CFD analysis of Rectangular Thermal Energy Storage System using Polyethylene Glycol 1500 as a PCM with fins

OPEN ACCESS

Manuscript ID:

AG-2023-3008

Volume: 2

Issue: 3

Month: August

Year: 2023

ISSN: 2583-7117

Published: 12.08.2023

Citation:

Vishwjeet Kumar and Shivendra Singh "CFD analysis of Rectangular Thermal Energy Storage System using Polyethylene Glycol 1500 as a PCM with fins" International Journal of Innovations In Science Engineering And Management, vol. 2, no. 3, 2023, pp. 62–71.

Vishwjeet Kumar[1], Shivendra Singh[2]

[1]Research Scholar, Department of Mechanical Engineering, Corporate Institute of Science and Technology
[2]Assistant Professor, Department of Mechanical Engineering, Corporate Institute of Science and Technology

Abstract

Reduced dependence on fossil fuels is important for environmental and economic reasons, and this is why energy storage technologies are so vitally important. "Phase change materials" (PCM) are ideal choices due to their high latent heat storage capacity. When building a system to store energy, it is crucial to think about factors including the materials used, the operating conditions, and the geometrical arrangements. The primary goal of this research is to evaluate the melting time and heat transmission processes for the rectangular enclosures containing the same volume of polyethylene glycol 1500 as the PCM and completely isothermal walls via the use of a computer simulation. The fins attached to the enclosure are meant to decrease melting time and increase heat transmission to the PCM. Some industrial applications (heating-cooling systems & air conditioning, wall panels, the automotive industry, & the textile industry, to name a few) require full contact of the enclosure's walls with the surrounding fluids like air, oil, and so on. The findings showed that natural convection was more influential in melting PCM in rectangular enclosures with 14 fins because of the greater contact area between the heated wall and fins' wall. Case 4 had a greater amount of liquid fraction at any given moment, as shown by the data.

Keyword: Fins, Enclosure, Liquid fraction, Polyethylene glycol 1500, Thermal energy storage, PCM.

I. INTRODUCTION

One method of storing power is via "thermal energy storage" (TES). As the temperature of a substance rises, it absorbs energy, and as it falls, it releases it. Taking use of this feature enables the use of a wide range of materials, each with its own unique thermal characteristics and a range of potential outcomes for thermal energy storage (including heating and cooling).[1] When used to thermal systems, TES may assist maintain a stable daily, monthly, or seasonal energy supply & demand. In addition to lowering peak demand, energy consumption, carbon dioxide emissions, and associated costs, TES may improve energy system efficiency altogether.[2]

"Solar thermal systems" are the most prevalent use of the "thermal energy storage". As a result of its many advantages, TES is also used in a wide variety of other contexts, including those found in CELSIUS demonstrators, where it is employed for purposes like storing heat in buildings, coupling waste heat and district heating systems, and coupling heat pumps and "combined heat and power" (CHP) generators in the district heating networks.[3]

Research and development of the energy storage systems has become more important in the recent two decades due to the rise in the renewable energy utilization. The pace at which intermittent energy sources like wind, sun, and tidal may provide energy is not necessarily commensurate with the rate at which energy is used in urban areas.[4] The transition from fossil fuel-based to renewable energy-based energy systems causes supply & demand mismatches, known as load imbalances.[5]

1.1. Basic Principle

All TES implementations have the same core idea. A storage system receives energy for later retrieval and use. The primary distinctions are in the amount and kind of storage space provided. There are three stages to a cycle that characterize the process of thermal energy storage.[6] Charging, storing, & discharging are the three stages involved. Sensible, latent, and chemical storage all use the same storage cycle; the material, operating temperature, and a few other factors are the key distinctions between the three. The most common medium for the sensible storage is water, however this varies greatly across uses.[7]

The duration of energy storage is another crucial component of TES systems. Short-term energy storage (TES) and long-term energy storage (sometimes called seasonal storage) are the two most common types of TES.[8] The peak output of the heat generators in the DHC systems may be decreased by using a buffer tank on a regular basis. The thermal output of the gas boilers or CHP plants may be reduced by using the heat or cold held in buffer tanks to meet a portion of thermal demand typically provided in mornings and evenings by the thermal systems.[9] While thermal energy storage is often employed for shorter time periods (days or weeks), it may be used for much longer durations.[10] To deal with temperature swings throughout the year, heat may be stored in huge water ponds (for instance, 60,000 m3) during the summer using the "solar thermal collectors". Then, in the winter, it may be released to homes after being stored. In contrast, a cold storage unit may be charged throughout the winter and put to use during the summer to offer cooling.[11]

1.2. Basic Principle

Energy storage in TES applications may make advantage of a wide variety of material features. Water and rock are examples of sensible TES; ice and salt hydrates are examples of latent TES; & chemical reactions and the sorption processes are examples of thermo-chemical reactions.[12] Latent storage occurs when phase of a substance is changed ("solid to liquid or liquid to vapor") without a change in temperature, while sensible storage occurs when temperature of the material is increased or dropped. Both processes are possible simultaneously in the same substance. The third mechanism involves something happening on the surface of a substance, either via the chemical reaction or the sorption process. Heat may be absorbed or dissipated by any substance.[13]

1.2. Phase Change Material

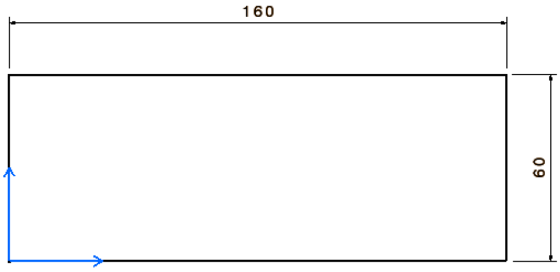
The significant latent heat with the relatively moderate temperature or volume change makes "solid-liquid phase change materials" (PCMs) attractive for use in thermal management and energy storage.[14] The increasing popularity of the "high-power-density electronic devices and machineries", electrification (photovoltaics and wind), energy conversion, electrified transportation, and building air conditioning, as well as the corresponding developments and problems in each of these areas, have rekindled interest in the PCM thermal storage.[15] Buffering fluctuating heat demands, balancing renewable energy supply and demand, storing energy at the grid scale, recovering waste heat, and moving toward carbon neutrality are all made possible by thermal storage employing a phase change material (PCM).[16] PCMs are appealing because of their cheap cost and the simplicity with which they may be integrated with widely accessible energy supplies like solar electricity, in comparison to other energy storage systems like electrochemical batteries.[17]

II. Methodology

Design

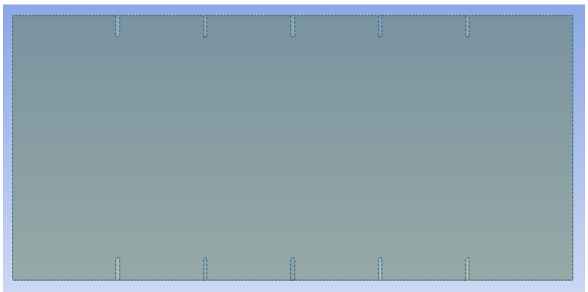
In this study the selected 2d domain is a close rectangle whose length and width are 0.16 m and 0.06 m respectively. The surface area of the rectangle domain in all design is 9.6×10^{-3} m^2. In case 1 rectangular enclosure is without fins. The PCM was filled inside the enclosure. In the case 2 there is fins present inside the enclosure to enhance the melting time of the PCM. 10 numbers of fins attached to the enclosure and arranged in a 2 row, 1st in the base wall and 2nd in the upper wall. Both walls have an equal number of fins. Distance between each fin is 24 mm and fins area are 1×5 ($5\ mm^2$). Fins are starting from the left wall at 29.5 mm distance. Both rows are identical and design of case 2 show in figure below.

(a)

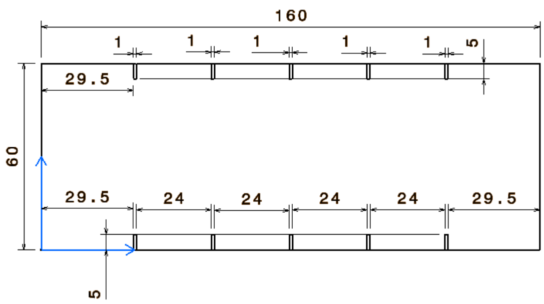


(b)

Figure 1 (a) – Design of case 1, (b) Dimension of geometry in mm



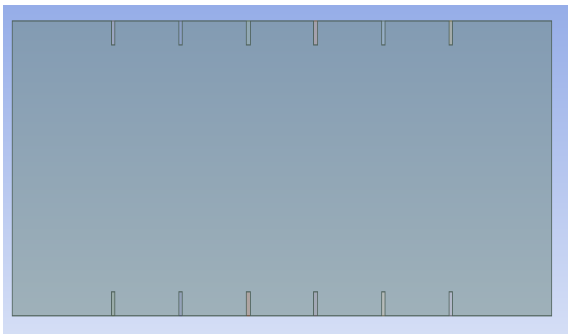
(a)



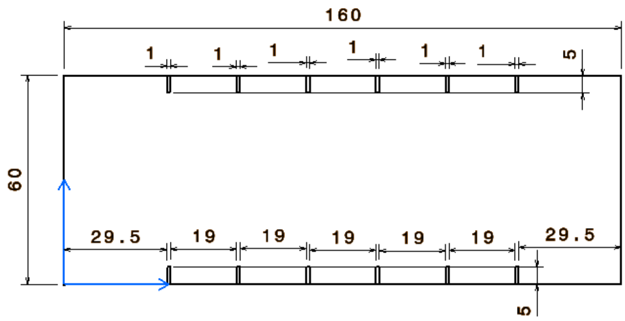
(b)

Figure 2 (a) – Design of case 2, (b) Dimension of geometry in mm

In the case 3, 12 number of fins are attaching in the rectangle encloser. Fins arranged in the 2 rows, 1st row consisting of 6 fins are in the bottom wall and 2nd row also consisting 6 fins are in upper wall of the rectangle encloser. Fins area is same as use in the case 2 and distance between each fin are 19 mm. Both row of the fins is stating 29.5 mm from the left wall. In the case 4, 14 numbers of fins attached in the encloser. 12 fins are arranged in the 2 rows similar to the case 3. Remanning 2 fins are attach in the middle of the both the side walls. In this case 2 type of the fins considered, 1st is in the upper and bottom walls whose area is 1×10 ($10\ mm^2$) and 2nd are in both side walls whose area is 2×10 ($20\ mm^2$). Design of all case with dimensions are show in the figure below.

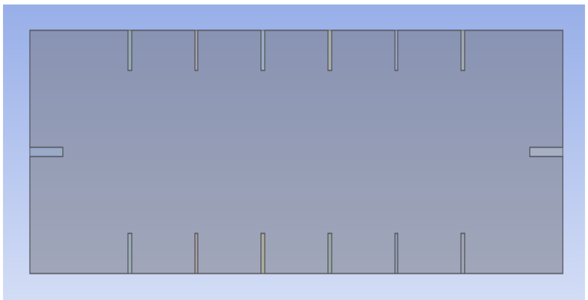


(a)

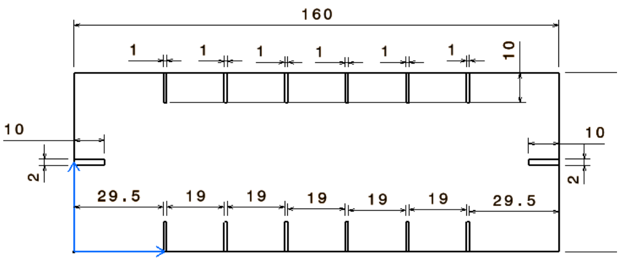


(b)

Figure 3 (a) – Design of case 3, (b) Dimension of geometry in mm



(a)



(b)

Figure 4 (a) – Design of case 4, (b) Dimension of geometry in mm

All cases name and respective design are mention in below table,

Table 1 Overview of all cases

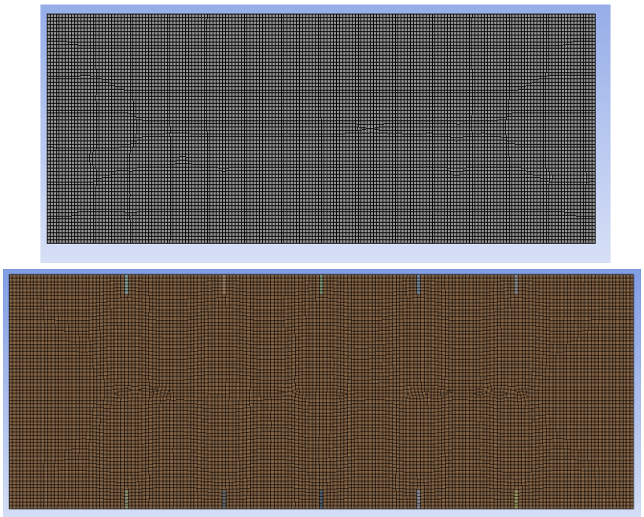
Case 1	Rectangle without fins
Case 2	Rectangle with 10 fins
Case 3	Rectangle with 12 fins
Case 4	Rectangle with 14 fins

Meshing

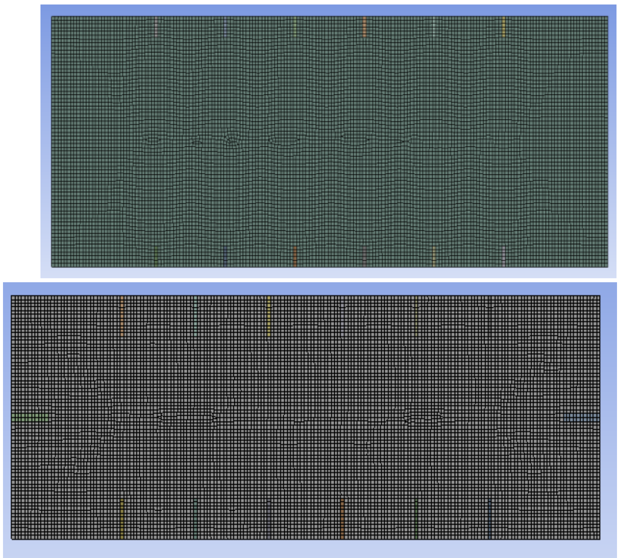
The mesh was generated in the ANSYS Fluent workbench. For all the cases element shape is quadrilateral and element order is linear. In the meshing process nodes and elements re generated. For all cases nodes and elements are not same numbers which is mention in table below.

Table 2 number of element and nodes in all cases

Cases	Nodes	Element
Case 1	12169	11924
Case 2	12424	12042
Case 3	12300	11893
Case 4	12292	11712



(a) Case 1 – without fins **(b) Case 2 – 10 fins**



(c) Case 3 – 12 fins **(d) Case 4 – 14 fins**

Figure 5 Meshing of all cases

Governing equation

We assumed incompressible, laminar, and the two-dimensional flow in our melting & solidification simulations. It was assumed that PCM & solid walls were both isotropic and homogenous. Formulas were discretized using the finite volume technique, and solidification and melting were modeled using enthalpy-porosity methodology in order to run simulations. In order to maintain conservation, the following equations must be met;

Continuity;

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho V) = 0$$

Momentum;

$$\frac{\partial (\rho V)}{\partial t} + \nabla.(\rho V) = -\nabla.(P) + \mu \nabla^2 V + \rho g + S$$

Energy;

$$\frac{\partial (\rho H)}{\partial t} + \nabla.(\rho V H) = k \nabla^2 T$$

where q and k stand for density & thermal conductivity. Fluid velocity (V), pressure (P), temperature (T), and dynamic viscosity (l) are the variables in this equation. Latent heat (DH) & sensible enthalpy (h) are added together to get specific enthalpy (H), with g standing for acceleration due to gravity.

Boundary condition

In this study, a closed rectangle enclosure is use as a heat transfer and inside the enclosure PCM was filled at initially solid state. “Polyethylene glycol” 1500 (PEG 1500) use as a PCM and physical properties of PCM are described in Table below. Stage-I included simulating a model to verify the prior simulation results, and Stage-II involved expanding geometry domain to examine melting process of "PEG 1500" in 2D rectangular, enclosed approaches. It was determined that the aforementioned rectangular enclosure having a surface area of 9.6 $*10^{-3}$ m2.

Within PCM, the natural convection was implemented using the Boussinesq approximation. The momentum & energy equations are solved using "QUICK spatial discretization" technique. For pressure correction equation, we utilize PRESTO scheme, and for pressure-velocity coupling, we use semi-implicit technique for the "pressure-linked equations (SIMPLE) algorithm". In every scenario, we used the same mesh element size. The "melting processes" were assumed to be isothermal, with temperature of the whole wall and all the fins set to 353 K and the starting melting temperature of PCM set to 298 K. Heat loss and environmental convention were not taken into account in any of the models. We utilized physical parameters that are not affected by temperature in order to keep the model simple. However, the simulation findings matched up well with the ones from before.

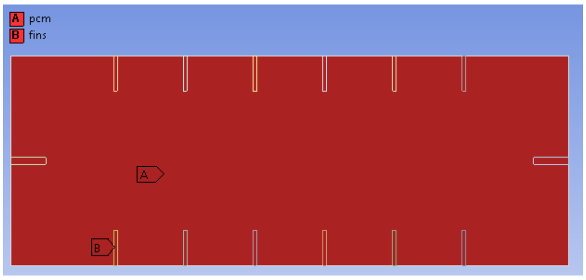


Figure 6 Domain representation in all design

Table 3 Polyethylene glycol 1500 (PCM) properties

Properties	**Value (PEG 1500)**
Thermal conductivity (W/m.K)	0.234
Melting temperature (K)	317
Specific Heat (J/kg.K)	1920
Latent heat of the fusion (J/kg)	196,000
Density (kg/m^3)	1270
Viscosity (kg/m.s)	0.018

III. Validation results

Figure below represent the simulation liquid fraction vs. time in this study and is compared with previous simulation result by (Soodmand et al., 2022) [22]. In the previous simulation a rectangular enclosure which is filled with PEG 1500 (PCM) and the hot walls of the enclosure considered isothermal at 353 K. In Figure, simulated and the previous simulation results by (Soodmand et al., 2022) are compared. Excellent agreement between predicted and experimental CFD findings validates and verifies our model for future study.

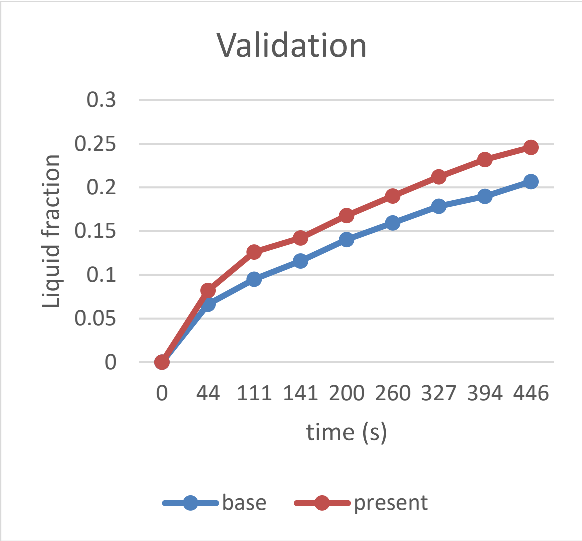


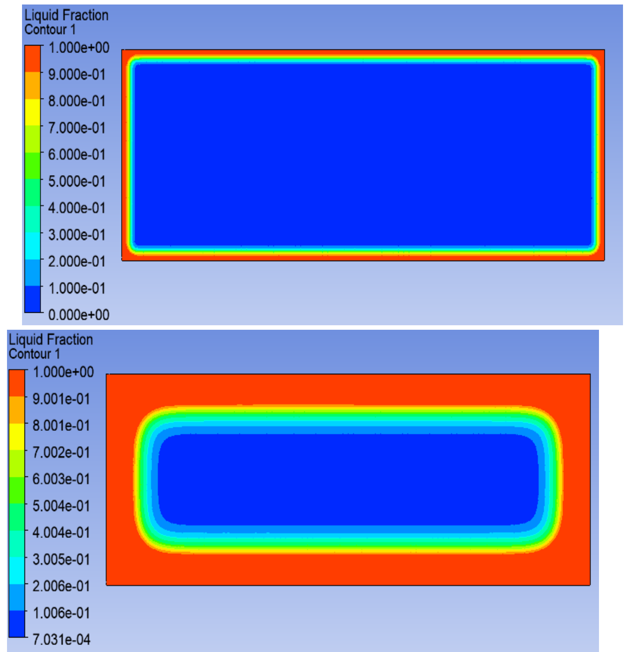
Figure 7 Validation result

IV. Result and discussion

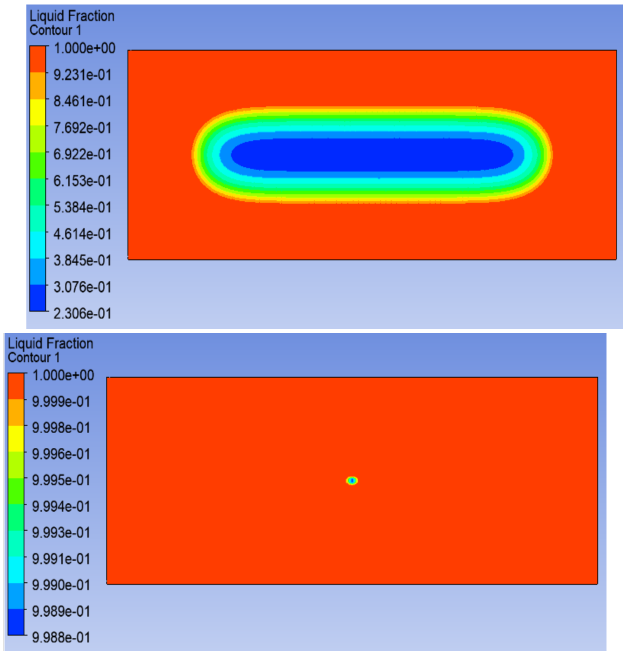
Liquid fraction

Case 1 – without fins

In this case there is no fins attach with enclosures. So, all sides of the rectangular enclosure were treated as hot wall which is transfer the heat to the PCM. When the simulation was started after some time PCM start melting. All the time of melting process PCM melt linear with all of the side and increase with respect to time. Before 300s PCM 20% melt. 50% of the PCM melt at 2100s simulation time. In the 5000 s, an elliptical interface appeared, which was because of an accumulation of the “small circulations building” in both side (left and right) into one small circulation. After 3000s the melting process get slow and 13,420s PCM complete melt.



(a) 100s **(b) 2100s**



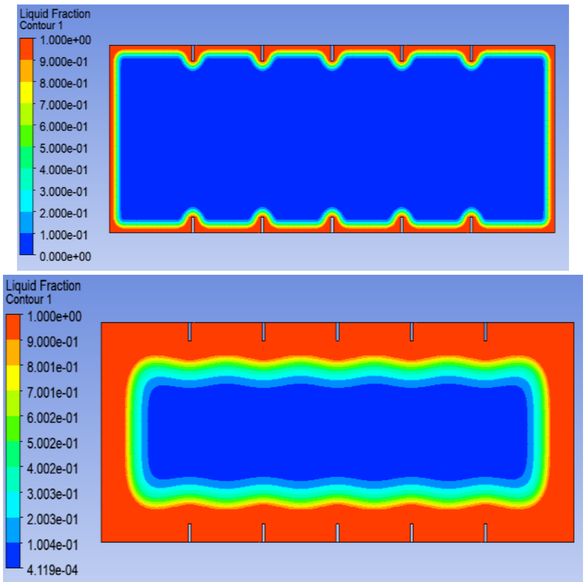
(a) 7000s **(b) 13420s**

Figure 8 Liquid fraction of the Case 1

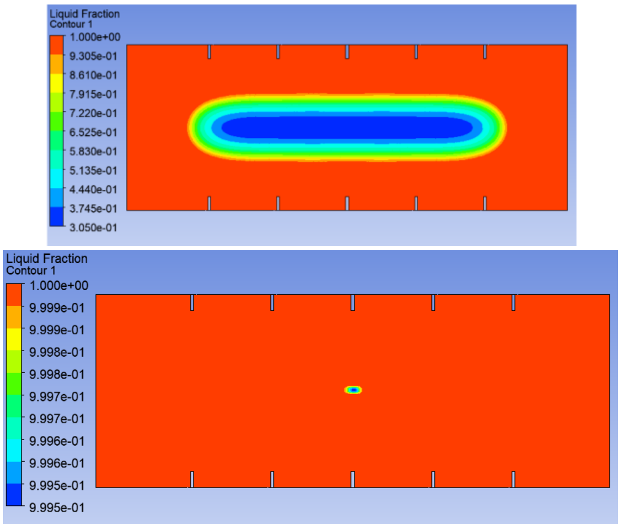
Case 2 – 10 fins

In this case there is 10 fins attach with enclosures. So, all sides of the rectangular enclosure and fins wall was treated as hot wall which is transfer the heat to the PCM. When the simulation was started after some time PCM start melting.

All the time of melting process PCM melt linear with all of the side and increase with respect to time. In 220s PCM 20% melt. 50% of the PCM melt at 1800s simulation time. When PCM melt 50% after that melting process get slow. In the completion of 4000s simulation, an elliptical interface appeared, which was because of an accumulation of the "small circulations building" in both the side (left and right) into one small circulation. PCM is complete melt at 12018s which is earlier that the case 1.



(a) 100s **(b) 1800s**

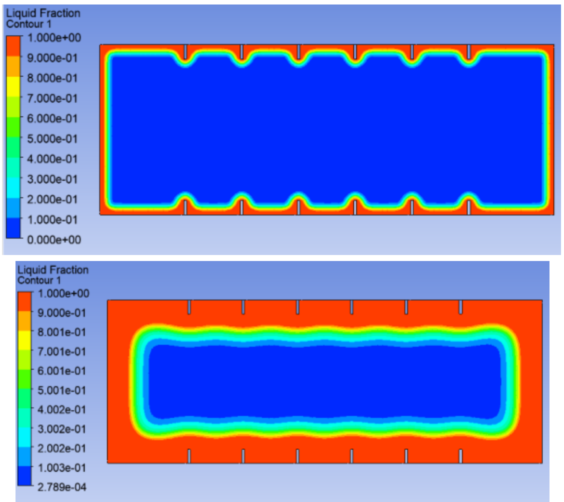


(a) 7000s **(b) 12018s**

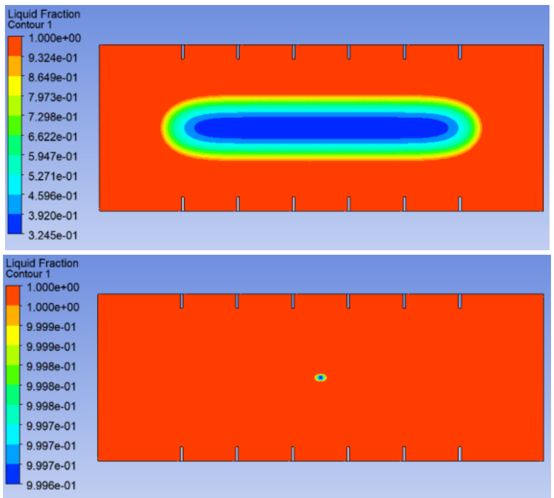
Figure 9 Liquid fraction of the Case 2

Case 3 – 12 fins

In this case there is 12 fins attach with enclosures. So, all sides of the rectangular enclosure and fins wall was treated as hot wall which is transfer the heat to the PCM. When the simulation was started after some time PCM start melting. All the time of melting process PCM melt linear with all of the side and increase with respect to time. In 200s PCM 20% melt. 50% of the PCM melt at 1650s simulation time. When PCM melt 50% after that melting process get slow. In the completion of 4000s simulation, an elliptical interface appeared, which was because of an accumulation of "small circulations building" in both side (left and right) into one small circulation. PCM is complete melt at 11736s which is earlier that the case 1, 2.



(a) 100s **(b) 1650s**

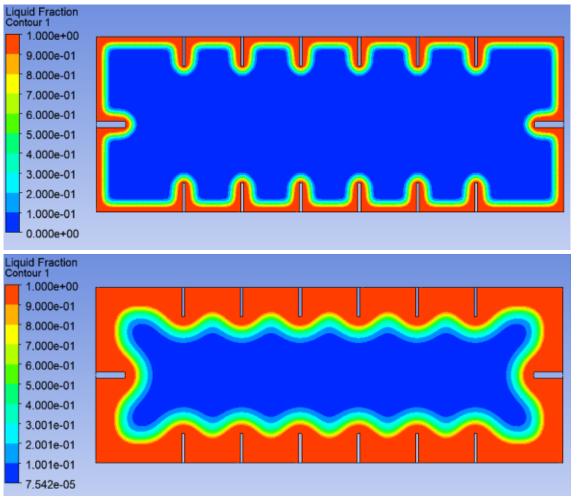


(c) 7000s **(d) 11736s**

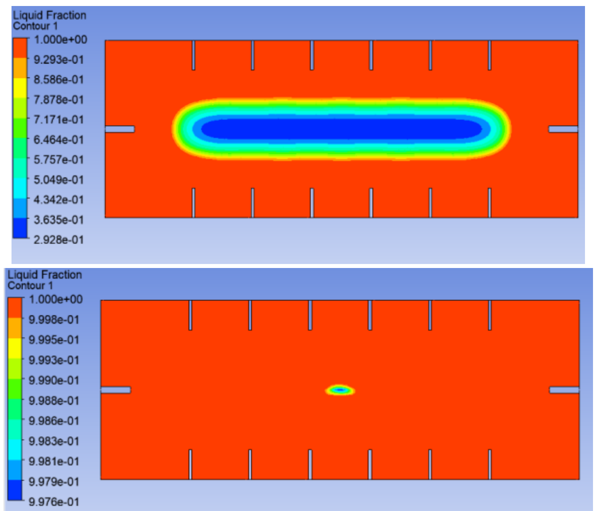
Figure 10 Liquid fraction of the Case 3

Case 4 – 14 fins

In this case there is 14 fins attach with enclosures. So, all sides of the rectangular enclosure and fins wall was treated as hot wall which is transfer the heat to the PCM. When the simulation was started after some time PCM start melting. All the time of melting process PCM melt linear with all of the side and increase with respect to time. In 120s PCM 20% melt. 50% of the PCM melt at before 1000s simulation time. When PCM melt 50% after that melting process get slow. In the completion of 4000s simulation, an elliptical interface appeared, which was because of an accumulation of the “small circulations building” in both side (left and right) into one small circulation. PCM is complete melt at 8630 which is earlier that the case 1, 2and 3.



(a) 120s **(b) 1000s**



(a) 5000s **(b) 8630s**

Figure 11 Liquid fraction of the Case 4

Comparison of all cases

Result of the simulation show that PCM melt fast up to 2000s in all the cases. In that time PCM melt 50% of the total volume than melting process get slow. Case 1 is the simple geometry of the rectangle enclosure, because of that melting time is higher than remaining cases. Reducing the melting time of selected PCM, attach the fins in rectangle enclosure. In case 2, and 3, rectangle enclosure attaches with 10 fins and 12 fins due to this melting time reduce at 10 % and 12.55% respectively. After that investigate the effect in PCM of increasing the fins quantity and length of fins in the geometry. In case 4, enclosure attach with 14 fins and length of the fins is just double as compare to fins use in the case 2, and 3. In case 4, the melting time is reduced 35.5% from case 1. In 8600s PCM get complete melt in case 4.

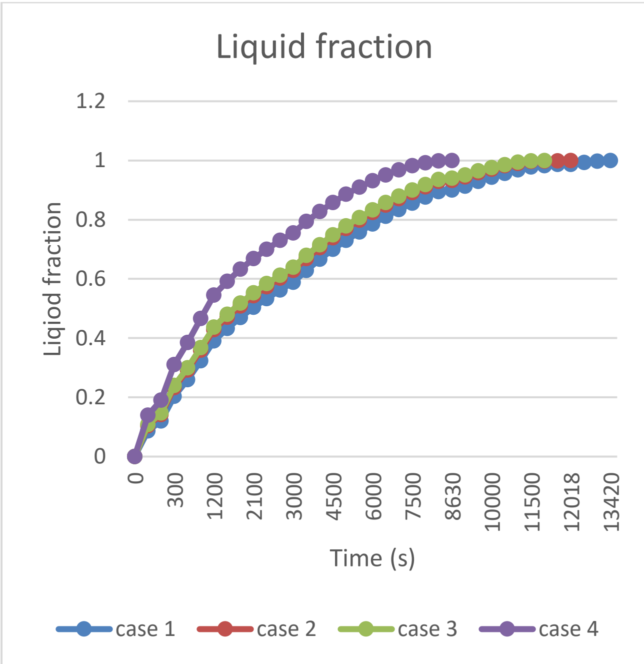


Figure 12 Liquid fraction comparison of all cases

Conclusion

In this work, we apply computational fluid dynamics (CFD) simulation to learn more about melting process of the PEG 1500, one of the most popular commercial PCMs with the "fully isothermal walls conditions". Before considering the impacts of affixing fins inside the enclosure, we first verified the model using earlier simulation results in the rectangular form enclosure. Four case considered in which 1st is without fin, 2nd is 10 fins, 3rd is 12 fins, and 4th is 14 fins. In 2nd and 3rd case, fins width and height are same but in the case 4 fins height is increase.

Some conclusions can be drawn as follows:

- Rectangle with fins showed the fastest melting process due to fin, they are assumed to have a key role in driving natural convection.
- The PCM temperature increases by transmitting the heat from a hot wall to PCM in the melting process and eventually achieves a melting temperature.
- Melting time is decreasing of case 2, 3, and 4 as compared to case 1 is 10%, 12.55%, and 35.5 %.
- Result of the melting Process showed that case 4 is the most suitable geometry for transferring the heat to the PCM.

References

[1] K. Hosseinzadeh, E. Montazer, M. B. Shafii, and A. R. D. Ganji, "Solidification enhancement in triplex thermal energy storage system via triplets fins configuration and hybrid nanoparticles," *J. Energy Storage*, vol. 34, no. September 2020, p. 102177, 2021, doi: 10.1016/j.est.2020.102177.

[2] Y. Kou *et al.*, "Thermal analysis and heat capacity study of polyethylene glycol (PEG) phase change materials for thermal energy storage applications," *J. Chem. Thermodyn.*, vol. 128, pp. 259–274, 2019, doi: 10.1016/j.jct.2018.08.031.

[3] Z. Khan, Z. Khan, and A. Ghafoor, "A review of performance enhancement of PCM based latent heat storage system within the context of materials, thermal stability and compatibility," *Energy Convers. Manag.*, vol. 115, pp. 132–158, 2016, doi: 10.1016/j.enconman.2016.02.045.

[4] E. Alehosseini and S. M. Jafari, "Nanoencapsulation of phase change materials (PCMs) and their applications in various fields for energy storage and management," *Adv. Colloid Interface Sci.*, vol. 283, p. 102226, 2020, doi: 10.1016/j.cis.2020.102226.

[5] K. Faraj, M. Khaled, J. Faraj, F. Hachem, and C. Castelain, "A review on phase change materials for thermal energy storage in buildings: Heating and hybrid applications," *J. Energy Storage*, vol. 33, no. September, p. 101913, 2021, doi: 10.1016/j.est.2020.101913.

[6] P. Singh, R. K. Sharma, A. K. Ansu, R. Goyal, A. Sarı, and V. V. Tyagi, "A comprehensive review on development of eutectic organic phase change materials and their composites for low and medium range thermal energy storage applications," *Sol. Energy Mater. Sol. Cells*, vol. 223, no. October 2020, p. 110955, 2021, doi: 10.1016/j.solmat.2020.110955.

[7] P. K. S. Rathore and S. K. Shukla, "Enhanced thermophysical properties of organic PCM through shape stabilization for thermal energy storage in buildings: A state of the art review," *Energy Build.*, vol. 236, p. 110799, 2021, doi: 10.1016/j.enbuild.2021.110799.

[8] C. Zhang, Q. Sun, and Y. Chen, "Solidification behaviors and parametric optimization of finned shell-tube ice storage units," *Int. J. Heat Mass Transf.*, vol. 146, p. 118836, 2020, doi: 10.1016/j.ijheatmasstransfer.2019.118836.

[9] S. S. Magendran *et al.*, "Synthesis of organic phase change materials (PCM) for energy storage applications: A review," *Nano-Structures and Nano-Objects*, vol. 20, p. 100399, 2019, doi: 10.1016/j.nanoso.2019.100399.

[10] N. H. S. Tay, M. Belusko, M. Liu, and F. Bruno, "Investigation of the effect of dynamic melting in a tube-in-tank PCM system using a CFD model," *Appl. Energy*, vol. 137, pp. 738–747, 2015, doi: 10.1016/j.apenergy.2014.06.060.

[11] X. Huang, C. Zhu, Y. Lin, and G. Fang, "Thermal properties and applications of microencapsulated PCM for thermal energy storage: A review," *Appl. Therm. Eng.*, vol. 147, no. November 2018, pp. 841–855, 2019, doi: 10.1016/j.applthermaleng.2018.11.007.

[12] F. A. Hamad, E. Egelle, K. Cummings, and P. Russell, "Investigation of the melting process of polyethylene glycol 1500 (PEG 1500) in a rectagular enclosure," *Int. J. Heat Mass Transf.*, vol. 114, pp. 1234–1247, 2017, doi: 10.1016/j.ijheatmasstransfer.2017.07.014.

[13] J. Vogel and A. Thess, "Validation of a numerical model with a benchmark experiment for melting governed by natural convection in latent thermal energy storage," *Appl. Therm. Eng.*, vol. 148, pp. 147–159, 2019, doi: 10.1016/j.applthermaleng.2018.11.032.

[14] O. Mahian, S. Ghafarian, H. Sarrafha, A. Kasaeian, H. Yousefi, and W. M. Yan, "Phase change materials in solar photovoltaics applied in buildings: An overview," *Sol. Energy*, vol. 224, no. October 2020, pp. 569–592, 2021, doi: 10.1016/j.solener.2021.06.010.

[15] H. Liu *et al.*, “Two-dimensional materials and their derivatives for high performance phase change materials: emerging trends and challenges,” *Energy Storage Mater.*, vol. 42, no. August, pp. 845–870, 2021, doi: 10.1016/j.ensm.2021.08.022.

[16] J. Y. Ho, Y. S. See, K. C. Leong, and T. N. Wong, “An experimental investigation of a PCM-based heat sink enhanced with a topology-optimized tree-like structure,” *Energy Convers. Manag.*, vol. 245, 2021, doi: 10.1016/j.enconman.2021.114608.

[17] A. O. Elsayed, “Numerical investigation on PCM melting in triangular cylinders,” *Alexandria Eng. J.*, vol. 57, no. 4, pp. 2819–2828, 2018, doi: 10.1016/j.aej.2018.01.005.

[18] K. Hosseinzadeh *et al.*, “Effect of two different fins (longitudinal-tree like) and hybrid nano-particles (MoS2-TiO2) on solidification process in triplex latent heat thermal energy storage system,” *Alexandria Eng. J.*, vol. 60, no. 1, pp. 1967–1979, 2021, doi: 10.1016/j.aej.2020.12.001.

[19] Y. Zhao, X. Zhang, and W. Hua, “Review of preparation technologies of organic composite phase change materials in energy storage,” *J. Mol. Liq.*, vol. 336, p. 115923, 2021, doi: 10.1016/j.molliq.2021.115923.

[20] F. S. Javadi, H. S. C. Metselaar, and P. Ganesan, “Performance improvement of solar thermal systems integrated with phase change materials (PCM), a review,” *Sol. Energy*, vol. 206, no. April, pp. 330–352, 2020, doi: 10.1016/j.solener.2020.05.106.

[21] K. Hosseinzadeh, M. A. E. Moghaddam, A. Asadi, A. R. Mogharrebi, and D. D. Ganji, “Effect of internal fins along with Hybrid Nano-Particles on solid process in star shape triplex Latent Heat Thermal Energy Storage System by numerical simulation,” *Renew. Energy*, vol. 154, pp. 497–507, 2020, doi: 10.1016/j.renene.2020.03.054.

[22] A. M. Soodmand, S. Nejatbakhsh, H. Pourpasha, H. Aghdasinia, and S. Z. Heris, “Simulation of melting and solidification process of polyethylene glycol 1500 as a PCM in rectangular, triangular, and cylindrical enclosures,” *Alexandria Eng. J.*, vol. 61, no. 11, pp. 8431–8456, 2022, doi: 10.1016/j.aej.2022.02.011.