



CFD Analysis of PCM-Based Thermal Energy Storage Systems for Cold Storage Applications– A Review

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ABSTRACT

The increasing demand for energy-efficient thermal management systems has accelerated the application of Phase Change Materials (PCMs) in thermal energy storage (TES), particularly for cold-storage applications. This research presents a Computational Fluid Dynamics (CFD) analysis of a PCM-based thermal energy storage system for cold-storage applications. The study focuses on the numerical investigation of PCM charging and discharging behaviour under different thermal operating conditions. A three-dimensional computational model of the PCM storage system is developed, incorporating the PCM region, metallic storage container, and surrounding thermal environment. The transient phase-change process is simulated using the enthalpy–porosity method to predict temperature distribution, liquid fraction, phase-change progression, heat-transfer rate, and thermal energy storage characteristics. The effects of important parameters such as PCM quantity, melting temperature, thermal conductivity, boundary temperature, and storage configuration are investigated through parametric CFD simulations. The charging process is analysed by simulating heat removal from the PCM, resulting in solidification and cooling-energy storage, while the discharging process is analysed by applying heat to the PCM to simulate melting and release of the stored cooling energy.

Keywords: Phase Change Material (PCM); Thermal Energy Storage (TES); Cold Thermal Energy Storage (CTES); Computational Fluid Dynamics (CFD); Enthalpy–Porosity Method; Latent Heat Storage; Charging and Discharging; Liquid Fraction; Thermal Performance; Cold Storage System.

1: Introduction

1.1 Introduction

Energy plays a vital role in industrial, commercial, and domestic sectors. The increasing demand for cooling systems, refrigerated storage, and air-conditioning has resulted in higher electricity consumption worldwide. Conventional refrigeration systems operate continuously to maintain the desired storage temperature, leading to increased energy costs and greenhouse gas emissions. Therefore, improving the energy efficiency of cold storage systems has become an important area of research.

Thermal Energy Storage (TES) is an effective technique for storing thermal energy during periods of low energy demand and releasing it during peak demand. TES systems help improve energy efficiency, reduce electricity consumption, and stabilize temperature fluctuations. Among the different TES methods, **latent heat thermal energy storage (LHTES)** using **Phase Change Materials (PCMs)** has attracted significant attention because of its high energy storage density and nearly constant temperature during the phase change process.

A Phase Change Material absorbs or releases a large amount of latent heat while changing its physical state from solid to liquid or liquid to solid. During the melting process, the PCM stores thermal energy without a significant increase in temperature. During solidification, the stored energy is released, maintaining a nearly constant cooling temperature. This characteristic makes PCM highly suitable for cold storage, refrigeration, vaccine preservation, food transportation, dairy industries, and pharmaceutical applications.

The integration of PCM into cold storage systems can reduce compressor operating time, decrease peak electricity demand, improve temperature stability, and enhance the overall energy efficiency of refrigeration systems. The performance of a PCM-based TES system depends on the type of PCM, melting temperature, latent heat capacity, thermal conductivity, encapsulation method, and operating conditions.

This research experimentally investigates the charging and discharging performance of a PCM-based thermal energy storage system under controlled laboratory conditions. The study evaluates temperature distribution, charging time, discharging time, heat storage capacity, thermal efficiency, and energy-saving potential. The results are compared with those of a conventional cold storage system to assess the effectiveness of PCM integration.

The findings of this work are expected to contribute to the development of sustainable and energy-efficient cold storage technologies that reduce electricity consumption and improve thermal reliability.

1.2 Background of the Study

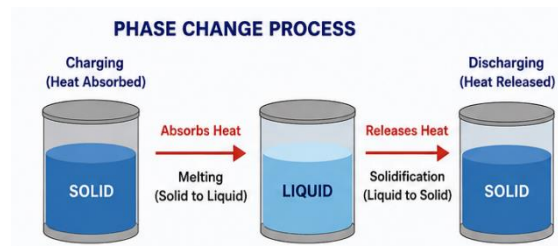
- Global increase in electricity demand for refrigeration.
- Importance of energy conservation.
- Need for sustainable cooling technologies.
- Role of thermal energy storage.
- Advantages of PCM-based latent heat storage.
- Industrial applications of PCM.

1.3 Thermal Energy Storage (TES)

Thermal Energy Storage is the process of storing heat or cooling energy for later use. It allows energy generated during off-peak hours to be used during periods of high demand, improving system efficiency.

Types of TES

- Sensible Heat Storage
- Latent Heat Storage (PCM)
- Thermochemical Storage

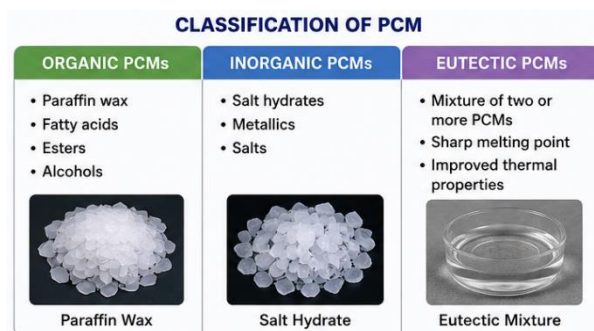


1.4 Phase Change Materials (PCM)

Phase Change Materials are substances that absorb or release a large amount of latent heat during a phase transition while maintaining a nearly constant temperature.

Classification of PCM

- Organic PCMs (Paraffin wax, fatty acids)
- Inorganic PCMs (Salt hydrates)
- Eutectic PCMs



1.5 Need for PCM in Cold Storage

- Maintains constant storage temperature.
- Reduces compressor running time.
- Saves electrical energy.

- Improves product quality.
- Provides backup cooling during power failures.
- Reduces peak electricity demand.

1.6 Problem Statement

Conventional refrigeration systems consume significant electrical energy because compressors operate frequently to maintain the required temperature. Temperature fluctuations during power interruptions or compressor cycling can adversely affect stored products. Integrating PCM into cold storage systems can enhance thermal storage capacity and reduce energy consumption, but experimental data under practical operating conditions are still limited. This study addresses this gap by experimentally evaluating a PCM-based TES system.

2. LITERATURE REVIEW

2.1 Introduction

Phase Change Material (PCM)-based Thermal Energy Storage (TES) has become one of the most promising technologies for improving the energy efficiency of refrigeration and cold storage systems. In recent years, researchers have focused on enhancing heat transfer characteristics, increasing storage capacity, reducing charging and discharging time, and extending cold retention duration. Experimental investigations have demonstrated that PCM integration can significantly reduce compressor operating hours, maintain stable temperatures, and decrease overall electricity consumption. This chapter reviews recent studies related to PCM-based cold thermal energy storage, emphasizing experimental investigations, heat transfer enhancement techniques, system optimization, and practical cold storage applications.

2.2.1 Mittal and Tarannum (2026)

Mittal and Tarannum (2026) investigated the relationship between **PCM encapsulation techniques, thermal conductivity enhancement, and the overall performance of thermal energy storage systems**. The authors highlighted that although PCMs possess a high latent heat storage capacity, their practical application is limited by low thermal conductivity. Different encapsulation methods, including spherical capsules, cylindrical capsules, shell-and-tube configurations, and macro-encapsulation, were compared to improve charging and discharging performance.

The study discussed the influence of capsule geometry, shell material, and encapsulation size on the heat transfer rate. Metallic shells exhibited faster heat transfer but increased system cost, whereas polymer shells provided corrosion resistance with slightly lower thermal conductivity. The researchers also examined the effect of graphite additives, aluminum fins, and copper inserts in improving thermal response.

2.2.2 Semane et al. (2026)

Semane et al. (2026) presented a comprehensive review of **heat transfer enhancement techniques for latent heat-based cold thermal energy storage (CTES)**. The authors emphasized that the low thermal conductivity of most PCMs limits charging and discharging performance and evaluated passive enhancement methods including fins, optimized storage containers, nanomaterials, metal foams, and hybrid enhancement strategies.

The review reported that adding **nanoparticles** such as graphene, Al_2O_3 , and CuO increased the effective thermal conductivity of PCM. **Metal foams** substantially accelerated heat transfer due to their large conductive network, while **optimized fin geometries** shortened charging time and improved temperature distribution. The paper also discussed the trade-off between faster charging and longer cold retention.

2.2.3 Odoi-Yorke et al. (2026)

Odoi-Yorke and co-authors (2026) reviewed nearly three decades of research on **phase change materials for cold energy storage**. The study categorized PCMs into organic, inorganic, and eutectic materials and compared their thermal properties, latent heat capacity, melting temperature, stability, and suitability for cold-chain applications.

The authors highlighted that paraffin-based PCMs are widely used because of their chemical stability and compatibility with refrigeration systems, while salt hydrates provide higher thermal conductivity but are affected by supercooling and phase segregation. The review also examined encapsulation technologies, heat transfer enhancement techniques, and applications in food preservation, vaccine storage, pharmaceutical transport, and refrigerated logistics.

2.2.5 Lao, Nie, and He (2026)

Lao, Nie, and He (2026) investigated **mobile cold energy storage systems** for refrigerated transportation. The study explored the use of PCM modules in refrigerated vehicles to reduce fuel consumption and improve temperature control during food distribution.

Different PCM module configurations were analyzed under varying transportation conditions. The results showed that PCM storage units maintained stable temperatures for extended periods even during compressor shutdown, reducing fuel use and greenhouse gas emissions.

The authors concluded that mobile PCM-based cold storage systems are promising for food logistics, vaccine transportation, and pharmaceutical supply chains.

2.2.6 Ouaouja et al. (2025)

Ouaouja et al. (2025) presented a comprehensive review of **Phase Change Materials (PCMs) for Cold Thermal Energy Storage (CTES)**, with particular emphasis on refrigeration systems and the potential of bio-based PCMs. The authors explained that integrating PCMs into refrigeration systems can significantly improve energy efficiency by storing cooling energy during off-peak periods and releasing it during compressor-off cycles. They compared conventional organic, inorganic, and eutectic PCMs with newly developed bio-based materials in terms of melting temperature, latent heat, thermal conductivity, stability, and environmental impact.

The review discussed the influence of PCM placement, encapsulation, and heat exchanger design on overall refrigeration performance. Bio-based PCMs were highlighted as promising alternatives because of their renewability, lower environmental impact, and good thermal performance. However, the authors noted that these materials require further long-term testing before large-scale commercialization.

2.2.8 Zhang et al. (2025)

Zhang and co-workers reviewed recent developments in improving the performance of PCM-based cold thermal energy storage systems. The authors focused on methods to overcome the low thermal conductivity of PCMs, including metallic fins, graphite additives, metal foams, nanoparticles, and optimized encapsulation.

The study concluded that combining multiple enhancement techniques provides the greatest improvement in charging and discharging rates. Numerical simulations and experimental investigations showed that optimized fin geometry and conductive additives can significantly reduce melting and solidification time while maintaining stable storage temperatures.

2.2.9 Kumar and Singh (2025)

Kumar and Singh experimentally investigated a **PCM-integrated refrigeration system** for cold-storage applications. A paraffin-based PCM module was installed inside the refrigeration chamber, and the system was tested under different cooling loads.

Temperature measurements, compressor operating time, and electricity consumption were recorded during charging and discharging cycles. The experimental results showed that PCM maintained a more uniform storage temperature, reduced compressor cycling, and lowered total energy consumption compared with a conventional refrigeration system.

The study concluded that PCM integration enhances system reliability during power interruptions and improves food preservation by reducing temperature fluctuations.

2.2.10 Sharma and Sharma (2025)

Sharma and Sharma experimentally analyzed the thermal performance of a latent heat thermal energy storage unit using paraffin wax as the PCM. The research investigated charging time, discharging time, heat storage capacity, and temperature distribution under different operating conditions.

The results indicated that paraffin wax exhibited excellent thermal stability and repeatable melting-solidification behavior. During discharging, the PCM released stored cooling energy gradually, maintaining a nearly constant temperature over an extended period. The study also showed that increasing the heat transfer area improved charging efficiency.

2.4 Research Gap Analysis

From the reviewed literature, the following research gaps have been identified:

1. Most studies focus on laboratory-scale experiments, while commercial-scale cold storage applications are limited.
2. Low thermal conductivity of PCM continues to reduce charging and discharging performance.
3. Long-term thermal cycling and reliability studies are insufficient.
4. Comparative investigations of different PCM materials under identical operating conditions are limited.
5. Techno-economic analyses are rarely included.
6. Optimization of PCM placement inside cold storage chambers requires further research.

7. The combined influence of PCM quantity, insulation thickness, and refrigeration load has not been extensively investigated experimentally.

2.5 Key Findings of Literature Review

- PCM significantly improves refrigeration efficiency.
- Compressor operating time decreases.
- Electricity consumption is reduced.
- Stable storage temperature enhances food quality.
- Organic PCMs exhibit excellent thermal stability.
- Heat transfer enhancement techniques improve PCM performance.
- Proper encapsulation increases PCM durability.
- Optimization of system design is essential for maximum energy savings.

2.6 Limitations of Existing Literature

- Low thermal conductivity of most PCMs.
- High installation cost.
- Limited commercial implementation.
- Insufficient long-term reliability studies.
- Lack of comprehensive economic analysis.
- Limited experimental validation under real industrial conditions.

3. PROPOSED METHODOLOGY

3.1 Research Methodology

The research methodology begins with an extensive study of existing literature related to thermal energy storage, latent heat storage, phase change materials (PCMs), cold thermal energy storage (CTES), refrigeration systems, and PCM-based cold storage applications. The literature review is used to identify the limitations of existing systems, commonly used PCM materials, numerical modelling approaches, and important parameters affecting the thermal performance of PCM-based cold storage systems. Based on the identified research gap, a suitable PCM and CFD-based numerical methodology are selected for the present investigation.

The selected PCM is evaluated based on its melting temperature, latent heat of fusion, thermal conductivity, density, specific heat, viscosity, chemical stability, safety, availability, and cost. Since the proposed application is cold storage, the phase-change temperature of the PCM should be close to the desired operating temperature of the cold storage system. After PCM selection, a three-dimensional computational model of the PCM storage unit is developed using suitable CAD modelling software. The PCM is considered to be enclosed within a metallic container, preferably aluminium, to provide effective heat transfer between the PCM and its surrounding environment.

The computational domain is subsequently imported into the CFD software and discretized into a suitable computational mesh. Thermophysical properties of the PCM and container material are defined in the numerical model. The phase change of the PCM is simulated using the enthalpy–porosity method, in which the liquid fraction is used to represent the solid, mushy, and liquid regions during phase transformation. Appropriate governing equations, initial conditions, and thermal boundary conditions are applied to simulate the charging and discharging processes.

During the charging simulation, heat is removed from the PCM through the cold boundary representing the refrigeration or evaporator condition. The PCM undergoes solidification and stores cooling energy in the form of latent heat. During the discharging simulation, heat is supplied to the PCM from the surrounding chamber or thermal load, resulting in melting of the PCM and release of the stored cooling capacity. The transient temperature field, liquid fraction, heat transfer rate, and phase-change behaviour are monitored throughout the simulation.

The CFD results are post-processed to evaluate temperature distribution, liquid-fraction distribution, phase-change time, heat storage capacity, cooling retention capability, and thermal performance. Parametric simulations may then be performed by varying important operating and design parameters such as PCM quantity, PCM melting temperature, container geometry, boundary temperature, charging/discharging conditions, and thermal conductivity enhancement. The numerical results are compared with published literature wherever suitable to assess the reliability of the developed CFD model.

3.2 Selection of PCM

Selection of an appropriate PCM is one of the most important stages of the CFD investigation because the thermophysical characteristics of the PCM directly influence the predicted thermal performance of the cold thermal energy storage system. For a cold storage application, the PCM should have a phase-transition temperature within or close to the required operating temperature range. A PCM with an unsuitable melting temperature may not provide effective thermal storage even when it possesses a high latent heat capacity.

The PCM selected for the CFD analysis should possess a high latent heat of fusion so that a comparatively small quantity of material can store a significant amount of cooling energy. The thermal conductivity of the PCM is also an important parameter because it determines the rate at which heat can be transferred into or out of the PCM during phase change. Density and specific heat are required for determining the sensible heat contribution, while viscosity is important for modelling natural convection in the liquid PCM region.

Other selection criteria include chemical stability, thermal cycling stability, low supercooling, non-corrosiveness, safety, environmental compatibility, availability, and cost. The thermophysical properties obtained from reliable literature sources are incorporated into the CFD model. The selected PCM properties include density, specific heat, thermal conductivity, dynamic viscosity, melting temperature, and latent heat of fusion.

For the present cold-storage application, particular emphasis is given to the melting temperature and latent heat of fusion because these properties determine the useful operating temperature range and cooling energy storage capability of the PCM.

3.3 Computational Geometry Development

A three-dimensional computational geometry of the PCM-based cold thermal energy storage system is developed using suitable CAD modelling software. The geometry consists of the PCM storage container, PCM region, surrounding cold-air or thermal-fluid region, and insulated cold-storage chamber where required by the selected modelling approach.

The PCM is assumed to be contained within a metallic enclosure. Aluminium is considered as the container material because of its relatively high thermal conductivity and suitable mechanical properties. The dimensions of the PCM container and the surrounding computational domain are selected according to the intended cold-storage configuration.

The computational geometry is simplified where necessary to reduce computational requirements while retaining the major heat-transfer characteristics of the system. The final geometry is checked for continuity, appropriate interfaces, and absence of unnecessary geometrical features before being transferred to the CFD pre-processing environment.

3.4 Computational Domain and CFD Model

The computational domain is divided into appropriate regions representing the PCM, container material, and surrounding thermal environment. A transient conjugate heat-transfer model may be employed to account for heat transfer between the PCM and the metallic container and between the container and surrounding fluid.

The PCM region is modelled as a phase-changing material. The surrounding region is modelled according to the selected physical configuration of the cold-storage system. Depending on the modelling objective, the surrounding cold air may be represented using a fluid domain, while the refrigeration effect may be represented through a specified wall temperature or heat-transfer boundary condition.

The CFD model is developed to predict the transient thermal behaviour of the PCM during both charging and discharging. The model accounts for heat conduction within the solid PCM and natural convection within the liquid PCM region, where applicable.

3.5 PCM Storage Container

The PCM storage container acts as the thermal storage module in the numerical model. The container is represented using a metallic material having relatively high thermal conductivity and adequate mechanical strength. Aluminium is selected as the representative container material because of its favourable thermal conductivity and lightweight characteristics.

The PCM container is filled with a predefined volume or mass of PCM in the computational geometry. An appropriate interface between the PCM and container wall is defined to enable heat transfer between the two regions. The container thickness is incorporated into the numerical model because it can influence the thermal resistance between the PCM and the surrounding environment.

Different container dimensions or configurations can also be investigated through parametric CFD simulations to determine their influence on heat transfer and phase-change behaviour. The container geometry can therefore be optimized based on charging time, discharging time, temperature uniformity, and stored cooling energy.

3.6 Material Properties and Thermal Modelling

Accurate thermophysical properties are essential for obtaining reliable CFD predictions of PCM behaviour. The density, specific heat, thermal conductivity, viscosity, melting temperature, and latent heat of fusion of the selected PCM are specified in the numerical model.

The phase change is represented using the enthalpy formulation. The total enthalpy of the PCM consists of sensible and latent components. The latent heat contribution is activated within the phase-transition temperature range. The liquid fraction varies from zero in the completely solid state to unity in the completely liquid state.

The thermal conductivity and specific heat may be defined as temperature-dependent properties when reliable temperature-dependent data are available. Similarly, density and viscosity can be specified according to the requirements of the selected CFD solver and numerical model. These material properties allow the CFD model to represent the coupled heat-transfer and phase-change behaviour of the PCM.

3.7 Charging Process

The charging process represents the storage of cooling energy within the PCM. In the CFD model, the initial temperature of the PCM is specified according to the selected operating condition. A low-temperature boundary condition representing the refrigeration system or evaporator is applied to the appropriate surface of the PCM storage module.

At the beginning of the charging process, the PCM is considered to be in the liquid or partially liquid state, depending on the selected initial condition. Heat is continuously removed from the PCM through the container wall. As the PCM temperature decreases and reaches its phase-transition temperature, solidification begins.

During solidification, latent heat is released from the PCM while the temperature remains within the phase-change range. The CFD solver calculates the temperature field, enthalpy, and liquid fraction at each time step. The charging process is continued until the desired degree of solidification is achieved or the PCM reaches the specified final temperature.

The charging time and temperature distribution are extracted from the transient CFD results to evaluate the cooling-energy storage characteristics of the PCM.

3.8 Discharging Process

The discharging process represents the release of cooling energy stored within the PCM. After completion of the charging process, the thermal boundary condition is changed to represent the heat load or warmer surroundings inside the cold-storage chamber.

Heat enters the PCM through the container wall and causes the solid PCM to undergo melting. As the temperature increases to the phase-transition range, the stored latent heat is progressively released to the surrounding cold-storage environment.

The liquid fraction increases progressively during the melting process. The CFD model tracks the movement of the solid-liquid interface through the liquid-fraction distribution. Temperature contours, liquid-fraction contours, and heat-transfer rates are monitored throughout the transient simulation.

The discharging time is determined based on the selected criterion, such as complete melting, a specified liquid fraction, or the time required for the chamber temperature to reach a predetermined limit.

3.9 CFD Simulation Procedure

Before beginning the numerical simulation, the computational geometry is checked for geometric errors and appropriate fluid-solid interfaces. The computational domain is discretized using a suitable mesh. Mesh quality parameters such as skewness, orthogonal quality, and element distribution are evaluated.

The thermophysical properties of the PCM, container, and surrounding fluid are then specified. Appropriate governing equations and phase-change models are activated. The enthalpy-porosity method is used to model the solidification and melting behaviour of the PCM.

Initial temperature conditions are assigned to the PCM and surrounding domain. Boundary conditions representing the charging and discharging conditions are then applied. A transient solver is used because the temperature and phase distribution vary continuously with time.

The time step is selected carefully to provide stable and accurate prediction of the phase-change process. The simulation is continued until the specified convergence criteria and termination conditions are satisfied. Residuals and important monitoring parameters are examined throughout the simulation to ensure numerical stability.

The charging and discharging simulations are subsequently repeated for different operating conditions to investigate the influence of selected parameters on the thermal performance of the PCM-based cold-storage system.

3.11 CFD Simulation Variables

The numerical investigation considers independent and dependent parameters. The independent parameters may include PCM quantity, PCM melting temperature, initial PCM temperature, charging temperature, discharging temperature, boundary temperature, container thickness, PCM container geometry, thermal conductivity, and operating time.

The dependent parameters obtained from the CFD simulations include PCM temperature, cold-storage temperature, temperature distribution, liquid fraction, solid fraction, phase-change time, heat-transfer rate, stored thermal energy, released thermal energy, and cooling retention time.

The effect of each independent parameter on the thermal performance of the PCM-based cold-storage system is investigated through parametric CFD simulations. The results are compared to identify suitable operating and design conditions.

3.12 CFD Data Acquisition and Post-Processing

In the present study, data are obtained directly from the transient CFD simulations rather than from physical experimental instruments. Temperature, liquid fraction, enthalpy, heat-transfer rate, and other relevant thermal parameters are recorded at predetermined time intervals during the charging and discharging processes.

Temperature monitors are defined at selected locations within the PCM and surrounding domain to obtain temperature-versus-time data. Contour plots are generated at different time steps to visualize the temperature distribution and phase-change progression.

Liquid-fraction contours are used to identify the melting and solidification behaviour of the PCM. The heat-transfer rate through the container wall is also extracted from the CFD results to determine the rate of thermal energy transfer.

The numerical data are subsequently processed to calculate the total stored or released thermal energy, charging time, discharging time, average PCM temperature, temperature uniformity, and cooling retention period. Graphs such as temperature versus time, liquid fraction versus time, heat-transfer rate versus time, and stored energy versus time are generated for comparison of different simulation cases.

The CFD results are finally compared for different PCM configurations and operating conditions to identify the parameters that provide improved thermal performance of the cold thermal energy storage system.

4. CONCLUSION

4.1 Introduction

The extensive literature review presented in Chapter 2 examined recent developments in Phase Change Material (PCM)-based Thermal Energy Storage (TES), with particular emphasis on cold thermal energy storage and refrigeration applications. The reviewed studies covered PCM selection, thermophysical properties, encapsulation, heat-transfer enhancement, refrigeration integration, charging and discharging behaviour, energy consumption, temperature stability, numerical modelling, CFD simulation techniques, and practical cold-storage applications.

The literature indicates that PCM-based thermal energy storage is a promising approach for improving the thermal performance, temperature stability, and energy efficiency of conventional refrigeration and cold-storage systems. However, the thermal behaviour of PCM during melting and solidification is highly dependent on material properties, geometry, operating conditions, and heat-transfer characteristics. Therefore, Computational Fluid Dynamics (CFD) provides an effective numerical approach for investigating the transient thermal behaviour and phase-change characteristics of PCM-based cold-storage systems.

4.2 Overall Findings from the Literature

The literature demonstrates that PCM-based TES systems have significant advantages over conventional sensible thermal storage systems because they utilize the latent heat associated with phase transformation. During charging, the PCM stores cooling energy and changes from liquid to solid, while during discharging, it releases the stored cooling energy and changes from solid to liquid. This allows a relatively large amount of thermal energy to be stored within a small temperature range. Consequently, PCM systems can provide improved temperature stability in cold-storage applications.

A major finding from the reviewed studies is that PCM selection is critical to system performance. The melting temperature of the PCM should be compatible with the required cold-storage temperature. In addition to melting temperature, latent heat, thermal conductivity, density, specific heat, thermal stability, chemical compatibility, safety, cost, and availability must be considered.

Another important finding is that the low thermal conductivity of many PCMs remains a major limitation. Although PCMs possess high latent heat capacity, their relatively low thermal conductivity can result in slow charging and discharging. Researchers have therefore investigated fins, metallic structures, graphite, metal foams, nanoparticles, encapsulation, and other conductive structures to improve heat transfer.

CFD analysis provides an effective method for studying these heat-transfer limitations because temperature distribution, liquid fraction, solid fraction, heat-transfer rate, and phase-change progression can be predicted at different locations and time steps. The influence of PCM geometry, container

configuration, boundary conditions, and thermal enhancement techniques can therefore be investigated without requiring physical modification of the storage system for every operating condition.

The reviewed literature also indicates that PCM integration with refrigeration systems can reduce compressor operating time and electrical energy demand. During periods when refrigeration is available, the PCM can store cooling energy. During compressor-off periods or increased cooling demand, the PCM can release the stored cooling energy and help maintain the required cold-storage temperature. CFD modelling can be used to investigate this thermal buffering behaviour and determine suitable PCM operating conditions.

4.3 Charging and Discharging Behaviour

The charging and discharging characteristics are important performance indicators for PCM-based TES systems. During charging, heat is removed from the PCM and the material initially undergoes sensible cooling followed by phase transformation from liquid to solid. During the phase-change process, a significant amount of energy is stored as latent heat while the temperature remains within the phase-transition range.

During discharging, heat is transferred to the PCM from the surrounding cold-storage environment or thermal load. The solid PCM progressively melts and releases the previously stored cooling energy. The phase-change process can be represented numerically through the enthalpy–porosity method, which enables prediction of the temperature field and liquid-fraction distribution throughout the computational domain.

The duration of the phase-change process depends on PCM quantity, thermal conductivity, heat-transfer area, temperature difference, container geometry, boundary conditions, and operating conditions. Increasing PCM quantity generally increases the available thermal storage capacity but may also increase the time required for complete charging or discharging.

CFD parametric analysis can therefore be used to determine the effect of PCM quantity, operating temperature, container dimensions, and heat-transfer conditions on charging and discharging time. The optimum configuration can be identified based on the numerical results.

4.4 Effect on Cold Storage Temperature

One of the most significant advantages identified from previous studies is the ability of PCM to reduce temperature fluctuations inside a cold-storage chamber. Conventional refrigeration systems may produce cyclic temperature variations because the compressor operates according to the cooling demand or thermostat conditions. PCM can act as a thermal buffer by storing cooling energy during the charging period and releasing it during the discharging period.

CFD analysis can be used to investigate the temperature distribution within the cold-storage chamber and PCM region. Temperature contours and temperature-versus-time plots can be generated to determine the effectiveness of PCM in maintaining a relatively stable storage temperature.

The temperature stabilization provided by PCM is particularly beneficial for applications involving food, agricultural products, pharmaceuticals, and other temperature-sensitive materials. A numerical investigation can determine the ability of different PCM configurations to maintain the storage temperature within a specified acceptable range.

4.5 Effect on Energy Consumption

PCM integration has the potential to reduce refrigeration energy demand by storing cooling energy during suitable operating periods and releasing it when additional cooling support is required. Although electrical energy consumption cannot be directly measured in a CFD model, the thermal energy transfer and cooling load can be calculated numerically.

The thermal energy stored in the PCM can be determined from the sensible and latent energy components. The heat-transfer rate through the PCM container and the total cooling energy transferred during charging and discharging can be obtained from the CFD solution.

The numerical investigation can therefore be used to compare different PCM configurations in terms of cooling capacity, heat-transfer rate, charging time, discharging time, and thermal storage effectiveness. Where compressor power and refrigeration-system characteristics are incorporated into the numerical model, an estimated reduction in cooling energy demand can also be evaluated.

4.6 Research Gap Identified from Literature

Based on the comprehensive review, the following major research gaps have been identified:

1. Limited detailed CFD investigation: Although several studies have investigated PCM-based cold thermal energy storage, detailed CFD studies considering transient temperature distribution, phase-change progression, and liquid-fraction behaviour under cold-storage conditions remain limited.
2. Low thermal conductivity: The low thermal conductivity of commonly used PCMs continues to restrict heat-transfer rates during charging and discharging. Further CFD investigation is required to evaluate the influence of thermal conductivity on phase-change behaviour.

3. PCM quantity optimization: There is insufficient numerical information regarding the optimum PCM quantity required to provide effective thermal storage while avoiding unnecessarily long charging and discharging periods.
4. Temperature stability: Further CFD investigation is required to quantify the ability of PCM to reduce temperature fluctuations and maintain the desired cold-storage temperature.
5. Thermal energy performance: Comparative numerical analysis of conventional and PCM-assisted cold-storage configurations under identical thermal boundary conditions is required.
6. Charging and discharging time: The influence of PCM properties, boundary temperature, geometry, and operating conditions on charging and discharging duration requires further numerical investigation.
7. Cold-retention capability: CFD analysis is required to determine the duration for which a PCM-based cold-storage system can maintain an acceptable temperature after the refrigeration cooling condition is removed.
8. Realistic operating conditions: Many numerical studies use simplified boundary conditions. Further CFD investigation under variable thermal loads, ambient temperatures, and refrigeration operating conditions is required.
9. Geometrical optimization: The influence of PCM container dimensions, PCM thickness, heat-transfer area, and PCM placement on thermal performance requires additional numerical investigation.
10. Long-term cyclic performance: Numerical investigation of repeated charging and discharging cycles can provide information about the thermal behaviour and performance degradation associated with repeated PCM phase transformations.

4.7 Proposed Research Work

Based on the identified research gaps, the present research proposes a CFD Analysis of a PCM-Based Thermal Energy Storage System for Cold-Storage Applications.

A suitable PCM having a phase-transition temperature appropriate for the selected cold-storage temperature range will be selected based on its thermophysical properties. A three-dimensional computational model of the PCM-based thermal energy storage system will be developed using suitable CAD modelling and CFD software.

The computational domain will consist of the PCM region, metallic storage container, and surrounding thermal environment. Aluminium may be considered as the container material because of its relatively high thermal conductivity. The thermophysical properties of the selected PCM, including density, specific heat, thermal conductivity, viscosity, melting temperature, and latent heat of fusion, will be incorporated into the CFD model.

The transient phase-change behaviour of the PCM will be simulated using the enthalpy–porosity method. Appropriate governing equations, initial conditions, and thermal boundary conditions will be applied.

Two major simulation stages will be considered:

Charging Simulation

During the charging process, heat will be removed from the PCM through the cold boundary representing the refrigeration or evaporator condition. The PCM will undergo cooling followed by solidification. The temperature distribution, solid fraction, liquid fraction, enthalpy, and heat-transfer rate will be monitored throughout the simulation.

Discharging Simulation

During the discharging process, the refrigeration cooling condition will be removed and heat will be supplied to the PCM through the surrounding thermal environment. The PCM will progressively melt and release the stored cooling energy. The temperature field, liquid fraction, phase-change interface, and heat-transfer rate will be evaluated.

The following parameters will be evaluated from the CFD results:

- PCM temperature distribution.
- Cold-storage chamber temperature distribution.
- Temperature variation with time.
- Liquid-fraction distribution.
- Solid-fraction distribution.
- Charging time.
- Discharging time.

- Heat-transfer rate.
- Latent heat storage capacity.
- Total thermal energy stored.
- Total thermal energy released.
- Cooling retention period.
- Temperature uniformity.
- Effect of PCM quantity.
- Effect of PCM thermal conductivity.
- Effect of PCM melting temperature.
- Effect of container geometry.
- Effect of boundary temperature.

Parametric CFD simulations will be performed by varying the selected operating and geometrical parameters. The results will be compared to determine the configuration providing improved thermal performance.

4.8 CFD Model Validation and Numerical Reliability

The reliability of the developed CFD model will be assessed through appropriate numerical verification and validation procedures. A mesh independence study will be performed using different mesh sizes to determine whether the calculated temperature, liquid fraction, and heat-transfer characteristics are independent of further mesh refinement.

A time-step independence study will also be performed by comparing the results obtained using different transient time steps. The selected time step will provide a suitable balance between computational accuracy and simulation time.

Where suitable published experimental or numerical results are available, the CFD predictions will be compared with the reported temperature distribution, melting/solidification time, liquid fraction, or other relevant thermal parameters. The comparison will be used to assess the reliability of the numerical model.

The validation process will help establish confidence in the CFD model before performing the detailed parametric analysis.

4.9 Expected Contribution of the Research

The proposed CFD investigation is expected to provide detailed numerical information regarding the thermal behaviour of PCM-based thermal energy storage systems for cold-storage applications.

The study will establish the relationship between PCM thermophysical properties, storage geometry, boundary conditions, and phase-change behaviour. The CFD model will provide detailed information regarding temperature distribution, liquid fraction, heat-transfer rate, and thermal energy storage during charging and discharging.

The numerical results are expected to identify suitable PCM operating conditions and storage configurations that can improve temperature stability and thermal energy storage performance.

The study may also provide useful guidelines for:

- Selection of suitable PCM melting temperature.
- Selection of appropriate PCM quantity.
- Optimization of PCM container geometry.
- Improvement of heat-transfer characteristics.
- Reduction of charging and discharging time.
- Improvement of cooling retention.
- Improvement of temperature uniformity.
- Optimization of cold-storage operating conditions.

The developed CFD methodology can subsequently be used as a numerical design tool for evaluating PCM-based cold thermal energy storage systems before physical prototype development.

4.10 Conclusion

The literature review confirms that PCM-based thermal energy storage is a promising technology for improving the thermal performance and energy efficiency of cold-storage systems. The high latent heat capacity of PCMs enables substantial cooling energy to be stored within a relatively narrow temperature range. PCM integration can improve temperature stability, extend cooling retention, reduce compressor operating requirements, and provide thermal buffering during periods of reduced refrigeration availability.

However, several challenges remain, particularly the low thermal conductivity of PCM, long charging/discharging time, optimum PCM quantity, container configuration, and non-uniform heat transfer during phase transformation. These challenges require detailed investigation of the temperature and phase-change behaviour within the PCM.

Therefore, the present research focuses on the CFD analysis of a PCM-based thermal energy storage system for cold-storage applications, with particular emphasis on charging and discharging characteristics, temperature distribution, liquid-fraction behaviour, thermal energy storage capacity, cooling retention, heat-transfer rate, and overall thermal performance.

The use of CFD and the enthalpy–porosity method will enable detailed visualization and quantitative analysis of the phase-change process. Parametric simulations will further help identify suitable PCM properties, storage configurations, and operating conditions. The outcomes of the research are expected to contribute toward the development and numerical optimization of more energy-efficient, thermally stable, and reliable PCM-based cold-storage systems.

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