Solar Thermal Storage Systems Using Phase Change Material: Design Criteria

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Abstract.

Solar energy is a clean, abundant and easily accessible form of energy; however, its intermittent nature makes thermal energy storage systems valuable for many applications. Latent heat thermal energy storage (LHTES) using phase change materials (PCMs) can adjust the mismatch between energy supply and demand, so that energy needs may be met all the time. This paper reports the latest findings of the author as part of his contributions to the International Energy Agency (IEA) - Energy Conservation through Energy Storage, Annex 31. The main contributions of Annex 31 lie on addressing the existing hindrance in developing simplified models, optimization tools and performance evaluation criteria related to energy efficient buildings/districts with energy storage.
In this regard, a series of numerical and experimental studies have been carried out to investigate the design considerations and critical parameters of LHTES units using phase PCMs. The results will benefit researchers in identifying and reducing the existing research gaps in designing, modeling and optimizing LHTES systems in buildings and districts levels.

INTRODUCTION

The building sector accounted for 32% of the global energy consumption in 2010 which escalated up to 40% in 2018 [1]. This change in the trend of energy consumption in buildings not only increased the energy demand, but also increased the greenhouse gas (GHG) emissions (CO2 from 19% in 2010 to 39% in 2017). To resolve this, efficient utilization of renewable energy sources is a potential alternative to meet the increasing energy demand in buildings. Statistical data convey that the power generation from renewables grew by 17% in 2017, contributing to 8% of the global electricity. In addition, the concepts of district level generation, cogeneration systems together with energy storage technologies and energy-efficient buildings have also been accepted globally by the building community to achieve the future goal of energy roadmap defined by the international energy agency (IEA).

Latent heat thermal energy storage (LHTES) using phase change materials (PCMs) can adjust the mismatch between energy supply and demand, so that energy needs may be met all the time. A comprehensive review performed by the authors [2] showed that LHTES has gained significant research attention due to its high storage density with small temperature change during melting/solidification processes. However, the low thermal conductivity of PCMs has hindered their commercialization and more widespread applications.

There are several solutions to improve the heat transfer rate between the heat transfer fluid (HTF) and the PCM. Three main areas in the literature are (1) understanding the heat transfer mechanism within PCMs and (2) the configuration of the LHTES units, and (3) heat enhancement techniques. This paper reports the latest findings of the author as part of his contributions to the IEA - Energy Conservation through Energy Storage (ECES), Annex 31. In this regard, a series of numerical and experimental studies have been carried out to investigate the design considerations and critical parameters of LHTES units using PCMs.

EXPERIMENTAL PROCEDURES

A series of experimental rigs were set up to investigate the thermal performance of LHTES systems using PCMs. Figure 1 shows a generalized schematic of the experimental setups in which the PCM filled the shell side. The hot (cold) water from the hot (cold) tank was circulated through the HTF tube during the charging (discharging) process. The temperatures in different locations within the PCM were measured by T-type thermocouples with an accuracy of ±0.2 °C and recorded by a data acquisition system (National Instruments NI9411).

The PCM used in these experimental rigs was RT60 paraffin wax from Rubitherm Technologies GmbH. The PCM thermophysical properties as well as testing conditions are listed in Table 1.

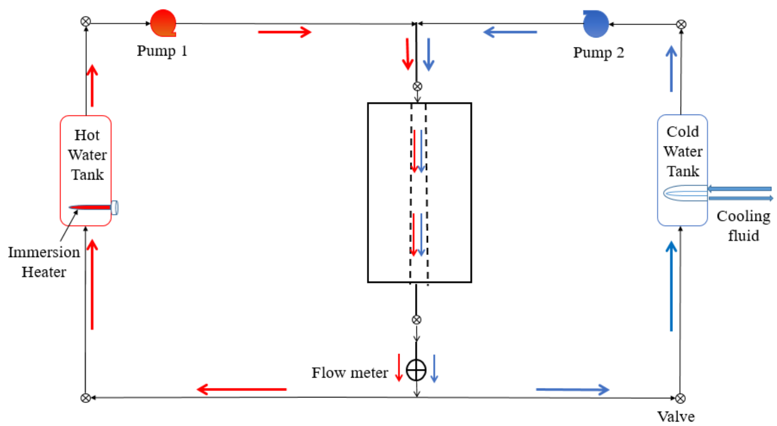


FIGURE 1. Schematic representation of the experimental setups.

TABLE 1. PCM thermophysical properties and test conditions

PCM (RT60)		**HTF (water)**		**Dimension**
Liquidus temperature:	61	Charging temperature:	80	°C
Solidus temperature:	55	Discharging temperature:	10	°C
Specific heat:	2	Specific heat:	4.18	kJ/kg.K
Thermal conductivity:	0.2	Thermal conductivity:	0.58	W/m.K
Solid density:	880 (at 15 °C)	Density:	998	kg/m^3
Liquid density:	770 (at 80 °C)			kg/m^3
Latent heat of fusion:	123.5			kJ/kg
Volume expansion:	12.5			%
Dynamic viscosity:	3.705×10^{-5}			kg/m.s

NUMERICAL APPROACH

To further investigate the experimental findings, the combined conduction and natural convection (CCNC) model based on enthalpy method was used to investigate natural convection within the PCM. The computational studies were performed using the melting and solidification model in ANSYS Fluent 17 software. Adiabatic boundary conditions were imposed on the outer walls as well as the top and bottom ends to simulate insulation. The assigned boundary condition on the HTF tube was assumed a constant surface temperature. The PCM was initially set to solid state with a temperature of 15 °C and the HTF inlet temperatures were 80 °C and 10 °C during the charging and discharging processes, respectively. The details of the numerical approach can be found in [3 and 6-7].

DISCUSSION

This section reports the authors' findings in the following areas:

Heat transfer mechanism in vertical LHTES [3,4]

A combined experimental and numerical study was performed in a vertical LHTES unit. Figure 2 shows the evolution of the liquid/solid PCM interface during charging. According to the results, the liquid PCM accumulates at the top of the storage unit and forms a cavity like an inverted cone. The conic liquid/solid interface surface gradually moves down and the liquid PCM region extends downward. This movement indicates that the PCM melts from the top to the bottom along the conic liquid/solid interface in the storage unit.

The reason of such interface movement is that at the beginning of melting, conduction is the dominant heat transfer mechanism resulting in an annular liquid layer around the HTF tube. Later, natural convection establishes, and the thermal energy is transferred from the HTF to the liquid PCM, which then moves to the upper part of the storage system by the vertical convection in the liquid PCM layer around the HTF tube. The motion induces horizontal convective circulation within the liquid PCM at the upper part of the system and is transferred outward towards the shell. These findings clearly demonstrate that natural convection plays an important role in the heat transfer during the melting process.

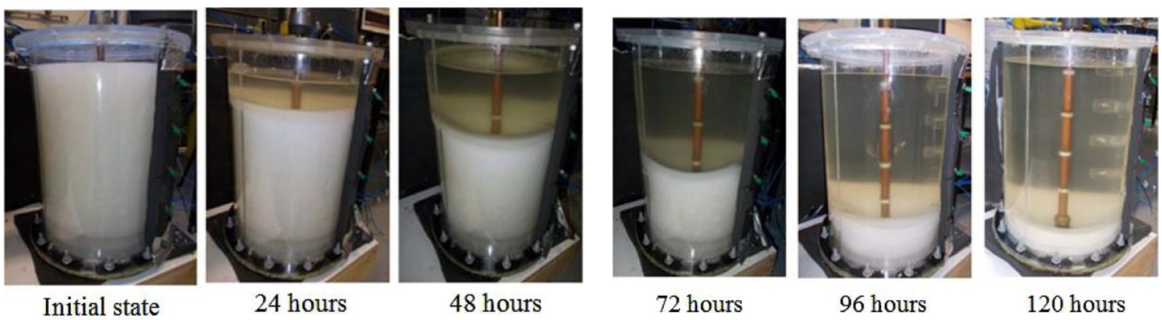


FIGURE 2. Evolution of the liquid/solid PCM interface at different charging times

Shape effect on vertical LHTES units: cylindrical vs. conical [5]

Figure 3 compares the simulated contours of the PCM in cylindrical (left) and conical (right) storage units at the same operation conditions. Note that each contour shows liquid fraction (left side) and temperature field (right side). During charging, the liquid PCM was found to accumulate at the upper part of the system due to the natural convection and hence the heat transfer is more effective at the upper part with both designs. The conical design could effectively utilize these natural convection forces simply by packing more PCM in the convection-dominated zone during melting. Comparatively, it was found that the PCM in the conical system melted about 12% faster in terms of stored energy at a given time in comparison to the cylindrical system.

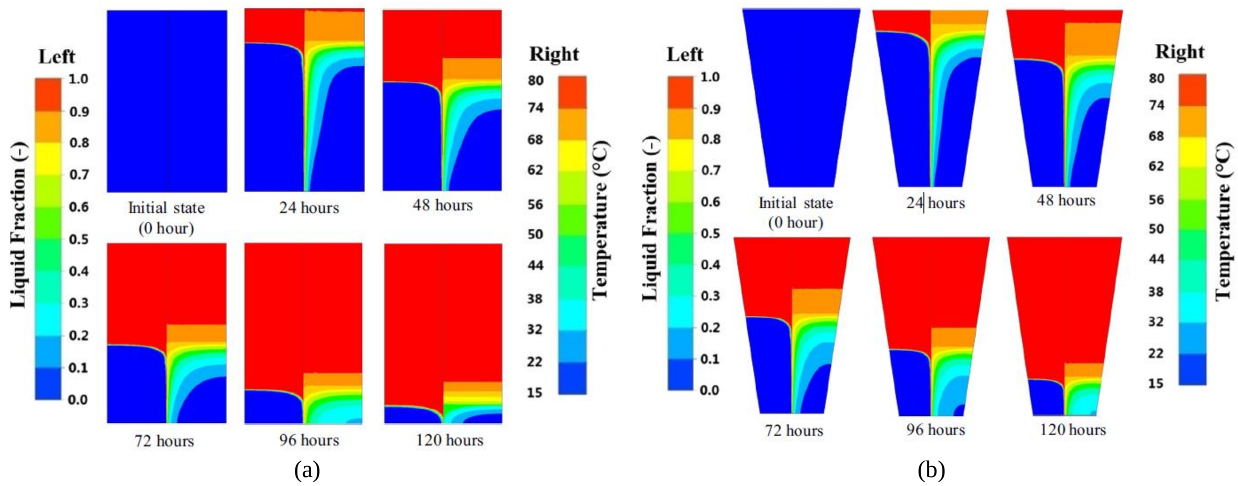


FIGURE 3. The contours of the PCM liquid fraction (left) and temperature (right) in the (a) cylindrical and (b) conical systems during charging

Orientation effect on LHTES units: vertical vs. horizontal [6]

The thermal behaviors in vertical and horizontal shell-and-tube LHTES units were numerically compared. Figure 4 shows the contours of PCM liquid fraction during a charging process in the horizontal (Figure 4a) and vertical (Figure 4b) orientations of LHTES units.

In the horizontal LHTES system, the melted PCM forms a recirculation region normal to the tube direction and around the HTF tube. The liquid PCM rapidly fills the upper part of the LHTES unit as shown in the figure. Once the upper half of the energy storage unit is fully melted, the temperature in the liquid PCM becomes more uniform, reducing the strength of the convection. However, the liquid PCM gradually fills the upper region in the vertical LHTES unit. The PCM always surrounds the vertical tube and the movement exists throughout the entire charging process. The convective heat transfer is active throughout the whole melting process resulting in an almost constant melting rate for the entire process.

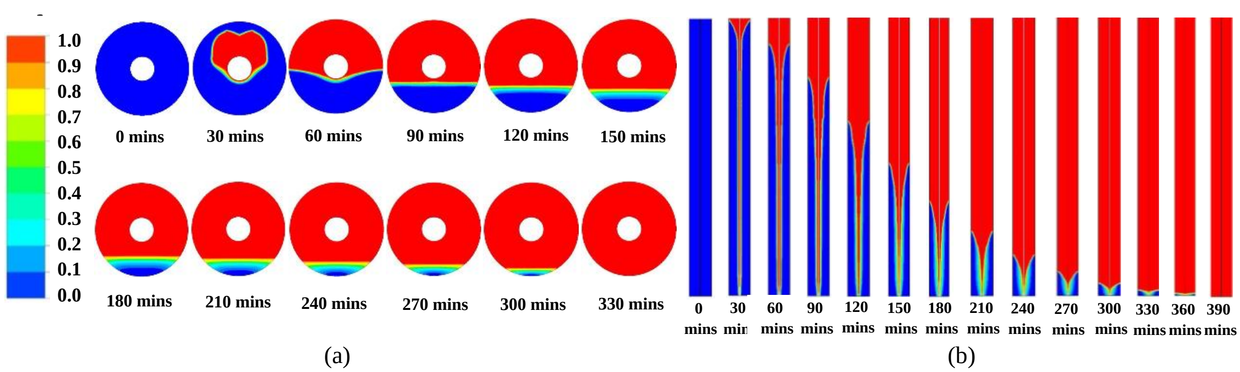


FIGURE 4. Contours of PCM liquid fraction during charging process in (a) horizontal and (b) vertical units

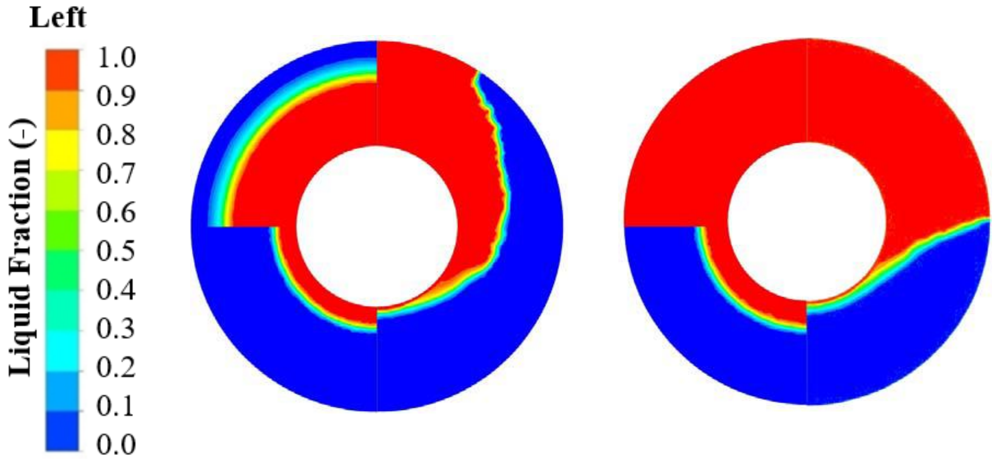
Heat transfer mechanism in horizontal LHTES [7]

Our earlier study [4] revealed that the horizontal latent heat storages are suitable for partial melting. However, detecting such conditions requires sophisticated numerical analysis with the CCNC model. Therefore, a novel front tracking method is presented which considers separate melting fronts for the upper and lower halves of a horizontal storage. The logic behind the method is to assume that the difference between the results of the CCNC and pure conduction (PC) models is due to the natural convection.

This method assumes that the natural convection contributes only to the upper half until the upper half liquid fraction value reaches one. Meanwhile, the lower half melting front is assumed to be the same as that of the PC model.

Once the upper half is totally melted, the method attributes the rest of the natural convection to the lower half of the system.

In Figure 5, each contour shows the CCNC model results on the right, whereas the PC model results based on the novel front tracking method (for the upper and lower halves) are shown on the left. According to the contours, an acceptable visual agreement exists between the real cases and the upper half values of the front tracking method.



Upper half liquid fraction: 0.5 Upper half liquid fraction: 1

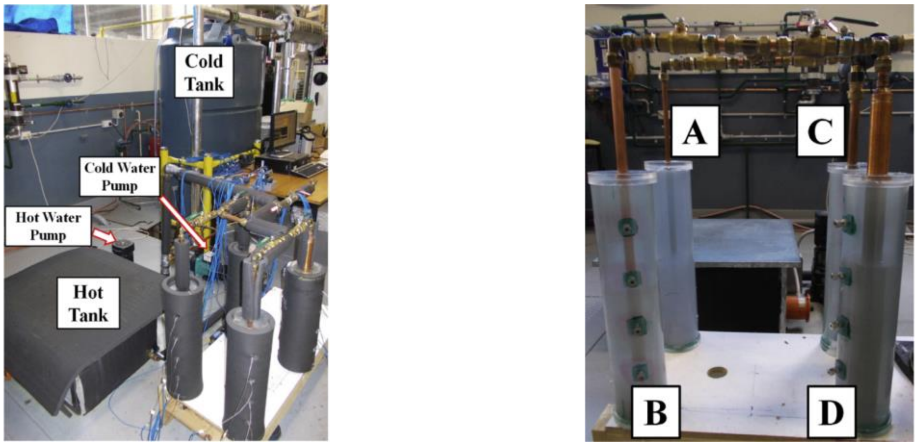
FIGURE 5. Logic verification where each contour shows the CCNC model (right) and the corresponding novel method results (left)

The main benefits of the novel front tracking method are:

- Compared to the effective thermal conductivity method, the novel method is not only simpler, but also provides information about the melting front location,
- The novel method provides identification of partial melting, which is greatly important for horizontal storages,
- The correlations are developed based on dimensionless parameters of shell-to-tube radius ratio as well as the liquid fraction of PC model (the latter is used instead of Fourier number),
- The location of the melting front is compatible with reality and can be more accurately tracked compared to the hypothetical PC model,
- Users do not need to go through the complicated CCNC model and yet obtain acceptably accurate results (within maximum 15% discrepancy),
- The method is applicable to horizontal shell and tube heat exchangers; e.g. for solar thermal applications.

Ratio effects in vertical LHTES unit: Shell to tube radius ratio [8]

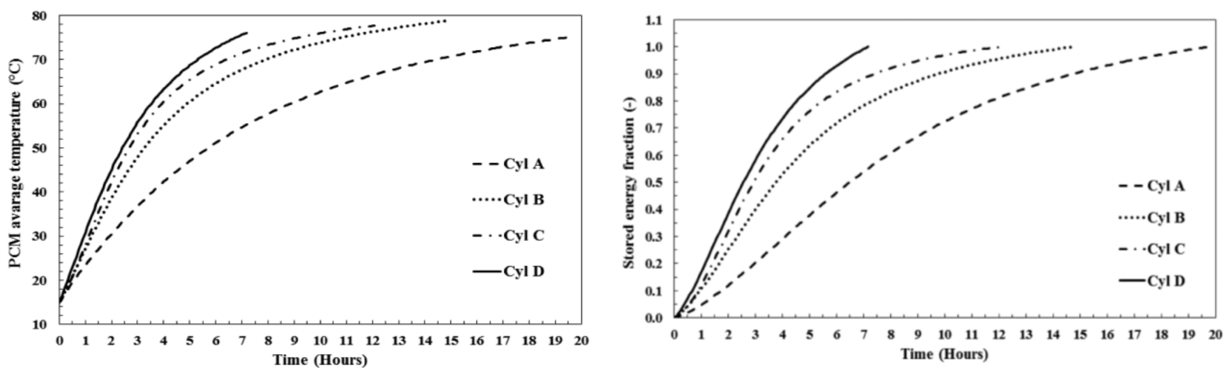
An experimental rig was set up to investigate the effect of geometrical and operational parameters on vertical cylindrical shell-and-tube LHTES systems as seen in Figure 6. Four different ratios of the shell-to-tube radius were considered with PCM at the shell side and the HTF flowing through the tube. The PCM temperature distributions were measured and compared among the studied storage units. A weighting method was utilized to calculate the average PCM temperature and stored energy fraction to evaluate the performance of the storage units.



(a) (b)

FIGURE 6. Pictorial views of (a) the whole experimental rig (b) the four PCM storage cylinders

Figure 7 compares the average PCM temperature and stored energy fraction of the LHTES systems during the charging process with the HTF temperature of 80 °C and the flow rate of 10 L/min. The results show that the trends in all cylinders are similar. However, among the cylinders, Cylinder A with the largest shell to tube radius ratio, has the slowest energy storage process. On the other hand, the energy storage rate increases as the shell to tube radius ratio decreases. The energy storage rate from Cylinder C to D is much lower than that from Cylinder A to B. These results indicate that an optimal shell to tube radius ratio exists. By considering the variation of the charging/discharging times, stored energy and average energy storage rate under different HTF temperatures and flow rates, a shell-to-tube radius ratio of 5.4 was found to offer the best system performance.



(a) (b)

FIGURE 7. Comparison of the (a) PCM average temperature, and (b) stored energy fraction during the charging process

Enhancement technique in horizontal LHTES units: using triplex tubes [9]

The performance of the simple and fast PC model was compared with the complicated time consuming CCNC model in a triplex tube heat exchanger (TTHX) under simultaneous charging and discharging (SCD). Figure 8 shows the schematic of the triplex LHTES unit in SCD mode where PCM is in the middle and hot and cold HTFs are in the inner and outer tubes, respectively.

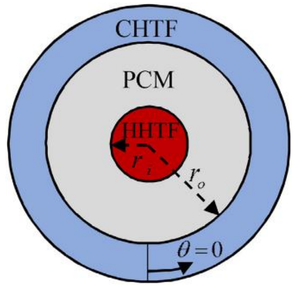


FIGURE 8. The schematic of the triplex tube heat exchanger.

The most important findings are:

- For internal heating/external cooling, the natural convection did not affect the lower half of the system since it had almost similar temperature distribution; however, the upper half was greatly affected by the buoyancy forces and natural convection of the melted PCM. On the other hand, for internal cooling/external heating, the buoyancy-induced upward melted PCM motion affected the entire domain, enabling maximum storage.
- Depending on the initial condition of the PCM, different liquid fraction, temperature and liquid/solid interface locations were observed, which was totally different from the results obtained from the PC model. This behavior shows how far from reality is such an assumption and to have accurate modeling of SCD, natural convection should be considered.
- Comparing the average temperature and liquid fraction showed that the PC model can be used for initially fully melted PCMs under SCD with small error. On the other hand, for initially solidified PCMs neglecting the natural convection would result in unacceptably large error.

Enhancement technique in horizontal TTHX unit: using fins [10]

In this study, utilization of extended surfaces (by longitudinal fins) was investigated to study the performance of a TTHX equipped with a PCM under SCD and non-SCD conditions. Three conventional fin geometries and six developed fin configurations were compared based on the temperature, liquid fraction and natural convection behavior (see Figure 9).

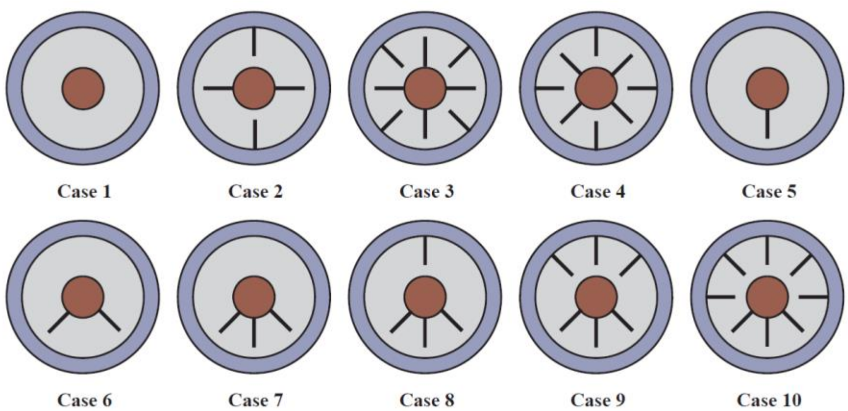


FIGURE 9. The schematic representation of the investigated cases.

Figure10a shows the liquid fraction contours of the conventional cases under melting (left of each contour) and solidification (right) from both sides of the storage. The same contours for the developed fin configurations are shown in Figure10b.

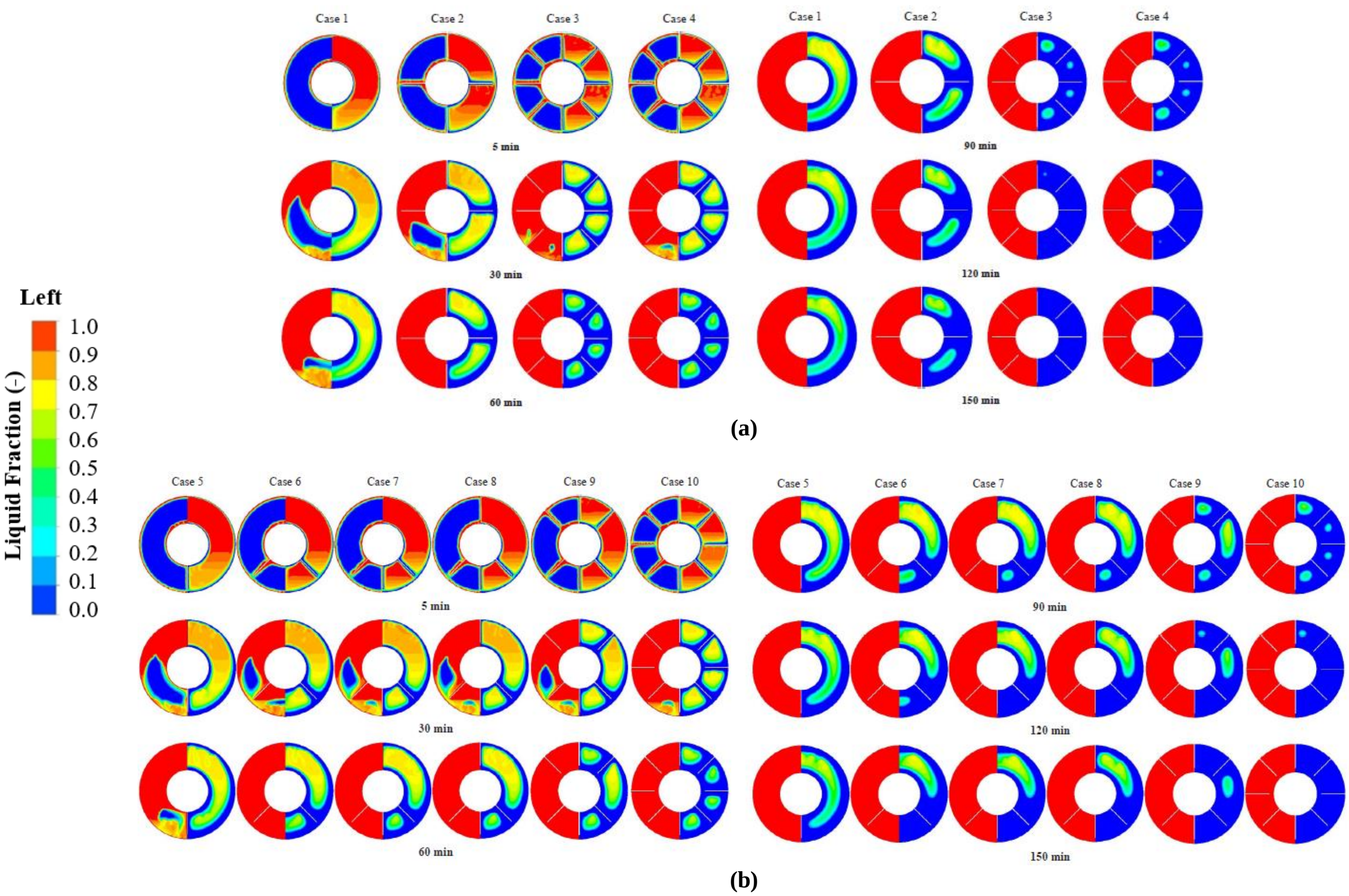


FIGURE 10. Liquid fraction contours for (a) conventional and (b) developed fin configurations under melting (left) or solidification (right) from both sides.

As Figure 10 shows, for melting under both sides heat transfer, the higher heat transfer surface area (compared to one side heat transfer) together with the buoyancy-driven motion significantly shortened the phase change process. Therefore, all cases achieved the fully melted condition within 90 min. On the other hand, although the heat transfer surface area attributed to shortening the solidification period, due to the lack of natural convection, the process was longer than melting. Interestingly, addition of more fins created some liquid cells surrounded by solid PCM for Cases 3, 4, 9 and 10 after 60 min. This finding underscores the significance of fins to enhance solidification. It shows how fast melting is compared to solidification thanks to the natural convection. This reveals that the bottleneck is to find a suitable geometry that accelerates solidification by enhancing the conductive heat transfer through the PCM. The most important findings were:

- For systems with SCD applications, the recommended fin configuration includes one external (at 90°) and three internal fins (at 225°, 270° and 315°).
- For systems with non-SCD applications having both sides heat transfer, the recommended fin configuration includes four internal fins (at 0°, 90°, 180°, 270°) and four external fins (at 45°, 135°, 225° and 315°).
- For systems with non-SCD applications having one side heat transfer, the recommended fin configuration includes five external fins (at 0°, 45°, 90°, 135° and 180°) at the upper half and three internal fins (at 225°, 270° and 315°) at the lower half of the system.
- Under SCD conditions, the effect of fin thickness was negligible. However, their number and length enhanced the heat transfer if the fins did not suppress the natural convection.

CONCLUSION

This paper presented the latest findings of the author as part of his contributions to the International Energy Agency (IEA) - Energy Conservation through Energy Storage (ECES), Annex 31. According to the results, comparative studies are required for the selection of the correct heat transfer enhancement techniques applied in PCMs. In addition, system optimization needs to be focused for future research.

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