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Recent Breakthroughs and Improvements in Phase Change Material Melting in a Triple-Tube Thermal Storage Unit

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ABSTRACT

PCMs have a huge storage capacity, improved heat transfer capability, and a constant operating temperature. PCMs have a weak conduction heat transfer coefficient, which slows melting and reduces energy storage. To increase thermal energy storage system efficiency, performance augmentation technologies are being developed. These strategies include using fins, metal foams in PCMs, and high-thermal-conductivity nanoparticles. This article presents a complete overview of experimental, numerical, and experimental and numerical investigations on melting enhancement of phase change material in triplex-tube thermal energy storage. Fins, nanoparticles, and both are used. This article reviews works on melting enhancement of phase transition material in triplex-tube thermal energy storage. In addition, recent findings and research developments will be summarized. This article covers setting up, examining settings, and discovering results.

1. INTRODUCTION

For the goal of protecting the world's energy resources, we need renewable energy sources and efficient energy conversion [1, 2]. Inefficient energy conversion causes nearly a third of the world's energy supply to be lost, which harms the environment [3, 4]. Some renewable energy sources, such as wind, geothermal, and solar thermal, have unstable power supply. This results in an imbalance between energy production and consumption. A thermal energy storage (TES) system is a viable technology for filling the gap; for example, it may store solar energy during the day and use it at night or when demand is high [5-10]. A TES system may also store energy from a nuclear power station during the day and utilise it at night. Thermochemical storage, sensible heat storage, and latent heat storage are TES subcategories. TES systems must reduce energy loss and costs to allow manufacturers to produce effective and affordable energy conversion devices [11, 12]. Phase change materials, or PCMs, are generally recognized as one of the most promising types of materials for storing and recovering thermal energy [13-37]. Thermal energy storage systems, especially latent heat energy storage, have gained attention owing to global environmental concerns and the need to boost energy efficiency. The inability of phase-change materials to retain thermal energy owing to their weak thermal conductivity, which prolongs the charging process, and their thermal discharging properties make them unsuitable for this use. Researchers have looked at a range of ways to increase heat transfer between phase-change material and participant fluid. These strategies include widening the heat transfer surface area, using finned tubes or a multi-tube heat exchanger [38-67], boosting the thermal conductivity of phase-change material using methods such as metal matrix insertion, and saturating the phase-change material with a fluid. Materials that contain pores. Most investigations have demonstrated that increasing the heat transfer surface increases the amount of heat transfer between the phase change material and working fluid [68-73]. Because of its ease of production, cheap cost, and simplicity, using fins is the most effective method for increasing heat transfer in phase-change materials. This is due to the fact that producing fins requires very little effort. Outer fins, inner fins, circular fins, and longitudinal fins are only few of the several types of fins that may be used to improve the impact of conduction in phase-change materials [68]. Numerous pieces of research have been done that concentrate on the use of fins as a means of improving the rate at which heat is transferred inside latent heat thermal energy storage (LHTES) systems. The melting process of PCMs was given by Kamkari and Shokouhmand [74] in an experimental investigation. The PCMs were contained in a clear rectangular container with or without horizontal fins. According to the findings, there was a correlation between the total efficacy of the fins and the melting enhancement ratio, which increased as the number of fins increased. Yildiz et al. [75] conducted a numerical analysis to determine the effect of two different kinds of fins, including rectangular and tree-like branching fins, on a photovoltaic (PV) module that also included PCMs. According to the findings, using a fin that was shaped like a tree with many branching points at the same PCM mass was not nearly as constructive as using a rectangular fin. The process of melting was investigated by Tang et al. [76] in a heat exchanger unit that made use of non-uniform fins. Research was conducted to determine how the thermal performance of a horizontal thermal storage unit would be affected by a variety of fin configurations, angles, and lengths. According to the findings, selecting the optimal design led to a decrease of 83.9% in the amount of time required for the PCM unit to melt, while simultaneously leading to an increase of 466% in the amount of thermal storage unit density.

There is, as far as the authors are aware, no systematic assessment of the improvement of phase change material melting in a triple-tube energy storage unit that can be found in the published research. In light of this, the purpose of this work is to critically assess the integration technology of melting enhancement of PCM, draw some major conclusions from the existing literature, and identify a number of outstanding questions for further study. This study includes a broad variety of subjects, some of which are how to construct phase change materials and fins, how to integrate phase change processes, how to evaluate life cycle studies, and possible downsides of employing these materials.

2. MELTING ENHANCEMENT USING FINS

LTES's biggest concern is PCMs' weak heat conductivity. This issue may slow heat transmission during energy storage. Adding fins is one way to boost the LTES unit's heat transfer rate for engineering application. This promotes the LTES's engineering use. Fins were utilized to facilitate the melting of phase change material in thermal energy storage with triple tubes.

Mat et al. [77] analyzed the melting process in a triple-tube heat exchanger using PCM (RT82). Fluent 6.3.26 creates two-dimensional numerical models. Three heating procedures were utilized to melt PCM from the inner, outer, and both tubes. Several ways for improving the PCM's interior, exterior, and both were examined to maximize heat transmission. Several enhancing options were compared, including heating the tube from the inside, outside, both tubes, and internally finned tubes. How fin length affects boosting techniques was studied. Using a triple-tube heat exchanger with internal–exterior fins, melting time may be reduced by 43.3% in the triplex tube without fins.

Abdulateef et al. [78] developed, tested, and evaluated an experimental energy storage system using a horizontal triplex tube heat exchanger with internal longitudinal fins incorporating phase-change material. Abdulateef et al. created this system (PCM). The effects of 16.2, 29.4, and 37.4 min/kg mass flow rates on PCM average axial temperature were studied. Non-steady state 29.4 kg/min needed less time to melt PCM than steady state 29.4 kg/min at 16.2 and 37.5 kg/min charging temperatures. Internal, internal-external, and exterior triangular fins improved by 11%, 12%, and 15% over longitudinal fins.

Yang et al. [79] quantified the melting performance of Ba(OH)28H2O in a triplex tube heat exchanger (TTHX). TTHX's physical and mathematical models are created first. Then, the governing equations are discretized using finite volume (FVM). In the last phase, the newly constructed numerical method is written into FORTRAN code and run. PCM melting performance and exergy efficiency ratio of the investigated TTHX are affected by heat transfer fluid (HTF) input temperature and flow condition. Increasing HTF input temperature and turbulent condition may speed up phase change. Increasing the HTF mass flow rate reduces the TTHX's exergy efficiency ratio. In conclusion, raising the HTF intake temperature and reducing the mass flow rate of the HTF in a turbulent condition may increase the thermal performance of the examined TTHX when considering both melting time and exergy efficiency ratio.

Xu et al. [80] evaluated the melting performance of triplex-layer PCMs in a horizontal shell and tube LTES unit. PCMs having RT42, RT50, and RT60 paraffin wax melting temperatures. Innovatively, a comprehensive storage density evaluation (CSDE) criteria was presented to evaluate the LTES unit with triplex-layer PCMs. Metal fins increase heat transmission and reduce thermal energy storage capacity. Using a two-dimensional transient model, partition walls and fin layouts were discussed. This rating was based on storage density (CSDE). Surprisingly, barrier walls hindered liquid PCMs' natural convection. Adding fins to triplex-layer PCMs decreased melting time by 55.3% (Case 2), 66.1% (Case 3), and 71.0% (Case 1). (Case 4). (Case 4). Case 4 has the greatest CSDE due to its uniform radial fin arrangement across PCM layers.

Mahdavi et al. [81] used ANSYS 15.0 to simulate a concentric and eccentric triplex tube heat exchanger (TTHX) in porous medium with different operating circumstances. Tested the TTHX. Porous medium and eccentric layout reduce melting time by 81% and 25%, respectively, according to an experiment. Combining these two scenarios reverses the growing trend by 24.75 percent compared to the concentric porous scenario. Applying the situations independently improves melting behavior.

Data analysis and statistical methodologies were offered by Sudharsan [82] in order to get a better understanding of the melting process under a variety of fin configurations. The results from the publicly available literature have been retrieved, and polynomial regression modeling has been used to construct equations for the liquid fraction. The rate of melting is tracked over time in order to account for the pace at which the liquid percentage is changing. The analysis revealed that the amount of time required was not dependent on the position of the fins during the first phase (up to about 45% liquid melt), but that the amount of time required rose linearly with the number of fins. Surprisingly, throughout the melting process, the top portion of the fin has a larger melting rate in the first phase, but this rate quickly drops once it peaks. Later, when the liquid fraction reaches 45% to 90%, the bottom fins sustain and accelerate this decrease, decreasing the melt time. This phase is between 45% and 90% liquid.

Eslamnezhad and Rahimi [83] evaluated numerically the addition of rectangular fins to a triplex tube heat exchanger to melt phase-change material. Fluent's two-dimensional numerical model simulates conduction and natural convection. The design of the rectangular fins along the triplex tube heat exchanger is a major melting factor. This arrangement has also been utilized to discover the ideal kind for enhancing heat exchanger efficacy and minimizing melting time.

Tiji et al. [84] analyzed the energy charging process to investigate the influence of design alterations on the thermofluidic behavior of a PCM in a triplex tube. This was done to investigate how design changes affect a phase change material's thermofluidic behavior (PCM). Three outcomes are possible: Converting the central tube, inner tube, or both to frustum tubes. We examined how alternate tube shapes and broader spacing may impact things. Compared to straight tube systems, frustum tube systems have greater heat storage rates. The case with a 5-millimeter gap is the optimum for melting time and heat storage, according to the research. Using frustum tubes with a 5-millimeter gap reduces melting time by 25.6% and increases heat storage by 32.8% compared to straight tubes.

Nakhchi and Esfahani [85] performed a numerical study on LHTES systems with vertically heated PCMs and novel stepped fins. Using upward and downward stepped fins with step ratios of 0.66, 1, 1.5, 2.33, and 4 may improve PCM melting efficiency. The downward fins with b/c=0.66 enhance PCM melting rate at the beginning of the process. This is because heat is transported to the container's bottom along the fins and trapped between the heated wall and the fins. According to the results, stepped fins melt faster than standard horizontal fins. Using downward stepped fins (b/c=0.4) instead of horizontal fins may enhance melting by 56.3% at t=800 sec and 65.5% at t=3600 sec.

Sun et al. [86] advised utilizing circular fins with staggered distribution in a vertical triple-tube heat exchanger with two opposing fluid flow streams to improve PCM thermal response rates. To do this, do this (HTF). Staggered fins increased PCM melting rates. Staggered distribution may increase melting and heat charging rates by 37.2% and 59.1%, respectively. Using long, thinner fins in the vertical direction of the storage unit improved natural convection, resulting in faster melting rates. Compared to 2 x 5 millimeters, 0.666 x 15 millimeter fins increase melting rate by 23.6%. Last but not least, Reynolds number and HTF intake temperatures had a big impact on how much time round fins with a staggered distribution saved during the melting process.

Hossieni and Rahimi [87] quantified the melting process in a PCM-RT82 triplex tube heat exchanger. For melting simulation, Ansys Fluent 16 was used to create a two-dimensional numerical model. This inquiry considered conduction and spontaneous convection. Certain designs of rectangular fins were selected depending on how efficiently they diffused heat. Fin lengths and positions were options. Choose ideal cuts meeting time by 28.4%.

Ghalambaz et al. [88] compared twisted fins to straight fins and no fins in a triple-tube heat exchanger for latent heat storage. The suggested heat exchanger uses an improved approach to melt PCM and store thermal energy. PCM is put between the heat exchanger's center annulus, and hot water flows between the inner tube and outside annulus in a counter-current way. The system's temperature and liquid fraction distributions, charging time, and energy storage capacity were examined. Four twisted fins reduced melting time by 18% compared to the same number of straight fins and by 25% compared to no fins with a similar PCM mass. Four straight fins reduced melting time by 8.3% compared to no fins. When increasing from two to four or six fins, heat storage increased by 14.2% and 25.4%. Table 1 shows the outline of studies on melting enhancement using fins.

Table 1. Outline of studies on melting enhancement using fins

Authors (year) [reference]	Configuration	Type of study	Studied parameters	Highlighted results/findings
Mat et al. (2013) [77]	Internal, external, and internal-external fins on PCM RT82 triplex-tube heat exchanger.	Numerical	Fin length affects enhancing procedures.	Using a triplex-tube heat exchanger with internal–exterior fins, melting time may be reduced by 43.3% in the triplex tube without fins.
Abdulateef et al. (2017) [78]	Horizontal TTHX phase-change fins (PCM).	Experimental and Numerical	Internal-external and external triangular fins.	Internal, internal-external, and exterior triangular fins improved by 11%, 12%, and 15% over longitudinal fins.
Yang et al. (2019) [79]	Ba(OH)28H2O, a phase-change material, is used in a triplex tube heat exchanger (TTHX).	Numerical	HTF inlet temperature and flow rate.	Increasing the HTF intake temperature and reducing its turbulent mass flow rate may improve the thermal performance of the TTHX.
Xu et al. (2020) [80]	Triplex-layer latent thermal energy storage (LTES) materials in a horizontal shell and tube structure.	Numerical	Walls and fins' impact.	Laboratory partitions hindered the natural convection of liquid PCMs. Adding fins to triplex-layer PCMs decreased melting time by 55.3% (Case 2), 66.1% (Case 3), and 71.0% (Case 1).
Mahdavi et al. (2021) [81]	A heat exchanger with a triplex tube that is both concentric and eccentric (TTHX).	Numerical	Impact of porous media and eccentric arrangement.	Porous medium and eccentric arrangement reduce melting time by 81% and 25%, respectively.
Sudharsan (2021) [82]	The melting process was carried out using a variety of different fin arrangements.	Numerical	Influence of using fins at different locations.	When the liquid percentage is between 45% and 90%, the top fin melts faster than the others, but this rate immediately falls and is subsequently augmented by the lower fins.
Eslamnezhad and Rahimi (2017) [83]	Rectangular-finned triplex tube heat exchanger.	Numerical	Fins in triplex heat exchangers.	The layout of the rectangular fins along the triplex tube heat exchanger is one of the most essential aspects in melting, and there is a certain sort of configuration that boosts the heat exchanger's performance.
Tiji et al. (2022) [84]	Thermofluidic behavior of a PCM in triplex tube confinement.	Numerical	Frustum tube configuration.	In terms of the amount of time it takes to melt and the amount of heat it can store, the case with a gap width of 5 millimeters is the best of the ones that were evaluated. In comparison to the standard scenario of straight tubes, using the frustum tube layout with a gap width of 5 millimeters would

				reduce the amount of time needed for melting by 25.6% while also increasing the rate of heat storage by 32.8%.
Nakhchi and Esfahani (2020) [85]	LHTES systems that use phase change materials (PCMs) and have innovative stepped fins and are heated vertically from one side are described.	Numerical	Impact of using stepped fins.	Stepped fins melt faster than horizontal fins when tested. Traditional horizontal fins with a b/c ratio of 0.4 might enhance melting by 56.3% at t=800sec and 65.5% at t=3600sec.
Sun et al. (2021) [86]	Triple-tube vertical heat exchanger with asymmetrical round fins.	Numerical	Staggered circular fins' effect.	When circular fins with a staggered distribution were inserted, the values of the Reynolds number and the intake temperatures of the HTF had a considerable influence on the amount of time that could be saved during the melting process.
Hossieni and Rahimi (2018) [87]	Triplex tube heat exchangers have PCM RT82 and rectangular fins.	Numerical	Impact of using arrangements of rectangular fins.	The time needed for meetings is cut down by 28.4% thanks to the choose optimal model.
Ghalambaz et al. (2021) [88]	Fins that are twisted inside of a heat exchanger that has three tubes.	Numerical	Impact of using twisted fins.	Four twisted fins decrease melting time by 18% compared to straight fins. Four twisted fins decrease melting time by 25% compared to no fins.

The research above showed that employing four twisted fins lowered melting time by 18% compared to using the same number of straight fins and by 25% compared to no fins with a similar PCM mass. Every stepped fin studied melted faster than horizontal fins. Traditional horizontal fins with a b/c ratio of 0.4 might enhance melting by 56.3% at t=800sec and 65.5% at t=3600sec. The top fin has a higher melting rate in the early phase, but it decreases fast, while the bottom fins increase it when the liquid fraction is between 45% and 90%.

3. MELTING ENHANCEMENT USING NANOPARTICLES

PCMs may store five to fourteen times more energy than practical storage materials in the same volume. Most PCMs have low heat conductivity. This slows the system's energy discharge and charging rates and response time. Adding highly conductive nanoparticles with 1 to 100 nm sizes to the PCM container structure is one solution. Find another answer to this issue. Dispersing nanoparticles into phase change material may boost its melting rate in thermal energy storage triplex tubes.

Mahdi and Nsofor [89] used porous-foam/nanoparticles to boost the melting of a phase change material (PCM) in a triplex-tube heat exchanger pertinent to liquid desiccant air-conditioning systems. A mathematical model considers non-Darcy effects of porous foam and Brownian motion of nanoparticles. Similar experimental testing verified this hypothesis. Dispersing nanoparticles in metal foams may decrease melting time by up to 90%, depending on foam structure and nanoparticle concentration. Even though melting time decreases as porosity and/or volume fraction increase, metal foam with the lowest volume percentage nanoparticles and the maximum porosity is ideal.

Hasan [90] presented two thermal storage concepts (TES). First model had three PCMs with different melting temperatures; second model only one. Both were TES. Both models employed 1%, 4%, 7%, and 10% Al_2O_3 nanoparticles to increase PCM conductivity. 1% to 4% concentrations. The study found that the first model had better heat transmission than the second, that nanoparticles sped up the melting process compared to pure PCMs, and that increasing their concentration sped it up even more. At 10% concentration, thermal conductivity increased by 33% and melting time decreased by 10%. This was the maximum upgrade. Nanoparticles lowered the HTF exit temperature during melting. Table 2 shows the outline of studies on melting enhancement using nanoparticles.

The prior investigation indicated that the first model had better heat transmission than the second. Nanoparticles accelerated the melting process compared to pure PCMs, and increasing their concentration made it even faster. Dispersing nanoparticles in metal foams reduces melting time by up to 90%, depending on foam structure and nanoparticle concentration.

Table 2. Outline of studies on melting enhancement using nanoparticles

Authors (year)	Configuration	Type of study	Studied parameters	Highlighted results/findings
Mahdi and Nsofor (2017) [89]	Compound porous foam with nanoparticles inside of a heat exchanger with triplex tubes.	Numerical	Nanoparticles and metal foam porosity.	Nanoparticles scattered in metal foams may decrease melting time by up to 90%, depending on foam structure and nanoparticle concentration.
Hasan (2021) [90]	There were two distinct types of TES. The first model had three PCMs that melted at varying temperatures, whilst the second model utilized just a single PCM. In all models, PCMs and Al_2O_3 nanoparticles were included at varying quantities (1%, 4%, 7%, and 10% respectively).	Numerical	Impact of using nanoparticles (Al_2O_3) with PCMs.	Nanoparticles speed up the melting process compared to pure PCMs, and increasing their concentration speeds it up even more. First model had greater heat transmission than second model, and nanoparticles caused melting quicker than pure PCMs. Nanoparticles lowered the HTF exit temperature during melting.

4. MELTING ENHANCEMENT USING FINS AND NANOPARTICLES

Latent thermal energy may be stored using phase-change materials (PCMs). Low thermal conductivity of most PCMs slows heat transmission during energy charging and discharging, which needs careful consideration. Using an appropriate containment tank that can offer adequate heat transmission from the HTF to the PCM is one possibility. High-conductivity solid nanoparticles, metal fins, heat pipes, and metal foams may improve heat transmission. Melting increase of phase transition material in triplex-tube thermal energy storage by fins and nanoparticles:

Mahdi and Nsofor [91] researched three augmentation ways to overcome this restriction. Fins, nanoparticles, and a combination were used. A numerical study based on the enthalpy technique was used to examine these strategies' effects on PCM melting rate in triplex-tube latent heat storage systems. A mathematical model tested well against experimental evidence. This model includes natural convection and nanoparticle Brownian motion. The researchers evaluated the effects of fin size and nanoparticle volume fraction on solid-liquid interfaces, isotherm distribution, and liquid fraction temporal profile during melting. Using the explored procedures improves PCM melting, according to the results. Fins alone are better than nanoparticles alone or a combination of fins and nanoparticles.

Mahdi et al. [92] used the innovative fin structure in triplex-tube storage to increase PCM melting rate over nanoparticles. Viscosity increases and sedimentation won't be a problem. Because heat transmission varies throughout the unit, numerical simulations of PCM melting in the triplex-tube were used to test different fin shapes. Different parts of the device transmit heat differently. By arranging the fins in novel ways, PCM melting rate was increased. Using long fins in the bottom part of the storage unit, where conduction dominates, sped up the melting process. Using fewer, shorter fins at the top of the unit improves its performance. Compared to employing fin-nanoparticles combination or nano-enhanced PCM in the same volume of the triplex-tube heat exchanger, this arrangement sped up PCM melting.

Mahdi et al. [93] studied how a novel fin configuration improved TTHX performance in SCD mode. Numerical simulations were used to examine the system's performance with different fin geometries. Using RSM, the best fin configuration was determined. Nanoparticles of aluminum oxide (Al_2O_3) were also added to PCM. The ideal fin structure in the TTHX for SCD operations is superior to incorporating nanoparticles, according to the results.

Abdulateef et al. [94] investigated a Triplex Tube Heat Exchanger (TTHX) TES system using Paraffin (RT82) with Alumina (Al_2O_3) nanoparticles at 78.15–82.15°C. Their discoveries were based on math and experiments. According to tests, paraffin does not melt completely in four hours using internal heating at 97 degrees Celsius. When charging temperatures were altered, paraffin melted faster in an unstable situation at 29.4 kg/min. Inner and outer tubes have 16.2 and 37.5 kg/min, respectively. Fins and nanoparticles improved paraffin melting performance over fins alone. In numerical study, TTHX with longitudinal fins (12%) and TTHX with triangular fins (22%), for PCM containing 10% nanoparticles, melted faster than pure paraffin.

Table 3. Outline of studies on melting enhancement using fins and nanoparticles

Authors (year)	Configuration	Type of study	Studied parameters	Highlighted results/findings
Mahdi et al. (2017) [91]	PCM latent heat storage device using fins, nanoparticles or both.	Numerical	The effect of using various diameters of fin as well as various nanoparticle volume fractions.	The introduction of long fins at the bottom of the storage unit, where conduction is the predominant heat transmission method, sped up the melting process. When compared to employing fin-nanoparticles or nano-enhanced PCM in the same volume of the triplex-tube heat exchanger, this configuration increased the melting rate of pure PCM.
Mahdi et al. (2018) [92]	Innovative arrangement of fins in the triplex-tube storage.	Numerical	The effect of utilizing fins that are shorter at the top portion.	Better performance may be achieved by using a lower number of fins that are also substantially shorter in length in the top portion of the unit.
Mahdi et al. (2019) [93]	TTHX using an unconventional arrangement for the fins while operating under SCD circumstances and enhancing the PCM using nanoparticles of aluminum oxide (Al_2O_3).	Numerical	The impact of using a fin arrangement and supplementing with nanoparticles of aluminum oxide (Al_2O_3).	When it comes to SCD operations, the ideal fin structure that has been recommended to be included in the TTHX is superior to the incorporation of nanoparticles in the same system's volume utilization.
Abdulateef et al. (2021) [94]	TES system employing Paraffin (RT82) and Alumina (Al_2O_3) nanoparticles	Experimental and Numerical	Impact of using nanoparticles and longitudinal fins in the design.	Compared to pure paraffin, TTHX with longitudinal fins (12%) and TTHX with triangular fins (22%) melted faster in PCM containing 10% nanoparticle.
Zhang et al. (2022) [95]	Fins and Al_2O_3 nanoparticles were added to a triplex-tube heat exchanger.	Numerical	The influence of using nanoparticles and fins.	Innovative fins reduce melting time by 80.65%, 77.62%, 77.33%, and 80.35%. Al_2O_3 nanoparticles in PCMs lower melting time by 13.1%, 15.6%, and 18.8%.
Abdulateef et al. (2017) [96]	In a big TTHX, internal longitudinal fins are constructed using PCM first and then nano-PCM second.	Experimental and Numerical	Internal longitudinal fins with PCM and nano-PCM as key PCM components.	When compared to using PCM alone, the melting time is cut by 12%; hence, a strategy using longitudinal fins combined with nano-PCM was successful in achieving total PCM melting in a relatively short amount of time (218 minutes).

Zhang et al. [95] proposed integrating a novel fin structure with Al_2O_3 nanoparticles to increase PCM melting performance for latent heat thermal energy storage devices. A mathematical model of PCMs melting in a triple-tube heat exchanger has been built and tested against experimental data. Using experimental data, the model was verified. Different fin design and nanoparticle volume fractions affect melting. This involves the development and deformation of solid–liquid interfaces, isotherm distribution, and time-varying liquid fraction and average temperature during melting. Using fins and nanoparticles improves melting, according to the study. Four unique fins have 80.65%, 77.33%, 77.33%, and 77.62% less melting time than the original structure. These findings may be due to fin designs increasing heat transfer. Al_2O_3 nanoparticles in PCMs at 3%, 6%, and 9% decrease melting time by 13.1%, 15.6%, and 18.8%, respectively.

Abdulateef et al. [96] examined heat transfer enhancement with internal longitudinal fins using PCM and nanoPCM in Fluent 15. Adding 10% alumina (Al_2O_3) nanoparticles to pure PCM increased its heat conductivity from 0.2 W/m.K to 25%. A longitudinal fins-nano-PCM technique melted PCM in a relatively short period compared to PCM alone (218 minutes).

The overview of investigations on the augmentation of melting with the use of fins and nanoparticles is shown in Table 3.

The prior work demonstrated that longitudinal fins-nano-PCM reduces PCM melting time by 12% compared to PCM alone. Therefore, a technique utilizing longitudinal fins-nano-PCM swiftly melted PCM (218 minutes). Long fins in the storage unit's bottom half, where conduction is strongest, accelerated melting. The ideal fin structure in TTHX is preferable to the introduction of nanoparticles for SCD activities since both employ the same system volume.

5. CONCLUSIONS

Rising energy prices and environmental considerations have spurred interest in thermal energy storage, especially latent heat energy storage. Phase-change materials' low thermal conductivity, long charging time, and thermal discharge prevent thermal energy storage. How to improve heat transfer between the fluid and phase-change material has been studied. Increase the heat transfer surface area, use finned tubes or multi-tube heat exchangers, add metal matrix to phase-change materials, or use saturated porous materials. This article analyzes triplex-tube thermal energy storage (TTTES) arrangements and current advancements. Design and setup of TTTES, as well as ways for increasing the melting of phase transition materials including fins, nanoparticles, and both. Key findings:

1. A longitudinal fins-nano-PCM technique reduced melting time by 12% compared to PCM alone, swiftly melting the PCM (218 minutes).
2. Four unique fins' melting durations are reduced by 80.35, 77.62, 77.33, and 80.65 percent. 3%, 6%, and 9% Al_2O_3 nanoparticles lower PCM melting time by 13.1%, 15.6%, and 18.8%, respectively.
3. For TTHX with longitudinal (12%) and triangular (22%) fins, the 10% nanoparticle PCM decreased melting time compared to pure Paraffin.
4. Fewer, shorter fins improve the unit's top. Depending on foam structure and nanoparticle concentration, distributing nanoparticles in metal foams may decrease melting time by up to 90%.
5. The melting time in a triplex tube without fins is reduced by 43.3% when utilizing an internal-external finned heat exchanger.
6. Compared to longitudinal fins, internal, internal-external, and external triangular fins improved 11%, 12%, and 15%.
7. Increasing the HTF turbulent mass flow rate and intake temperature may improve the thermal performance of the studied TTHX.
8. Porous medium and eccentric arrangement minimize melting time by 81% and 25%, respectively.
9. Compared to horizontal fins, stepped fins melt faster. Using downward stepped fins (b/c=0.4) instead of horizontal fins may speed up melting by 56.3% in 800 seconds and 65.5% in 3600 seconds.

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NOMENCLATURE

Symbol	**Definition**
TES	Thermal energy storage
FVM	Finite volume method
LHTES	Latent heat thermal energy storage
PCM	Phase change material
TTHX	Triplex tube heat exchanger
HTF	Heat-transfer fluid
CSDE	Comprehensive storage density evaluation