State of the Art of Phase Change Material (PCM) for the Purpose of Heat Storage and Transfer in Cylindrical and Rectangular/Square Shells/Tubes – A Review

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Abstract: - The state of the art of the PCM's reveals enabled characteristics that opens the door for multiple heat transfer and storage phenomena. The PCM absorbs, stores, and releases the energy during its phase change thus it most widely helps in latent heat transfer techniques. Nowadays Nano-fluid and Nano-phase change materials are replacing the general phase change materials because of its high heat transfer and storage capability. Further, varieties of passive heat transfer techniques such as heat exchangers of shell/tube type of various patterns and geometries are utilized to optimize the thermal energy. The artificial neural network is embedded in the system to recognize the pattern for faster processing. In this article, the PCM heat storage and transfer techniques are critically reviewed in comparison with the Cylindrical and Rectangular/Square shells/tubes based on the effect of parameters such as solidification/melting performance, enthalpy, fluid flow pattern in the liquid molten state, types of PCM used, etc. The numerical/analytical and experimentation techniques are categorized based on the results of various researcher and conclusion is established.

Keywords: Phase change material (PCM), Energy storage, Heat transfer enhancement, Latent heat, natural convection, melting/solidification time.

1. Introduction
In the area of energy sector, storing and transferring the thermal energy without loss is a vital factor. From the earlier days there has been good number of techniques been used such as heat exchangers, chemicals etc., to overcome this issue. As the industries and researchers progress they came across the new composed materials called PCM’s, which revealed to be unique for storing and transferring the energy, but since it possesses low thermal conductivity, modifications based on utilization were applied in the form of active and passive techniques to overcome this problem. The PCM is broadly classified under organic and non-organic materials. The prominent PCM materials such as Cu, Al₂O₃, Au, SiC, SiO₂, and TiO₂ [1] are considered for an improved rate of heat transfer. Further, by utilizing various geometries of shells and tubes the heat transfer rate is enhanced. Nowadays Nanofluid and Nanophase change materials are replacing the general phase change materials because of its high heat transfer and storage capability. Further, the artificial neural network is embedded in the system to recognize the pattern for faster processing. The applications of PCM are 1. To dissipate the heat from the photovoltaic panels to maintain its voltage thus generating the electric pulses uninterrupted. 2. To dissipate the heat from electronic equipment's which generates more heat due to 24/7 working conditions such as industrial relays, transmitters, junction elements, etc. 3. To regain solar energy in its absence from the latent heat thermal energy storage (LHTES) system. 4. Portable/central space heaters and greenhouse application etc. This article concentrates on reviewing, how the PCM is utilized to store and transfer the heat in the Cylindrical and Rectangular/Square Tube/shells for different applications.

2. PCM heat transfer in cylindrical shells/tubes.
The containers of the PCM should be optimized based on the type of geometry and material used to store and transfer the heat energy as required. Further, the cylindrical shells/tubes are used to carry the PCM's and sometimes Nanoparticles are dispersed in the PCM's to enhance the heat transfer rate. These are made of different materials and sizes based on the given application. It is subjected to a different rate of heat to identify the PCM solidification/melting temperature. Below are the reviews on
different types of techniques/methods used to analyze the heat transfer in cylindrical shells/tubes. Fang et al. [2], developed an index value significantly characterizing the stored energy ratio with respect to LHTES systems. This index value was used to analyze the heat transfer effectiveness of multiple tube tank design as shown in Fig. 1 [3] by using numerical method of conjugate fluid flow and enthalpy technique. This was later compared to stratified water storage (SWS) system on ideal condition. Thus the heat transfer effect of PCM in the container was defined in the form of compact factor (CF). The developed index value was found to be directly proportional at any value of CF, but at any optimal value of CF, quite a percentage of theoretical energy storage was not utilized. Thus it showed that Heat transfer in the working fluid can be further improved.

Jones et al. [4] performed experimental measurements in a cylindrical enclosure melting the n-eicosane material from the side in a well-controlled environment as showing in Fig 2. The authors photographed the melt and ascertained it using an image processing procedure. Comparison between the numerical and experimental methods was done based on the temperature data taken based on the melt location taken. The enthalpy method and multi-block finite volume method of numerical investigation reveals good agreement, with the best at the lower Stefan number 0.1807. The experimental result based on a Stefan number of 0.0836 was recommended for validation against numerical data.

Regin et al. [5] conducted a series of experiments on the LHTES system considering paraffin wax as PCM filled in horizontal cylindrical capsules. The PCM was melted using hot water around it. The
capsule radius effect and working fluid temperature effect on the melting of PCM was investigated. Numerical analysis was carried out by using the enthalpy method to determine the phase change for a range of temperatures instead of constant temperature. The results were analyzed with experimental data, which was processed by the visualization technique considering three stages of melting (natural convection, contact melting, and the phase change temperature range) without disturbing the actual melting process. Both experimental and theoretical results show that heat transfer is significantly enhanced due to variation in the range of temperature. These results were also governed by the immensity of the Stefan number considering the temperature range and capsule radius.

Sparrow and Broadbent [6] conducted experiments on PCM filled inside the vertical tube with top surface being insulated by air space. The PCM was subjected to melt affecting the motions in the liquid melt due to change in the volume and natural convection. Their experimental results showed that the heat transfer rate was increased by fifty percent in comparison to the conduction model. Further, they measured that energy in the melt was twice the pure conduction prediction model. The Dimensionless number group involving Fourier, Stefan, and Grashof numbers were used to correlate the prediction data.

Saitoh and Hirose [7] analyzed the n-octadecane or water in a horizontal circular cylinder capsule as PCM for its melting rate and heat transfer rate for Rayleigh numbers. They obtained numerical solutions to find a solution to high Rayleigh numbers and to improve their resolution against heat transfer parameters. The researchers have shown that based on the position of PCM systems, the storage density and heat transfer rate is affected.

The authors Tay et al. [8] performed experimental investigations based on cold storage applications, by considering its thermal energy with coils of the tube inside a cylinder tank filled with salt hydrate as PCM along with water at -27°C as shown in fig 3. They showed that multiple tube tank design can deliver high storage density with a compact factor of 90% and above. Further by providing the optimized heat transfer techniques, the stored energy can be increased to 70% considering average heat exchanger effectiveness.

Rieger and Beer [9] investigated melting ice phenomena inside an isothermal horizontal cylinder experimentally and analytically. The mechanisms governing the heat transfer during the melting process is studied numerically as well as experimentally. In both cases, the heat transfer is said to be increased at the bottom part of the ice body at 8°C. This shows density effect resulting in an upward movement of the solid ice. A close relativeness is said to be found between the numerical and experimental data. Similarly, Rieger et al. [10] followed the same technique to determine the melting heat transfer inside the horizontal tube using n-octadecane as PCM. Thus the phenomena is better understood in phase change process.
Wu and Lacroix [11] performed the computational technique based on body-fitted coordinates to analyze the natural convection melting in an isothermal cylinder mounted vertical. The authors utilized the governing conservation equation considering vorticity, stream function, and temperature. Their analysis shows that the heat transfer rate in the upper surface reduced systematically to zero as convection heat transfer completely raised in the melt. Whereas the bottom surface was observed with intensive heat transfer. The convective flow pattern concerning time was seen to be complicated in comparison to both the top and bottom surface.

The authors Cabeza et al. [12] worked on the storage of solar energy which is the major issue due to drastic changes in climatic conditions. They utilized the different PCM’s such as fatty acids, trihydrate and paraffin in the system at the top of a stratified water storage tank as shown in fig 4. This PCM system used multiple cylinders at the top of the water tank. The solar pilot plant was developed to test the behavior of the PCM in a real situation to test the solar system. Plenty tests were carried out by varying the cooling down process, reheating process, and solar penetration with different volume of PCM, and temperature range. It was found that adding the PCM system for the domestic solar water heater is a promising technique. This would allow having a continuous supply of hot water without any external source of energy.

![Figure 4. Water tank with PCM modules of different configurations [12]](image)

Sun et al. [13] experimentally and numerically inspected the effect of partial volume fraction of solidification/melting phase change processes in particle-laden fluids. Inspectors observed that similar to the behavior (strong melt convection) of pure wax the slurry with 5% volume fraction behaves. For a volume fraction of 50% and 25%, heat conduction dominated in the melting process, and transition heat transfer was observed respectively. The diffusive flux model was used for numerical analysis which displays reasonable agreement for the partial volume of 5% and 50% for dilute and very dense slurry respectively. Further, they stated that more advanced numerical models are required to forecast to analyze the heat transfer behavior of particle-laden fluids. This study was further testified by Jones et al. [14]

An experimental investigation was performed by Zeng et al. [15] based on Nanoparticle enhanced phase change materials (NePCM’s) in a vertical cylindrical cavity – bottom heated. They dispersed multi-walled carbon nanotubes (CNT’s) into 1-dodecanol to prepare NePCM samples in liquid phase with various loadings (0 wt.%, 1 wt.%, and 2 wt.%) and found that melting decelerated in the presence of CNT’s due to increased viscosity. Natural convection was found to be decreased even though heat conduction was enhanced thus affecting the melting rate for the 1 wt.% sample, but for the 2 wt.%
sample melting rate was completely sealed. The authors declared that there is partial relevancy between experimental and numerical results in terms of melting behavior, this is because of the uncertainty of thermo-physical properties of NePCM's used in the computational models. Hence it is suggested to use measured thermos physical properties of NePCM's instead of using prediction models or correlations.

3. PCM heat transfer in rectangular/square shape shells/tubes.

The different patterns of rectangular/square shells/tubes are used with or without internal/external fins to determine the melting/solidification rate to drive the heat transfer. These arrangements are further utilized with bottom heating or side heating to enhance heat transfer. Apart from the heated sections, other sections are usually well insulated to prevent heat transfer from the respective direction. The horizontal or vertical orientation of the containers are also said to be impacting the heat transfer rate. Below are the studies done by several authors considering the respective geometries.

Ho and Gao [16] conducted melting experiments using n-octadecane as PCM and dispersed Al2O3 as nanoparticles utilized in 25mm square and 60mm long vertical enclosure as shown in figure [5]. The mixture was heated from the vertical sidewalls isothermally insulating other sidewalls. The heat transfer rate was measured across the negligibly subcooled wall which demonstrates that natural convection dominates across the melting region, adding nanoparticles outweighed the dynamic viscosity, the quasi-steady Nusselt number rises to 60% because of increase in 10 wt.% of alumina particles. Thus the particle dispersed heat transfer rate is outweighed by the natural convection heat transfer rate.

Motahar et al. [17] experimentally investigated the effect of titanium oxide dispersed as nanoparticles in the n-Octadecane as the PCM in the vertical rectangular enclosure heated on one side to measure its melting rate. Before adding the nanoparticle, PCM is said to have good conductivity, later it is dominated by natural convection. After the dispersion of nanoparticle, the viscosity increased, and thus the heat transfer rate is said to be deteriorated in the form of convection decreasing the melting rate. The melted volume fraction at the Fo number of 0.578 and heat flux of 2500 W/m² were measured at a different rate of wt.%. The quasi-state Nusselt number reduced with an increase in Bingham number because of an increase in viscous force at odds with buoyant force. The authors developed two universal correlations which were satisfying by considering the uncertainty below ±12%, and ±17%, for the Nusselt number and melted volume fraction respectively.

Bashar and Kamran [18] utilized the rectangular enclosure as shown in figure 6, to experiment on paraffin as PCM with dispersed Nano particles to observe the mixture characteristics. The
nanoparticles of aluminum, copper oxide, silver and others were used. After conducting series of experiments they came to the conclusion that enriched-optimum Nano particle-PCM mixture has enhanced thermal behavior in comparison to the pure PCM (CuO-18% and silver-14%). But when the mix ratio is not optimal, it resulted in dense viscosity degrading the characteristics of PCM. The high thermal characteristics was observed at optimal mix ratio for copper oxide-paraffin (0.6:10) and the melt rate/heat flux rate were increased to 25% higher than that of pure PCM.

![Figure 6. Schematic diagram of the experimental setup. The horizontal heat source (HTF tube) is shown near the bottom of the chamber. [18]](image)

Hoseinzadeh et al. [19] numerically investigated the performance of latent heat thermal storage [LHTS] system consisting of several rectangular PCM slabs by considering the variation in geometries like breadth, length, and width of the wall. In this system, the air is considered as the heat transfer fluid (HTF) to cool/heat the system. The method of enthalpy was used to solve fundamental equation for the melting process in PCM’s (CaCl2, 6H2O, and RT25). The general convective heat transfer equation was used to investigate the heat transfer in the air channels. The better results were obtained by using thinner and longer PCM slabs, and by using tiny air channels. The results show that when the outlet air temperature is increased, the flow rate as well as the fraction of molten PCM also increased.

Mosaffa et al. [20] studied the 2-d numerical model using the enthalpy method for a with internal horizontal fins for a rectangular container to predict the solidification temperature of PCM between the melting and solidification interface in the storage. The PCM melting and solidification factor was analyzed for different cell aspect ratio using the derived predication model. The result shows that the temperature of the working fluid or heat transfer fluid (HTF) increased to reduce the solidification time.

Talati and Taghilou [21] utilized the internal finned rectangular container to determine the melting/solidification temperature of the PCM. The authors utilized the lattice Boltzmann method (LBM) to analyze the same. They solved the problem of PCM by the analytical method and compared it against the finite volume method which was later used to predict the accuracy of the system. The freezing time of the PCM was observed half of the time of melting. The analytical solution of the model predicts the required time for solidification of PCM and it is said to be overestimated. Heat loss is reduced at the insulated composite walls of the PCM.
Zivkovic and Fujii [22] performed the numerical analysis on melting time of PCM encapsulated in single rectangular container using simple computational model. They simulated the transient behavior of isothermal phase change and the results were compared with solved test problem as well as with the experimental data showing close agreement. They concluded their work with the following points:
1. The accuracy of the computational data doesn’t change even though the containers conduction resistance is omitted.
2. The PCM conduction heat transfer can be ignored the direction of HTF flow as its value was negligible.
3. The prediction of temperature variation within the flat thin container of liquid PCM is found to be having negligible error even though the effect of natural convection is ignored.

Hoseinzadeh and Chamkha [23] worked on the performance of multiple PCMs in different rectangular slabs by maintaining almost constant temperature difference between HTF and PCM. The air was used as the HTF and CaCl2, 6H2O and RT25 as the PCMs. They carried out 2-d numerical investigations of LHTES using enthalpy method and investigated the effect of dimensional parameters such as the PCM slab width and the breadth, apart from this the effect of air flow rate in the exhaust air temperature of system was also measured. Their results seek that using less width PCM slabs, the number of PCM container decreases and good characteristic performance was obtained by using longer and small width PCM slabs. This leads to increased storage volume thus resulting in higher pressure drop in the system. It also shows that when the flow rate of air is increased, the fraction of the molten PCM is also increased.

Krishna et al. [24] analyzed the heat transport phenomena in melting and laminar film condensation in rectangular container of LHTES system. They performed the numerical simulation by employing formulation of modelling for the transient characteristics for PCM with foam with porous structure and is analyzed by finite element method for various dimensions of rectangular container. The results of the simulations show that selection of right aspect ratio of PCM containers is crucial to increase the energy storage and heat transfer. This effect is further deliberated by thermal resistance ratio. The film condensation in the vertical outside walls of containers was considered for the scenario, and the value of best aspect ratio is 1, irrespective of PCM, foam and heat extraction methods. It was also found that utilizing high thermal conductivity foam only doesn’t increase the heat storage capacity but appropriate foam type with a large thermal mass or a high thermal conductivity respectively forms the right choice.

Taghilou and Talati [25] presented an approximate analytical/numerical model for the purpose of investigating the solid-liquid interface and temperature distribution of PCM during the solidification of PCM inside a container connected to fins with boundary conditions of time dependent. The numerical and analytical results for the solidification front and temperature distribution are compared with results obtained by the Lattice Boltzmann method. It was found that the use of fin to increase the rate of heat transfer is justifiable in the container with the aspect ratio of less than 1. The highest error rate of 0.5 in aspect ratio was found by using analytical model used for the purpose finding the time required for complete freezing and the lowest was 0.25.

Imen and Mounir [26] investigated the PCM solidification in a finned rectangular heat exchanger including natural convection to exploit solar energy continuously. In the first step they analyzed all the models of solidification and also the temperature/velocity distribution using the numerical model of conservation equations. Their study also showed longitudinal air temperature profiles with the transient evolution. It also shows the effect of number of fins on heat transfer enhancement and the temporal evolution of the solidification front. This study showed the maximum amount of heat extracted during the solidification of the PCM.

Nabeel et al [27] performed experimental and numerical investigation on melting of n-octadecane with CuO nanoparticle suspensions in a square enclosure. The container was thermally insulated and provision was given on one side to heat it at a constant heat flux. They recorded the temperature at different junctions pertained to time-dependent. The finite element method was used to solve the
momentum, coupled continuity and energy coupled equations numerically. The loading of nanoparticles into the PCM has a rising effect in thermal conductivity of the PCM/nanoparticle composite, thus augmenting the heat transfer rate results in decreased charging time. But caution should be taken for agglomeration of nanoparticles which increases the viscosity and precipitation. By competing heat transfer mechanisms, the shape of the melting interface is affected highly by the. The flat shape interface is present in the conduction-dominant regime, while curved shape of the interface emphasizes development of natural convection.

Hossein and Babak [28] experimentally investigated the characteristics of lauric acid as PCM in a rectangular thermal storage unit heated from one side. It satisfies thermos-physical properties of PCM as medium temperature PCM. The melt fraction and other heat transfer characteristics such as average Nusselt number, melt front, and soli-liquid interface morphology was studied using image processing technique. The results of the experiments show that the heat conduction was dominant during initial stage of heat transfer, followed by transition from conduction to convection regime, which dominates the heat transfer at later times. Approaching the end of the melting process, bulk temperature of the liquid PCM increases and stratified temperature field appears at upper part of the enclosure which reveals depression of the convection currents.

Soares et al. [29] experimentally investigated the heat transfer with two different PCM (the free-form PCM-Rubitherm the microencapsulated PCM-Micronal) in a vertical stack of rectangular cavities for both melting and solidification processes. The main goal of author was to discuss which type of PCM is better for building applications. They investigated the control temperature value on the hot surface of test sample and the period thermal regulations. The free PCM was found to be better for thermal control of vertical systems due to improved natural convection. But the control temperature effect and thermal regulation period both were reduced. During the discharging process, subcooling palyed an important role during the solidification of the free PCM and its effects can’t be neglected.

4. Conclusion.
This paper shows the quench of experimental and numerical studies carried out by researchers considering the effect of PCM's in cylindrical/rectangular containers and their positions. Most of the researchers used the vertical position of cylindrical containers instead of horizontal position as it consumes less ground space, increased storage density ratio, enhanced heat transfer rate from 40% to 60%. In the horizontal cylinders, the heat transfer rate is said to be more at the lower part of the container, this is because of the high storage density effect as the result of the upward movement of the working fluid. The convective heat transfers in both the position of cylinders seemed to be more and as the time progressed the authors found it to be more complicated. In most cases, the diffusive flux model and enthalpy model were used to predict the heat transfer behavior which seemed to be not quite accurate hence there was a difference in results in comparison to experimental and numerical techniques. In the rectangular PCM containers, the dispersion of Nanoparticles increased the convective heat transfer rate in comparison to the natural convection at the beginning, but as time progressed the dispersed particles increased the dynamic viscosity of the working fluid and thus heat transfer rate is degraded for over a while. The heat transfer in the PCM was due to conduction before adding the Nanoparticle in the rectangular enclosure, later it was dominated by natural convection. The cylindrical and rectangular containers are seemed to be more effective in lower and higher storage capacity ratio respectively as well as the heat transfer rate.

References:
[1] Rehman, Tauseef-ur, et al. "A critical review on heat transfer augmentation of phase change materials embedded with porous materials/foams." Int. J. Heat Mass Transf. 135 (2019): 649-673.
[2] Fang, Yuhang, Jianlei Niu, and Shiming Deng. "Numerical analysis for maximizing effective energy storage capacity of thermal energy storage systems by enhancing heat transfer in PCM." Energy and Buildings 160 (2018): 10-18.
[3] Trp, Anica. "An experimental and numerical investigation of heat transfer during technical grade paraffin melting and solidification in a shell-and-tube latent thermal energy storage unit." Solar energy 79.6 (2005): 648-660.
Soares, N., et al. "Experimental study of the heat transfer through a vertical stack of rectangular cavities filled with phase change materials." *Heat and Mass Transfer* 133 (2018): 69-81.

Dhaidan, Nabeel S., et al. "Experimental and numerical investigation of melting of phase change materials." *International Journal of Heat and Mass Transfer* 56 (2013): 111-117.

Taghilou, Mohammad, and Faramarz Talati. "Analytical and numerical analysis of PCM solidification inside a rectangular finned container with time-dependent boundary condition." *International Journal of Heat and Mass Transfer* 52.13-14 (2009): 2966-2978.

Hoseinzadeh, S., et al. "Numerical investigation of rectangular thermal energy storage units with multiple phase change materials." *Journal of Molecular Liquids* 271 (2018): 655-660.

Mosaffa, A. H., et al. "Approximate analytical model for PCM solidification in a rectangular finned container with convective cooling boundaries." *International Communications in Heat and Mass Transfer* 39.2 (2012): 318-324.

Ho, Ching-Jenq, and J. Y. Gao. "An experimental study on melting heat transfer of paraffin dispersed with Al2O3 nanoparticles in a vertical enclosure." *International Journal of Heat and Mass Transfer* 62 (2013): 2-8.

Jones, Benjamin J., et al. "Experimental and numerical study of melting in a cylinder." *International Journal of Heat and Mass Transfer* 49.15-16 (2006): 2724-2738.

Rieger, H., et al. "Heat transfer during melting inside a horizontal tube." (1983): 226-234.

Sparrow, Ephraim M., and J. A. Broadbent. "Inward melting in a vertical tube which allows free expansion of the phase-change medium." (1982): 309-315.

Saitoh, Y., and K. Hirose. "High Rayleigh number solutions to problems of latent heat thermal energy storage in a horizontal cylinder capsule." (1982): 455-553.

Tay, N. H. S., M. Belusko, and F. Bruno. "Experimental investigation of tubes in a phase change thermal energy storage system." *Applied Energy* 90.1 (2012): 288-297.

Rieger, H., and H. Beer. "The melting process of ice inside a horizontal cylinder: effects of density anomaly." (1986): 166-173.

Hoseinzadeh, S., et al. "Numerical investigation of rectangular thermal energy storage units with multiple phase change materials." *Journal of Molecular Liquids* 271 (2018): 655-660.

Motasem, Sadegh, Ali A. Alemrajabi, and Rahmatollah Khodabandeh. "Experimental investigation on heat transfer characteristics during melting of a phase change material with dispersed TiO2 nanoparticles in a rectangular enclosure." *International Journal of Heat and Mass Transfer* 109 (2017): 134-146.

Bashar, Mohammad, and Kamran Siddiqui. "Experimental investigation of transient melting and heat transfer behavior of nanoparticle-enriched PCM in a rectangular enclosure." *Journal of Energy Storage* 18 (2018): 485-497.

Hoseinzadeh, S., et al. "Numerical investigation of rectangular thermal energy storage units with multiple phase change materials." *Journal of Molecular Liquids* 271 (2018): 655-660.

Saitoh, T., and K. Hirose. "High Rayleigh number solutions to problems of latent heat thermal energy storage in a horizontal cylinder capsule." (1982): 226-234.

Cabeza, Luisa F., et al. "Experimentation with a water tank including a PCM module." *Solar Energy Materials and Solar Cells* 90.9 (2006): 1273-1282.

Sparrow, Ephraim M., and J. A. Broadbent. "Inward melting in a vertical tube which allows free expansion of the phase-change medium." (1982): 309-315.

Saitoh, Y., and K. Hirose. "High Rayleigh number solutions to problems of latent heat thermal energy storage in a horizontal cylinder capsule." (1982): 455-553.

Tay, N. H. S., M. Belusko, and F. Bruno. "Experimental investigation of tubes in a phase change thermal energy storage system." *Applied Energy* 90.1 (2012): 288-297.

Rieger, H., and H. Beer. "The melting process of ice inside a horizontal cylinder: effects of density anomaly." (1986): 166-173.

Hoseinzadeh, S., et al. "Numerical investigation of rectangular thermal energy storage units with multiple phase change materials." *Journal of Molecular Liquids* 271 (2018): 655-660.

Motasem, Sadegh, Ali A. Alemrajabi, and Rahmatollah Khodabandeh. "Experimental investigation on heat transfer characteristics during melting of a phase change material with dispersed TiO2 nanoparticles in a rectangular enclosure." *International Journal of Heat and Mass Transfer* 109 (2017): 134-146.

Bashar, Mohammad, and Kamran Siddiqui. "Experimental investigation of transient melting and heat transfer behavior of nanoparticle-enriched PCM in a rectangular enclosure." *Journal of Energy Storage* 18 (2018): 485-497.

Hoseinzadeh, S., et al. "Numerical investigation of rectangular thermal energy storage units with multiple phase change materials." *Journal of Molecular Liquids* 271 (2018): 655-660.

Saitoh, T., and K. Hirose. "High Rayleigh number solutions to problems of latent heat thermal energy storage in a horizontal cylinder capsule." (1982): 226-234.