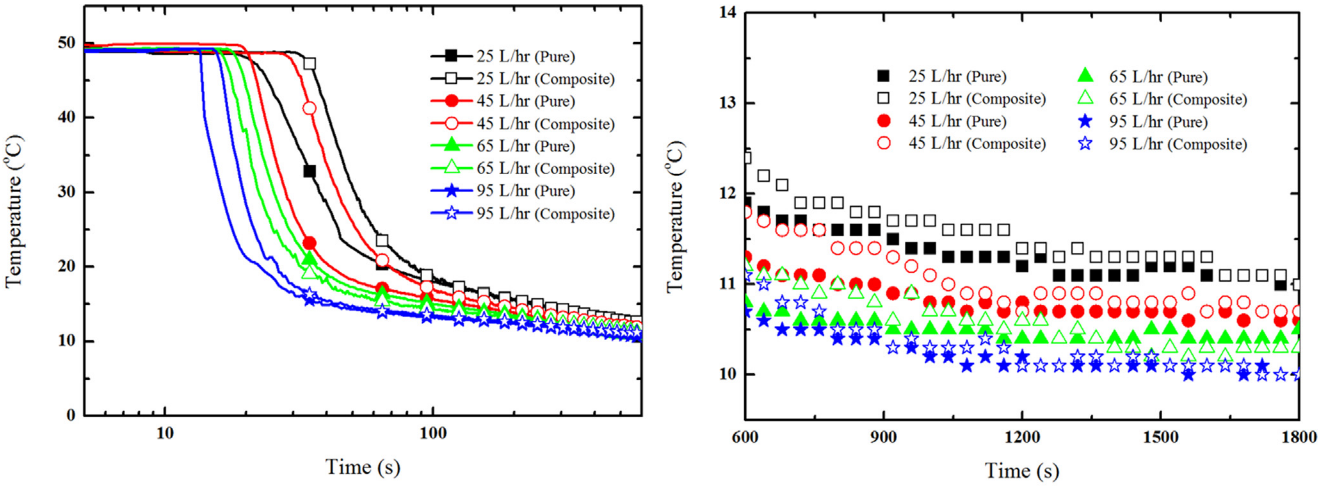
(a) (b)

Fig. 8. The outlet temperature of heat exchanger filled with MEPCM for various flow rates in the case of energy discharge; (a) Initial states, (b) Steady state.



(a) (b)

Fig. 9. Outlet temperature of heat exchanger filled with MEPCM and MEPCM + 30% EG for various flow rates in the case of energy storage; (a) Initial states, (b) Steady state.



(a) (b)

Fig. 10. Outlet temperature of heat exchanger filled with MEPCM and MEPCM + 30% EG for various flow rates in the case of energy discharge; (a) Initial states, (b) Steady state.

4.3. Effect of EG composite

The measurement of thermal conductivity for MEPCM and MEPCM + EG confirmed that the presence of EG particles notably enhances the thermal conductivity of MEPCM. However, the thermal capacity of MEPCM + EG was reduced. Here, the effect of using EG as an additive to MEPCM on the charging behaviour of heat exchanger is investigated.

Figs. 9 and 10 aim to compare the outlet temperature heat exchangers for cases of heat exchangers filled with pure MEPCM as well as the composite of MEPCM and 30% EG for various water flow rates. Fig. 9 illustrates the results for the case of energy storage with an inlet temperature of 50 °C, and Fig. 10 displays the results for the case of energy discharge with an inlet temperature of 10 °C. These figures demonstrate that the presence of EG has notably enhanced the heat transfer capability of the heat exchanger. Attention to the delay of the outlet temperature indicates that the outlet temperature remains steady for a longer time in the case of MEPCM + EG. Indeed, the contribution of the heat exchangers sensible heat and latent heat is compelling and keeps the outlet steady for a longer delay. After the delay, and in the initial stage of transient heat transfer, the outlet temperature moves gradually toward the inlet temperature. However, the heat exchanger tries to hold the outlet temperature as far from the inlet temperature as possible. In the initial states, the temperature difference between the inlet and the outlet temperature is higher in the case of MEPCM + EG, indicating the heat transfer advantage of EG particles. In the case of 25 L/hr, the MEPCM + EG composite provides a 15 °C temperature difference at the outlet of the heat exchanger.

For longer times, t > 100 s, when the heat transfer of MEPCM bed is the dominant mechanism of heat transfer, the enhancement of using EG is notable by preventing the outlet temperature from reaching the inlet temperature. At longer times that the outlet reaches its steady temperature, the temperature difference between the inlet and the outlet is higher for the case of MEPCM + EG. This is due to higher heat losses from the insulation cover of heat exchangers because of the higher thermal conductivity of MEPCM + EG bed.

5. Conclusions

MEPCM are utilized as a thermal storage medium due to the advantages of microencapsulation. As the phase change materials are sealed in a capsule, the energy storage equipment is not directly involved with the liquid on phase change. The effect of using MEPCMs on thermal energy storage of a heat exchanger is experimentally addressed. The heat exchanger is confined in a bed of compressed MEPCMs. The hot water can flow in the heat exchanger and stored a significant amount of energy in the paraffin core of MEPCMs particles due to the latent heat of soli/liquid phase change. Later, the cold water enters the heat exchanger and absorbs the storage energy of MEPCM particles. In the present study, EG microparticles are utilized to form a composite of MEPCM + EG phase change material with enhanced phase changed properties. The thermophysical properties MEPCM and MEPCM + EG composite were studied and reported. An experimental setup was designed to study the effect of various flow rates on the charging and discharging of the heat exchanger for two cases of MEPCM and MEPCM + EG. The outcomes can be summarized as follows:

1- The thermal conductivity of MEPCM and MEPCM + 30EG was measured using KD2-Pro. It was found that the thermal conductivity of MEPCM was 0.22 W/m K, and by using EG, it was enhanced to 0.51 W/m K for MEPCM + EG composite.
The specific heat capacity of MEPCM and MEPCM + 30% EG was studied using DSC curves. It was found that the specific heat of the MEPCM was 25 kJ/kg K, and it was reduced to18 kJ/kg K by adding EG. The density of MEPCM was 452.6 kg/m^{3,} and by using EG, it was increased to 485.1 kg/m^3 for MEPCM + 30%EG.
2- At the initial charging/discharging stages (time less than 100 s), the heat transfer between the heat exchanger and water flow inside the heat exchanger is limited to the heat release/absorption capacity of water flow when the flow rate is low (15 L/h or 25 L/h). For high flow rates, the heat transfer is limited to the heat release/absorption capability of the heat exchanger. At longer times (time greater than 100s), regardless of flow rate, the heat transfer is limited by the heat release/absorption capability of the heat exchanger.
3- Using EG microparticles as additives, notably enhance the heat transfer release/absorption not only at the initial times but also at the longer times. The MEPCM + EG composite provided a 15 °C temperature difference at the outlet of heat exchanger compared to pure MEPCM when the flow rate was 25 L/hr.

In the present study, MEPCMs enhanced with EG were used as an energy storage medium. The water inside the copper pipes of heat exchanger charged or discharged the MEPCM cores. The outcomes show that the steady outlet temperature of the heat exchanger cannot reach the inlet temperature due to losses from the experimental test module. So, performing experiments with very low heat flux was not possible. It is evident that employing better insulation techniques or using a larger heat storage capacity could improve the experiment conditions. Thus, the effect of the size of the heat storage test module with a better insulation cover can be the subject of future studies.

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