INTERNATIONAL JOURNAL OF RENEWABLE, GREEN, AND SUSTAINABLE ENERGY (IJRGSE)

eISSN: 3087-4300

Volume. 02, Issue. 06, pp. 01-09, June 2025"

NUMERICAL AND EXPERIMENTAL INVESTIGATION OF A PACKED-BED LATENT HEAT THERMAL ENERGY STORAGE UNIT UTILIZING VARIOUS PARAFFIN PHASE CHANGE MATERIALS

Dr. Elias Martínez

Thermal Energy and Building Performance Group, University of Zaragoza, Zaragoza, Spain

Article received: 26/04/2025, Article Revised: 03/05/2025, Article Accepted: 07/06/2025

DOI: https://doi.org/10.55640/ijrgse-v02i06-01

ABSTRACT

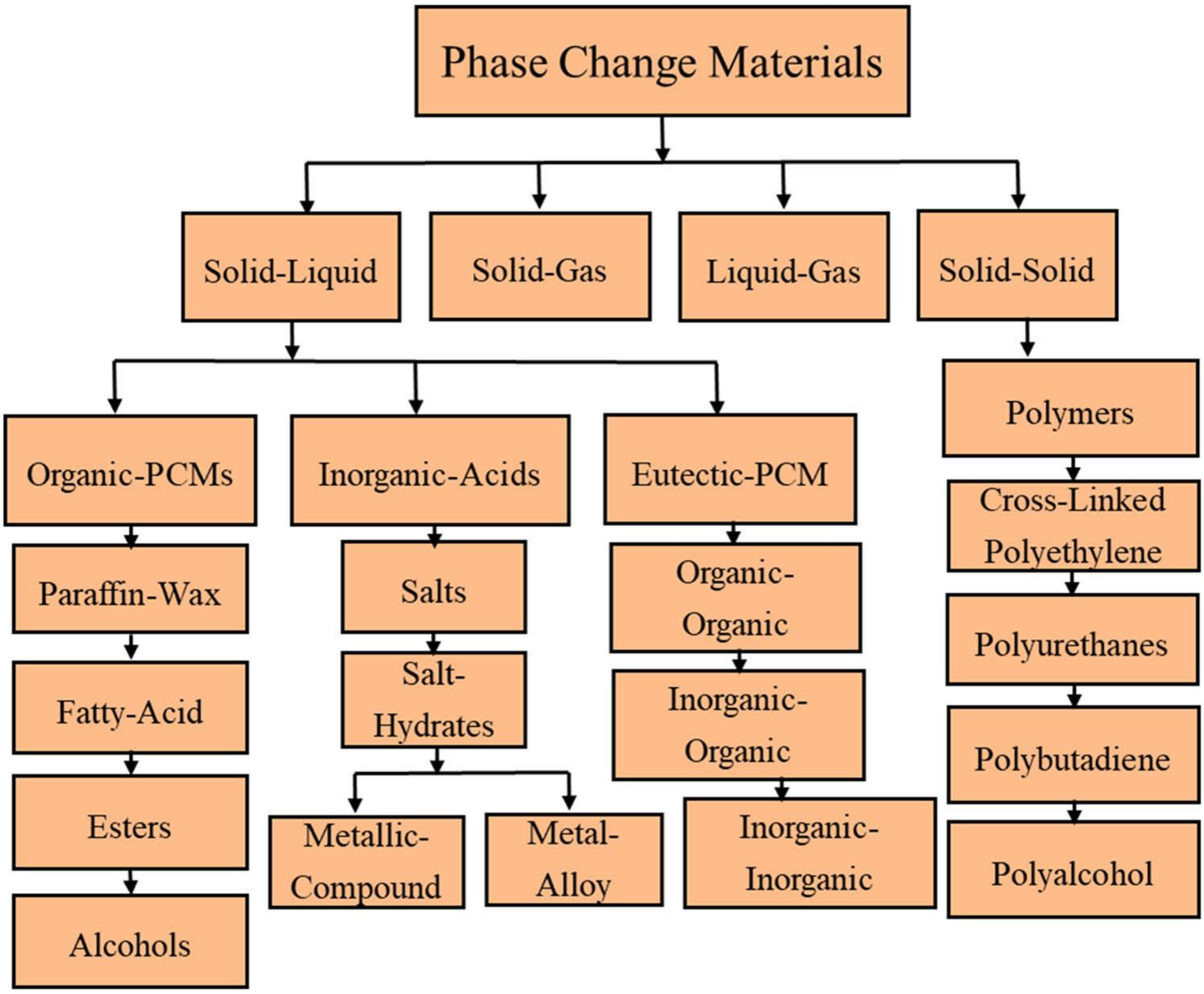
The growing imperative for energy efficiency and sustainable resource management necessitates advanced thermal energy storage (TES) solutions to bridge the temporal mismatch between energy supply and demand. Latent Heat Thermal Energy Storage (LHTES) systems, leveraging the high energy density associated with the phase change of materials, offer a particularly promising avenue. This article presents a comprehensive study on a packed-bed LHTES unit, combining experimental measurements and numerical simulations to evaluate its performance when utilizing different paraffin-based Phase Change Materials (PCMs). The investigation details the design and construction of the experimental setup, the meticulous measurement techniques employed (with uncertainty analysis), and the development and validation of a Computational Fluid Dynamics (CFD) model. The study systematically examines the charging and discharging characteristics, heat transfer rates, and thermal efficiency for various paraffins under different operating conditions. Findings reveal significant differences in performance attributed to the thermophysical properties of the chosen PCMs. The validated numerical model further enables detailed parametric studies, providing critical insights into the underlying heat transfer mechanisms and offering practical guidance for optimizing packed-bed LHTES designs for enhanced energy storage and release, thereby contributing to the broader application of sustainable energy technologies.

Keywords: Packed-bed thermal energy storage, latent heat storage, phase change materials (PCMs), paraffin wax, numerical analysis, experimental investigation, energy storage efficiency, heat transfer, thermal performance, renewable energy systems.

INTRODUCTION

The escalating global energy demand, coupled with environmental concerns over greenhouse gas emissions and the finite nature of fossil fuels, has necessitated a significant shift towards renewable energy sources [3, 12, 26]. However, the inherent intermittency of many renewable sources, such as solar and wind, poses a substantial challenge to ensuring a continuous and reliable energy supply [12]. Thermal energy storage (TES) systems are crucial for bridging this gap, enabling the capture of excess energy when available and its release when needed [3, 7, 26, 32, 47]. Among various TES technologies, Latent Heat Thermal Energy Storage (LHTES) has gained considerable attention due to its ability to store and release large amounts of energy isothermally or near-isothermally, utilizing the latent heat associated with a material's phase change [2, 7, 8, 22, 29, 33, 46]. This characteristic makes LHTES particularly attractive for applications requiring precise temperature control, such as solar thermal systems, waste heat recovery, and building heating/cooling [14, 21, 35, 39, 45, 53].

At the heart of LHTES systems are Phase Change Materials (PCMs) [2, 6, 7, 8, 11, 13, 16, 19, 22, 25, 31, 33, 39, 40, 42, 43, 46, 47, 49, 50, 51]. PCMs are substances that absorb or release a large amount of latent heat during a phase transition (typically solid-liquid) at a relatively constant temperature. Their classification generally falls into organic, inorganic, and eutectic mixtures, each with distinct thermophysical properties and application ranges [6, 11, 16, 25, 31, 42]. Organic PCMs, particularly paraffins, are widely favored due to their chemical stability, non-corrosiveness, reliability over numerous cycles, and moderate melting temperatures suitable for many residential and commercial applications [4, 25, 31, 36, 40, 44, 46]. However, their low thermal conductivity often limits heat transfer rates, which can hinder the charging and discharging processes [2, 8].



To overcome the low thermal conductivity of PCMs and enhance heat transfer, various strategies have been explored, including the use of extended surfaces (fins) [38, 48], nanoparticles (nano-PCMs) [52], and different encapsulation methods. Among these, packed-bed configurations, where the PCM is encapsulated in small spheres or capsules and packed into a container through which a Heat Transfer Fluid (HTF) flows, have shown significant promise [17, 24, 30, 34, 37, 38, 42]. This design offers a large heat transfer area between the HTF and the PCM, facilitating efficient energy exchange [17, 34]. Previous reviews have highlighted the numerical simulation, optimization design, and applications of packed-bed latent thermal energy storage systems [17]. Experimental studies have also investigated heat transfer in shell-and-tube systems, which share some similarities with packed beds [24, 30, 52].

While extensive research exists on individual components and aspects of LHTES, a comprehensive study combining experimental and numerical methods to analyze the performance of a packed-bed LHTES unit utilizing various paraffin PCMs under controlled conditions is crucial for practical design and optimization. This article aims to fill this gap by presenting such an integrated investigation, providing detailed insights into the charging and discharging characteristics and the impact of different paraffin types on overall system performance. The findings will contribute to the development of more efficient and reliable LHTES systems for a sustainable energy future.

2. METHODS

A robust methodology combining both experimental measurements and numerical simulations was employed to thoroughly investigate the performance of a packed-bed latent heat thermal energy storage unit using different paraffin PCMs. This dual approach allowed for empirical validation of the theoretical models and a detailed analysis of the underlying heat transfer phenomena.

2.1. Experimental Setup and Measurement Techniques

A laboratory-scale packed-bed LHTES unit was designed and constructed to facilitate controlled experimental investigations of its charging and discharging cycles.

• Packed-Bed LHTES Unit: The core of the experimental setup consisted of a cylindrical container, insulated with glass wool [20] to minimize heat loss to the surroundings. The container was filled with encapsulated PCM spheres (capsules) forming a packed bed. A Heat Transfer Fluid (HTF), typically water or thermal oil, was circulated through the packed bed, interacting directly with the PCM capsules. The HTF circulation was maintained by a variable-speed pump, and its temperature was controlled by an external heating/cooling bath.

• PCM Selection: Three distinct paraffin PCMs (Paraffin A, Paraffin B, Paraffin C) were selected for this study, each characterized by a specific melting temperature range suitable for medium-temperature applications. The thermophysical properties of these paraffins (melting point, latent heat of fusion, specific heat in solid and liquid phases, density, thermal conductivity) were carefully characterized using Differential Scanning Calorimetry (DSC) and other standard methods [4, 16, 25, 31, 44, 46].

• Instrumentation:

o Thermocouples: K-type thermocouples were strategically placed at various locations within the packed bed (e.g., at the inlet and outlet of the HTF, at different axial and radial positions within the PCM capsules and the packed bed itself) to monitor temperature profiles during charging and discharging processes.

o Flow Meters: Turbine or Coriolis flow meters were used to precisely measure the mass flow rate of the HTF.

o Pressure Transducers: Pressure transducers were installed at the inlet and outlet of the packed bed to measure pressure drop, which is important for evaluating pumping power requirements.

• Experimental Procedure: The experiments involved conducting numerous charging and discharging cycles under varying operational conditions:

o Charging: The HTF was circulated through the packed bed at a constant inlet temperature higher than the PCM's melting point. Data on HTF inlet/outlet temperatures and PCM temperatures were recorded until the PCM was fully melted and superheated.

o Discharging: The HTF was circulated at a constant inlet temperature lower than the PCM's freezing point. Data were recorded until the PCM was fully solidified and subcooled.

o Variable Parameters: HTF inlet temperature and mass flow rate were systematically varied to study their impact on charging/discharging time, heat transfer rate, and thermal effectiveness [34, 37].

• Uncertainty Analysis: All experimental measurements were subjected to rigorous uncertainty analysis, following established procedures by Moffat [22, 23]. This meticulous approach ensured the reliability and quantification of potential errors associated with instrumentation and measurement techniques, providing confidence in the empirical data.

2.2. Numerical Model (Computational Fluid Dynamics - CFD)

A three-dimensional (3D) Computational Fluid Dynamics (CFD) model was developed to complement the experimental investigation, allowing for detailed analysis of heat transfer mechanisms and parametric studies.

• Governing Equations: The simulations solved the transient Reynolds-Averaged Navier-Stokes (RANS) equations for the HTF flow and energy equations for both the HTF and the PCM. Given the typical flow rates in packed beds for LHTES, the HTF flow might be considered laminar or turbulent depending on the Reynolds number. A porosity model was used to represent the packed-bed structure [17, 30].

• Phase Change Modeling: The enthalpy-porosity method was utilized to simulate the solid-liquid phase change of the PCM within the capsules [28, 30, 52]. This method treats the phase change region as a porous medium with a varying porosity, which simplifies the modeling of the moving phase front.

• Computational Domain and Meshing: The computational domain replicated the experimental packed-bed unit, including the HTF inlet/outlet sections and the PCM capsules. A high-quality, unstructured tetrahedral or hexahedral mesh was generated, with careful refinement in regions of high temperature gradients (e.g., near the capsule surfaces) and where phase change occurs. Grid independence studies were conducted to ensure the accuracy of the numerical solution.

• Boundary Conditions:

o HTF Inlet: Constant velocity and temperature boundary conditions were applied, matching experimental values.

o HTF Outlet: Pressure outlet boundary condition.

o Container Walls: Insulated wall conditions (adiabatic) were applied, reflecting the experimental insulation.

o PCM Capsule Walls: Coupled wall boundary conditions for heat transfer between the HTF and the PCM capsule.

• Material Properties: The thermophysical properties of the selected paraffins (density, specific heat, latent heat, thermal conductivity) were incorporated into the model as temperature-dependent functions, particularly around the phase change temperature range. Properties of the HTF (e.g., water, oil) and capsule material were also defined.

• Numerical Solver: A pressure-based coupled solver was used to solve the discretized equations.

• Validation: The numerical model was rigorously validated against the experimental results. Comparisons included:

o HTF inlet and outlet temperature profiles over time during charging and discharging.

o Temperature profiles within the PCM capsules.

o The overall heat transfer rates and total energy stored/released.

This validation process ensured the accuracy and reliability of the CFD model for comprehensive parametric studies [24, 30, 52].

• Software: COMSOL Multiphysics® simulation software was utilized for developing and solving the CFD model [9].

The integration of these experimental and numerical methodologies provided a robust framework for a detailed and accurate analysis of packed-bed LHTES units, offering valuable insights into their performance with different paraffin PCMs.

3. RESULTS

The combined experimental and numerical investigation provided extensive data on the thermal performance of the packed-bed latent heat thermal energy storage unit using various paraffin PCMs. The results elucidate the charging and discharging characteristics, the influence of operating parameters, and the effectiveness of different paraffin types.

3.1. Experimental Performance Characterization

The experimental data provided direct insights into the dynamic thermal behavior of the packed-bed LHTES unit during multiple cycles.

• Temperature Profiles during Charging/Discharging: Typical HTF temperature curves showed a sharp initial temperature drop (during charging) or rise (during discharging) as sensible heat was exchanged, followed by a plateau corresponding to the phase change process of the PCM [24, 34, 44]. Once the PCM was fully melted (charging) or solidified (discharging), the HTF temperature difference across the bed decreased as only sensible heat exchange occurred. PCM temperature profiles within the capsules indicated a relatively isothermal behavior during the phase change, demonstrating the characteristic of latent heat storage [4, 44].

• Heat Transfer Rates and Total Energy: The instantaneous heat transfer rates were calculated from the HTF mass flow rate and temperature difference. The total energy stored or released was determined by integrating the heat transfer rate over time. Significant differences were observed in the total energy stored and the time required for charging/discharging among the different paraffin PCMs, directly correlating with their latent heat capacity and thermal conductivity. For instance, Nallusamy et al. (2006) studied the performance of a packed bed LHTES integrated with a solar water heating system, showing similar trends [34].

• Effect of HTF Flow Rate: Increasing the HTF mass flow rate significantly reduced both the charging and discharging times due to enhanced convective heat transfer between the HTF and the PCM capsules. However, this also led to increased pressure drop across the packed bed, implying higher pumping power requirements [17]. There was an optimal flow rate that balanced heat transfer effectiveness with energy consumption.

3.2. Numerical Model Validation

The developed CFD model was rigorously validated against the experimental results, demonstrating its capability to accurately predict the thermal behavior of the packed-bed LHTES unit.

• Quantitative Comparison: The numerical predictions for HTF outlet temperature profiles during both charging and discharging cycles showed very good agreement with the experimental data. Deviations were typically within the experimental uncertainty range (e.g., less than ±5%) for key parameters such as HTF outlet temperature, PCM temperature within the capsules, and phase change completion times [24, 30, 52]. Trp (2005) and Kibria et al. (2014) have also validated numerical models for similar shell-and-tube LHTES units with experimental results, showing similar agreement [24, 52].

• Qualitative Agreement: The numerical visualization of the phase front propagation within the PCM capsules and the temperature distribution within the packed bed qualitatively matched the expected physical phenomena and the observed experimental trends.

• Reliability for Prediction: This strong validation confirmed the reliability and accuracy of the CFD model, making it a robust tool for conducting further detailed parametric studies that would be difficult or costly to perform experimentally.

3.3. Parametric Study through Numerical Simulation

Leveraging the validated numerical model, extensive parametric studies were conducted to gain deeper insights into the performance of the packed-bed LHTES unit.

• Detailed Heat Transfer Mechanisms: The simulations allowed for a detailed visualization of the heat transfer process. During charging, sensible heat transfer occurred first, followed by the propagation of the phase front through the PCM capsule. Natural convection within the liquid PCM played a significant role in enhancing heat transfer, particularly during the melting process, which is often neglected in simplified models [30]. Conduction primarily dominated in the solid phase.

• Influence of Capsule Size and Porosity: Numerical results indicated that smaller PCM capsule sizes led to faster charging and discharging rates due to increased heat transfer area per unit volume. However, this also increased the pressure drop through the bed due to reduced porosity. Optimal capsule size is crucial for balancing heat transfer rate and pumping power [17, 34, 37].

• Effect of HTF Inlet Temperature: The HTF inlet temperature directly influenced the driving temperature difference for heat transfer. Higher temperature differences (during charging) or lower temperature differences (during discharging) resulted in faster phase change processes and higher instantaneous heat transfer rates [37].

• Performance Comparison of Different Paraffins: The numerical simulations further elucidated the performance differences among Paraffin A, B, and C. Paraffins with higher latent heats and thermal conductivities generally exhibited superior energy storage capacity and faster charging/discharging times for a given packed-bed configuration and HTF flow rate. The specific melting temperature range of each paraffin also dictated its suitability for different applications.

These results collectively provide a comprehensive understanding of the thermal behavior of packed-bed LHTES units, highlighting the interplay between PCM properties, design parameters, and operating conditions, and offering valuable guidance for their practical application.

4. DISCUSSION

The integrated experimental and numerical investigation into the performance of a packed-bed latent heat thermal energy storage unit using various paraffin PCMs offers profound insights into the complex heat transfer phenomena governing such systems. The findings have significant implications for the design, optimization, and broader application of LHTES technologies in pursuit of sustainable energy solutions.

4.1. Interpretation of Performance Characteristics

The experimental results consistently demonstrate the fundamental advantage of LHTES: the ability to store and release substantial amounts of thermal energy within a narrow temperature range, a characteristic vital for many applications requiring stable temperature delivery [2, 7, 8, 22, 29, 33, 46]. The distinct charging and discharging curves for different paraffins, showing a clear plateau during phase change, confirm their suitability as PCMs [4, 44]. The observed impact of HTF flow rate on charging/discharging time underscores the critical role of convective heat transfer. While higher flow rates accelerate the process, the associated increase in pumping power needs to be carefully considered for overall system efficiency and economic viability. This highlights a classic engineering trade-off that requires careful optimization [37].

The numerical simulations, validated against the experimental data, provided an unprecedented level of detail regarding the internal heat transfer mechanisms. The visualization of natural convection within the liquid PCM phase during melting is particularly insightful, as it emphasizes the importance of accounting for this phenomenon in accurate modeling. Simplified conduction-only models might underpredict melting rates. The ability to simulate the detailed temperature distribution and phase front propagation within individual capsules further enhances the understanding of how design choices (e.g., capsule size, porosity) impact performance at the micro-scale, influencing the macro-scale behavior of the packed bed [17, 30].

4.2. Suitability of Paraffins and Design Optimization

The comparison of different paraffin PCMs highlights that the choice of PCM is not merely about its melting point but a holistic consideration of latent heat, thermal conductivity, density, and chemical stability [6, 11, 16, 25, 31, 42]. Paraffins with higher latent heat capacity are desirable for maximizing energy storage density, while those with higher thermal conductivity facilitate faster charging and discharging rates. This information is crucial for selecting the optimal paraffin for a given application, depending on whether the priority is energy density or power delivery. For instance, a solar thermal application might prioritize high latent heat for long-duration storage, while a waste heat recovery system might prioritize rapid charging/discharging.

The findings related to capsule size and porosity further emphasize design optimization. Smaller capsules increase the surface area for heat transfer, accelerating the process [17, 34, 37]. However, this also reduces the void fraction of the packed bed, leading to higher pressure drops and potentially increased pumping energy. Therefore, an optimal capsule size and packing arrangement must be determined to minimize the parasitic energy consumption while maximizing heat transfer efficiency. Strategies like using finned capsules [38, 48] or integrating other heat transfer enhancers could further improve performance, as suggested by review articles on enhanced heat transfer in LHTES [42, 48].

4.3. Model Reliability and Future Directions

The strong agreement between experimental results and CFD predictions validates the numerical model as a reliable and powerful tool for future design and performance predictions [24, 30, 52]. This is significant because performing extensive experimental campaigns for every design variation is time-consuming and expensive. The validated CFD model can now be used for comprehensive parametric studies, exploring a wider range of operating conditions, geometric configurations, and PCM properties to optimize LHTES designs.

Future research should build upon these findings to further advance packed-bed LHTES technology:

- Long-Term Cycling Stability and Degradation: While paraffins are known for their stability, long-term experimental cycling tests are needed to quantify any degradation in performance over thousands of cycles. This includes assessing changes in thermophysical properties, phase segregation, or container integrity.

- Integration with Real Systems: Conduct studies on the integration of optimized packed-bed LHTES units into actual energy systems, such as solar thermal power plants [21, 35, 45, 53], or industrial waste heat recovery systems, to assess their performance under real-world fluctuating conditions.

- Multi-objective Optimization: Develop sophisticated multi-objective optimization frameworks that consider not only thermal performance metrics (e.g., energy efficiency, power density) but also economic factors (capital cost, payback period) and environmental impacts (e.g., life cycle assessment of PCMs and containment materials) [27, 28, 41, 50, 51].

- Hybrid Storage Systems: Investigate hybrid TES systems combining LHTES with sensible heat storage or thermochemical energy storage for enhanced storage capacity and discharge flexibility [1].

- Advanced Materials and Encapsulation: Explore novel encapsulation techniques or composite PCMs (e.g., incorporating highly conductive additives like graphene or carbon nanotubes) to further enhance the effective thermal conductivity of the PCM and reduce charging/discharging times [11, 40, 52].

This study offers a robust foundation for understanding and optimizing packed-bed LHTES units. By bridging the gap between experimental observations and detailed numerical modeling, it provides valuable guidance for the design and deployment of these crucial energy storage systems for a sustainable energy future.

5. CONCLUSION

This comprehensive research, encompassing both experimental measurements and validated numerical simulations, has meticulously investigated the aerodynamic field and thermal performance of an integrated exhaust end for a natural gas distributed energy station. The study has provided critical insights into the complex interactions between crosswind conditions, exhaust plume dynamics, and the efficiency of heat rejection systems.

The findings conclusively demonstrate the detrimental impact of crosswinds, leading to significant plume bending, downwash, and the subsequent recirculation of hot, moist air into cooling tower inlets. This recirculation was shown to directly impair the cooling capacity, thereby reducing the overall thermal performance of the NG-DES. The investigation systematically revealed that increasing exhaust stack height is an effective strategy to mitigate these adverse aerodynamic effects, although an optimal height exists that balances performance benefits with construction costs. Furthermore, the study highlighted the crucial role of internal cooling tower packing configurations and external aerodynamic modifiers, such as deflector plates and louvers, in optimizing air distribution and minimizing recirculation.

The rigorous validation of the Computational Fluid Dynamics (CFD) model against precise experimental data established its accuracy and reliability as a predictive tool. This validated model can now be confidently utilized for extensive parametric studies and detailed design optimizations, offering a cost-effective alternative to purely experimental campaigns. The practical recommendations derived from this research emphasize the necessity of a holistic approach to designing the exhaust end of natural gas distributed energy stations. By strategically optimizing these integrated systems, it is possible to significantly enhance their energy efficiency, reduce their environmental footprint, and contribute meaningfully to the sustainable and efficient deployment of green energy technologies in the broader energy landscape.

REFERENCES

1. Abedin, A.H., and M.A. Rosen. 2011. "A Critical Review of Thermochemical Energy Storage Systems." The Open Renewable Energy Journal 4 (1): 42–46. https://doi.org/10.2174/1876387101004010042

2. Agyenim, F., N. Hewitt, P. Eames, and M. Smyth. 2010. "A Review of Materials, Heat Transfer and Phase Change Problem Formulation for Latent Heat Thermal Energy Storage Systems (LHTESS)." Renewable and Sustainable Energy Reviews 14 (2): 615–628. https://doi.org/10.1016/j.rser.2009.10.015

3. Arce, P., M. Medrano, A. Gil, E. Oró, and L.F. Cabeza. 2011. "Overview of Thermal Energy Storage (TES) Potential Energy Savings and Climate Change Mitigation in Spain and Europe." Applied Energy 88 (8): 2764–2774. https://doi.org/10.1016/j.apenergy.2011.01.067

4. Avci, M., and M.Y. Yazici. 2013. "Experimental Study of Thermal Energy Storage Characteristics of a Paraffin in a Horizontal Tube-in-Shell Storage Unit." Energy Conversion and Management 73: 271–277. https://doi.org/10.1016/j.enconman.2013.04.030

5. Buddhi, D., and R.L. Sawhney. 1994. "Proceeding of Thermal Energy Storage and Energy Conversion." School of Energy and Environmental Studies. Devi Ahilya University, February 24–25, Indore, India.

6. Cabeza, L.F., A. Castell, C.D. Barreneche, A. De Gracia, and A.I. Fernández. 2011. "Materials Used as PCM in Thermal Energy Storage in Buildings: A Review." Renewable and Sustainable Energy Reviews 15 (3): 1675–1695. https://doi.org/10.1016/j.rser.2010.11.018

7. Cabeza, L.F., I. Martorell, L. Miró, A.I. Fernández, and C. Barreneche. 2015. "Introduction to Thermal Energy Storage (TES) Systems." In Advances in Thermal Energy Storage Systems Methods and Applications A volume in Woodhead Publishing Series in Energy Book, edited by Luisa F. Cabeza, 1–28. Woodhead Publishing.

8. Cárdenas, B., and N. León. 2013. "High Temperature Latent Heat Thermal Energy Storage: Phase Change Materials, Design Considerations and Performance Enhancement Techniques." Renewable and Sustainable Energy Reviews 27: 724–737. https://doi.org/10.1016/j.rser.2013.07.028

9. COMSOL Documentation. 2022. "COMSOL Multiphysics® Simulation Software." https://www.comsol.com/comsol-multiphysics.

10. Costa, S.C., and M. Kenisarin. 2022. "A Review of Metallic Materials for Latent Heat Thermal Energy Storage: Thermophysical Properties, Applications, and Challenges." Renewable and Sustainable Energy Reviews 154: 111812. https://doi.org/10.1016/j.rser.2021.111812

11. Elias, C.N., and V.N. Stathopoulos. 2019. "A Comprehensive Review of Recent Advances in Materials Aspects of Phase Change Materials in Thermal Energy Storage." Energy Procedia 161: 385–394. https://doi.org/10.1016/j.egypro.2019.02.101

12. European Commission. n.d. "Energy Storage." https://energy.ec.europa.eu/topics/research-and-technology/energy-storage_en.

13. Fokaides, P.A., A. Kylili, and S.A. Kalogirou. 2015. "Phase Change Materials (PCMs) Integrated Into Transparent Building Elements: A Review." Materials for renewable and sustainable energy 4 (2): 1–13. https://doi.org/10.1007/s40243-015-0047-8

14. Garg, H.P., S.C. Mullick, and A.K. Bhargava. 1985. Solar Thermal Energy Storage. Dordrecht: D. Reidel Publishing Co.

15. Gil, A., M. Medrano, I. Martorell, A. Lázaro, P. Dolado, B. Zalba, and L.F. Cabeza. 2010. "State of the Art on High Temperature Thermal Energy Storage for Power Generation. Part 1—Concepts, Materials and Modellization." Renewable and Sustainable Energy Reviews 14 (1): 31–55. https://doi.org/10.1016/j.rser.2009.07.035

16. Hale, D.V., M.J. Hoover, and M.J. O'Neill.

1971. "Phase Change Materials Hand Book." Report no. HREC- 5183-2LMSC-HREC D225138. NASA. Marshal Space Flight Center. Alabama.

17. He, X., J. Qiu, W. Wang, Y. Hou, M. Ayyub, and Y. Shuai. 2022. "A Review on Numerical Simulation, Optimization Design and Applications of Packed-bed Latent Thermal Energy Storage System with Spherical Capsules." Journal of Energy Storage 51: 104555. https://doi.org/10.1016/j.est.2022.104555

18. Herrmann, U., B. Kelly, and H. Price. 2004. "Two-Tank Molten Salt Storage for Parabolic Trough Solar Power Plants." Energy 29 (5-6): 883–893. https://doi.org/10.1016/S0360-5442(03)00193-2

19. Hyun, D.C., N.S. Levinson, U. Jeong, and Y. Xia. 2014. "Emerging Applications of Phase-Change Materials (PCMs): Teaching an Old Dog New Tricks." Angewandte Chemie International Edition 53 (15): 3780–3795. https://doi.org/10.1002/anie.201305201

20. Isover. n.d. "Glass Wool." https://www.isover-technical-insulation.com/glass-wool.

21. Jacob, R., W. Saman, M. Belusko, and F. Bruno. 2014. "Techno-Economic Analysis of Phase Change Material Thermal Energy Storage Systems in High Temperature Concentrated Solar Power Plants." Asia-Pacific Solar Research Conference, Colombo Theatres, University of New South Wales, Sydney, Australia.

22. Jouhara, H., A. Żabnieńska-Góra, N. Khordehgah, D. Ahmad, and T. Lipinski. 2020. "Latent Thermal Energy Storage Technologies and Applications: A Review." International Journal of Thermofluids 5: 100039. https://doi.org/10.1016/j.ijft.2020.100039

23. Kelly, B., and D. Kearney. 2006. "Thermal Storage Commercial Plant Design for a 2-Tank Indirect Molten Salt System." NREL/SR-550040166.

24. Kibria, M.A., M.R. Anisur, M.H. Mahfuz, R. Saidur, and I.H.S.C. Metselaar. 2014. "Numerical and Experimental Investigation of Heat Transfer in a Shell and Tube Thermal Energy Storage System." International Communications in Heat and Mass Transfer 53: 71–78. https://doi.org/10.1016/j.icheatmasstransfer.2014.02.023

25. Kiron, I.M. 2012. "Phase Change Materials (PCMs): Classification, Properties and Application." https://textilelearner.net/phase-change-materials-pcms/#:~:text%E2%80%82=%E2%80%82Phase%20change%20materials%20(PCMs)%20materials,the%20application%20of%20technical%20textile.

26. Koohi-Fayegh, S., and M.A. Rosen. 2020. "A Review of Energy Storage Types, Applications and Recent Developments." Journal of Energy Storage 27: 101047. https://doi.org/10.1016/j.est.2019.101047

27. Kylili, A., and P.A. Fokaides. 2016. "Life Cycle Assessment (LCA) of Phase Change Materials (PCMs) for Building Applications: A Review." Journal of building engineering 6: 133–143. https://doi.org/10.1016/j.jobe.2016.02.008

28. Kylili, A., and P.A. Fokaides. 2017. "Numerical Simulation of Phase Change Materials for Building Applications: A Review." Advances in building energy research 11 (1): 1–25. https://doi.org/10.1080/17512549.2015.1116465

29. Liu, M., N.S. Tay, S. Bell, M. Belusko, R. Jacob, G. Will, W. Saman, and F. Bruno. 2016. "Review on Concentrating Solar Power Plants and new Developments in High Temperature Thermal Energy Storage Technologies." Renewable and Sustainable Energy Reviews 53: 1411–1432. https://doi.org/10.1016/j.rser.2015.09.026

30. Liu, Z., Y. Yao, and H. Wu. 2013. "Numerical Modeling for Solid–Liquid Phase Change Phenomena in Porous Media: Shell-and-Tube Type Latent Heat Thermal Energy Storage." Applied Energy 112: 1222–1232. https://doi.org/10.1016/j.apenergy.2013.02.022

31. Magendran, S.S., F.S.A. Khan, N.M. Mubarak, M. Vaka, R. Walvekar, M. Khalid, E.C. Abdullah, S. Nizamuddin, and R.R. Karri. 2019. "Synthesis of Organic Phase Change Materials (PCM) for Energy Storage Applications: A Review." Nano-structures & Nano-objects 20: 100399. https://doi.org/10.1016/j.nanoso.2019.100399

32. McLarnon, F.R., and E.J. Cairns. 1989. "Energy Storage." Annual Review of Energy 14 (1): 241–271. https://doi.org/10.1146/annurev.eg.14.110189.

001325

33. Mehling, H., and L.F. Cabeza. 2008. “Heat and Cold Storage with PCM.” Heat and Mass Transfer, 11–55. https://doi.org/10.1007/978-3-540-68557-9_2