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Recent advances of selected passive heat transfer intensification methods for phase change material-based latent heat energy storage units: A review

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ABSTRACT

The following article overviews recent studies regarding heat transfer enhancement methods, explicitly focusing on fins and coils utilization, in phase change material-based latent heat thermal energy storage systems. It discusses the influence of various geometrical and material parameters on the melting and solidification processes, as well as the orientation of the heat transfer surface within the storage tank. Additionally, the article examines the use of a range of phase change materials regarding their melting temperature. Results show that there are research gaps regarding a few ranges of phase change materials of certain previously studied melting points. This paper's main goal was to detect possible research gaps within the phase change studies field. It should be highlighted that a vast amount of numerical studies of both finned and coiled geometries is in need of experimental verification. More than 62% of analyzed studies were performed numerically, while only 37% were performed experimentally. What is more, there were only a few studies concerning experimental investigations for melting temperatures higher than 60 °C. Furthermore, the majority of experimental as well as numerical studies were concerned only with melting phenomena. This paper also advocates for more standardized studies regarding coil geometries using non-dimensional parameters.

1. Introduction

Due to the unsteady nature of energy demand and supply, unreliable suppliers of energy-source materials as well as climate-friendly concerns, various governments attempt to pass legislation regarding the decrease in fossil fuels used in energy and industry sectors. More attention is being directed toward waste heat recovery [1,2] and renewable energy sources, such as solar, which abundance and availability make it one of the most promising energy sources of the future. Photovoltaic panels and solar collectors could provide humanity with clean electricity and heat supply. However, conditions of recovered waste heat utilization are relatively strict and solar power sources are heavily dependent on localization and the current weather state, thus applying some kind of storage system seems reasonable. LHTE storage systems are gaining attention due to their nearly isothermal conditions and relatively high energy density compared to sensible ones.

Besides applications mentioned above, such as heat recovery systems (both industrial [3–5] and domestic [6,7]) and storing heat harvested from solar collectors [8–13] PCMs are gaining interest in thermal management systems of electronics [14–16], energy efficiency and thermal management of buildings [18]– [21], battery thermal management systems [17–21]. The choice of phase change substance for thermal storage usage should be generally justified by energy, economic, material, and environmental parameters. Generally, the largest potential for heat recovery in the EU is from the Iron & steel and Chemical & petrochemical industries. The big potential show also food & tobacco, Non-metallic minerals or Paper, pulp & print industries (see Fig. 1).

However, these types of industries represent different thermal potentials (temperature source level) for energy storage systems. Regarding that fact, it is important to define a wide range of PCM substances with different melting temperature levels as potential substances for future applications. It is important to avoid substances with undesirable properties (see Fig. 2), which could slow or obstruct the energy storing process.

The ideal material should have high thermal conductivity and large latent heat (see Fig. 3). The other option is to use cascaded systems with few kinds of PCM, especially when there's a lack of substances with specific melting temperatures.

Organic PCMs' relatively low cost makes them a promising thermal storage medium. Paraffin-based materials and salt hydrates are promising within the thermal storage field regarding their economic and

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Nomenclature

d	diameter (m)
g	gravitational acceleration
H, h	Height (m)
k	thermal conductivity (W/mK)
p	pitch (m)
T	temperature (°C)
t	thickness (m)
ρ	density (kg/m^3)

Abbreviations

CFD	Computational fluid dynamics
HTF	Heat transfer fluid
HTT	Heat transfer tube
EU	European Union
LHTE	Latent heat thermal energy
NE	Nano-enhanced
NEPCM	Nano-enhanced phase change material
PCM	Phase change material
SLS	Selective laser sintering
TTHX	Triplex-tube heat exchanger

Subscripts

L,PCM	The liquid phase of phase change material
S,PCM	The solid phase of phase change material
c	coil
in	inlet
t	tube
sh	shell
out	outlet

environmental parameters. Their wide range of melting temperatures allows for usage in various areas. However, non-metallic PCMs, such as paraffin, salt hydrates, and non-metallic eutectics [24–28] commonly used in low- and medium-temperature thermal storage units experience relatively low thermal conductivity [27]– [31]. The thermal efficiency of the charging/discharging process could be emphasized by different kinds of heat transfer intensification methods. Heat transfer intensification can be divided into active, passive, and hybrid methods (see Fig. 4).

Active methods are currently gaining more and more attention from researchers, but they require the utilization of an external force of some

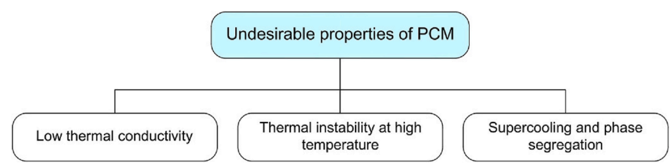

Fig. 2. Undesirable properties of PCM [23].

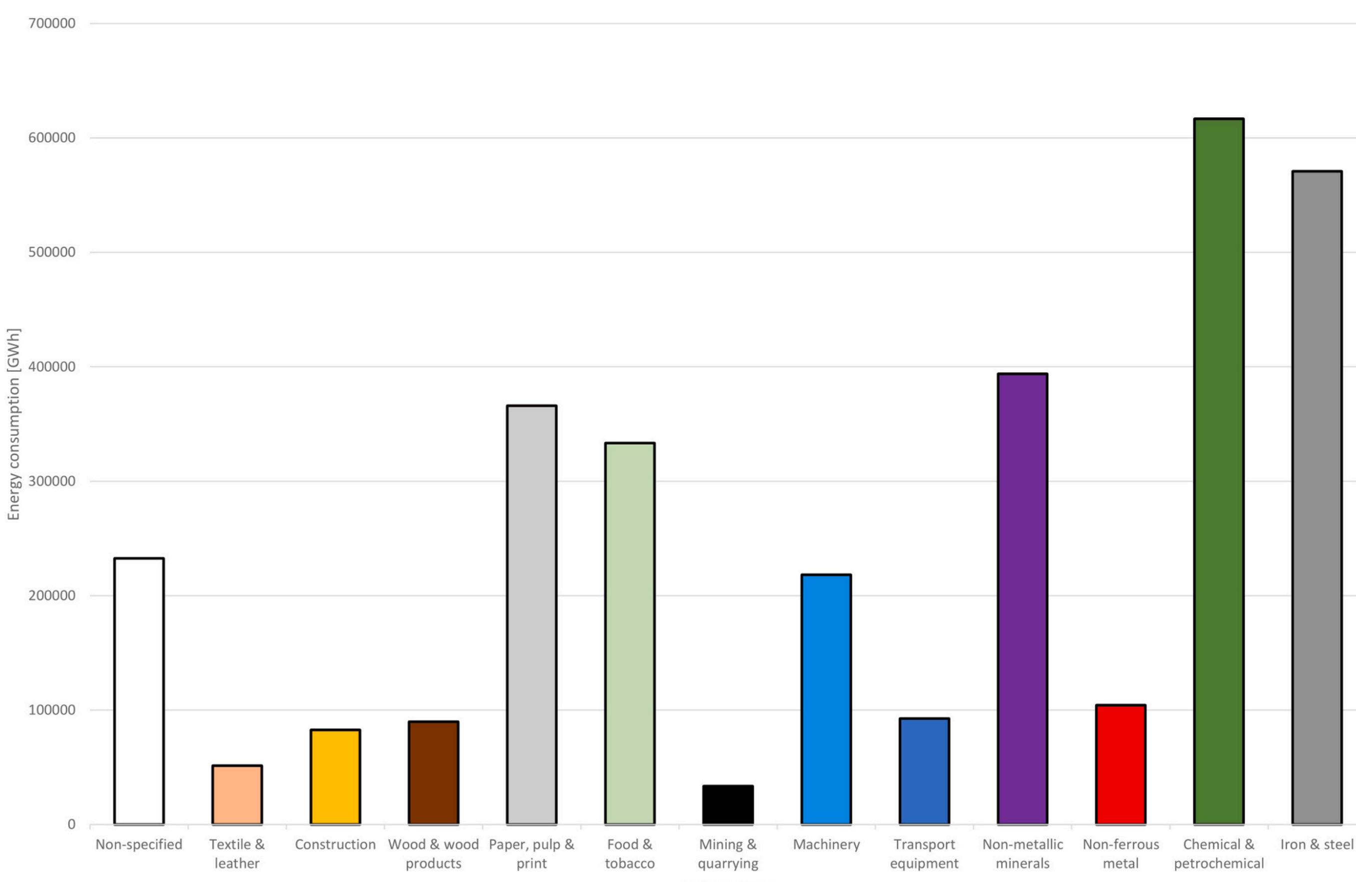

Fig. 1. Main energy consumption of various industrial sectors in the EU [22].

sort [29–35]. In the case of the passive one, there is no need for any additional energy. What is more, there are mostly maintenance-free and reliable. These advantages often prompt the passive methods to use in different applications rather than the active ones.

Regarding heat transfer in LHTE storage units where the free convection mechanism is dominant during the melting process, it could be intensified either by increasing the heat transfer coefficient or by increasing the heat transfer surface. However, the latter method might lead to less volume occupied by PCM and loss of energy density. What is more, it is possible to use nanoparticles to modify the thermal properties of PCM. There have been multiple publications regarding the usage of nanoparticles to form a NEPCM and although the heat transfer rate is increased in most cases, this method is not yet stable enough for long-term usage purposes because nanoparticles undergo sedimentation after several thermal cycles [36]. Nevertheless, NEPCMs is a promising branch of thermal energy storage science. Enhancement and shape optimization of heat transfer surfaces however offers an increased heat transfer rate with no need to interfere with PCM itself.

Usage of fins, coils, and other surface enhancement methods not only provides an overall larger heat transfer surface area but when correctly oriented and localized within the thermal storage tank allows for better penetration of a PCM, thus leading to a shorter melting/solidification process. Furthermore, when incorrectly oriented and localized these geometries can obstruct convective flow and therefore decrease the heat transfer rate. The compatibility of materials is also a major concern for researchers and designers. All the materials where PCM gets in direct contact, from shells and HTT to gaskets and other seals should be compatible with used PCM otherwise it may lead to a lack of tightness. Application of hybrid methods of heat transfer intensification is a promising approach and needs more attention from future experimental and numerical researchers, since from 127 articles regarding heat transfer intensification using coils and fins, which were cited in this publication, only about a quarter regards hybrid methods (Fig. 5).

2. State of the art

Even though the total number of publications focused on the utilization of fins and coil heat transfer surfaces is the same, review articles regarding advances in the field of fins utilization in LHTE storage tanks were extensively published in recent years [37–44], while no article regarding the review of coil shapes was published.

X. Zhu et al. [37] reviewed the design of fins, which involves their geometry, quantity, and arrangement within the storage tank. Additionally, it offers suggestions and insights to improve heat transfer in phase change accumulators by enhancing fin performance. Their work points out that the best fin shape, in terms of heat transfer performance, is a multiply bifurcated one. Their article also points out that a non-uniformity of heat transfer surface arrangement performs better during melting or solidification. Also, an optimal amount of fins exists for a specific storage tank. After exceeding a certain number of fins heat transfer enhancement can be considered negligible.

A. Khademi et al. [38] reviewed single and hybrid methods of heat transfer intensification. A novelty in their work is highlighting the absence of research regarding the phase change processes when an auxiliary fluid is introduced to the LHTE storage tank alongside PCM. They point out that implementing such an auxiliary fluid alongside other heat transfer enhancement methods, such as nanoparticles, fins, and metal foams could improve the LHTE storage system even more.

M. Al-Maghalseh and K. Mahkamov [39] extensively reviewed different methods of heat transfer enhancement. They point out that the implementation of an additional heat transfer surface inside the LHTE storage tank always associates with a decrease in PCM-occupied volume, thus resulting in a decrease in the total amount of stored energy. Additionally, the authors point out the importance of natural convection in phase change processes. The authors underline that natural convection can easily be obstructed by adversely located heat transfer surfaces within the LHTE storage tank, thus preventing the LHTE storage system from reaching its apex performance.

B. M. S. Punniakodi and R. Senthil [40] studied the geometries and orientations of containers, as well as the addition of nanoparticles

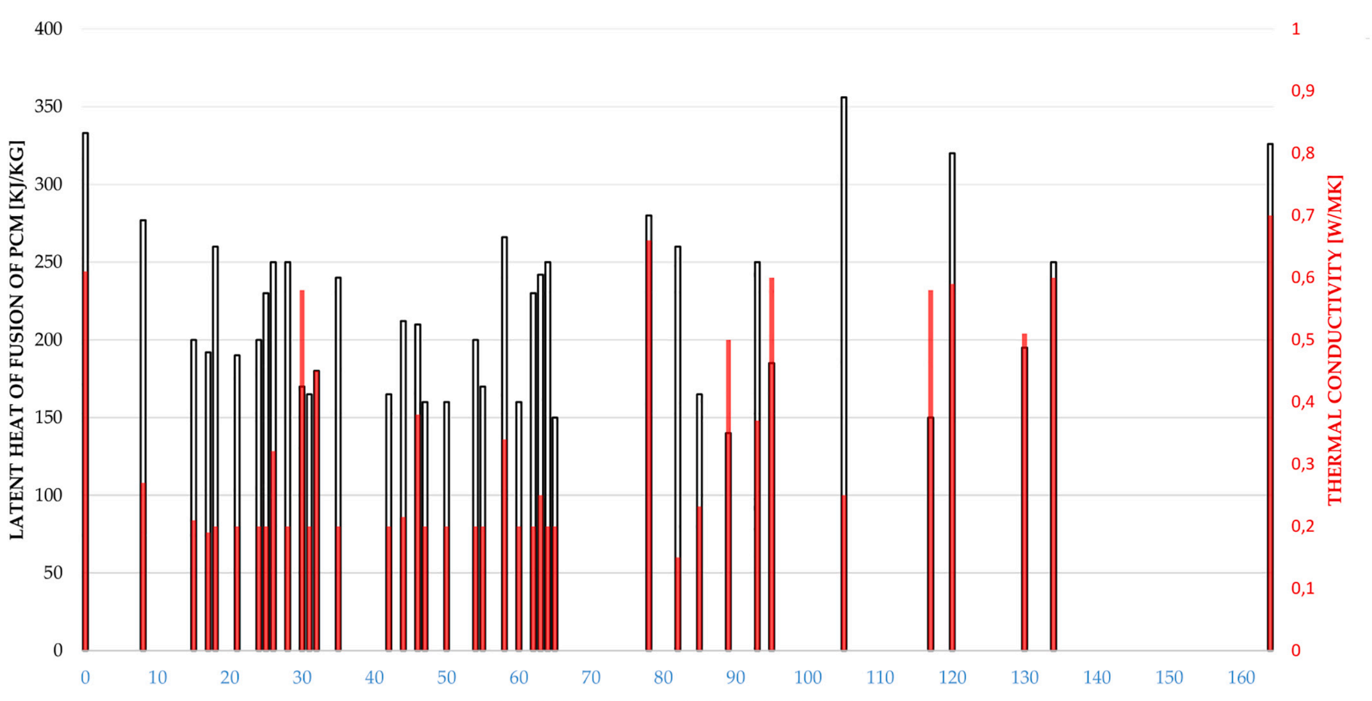

Fig. 3. Thermal properties (thermal conductivity – red, bars and latent heat of fusion – black bars) of selected substances for a range of melting temperatures from 0 °C to 167 °C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

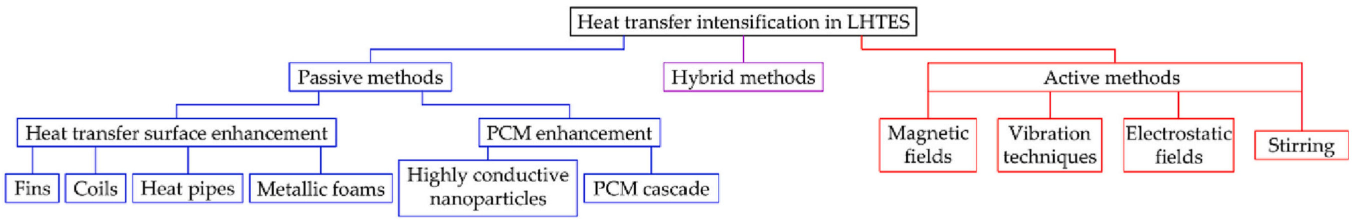

Fig. 4. Heat transfer intensification methods during melting/solidification processes.

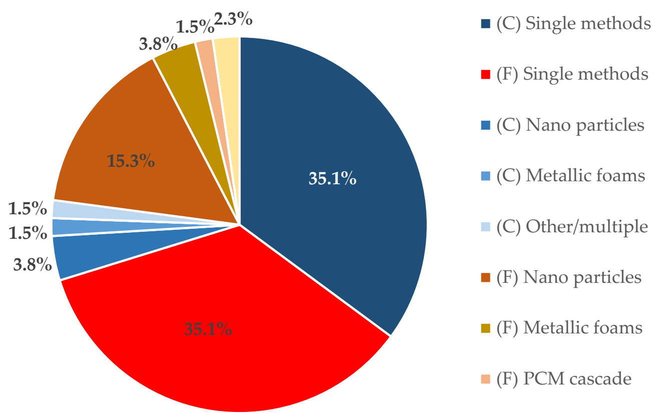

Fig. 5. Pie chart presenting the number of publications regarding either single heat transfer intensification method (fins or coils) or various hybrid heat transfer intensification methods; (F) – fins, (C) – coils

specifically for solar applications of LHTE storage systems. Their work compares different approaches to heat transfer enhancement during the phase change processes of PCMs. They also point out the need for the employment of hybrid methods, such as metal foams alongside NEPCM, to further improve the performance of the LHTE storage systems. What is more, the authors highlight the importance of creating a turbulent flow on the HTF side of the storage tank due to its addition to overall heat transfer intensification.

S. Jain et al. [41] reviewed the existing research done on obvious heat transfer enhancement during phase change of PCMs, such as the incorporation of fins, NEPCM, and metal foams, while also reviewing the utilization of the PCM cascade method. They discuss the properties of the LHTE storage system where such a cascade is used for both the charging and discharging cycle. In their work, they discuss both pros and cons of each method. The authors also advocate for experimental investigations in the field of PCM cascade utilization.

M.E. Zayed et al. [42] focused their study on the geometrical parameters of LHTE storage tanks and their working elements, such as fins and metal foams. Their work highlights the superiority of metal foams and porous material used as a heat transfer enhancement method. The authors also advocate for further experimental and optimization research within the hybrid methods area, which could validate the already existing vast database of numerical simulations.

C. Zhao et al. [43] reviewed the utilization of fins alone and alongside metallic foams in theoretical studies. They compare various mathematical methods used in such studies, highlighting their advantages and disadvantages. The authors point out, is that analytical works done on metallic foams incorporated into LHTE storage systems are limited and the existing ones assume imaginary isotropic and homogenous material. An important conclusion that can be drawn out from this fact is that this field is in dire need of experimental studies.

R.A. Lawag and H.M. Ali [44] in their review article focused their study on the utilization of PCMs in heat sinks for enhancement of the thermal management of electronics. The authors point out the advantages of the introduction of nanoparticles in such thermal systems. They also suggest researching hybrid techniques such as the combination of fins nanoparticles.

The above-mentioned review articles focused on heat transfer intensification in the field of LHTE storage systems. However, review papers regarding the utilization of coils in LHTE storage tanks have not yet been published before. The following article tries to fill the gap regarding the utilization of coils, but also presents a different, summarizing approach in phase change materials research regarding both fins and coils utilization, additionally underlining the research gap regarding the usage of certain melting temperatures and experimental validation within certain temperature ranges.

3. Selected industrial used heat transfer surface enhancement methods

Enhancement of heat transfer surface e.g. by the introduction of fins on the side of the PCM allows for better heat penetration of the thermal storage medium. When considering the introduction of fins it is important to optimize their shape for the best performance, otherwise, the additional material used in fin fabrication will simply not conduct heat as efficiently as it could, thus resulting in less cost efficiency of the thermal storage tank as a whole (see Fig. 6)

Fins and coils fabricated from highly thermally conductive materials are among the most extensively used enhanced surface types in heat exchanger applications, therefore it comes with no surprise they have been attracting a lot of interest from researchers studying melting and solidification in phase change processes. Their relative manufacturing easiness and abundance in industrial applications make them an obvious choice when studying heat transfer in thermal storage tanks. However, an additional heat transfer surface is also going to occupy an additional volume of the storage tank, thus resulting in less volume left for PCM to occupy. It is important to optimize the relationship between energy density and the efficiency of the charging/discharging process.

3.1. Fins utilization

Finned pipe and finned wall are among the most fundamental, distinctive cases of fin utilization which will be comprehensibly reviewed in this publication. When assuming an enclosure of indefinite length both configurations could be simplified to a two-dimensional case and analyzed analytically or numerically in a faster manner than a three-dimensional case.

Fig. 7 portrays recent trends in finned wall configuration: a) simple rectangular fin, b) inclined rectangular fin, c,d,g,h) fins of various shapes and configurations, e,f) fins partially immersed in PCM, i) constructal/fractal fins, j) heat sinks, k,l) triangular fins of various configurations. Publications regarding such fins are listed and analyzed in Table 1. The number of citations of those articles was derived from Google Scholar website sources. The most of works focused on CFD calculations for selected kinds of PCM (Octadecane, RT42, n-Eicosane, Lauric acid, Paraffin wax) for rectangular fin shapes. What is more the majority of studies present analysis solely for the melting process. Only

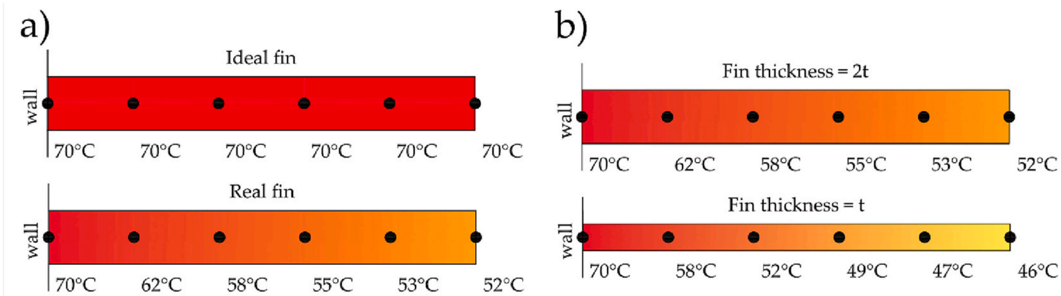

Fig. 6. Temperature distribution along fins; a) comparison between ideal and real fin, b) comparison between thick and thin fin.

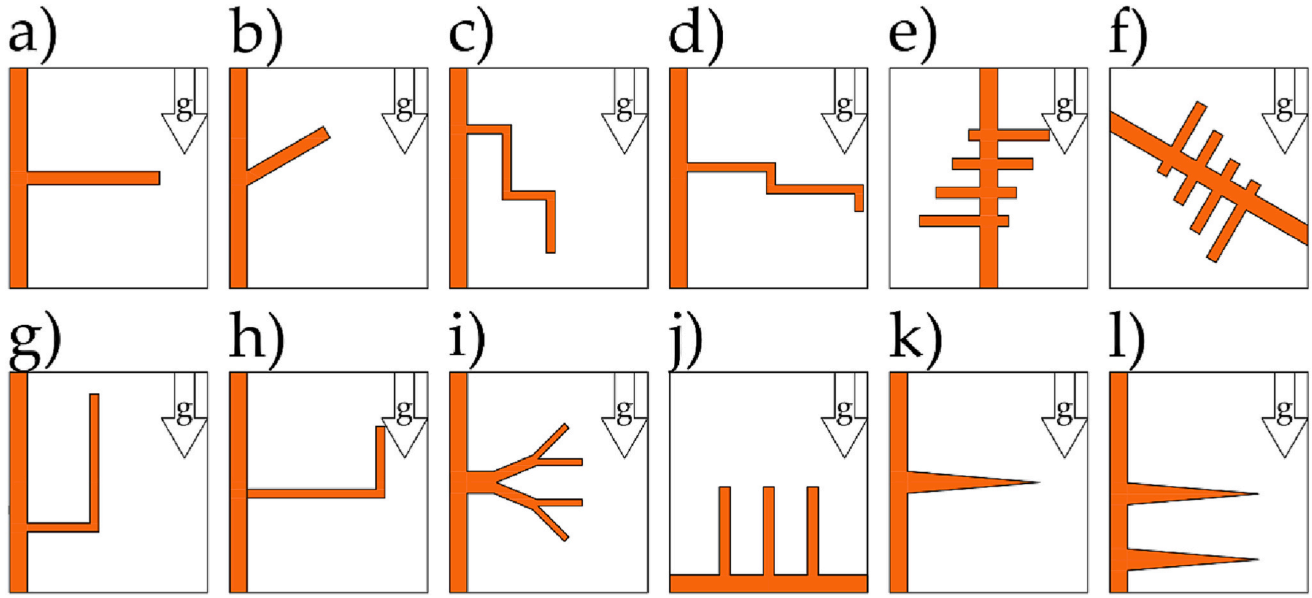

Fig. 7. Review of recently studied shapes of fins in finned wall configuration during melting/solidification phase change processes; vector of gravitational acceleration is pointed downwards in every case.

one of the presented studies provides an experimental database for both the melting and solidification of PCM.

The fin type presented in Fig. 7. a) is a single, vertical fin of a rectangular shape attached to a heated wall. Various researchers studied the effects of employing such fins in an enclosure filled with PCM. B. Kamkari and H. Shokouhmand [46] investigated and compared the effects of the utilization of a finless wall, a wall with one fin, and a wall with 3 fins. By plotting the fraction of liquid PCM in the whole volume of the enclosure on a graph for each case. They showed that the case with 3 fins melted the PCM in the shortest amount of time. Since the volume in an enclosure occupied by PCM (and thus its mass) is lesser with the implementation of more fins and the implementation of more fins introduced more heat transfer surface on the PCM side those results come with no surprise. Their results were later compared numerically by R. De C'esaro Oliveski et al. [52]. In that work, authors utilized a different approach and differed in the fin dimension. It has kept both masses of the PCM and heat transfer surface of fins constant. The main goal was the determination of the optimal aspect ratio regarding melting time and total stored heat. Such optimization, although promising, requires further experimental validation. T. Bouhal et al. [67] numerically investigated the effect of the finless wall, rectangular fin (Fig. 7. a)) and triangular fin (Fig. 7. k)) on the melting of Gallium. Their numerical model was validated for the finless wall using experimental research by Ambarita et al. [74], which was conducted on a similar, but finless enclosure using paraffin wax and stearic acid. In T. Bouhal et al. study [67] the implementation of both fin geometries resulted in a slight decrease in the melting time of Gallium of around 9%. The reason behind this meager improvement is a relatively high thermal conductivity of Gallium - 32 W/mK, compared with other commonly used PCMs like paraffin wax used by the above-mentioned Ambarita et al. [74] (thermal conductivity of approximately 0,2 W/mK). In that case, the relationship between the material conductivity of heat transfer and the thermal conductivity of PCM is not so high as in the case eg. of organic PCM. Despite its relatively high thermal conductivity of 32 W/mK and melting temperature in the range allowing for low-temperature thermal storage Gallium does not seem to be a promising substance for thermal storage because of its high price per kg [75–77].

L.-L. Tian et al. [50] numerically researched the effect of fin material on the melting behavior of lauric acid. Materials chosen for this study were: copper, aluminum, carbon steel, and AISI 302 steel. They also investigated the economical aspect of incorporating such fins into a hypothetical storage tank by introducing a specific cost for a kilogram for each of the studied materials, which happens to be an important aspect of their publication due to increasingly higher prices of certain metals. Melting fronts for each case are shown in Fig. 8. Additionally, by introducing six indicators for heat transfer intensification, thermal storage rate, and cost-effectiveness they were able to show that along with already extensively used copper and aluminum, carbon steel also shows potential in heat transfer enhancement by surface augmentation. However, such results require experimental verification.

Angled fins' effect on the melting behavior of PCM was numerically studied by C. Ji et al. [47] and M. Izadi et al. [60], while Z. Qin et al. [62]

Table 1
Publications regarding the investigation of melting (M)/solidification (S) behavior of a finned wall case performed experimentally (E) or numerically (N).

Fin shape	Year	Publication	PCM	M	S	E	N	Short description	Times cited (GS)
Rectangular	2011	[45]	Octadecane	✔	X	X	✔	Development of a numerical model showing the effect of implementing various numbers of fins inside a rectangular enclosure filled with PCM.	168
	2014	[46]	Lauric acid	✔	X	✔	X	Experimental investigation of the melting behavior of PCM inside a rectangular enclosure equipped with either a finless wall, a wall with a rectangular fin, or a wall with three rectangular fins.	261
	2018	[47]	RT42	✔	X	X	✔	Introduction of various cases of inclined fins inside a rectangular enclosure filled with PCM.	156
	2018	[48]	RT42	✔	X	X	✔	Introduction of various cases of non-uniform, horizontal fins inside a rectangular enclosure in which the melting process of a PCM takes place.	106
	2020	[15]	n-Eicosane	✔	X	X	✔	Study of PCM-filled heat sink for thermal management of electronics.	82
	2020	[49]	RT25	✔	X	X	✔	Introduction of "full" and "half" fins in vertical, horizontal, and 45 deg. inclined enclosure filled with PCM.	34
	2020	[50]	Lauric acid	✔	X	X	✔	Research of fin material effect on melting front propagation inside a rectangular enclosure.	67
	2020	[51]	Paraffin wax	✔	X	X	✔	Investigation of fin height and nano-particles on melting rate of PCM	79
	2021	[52]	Lauric acid	✔	X	X	✔	Optimization of the ratio between fin dimensions for melting time reduction inside a rectangular enclosure.	45
	2021	[53]	RT27	✔	X	X	✔	Numerical study of RT27 melting in the vertical, horizontal, and inclined finned wall. The volume occupied by the fin is added to the model to balance out the losses in the volume occupied by PCM.	32
	2021	[54]	n-Eicosane	✔	✔	✔	X	Experimental research on melting and the solidification behavior of n-Eicosane	7
	2021	[55]	Wood alloy RT70HC	✔	X	X	✔	Numerical study on melting of dual-PCM heat sink filled with Wood alloy and RT70	22
	2021	[56]	Not stated	✔	X	X	✔	Numerical comparison between different shapes of metallic foam pores inside a finned heat sink	60
	2022	[57]	Paraffin	✔	X	✔	X	Experimental investigation of costs and benefits of implementation of: fins, metallic foam, and a combination of these two inside a rectangular enclosure filled with PCM.	2
	2022	[58]	Gallium	✔	X	X	✔	Research on melting behavior for rectangular enclosure with vertical fins of various positions.	3
	2022	[59]	Lauric acid	✔	X	X	✔	Study of the effect of vertical fins thickness, distribution, and material within an enclosure on the melting behavior of PCM.	3
	2022	[60]	Not stated	✔	X	X	✔	Numerical study of two thermal storage tanks sharing a wall and a heat source.	0
	2022	[61]	Lauric acid	✔	X	X	✔	Numerical study of a three-dimensional case of the vertical enclosure with various rectangular fins arrangement.	0
	2022	[62]	RT42	✔	X	✔	X	Experimental study of the wall with angled fins of different orientations behavior on melting of PCM inside a rectangular enclosure.	7
	2022	[63]	Paraffin	✔	X	X	✔	Melting process study of wall equipped with fins oriented in various angles	1
	2022	[64]	Lauric acid	✔	✔	X	✔	Numerical study regarding fin geometry optimization for quicker melting and solidification of PCM	2
	2023	[65]	RT42	✔	X	X	✔	Numerical study of PCM thickness inside a rectangular enclosure with a finned wall comprising of downward oriented fins with a heat source based on climate data for PV panels thermal management.	0
	2023	[66]	PEG-6000 PT58	✔	X	X	✔	Numerical study of PCM-integrated heat sink performance	0
Other/Novel/ Comparison	2018	[67]	Gallium	✔	X	X	✔	Comparison between cases of: finless wall, rectangular and triangular fins	33
	2020	[68]	Lauric acid	✔	X	X	✔	Introduction of stepped fins of various geometries inside a rectangular enclosure and study of their effect on the melting process.	66
	2021	[69]	Lauric acid	✔	X	X	✔	Introduction of L-shaped fins of various geometries and orientations and investigation of the melting process within a rectangular enclosure.	12
	2021	[70]	Lauric acid	✔	X	X	✔	Study regarding the implementation of triangular fins located at the bottom of a rectangular storage tank filled with NEPCM and copper foam	41
	2022	[71]	RT28	✔	✔	X	✔	Research of melting and solidification behavior using tree-like fin shape with an increasing number of branches.	3
	2022	[72]	RT42	✔	X	X	✔	Comparison of various (rectangular, triangular, tree-shaped) fin shapes PCM melting performance for cases of horizontal and inclined orientation	1
	2022	[73]	Lauric acid	✔	✔	X	✔	Comparison between various fin shapes' effect on melting and solidification of PCM	1

performed experimental research on such geometry. C. Ji et al. [47] studied the case of two angled fins with heated sidewalls while M. Izadi [60] studied a case with two separate PCM domains obtained by mirror reflection of the case presented in Fig. 8 b) with a heated bottom wall. By varying the geometry of fins, the former obtained the best melting performance for long, downward inclined fins. The difference between the performance of fins grew with their length. The latter obtained the opposite results – the best melting performance was observed for upward inclined fins. Z. Qin et al. [62] experimental research, which studied similar geometry to the one researched by C. Ji et al. [47] seems to confirm the numerical study of the latter – downward inclined fins appear to be melting the PCM in the fastest manner. A novel proposed fin shape is a tree-like shape with an increasing number of fractal branches. A. Shukla et al. [71] studied such geometry numerically during the melting and solidification process. Their results show that both melting and solidification time decreases with the increasing number of branches, but there is a point at which the change is not significant anymore. A. Mostafavi and A. Jain [78] in their analytical paper derived expressions for fin effectiveness and efficiency when surrounded by phase change material. In their publication authors also study the influence of Stefan number and fin array spacing on fin performance parameters as a function of time. Their results provide a better insight into

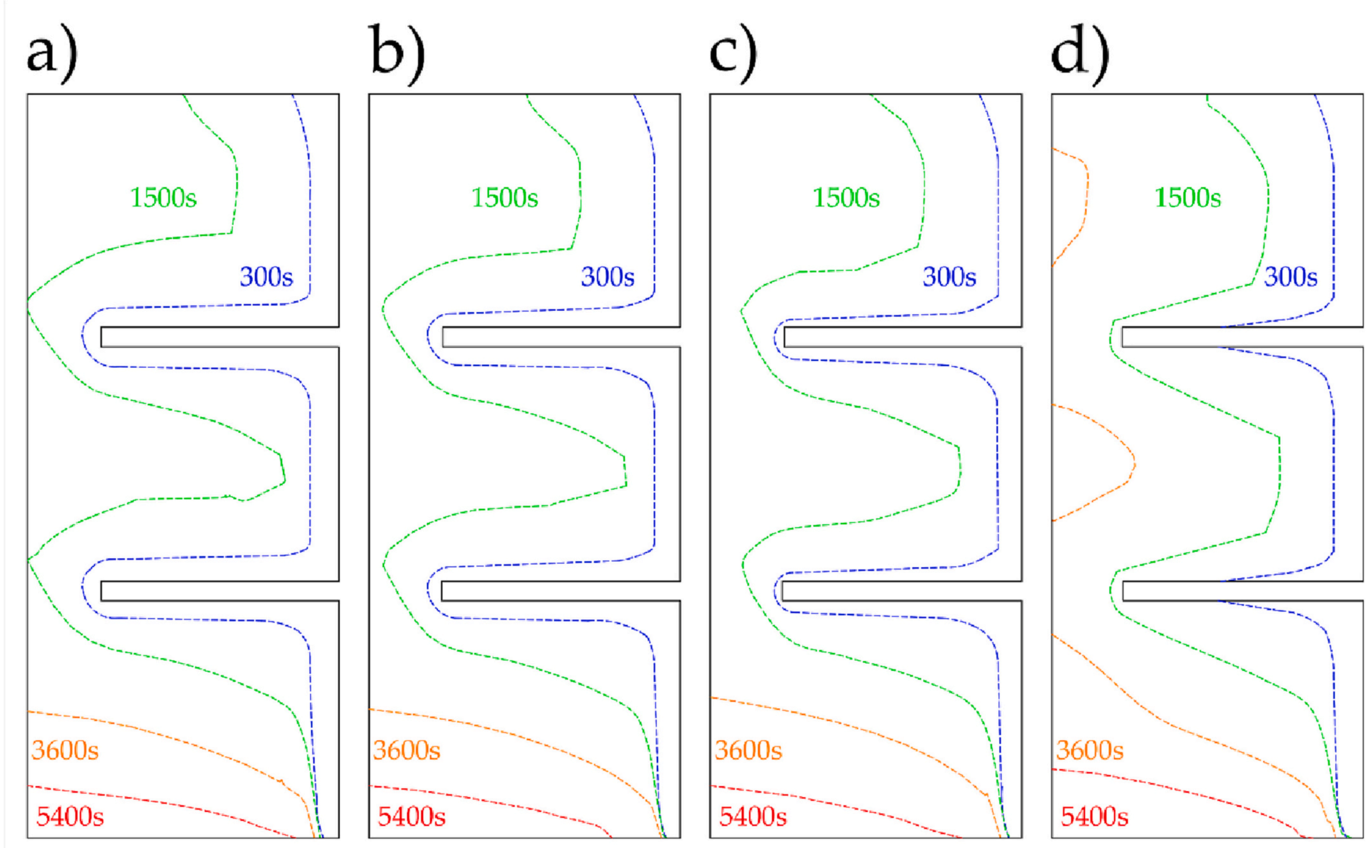

Fig. 8. Melting front evolution for geometrically identical finned walls of different metals: a) – copper; b) – aluminum; c) – carbon steel; d) – AISI 302 steel; developed based on research by L.-L. Tian et al. [50].

two-phase heat transfer and layout hints for more effective optimization.

Another fundamental case regarding fin utilization is the case of finned pipe. Some fin shapes, such as rectangular, were already extensively studied, while others, like tree-shaped, have just recently gained more attention from researchers. When considering fins on an outer wall, such as presented in Fig. 9. b) and Fig. 9. e) utilization of TTHX is required, such as presented in Fig. 10. In TTHX HTF flows through inner and outer HTT.

C. Nie et al. [80] numerically researched the influence of rectangular fins localization within cylindrical enclosures filled with PCM. Their main concern was the evaluation of the fin localization effect on both the melting and solidification time of PCM. Their results also show the influence of outer tube material on full phase change time duration. They point out that the utilization of highly conductive material for the outer

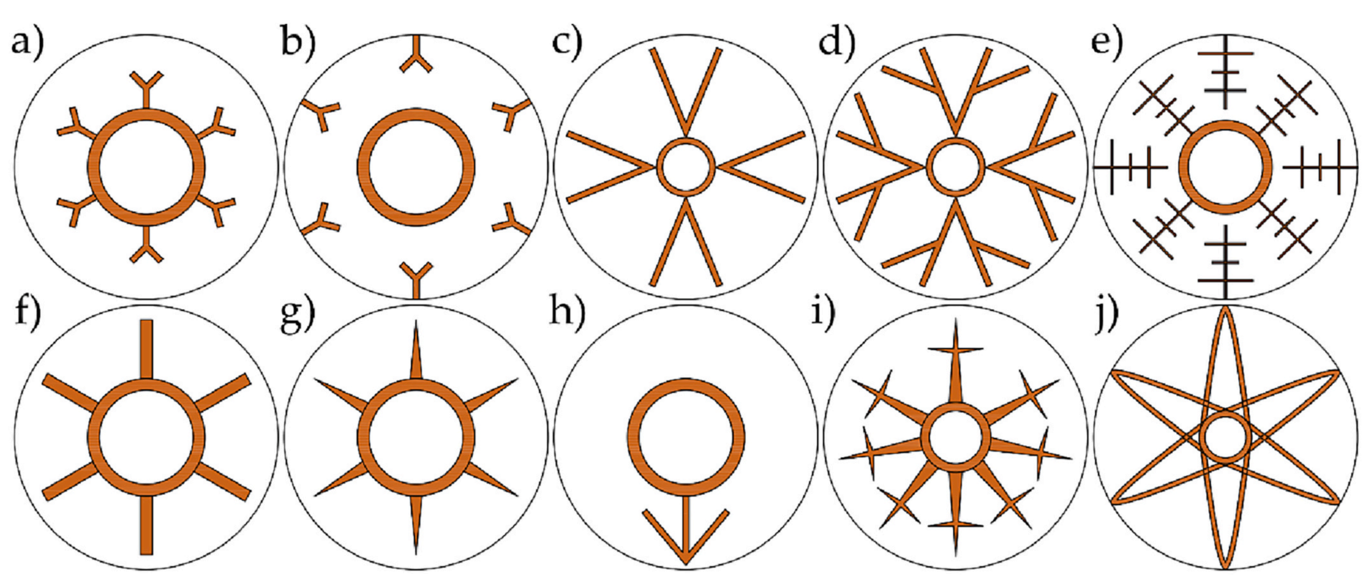

Fig. 9. Juxtaposition of cross-sections of selected fin shape longitudinally spaced across the circular pipe studied recently by various researchers.

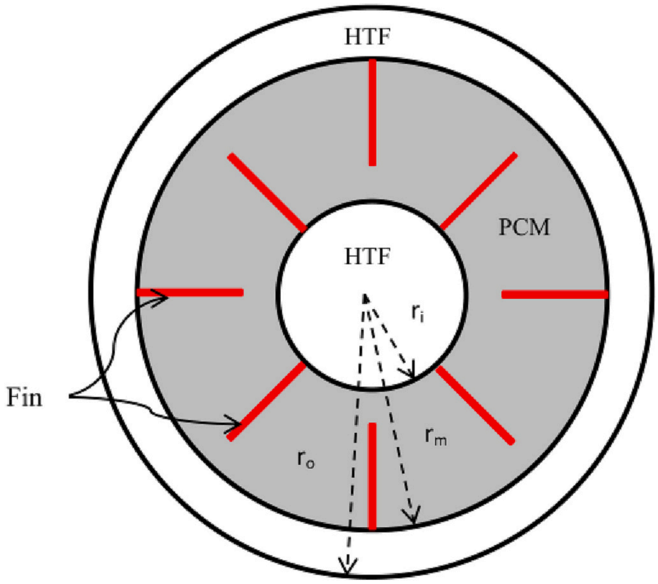

Fig. 10. Schematic representation of TTHX with simple rectangular, longitudinal fins [79].

tube affects the phase change process in a significant manner since melted PCM heats the outer tube. A. Jaberi Kosroshahi and S. Hossainpour [81] numerically investigated the effect of fins implementation in a fixed storage tank and a rotating storage tank on the melting behavior of PCM surrounding the finned circular pipe. The storage tank was oriented horizontally. Their research suggests that the implementation of optimally located fins leads to a decrease in melting time by 66%. This could be further reduced by introducing rotation and overall leads to a 72% reduction in melting time as well as a 115% improvement in total heat storage, thus leading to better exergetic efficiency. W. Ye and J.M. Khodadadi [82] performed a numerical investigation on the effect of an arrow-shaped fin located in the bottom part of the horizontally oriented circular storage tank. Parameters subjected to optimization were: the angle of the arrow lines and the length of the fin. The location of the fin in the bottom part allowed for better penetration of solid PCM which deposits on the bottom of the storage tank. All of the studied geometries reduced melting time by at least 80%, while optimal geometry of the shape of the arrow fin allowed for an 85% reduction.

X. Yang et al. [83] in their numerical study analyzed the effect of several rectangular fins on a circular pipe on the melting of PCM inside a circular, horizontally oriented storage tank. To maintain identical volume fins were made thinner each time their number was increased, thus their thickness was 0.9947 mm and 0.0663 mm for 4 and 60 fins respectively. Their results show that there is no need to further increase the number of fins above 52, since it does not significantly decrease melting time anymore (Fig. 11). Their results suggest that there is a limit regarding not only the technical capabilities of manufacturing such thin fins but also a thermal bottleneck regarding heat transfer processes itself. Heat is not conducted in thin fin as effectively as in thick fin (see Fig. 6.). The effect of fin number was also analyzed for temperature uniformity and mean temperature uniformity, and shown on graphs revealing that temperature was more uniform for a larger number of fins.

R.J. Patel et al. [84] numerically analyzed various cases of finned tubes inside TTHX filled with RT50 PCM during charging and discharging of the storage tank and compared them with finless tube case. Two cases were additionally equipped with simple rectangular on the outer surface of the PCM tube, while one of them had a slightly longer fin in the bottom part. The application of fins allowed for the reduction in melting and solidification time in every case, while the case with outer fins and the longer bottom fin was observed to give the best results.

Publications regarding longitudinally finned pipe configuration are listed and analyzed in Table 2. The number of citations of those articles was derived from Google Scholar website sources. The collected database once more time rooves a visible disproportion between numerical and experimental studies. However, the disproportion is not soo big as in the case of works focused on finned surfaces. Furthermore similarly to articles presented in Table 1, the majority of studies present analysis only for the melting process and for rectangular fins. There is more kind of results presented for different substances, although most of the substances have melting points between ~40 °C and 120 °C.

The research was also conducted for other novel cases such as finned non-circular pipes [126], stepped fins [127,128], continuous sloped fins [129] (see Fig. 12.), finned tubes in non-cylindrical enclosures [130] and so-called fractal or constructal fins [99,108,112,113]. Additionally, topological optimization for fin geometry determination is gaining more attention from researchers [114,115,120]. Such a method allows the establishment of the geometry of the most efficient fin for the specific case.

Another novel, distinctive type of fins which requires more attention from researchers are twisted fins, mainly on a circular pipe [131–134].

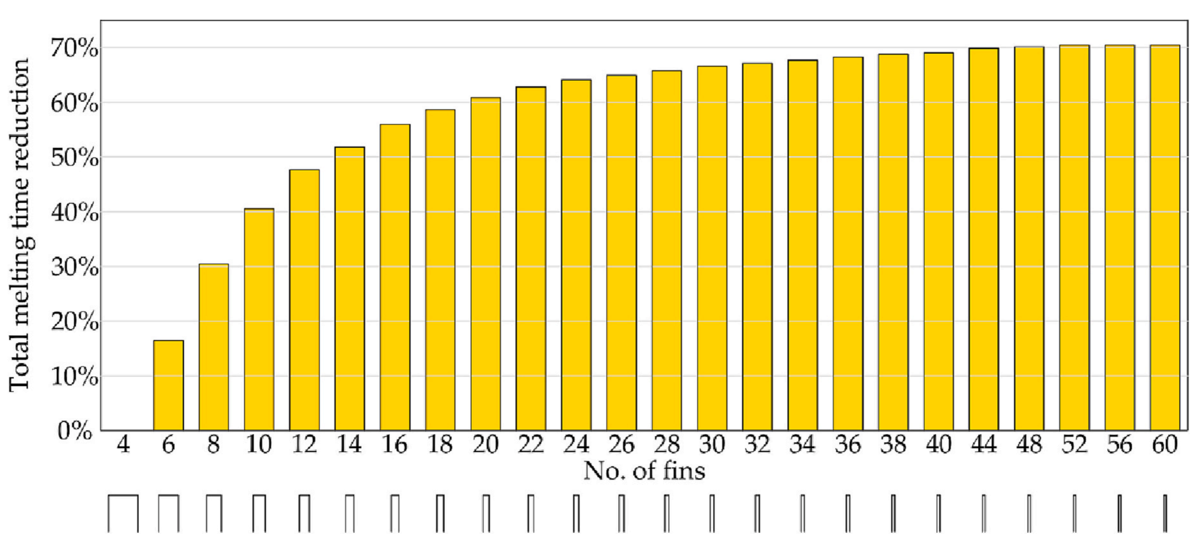

Fig. 11. Total melting time reduction for cases with different fin numbers and visualization of their corresponding decrease in fin thickness; developed based on X. Yang et al [83].

Table 2

Publications regarding longitudinally finned pipe configuration with highlighted distinctive fin shapes, phase change processes (melting (M); solidification (S)), and whether they were conducted experimentally (E) or numerically (N).

Fin shape	Year	Publication	TTHX	PCM	Orientation	M	S	E	N	Novelty	Times cited (GS)
Rectangular	2013	[79]	✔	RT82	Horizontal	X	✔	✔	X		282
	2015	[85]	X	RT50	Horizontal	✔	X	✔	X		164
	2019	[86]	✔	RT82	Horizontal	✔	X	X	✔	Introduction of metal foam in the storage tank	86
	2019	[87]	X	Lauric acid	Horizontal	✔	X	X	✔		119
	2020	[80]	X	Lauric acid	Horizontal	✔	✔	X	✔		20
	2020	[88]	X	Water	Horizontal	X	✔	X	✔		35
	2020	[89]	X	Paraffin wax	Vertical	✔	X	✔	X	Experimental comparison between transversal and longitudinal fins	33
	2020	[90]	X	Water	Vertical	X	✔	✔	X		28
	2020	[91]	✔	RT82s	Horizontal	X	✔	X	✔	Utilization of CuO nanoparticles	38
	2020	[92]	✔	NE Water	Horizontal	X	✔	X	✔	Utilization of hybrid nanoparticles and a hexagonal pipe in TTHX	76
	2020	[93]	✔	NE Water	Horizontal	X	✔	X	✔	Utilization of a star-shaped pipe alongside internal fins in TTHX	117
	2022	[81]	X	RT82	Horizontal	✔	X	X	✔	Rotation of storage tank	1
	2022	[94]	X	LiX3-KX3-NaX3 Erythritol RT100	Horizontal	✔	X	X	✔	Utilization of PCM cascade	1
	2022	[95]	X	NE and pure RT55 NE and pure RT60 NE and pure RT65	Horizontal	✔	✔	X	✔	Utilization of various PCM cascade configurations	3
	2022	[96]	X	NE RT28	Horizontal	X	✔	X	✔		53
	2022	[97]	X	NE and pure A58H	Vertical	✔	✔	✔	X		2
	2022	[98]	X	RT82	Horizontal	✔	✔	X	✔	Utilization of foam strips along fins	21
	2022	[83]	X	Paraffin	Horizontal	✔	X	X	✔	An increasing number of fins until no further performance enhancement is provided	50
Y-shape	2015	[99]	X	Paraffin wax	Horizontal	✔	X	X	✔		397
	2016	[100]	X	NE water	Horizontal	X	✔	✔	X		50
	2016	[101]	X	Water	Horizontal	X	✔	✔	X	The numerical comparison between the performance of longitudinal and transversal (radial) fins	21
	2019	[102]	✔	RT82	Horizontal	✔	X	X	✔	Introduction of Al2O3 nanoparticles	152
	2019	[103]	X	NE water	Horizontal	X	✔	X	✔		43
	2020	[104]	X	NE RT35	Horizontal	X	✔	X	✔		33
	2021	[105]	✔	NE n-octadecane	Horizontal	✔	X	X	✔		117
Hierarchical/ Dendritic/Fractal	2018	[106]	X	Lauric acid	Horizontal	✔	X	X	✔		5
	2020	[107]	X	Lauric acid	Vertical	X	✔	✔	X	Experimental work on hierarchical fins	158
	2021	[108]	X	RT82	Horizontal	✔	X	X	✔		8
	2021	[109]	X	Lauric acid	Various inclinations	✔	✔	✔	X	Experimental work on melting and solidification of PCM using fractal fins and various shell orientation	10
	2021	[110]	✔	NE Water	Horizontal	X	✔	X	✔	Utilization of hybrid nanoparticles and tree-like fin structure in TTHX	92
	2022	[111]	X	Sebacic acid EG lauric acid	Horizontal	✔	X	X	✔		1
	2022	[112]	X	Lauric acid	Horizontal	✔	X	X	✔		15
	2022	[113]	X	RT82	Horizontal	✔	X	X	✔		0
Other/Novel	2017	[114]	X	Not stated	Horizontal	✔	X	✔	X	Topologically optimized fin shape	173
	2017	[115]	X	Not stated	Horizontal	✔	X	✔	X	Topologically optimized fin shape in two- and three-dimensional cases	78
	2019	[116]	X	Sodium nitrate	Vertical	✔	✔	✔	X	Utilization of high melting temperature PCM and novel fins	9
	2019	[117]	X	RT82	Horizontal	✔	✔	✔	X	Utilization of triangular fins and Al_2O_3 nanoparticles	36
	2020	[118]	✔	NE RT35	Horizontal	✔	✔	X	✔		31
	2020	[119]	X	Sodium nitrate	Vertical	✔	✔	✔	X	Utilization of high melting temperature PCM and novel fins	7
	2021	[120]	X	RT82 RT60 RT50 RT35	Horizontal	✔	✔	X	✔	Topologically optimized fin shape	26
	2021	[121]	X	RT82	Horizontal	✔	X	X	✔	Comparison between various fin shapes	33
	2022	[122]	✔	NE RT82	Horizontal	✔	X	X	✔		5
	2022	[123]	X	RT50	Horizontal	✔	✔	X	✔	Introduction of vortex generators inside HTT	0
	2022	[82]	X	N-octadecane	Horizontal	✔	X	X	✔		1
	2022	[124]	X	NE RT82	Horizontal	✔	X	X	✔		2
	2022	[118]	X	NE RT82	Horizontal	✔	X	X	✔		31
	2022	[125]	✔	NE Water	Horizontal	X	✔	X	✔	Introduction of metal foam in TTHX	16

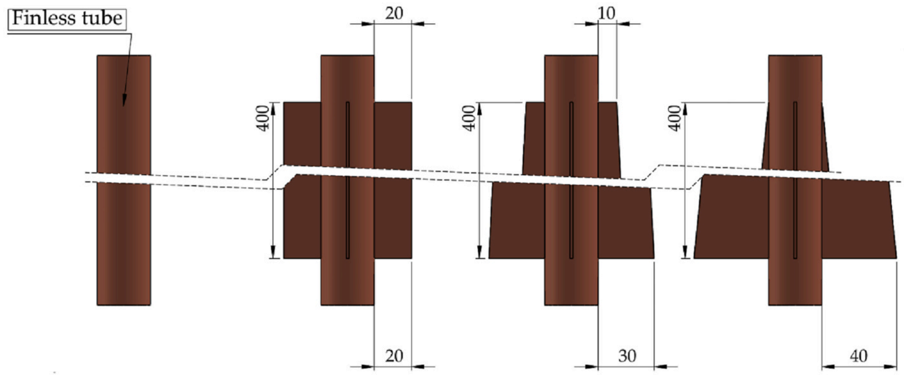

Fig. 12. Graphical representation of fin geometries studied by O.K. Yagci et al. [129].

This type of fins requires more experimental research for the validation of used numerical models.

3.2. *Coils utilization*

When PCM behavior during melting and solidification and the overall physics of those processes are considered the simplest cases are mostly used as a reference in future theoretical works. Regarding that assumption, all of the articles shown in Table 3 have been strictly chosen for their experimental character and a specific studied geometry, which is a concentric, single, helically coiled HTF tube with a constant pitch inside an enclosure in either the horizontal or the vertical orientation. Also, the articles shown in Table 3 are considered based on the phase change process researched in them. The number of citations of those articles was derived from Google Scholar website sources. The number of citations of certain articles (usually from 5+ years ago) suggests a growing interest in the area of heat transfer intensification by the implementation of coils, regarding phase change processes. Moreover, only about half of the articles presented in Table 3 consider the solidification process. Neither of them focused only on solidification

Table 3
Publications regarding a concentric, single, helically coiled HTF tube with a constant pitch inside an enclosure in either horizontal or vertical orientation and phase change process studied by them melting (M); solidification (S) and whether they were conducted experimentally (E) or numerically (N).

Year	Publication	p [m]	d_c [m]	d_t [m]	Shell shape	Shell C-S [m]	Shell length [m]	T_m [°C]	Orientation	M	S	E	N	Times cited (GS)
2014	[135]	–	⌀0,23	–	Cylindrical	⌀0,295	0,67	30 ÷ 55	Vertical	✔	X	✔	X	49 (GS)
2016	[136]	–	⌀0,05	–	Cylindrical	⌀0,085	0,14	74 ÷ 82	Vertical	✔	X	✔	X	77 (GS)
2016	[137]	–	⌀0,106	⌀0,008	Cylindrical	⌀0,2	0,3	30,9 ÷ 41,6	Horizontal	✔	X	X	✔	75 (GS)
2017	[138]	0,03	⌀0,1106	⌀0,009	Rectangular	0,36 × 0,45	0,61	58 ÷ 60	Horizontal	✔	✔	✔	X	21 (GS)
2017	[139]	0,075	⌀0,12	⌀0,015	Cylindrical	⌀0,196	1,68	–	Vertical	✔	✔	✔	X	15 (GS)
2017	[140]	0,03	⌀0,1	⌀0,019	Cylindrical	⌀0,3	0,6	60	Vertical	✔	X	✔	X	17 (GS)
2017	[141]	0,08	⌀0,14	⌀0,015	Cylindrical	⌀0,2	1,6	54	Vertical	✔	X	✔	✔	26 (GS)
2018	[142]	–	⌀0,08	⌀0,00635	Cylindrical	–	–	69 ÷ 71	Vertical	✔	X	✔	X	4 (GS)
2018	[143]	0,122	⌀0,122	⌀0,012	Cylindrical	⌀0,2	0,5	69 ÷ 71	Horizontal	✔	✔	✔	X	1 (GS)
2019	[144]	0,028575	⌀0,1016	⌀0,00953	Cylindrical	⌀0,1664	0,2953	51	Vertical	✔	✔	✔	X	41 (GS)
2019	[145]	0,013 0,0098 0,0044	⌀0,09 ⌀0,07 ⌀0,05	⌀0,005	Cylindrical	⌀0,09	0,4	35	Horizontal	✔	X	✔	X	27 (GS)
2019	[146]	0,03	⌀0,135	⌀0,00953	Cylindrical	⌀0,175	0,5	56 ÷ 58	Vertical	✔	✔	✔	X	41 (GS)
2019	[147]	0,08	⌀0,14	⌀0,015	Cylindrical	⌀0,2	1,6	332,72,329,72,327,53	Vertical	✔	X	X	✔	20 (GS)
2020	[148]	0,13 0,098 0,044	⌀0,05 ⌀0,07 ⌀0,09	⌀0,05	Cylindrical	⌀0,09	–	29 ÷ 36	Horizontal	✔	X	✔	X	45 (GS)
2020	[149]	–	–	⌀0,028	Cylindrical	⌀0,2725	0,3	127,52 120,01	Horizontal	✔	✔	✔	X	25 (GS)
2020	[150]	0,015	⌀0,028	⌀0,006	Cylindrical	⌀0,04	–	24 ÷ 26	Vertical	✔	✔	✔	X	1 (GS)
2020	[151]	0,03	⌀0,075	⌀0,00635	Cylindrical	⌀0,011	0,24	48,3 ÷ 62,1	Vertical	✔	X	✔	X	35 (GS)
2021	[152]	0,03	⌀0,104	⌀0,01	Cylindrical	⌀0,1524	0,45	31,3 ÷ 40,2	Horizontal	✔	✔	✔	X	0 (GS)
2022	[153]	0,04	⌀0,126	⌀0,00954	Cylindrical	⌀0,176	0,495	48.3 ÷ 62	Vertical	✔	✔	✔	X	0 (GS)
2022	[154]	0,026	⌀0,11,952	⌀0,009525	Cylindrical	⌀0,25	0,33	37	Vertical	✔	✔	✔	X	5 (GS)
2022	[155]	–	–	⌀0,00975	Cylindrical	⌀0,107	0,2	46 ÷ 48 51 ÷ 53	Vertical	✔	✔	✔	X	0 (GS)

phenomena. What is more only one article presents results for the shape of a shell different than a cylindrical one. In counter studies focused on finned geometries, the majority of works for coils geometry presented only experimental results. However, it should be noted that experimental databases are limited to PCMs within the low melting temperature range (30 °C-80 °C). Not all articles present all of the crucial geometrical parameters for shell and coil geometry.

M. Delgado et al. [135] studied a thermal energy storage system using a coil immersed in a PCM emulsion which, as the authors stated, was an offshoot from the refining process in the petrolic industry. The main goal was to compare PCM emulsion and water as thermal storage mediums in an already existing storage tank. Using a PCM emulsion resulted in a 34% increase in energy storage density as compared to water, but a decrease in global heat transfer occurred from 500 to 100 W/m^2*K due to the larger viscosity, but also due to lower thermal conductivity of this emulsion, since the thermal conductivity of paraffins is on average 8 times lower than of water. The authors utilized a non-transparent shell, as the physics of the phase change process was not a priority in their study. Their later study [156] included stirring inside the storage tank. Due to boosting convection heat transfer and volumetric energy density, it is said to be a promising TES system proposal. A.I.N. Korti and F.Z. Tlemsani [136] in their experimental research studied three different PCMs in a transparent LHTES equipped with a copper helical coil. They studied both the charging and discharging of the storage tank for various inlet temperatures and flow rates. The effectiveness of each process was also analyzed and shown in Fig. 13. Effectiveness of the charging process is a few times larger than discharging due to the fact that convective heat transfer dominates in melting. Another conclusion from this publication is the great influence of the inlet temperature of HTF on both the charging and discharging range.

A. Dinker et al. [138] performed an experimental study on charging and discharging a rectangular storage tank filled with beeswax with HTF flowing through a helical coil. Beeswax is a natural and non-toxic substance whose thermal stability makes it a viable PCM for ranges of temperature up to 90 °C. The authors studied four different fluid rates and three different inlet temperatures of HTF. The temperature appeared to have a great influence on the efficiency of the melting and solidification processes occurring in the tank. Both S. Zhang et al. [139] and M. Tayssir et al. [140] studied the charging of the thermal storage tank filled with paraffin at an approximate melting point. The former also studied the discharging process. In both publications, similar conclusions were drawn out about the convective heat transfer domination during the melting process. X. Yang et al. [141] and Y. Wang et al. [157] numerically and experimentally researched the melting performance of the same single, helically coiled LHTES using RT54 substance as a PCM in solar collector application. In the former [141] publication part authors distinguished between phase change solely by conduction and phase change by conduction and convection to observe the effect of introducing convection to a simulation. Their results, presented in Fig. 14 show great enhancement of heat transfer when including convection, though convective effects are more visible in numerical rather than experimental studies. The latter study [157] was devoted to investigating the effect on the thermal performance of this solar heat storage system of design, operational and climatic parameters.

V. Saydam et al. [144] studied both the charging and discharging of a thermal storage tank equipped with a helical coil as an HTT and filled with paraffin wax as a storage medium. Due to the transparency of their cylindrical shell, it was possible to document the melting/solidification processes of a PCM at various stages using a photographic camera. Researchers observed that their coil geometry allowed for a quicker melting of paraffin wax on the outer surface of the storage tank while remaining solid closer to the axis of the storage tank. Due to convection, the remaining solid part of the PCM was an upward tapered conically-shaped located at the bottom of the tank. This would suggest that locating more coils on the bottom of the tank would hasten the solidification process. Visual observation of discharging process was obstructed due to the accumulation of solidified PCM on the walls of the tank, but temperature readings showed that again the process took longer closer to the axis of the tank. M. Rahimi et al. [145] in their publication conducted experimental research to investigate the effect of one of the geometrical parameters of the coil on the melting process of RT-35 paraffin inside a horizontal shell. Also to evaluate the inlet temperature effect on the performance of this storage tank a dimensionless parameter of Stefan number was introduced. Such an approach allowed researchers to decrease the melting time of PCM by 72.6% for a certain Stefan number. The evolution of the melting front for studied geometries of the coil is shown in Fig. 15.

In their later study, M. Rahimi et al. [148] conducted an exergy analysis with identical storage tank and coil dimensions and the same PCM as previously. Also, a parameter of dimensionless time was introduced in this paper. Their study showed that although charging of the storage tank was the shortest for the largest diameter of the coil it experienced the lowest exergy efficiency. R. Du et al. [147] numerically investigated the influence of nanoparticle dispersion on the melting process of PCM inside a coil-in-shell heat exchanger. This study was later validated on a research stand with satisfying results. Their research has shown that introducing nanoparticles to the base material in various volume fractions shortened the melting process in each case. What is more introducing nanoparticles allowed for more uniform melting of

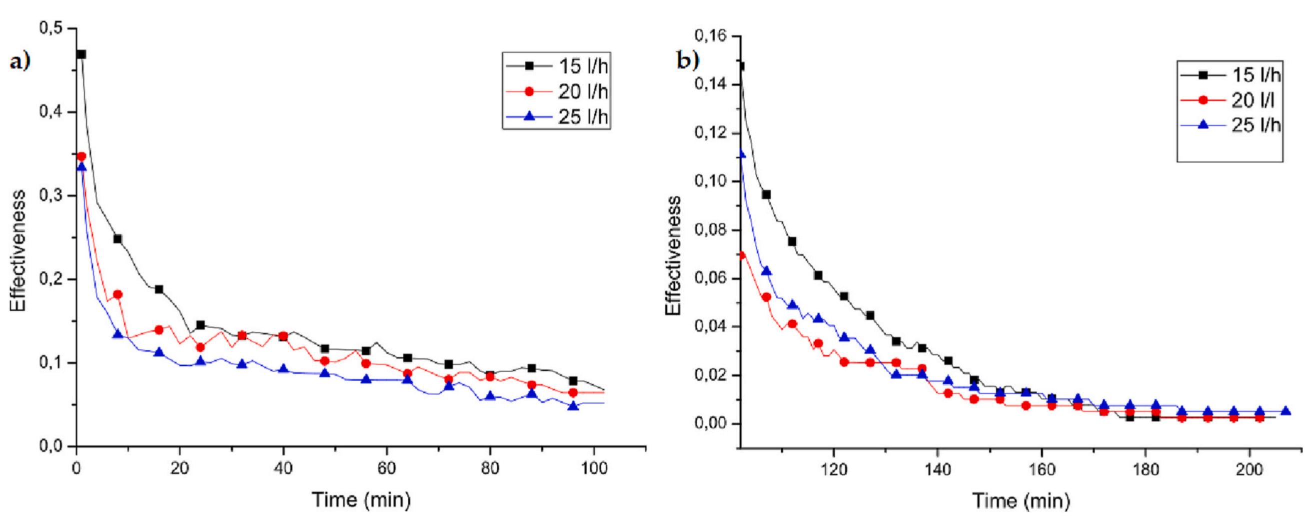

Fig. 13. Efficiency of a) charging and b) discharging of the coil-in-shell thermal storage tank [136].

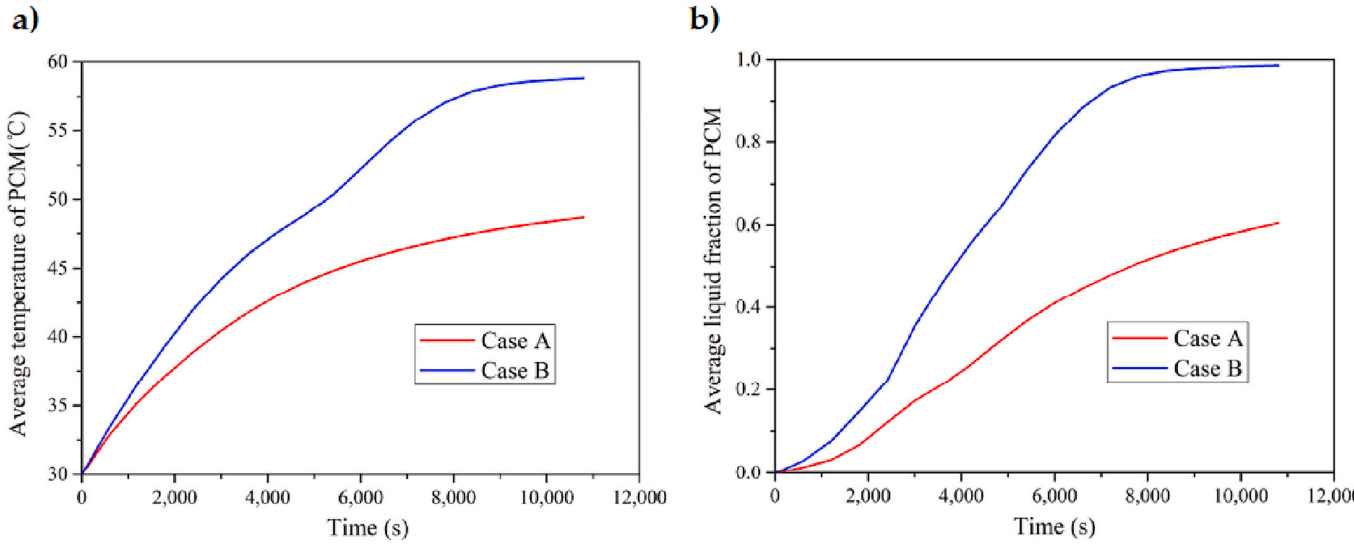

Fig. 14. Comparison of the average temperature of PCM (left) and liquid fraction of PCM (right) when the melting process occurs only with conduction (red) and with conduction and convection mechanisms combined (blue) [141]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

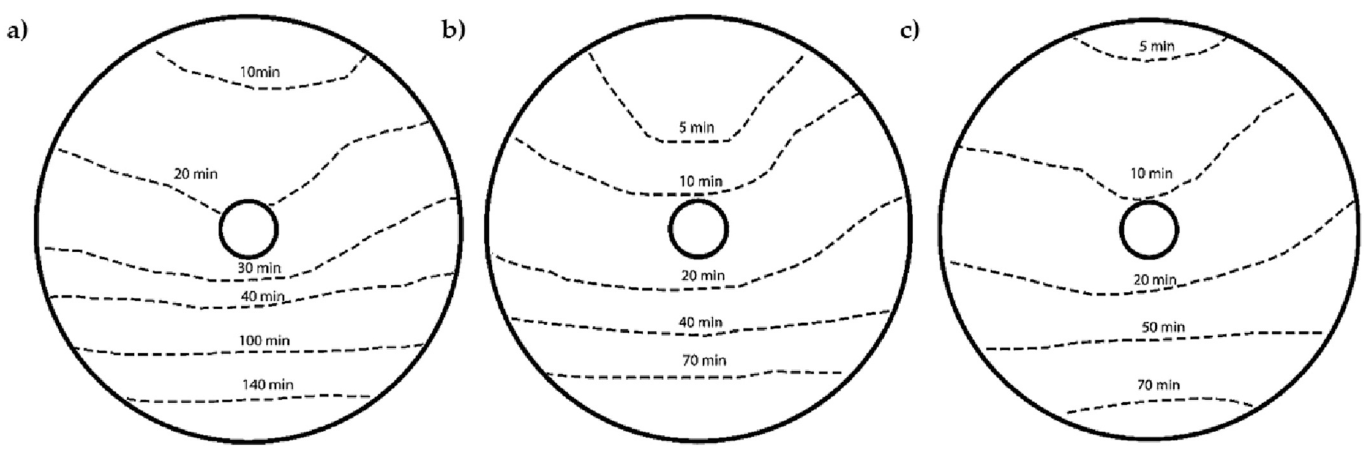

Fig. 15. Location of melting front for cases with different diameters of the coil while the diameter of the storage tank remained constant; deposition of a solidified chunk of PCM on the bottom of the tank can be observed (a) – the largest diameter of the coil; b) – medium-sized diameter of the coil; c) – the smallest diameter of the coil) [145].

PCM, in contrast, a small 5% portion of solidified pure PCM remained on the bottom of the tank for a quarter of the time. Such uniformity is said to save melting time and thus lead to the shorter charging time of the storage tank. A comparison between pure PCM and NEPCM during melting is shown in Fig. 16. V. Mayilvelnathan and A. Valan Arasu [149] experimentally researched both the melting and solidification behavior of helical coil immersed in pure erythritol and erythritol with 1%wt graphene nanoparticles. Adding nanoparticles, like in another above-mentioned publication [147] resulted in faster charging and discharging of the storage tank, but also graphene nanoparticles reduced the unwanted subcooling effect of erythritol. This effect delays the onset of solidification of PCM, thus resulting in the need for a lower temperature source to discharge the tank.

R. Andrzejczyk et al. [150] experimentally compared the melting and solidification behavior of PCM, which in this case was coconut oil. Two geometries were considered: a straight and a helically coiled pipe which is non-equidistantly spaced along the vertical direction. Each manufactured geometry has a similar heat transfer area. The helically coiled pipe was either positioned with coils on the bottom or at the top of the shell, thus overall three cases were considered in their study. Melting and solidification processes were observed using a photographic camera through a transparent shell and were brought together in a juxtaposition for identical timestamps. Alongside observations, temperature measurements were carried out and analyzed. Dimensionless temperature analysis showed that although the melting process for both coiled cases developed similarly, coils located at the top were superior during the solidification process. This contradicts conclusions that could be drawn from V. Saydam et al. publication [144], thus heat transfer mechanisms during the solidification process require more attention from future researchers. M.S. Mahdi et al. in their publications [146,151] experimentally studied the behavior of PCM inside a cylindrical shell using a helical coil as an HTT. The former study [146] was devoted to investigating melting and solidification processes using a simple helical coil. Because of the relative proximity of the coil surface to the shell surface, a conical chunk of solidified PCM took the longest to melt. The shape of solidified PCM is similar to one observed by V. Saydam et al. [144]. This could be accounted for a relatively large coil diameter to shell diameter ratio. The latter study of M.S. Mahdi et al. [151] was an experimental comparison of melting behavior using a simple and upward-tapered conically-shaped helical coil. Utilizing a conical shape of the coil

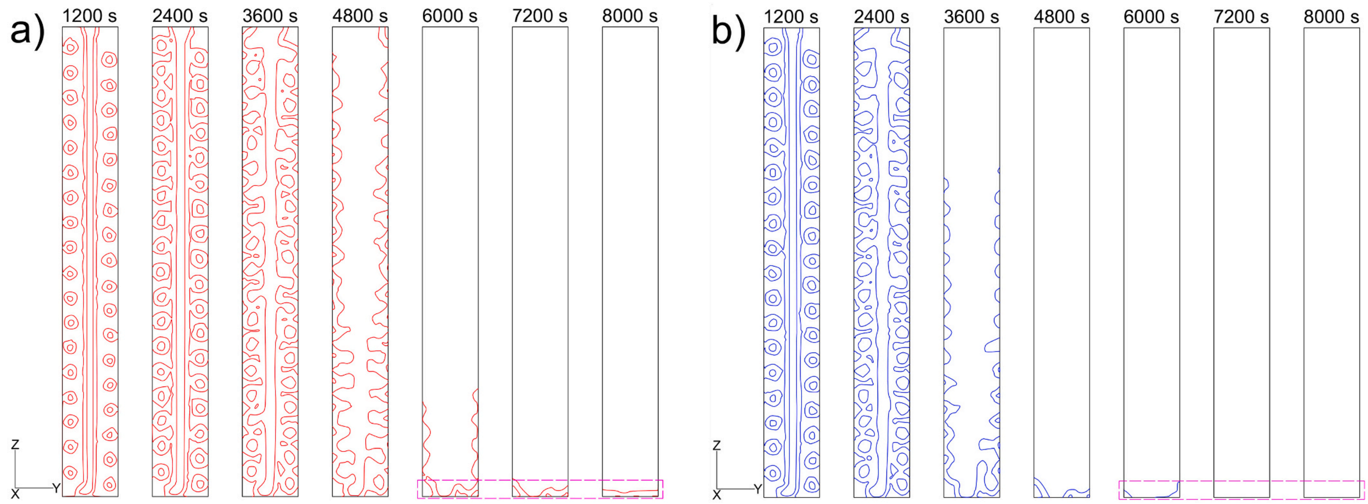

Fig. 16. Melting behavior of a) pure PCM and b) NEPCM in the coil-in-shell heat exchanger; violet dashed lines show the bottom of the tank where the melting process in both a) and b) took the longest [147]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

allowed for a quicker melting of the PCM.

Single helically coiled pipe as an HTT in melting/solidification phase change processes requires more thorough research done more uniformly, thus standardization of the research process should be employed in future publications. As shown in Table 3 not all of the analyzed articles provided full info about the geometries of either coils or shells. It makes it difficult to perform modeling on such geometries. The suggestion for future researchers would be to rather use non-dimensional parameters. Such an approach was already proposed in a publication regarding single-phase heat transfer [158], like:

- $$\frac{p}{d_t}$$
- $$\frac{d_c}{d_t}$$
- $$\frac{d_c}{d_{sh}}$$
- $$\frac{H_{sh}}{d_{sh}}$$

Another important parameter in storage tank geometry would be the ratio between the spacing of the inlet/outlet and the beginning of the straight lead out from the shell. The suggestion would be to use the parameter as shown below:

- $$\frac{h_{in}}{h_{out}}$$

This parameter would serve the purpose of evaluating the influence of coil surface localization on the PCM melting/solidification process. It has been reported by various researchers that certain coil localizations may speed up the phase change process of PCM [150,159]. The density difference in liquid and solid phases of certain PCMs usually leads to the deposition of solid PCM in the lower parts of a vertical shell. Those parts of solid PCM are taking longer to melt, due to worse penetration. Non-uniform heat transfer surface spread across the volume of the tank. If rectangular and cylindrical shells were to be compared in such non-dimensional comparison the cross-sectional dimensions of the rectangular shell should be replaced with characteristic length. All of the above-mentioned non-dimensional parameters of coils are shown in Fig. 17.

All of the above-mentioned dimensionless, geometrical parameters, as well as thermo-physical properties of both HTF and PCM undergoing melting/solidification processes, could later be used to formulate correlations for heat transfer coefficient in the helically coiled storage tank, e.g.:

- $$\alpha = f\left(\frac{p}{d_t}, \frac{d_c}{d_t}, \frac{d_c}{d_{sh}}, \frac{H_{sh}}{d_{sh}}, \frac{h_{in}}{h_{out}}, k_{HTF}, \dots, k_{PCM}, \rho_{L,PCM}, \rho_{S,PCM}, \dots\right)$$

Such models could later be used for industrial purposes for heat transfer calculations within LHTE storage tanks.

Most recent publications have also studied more complex coil geometries, such as double helical coils consisting of a single tube inside a cylindrical shell, double helical coils consisting of two separate tubes inside a cylindrical shell, but also double-pipe helical coil heat exchangers where the shell of the storage tank, as well as an HTT, were in the shape of a helical coil. Some of the mentioned complex coil geometries are shown in Fig. 18.

Z. Ling et al. [160] experimentally studied the performance of a heat exchanger consisting of two coils (hot and cold) immersed in mannitol. The same geometry was furtherly studied by W. Lin et al. [161] using sebacic acid. The latter was also enhanced with expanded graphite particles to eradicate the low thermal conductivity of base PCM. R. Anish et al. in their three publications [162–164] experimentally studied

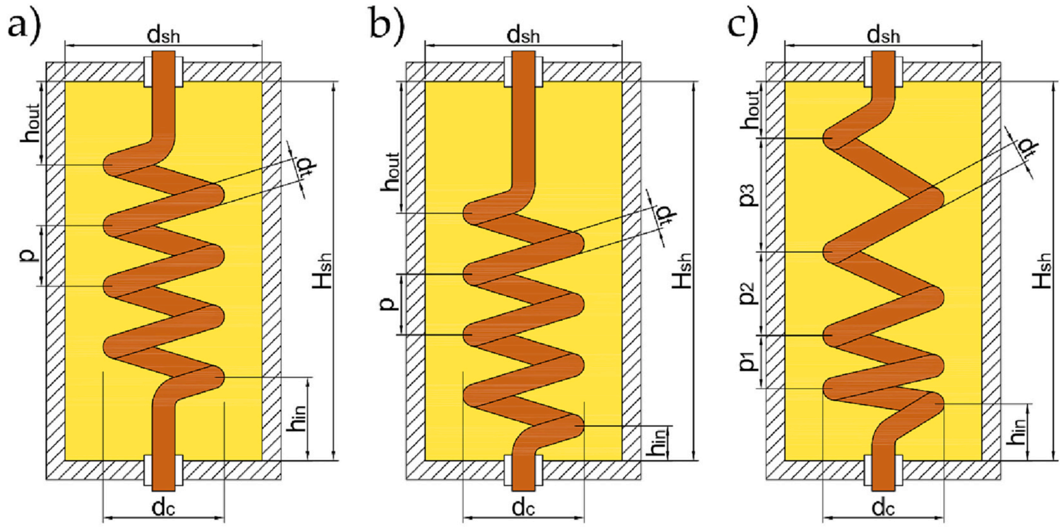

Fig. 17. Schematic representation of selected coil-in-shell heat exchanger configurations (a) simple helical coil, b) non-equidistantly spaced helical coil, c) helical coil with a variable pitch).

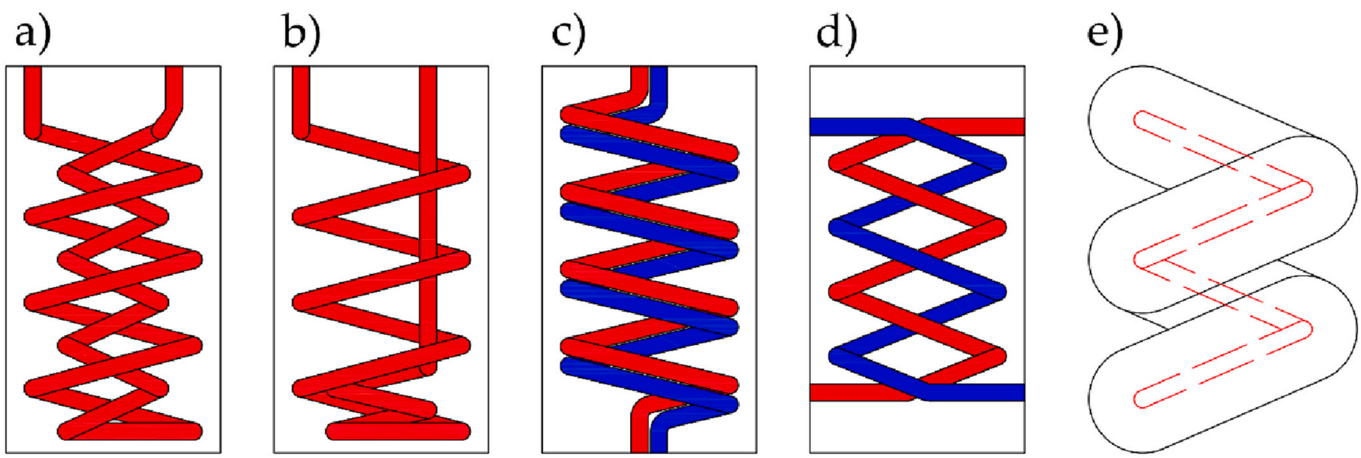

Fig. 18. Examples of selected complex helical coil geometries studied in various publications; heat exchangers containing both red (hot) and blue (cold) coils allow for simultaneous charging and discharging of storage tank. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

both melting and solidification processes using a double helical coil consisting of a single tube. In those publications, a significant difference between the temperatures of the bottom and top part of the tank is visible during the melting process, while solidification seems to proceed more uniformly. B.M.S. Punniakodi and R. Senthil [159] proposed a novel approach to the HTT location within the tank during the melting process using a double coiled fabricated from a single tube. The outer coil is located along the entire height of the tank, while the inner coil is located only in the bottom part of the tank. Such distribution of the HTT surface is observed to decrease the melting time by 36.84% while comparing it with a case that is lacking such an inner coil. F. Afsharpanah et al. [165] numerically performed a parametric study on an ice bank unit consisting of a single helically coiled copper tube working as an HTT connected with a copper plate, which worked as a thin cylindrical fin. By operating just the geometrical parameters while the heat transfer surface area remained constant, they were able to intensify the charging rate by up to 18.84%. D. Lafri et al. [166] experimentally studied the utilization of helical coil in hybrid sensible and latent heat storage in two concentric configurations: A – with PCM on the outer surface and B – with PCM in the center of the axis of the thermal storage reservoir. This research showed that such deposition of PCM not only accelerated the melting process but also increased the insulation of the storage tank. H. Liu et al. [167] and A.R. Karimi et al. [168] in their studies utilized copper foams alongside helical coils. The former [167] parametrically studied the usage of helical coils and copper foam within the PCM for the battery thermal management system, while the latter [168] experimentally researched the influence of introducing copper foam into the storage tank. Their hybrid concept shows that the usage of such highly conductive, porous media speeds up heat propagation within the storage medium, but cost-effectiveness makes it improbable to be employed in large applications. Application of a double helical coil instead of a single helical coil provides more heat transfer surface and in some cases leads to better heat penetration of PCM. Utilizing two separate helical tubes in a storage tank allows the application of two separate fluid loops, which leads to making charging and discharging processes independent of each other. This allows the storage system to be simultaneously charged and discharged.

Helical coils provide an enhanced heat transfer surface with relative ease in manufacturing and are very prone to geometrical optimization. Such an optimization process was shown by S. Lorente et al. [169], C.

Chen et al. [137] and X. Zheng et al. [170]. S. Lorente et al. [169] applied constructal law [171] to determine the geometrical parameters of the helical coil for the highest value of stored heat along with the best thermal performance. C. Chen et al. [137] numerically studied the melting behavior of PCM using four geometries of coils and validated the performance of one of them experimentally. A parameter subjected to optimization was the ratio of the radius of the coil to the radius of the storage tank. Researchers changed the radius of the coil while keeping a constant radius of the tank. Such a dimensionless approach allowed them to appoint a range at which an optimal ratio of radiuses exists. What is more, their later study proved that this ratio is also optimal for a storage tank that is two times larger, which suggests this method is a viable approach for optimization. The latter [170] used an analytical quasi-state method on indefinite cylinder authors were able to shorten the melting process by 25% when changing single coil tube to double coil tube. Further optimization of coil geometry oriented toward performance improvement was also recently numerically investigated by other scientists in the field of simple helical coils [172–178] and other, more complex geometries [179–186].

4. Conclusion

The following article emphasized different approaches in the phase change material research regarding fins and coils utilization. Additionally, the research gap regarding experimental investigations for a wide range of substances with different melting temperatures was underlined. It has been found that the majority of studies presented results only for CFD (Computational fluid dynamics) or analytical calculations. There is a visible disproportion between experimental and theoretical works. It is a clear room for experimental investigations. Special attention should be focused on different fin geometries and a better understanding of the physics of solidification phenomena. What is more, there is a literature gap for a wide range of PCM substances with melting temperatures higher than 60 °C. Regarding the results of the presented analysis, several conclusions regarding fins and coils utilization within the LHTE storage systems could be formulated:

1. Numerical research proves that a limiting amount of fins inside a finned pipe configuration exists. Exceeding this specific amount of fins would no longer increase the performance of the LHTE storage system. From the manufacturing point of view, there is also a limiting amount of fins regarding their thickness. Extremely thin fins are complex and costly to manufacture. Their relatively small thickness also negatively influences their stiffness.
2. Tree-like and topology-optimized fin structures are gaining more attention due to their superior performance within the LHTE storage systems. Such structures, while difficult to obtain using conventional manufacturing processes, such as machining, are not a problem for additive manufacturing techniques, such as metal 3D printing technologies.
3. Porous foams manufactured from thermally conductive are gaining more attention from researchers in recent years, due to their heat transfer enhancement properties. This method alongside the implementation of fins, therefore becoming a hybrid method, would further increase the thermal performance of the LHTE storage system.
4. Several authors reported the observation of the creation of a solid, conical chunk in the bottom of the tank, in its center, during their melting studies. This phenomenon seems to occur when the ratio of the diameter of the coil and the diameter of the shell $\frac{d_c}{d_{sh}}$ exceeds a certain value. This solid chunk takes more time to melt, resulting in an overall increase in the time needed to fully charge the storage tank. If industrial applications were considered, a geometry that would provide more uniform melting should be considered.
5. Few experimental approaches reported contradicting conclusions regarding the influence of coil localization within the storage tank on the solidification process. Since coil geometry and shell geometry were different in each case, a more standardized research approach with non-dimensional coil parameters is needed to further research this topic.
6. When considering the influence of volume flow inside the HTT and the temperature difference between the melting point of PCM and HTT temperature, the latter is reported to have a greater influence on phase change processes, both melting, and solidification. This conclusion seems to provide a clear guideline for industrial applications, that it is beneficial to lower volume flow to achieve a higher temperature.
7. Numerical studies show that when convective heat transfer is excluded from the calculations melting process of PCM occurs in a much slower manner. This observation shows that convective heat transfer is crucial for the high performance of the LHTE storage system, thus the heating surface should be located in the storage tank in such a manner as to not obstruct the convective flows.

A few recommendations could also be formulated based on the following literature study:

1. Experimental study of more than one geometry should be preceded by proper analytical or numerical calculations. Comparison of results for each studied geometry is an appropriate approach to optimize total phase change time and observe spatial arrangement influence on melting and solidification processes.
2. Most numerical studies show that liquid PCM upward flow velocities are relatively low [48]. However numerical studies should direct attention to more aerodynamic shapes of fins to study the effect of potential hydrodynamic drag on the melting process.
3. Future experimental investigations for shell and coil geometries should be focused on various shell geometries such as rectangular or hexagonal, which are easier to utilize in modular thermal storage systems
4. Minimalization of heat losses is crucial for precise observation of phase change processes, particularly solidification. In improperly insulated storage tanks solidification process might appear to be occurring on the surface of the storage tank due to heat losses and not from the HTT surface itself
5. Convection flows go upwards, thus, when melting occurs a solidified chunk of PCM on the bottom of the tank lasts the longest time in both horizontal and vertical configurations. Convection is more apparent in melting, while solidification is driven by conduction more than by convection.
6. There is a need to study the thermal properties and melting/solidification behavior of salt hydrates and their eutectic compounds, since some of them seem to possess higher thermal conductivity and higher melting temperatures than paraffin-based organic substances [28], thus making them promising PCMs for mid-temperature applications.
7. Studies on coils necessitate for more standardized form, such as usage of non-dimensional geometrical parameters such as: $\frac{p}{d_t}$, $\frac{d_c}{d_t}$, $\frac{d_c}{d_{sh}}$, $\frac{H_{sh}}{d_{sh}}$, and require full transparency from researchers (including dimensions and pictures of studied geometries)
8. There is a major deficiency in experimental work within the phase change processes studies within finned and coiled geometries (see Fig. 19.) Out of 97 papers regarding fundamental cases (see Tables 1–3) 59% focused on melting, 14% focused on solidification and 27% of those articles studied both the melting and solidification processes. 62% of those papers focused on numerical studies and 37% on experimental studies, and one paper performed both numerical and experimental studies. Experimental validation is crucial

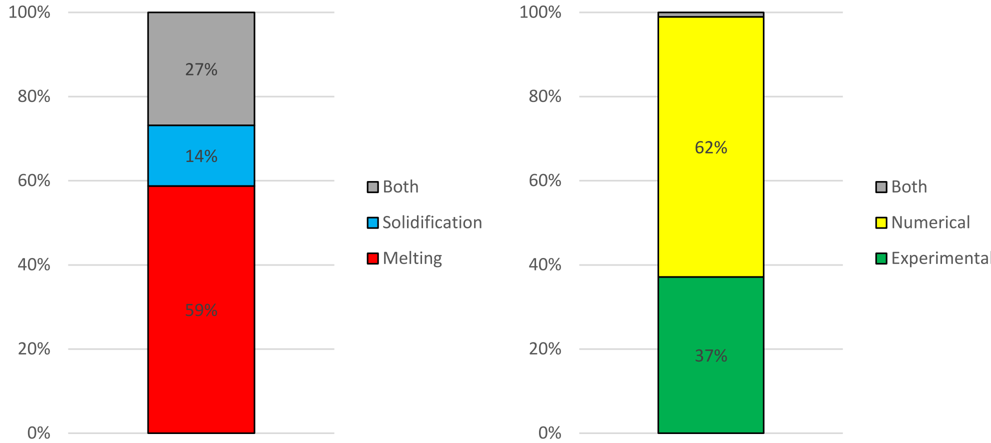

Fig. 19. Percentage of studies regarding the type of studied phase change process and numerical or experimental approach

for a better understanding of phenomena occurring during phase change processes.

9. There is a literature gap for a wide range of PCM substances with melting temperatures larger than 60 °C (see Fig. 19.).

The graph illustrated in Fig. 20 presents the number of studies performed on a certain range of melting temperatures, conducted either experimentally or numerically regarding coils and fins utilization. Most researchers used paraffin or paraffin-based materials, which are of natural origin. Few researchers used plant-based PCMs, e.g.: coconut oil, erythritol, and shea butter. The reason why so few of the researchers use plant-based PCMs, or organic PCMs in general may be the fact that rather than experiencing melting or solidification on the interface of HTT and PCM with a visible melting or solidification front these substances often experience subcooling and their melting and solidification processes occur in their volume. These phenomena negatively affect the observation process when the phase change process ends. Fig. 20. also presents research gaps regarding the melting temperatures of materials used in cited articles. Those gaps could be distinguished for a few ranges of melting temperatures, mainly:

- 0 °C – 22 °C (called subambient)
- 60 °C – 95 °C (except extensively studied RT82)
- 95 °C – 310 °C (except xylitol, erythritol, mannitol, and sodium nitrate with respective melting temperatures of around 95 °C, 120 °C, 167 °C, and 306 °C)

Filling those gaps by researchers could potentially lead to more energy-saving applications of PCMs e.g.:

- Food preservation [188]
- Refrigerated vehicles [189]
- Automotive HVAC systems [190]
- Thermal management of buildings [191]
- Thermal management of electronics [16]
- Concentrated solar power plants [192]
- Heat pump cooperation [178]
- Waste heat recovery from power plants [5]

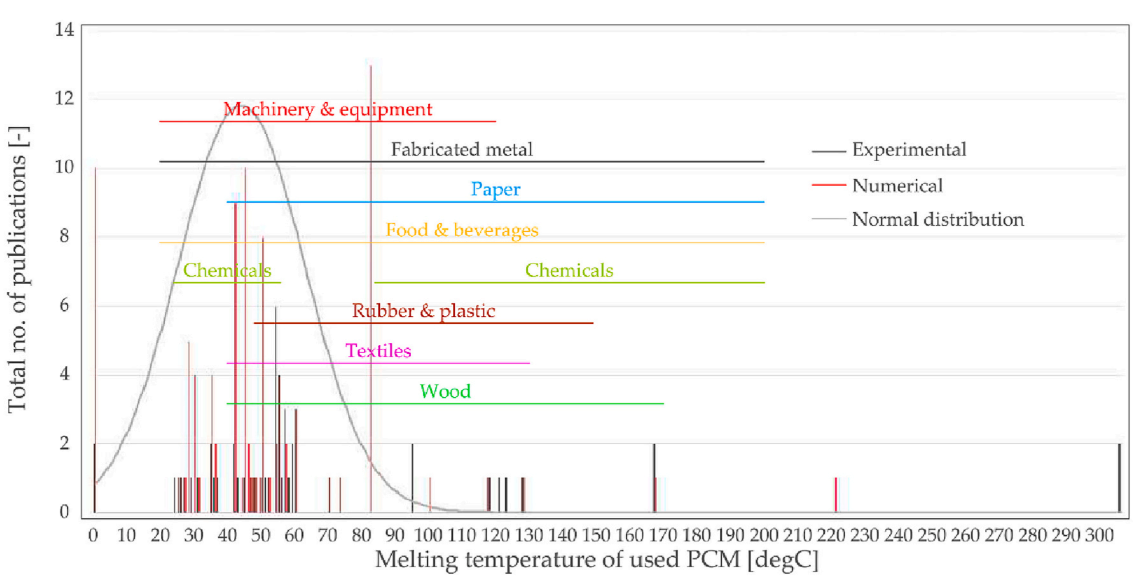

Fig. 20. Melting temperature of used PCM and number of publications regarding fins and coils usage in phase change material studies conducted either experimentally (black bar) or numerically (red bar) and normal distribution curve (grey) for used data, and temperature levels estimation for various industrial processes (based on [187]) imposed with visible research gaps for specific temperature ranges. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

10. What should not be omitted is that PCMs are also recently finding their way in near-zero and below-zero temperatures applications [193], thus research on the thermal performance of viable PCMs performance in such temperatures should be performed.
11. Methods of measuring the liquid/solid fraction utilized in a wide range of studies are: observation of the liquid front, measuring the PCM-head, or calculating the average temperature of PCM as a whole and using it to further calculate the fraction of the liquid PCM inside the tank. However, the last one mentioned is a maintenance-free method it requires the utilization of a large number of temperature sensors for more precise calculations. That is why another maintenance-free method of measuring the solid/liquid fraction of the PCM should be employed if LHTE storage systems are to find application in domestic and industrial use.
12. Emerging metal-based additive manufacturing, like SLS, will enable the production of topologically optimized geometries of fins of high complexity, impossible to obtain otherwise. Such manufacturing methods also allow for the production of metallic foams of high porosity, which also gain more attention from researchers (see Fig. 5.) as an insert for thermal storage.

CRediT authorship contribution statement

M. Rogowski: Formal analysis, Visualization, Writing – original draft. **R. Andrzejczyk:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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