CHEMICAL ENGINEERING TRANSACTIONS

VOL. 81, 2020

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

ISBN 978-88-95608-79-2; **ISSN** 2283-9216

DOI: 10.3303/CET2081005

Systematic Investigations on Charging Performance Enhancement of PCM-Based Thermal Energy Storage System by Fin Arrangements

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The poor charging performance of the phase change materials with low thermal conductivity significantly inhibits their extensive and practical applications. Highly conductive metallic fins can greatly improve the charging performance of the PCM-based thermal energy storage system and have been applied to promote their charging performances. However, the influence of the fin parameters on the charging performance has not been deeply investigated and optimized. In this work, the influence of the fin arrangements on the charging performance of PCM-based TES with three fins is systematically analysed applying a porosity-enthalpy method under different heating conditions including bottom, side and top heating. The triple-fin system with the same length is applied as a baseline. The comparison results demonstrate that the influence of fin arrangement on charging performance under top heating is the most significant, then the bottom heating and side heating is the least significant. The total charging time rapidly increases with the increase of the ratio l_{middle}/l_{side} at the begging but obviously decreases after the ratio is larger than 1.0 for the top heating condition. Take the heating temperature is 90 °C as an example, up to 95.1 % of total charging time is shortened by appropriately arranging the fins with their total length constant by completely integrating the natural convection and conduction. Around 41.7 % and 34.9 % of the total charging times are shortened under bottom heating and side heating through optimizing the fin arrangement. The results support a good guideline to design an appropriate fin arrangement for enhancing the average charging performances of PCM-based TES in practical applications.

1. Introduction

Phase change materials have been extensively applied in the thermal energy storage systems in buildings management (Faraj et al., 2020) and energy saving (Zheng, 2017), thermal management systems (Shamberger and Bruno, 2020), renewable energy applications (solar energy) (Jiang et al., 2019) and waste heat recovery systems (Li et al., 2019) due to their stable temperature during charging, the appropriate melting point and relatively high energy density. The phase change materials normally include metallic and nonmetallic materials. The metallic PCM such as eutectic PCM has high thermal conductivity (Nazir et al., 2019) and volumetric energy density (Peng et al., 2019) but the capital cost is high. The large-scale applications of the metallic PCM are inhibited. The nonmetallic PCM such as organic PCM (paraffin wax) and inorganic hydrate salts are regularly chosen to apply in the relatively large-scale such as thermal management of building due to their high energy density and low capital cost.

However, the poorly thermal conductivities of the organic PCM and inorganic hydrate salts (Nazir et al., 2019) compared to the metallic PCM significantly inhibit their applications in the conditions where the rapid charging rate needed. Many methods and techniques have been used to promote the charging performance of the PCM-based thermal energy storage systems with relatively low thermal conductivity (Tao and He, 2018). Nanoparticles made of relatively highly conductive materials (Bazri et al., 2018), metal foam (Yang et al., 2019), the nanoparticle-metal foam (fin) combination techniques (Mahdi and Nsofor, 2018), micro/nano capsulations (Jia et al., 2019) and the metallic fins (Bazri et al., 2018) with high thermal conductivities have been extensively used to enhance the charging performances of PCM and the charging performances are

Paper Received: 30/03/2020; Revised: 21/04/2020; Accepted: 26/04/2020
Please cite this article as: Peng B., He Z., Wang H., Su F., 2020, Systematic Investigations on Charging Performance Enhancement of PCM-Based Thermal Energy Storage System by Fin Arrangements, Chemical Engineering Transactions, 81, 25-30 DOI:10.3303/CET2081005

numerically analysed and experimentally measured. However, the aggregation problem of the nanoparticles with high thermal conductivity restricts their reliabilities and efficiencies during the charging performance enhancement of PCM. The difficulty and high cost in the preparation of micro/nano capsulations constrains their large-scale application. Metallic fins can overcome these weaknesses and seem as effective techniques to prompt the charging/discharging performances of PCM and many numerical (Joybari et al., 2017) and experimental (Kamkari and Groulx, 2018) investigations have been conducted. The results clearly demonstrated that the metallic fins can greatly enhance the charging and discharging performance of PCM-based TES system with low thermal conductivities. The influence of the fin arrangement (Ji et al., 2018), fin size, fin distributions (Pascal et al., 2018), fin thickness, number and height (Pakrouh et al., 2015) on the charging performance of PCM-based TES have been investigated. The effect of fin orientations (Govindaraj et al, 2017) on the effective heat transfer enhancement in a spherically encapsulated PCM has been also investigated. However, the length of the fins in each case are uniform the length distribution of the fins needs to be deeply investigated. Because the fin system with unequal length may have a better effect on charging performance enhancement of PCM-base TES than that induced by the equal fin system. The higher charging performance of PCMs can significantly enhance the absorption of the solar energy and waste heat from warships, which can effectively solve the nonuniform temporal and spatial distributions of resources. The systematic investigations of the patterned-fins to enhance the charging performances of PCMs can actualize the comprehensive utilization of energy and efficiently contribute to the sustainable development

Heating conditions also greatly affect the charging performance of PCM-based TES due to the convection heat transfer effect for paraffin wax but that is not obvious for metallic alloy PCM (Peng et al., 2019). The experimental and numerical results conducted by Peng et al (Peng et al., 2019) demonstrate that the charging performance under bottom heating is much better than that under top heating in the charging process of paraffin wax because the convection effect is diminished under top heating. However, the integration effect of heating conditions and fins has not been investigated completely yet. Summary, few investigations have focused on the systematic investigations of the fin parameter optimization under different heating conditions, although the investigations have been conducted in one or several aspects. The charging performance enhancement of PCM-based TES under various heating conditions induced by the metallic fins are numerically studied and analysed applying a porosity-enthalpy method. A non-clear mush zoom is applied to define the liquid-solid mixture region in the melting-solidification model. The liquid fraction ranges from 0.0 to 1.0 in this zoom. Porosity-enthalpy method has been extensively applied due to it is simple and reliable which can efficiently solve the charging/discharging processes of PCMs. According to this method, the liquid fraction and velocity evolutions during the charging/discharging processes can be also demonstrated and can present the control conditions of charging process. An effective strategy to diminish the restrictions can be obtained significantly shorten the charging/discharging times and save the metallic materials. As a result, aim to demonstrate the influence of the heating conditions on the total charging time induced by fins arrangement, three heating conditions are considered by porosity-enthalpy method. The fin arrangements have been considered and optimized under three heating conditions including bottom heating, side heating and top heating by applying the above method. An appropriate fin arrangement for each heating condition has been obtained. The results can support a good and reliable guideline for designing an optimum fin system to enhance the charging performance of PCM with relatively low thermal conductivity expand their applications especially for the occasions need rapid charging property.

2. Problem Descriptions and Simulation Method

2.1 Problem Descriptions

The PCM-based TES system is simplified to a two dimensions rectangular enclosure. The length and the width are 50 mm and 50 mm. Three copper fins with the constant total length (90 mm) and almost uniform distance are installed in the enclosure to enhance the charging performance of PCM. The triple-fin systems with the same length are applied as baselines. The total length and the thickness of the fins are 90 mm and 3 mm. About 10.8 % volume of the enclosure is occupied by the metal fins. The distance between the two neighboring fins (d_{a2}, d_{b2} and d_{c2}) is 9.5 mm, the distance between the side fin and the corresponding wall (d_{a1}, d_{b1} and d_{c1}) is 11 mm. The influence of the fin length arrangements on the total charging time of PCM are systematically analysed in this study. For the bottom heating condition, the lengths of the left and right fins remain the same but the ratio l_{a2}/l_{a1} is variant. For the side heating condition, the ratio of l_{b1}/l_{b3} is variant but l_{b2} is constant. For the top heating condition, the lengths of the left and right fins remain the same but the ratio l_{c2}/l_{c1} is variant during the analysis. The paraffin wax with relatively low thermal conductivity is chosen as a phase change material. The constant temperature heating condition (one heating temperature of 90 °C is used) is applied for charging.

Table 1: The thermophysical properties of phase change material and the metallic (copper) fins (at room temperature, 25 °C except specifically explained)

Property	PCM (paraffin wax)	Fins (Copper)
Melting point (°C)	69 - 73	-
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	0.25	380
Specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)	~2,450	390
Viscosity of liquid (Pa·s)	0.004	-
Density ($kg \cdot m^{-3}$)	~900	8,960
Latent heat of fusion ($kJ \cdot kg^{-1}$)	210	-
Coefficient of thermal expansion （K^{-1}）	7.03×10^{-4}	-

The detailed thermophysical properties of the paraffin wax can be found in the previous paper (Peng et al., 2019) and displayed in Table 1.

2.2 Model Description and Simulation Process

Model Description

The charging process of the PCM is numerically analysed by an enthalpy-porosity method and have been extensively applied to analyse the charging process of PCM (2013). The total charging time and the transient charging rate of PCM in the fin enhanced TES under different heating conditions are simulated by above method. The liquid fraction evolutions are demonstrated. The mechanism of the fin arrangement optimization on charging performance of PCM is discussed and the appropriate triple-fin systems are obtained.

Grid size and time step independent verification

The grid size and time step independent verification are the first step. Three node numbers of 5,026, 11,751 and 43,620 are applied to verify the independent of the grid size, the time step is chosen as 0.1 s. The results are clearly shown in Figure 1(a). Time steps of 0.025 s, 0.1 s and 0.25 s are used to verify the time step independent, the node number 11751 is applied. The results are displayed in Figure 1(b).

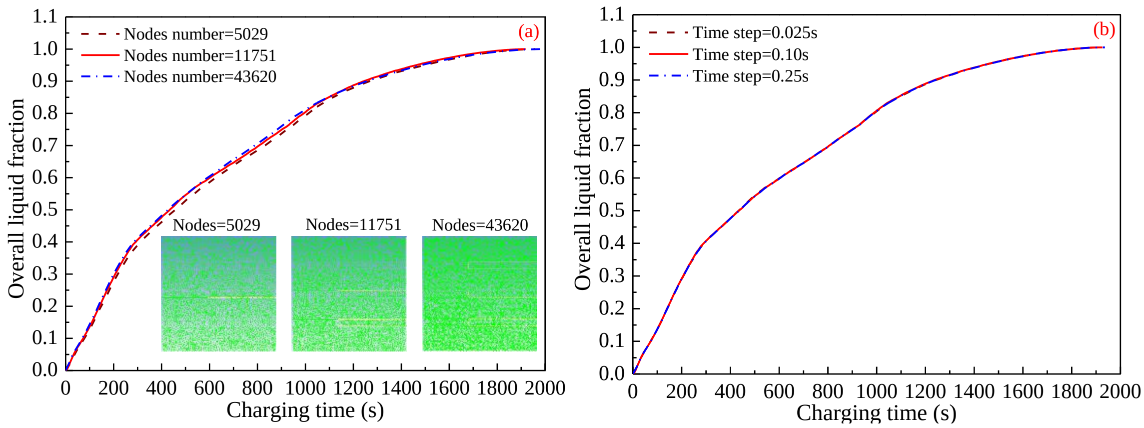

Figure 1: Grid size and time step independent verification under side heating condition with the temperature of the heated wall t_{heat}=90 °C，(a) grid size independent verification；(b) step time independent verification

From Figure 1, it clearly found that, when the node number increases from 11,751 to 43,620, the liquid fraction evolution is almost the same, only about 1.0 % difference. When the time step increases from 0.1 s to 0.25 s, the liquid fraction evolutions are almost the same, the difference is smaller than 1.0 %, and the node number 11,751 and time step 0.1 s are chosen for the following analysis.

3. Results and Discussions

3.1 Influence of Fin Arrangement on Overall Charging Performance of PCM

The total charging time is frequently applied to demonstrate the charging performance of PCM. The influence of fin arrangements on charging performances of PCM under different heating conditions are displayed in Figure 2. The total charging times of the PCM-based TES without fins are not presented to guarantee the mass of the PCM in the container is constant and the main objective of this work focuses on the influence of fin arrangement rather than the orientations on the charging time under various heating conditions. Actually, the total charging times of PCM without fins are much longer than that with fins.

From Figure 2, it clearly demonstrates that the fin arrangements significantly affect the total charging time of PCM for all the heating conditions. When the heating temperature is 90 °C, the total charging time increases from around 724 s to 1241 s when the ratio l_{a2}/l_{a1} (l_{middle}/l_{side}) increases from 0.0 to 1.27 then decreases to 1,058 s when the ratio further increases to 2.0 under bottom heating condition shown in Figure 2(a). Obviously, the optimum ratio l_{a2}/l_{a1} in the simulation can shorten the total charging time up to 41.7 % by completely introducing the convection effect into the charging process. Compared to the uniform triple-fin system, the optimum fin arrangement system can shorten the total charging time up to 37.8 %, and the fins with the same length are not appropriate and reasonable. The detailed liquid fraction evolution during the charging process under bottom heating condition are schematically displayed in Figure 3(a).

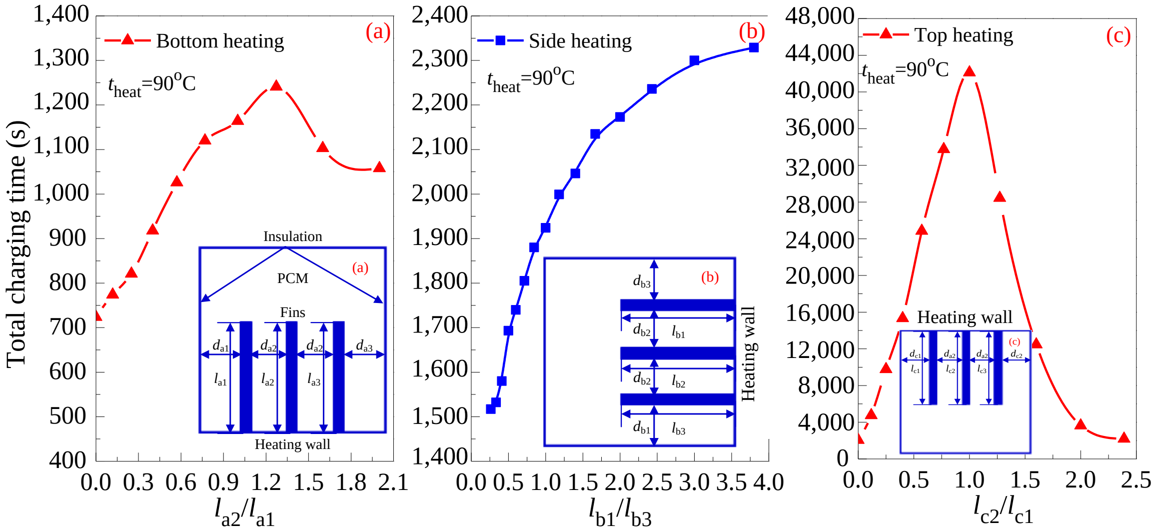

Figure 2: The influence of fin arrangements on the total charging time of paraffin wax under different heating conditions (t_{heat}=90 °C， (a) bottom heating condition, (b) side heating condition, (c) top heating condition)

From Figure 2(b), the total charging time increases from 1,517 s to 2,329 s when the ratio l_{b1}/l_{b3} (l_{top}/l_{bottom}) increases from 0.26 to 3.8 when the heating temperature is 90 ºC under side heating condition, up to 34.9 % charging time is shortened by the optimum fin arrangement, demonstrating that the uniform triple-fin system is not an appropriate choice for enhancing the charging performance of paraffin wax. Almost the same trend is found in the previous investigation (Ji et al., 2018a) which demonstrates that the simulation is reliable. Compared to the uniform triple-fin system, still up to 21.3 % total charging time is shortened induced by an appropriate fin arrangement by the synergy of convection-determined and conduction-determined regions during the charging process, which can be found in the liquid fraction evolution displayed in Figure 3(b). From Figure 2(c), for the top heating, the total charging time can be shortened from 42,118 s for the uniformly triple-fin system (l_{c2}/l_{c1}=l_{middle}/l_{side}=1.0) to 2,371 s for the optimized fin arrangement system (l_{c2}/l_{c1}=l_{middle}/l_{side}=2.39), up to 95.1% is shortened by introducing the convection into the charging process, when the heating temperature is 90 °C. The detailed liquid fraction evolution during the charging process under bottom heating condition are schematically displayed in Figure 3(c). According to the comparisons results shown in Figure 2 clearly demonstrate that fin arrangement optimization has the most significant influence on the charging performance of PCM under top heating condition (up to 94.5 % total charging time is shortened by the optimum fin arrangement) and has the least influence on that under side heating condition (about 34.9 % total charging time is shortened), and then that under bottom heating condition (around 41.7 % total charging time is shortened). The results demonstrate that although the enhancement factors induced by optimized fins arrangement under different heating conditions are different, all the enhancement factors are great and obvious. The fin arrangement optimization is necessary and effective for the charging performance enhancement of paraffin wax. The results also demonstrate that applying the metallic fins is an appropriate strategy to expand the large-scale applications of PCM with low thermal conductivity and supply a good guideline to structure an appropriate fin arrangement system for enhancing the charging performance of PCM-based TES.

3.2 Influence of the fin arrangement on the transient liquid fractions

The liquid fraction evolutions which can be applied to demonstrate the transient charging rate under various heating conditions are shown in Figure 3.

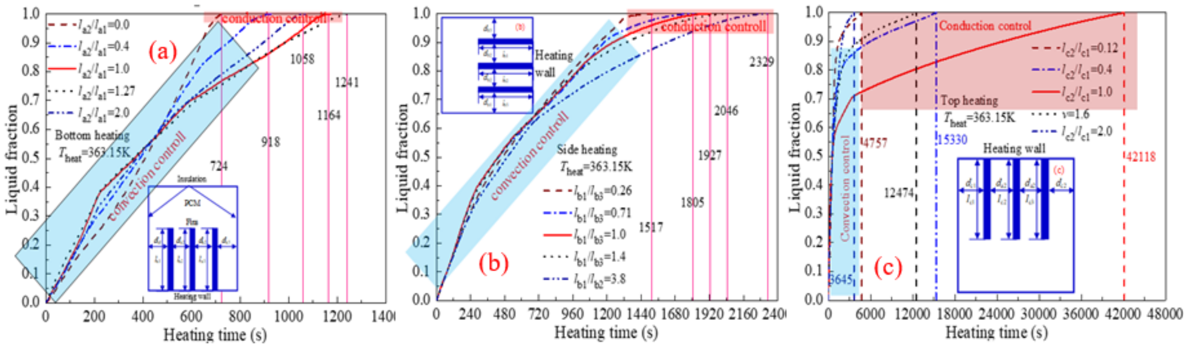

Figure 3 Liquid fraction evolutions and transient charging rate under various heating conditions (t_{heat}=90 °C, (a) bottom heating condition, (b) side heating condition and (c) top heating condition)

From Figure 3(a), it clearly demonstrates that there are two regions during the whole charging process: intense convection determined region, conduction determined region for all the fin arrangements. The transient charging rate is high and remains almost constant during the whole charging process of PCM when the ratio l_{a2}/l_{a1} (l_{middle}/l_{side}) is small such as l_{a2}/l_{a1}=0.0 under bottom heating condition, which clearly indicates that during the whole charging process, the convection effect is intense and plays the most significant role, greatly shortens the total charging time (724 s). With the increase of the ratio l_{a2}/l_{a1} (l_{middle}/l_{side}), the transient charging rate is almost the same and high for all the l_{a2}/l_{a1}, charging is determined by intense convection (intense convection region) at the beginning of the charging process (<700 s). The convection becomes weak when the charging further proceeds (>700 s) and the charging is determined by weak convection even by complete conduction. The transient charging rate decreases to the minimum when the ratio l_{a2}/l_{a1} (l_{middle}/l_{side}) increases to 1.27 and then enhances obviously when the ratio l_{a2}/l_{a1} increases to 2.0. The total charging time increases firstly and then decreases with the increase of the ratio l_{a2}/l_{a1}.

From Figure 3(b), it indicates that the transient charging rate gradually decreases with the increase of the charging time for all fin arrangements. At the beginning of the charging process (<720 s), the transient charging rates are almost the same for all the fin arrangements and remains a relatively high transient charging rate due to the convection effect, although the transient charging rate decreases with the charging time. The transient charging rate decreases with the increase of the ratio l_{b1}/l_{b3} due to the area of the conduction-determined region increases with the increase of this ratio. The optimized fin arrangement can greatly shorten the total charging time due to it can remain a relatively high transient charging rate during the whole charging process through integrating the convection and conduction effects. The convection-determined and conduction-determined regions are completely charged simultaneously by an optimized fin arrangement.

The results shown in Figure 3(c) demonstrate that the transient charging rate is significantly dependent of the ratio l_{c2}/l_{c1}. Obviously, the nonuniform fin length system can greatly expand the range of the convection-determined region during the charging process and shorten the charging time. For example, when the ratio l_{c2}/l_{c1}=1.0, the intense convection remains around 1,000 s which is the same as that with other ratios, the height of the convection-determined region is much smaller due to the much shorter of the maximum length of the fins. Only 30 mm height of the paraffin wax is mainly charged by convection. For the rest of the paraffin wax is mainly charged by the weak convection even by complete conduction. The overall charging performance is controlled by the conduction heat transfer. When the ratio l_{c2}/l_{c1} increases to 2.0 or decreases to 0.12, the intense convection effect can exist up to 1,500 s during charging process as well as the height of the convection-determined region is up to 45 mm even up to ~50 mm, significantly reduce the height of the conduction-determined region, accordingly, the total charging time is obviously shortened. The above results supply a good strategy to structure an appropriate fin system to enhance the charging performance of poorly conductive PCM-based TES and expand their applications under various heating conditions.

4. Conclusions

The influence of the fin arrangement on charging performance of lowly conductive PCM-base TES has been systematically and numerically investigated under various heating conditions through analysing the liquid fraction evolution during the charging process. The fin arrangement has been optimized and the following conclusions can be drawn. The fin arrangement has a significant influence on the charging performance (represents by the total charging time) of PCM under different heating conditions. The optimized fin arrangement can significantly enhance the transient charging rate shorten the total charging time (enhance the average charging performance) through inducing the charging of the convection-determined region and the conduction-determined regions are complete simultaneously (integrating the convection and conduction effects). The optimized fin arrangement has the greatest enhancement of charging performance under the top heating condition and has the least enhancement under side heating condition. Under the top heating condition, up to 95.1 % of the total charging time can be shortened induced by the optimized fin arrangement when the heating temperature is 90 °C. The total charging time can be shortened by 41.7 % and 34.9 % under bottom heating and side heating conditions. An effective strategy to design the appropriate fin arrangement for enhancing the charging performance of the lowly conductive PCM-based TES system is supplied.

Acknowledgements

The authors are grateful to the financial support of the National Natural Science Foundation of China (No.51906028) and the Research Start-up Funds of Dalian Maritime University (No.02503005).

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