NUMERICAL ANALYSIS OF LATENT THERMAL ENERGY STORAGE SYSTEM WITH EMBEDDED THERMOSYPHONS

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ABSTRACT:
Latent thermal energy storage (LTES) system offers high energy storage density and nearly isothermal operation for concentrating solar power generation. However, the low thermal conductivity possessed by the phase change material (PCM) used in LTES system limits the heat transfer rates. Utilizing thermosyphons to charge or discharge a LTES system offers a promising engineering solution to compensate for the low thermal conductivity of the PCM. The present work numerically investigates the enhancement in the thermal performance of charging and discharging process of LTES system by embedding thermosyphons. A transient, computational analysis of the LTES system with embedded thermosyphons is performed for both charging and discharging cycles. The influence of the design configuration of the system and the arrangement of the thermosyphons on the charge and discharge performance of the LTES installed in a concentrating solar power plant (CSP) is analyzed to identify configurations that lead to improved effectiveness.

INTRODUCTION
Concentrating solar power (CSP) plants harness solar energy from the sun and store as heat, which can be used to drive a turbine in a power plant to generate electricity. CSP plants provide for low-cost energy generation and have the potential to become the leading source of renewable energy for future power generation. Although energy from the sun is clean and abundant, the intermittent nature of solar availability makes it necessary to capture and store energy when available and discharge on demand. Also, storing energy for future use reduces the mismatch between the energy supply and demand by providing load leveling and helps to conserve energy by improving the reliability and performance of energy systems. Latent thermal energy storage (LTES) is the desired form of storing energy in a CSP plant due to its isothermal operation, high Rankine cycle efficiency, high latent heat of fusion and high volumetric energy density [1–2]. The latent heat of fusion and the volumetric energy density of the PCM are higher compared to the specific heat of PCM. For instance, the energy required to melt one kilogram of KNO₃ (latent heat) is 95 times higher compared to the energy required to raise the temperature of one kilogram of KNO₃ by 1K (sensible heat). Thus, LTES offers compact energy storage compared to a sensible energy storage system.

In the LTES system, a heat transfer fluid (HTF) exchanges energy with a PCM during the charging and discharging processes. During charging, hot HTF from the solar field transfers energy to a PCM resulting in its melting. During discharging, the PCM solidifies by transferring heat to the circulating cold HTF; the heated HTF may then be used to produce steam in order to run a turbine and generate electricity. Usually, the charging process occurs during the day when solar energy is available, while discharging aids in producing electricity even when solar energy is not available.

A fundamental challenge with LTES systems, however, is the low thermal conductivity of the PCM used, which reduces the rate of heat transfer. Several approaches to reduce the thermal resistance within the PCM are reported in the literature. Jegadheeswaran et al. [3] presented a brief review of the literature over the past decade on enhancing the performance of LTES. Extended surfaces such as fins are commonly used to provide additional heat transfer area for heat transfer in thermal energy storage systems [4, 5]. The use of embedded heat pipes or thermosyphons between the PCM and the HTF as a means of enhancing the thermal energy transport between them has also been explored: Horbaniuc et al. [6] reported on modeling of two-dimensional solidification of a low melting temperature PCM surrounding a longitudinally finned heat pipe, and investigated the duration of freezing as a function of the number of fins. By simulating a two-dimensional solidification of the PCM they demonstrated that the usage of more fins lead to increased solidification rates. Liu et al. [7] extended the work of Horbaniuc et al. [6] using a circumferentially finned thermosyphon, to analyze the effect of HTF inlet temperature and the flow rate on the freezing rate of paraffin PCM. Lee et al. [8] used a thermosyphon to investigate its...
sensitivity on various PCMs. Tardy and Sami [9] investigated numerically and experimentally the use of heat pipes to melt a low melting-temperature PCM and presented a thermal resistance model to determine the heat transfer rate with the HTF (air), and the associated melting process. Farsi et al. [10] conducted an experimental study to analyze the transient behavior of the thermosyphons.

Storage of PCM in a cylindrical tube capsule is of interest among the researchers because for a given volume a larger surface area of the tube is exposed to the HTF. Trp [11] investigated numerically a two-dimensional model of a shell and tube LTES configuration and quantified the thermal performance by analyzing the temperature distributions within the PCM. Two recent publications [12, 13] considered a LTES configuration with embedded heat pipes and presented numerical analysis based on a simplified network modeling to provide a quick estimate of the qualitative trends in the LTES performance with respect to the various operational and design parameters. Nithyanandam and Pitchumani [14, 15] presented a three-dimensional computational study of an LTES with embedded heat pipes. The enhancement in the melting of PCM due to the formation of natural convection currents was clearly illustrated. Nithyanandam and Pitchumani [16] also presented a two-dimensional computational study of the dynamic performance of LTES with embedded heat pipes for low temperature applications. The behavior of the system effectiveness for different charge to discharge ratios was discussed.

To the author’s knowledge, a detailed computational study of the LTES with embedded thermosyphons is not reported in the literature. Thermosyphons are considered here (instead of heat pipes) due to their simplicity of construction and low cost. The objective of the present study is to conduct a detailed three-dimensional (3-D) computational study of an LTES with embedded gravity-driven thermosyphons. Considering different number and orientation of thermosyphons, the performance of this integrated system is systematically analyzed during charging and discharging operations, to elucidate the complex interplay between the governing heat transfer and fluid dynamics phenomena. Based on the studies, optimum orientation of thermosyphons and design parameters of the system are obtained for maximizing targeted performance measures of the LTES system.

**MATHEMATICAL MODEL**

The physical system considered in this study resembles the LTES commonly found in CSP plants. The LTES configuration consists of a rectangular array of tubes of outer radius \( r \), and tube wall thickness \( b \), arranged with a horizontal center-to-center spacing \( S_L \) and a vertical center-to-center spacing \( S_T \) and enclosed in a shell as in Fig. 1(a). The PCM is contained within the tube over which the HTF flows transverse to the tube axis. The periodic configuration of the thermosyphon-embedded tube-in-shell geometry allows for identification of a representative three-dimensional rectangular volume element of dimensions \( S_T \times S_L \times L_m \) as shown in Fig. 1b for the analysis. The thermosyphons are placed in such a way that the center of the adiabatic sections of the thermosyphon coincides with the wall of the tube in contact with the HTF.

The flow of the HTF is considered incompressible and the properties of the PCM are considered to be constant in both the solid and the liquid phases. The PCM is treated as a pure substance, which undergoes phase change at a constant temperature. The natural convection effects are modeled by the Boussinesq approximation. The melting and solidification processes within the PCM are modeled by the enthalpy-porosity technique as explained in [17, 18]. In this approach, the solid-liquid interface is represented by a numerical mushy region, which is approximated as a porous medium wherein the porosity in each cell is set equal to the cell liquid fraction, \( \gamma \), which takes the value of 1 for a fully liquid region, 0 for a solid region, or \( 0 < \gamma < 1 \) for a partially solidified region ( mushy zone).

Based on the foregoing assumptions, the coupled system of continuity, momentum and energy equations governing the three-dimensional processes in both the HTF and the PCM are as follows:

\[
\nabla \cdot (\rho \vec{V}) = 0
\]

\[
\rho \frac{D\vec{V}}{Dt} = -\nabla p + \nabla \cdot \vec{f} + S_g
\]

\[
\rho c_p \frac{DT}{Dt} = \nabla \cdot (k \nabla T) + S_h
\]

where \( \rho \) is the phase density, \( k \) is the thermal conductivity, \( p \) is the pressure, \( t \) denotes time, \( T \) is the temperature, \( \vec{V} \) denotes the superficial velocity vector with components \( u, v, \) and
where the change
is a relaxation factor, which is set
for the HTF,
\( H_n \) in conjunction with the temperature,
to
in [13].
computational simplicity without loss of accuracy as reported
work model was implemented in the present work based on its
take the following form as reported in [18] for a pure substance,
latent heat source term is incorporated in the energy equation as
latent enthalpy takes the value of,
\( \Delta H = \rho \dot{h_d} \), where \( \dot{h_d} \) is the
latent heat content of the PCM.
The modeling of thermosyphons follows the equivalent
thermal resistance network description similar to that developed
for heat pipes by Nithyanandam and Pitchumani [13],
which accounts for the conduction within the thermosyphon
wall and the effects of evaporation and condensation within
the core. A similar, simplified thermal network model for rect-
gular thermosyphons was developed and tested by Ziapour
et al. [19]. The effect of gravity on inclined thermosyphons
and the dependence of evaporation-condensation phase change
on the saturation vapor temperature were not accounted for.
In the present study, the resistance network model developed by
Ziapour et al. [19] was modified for a cylindrical thermosyphon by including radial heat conduction elements.
Also the dependence of the condensation heat transfer coeffi-
cient on the inclination of the thermosyphon is modeled using the
expression derived by Hussein et al. [20]. The evaporation
heat transfer coefficient is modeled using appropriate correla-
tion for the nucleate boiling heat transfer coefficient in the
pool region of the evaporator section [21]. Since thermosyphons operate only when the direction of heat transfer
is opposite to that of gravity, the evaporator section should
always be located below the condenser section. The mathe-
matical details of the network model are omitted here for brev-
ity but may be found in [13, 19]. The thermal resistance network
model was implemented in the present work based on its
computational simplicity without loss of accuracy as reported in [13].
The mass flow rate and temperature of the HTF were
specified as inlet boundary conditions, and the outlet was de-
scribed as an outflow boundary condition, which imposes a
zero normal gradient for all flow variables except pressure
thus characterizing a fully-developed flow. The top and bot-
tom faces of the three-dimensional unit cell surrounding the
transverse flow of the HTF (Fig. 1b) are set to have periodic
boundary conditions while the front and back faces of the
PCM were set to be symmetric. The tube wall adjoining both
PCM and HTF was prescribed as a coupled boundary condi-
tion. Based on the design data available for 80 MW_c CSP plant
[12, 22] and assuming 20 rows of periodic arrangement
of tubes (Fig. 1a), the mass flow rate of HTF entering the
module was set at 0.706 kg/s The HTF inlet temperature was
set at \( T_C = 664 \) K and \( T_D = 568 \) K for charging and discharging
respectively.
Table 1 and 2 presents the geometrical and physical pa-
rameters used in the simulations of the LTES with embedded
thermosyphons, where the dimensions listed are representative
of those used for large-scale energy storage [22]. Therminol
VP1-Stainless steel thermosyphon is used for the present anal-
ysis while the HTF and PCM materials are Therminol-VP1
and KNO_3, respectively. The selection of Therminol-VP1 as
the thermosyphon working fluid is based on the life-test re-
results presented in [23].
In general, thermosyphons operate only if the directions of heat transfer and gravity are opposite. For the design con-
figuration considered in the present study (Fig. 1b), during
discharging, the PCM within the tubes (\( T_{m} \)) will be at a higher
temperature than the HTF discharge temperature (\( T_D \)). Hence
evaporation takes place in the section of the thermosyphon
adjoining the PCM while condensation takes place in the sec-
tion of the thermosyphon exposed to the cold HTF. Hence in
the thermosyphons placed below the horizontal diametral axis
of the tube, the return of the liquid condensate to the evapora-
tor section is thwarted by the opposite direction of gravity.
Since the thermosyphons placed above the horizontal tube
diametral axis operate only during discharging, the boiling
point temperature of the working fluid in the thermosyphon
should be between \( T_D \) and \( T_{m} \). Hence the properties of the
Therminol VP-1 in the thermosyphon placed above the hori-
zontal tube diametral axis correspond to the vapor pressure of
583 K as obtained from [24]. Similarly, the properties of the
thermosyphon placed below the horizontal tube diametral axis
 correspond to the vapor pressure of 633 K, thus making sure
that the phase change temperature lies between \( T_{m} \) and \( T_C \).
The complete three-dimensional model of the system de-
cribed above was implemented in a commercial finite-volume
based computational fluid dynamics solver, FLUENT. The
thermal network modeling of thermosyphons and the source
terms for the momentum and energy equations as explained
above was implemented in FLUENT through a user-defined
function. The computational grid was built of hexahedral ele-
ments (typically 300,000 cell elements) with optimal mesh
size determined based on a systematic grid refinement process.
In order to accurately predict the liquid fraction in the fixed
grid enthalpy-based procedure, the latent heat content of each
computational cell, \( \Delta H_i \) in conjunction with the temperature
predicted by Eq. (3), was updated at each iteration within a
time step. In the present case, the enthalpy iterative updating
scheme takes the following form as reported in [18] for a pure
PCM, which melts at constant temperature:
\[
\Delta H_i^{n+1} = \Delta H_i^n + \frac{a_i}{a_i^*} \varphi_i \left[T_i^n - F^{-1}(\Delta H_i^n)\right]
\]
(4)
In the above equation, \( a_i \) is the coefficient of \( T_i \) for the nodal
point \( i \) in the discretized equation of the energy equation for
PCM, which is obtained directly from the FLUENT interface,
\( n \) is the iteration number, \( \varphi_i \) is a relaxation factor, which is set
to 0.05 for the present case, \( F^{-1} \) is the inverse of latent heat
function which takes the value of \( T_{m} \) for a pure substance, and
The energy charged (discharged) by the PCM at any instant of time is composed of the summation of energy stored in all the PCM thermal elements which can be determined from the following expressions:

\[ Q_{C(D)} = \sum_{i=1}^{n} \left[ \rho_{PCM} c_{p} (T_{i} - T_{m}) + \rho_{PCM} \Delta h_{f} \times \Delta V_{i}, T_{i} > T_{m} \right] \]

where, \( Q_{C(D)} \) represents the energy stored (discharged) at any instant of time and \( T_{m} \) denotes the melting temperature of PCM and \( n \) denotes the total number of discretized cell volumes in the computational grid. For \( T_{i} < T_{m}, Q_{C(D)} = 0 \) The different thermosyphon arrangements studied and the corresponding results are discussed in the following section.

RESULTS AND DISCUSSIONS

The numerical model is validated by comparing the results obtained for melting of PCM in an axi-symmetric domain with the experimental data reported by Jones et al. [25]. The details of the geometry and the properties of PCM can be found in Ref. [25]. It can be observed from Fig. 2 that the numerical result obtained for the transient evolution of liquid melt volume fraction of the PCM for a Stefan number of 0.3265 compares well with the experimental data reported in Ref. [25]. The validity of the network model for thermosyphons is verified by comparing the numerical results of the transient variation of the working fluid temperature with experimental results obtained from Farsi et al. [10] as reported in [19] and is not repeated here.

The different arrangements of thermosyphons in the LTES system considered in the present study are illustrated in Fig. 3. For a LTES system embedded with \( m = 2 \) thermosyphons, the two thermosyphons are oriented vertically as in Fig. 3a, referred to as 2-VT in this study. For a LTES with \( m = 3 \) thermosyphons, two different arrangements are considered: a tri-star pattern as depicted in Fig. 3b (referred to as 3*-VT) and a Y-pattern as in Fig. 3c (referred to as 3-3Y). The simulations were performed for charging as well as discharging processes for a maximum period of 12 hours each, which is assumed to be the average length of a day and night.

Figure 4a-c presents the contours of the PCM melt volume fraction and the stream lines of flow fields within the molten PCM at various instants of time during the charging process for the configuration without any embedded thermosyphons. This arrangement serves as a reference for comparison with the simulations of LTES system with thermosyphons to establish the degree of heat transfer augmentation in the presence of thermosyphons. The end views of the PCM melt volume fraction contour on the vertical diametral axis along the plane A-A' (to the left of each subfigure) and the horizontal diametral axis along the plane B-B' (to the bottom of each subfigure) are also shown in Figs. 4a-c. The solid PCM inside the tube is represented by the blue colored area while the red colored area represent the molten PCM formed during charging. Figure 4a shows that at \( t = 1 \) h, the natural convection cells formed extend from the bottom of the tube to the top forming a clockwise vortex to the left and an anti-clockwise vortex to the right of the tube. With progression of time, the convection cells were found to be stronger and the Rayleigh-Benard convection cells are seen to extend all the way from the bottom of the tube to the top of the tube and the PCM melt fraction at the end of 3 hours is 46.64 %. It is to be noted that the local heat transfer coefficient varies along the circumference of the tube, with the
heat flux being highest at the top and bottom of the tube vertical diametral cross section. As a result, thermal stratification sets in, as seen in Fig. 4c at $t = 5$ h, which restricts the natural convection cells to extend until the top of the PCM. The melt fraction at that instant of time is 72.59%. Complete melting was attained at 8.31 h.

The time evolution of the molten PCM fraction contour for charging of LTES with 2-VT (Fig. 3a) is shown in Figs. 5a–c. The end views on the vertical diametral axis depicting the melting around the two thermosyphons along the plane A-A’ in Fig. 3a and the horizontal diametral axis portraying the melting along the plane B-B’ in Fig. 3a are also shown. Figure 5a, at $t = 1$ h, shows that the flow field has similar characteristics as the case with no thermosyphons but also exhibits additional recirculation cells in the vicinity of the thermosyphon located at the bottom. As discussed before, the thermosyphon placed below the horizontal diametral axis of the tube transfers heat based on evaporative cooling while the thermosyphon placed above the horizontal tube diametral axis functions as a fin transporting heat only through its walls. The top thermosyphon which acts as a fin which is observed to be less effective as seen by the less amount of molten PCM in its vicinity compared to the bottom in Fig. 5a. As melting progresses, the convection currents from the thermosyphon at the bottom do not extend all the way to the top of the PCM resulting in a reduced melting rate near the thermosyphon at the top as observed along the plane A-A’ in Fig. 5b. At $t = 3$ h, which is illustrated in Fig. 5b, it is observed that the a greater volume of the solid PCM near the top of the tube is molten as the recirculation cells which get heated in the process of ascending from the bottom of the tube, transfers greater amount of thermal energy to the solid PCM at the top due to higher temperature gradient between the cold solid PCM and the hot, lighter melt. As the molten PCM descends, losing heat in the process, the temperature gradient progressively decreases and the solid PCM at the bottom does not melt faster. The amount of PCM melt fraction available at $t = 3$ h corresponds to 60.23%. With further progression of the charging process, the intense convection effects circulate the hot melt from the bottom along the walls of the tube to the top of the solid PCM aiding the melting process and simultaneously thickening the thermally stratified molten layer at the top of the tube as seen by the absence of free convection currents in Fig. 5c. Overall the PCM melting is complete at 5.76 h.

Figure 6a–c represents the liquid fraction contour plots of the molten PCM for various instants of time in LTES embedded with three thermosyphons at an angle of 120° to each other (Fig. 3b) referred to as 3-*T. This arrangement is chosen to investigate the augmentation in the thermal performance of LTES due to embedding more thermosyphons in the bottom to
improve the conduction-dominated melting in the lower region of LTES as opposed to the already efficient convection-dominated melting in the top layer of LTES. The contour at the bottom depicts the melt front in the vicinity of thermosyphons along a plane normal to the page as seen from the top (C-C'-C" in Fig. 3b). Overall, two recirculation cells are observed in this configuration at a time instant of \( t = 1 \) h (Fig. 6a) on either side of the thermosyphons located at the bottom. The molten PCM was found to rise along the tube from its bottom getting heated in the process and on reaching the top of the PCM descends down along the solid PCM.

While descending, thermal energy acquired during ascension of the molten PCM is transferred to melting the solid PCM, thus entraining more molten PCM as it descends down and on reaching the thermosyphon located at the bottom it rises up again along the condenser of the thermosyphon before descending to the bottom of the tube to complete the recirculation loop. As the convection currents rise along the top portion of the thermosyphon located at the bottom and descends towards the bottom of the tube, a localized vortex is formed as some of them rise along the lower portion of the hot thermosyphon. In contrast to the 2-VT arrangement (Fig. 3a), thermal stratification is observed only at a later time due to efficient mixing of the molten PCM by the natural convection currents. The PCM melt fraction at the end of 1 hour is calculated to be 23.26%. As observed for the 2-VT configuration, the top thermosyphon acts like a fin and conduction dominated melting prevails in its vicinity until the end of 1 h. From Fig. 6b, it was observed that the localized convection cells formed between the two bottom thermosyphons is stronger compared to the convection cell extending from the bottom to the top thermosyphon. This can be attributed to the shorter distance of travel and subsequently faster generation of liquid melt in the vicinity of thermosyphons located at the bottom. The melting of the PCM completed at 5.94 h, which is longer compared to 5.76 h for the 2-VT arrangement due to the obstruction of the natural convection currents by the presence of an additional thermosyphon.

Figure 7a-c illustrates the contours of the melt fraction for LTES embedded with 3-YT at the time instants of 1 hour, 3 hours and 5 hours, respectively. Figure 7a, which illustrates the contours of the melt fraction at a time instant of 1 hour shows that the volume of molten PCM with 3-*T arrangement is larger compared to that in the 3-YT arrangement at a corresponding time. This can be attributed to the fact that the thermosyphons installed at the top half of the tube operate as fins due to reasons stated before and hence the melting rate is slower. As time progressed, the convection cells between the two inclined thermosyphons diminished as the molten PCM at the top of the tube became thermally stable owing to thermal stratification and at the time instant of \( t = 3 \) h corresponding to Fig. 7b, only the recirculation cells on either side of the thermosyphon located at the bottom was observed giving rise to clockwise (anti-clockwise) vortex to the left (right) of the tube. The PCM was fully melted at 6.03 hours (Fig. 7c) compared to 5.94 hours obtained for the 3-*T (Fig. 6c). Even though the presence of an extra thermosyphon at the top assists in the faster formation of natural convection currents in the top region of the PCM, the top two thermosyphons operate only as fins due to the same directions of heat transfer and gravity. Hence a slower melting rate compared to 3-*T configuration was observed in which only one thermosyphon operated as a fin.
Figures 4–7 presented the time evolution of the melt front progression for different arrangements of the thermosyphons. It is also instructive in examining the variation of energy stored and the charging effectiveness with time. Figures 8a and b illustrate the time history of energy stored within the PCM and the charging effectiveness for the various arrangements of embedded thermosyphons considered (Fig. 3). It is observed in Fig. 8a that the rate of melting is highest for LTES embedded with thermosyphons oriented in 3-*T arrangement followed by the 3-YT arrangement. The product of the total PCM volume and its latent heat of fusion, \( h_{\text{sl}} \), yield the maximum latent energy that could be stored in the PCM as 4.69 MJ. From Fig. 8a, it can be observed that the energy stored for the LTES with various thermosyphon arrangements is higher than 4.69 MJ due to the storage of sensible energy in addition to the latent thermal energy storage. Even though the melting rate of the 2-VT arrangement is slightly higher than the 3-*T and 3-YT arrangements as a result of the obstruction to the flow of natural convection currents in the presence of additional thermosyphon as explained before, the charge rate is faster for 3-*T and 3-YT arrangements because of enhanced sensible energy storage.

The charging effectiveness is defined to quantify the augmentation in the performance of LTES system in the presence of thermosyphons as, \( \varepsilon_C = Q_C/Q_{C,0} \), where \( Q_C \) is the energy stored for the case of tube embedded with thermosyphons while \( Q_{C,0} \) represents the energy stored for the case without any thermosyphons. From Fig. 8b it can be seen that the effectiveness starts from a high value due to the earlier onset of melting around the thermosyphons compared to melting around the tube, resulting in a high value for the ratio \( Q_C/Q_{C,0} \). The effectiveness curve then gradually decreases once the melting of the PCM around the tube also initiates at a time of approximately 7 minutes for the three thermosyphon arrangements and 11 minutes for the 2-VT arrangement when the effectiveness increases sharply. The increase can be attributed to the merging of the melt fronts near the tube and the thermosyphons, which amplifies the strength of natural convection currents existing within the molten PCM. After 40 minutes, the effectiveness remains fairly constant until it decreases at the end when the percentage of sensible energy stored also increases. This suggests that it is reasonable to stop the charging process when the effectiveness starts to decrease, which occurs at approximately \( t = 5h \) for all the arrangements, at which time the effectiveness values are 1.23, 1.30, and 1.25 for the 2-VT, 3-*T, and 3-YT arrangements, respectively. The effectiveness values at the end of the charging period in Fig. 8b are seen to decrease to 1.21, 1.26, and 1.22 for the 2-VT, 3-*T, and 3-YT arrangements, respectively.

During discharging, the PCM at its melting temperature, \( T_m = 608 \text{ K} \) will be at a higher temperature than the HTF. Thus the section of the thermosyphon inside the tube acts as the evaporator and liquid condensate is formed in the section exposed to the HTF. Consequently, the direction of heat flow is from the PCM to the HTF and only the thermosyphons located above the horizontal diametral axis works based on evaporative cooling while the rest acts like a fin. Figure 9a–d represents the solid regions (blue colored areas) at the end of the 12 hour discharging period for the four arrangements with or without thermosyphons. The solidification of the PCM is seen to be uniform throughout the solid fraction adjoining the tube and around the thermosyphons due to the absence of free
convection currents. As mentioned before, the solid fraction is found to be higher in the vicinity of the gravity-driven thermosyphons placed above the horizontal diametral axis while the thermosyphons placed below the horizontal diametral axis acts as a fin and consequently leads to lower energy extraction in its vicinity. It was found that the fraction of solid PCM at the end of the 12 hour discharging period was 55.05% for the LTES embedded without any thermosyphons (Fig. 9a), 61.18% for the 2-VT arrangement (Fig. 9b), 62.49% for the 3-*T arrangements (Fig. 9c) and 64.95% for the 3-YT arrangement (Fig. 9d). The 3-YT arrangement possesses a higher solid fraction at the end of the 12 hour period due to the presence of two thermosyphons in the top quadrant of the tube compared to only one thermosyphon operating based on evaporative cooling for the other two thermosyphon arrangements.

Figure 10 illustrates the time history of the energy discharged and the discharge effectiveness for the different arrangements of thermosyphons. From Figs. 10a and b it is observed that the solidification rate and the discharge effectiveness is highest for the 3-YT arrangement followed by the 3-*T. Even though only one thermosyphon acts based on evaporative cooling in the cases of both 3-*T and 2-VT arrangements, the 3-*T arrangement possesses a slightly higher discharge rate due to the presence of additional thermosyphon which acts like a fin. The effectiveness variation starts from a low value and increases due to the fact that the solid fraction adjoining the thermosyphons develops faster when no substantial solid fraction is formed along the tube. Unlike in charging, the sharp increase in effectiveness characterizing the start of free convection effects is not observed in Fig. 10b due to the conduction-dominated solidification of PCM while a gradual increase in the discharging effectiveness is observed for various configurations of LTES even after a time instant of approximately 3 h. This can be attributed to the sub-cooling of the solid PCM adjoining the tube when the PCM around the thermosyphons is only sub-cooled to a lesser degree, resulting in the gradual rise of discharge effectiveness. Of all the thermosyphon arrangements, in Figs. 10a and b, it was found that 3-YT arrangement provided the highest effectiveness of \( e_D = 1.17 \) at the end of the 12 hour discharging period.

The findings of the present study detailed the enhancement in the melting rate of PCM embedded with thermosyphons of different orientations for a particular configuration of LTES. Future studies will involve a more detailed modeling of thermosyphons to analyze its impact on the steady and dynamic performance of various configurations of LTES as reported for heat pipes in [13–15].

**CONCLUSIONS**

The results presented in this paper illustrate a methodology to determine the performance enhancement in LTES with embedded thermosyphons. It was found that the effectiveness was higher for the case of 3-*T and 3-YT during charging and discharging respectively. The 2-VT arrangement resulted in the faster melting rate while 3-YT arrangement resulted in the faster solidification rate. The inefficiency of the thermosyphons in transporting heat when the evaporator section is above the condenser is clearly demonstrated. Hence the thermosyphons operate as fins when the direction of heat transfer is the same as gravity, thus transferring heat only by means of conduction in the walls. The results also showed that the natural convection currents mainly influenced the perfor-
formance of LTES embedded with thermosyphons over the heat transfer between HTF and thermosyphons during charging.

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NOMENCLATURE

\[ b \] thickness [m]
\[ c_p \] specific heat [J/kg-K]
\[ h_{ev} \] heat of evaporation of thermosyphon fluid [J/kg]
\[ h_{lf} \] latent heat of fusion of PCM [J/kg]
\[ H \] total enthalpy [J/kg]
\[ k \] thermal conductivity [W/m-K]
\[ L \] length [m]
\[ Q \] energy charged (discharged) in (from) LTES embedded with thermosyphons [J]
\[ Q_0 \] energy charged (discharged) in (from) LTES without thermosyphons [J]
\[ Q_{C,I} \] energy stored in the LTES in a cycle [J]
\[ Q_{D,I} \] energy discharged from LTES in a cycle [J]
\[ r \] radius [m]
\[ S_L \] width of the module [m]
\[ S_T \] height of the module [m]
\[ T \] temperature [K]
\[ T_m \] melting temperature [K]
\[ t \] time [s]
\[ u \] x-component velocity [m/s]
\[ v \] y-component velocity [m/s]
\[ w \] z-component velocity [m/s]

Subscripts and Superscripts

a adiabatic
c condenser
C charging
D discharging
e evaporator
t tube
T thermosyphon
VT vertical thermosyphon

Greek Symbols

\[ \beta \] thermal expansion coefficient
\[ \varepsilon \] effectiveness
\[ \mu \] dynamic viscosity
\[ \rho \] density
\[ \gamma \] liquid fraction

REFERENCES


