Effect of rows and columns on the heat transfer characteristics of PCM staggered capsules bundle

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Effect of Rows and Columns on Heat Transfer Characteristics of Staggered Phase Change Materials Capsule Bundles

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Abstract

The current work is a heat exchanger incorporating several oval capsules filled with phase change materials (PCM) as staggered bundles in a shell. Through the charging process, the PCM, initially at 299 K, is heated by passing a cross flow of hot water in the upward direction by a value of 343 K. After complete melting, the solidification process is started by passing water at a temperature of 283 K. The proposed unit is studied with different rows (3 and 5 rows), and columns (3 and 5 columns), including 8, 13, 14, and 23 capsules. The number of rows and columns gets four configurations (3 rows £ 3 columns, 3 rows £ 5 columns, 5 rows £ 3 columns, and 5 rows £ 5 columns). The staggered bundle configurations were established to study the optimum case by calculating PCM temperature, stored energy, and the melting, solidification, and overall exergy. The results showed that the total melting and solidification time increases with the number of columns due to the increase in the number of capsules and that increases the amount of PCM. The exergy efficiency increases with the number of capsules at the same number of columns compared with the case of increasing the row numbers. The highest values of melting, solidification, and overall exergy efficiencies are 69.21, 23.85, and 16.52%, respectively, which occurred in the case of 5 rows £ 3 columns with 13 capsules.

Keywords: Bundle capsules, Heat transfer fluid, Melting and solidification, Numerical analysis, Phase change materials

1. Introduction

Thermal energy storage is important for bridging the energy supply and demand gap in addition to enhancing the efficiency of solar energy systems. The increased interest in renewable energy has made it viable to use this technology in the industry.

Thermal energy is stored in three different forms: sensible heat, latent heat, and thermochemical heat. Compared with alternative storage techniques, latent heat storage in phase change materials (PCMs) offers more useful characteristics. Using PCM as a heat source allows for modest temperature drops during the melting and solidification processes while maintaining a consistent temperature. It is chemically stable, has no corrosion, and can store a lot of energy in a small amount of space (Soliman et al., 2021c, 2021d). Therefore, one of the most effective ways for thermal energy storage applications is PCM (Guerraiche et al., 2020; Haghighi et al., 2019). The PCM is also relevant to several technical applications, including absorption systems (Soliman et al., 2021a), waste heat recovery (Soliman et al., 2021b, 2022a), air conditioning systems (Zhao and Tan, 2015; Soliman et al., 2023), and photovoltaic cell systems (Soliman et al., 2022).

Several studies have been established to improve the thermal performance of the PCM by using fins or baffles (Saha and Dutta, 2010; Shatikian et al., 2008; Soliman et al., 2022d), porous material (Japili et al., 2020; Gao et al., 2010), and using one storage unit with multiple PCMs (Soliman et al., 2022c; Wang et al., 2015). In another way, adding fine
particles (Wang et al., 2009; Seeniraj et al., 2002) and nanoparticles (Soliman et al., 2021b; Zarma et al., 2019) to the PCM enhances its thermal performance.

Note that the two primary types of metal foams are open-cell and closed-cell. For open-cell metal foams, the main parameters that define the foam structure are porosity and pore density. Porosity is the ratio of empty volume to the total volume of the metal foam, while pore density determines the number of cells in a given length. In the open-cell type, the cells in the structure are interconnected, and a liquid can move through those cells. However, in a closed-cell metal foam, the cells are separated by the metal structure surrounding each cell (Aramesh and Shabani, 2022).

The melting process of PCM is started by conduction followed by natural convection, which is affected by the design of the heat exchanger. Therefore, there are several designs for PCM heat exchangers, which were used to improve the PCM thermal performance (triplex tube, double tube, and shell-and-tube heat exchanger).

First, the triplex-tube heat exchanger (TTHX) with PCM was studied in several types of research as follows: the melting process in a TTHX with PCM (RT82) was numerically examined by Mat et al. (2013). The PCM was melted from the inside tube, outside tube, and both tubes using three different heating techniques. To boost the heat transmission between the heat transfer fluid (HTF) and the PCM, internal, external, and internal–external fin augmentation approaches were investigated. The impacts of fin length were investigated in the previous cases. The results concluded that the melting time was reduced by 43.3% in the TTHX with internal–external fins compared with the TTHX without fins.

A vertical triplex-tube casing with circular fins of nonuniform diameters was studied by Najim et al. (2022). The parametric study was established with different fin structures to get the best fin structure while preserving the same design fin constraints (material and volume). The findings showed that compared with a uniform fin size, varying the fin dimensions in the direction of the heat flow increased the melting and storage rate with a more uniform distribution of temperature. Compared with the reference fin size, the heat storage rate increased by 9.3%.

Nematpour Keshteli et al. (2022), numerically studied the PCMs melting process in a TTHX by taking into account three different approaches, including separately or together metal foams, adding nanoparticles, and using finned surfaces. Depending on local temperatures, PCMs with various melting temperatures are used in the central tube of the TTHX to optimize the latent heat. Water is also taken into account as an HTF between inner and outer tubes. The findings indicate that a PCM/metal foam composite with porosity ranging from 0.98 to 0.92 produces a faster melting rate than pure PCM. When compared with pure PCM, the melting time can be reduced by 69.52% by adding nanoparticles with a 5% volume fraction and metallic foam with varying porosities to TTHX. Regarding the melting procedure in pure multilayer PCM, the foam/nano-PCM device exhibits a reduced melting time for all metal foam porosities even if nanoparticles have a minimal impact in comparison to metal foams, reaching an 83.48% decrease if nanoparticles and metal foams.

Second, the double-pipe heat exchangers with phase-change material were studied in several investigations. Motevali et al. (2021) studied the melting process of nano-enhanced PCM. A double pipe heat exchanger was used to test the influences of three distinct dispersion techniques: dispersion of nanoparticles in the PCM (nano-enhanced PCM), in the HTF (nano-HTF), and the PCM and HTF (nano-enhanced PCM, nano-HTF). The findings demonstrated that the 1% nano-HTF and 3% nano-enhanced PCM nanoparticles of single-walled carbon nanotubes had the greatest impact of
the various factors on the PCM melting process, which reduced the PCM melting rate by 39%.

Abidi et al. (2021) investigated the melting and solidification processes of PCM (CaCl₂·6H₂O) containing graphene nanoparticles in a double-pipe heat exchanger. The heat exchanger was established so that the inner tube has a high temperature (melting mode) and low temperature (solidification mode), and the outer tube is insulated. The inner tube’s walls were covered with 12 rectangular blades that had the same temperature as the walls. By increasing the blade length, the molten PCM is in the charging process and the solidified PCM is in the discharging process.

Finally, the shell-and-tube heat exchanger with PCM were studied as follows: Tian and Zhao (Tian and Zhao, 2019) established multiple tube energy storage tanks with PCM. The effects of the tube circle diameter and the inner annulus temperature on the storage performance were studied. The findings demonstrated that increasing the inner wall temperature could significantly shorten the storage time and that increasing the tube diameter could significantly enhance the storage efficiency. However, as the tube diameter increased, the effect of inner wall temperature on reducing heat storage time gradually diminished.

The melting and solidification processes were numerically and experimentally investigated of the shell-and-tube heat exchanger with longitudinal fins using RT-25 as the PCM and water as the HTF (Törbarina et al., 2022). The influences of the flow rate and inlet temperature of HTF on thermal performance were studied. The thermal performance improved by raising the HTF inlet temperature in the melting process or lowering the HTF inlet temperature in the solidification process. The heat transfer between the HTF and PCM did not significantly improve when the HTF flow rate was increased, both during the melting and solidification process.

From the review of the available literature, it was found that the used PCM heat exchangers were divided into three types, which are: triplex tube, double pipe, and shell-and-tube heat exchangers. The phase-change materials, which were sometimes mixed with nanoparticles to improve thermal conductivity, were often in the space between the tube and the shell. Also, the PCMs were often charged in the shell containing the tubes through which the HTF flows.

The purpose of this study is to investigate the configuration and operational effects on the thermal performance of a thermal energy storage tank based on different configurations of oval capsules that are filled with phase-change materials (paraffin wax). This configuration had not been studied before through the melting or the solidification process. The HTF flows perpendicular to the capsules in the direction upward opposite to gravity. Also, the oval capsule position is as follows: the largest axis is in the direction of the HTF flow while its smaller axis is perpendicular to the direction of flow.

The effect of the row numbers (3 and 5 rows) and column numbers (3 and 5 columns) was studied in the proposed bundle configuration of the PCM oval capsules through the charging (melting) and discharging (solidification) process. The PCM temperature, liquid fraction, as well as the stored energy in the PCM, and the accumulated released energy from the PCM in the melting and solidification process, respectively, were studied. In addition, an exergy analysis was carried out to obtain the optimal shape of the bundle capsules, which gives the greatest thermal performance of the system in the melting and solidification process.

2. Physical model

The latent heat thermal energy storage unit that is investigated in the present work is a staggered bundle of oval capsules in a shell. The oval capsules are filled with paraffin wax as a PCM. The proposed unit diagram with different row numbers (3 and 5 rows) and column numbers (3 and 5 columns), including 8, 13, 14, and 23 oval capsules is illustrated in Fig. 1. The numbers of rows and columns could get four configurations: 3 rows × 3 columns, 3 rows × 5 columns, 5 rows × 3 columns, and 5 rows × 5 columns. To eliminate the impact of environmental conditions the heat exchanger’s right and left walls were insulated with no-slip boundary conditions. The HTF (water) enters the heat exchanger from the bottom part with an inlet temperature of 343 K in the melting process and 283 K in the solidification process. The height of the shell was assumed to vary from 350 to 550 mm, and the width varied from 72 to 120 mm, for the 3 rows × 3 columns and 5 rows × 5 columns, respectively. The dimensions of the vertical oval capsule are \(a = 1.15\) and \(b = 3\), where the \(a\) and \(b\) are half of the horizontal and vertical axis of the oval capsule (Soliman et al., 2024a).

The optimization process is discussed comprehensively in the results and discussion. The thermophysical properties of the PCM (paraffin wax) are presented in Table 1.

Note that the paraffin wax was selected in the present study due to its stability. The degeneration
of the heat of fusion of paraffin wax was 9.1% after 10,000 thermal cycles while that of the melting point was negligible (Zhang and Dong, 2017).

3. Theoretical model

The enthalpy porosity method was used to combine the convection–diffusion phase transition. In this method, the solid–liquid interface is not tracked directly. The solid–liquid mushy zone is a porous region with appropriate momentum sink terms applied to the equations of momentum, which is the cause of the pressure drop as solid material exists (Brent et al., 1988).

The difference in density of the PCM in the buoyancy term is expressed by the Boussinesq approximation, which contains thermal buoyancy. The buoyancy-driven conventional governing equations contained in the 2D transient model are as follows (Soliman et al., 2024a):

The continuity equation:
\[
\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial (r \rho V_r)}{\partial r} + \frac{1}{r} \frac{\partial (\rho V_q)}{\partial \theta} = 0
\] (1)

The momentum equations:

Momentum \( r \):
\[
\rho \left( \frac{\partial (V_r)}{\partial t} + V_r \frac{\partial (V_r)}{\partial r} + \frac{\partial (V_q)}{\partial \theta} \right) = - \frac{1}{r} \frac{\partial P}{\partial r} + \mu \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial (V_r)}{\partial r} \right) \right)
\] (2)

Momentum \( \theta \):
\[
\rho \left( \frac{\partial (V_\theta)}{\partial t} + V_r \frac{\partial (V_\theta)}{\partial r} + V_\theta \frac{\partial (V_\theta)}{\partial \theta} + \frac{V_r V_\theta}{r} \right) = - \frac{1}{r} \frac{\partial P}{\partial \theta} + \mu \left( \frac{1}{r} \frac{\partial}{\partial \theta} \left( r \frac{\partial (V_\theta)}{\partial \theta} \right) \right)
\] (3)

The parameter \( S \) is Darcy’s law damping term that was added to the momentum equation due to the impact of the convective phase change. This term depends on both the mushy zone constant \( A_{mash} \) and the liquid fraction \( (\lambda) \), which can be expressed as follows:

\[
\bar{S} = \frac{(1-\lambda)^2}{(\lambda^3 + \gamma) A_{mash}} V
\]
where \( \gamma \) is a small number usually about \( 10^{-3} \) applied to prevent division by zero in the damping term of Darcy’s law. The mushy zone constant \( A_{mush} \) value is high and can be nominated between \( 10^4 \) and \( 10^5 \). In this study, \( A_{mush} \) is defined to be \( 10^6 \), where different investigations recommended considering the \( A_{mush} \) value equal to \( 10^6 \), which gives the best match between the experimental and numerical outcomes (Soliman et al., 2022b).

The equation of energy is as follows:

\[
\frac{\partial h}{\partial t} + \frac{\partial}{\partial t} (\nabla h) = \nabla \cdot (\frac{k}{\rho c_p} \nabla h)
\]  

(4)

The \( H \) factor defines the PCM enthalpy and the \( h_1 \) parameter is the value of the sensible enthalpy, and the latent heat is expressed by \( \Delta H \) (Abo-Elnour et al., 2023):

\[
H = h_1 + \Delta H
\]  

(5)

\[
h_1 = h_{ref} + \int_{T_{ref}}^{T} C_p \, dT
\]  

(6)

where \( h_{ref} \) is the reference enthalpy at the reference temperature of \( T_{ref} \) and the term of latent heat can be written as a function of the total PCMs latent heat (L) as follows:

\[
\Delta H = \lambda L
\]  

(7)

where \( \Delta H \) varies from L (liquid) to zero (solid). So, the liquid fraction \( \lambda \) can be expressed by the following equation:

\[
\begin{aligned}
\lambda &= \begin{cases} 
\frac{\Delta H}{L} = 0 & T < T_m \\
\frac{\Delta H}{L} = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} & T_{liquidus} < T < T_m + \Delta T_m \\
\frac{\Delta H}{L} = 1 & T > T_m + \Delta T_m
\end{cases}
\end{aligned}
\]  

(8)

The \( \Delta T_m \) parameter can be expressed as the change between the temperature values of the PCM liquid and solid phases (Soliman et al., 2023):

\[
\Delta T_m = T_{liquidus} - T_{solidus}
\]  

(9)

The PCM thermal conductivity and density depend on the phase change process as follows (Soliman, 2023):

\[
\rho_{pcm} = \begin{cases} 
\rho_1 T < T_m \\
\frac{\rho_1 + \rho_1}{2} T_m < T < T_m + \Delta T_m \\
\rho_1 T > T_m + \Delta T_m
\end{cases}
\]  

(10)

\[
k_{pcm} = \begin{cases} 
k_1 T < T_m \\
\frac{k_1 + k_1}{2} T_m < T < T_m + \Delta T_m \\
k_1 T > T_m + \Delta T_m
\end{cases}
\]  

(11)

The exergy balance for a typical LHTS system during the charging process is illustrated in Fig. 2. Based on the exergy balance, the corresponding exergy expressions for the discharging process can be obtained similarly corresponding to the charging process.

The related expressions for the charging process suggested (Ramaya and Ramesh, 1998; Jegadeeswaran et al., 2010) are as follows:

Exergy input:

\[
\dot{E}_{input} = m_{HTF} C_{HTF} \left[ T_{HTF, in} - T_{HTF, out} \right] - T_0 \ln \left( \frac{T_{HTF, in}}{T_{HTF, out}} \right)
\]  

(12)

Exergy stored:

\[
\dot{E}_{stored} = ML \left[ T_0 \ln \left( \frac{T_{HTF, in}}{T_{HTF, out}} \right) \right] + M_{PCM, S} \left[ T_{PCM, init} - T_m \right] - T_0 \ln \left( \frac{T_{PCM, init}}{T_m} \right) + M_{PCM, I} \left[ T_m - T_{PCM, final} \right] - T_0 \ln \left( \frac{T_m}{T_{PCM, final}} \right)
\]  

(13)

Exergy input:

\[
\dot{E}_{input} = m_{HTF} C_{HTF} \left[ T_{HTF, out} - T_{HTF, in} \right] - T_0 \ln \left( \frac{T_{HTF, out}}{T_{HTF, in}} \right)
\]  

(14)

Watanabe and Kanzawa (Watanabe and Kanzawa, 1995) expressed the exergy efficiency as follows:
As the heat transfer in LHTS systems is time dependent, the evaluation of the exergy efficiency during melting at any time is also important. This motivates us to determine the exergy efficiency in the shape of the exergy rate:

$$\psi_{ch} = \frac{\text{PCM stored Exergy}}{\text{HTF supplied Exergy}}$$  \hspace{1cm} (15)

Thus, Rosen and Dincer (Rosen and Dincer, 2003) had informed that the pumping power to handle the HTF must be taken into account in the evaluation of exergy efficiency. They proved that the difference between the exergy efficiency that considers the pumping power and that neglects it is considerable. Moreover, this variance is more studied in the case of exergy efficiency than in the case of energy efficiency. Öztürk (2005) gave an exergy efficiency expression that considers the pumping power which is given below:

$$\psi_{char} = \frac{\text{The PCM exergy stored rate}}{\text{The HTF supplied exergy rate + Mechanical power input to HTF}}$$  \hspace{1cm} (16)

To validate the numerical model of melting in the present study, a comparison was established with the literature in two steps. First, the numerical model was compared with the experimental results of Soliman et al. (2021d) for PCM temperature and energy stored in a vertical cylinder that was heated by a constant heat flux of 1300 W/m². Second, the comparison was between the present numerical model with the experimental data of Kamkari et al. (2014) for a vertical rectangular enclosure that was heated by a constant wall temperature. The same operating conditions for the present model and the experimental study in the literature were verified. Fig. 4a and b indicates the PCM temperature and stored energy, as well as the PCM liquid fraction as shown in Fig. 4c, with the melting time for the experimental results (Soliman et al., 2021d; Kamkari et al., 2014), with the present numerical results. As can be noted from the figure, the present numerical results are in good agreement with the experimental results.
Fig. 4. PCM: (a) temperature, (b) stored energy, and (c) liquid fraction versus for the present numerical study and experimental results (Soliman et al., 2021d; Kamkari et al., 2014). PCM, phase change materials.
3.3. Mesh dependency study

In the present numerical model, a free triangular mesh was established. To test the effect of the number of meshes on the numerical results, a simulation is run with the oval capsules system. The capsules are initially at 299 K and the HTF (water) temperature is at 340 K (in the melting process). The average temperature of the PCM inside the capsule is compared for different numbers of element sizes (102 302, 242 675, 309 164, 413 032, 582 006, and 103 5450) as shown in Fig. 5. It is observed from the figure that there is a slight difference between the PCM average temperature for the number of elements of 582 006 and 1 035 450. Therefore, to save time, the number of elements equal to 582 006 is used for the present study. In the present study, the time step is 0.5 s throughout all models due to it having high accuracy in oval capsules (Soliman et al., 2024b). The mesh domain of one capsule for the proposed system is presented in Fig. 6.

4. Results and discussion

In this section, a parametric analysis of the staggered bundle configuration is performed under different rows (3 and 5 rows) and columns (3 and 5 columns) on the liquid fraction and the total energy stored in the PCM. After that, the exergy analysis of the system is established to get the optimum configuration through the charging (melting) and discharging (solidification) process as shown in Fig. 7.

4.1. Melting process

The effect of bundle configuration through the melting process of the PCM is divided into three parts: PCM liquid fraction, temperature, and stored energy in the PCM as follows.

4.1.1. Effect of bundle configuration on liquid fraction

This group of figures indicates the relationship between the liquid fraction and melting time for different bundle configurations.

Fig. 5. PCM average temperature at a different number of element sizes. PCM, phase change material.

Fig. 6. Mesh domain of one capsule in the proposed system.
The liquid fraction contours for three rows at different columns (3 rows × 3 columns, and 3 rows × 5 columns) are presented in Table 2. It is observed that the melted PCM layers move toward the top portion of the capsule. As compared with the lower portion of the capsule, the melting rate is more pronounced in the upper part of the capsule. The liquid fraction in the case of 3 rows × 3 columns melts faster than 3 rows × 5 columns due to the increase of capsules number in the last case, and

Table 2. Liquid fraction contours for the configuration of 3 rows × 3 columns and 3 rows × 5 columns.

<table>
<thead>
<tr>
<th>3R × 3C</th>
<th>3R × 5C</th>
<th>3R × 3C</th>
<th>3R × 5C</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="3R × 3C" /></td>
<td><img src="image" alt="3R × 5C" /></td>
<td><img src="image" alt="3R × 3C" /></td>
<td><img src="image" alt="3R × 5C" /></td>
</tr>
<tr>
<td>10 min</td>
<td>20 min</td>
<td>30 min</td>
<td>37 min</td>
</tr>
<tr>
<td>59 min</td>
<td>37 min</td>
<td>59 min</td>
<td>59 min</td>
</tr>
</tbody>
</table>

Fig. 8. PCM liquid fraction with time at three rows and a different number of columns. PCM, phase change material.
that would increase the amount of PCM. Thus, the total melting time is 37 and 59 min for the configuration of 3 rows x 3 columns and 3 rows x 5 columns, respectively.

Figs. 8 and 9 indicate the effect of column number on the PCM liquid fraction and temperature, respectively, for three rows of bundle capsules having an axis ratio of 0.16, HTF inlet velocity of 0.003 m/s, and temperature of 343 K.

It is shown from the figures that liquid fraction increases with the melting time. The figure shows also that the total melting time increases with the number of columns due to the increase in the number of capsules and that increases the amount of PCM. The total melting time for the configurations of capsules of 3 rows x 3 columns and 3 rows x 5 columns is 37 and 59 min, respectively.

Through the charging time, the liquid fraction value for the three columns is higher than the five columns; therefore, the PCM temperature in the three columns is higher than the value of the five columns. At the complete melting of the system, the final PCM temperature and liquid fraction for both cases reach a rough value of 342 K and an exact value of 1, respectively.

Liquid fraction contours for the configuration of five rows at different numbers of columns (5 rows x 3 columns and 5 rows x 5 columns) are presented in Table 3. It is observed that, as mentioned in the previous cases, as compared with the lower portion of the capsule, the melting rate is more pronounced in the upper part of the capsule.

The liquid fraction in the case of 5 rows x 3 columns melts faster than 5 rows x 5 columns and that would increase the amount of PCM. Thus, the total melting time is 52 and 62 min for the configuration of 5
Figs. 10 and 11 indicate the effect of column numbers on the PCM liquid fraction and temperature, respectively, for five rows of bundle capsules having an axis ratio of 0.16, HTF inlet velocity of 0.003 m/s, and a temperature of 343 K. It is shown from the figures that liquid fraction increases with the melting time. The figure shows also that the total melting time increases with the number of columns due to the increase in the number of capsules and that increases the amount of PCM. The total melting times for the configurations of capsules of 5 rows × 3 columns and 5 rows × 5 columns are 52 and 62 min, respectively.

Increasing the number of rows at a constant number of columns increases the amount of capsulated PCM and consequently increases the energy required to melt the PCM which in turn increases the time required to melt this amount of capsulated PCM.

Through the charging time, the liquid fraction value for the three columns is higher than the five columns, therefore the PCM temperature in the three columns is higher than the value of the five columns. At the complete melting of the system, the final PCM temperature and liquid fraction for both cases reach a rough value of 342 K and an exact value of 1, respectively.

4.1.2. Effect of bundle configuration on stored energy

To eliminate the effect PCM amount capsulated inside the bundle, the energy stored per kilogram of PCM (paraffin) is calculated and compared. Fig. 12a and b indicate the relation between the energy stored per kilogram and the melting time for different bundle configurations (3 rows × 3 columns, 3 rows × 5 columns, 5 rows × 3 columns, and 5 rows × 5 columns).

This figure indicates the effect of the number of rows on PCM stored energy per kilogram of PCM for three and five columns, respectively. It is shown from the figures that stored energy increases with melting time. After the complete melting, the stored energy per kg of PCM for the 3 rows × 3 columns, 3 rows × 5 columns, 5 rows × 3 columns, and 5 rows × 5 columns are roughly the same value of 375 kJ/kg.

4.2. Solidification process

Figs. 13 and 14 indicate the effect of the number of columns on the PCM liquid fraction and temperature, respectively, through the solidification process for three rows and five rows of bundle capsules having an axis ratio of 0.16, HTF inlet velocity of 0.003 m/s, and temperature of 343 K.

It is shown in Fig. 13 that liquid fraction decreases with the solidification time. The figure shows also that the total solidification time increases with the number of columns due to the increase in the number of capsules and that raises the amount of heat stored in the PCM. Through the
solidification process, this energy is released from the PCM to the cold water (HTF) that is required to warm.

The total solidification times for the configurations of capsules of 3 rows × 3 columns, 3 rows × 5 columns, 5 rows × 3 columns, and 5 rows × 5 columns are 20.01, 24.16, 23.23, and 25.69 min, respectively.

Through the discharging time, the liquid fraction value for the five columns in the two cases three rows and five rows (3 rows × 5 columns and 5 rows × 5 columns) is higher than the liquid fraction value of the three columns in the two cases, three rows and five rows (3 rows × 3 columns, and 5 rows × 3 columns). This is due to the high energy stored in the five columns compared with the three columns. Therefore, the PCM temperature in the five columns is higher than the value of the three columns, as shown in Fig. 14. At the complete solidification of the system, the final liquid fraction reaches 0 (solid phase), and the PCM temperature for the 3 rows × 3 columns, 3 rows × 5 columns, 5 rows × 3 columns, and 5 rows × 5 columns are 294.02, 294.61, 290.27, and 293.52 K, respectively.

To eliminate the effect of the PCM amount capsulated inside the bundle, the accumulated energy per kilogram of PCM is calculated and compared with the other cases. Fig. 14 indicates the relationship between the accumulated energy per
kilogram and the solidification time for different bundle configurations (3 rows x 3 columns, 3 rows x 5 columns, 5 rows x 3 columns, and 5 rows x 5 columns).

Fig. 15a and b indicates the accumulated energy per kilogram of PCM for three rows and five rows, respectively. It is shown from the figures that the accumulated energy increases with the solidification time. At the end of the solidification process, the final accumulated energy per kg of PCM for the 3 rows x 3 columns, 3 rows x 5 columns, 5 rows x 3 columns, and 5 rows x 5 columns are 377.88, 401.89, 402.92, and 379.51 kJ/kg, respectively.

4.3. Effect of bundle configuration on exergy efficiency

The results showed that by increasing the number of capsules in the bundles (the number of rows and columns), the melting time and the amount of
energy stored inside the capsules increases, which makes it difficult to reach the most efficient configuration of the bundle unit (number of rows and columns). Therefore, to reach the most efficient situation, the exergy efficiency will be calculated for the cases that have been studied in three forms. First, the exergy is calculated for the melting process. Second, the exergy is calculated for the solidification process. Finally, the overall exergy is calculated by multiplying the exergy of the system in the melting process by the exergy of the system in the solidification process.

The three values of the exergy (melting, solidification, and overall) are compared to find out the optimal configuration (number of capsules in rows and columns) of the bundle capsules that give the highest exergy efficiency.

Fig. 16 indicates the effect of the number of capsules on the PCM exergy efficiency of all bundle capsules having an axis ratio of 0.16, HTF inlet velocity of 0.003 m/s, and temperature of 343 K (melting process) and 283 K (solidification process). Noted that the 3 rows x 3 columns, 3 rows x 5 columns, 5 rows x 3 columns, and 5 rows x 5 columns have several capsules of 8, 13, 14, and 23, respectively.

Two factors control the exergy efficiency: first, the amount of energy stored in PCM, which increases with the number of capsules, and the amount of input energy, which increases with the duct width at the same HTF inlet velocity. The duct width depends on the number of columns as the capsule configuration is the same (the horizontal axis and pitch). So, the input energy in the case of five columns will be higher than that in the case of three columns (by 1.667 times).

It is shown from the figure that exergy efficiency increases with the number of capsules until reaches the highest value at 5 rows x 3 columns due to the increase of the stored energy because of the increase in the number of capsules with the same number of columns (three columns). After that, the exergy efficiency decreases due to the increased number of columns, which may be due to the increase in channel width and consequently the increase in the input energy. The highest exergy efficiency in the melting process is 69.21%, which occurred in the case of 5 rows x 3 columns with several capsules of 13.

The exergy efficiency increases with the number of capsules at three columns and then decreases when the number of columns increases from three to five columns due to the increase of the input energy. This factor is inversely proportional to the exergy efficiency at the same amount of energy stored. The highest values of the melting, solidification, and overall exergy are 69.21, 23.85, and 16.52%, respectively, which occurred in the case of 5 rows x 3 columns with several capsules of 13. Therefore, the configuration of 5 rows x 3 columns is selected as the optimum case of the bundle unit through the melting and solidification process.

5. Conclusion

The current work is a shell-and-tube thermal heat exchanger incorporating several oval capsules filled
with PCM as staggered bundles in a rectangular container. Through the melting process, the PCM, initially at 299 K, is heated by passing hot water from the bottom side of the heat exchanger to the upper side by a value of 343 K. After complete melting, the solidification process is started by passing water at a temperature of 283 K. The proposed unit is studied with different rows (three and five rows), and columns (three and five columns), including 8, 13, 14, and 23 capsules. The proposed number of rows and columns gets four configurations (the 3 rows × 3 columns, 3 rows × 5 columns, 5 rows × 3 columns, and 5 rows × 5 columns). Numerical investigations were carried out to study the optimum case of the oval PCM capsules heat exchanger by calculating, PCM temperature, stored energy, and the melting, solidification, and overall exergy.

Based on the outcomes of the present numerical study:

1. The total melting and solidification time increases with the number of capsules and that increases the amount of PCM and consequently increases the stored and released energy.
2. The exergy efficiency increases with the number of capsules at the same number of columns compared with the case of increasing the row numbers.
3. The highest values of the melting, solidification, and overall exergy are 69.21, 23.85, and 16.52%, respectively, which occurred in the case of 5 rows × 3 columns with several capsules of 13.
4. The configuration of 5 rows × 3 columns is selected as the optimum case of the bundle unit through the melting and solidification process.

The proposed bundle configuration (5 rows × 3 columns) gives a high thermal performance of the capsules through the melting and solidification process and could be used in solar applications (to store some of the water solar collector energy to be used at nighttime).

In future work, adding nanoparticles to enhance the PCM thermal conductivity could be studied. Moreover, it is recommended to study the change of the inlet water temperature and mass flow rate through the charging and discharging process.

**Author contribution**

Ahmed S. Soliman: idea, methodology, writing the original draft, software, writing the initial draft, validation, writing, review, and editing. Mohamed A. Sultan: supervision, idea, writing the original draft, writing the initial draft, validation, writing, review, and editing. Mohamed A. Sultan: idea, methodology, writing the original draft, software, writing the initial draft, validation, writing, review, and editing.

**Conflicts of interest**

There are no conflicts of interest.

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