SRTTU
Journal of Computational and Applied Research in Mechanical Engineering
jcarme.sru.ac.ir
JCARME
ISSN: 2228-7922

Research paper

Experimental study of melting of composite phase change materials used in honeycomb energy storage system

Ahmed F. Hasan[a,*] and Salah N. Farhan[b]

[a] *Department of Materials Engineering, University of Diyala, Baquba 32001, Iraq*
[b] *Department of Chemical Engineering, University of Diyala, Baquba 32001, Iraq*

Article info:

Article history:

Received:	09/01/2022
Revised:	22/04/2022
Accepted:	25/04/2022
Online:	27/04/2022

Keywords:

Composite honeycomb,
Storage unit,
Phase change materials,
Latent heat,
Honeycomb structure.

***Corresponding author:**
ahmedfalh.eng@gmail.com

Abstract

Phase change materials have attracted a considerable attention in thermal energy storage research recently due to their thermal characteristic. Composite materials have great potential as one of the best alternative approach that would be utilized to increase the thermal performance of this sort of materials. This work aims to improve the Latent Heat energy Storage Unit (LHSU) in terms of thermal performance during the melting process by utilizing honeycomb metal structures configuration. An experimental study has been carried out to examine the thermal behavior of this particular material in honeycomb LHSU. The thermal performance evaluation in terms of melting time of the proposed honeycomb LHSU was conducted in comparison with the normal LHSU. The influences of using different heat transfer fluid temperature on the charging power are considered for the enhanced geometrical configuration. The results showed significant enhancement in the melting time which reached 87%. Also, the melting range in the lower part of the storage unit was improved compared with the normal one from 190 to 24 min in case of using honeycomb. For the propose of configuration, by increasing the fluid temperature, charging power was accelerated, which in turn reduces the charging time from 14% to 16.

1. Introduction

During the last two decades, a significant increase is observed in the number of studies on the renewable energy and alternative resource for the fossil fuels, like solar energy, wind energy, etc. The main deterrent to use these alternative energy sources is their availability for continuous time during the day. The emphasis of the current study has been shifted towards designing an efficient LHSU to reduce the differences between energy supply and demands.

The outcomes of the research concerned with the thermal energy storage unit (TESU) aim to improve the energy efficiency and energy conservation [1]. The key point for the LHSU is the Phase Change Materials (PCMs) [2 and 3]. these sorts of materials havea unique behavior, which is the ability to store and release energy during the phase transition cycle. This indicates that in case of energy availability, the energy can be absorbed and then released when the energy is needed [1, 4]. Even though PCMs have played an important role in the LHSU due to their aforementioned behavior, low thermal conductivity has been reported as the main drawback of those materials [3, 5]. Researchers who work in the field of energy and materials science have focused their attention to enhance the PCMs performance.

According to the literature published in the last few years, many alternative methods have been utilized to enhance the performance of the PCMs used in the TESU. So far, some of these techniques includ using fins, metals foams and particulate composite PCMs [4]. An employing composite PCM was being proceed towards as a method to improve the thermal properties of pure PCMs.

A study was conducted by Hong and Herling [6] that aimed to investigate a way to improve the thermal performance of the PCMs by using metals foam PCM base composite. Metals foam made from aluminum was used with ≈92% porosity. The study found that there was an increase in the measured thermal conductivity when the porosity of the metals foam reduced. They suggested that further investigation is needed to get more insight related to the foam pore size throughout two cycles of process (Melting and Solidification).

In the same field of study, Oya et al [7] performed an experimental investigation by using nickel foam, which is considered as composite PCMs used in high-temperature applications. The PCM used in their study was Erythritol that has melting points around 120°C. Their main finding showed that the thermal conductivity was enhanced by ten times when it eas compared with pure PCM LHSU.

Zhang et al [8] did a comprehensive research to determine the thermal characteristics of the PCM composite. The work used Paraffin wax as A PCM with a mesophase pitch, while the foam was made from graphite. Different types of foams were used which included a variety range of density and pore size. Four groups of PCM composite were used and they had different bulk density and foam pore size. The results demonstrated that the improvement of the thermal diffusivity due to using metal foam is more than 200 times when it was compared with plain paraffin wax. Moreover, in the case of considered thick metal foam skeleton with large porosity, the latent heat increased significantly.

Another interesting investigation was achieved by Mills et al. [9] when they carried out an experimental study on using Paraffin wax and Expanded graphite as a PCM composite LHSU. Their investigation concluded that expanded graphite improved this kind of material with regard to thermal conductivity. Additionally, this sort of composite PCM revealed a drop about 50% in the melting time of the LHSU.

An experimental work was achieved by Mattawee and Assass [10] to improve the thermal performance of the LHSU by using metals powder dispersed into paraffin. Aluminum powder was used as a dispersed powder that added to paraffin to produce composite PCM. It has been found that the time of fusion was reduced by 60%, which was lower than that of PCM without aluminum powder. It is worth mentioning that they considered a different range of a mass fraction of the powder. Their suggestion that was it is necessary to balance the mass fraction of the powder with PCM to achieve better performance for the LHSU.

A shape-stabilized PCM was studied by Xie et al. [11] with two cases; the first one was pure shape-stabilized PCM, and the other one included aluminum honeycomb structure, which was used as the thermal control system. The study concluded that the aluminum honeycomb structure included PCM might be considered an alternative approach that improves the storage unit thermal conductivity.

Thermal characteristics of the LHSU were intensively investigated by Lai and Hokoi [12]. The work used a new approach which was the structure of honeycomb wallboard imbedded with microencapsulated PCM. Their experiments equate to several modules which include mPCM with epoxy glass, iron wire, and pure mPCM. It has been found that this technique improved the thermal conductivity and structural strength of the unit, besides the

mPCM with honeycomb provided much superior temperature distribution on the unit.
Hasse and Grenet [13] investigated the thermal performance of honeycomb panels for heat storage used in the short-term unit. The authors used three cases which were honeycomb panels filled with air, water, and PCM. The implementation of the PCM with the honeycomb panels provides significant development in the thermal inertia in addition to the thermal conductivity. Moreover, PCM can be utilized to avoid thermal loss during the process.
As fluid flow and heat transfer characteristic is an important field of study, different numerical investigations have been conducted since the last decade to provide more insight for this topic. Some of them used analytical solution based on computer programming such as FORTARN following [14] D3Q19 model and the D3Q7 model [15, 16]. On the other hand, FEA analysis and CFD code have been utilized to cover many details that are in need of investigation as in References [17, 18 and 19].
A numerical examination was carried out by Schaefer [20] to predict the optimum output power of the pressure absorber. The modeled absorber had a honeycomb structure made from Zeolite materiel that is commonly used in thermal energy application. It has been found that by increasing the size of the honeycomb channel the resistance of the mass transfer reduces.
An experimental investigation was conducted by Sheng et al. [21] which aimed to increase the thermal properties of the PCM made from paraffin. A carbon fiber was used to form a composite honeycomb structure used in the high temperature energy storage unit. It has been found that a significant enhancement was gained when using carbon fibers with anisotropic properties of the PCM.
This piece of work aims to improve the Latent Heat energy Storage Unit (LHSU) with regard to thermal properties during the melting process by utilizing honeycomb metal structures configuration. An experimental study has been carried out to examine the thermal behavior of this sort of materials in honeycomb LHSU. The thermal performance evaluation in terms of melting time of the proposed honeycomb LHSU was conducted in comparison with the normal LHSU. The influences of using different heat transfer fluid temperatures on the charging power are considered for the enhanced geometrical configuration.
In summary, it is clear that phase change materials have been widely used in the LHSU, however, studies have documented that these particular materials have low thermal conductivity. That need to be enhanced in terms of thermal performance [4, 22]. Many alternative approaches have been suggested to improve the thermal performance of the LHSU [23, 24]. Honeycomb structures can be considered as one of these approaches due to their large surface contact area that can provide better enhancement in the storage unit. In the current study, an attempt was made to examine whether these composite structures can efficiently enhance the thermal preference of the storage unit during melting cycles.

2. Experimental procedure

In the above-mentioned literature, it can be seen that there are little works related to use of the honeycomb structures. Honeycomb has attracted a significant interest with regard to its lightweight core material, in which many cell sizes and thickness are available resulting a wide range of thermal and mechanical specifications [25]. The aluminum honeycomb pipe was selected in a square shape in this study, as it has a large contact surface area. An experimental investigation was conducted on a honeycomb made of Aluminum in order to increase the heat transfer of the LHSU performance using PCM. The effect of the heat transfer inlet temperature on the performance of the honeycomb LHSU throughout the melting process has also been studied.
The storage consists of 16 pipes, 8 for PCM and 8 for Heat Transfer Fluid (HTF) that is water in this study. All the pipes were made of aluminum and they had identical geometry of 2 cm × 2 cm × 0.36 cm and 0.01 cm thickness. The pipes were set in 4×4 square array where the PCM and HTF pipes were arranged alternatively as shown in Fig. 1. The pipes array were mechanically clamped using 4 clamps to ensure the perfect contact between the pipes. Four pieces of 2 cm thickness wood plate were used to uniformly

distribute the clamping pressure and to offer thermal insulation for the LHSU. The storage was mounted vertically, and the PCM pipes were sealed from the bottom and left open from the top, nevertheless, the HTF pipe was modified to allow the flow of the water. Two manifolds were used to distribute the water from the source to the HTF pipes and recollect it from the pipes to the source. To compare the thermal behavior of the designed honeycomb LHSU with that of a normal LHSU, a double pipe LHSU was set up. The double pipe LHSU was designed to contain an identical mass of PCM to that of the honeycomb LHSU. It consists of two pipes; the inner (HTF pipe) is identical for the HTF pipe in the honeycomb LHSU, the other geometrical details of the double pipe LHSU is presented in Fig. 1 .

To monitor and record the PCM temperature inside the honeycomb LHSU, 24 thermocouples of k-type ± 0.15°C were implemented in the PCM pipes, 3 thermocouples were put at each PCM pipe at three different locations (a, b, and c) as can be seen in Fig. 1. Further, two more thermocouples were fixed at the main inlet and outlet of the HTF.

The honeycomb storage and normal one were filled with 0.8 kg of lauric acid as a PCM. It has a 99% purity provided by Famouschem Technology Co. Ltd, in Shanghai China. The thermo physical properties of lauric acid are presented in Table 1 [26].

Fig. 2 shows the experimental apparatus that has been used in this study to examine the thermal performance of the LHSUs. It consists of 500L electric water bath, water pump, test rigs, ball valves, turbine flow meter, data logger and PC.

The experiments have been conducted at a room temperature of 23°C. The water feed with a temperature reached to 70 °C at the water bath and then pumped at a constant flow rate of 1 L/min (the maximum ability of the used pump) to the LHSU; the flow direction in the LHSUs is from lower to the upper section of the storage. The flow was continuous until all the thermocouples reading reached a specific value above the melting temperature of the lauric acid. Thermocouples were joined to the national instrument data logger that used to record the temperatures in the PC at each minute interval.

The uncertainty of the used k-type thermocouples and turbine flow meter is 0.15°C and 0.05 L/min, respectively. According to the power calculation equation used in this study (1), the bias uncertainty comes from the thermocouple and flow meter readings [27]:

$$Q = \dot{m}\, Cp\, \Delta T \tag{1}$$

Table 1.Thermo physical properties of lauric acid.

Property	Value
Melting temperature range (°c)	44.5 - 48.3
Latent heat (j/kg)	178780
Specific heat (j/kg k)	2200
Density (kg/m3)	858 (liquid at 67°C)
Thermal conductivity (w/m k)	0.157 (solid at 30°C)
Dynamic viscosity (pa s)	0.0063 (at 60°C)
Thermal expansion coefficient **β** (1/k)	6×10^{-4}

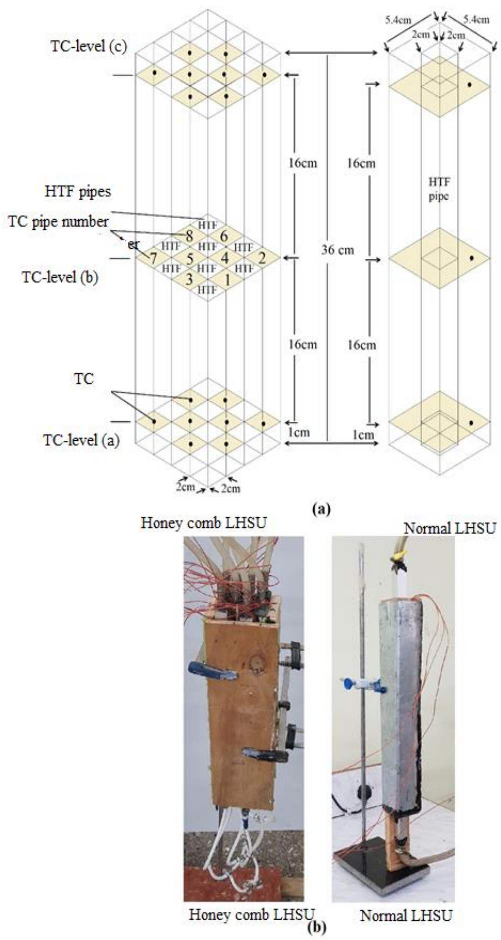

Fig. 1. (a) Test rigs illustration and thermocouple locations, and (b) experimental test rigs.

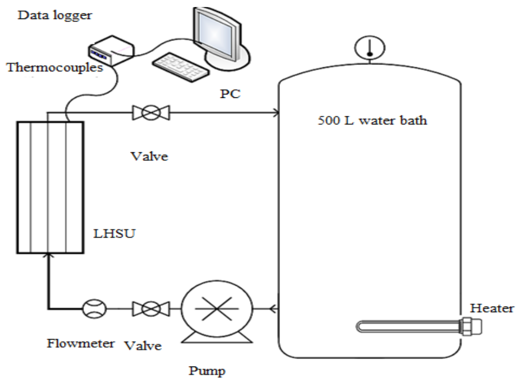

Fig. 2. Experimental apparatus diagram.

where Q is the heat (power) transfer from the water to the PCM, $\dot{m}$ is the HTF mass flow rate, Cp is the specific heat of the HTF at the average HTF temperature, and ΔT is the difference between HTF inlet and outlet temperatures.

Therefore the uncertainty for the power calculation is as follows [27]:

$$\frac{\partial Q}{Q} = \sqrt{\left(\frac{\partial \dot{m}}{\dot{m}}\right)^2 + \left(\frac{\partial \Delta T}{\Delta T}\right)^2} \quad (2)$$

The uncertainty of the instrument and the denominator are the maximum measured value, by substituting the values in (2) the maximum uncertainty for power calculation is 5 %.

3. Results and discussion

3.1. Thermal behavior of the honeycomb LHSU

Figs. 3, 4 and 5 show the temperature profile of the PCM at the locations of the thermocouples shown in Fig. 1 during the melting process when the HTF inlet temperature and flow rate were 70°C and 1 L/min, respectively.

Fig. 3 shows the temperature values inside the 8 PCM pipes at position a, though Fig. 4 and Fig. 5 demonstrate the temperature history at positions b and c, respectively. The general trend of the temperature curves is an increase as a function of which is due to the absorbed heat from the HTF. For each individual curve, three regions of temperature increase could be recognized. The first region (room temperature - 44°C) shows a moderate temperature increment as the heat transfers mainly by conduction to the solid PCM. The second region (44°C - steady-state temperature) initiates when the PCM reaches the melting temperature range. At this point, the convection plays an important role to significantly increase the PCM temperature up to the steady-state region which is the third region of the curve. At this stage, the PCM is completely melted, at that thermocouple position, and has a temperature which is almost equal to the HTF temperature.

According to the PCM height in the storage, it could be seen (see Fig. 3-Fig. 5) that position c for all PCM pipes melt at the binging of the process (5 min) then after position b (last pipe melt at 21 min) and lastly position a (last pipe melt at 24 minutes of the process).

According to the PCM height in the storage, it could be seen (see Fig. 3-Fig. 5) that position c for all PCM pipes melt at the binging of the process (5 min) then after position b (last pipe melt at 21 min) and lastly position a (last pipe melt at 24 minutes of the process).

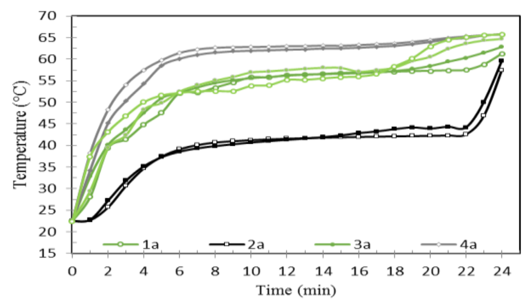

Fig. 3. PCM temperatures during the melting process of honeycomb LHSU at inlet temperature of the HTF of 70 °C and rate of flow 1 L/min for the thermocouples reading at level (a).

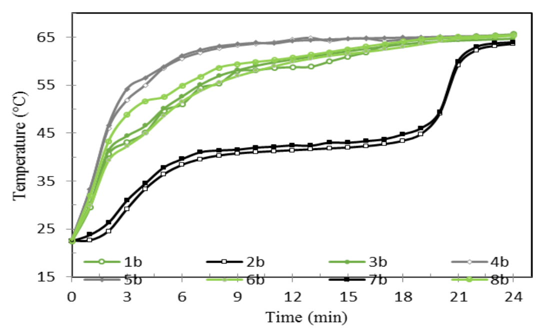

Fig. 4. PCM temperatures during the melting process of honeycomb LHSU at inlet temperature (HTF) of 70 °C and rate of flow 1 L/min for the thermocouples reading at level (b).

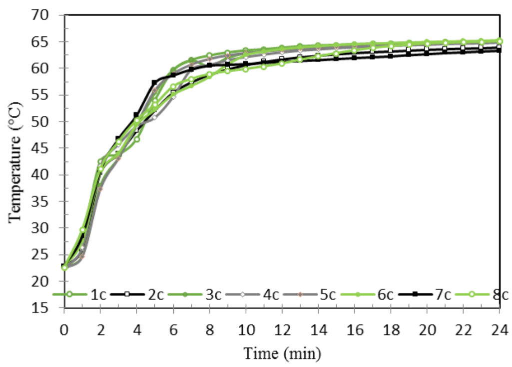

Fig. 5. PCM temperatures during the melting process of honeycomb LHSU at HTF temperature of 70 °C and 1 L/min of flow rate for the thermocouples reading at level (c).

This behavior indicates that the melting front starts from the top towards the bottom since the heating process of the PCM is dominated by natural convection [28, 29]; and the hot melted PCM buoys up causing the melting of the PCM in the top region and continue toward the bottom. According to the arrangements of the PCM and the HTF pipes in the proposed honeycomb LHSU shown in Fig. 1, three different heating arrangements of the PCM pipes could be recognized. PCM pipes No. 2 and 7 were heated by two HTF pipes, , PCM pipes No. 1, 3, 6 and 8 were heated by three HTF pipes, , and PCM pipes No. 4 and 5 were heated by four HTF pipes Accordingly, Fig. 3 and Fig. 4 show that the melting of PCM pipes No. 4 and 5 are at a faster rate when compared to PCM pipes No. 1, 3, 6 and 8; however, PCM pipes No. 2 and 7 melt lastly as they have the lowest heating rate arrangement. Though, this behavior is not obvious in Fig. 5 which shows almost identical heating behavior for all the PCM pipes. This can be attributed to the fact that position c already has a high heating rate due to the rising of hot liquid PCM which causes the melting of the PCM and its reach to the steady-state region at the early time of the process. Fig. 6 demonstrates a color representation for the PCM temperature distribution inside the honeycomb LHSU. These colors were given according to the location and reading of the thermocouples. The figure shows that the PCM pipes that are surrounded by more HTF pipes have a higher temperature. It could also be seen that the PCM temperature increases gradually from the upper to lower section pipes, as it was mentioned earlier that the melting starts from the top due to the density difference.

3.2. Thermal performance comparison of the honeycomb and normal LHSU

For a better comprehension of the thermal performance of the proposed honeycomb LHSU, the temperature history of the PCM at the honeycomb LHSU was compared to the one in the normal double pipe LHSU.

Fig. 7 shows the temperature history of the PCM at the thermocouples locations a, b and c during the melting process of a double pipe LHSU at inlet temperature equal to 70°C and HTF flow rate equal to 1 L/min.

Fig. 8 shows the average thermocouples temperatures for each location of a, b and c of the PCM pipes at the honeycomb LHSU for the same HTF condition of Fig. 6.

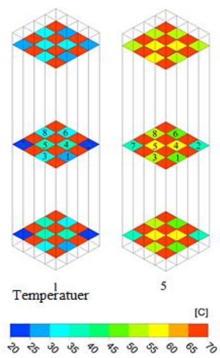

Fig. 6. PCM temperatures color during the melting process of honeycomb LHSU at HTF 70 °C and flow rate of 1 L/min.

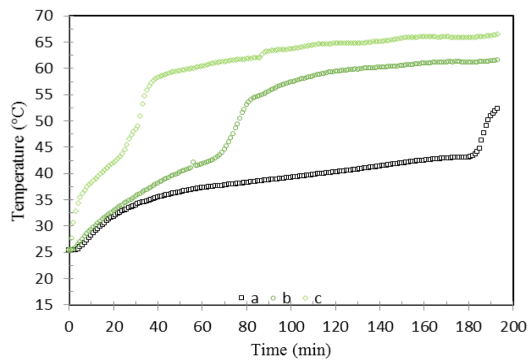

Fig. 7. PCM temperatures during the melting process of normal LHSU at HTF of 70 °C and flow rate of 1 L/min.

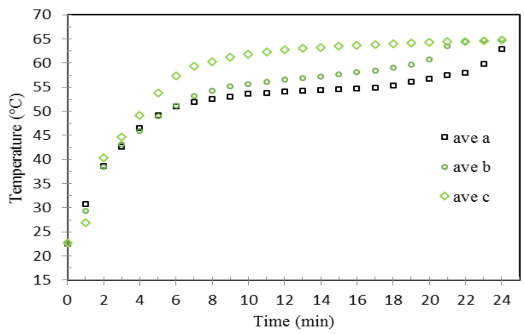

Fig. 8. Average PCM temperatures (for each location of a, b and c) during the melting process of honeycomb LHSU at HTF inlet temperature of 70 °C and flow rate of 1 L/min.

Noticeably, Fig. 7 proved information of the required melting time for PCM in the normal LHSU and the proposed honeycomb LHSU was 190 minutes and 24 minutes respectively, which indicates 87% reduction in the melting time. Also, it could be seen from Fig. 7 that, in the normal LHSU, there is a big time difference between the melting at the locations a and c, unlike that of the honeycomb LHSU, where the time difference is small. This could be because the honeycomb structure boosts the heat transfer rate in all the PCM locations of the LHSU when compared to normal LHSU. Moreover, the study showed that the honeycomb structure can prove good behavior for the materials in terms of agglomeration or materials sticking in specific locations; this was previously confirmed by [30, 31]. Table 2 represents an example for the data plotted for previous figures in this section, where the distribution of the temperature values for each sensor location can be seen.

3. 3. Charging power and the HTF temperature effect

A control volume energy balance was used to experimentally calculate the instantaneous power transfer to the PCM [32]. The measured temperature at the HTF inlet and outlet and the measured HTF flow rate were used in Eq. (1) to estimate the instantaneous power transfer Fig. 9 shows the time-wise variation of the power transfer at a different HTF inlet temperature of (65°C, 70°C and 75°C) and at a constant HTF flow rate of 1 L/min. The power increases significantly at the beginning of the melting owing to the high-temperature variance among the HTF and the PCM. The power then decreases as the temperature difference decreases.

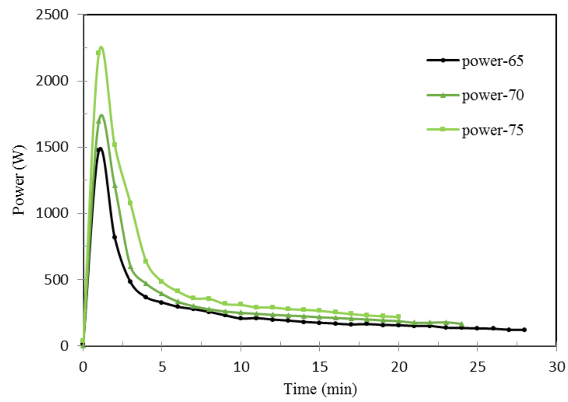

Fig. 9. Charging power during the melting process of honeycomb LHSU at HTF inlet temperature of (65°C, 70 °C and 75°C) and flow rate of 1 L/min.

Table 2. PCM temperatures during the melting process of honeycomb LHSU at inlet temperature of the HTF of 70 °C and rate of flow 1 L/min for the thermocouples reading at level (a).

Time min	Temperature value °C for each Sensor number							
	1a	2a	3a	4a	5a	6a	7a	8a
0	23	23	23	23	22	23	22	22
1	28	23	33	38	34	29	23	37
2	39	26	40	48	45	40	27	43
3	41	31	44	54	50	42	32	47
4	45	35	48	57	54	48	35	50
5	48	37	51	60	59	50	37	52
6	52	39	52	61	60	52	39	52
7	52	40	53	62	61	54	39	53
8	53	41	54	63	62	55	40	53
9	55	41	55	63	62	56	40	53
10	56	41	56	63	62	57	41	54
11	56	41	56	63	62	57	41	54
12	56	42	56	63	62	57	41	55
13	56	42	56	63	62	58	42	55
14	57	42	56	63	62	58	42	56
15	57	42	57	63	62	58	42	56
16	57	42	57	63	63	57	43	56
17	57	42	57	63	63	57	43	57
18	57	42	57	64	63	58	44	58
19	57	42	58	64	63	60	44	60
20	57	42	58	64	64	61	44	63
21	57	42	59	65	65	62	44	64
22	57	43	60	65	65	64	44	65
23	59	47	61	66	65	64	50	65
24	61	57	63	66	66	65	60	66

Fig. 9 also shows the effect of HTF inlet temperature; it could be seen that increasing HTF temperature could fasten the charging power rate and thus decreases the melting time as the temperature difference increases. The time required for complete PCM in the honeycomb melting is 28 minutes, 24 minutes and 20 minutes for HTF inlet temperature of 65°C, 70°C and 75°C, respectively.

4. Conclusions

A study has been carried out in this paper to investigate the thermal performance of the LHSU during the charging process in case of using a honeycomb composite structure storage unit. The work considered the thermal behavior comparison of the proposed honeycomb LHSU with normal (double pipe) LHSU. The main findings of this paper are briefly listed below:

- The general trends of the melting process in both plan and honeycomb configurations were almost similar. The convection heat transfer mechanism was dominated during the melting process; thus, the melting front was initiated from the top of the part of the storage and moved toward the down part.
- The honeycomb structure is an effective method that can be utilized to enhance the thermal performance of the storage system. A significant enhancement was seen in the case of using honeycomb composite structure in terms of decreasing the melting time particularly in the lower part of the unit, the overall enhancement was 87 %.
- The results revealed that when using a high value of HTF inlet temperature, the charging power was accelerated. Noticeably, this leads to enhance the performance of the storage system in terms of reduced melting time by 14 % and 16 % when increasing the HTF inlet temperature from 65°C, 70°C and from 70°C to 75°C, respectively.

References

[1] J. Giro-Paloma, M. Martínez, L. F. Cabeza, and A. I. Fernández, "Types, methods, techniques, and applications for microencapsulated phase change materials (MPCM): a review", *Renew. Sust. Energ. Rev.*, Vol. 53, pp. 1059-1075, (2016).

[2] P. Zhang, X. Xiao and Z. Ma, "A review of the composite phase change materials: Fabrication, characterization, mathematical modeling and application to performance enhancement", *Appl. Energy*, Vol. 165, pp. 472-510, (2016).

[3] H. El-Dessouky and F. Al-Juwayhel, "Effectiveness of a thermal energy storage system using phase-change materials", *Energy Convers. Manage*, Vol. 38, No. 6, pp. 601-617, (1997).

[4] M. S. Mahdi, A. F. Hasan, H. B. Mahood, A. N. Campbell, A. A. Khadom, A. M. e. A. Karim and A. O. Sharif, "Numerical study and experimental validation of the effects of orientation and configuration on melting in a latent heat thermal storage unit", *J. Energy Storage*, Vol. 23, pp. 456-468, (2019).

[5] H. Mehling and L. F. Cabeza, *Heat and cold storage with PCM*: Springer Berlin, Heidelberg, pp. XVI, 308, (2008).

[6] S. T. Hong and D. R. Herling, "Effects of surface area density of aluminum foams on thermal conductivity of aluminum foam-phase change material composites", *Adv. Eng. Mater.*, Vol. 9, No. 7, pp. 554-557, (2007).

[7] T. Oya, T. Nomura, N. Okinaka and T. Akiyama, "Phase change composite based on porous nickel and erythritol", *Appl. Therm. Eng.* , Vol. 40, pp. 373-377, (2012).

[8] Y. Zhong, Q. Guo, S. Li, J. Shi and L. Liu, "Heat transfer enhancement of paraffin wax using graphite foam for thermal energy storage", *Sol. Energy Mater. Sol. Cells*, Vol. 94, No. 6, pp. 1011-1014, (2010).

[9] A. Mills, M. Farid, J. Selman and S. Al-Hallaj, "Thermal conductivity enhancement of phase change materials using a graphite matrix", *Appl. Therm. Eng.*, Vol. 26, No. 14-15, pp. 1652-1661, (2006).

[10] E.-B. S. Mettawee and G. M. Assassa, "Thermal conductivity enhancement in a

latent heat storage system", *Solar energy*, Vol. 81, No. 7, pp. 839-845, (2007).

[11] B. Xie, W.-l. Cheng and Z.-m. Xu, "Studies on the effect of shape-stabilized PCM filled aluminum honeycomb composite material on thermal control", *Int. J. Heat Mass Transfer*, Vol. 91, pp. 135-143, (2015).

[12] C.-m. Lai and S. Hokoi, "Thermal performance of an aluminum honeycomb wallboard incorporating microencapsulated PCM", *Energy Build.*, Vol. 73, pp. 37-47, (2014).

[13] C. Hasse, M. Grenet, A. Bontemps, R. Dendievel and H. Sallée, "Realization, test and modelling of honeycomb wallboards containing a Phase Change Material", *Energy Build.*, Vol. 43, No. 1, pp. 232-238, (2011).

[14] J. Alinegad, "Hybrid lattice Boltzmann/Taguchi optimization approach for magnetohydrodynamic nanofluid natural convection in a hemisphere cavity", *Therm., Sci.*, Vol. 23, No. 3 Part B, pp. 1847-1859, (2019).

[15] M. M. Peiravi and J. Alinejad, "3D Numerical Simulation of Fibers Arrangement Effects On Thermal Conductivity of Polymer Matrix Composite", *Mech. Adv. Compus. Struct.* , (2022).

[16] J. Alinejad and J. Esfahani, "Lattice Boltzmann simulation of 3-dimensional natural convection heat transfer of CuO/water nanofluids", *Thermophys. Aeromech.* , Vol. 24, No. 1, pp. 95-108, (2017).

[17] M. M. Peiravi, P. Pasha and D. D. Ganji, "Hydro Magnetic Effect on ThreadStretching Surface with Mounted Obstacles inPorous Medium", *WSEAS Trans. Heat Mass Transfer*, Vol. 16, pp. 95-105, (2021).

[18] P. Pasha, H. Nabi, M. M. Peiravi and D. D. Ganji, "Hybrid investigation of thermal conductivity and viscosity changeable with generation/absorption heat source", *Comput. Therm. Sci.: Int. J.* , Vol. 14, No. 1, (2022).

[19] J. Alinejad, N. Montazerin and S. Samarbakhsh, "Accretion of the efficiency of a forward-curved centrifugal fan by modification of the rotor geometry: computational and experimental study", *Int. J. Fluid Mech. Res.*, Vol. 40, No. 6, (2013).

[20] M. Schäfer and A. Thess, "Simulation of a closed low-pressure honeycomb adsorber for thermal energy storage", *Int. J. Heat Mass Transfer* Vol. 126, pp. 796-807, (2018).

[21] N. Sheng, Z. Rao, C. Zhu and H. Habazaki, "Honeycomb carbon fibers strengthened composite phase change materials for superior thermal energy storage", *Appl. Therm. Eng.* , Vol. 164, pp. 114493, (2020).

[22] H. B. Mahood, M. S. Mahdi, A. A. Monjezi, A. A. Khadom and A. N. Campbell, "Numerical investigation on the effect of fin design on the melting of phase change material in a horizontal shell and tube thermal energy storage", *J. Energy Storage* Vol. 29, pp. 101331, (2020).

[23] A. M. Abdulateef, J. Abdulateef, A. A. Al-Abidi, K. Sopian, S. Mat and M. S. Mahdi, "A combination of fins-nanoparticle for enhancing the discharging of phase-change material used for liquid desiccant air conditioning unite", *J. Energy Storage* Vol. 24, pp. 100784, (2019).

[24] M. T. Barako, S. Lingamneni, J. S. Katz, T. Liu, K. E. Goodson and J. Tice, "Optimizing the design of composite phase change materials for high thermal power density", *J. Appl. Phys.*, Vol. 124, No. 14, pp. 145103, (2018).

[25] J. K. Paik, A. K. Thayamballi, and G. S. Kim, "The strength characteristics of aluminum honeycomb sandwich panels", *Thin-Walled Struct.*, Vol. 35, No. 3, pp. 205-231, (1999).

[26] X. Cao, Y. Yuan, B. Xiang and F. Haghighat, "Effect of natural convection on melting performance of eccentric horizontal shell and tube latent heat storage unit", *Sustainable Cities Soc.* , Vol. 38, pp. 571-581, (2018).

[27] M. Rahimi, M. Hosseini and M. Gorzin, "Effect of helical diameter on the performance of shell and helical tube heat exchanger: an experimental approach", *Sustainable Cities Soc.*, Vol. 44, pp. 691-701, (2019).

[28] M. S. Mahdi, H. B. Mahood, J. M. Mahdi, A. A. Khadom and A. N. Campbell, "Improved PCM melting in a thermal energy storage system of double-pipe helical-coil tube", *Energy Convers. Manage.*, Vol. 203, pp. 112238, (2020).

[29] M. S. Mahdi, A. A. Khadom, H. B. Mahood, M. A. R. Yaqup, J. M. Hussain, K. I. Salih and H. A. Kazem, "Effect of fin geometry on natural convection heat transfer in electrical distribution transformer: numerical study and experimental validation", *Therm. Sci. Eng. Prog.*, Vol. 14, pp. 100414, (2019).

[30] M. Cao, J. Huang and Z. Liu, "The Enhanced Performance of Phase-Change Materials via 3D Printing with Prickly Aluminum Honeycomb for Thermal Management of Ternary Lithium Batteries", *Adv. Mater. Sci. Eng.* , Vol. 2020, (2020).

[31] A. Hassan, M. Shakeel Laghari and Y. Rashid, "Micro-encapsulated phase change materials: a review of encapsulation, safety and thermal characteristics", *Sustainability*, Vol. 8, No. 10, pp. 1046, (2016).

[32] M. S. Mahdi, H. B. Mahood, A. N. Campbell and A. A. Khadom, "Experimental study on the melting behavior of a phase change material in a conical coil latent heat thermal energy storage unit", *Appl. Therm. Eng.*, Vol. 175, pp. 114684, (2020).

How to cite this paper:

Ahmed F. Hasan and Salah N. Farhan, "Experimental study of melting of composite phase change materials used in honeycomb energy storage system,", *J. Comput. Appl. Res. Mech. Eng.*, Vol. 12, No. 1, pp. 31-40, (2022).

DOI: 10.22061/JCARME.2022.8741.2175

URL: https://jcarme.sru.ac.ir/?_action=showPDF&article=1698