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Paraffin Wax-Based Thermal Composites

Gulfam Raza, Saqib Iqbal and Abdul Samad Farooq

Abstract

Paraffin waxes are organic phase change materials possessing a great potential to store and release thermal energy. The reversible solid–liquid phase change phenomenon is the under-lying mechanism enabling the paraffin waxes as robust thermal reservoirs based on inherently high latent heat (i.e., ~200–250 J/g). However, the main drawback of paraffin waxes is their inability to expedite the phase change process owing to low thermal conductivity (i.e., ~0.19–0.35 Wm⁻¹ K⁻¹). This drawback has long been documented as a technological challenge of paraffin waxes especially for temperature-control applications where faster thermal storage/release is necessitated, encompassing thermal management of batteries, thermoelectric modules and photovoltaic panels. Besides, sustaining the solid-like form of paraffin waxes (shape-stability) is also recommended to avoid the liquid drainage threats for crucial applications, like thermal management of buildings and fabrics. These objectives can be met by developing the paraffin wax-based thermal composites (PWTCs) with help of various thermal reinforcements. However, PWTCs also encounter severe challenges, probably due to lack of design standards. This chapter attempts presenting the recent advances and major bottlenecks of PWTCs, as well as proposing the design standards for optimal PWTCs. Also, the fundamental classification of phase change phenomenon, paraffin waxes and potential thermal reinforcements is thoroughly included.

Keywords: Paraffin wax, thermal energy storage, Phase change materials, Latent heat, thermal reinforcements

1. Introduction

Paraffin waxes are defined as the materials consisting of saturated carbon-hydrogen chains integrated with branched, straight and ring-like (aromatics) structures [1] that are relatively complex by nature. This chemical configuration endows the amorphous characteristics and inertness to paraffin waxes, resulting in inactive functional groups where the external chemical reactions become impossible. Based on this stance, paraffin waxes are supposed to be the green thermal reservoirs, lying within the sustainable targets of the current era. Therefore, the applications of paraffin waxes ranging from biomedical [2] to thermal storage/release [3–5] are declared relatively safe and environmental-friendly.

In thermal storage/release applications, phase change of the paraffin waxes is the backbone that governs the under-lying mechanism depending on thermal excitation or de-excitation driven by the heat source. Thermal excitation is the phase change process of melting during which thermal energy is absorbed, while

thermal de-excitation is the phase change process of solidification during which thermal energy is released. These both processes build up the reversible functionality involving the sensible heat and latent heat storage/release. In case of paraffin waxes (or generally for PCMs), the sensible heat is counted before the phase change process, while latent heat is considered during the phase change process. By definition, phase change [6] process refers to either structural change or state change, as shown in **Figure 1**. In structural change, a single phase of paraffin wax undergoes thermal excitation that brings about the conversion of the internal structures and it is called the solid–solid phase change. Whilst, in the state change, two phases of the paraffin wax undergoes thermal excitation, resulting in conversion of solid phase into liquid phase at the melting temperature, which is known as solid–liquid phase change. The occurrence of either kind of phase change is dependent on the melting temperatures of the paraffin waxes. The paraffin waxes with low-melting temperature such as $<40^{\circ}\text{C}$ (or also called soft paraffin waxes) do not demonstrate structural change, so they only undergo state change. While, the paraffin waxes with high-melting temperature (or also called hard paraffin waxes) provide both structural change and state change.

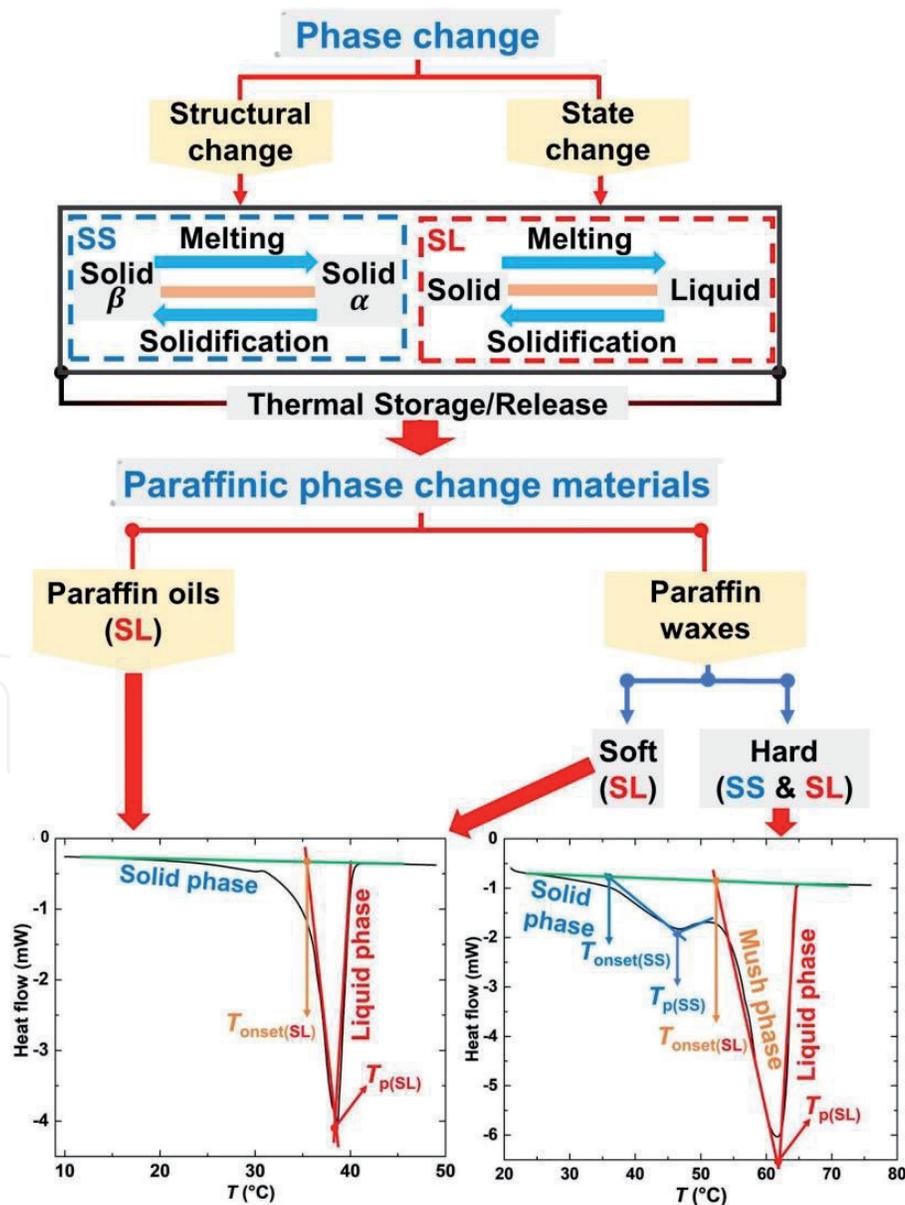


Figure 1. Classification of phase change and paraffin wax-based phase change materials. A few contents of this figure are partially restructured from references [6, 7].

In between structural change and state change, another phase consisting of solid flakes and liquid sites ensues which is called mush phase. Normally, the temperature range of the mush phase lies closer to the onset temperature of the liquid phase. In brief, all these phases are responsible for the total latent heat, while before and after these phases, total sensible heat is considered, depending on the melting temperatures of the involved paraffin waxes. Therefore, it is emphasized that the total thermal energy of the paraffin waxes should carefully include thorough observation of the onset and endset temperatures which can be determined either by DSC curves (**Figure 1**) or by the transient heat diffusion process (temperature versus time analysis). With help of transient heat diffusion process, the thermal storage/release performance of paraffin waxes can precisely be assessed by looking into the time consumed during the melting (thermal excitation) and solidification (thermal de-excitation) processes, which is called charging time and discharging time, respectively. It is generally deduced that, the charging/discharging time becomes short, if the heat diffusion occurs fast, and vice versa. The heat diffusion is further related to the intrinsic property of materials known as thermal conductivity, which is defined as the ability of material allowing the fast or slow transfer of heat. In short, with high thermal conductivity, the charging/discharging time are reduced on behalf of faster heat transfer. However, heat transfer in paraffin waxes is sluggish, and their charging/discharging time is sufficiently long based on the low thermal conductivity. The possible reason for the low thermal conductivity of paraffin waxes is their amorphous nature wherein tightly-packed and inter-connected thermal paths are unavailable. However, a great care is essential because every application may not need fast heat transfer rates, for example, thermal management of buildings where the objective is to keep the heat either outside the buildings in summer or inside the buildings in winter, which is possible only if paraffin wax serves as a thermal insulator necessitating slow heat transfer rates, but the challenge of liquid drainage needs to be simultaneously addressed. Therefore, depending on the target applications, enhancing the thermal conductivity of paraffin waxes is of great practical interest so that the charging/discharging can be reduced. For example, the long charging/discharging time of paraffin waxes is the major bottleneck that can potentially hampers their functionality for thermal management of batteries where the heat generation rate is prone to high and the objective is to dissipate the heat so that hot-spots can be avoided. Keeping different practical scenarios ahead, thermal reinforcements are essential to improve the thermo-physical bottlenecks of the base materials (paraffin waxes), helping create paraffin wax-based thermal composites (PWTCs) which are discussed henceforth.

2. Potential thermal reinforcements

Thermal reinforcements are defined as the external additives being mingled with paraffin waxes to fabricate PWTCs. Thermal reinforcements need to possess certain traits encompassing high/low thermal conductivity, good mechanical strength, porous surface geometry, adaptability and the uniform mingling-compatibility with the paraffin waxes. Depending on the chemistry of thermal reinforcements, they are majorly categorized into inorganic sorbents and organic encapsulants, as depicted in **Figure 2**. Inorganic sorbents are defined as thermal reinforcements providing the physical scaffolds wherein paraffin wax is infused through capillary action. These scaffolds can also be said as oleophilic (be noted all paraffinic PCMs have oiliness though the percentage may differ) that all paraffin waxes based on the wetting characteristics induced by micro/nano-porous structures. Inorganic sorbents are further classified into carbonic, silicate and metallic

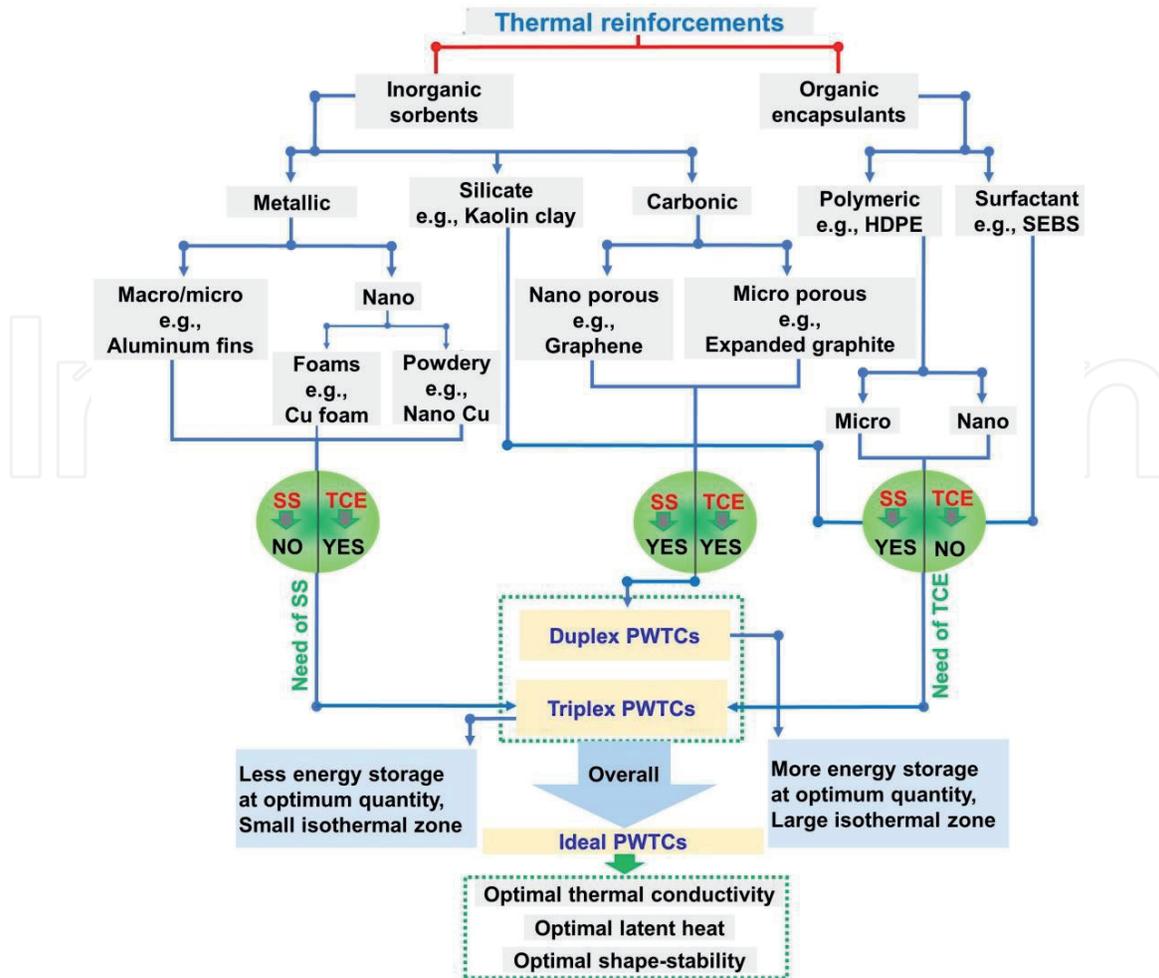


Figure 2. Classification of thermal reinforcements and their role as thermal conductivity enhancer (TCE) or shape-stabilizer (SS). A few contents of this figure are partially restructured from references [6].

thermal reinforcements. Organic encapsulants are defined as thermal reinforcements that build a shell (a boundary encircling the entity) wherein paraffin wax resides as the core material. The next section sheds a light on the preparation methods, morphologies and thermo-physical properties of PWTCs made of these thermal reinforcements.

In the light of application-dependent scenarios, there are two functions that PWTCs should endow to the paraffin wax: temperature-control capacity and shape-stability, but the existence of both functions may not be found in single PWTC. Temperature-control capacity is a coupled function of latent heat and thermal conductivity of PWTCs, imparting a suitable isothermal zone that is highly desired in thermal management applications. Thermal reinforcements that help enhances thermal conductivity of the paraffin waxes are called thermal conductivity enhancers (TCEs). As for the shape-stability of PWTCs, it is defined as the state in which the liquid drainage of the melted paraffin wax is minimized or eventually stopped, and such thermal reinforcements are termed as shape-stabilizers (SSs). In brief, thermal reinforcements can potentially act as the TCSs, SSs or both, and by incorporating the most appropriate thermal reinforcements; duplex or triplex PWTCs can be fabricated.

2.1 Inorganic sorbents

Inorganic sorbents and the corresponding PWTCs are discussed in the coming subsections.

2.1.1 Carbonic thermal reinforcements

Carbonic thermal reinforcements are documented as inherently high-thermal conductivity materials based on well-connected thermal networks. They majorly include graphite powder (PG), expanded graphite (EG, which is obtained by heat-treating the expandable graphite at high temperature of 800–900°C for a few seconds), single-wall carbon nano-tubes (SWCNTs), multi-wall carbon nano-tubes (MWCNTs), and graphene nano-platelets (GNPs). The salient properties of the carbonic thermal reinforcement include the appropriate infusion-compatibility and unique morphology consisting of micro/nano-porous structures, as shown in **Figure 3**, rendering them both TCEs and SSs.

However, the disadvantageous features of carbonic thermal reinforcements also exist, for example, anisotropic thermal conductivity of graphite, reduced thermal conductivity of graphene when it is mixed, and segregation of carbon nano-tubes. In addition, duplex and triplex PWTCs can be synthesized with them via dry or wet-physical methods. For example, a triplex PWTC has been fabricated by dry-physical method, employing 80% of paraffin wax (melting temperature of 48–50°C, thermal conductivity of, and latent heat of 207 Jg^{-1}), 20% of EG and 5% of GNPs. In addition to EG, the incorporation of GNPs has further introduced effective results with enhanced thermal conductivity (around 5.9 $\text{Wm}^{-1} \text{K}^{-1}$ at compress density of 505 kgm^{-3}) and latent heat of 159 Jg^{-1} [8], which is thus deemed to be feasible because the mass percent of all ingredients is somehow optimal. Nonetheless, graphene (also the graphene oxide) has been reported to have very high thermal conductivity (5000 $\text{Wm}^{-1} \text{K}^{-1}$), but EG/PWTC/GNP could not correspondingly achieve that high thermal conductivity, implying a surprising phenomenon. The reason is attributed to the design challenge of GNPs, i.e., when GNPs are joined together to form a compound, the phase segregation effect appears causing to cleave the internal thermal networks due to which the thermal conductivity of compound GNPs is much reduced [10]. Another case study of triplex PWTC [11] has been presented, consisting of 50% paraffin wax (melting temperature of 60–61°C, thermal conductivity of 0.26 $\text{Wm}^{-1} \text{K}^{-1}$, and latent heat of 223 Jg^{-1}), 10% of GP and

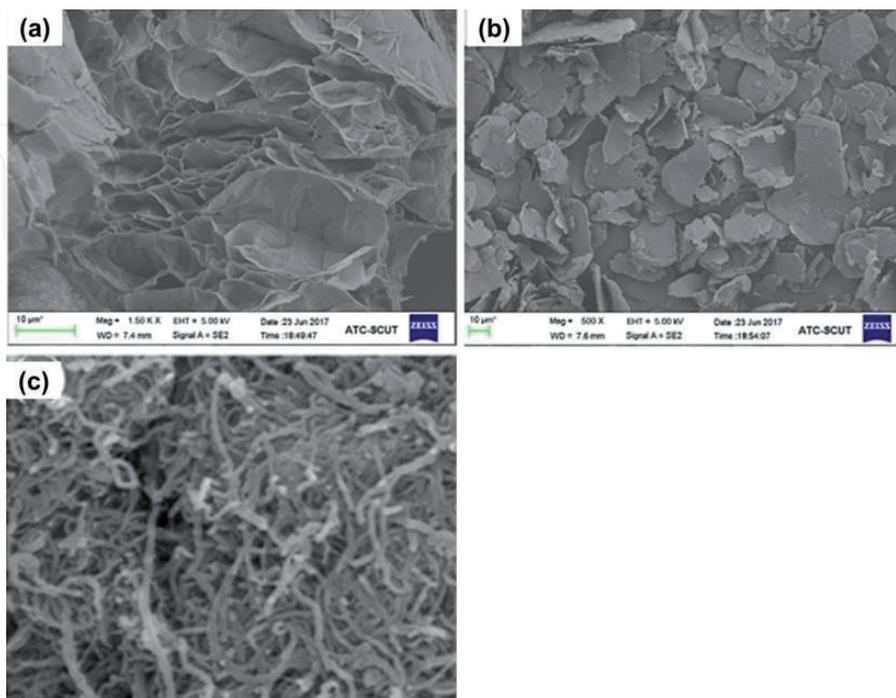


Figure 3. Micro/nano-porous morphology of (a) EG [8], (b) GNPs [8] and (c) CNTs [9].

40% of expanded perlite (EP). As-prepared GP/EP/PWTC has latent heat of 111.4 Jg^{-1} and thermal conductivity of $1.34 \text{ Wm}^{-1} \text{ K}^{-1}$. The question arises on the latent heat which reduces from 223 Jg^{-1} to 111.4 Jg^{-1} which is mainly because of 50% of EP. In the meanwhile, the EP/PWTC neither achieves high thermal conductivity nor shape-stability, while upon incorporation of 10% GP, high thermal conductivity as well as effective shape-stability has been attained, as shown in **Figure 4** [11].

As a conclusive viewpoint, the need of thermal reinforcements should be well-understood together with avoiding the unimportant thermal reinforcements while synthesizing PWTCs, which otherwise can definitely lead to severe shortcomings particularly for energy storage applications where high thermal storage capability is preferred. Therefore, instead of such triplex PWTCs (e.g., EP/GP/paraffin wax), duplex PWTCs (e.g., GP/paraffin wax) may result in more viable outcomes.

The anisotropic thermal conductivity of EG has a great influence on thermo-physical properties of the paraffin wax. The layered sheet/wall-like structure of EG is thus accountable for this effect, inhibiting the heat transfer when it is perpendicular to the graphite layered-structure, while expediting the heat transfer when it is parallel. Such anisotropic effects of has been studied recently for EG alone and EG/PWTCs, demonstrating the much higher thermal conductivity in parallel direction than that of normal direction depending on various temperatures (**Figure 5**) [12].

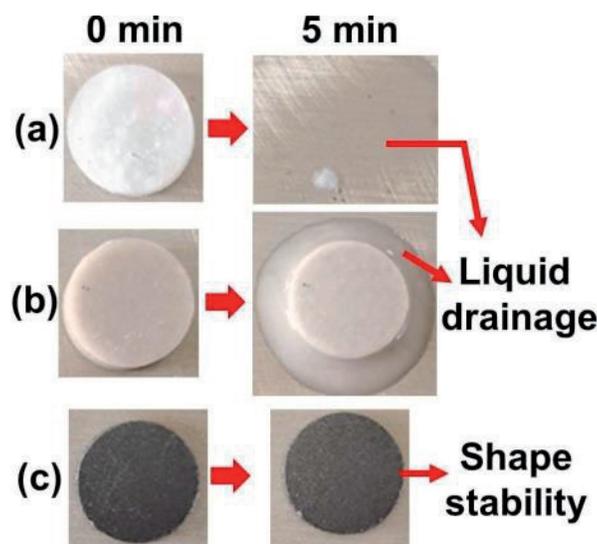


Figure 4. Shape-instability of (a) paraffin wax and (b) EP/PWTC, and (c) shape-stability of EP/GP/PWTC [11].

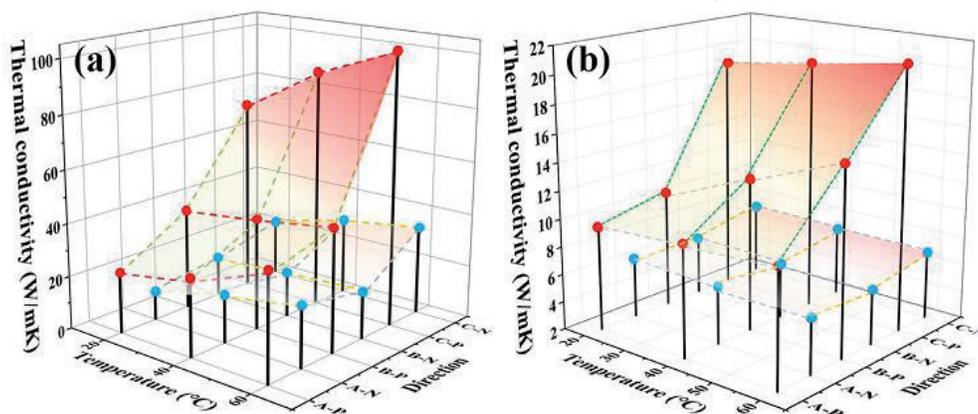


Figure 5. Directional thermal conductivity of (a) EG and (b) EG/PWTC. P: Parallel direction, N: Normal direction [12].

These results imply that the directional effects should also be considered while implementing the EG/PWTCs in applications. In addition, particle size effect of EG is also important. It has been investigated recently that the large-sized and small-sized particles of EG have thermal conductivities of $0.5 \text{ Wm}^{-1} \text{ K}^{-1}$ and $3.23 \text{ Wm}^{-1} \text{ K}^{-1}$, respectively, which are capable of enhancing thermal conductivity of PWTCs in the same order [13]. In general, thermal conductivity of PWTCs increase with increasing the percent contents of thermal reinforcement. However, it is achieved on the penalty of latent heat reduction [13]. This is the reason that PWTCs need to be optimized by keeping the design parameters ahead, so that the ideal PWTCs can be created as claimed above in **Figure 2**.

Thermal stability of paraffin waxes is defined as the maximum temperature limit after which thermal decomposition begins and it is normally $150\text{--}170^\circ\text{C}$ [9]. Evaluated with help of thermogravimetric analysis (in which the specimen material is evaporated at high temperature while simultaneously measuring the mass loss indicating the thermal decomposition), carbonic/PWTCs have been reported with enhanced thermal stability (around $190\text{--}200^\circ\text{C}$) [13] which is indeed attributed to the heat-withstanding strength of thermal reinforcements. The enhanced thermal stability also indicates the successful infusion of paraffin waxes into thermal reinforcements which then impart a kind of thermal protection during thermal processes.

2.1.2 Silicate-based thermal reinforcements

The silicate-based thermal reinforcements are regarded as low thermal conductivity materials, but their micro/nano-porous morphology (**Figure 6**) and consequential specific surface area allows them to impregnate with the paraffin waxes. More precisely, they come in class of clay-like materials and commonly termed as the clay minerals, for examples, expanded perlite (EP), kaolin clay, diatomite, palygorskite or attapulgite and vermiculate, etc., [14–16].

The silicate-based thermal reinforcements are available in abundance at cheap and economical rates, as well as they are notably non-toxic and have a good compatibility with the paraffin waxes based on which shape-stabilized PWTCs can be achieved. However, a large percent threshold of silicate-based thermal reinforcements is normally required to functionalize them as SS for PWTCs. In addition, for high thermal response of PWTCs with silicate-based thermal reinforcements, TCE in sufficient percent may be required; hence, the triplex PWTC cannot be avoided in that case, for example, carbonic TCEs have been incorporated [17]. In the meanwhile, the main point of focus, which is of great practical significance, is the consideration of applications of silicate/PWTCs. Normally, the most compatible features of silicate-based thermal reinforcements have been seen appropriate for the building materials, such as cement, gypsum and sand, etc., implying that

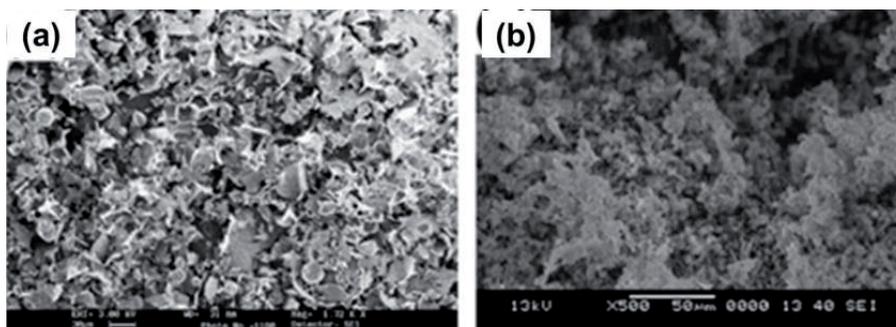


Figure 6.
Micro/nano-porous morphology of (a) EP [14] and (b) diatomite [15].

thermal management of buildings can be done if PWTCs. In such applications, very high latent heat enabled by large percent contents of paraffin waxes is completely undesired. For example, 20% of paraffin wax/expanded perlite is declared to be the optimum in the main skeleton of cement mortar [17]. The reason is the non-stiffness of paraffin waxes, leading to decrease the flexural and compressive strength of building materials at percent contents. Therefore, the quantitative optimization of silicate/PWTCs is highly crucial. Based on this design principle, low latent heat of paraffin wax/diatomite/gypsum triplex composite (around 45 J/g) has been found quite reasonable [18]. Nonetheless, enhancing the thermal response of silicate/PWTCs for building applications is debatable on the standpoint: buildings need to reserve the heat inside the room in winter or outside of it in summer, but high thermal conductivity of silicate/PWTCs is expected to boost up the heat transfer rate which is almost similar to the cement-based walls. For example, a case-study is depicted in **Figure 7** [19]. In heating mode (**Figure 7a**), the paraffin wax/diatomite thermal composite a larger isothermal zone (blue curve in **Figure 7a**) compared with that of paraffin wax/diatomite/CNT (red curve in **Figure 7a**), while in cooling mode (**Figure 7b**), the opposite trend holds true. This is ascribed to the high thermal conductivity of PWTCs achieved on behalf of CNTs. Suppose that this PWTC is applied in building walls in hot countries where the average temperature in summer is higher than 45; the high thermal conductivity of PWTC is deemed to allow heat transfer at fast rates, meaning that the time consumed in saturating the PWTC is less. With this trend, the overall time to keep the thermal management of buildings, both in heating and cooling modes, is expected to be decreased. In simple words, the isothermal zone should be long-lasting so that the more time can be ensured for thermal management. Therefore, there is a great need to decide whether silicate/PWTCs should have high or low thermal conductivity.

2.1.3 Metallic thermal reinforcements

Metallic thermal reinforcements are regarded as highly thermal conductive materials existing in three scaffolds, namely: fins that are extruded plate/tube-like thin structures, foams consisting of wire/fiber-based network with varying degree of number of pores, and powders that are composed of micro/nano-particles [20]. The micro/nano-porous scaffolds of metallic thermal reinforcements serve as the confinement sites wherein paraffin waxes reside, as demonstrated the surface morphologies in **Figure 8**.

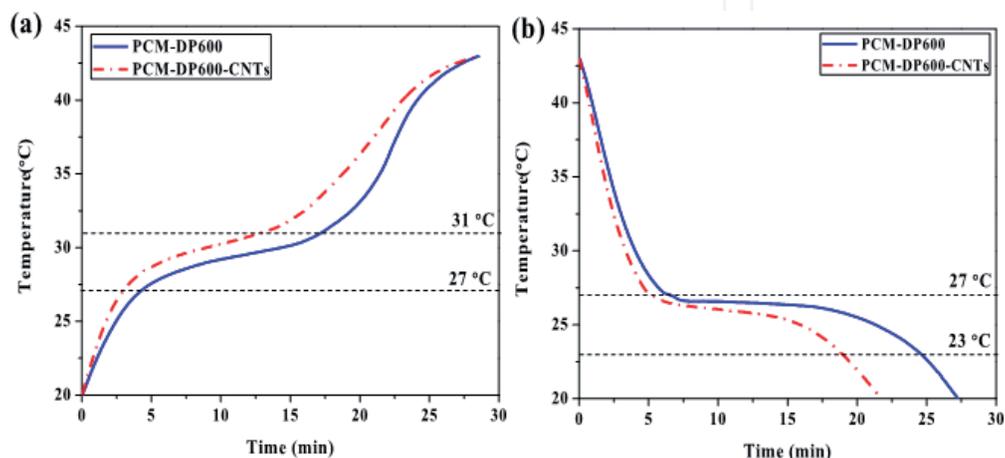


Figure 7. (a) Heating mode, and (b) cooling mode of PWTCs via transient thermal analysis [19].

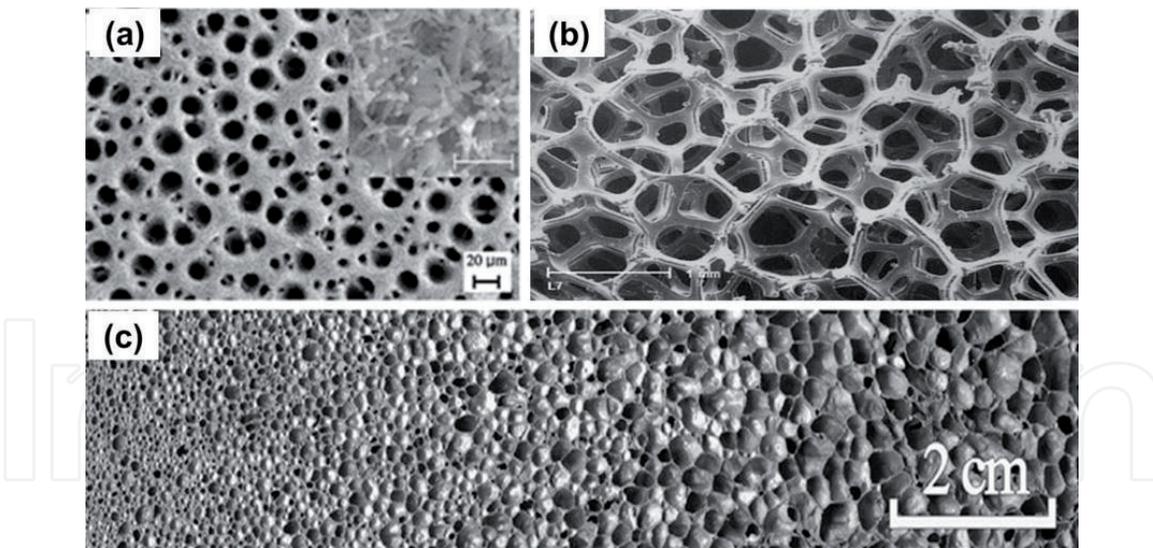


Figure 8. Micro/nano-porous scaffolds of (a) copper foam [21], (b) nickel foam [22] and (c) graded aluminum foam [23].

Metallic materials own a very high thermal conductivity owing to the freely available electronic carries and vibration-assisted modes of heat transfer. The same metallic material, for examples, copper, nickel and aluminum, can be either available in foam or powder, but their initial preparation methods differ a lot. Metallic thermal reinforcements can only act as TCEs, and shape-stability cannot be ensured since the interaction between their network and paraffin waxes is solely based on capillary forces lacking of the liquid-soaking capability.

This drawback may create additional challenges such as weakening the thermal interface between paraffin wax and metallic fibers. Nonetheless, the effective thermal conductivity of PWTCs via copper foams has been achieved very high, such as $16 \text{ Wm}^{-1} \text{ K}^{-1}$ which is based on the high inherent thermal conductivity of copper foam (i.e., $400 \text{ Wm}^{-1} \text{ K}^{-1}$) [24]. Overall, the work on improving the weak thermal interface is left as a research area of future.

2.2 Organic encapsulants

The organic encapsulants may be developed in two structural scales, such as nano or micro. They include polymers and surfactants that are being introduced to develop PWTCs. It is worth-noting that the surfactants are normally polymers, but precisely, they are thermo-plastic elastomers consisting of co-polymers blocks. The potential polymeric encapsulants include low-density polyethylene (LDPE), high-density polyethylene (HDPE), melamine-formaldehyde (MF), polypropylene and polyacrylate, etc., while surfactant-based encapsulants are styrene-b-(ethylene-co-butylene)-b-styrene (SEBS) tri-block copolymer, styrene-butadiene-styrene (SBS), olefin block copolymer (OBC) and polystyrene, among others. However, the main challenge with organic encapsulants is that their thermal conductivity is approximately similar to that of paraffin waxes [25]. Therefore, organic encapsulants are only SSs. The need of TCEs with encapsulated PWTCs definitely results in a triplex thermal composite, implying that the latent heat has to be further sacrificed. Such a design challenge can only be resolved by recommending the encapsulated PWTCs for those applications where thermal energy storage is moderately acquired but fast charging/discharging is not a primary objective, for example, in flame retardancy and thermal management of buildings, fabrics and food packages. The fabrication of encapsulated PWTCs is based on dry or wet-physical methods;

however, the fabrication of the encapsulants is usually enabled by the chemical reactions which are complex due to the inclusion of several preparation steps and process conditions [26]. The little variance in process conditions can result in broken capsules (shells), posing the liquid drainage threats for PWTCs. Until recently, encapsulated PWTCs have been successfully fabricated. For example, duplex encapsulated PWTCs have been presented comprising of paraffin wax (melting temperature of 52–54 C, latent heat of 182.6 Jg^{-1}) as a core and MF as shell, as shown in **Figure 9** [27]. With 10 g of paraffin wax and 61.6% encapsulation efficiency, the latent of encapsulated PWTC is 107.4 Jg^{-1} .

It is thus obvious that the encapsulation process covers the several steps at various process constraints to create the final PWTCs. Normally, the morphology is spherical and it is filled with paraffin wax, as shown in Figure, therefore encapsulation efficiency (how much core material can be surrounded and uptaken by the shell of encapsulant) is the fundamental parameter to be emphasized for encapsulated PWTCs. In another example of triplex PWTC is presented where HDPE has been employed as an encapsulant for paraffin wax (melting temperature of 54–56°C and latent heat of 199 Jg^{-1}), and copper metal foam has been introduced enhancing the thermal conductivity of HDPE/paraffin wax from $0.72 \text{ Wm}^{-1} \text{ K}^{-1}$ to $2.14 \text{ Wm}^{-1} \text{ K}^{-1}$ and reducing the latent heat as minimum as 151.6 Jg^{-1} . The PWTCs also

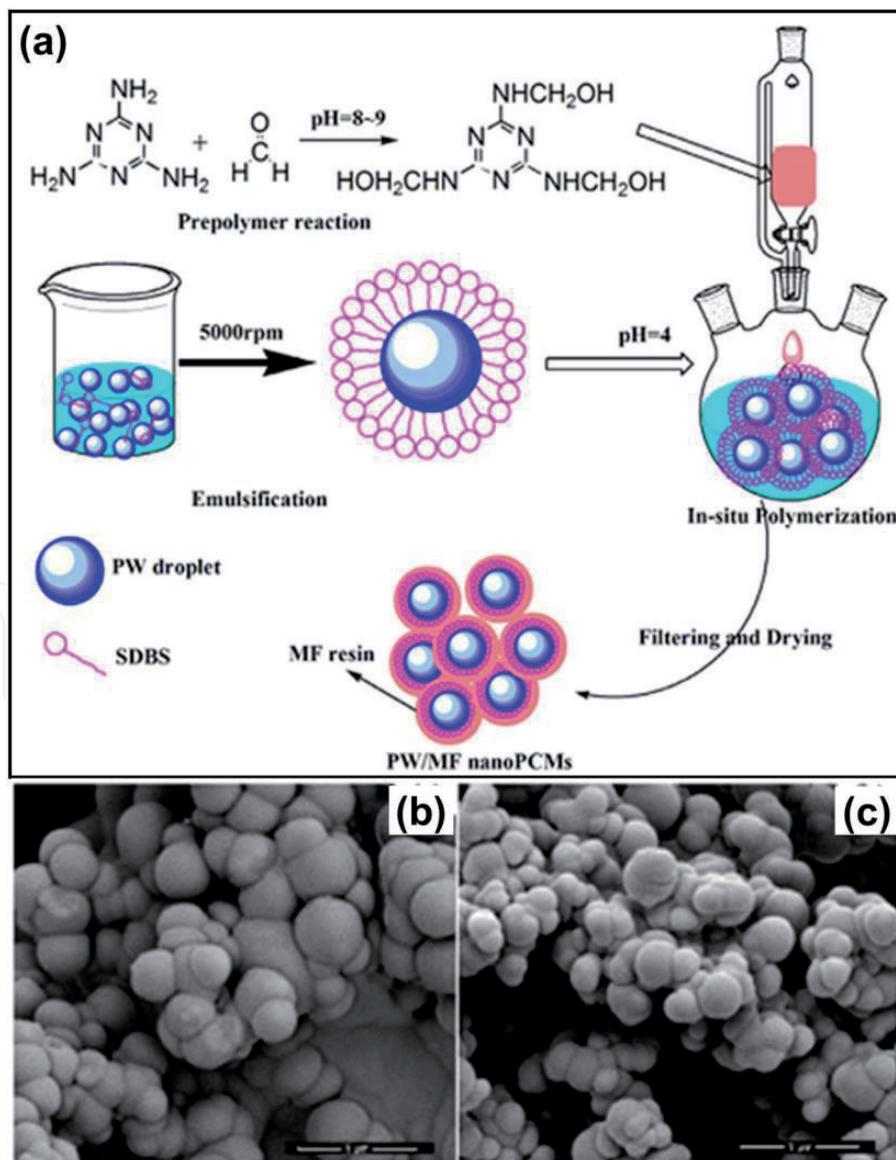


Figure 9. (a) Fabrication of encapsulated PWTC and (b-c) the corresponding morphology [27].

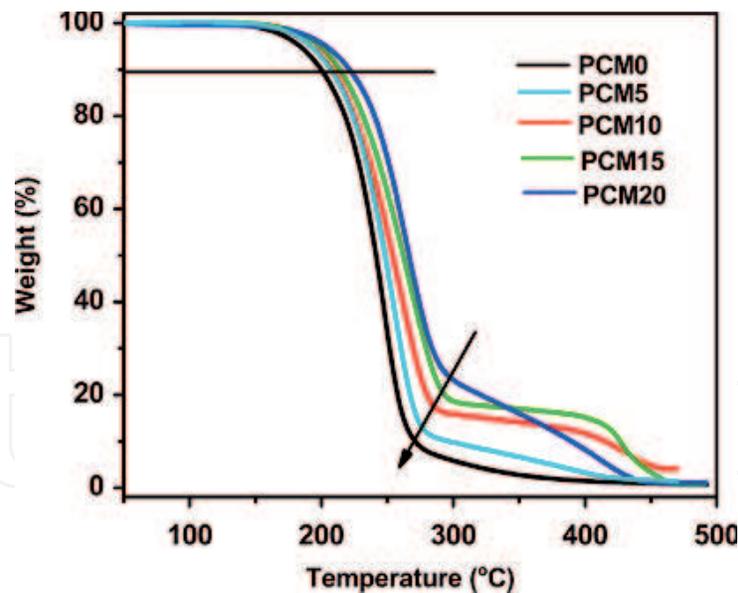


Figure 10.
Thermal stability of paraffin wax and PWTCs via TGA [30].

provided favorable shape-stability, allowing 2.3% mass loss of paraffin wax after 50 thermal cycles [28]. In a word, the stronger the encapsulant shell is, the more effective is the shape-stability. Generally, several other examples are also found where carbonic thermal reinforcements have been introduced to accelerate thermal response of encapsulated PWTCs, such as EG [25, 26].

Apart from the salient merits of providing shape-stabilization, organic encapsulants are thermally stable too [29], imparting the adequate thermal stability to PWTCs. For example, SEBS has been employed to encapsulate paraffin wax (melting temperature of 52–54°C and latent heat of 176.6 jg^{-1}) in different percent contents (5–20%), and 20% of SEBS enhances the thermal decomposition temperature of PWTC to around 221.4°C, as demonstrated in **Figure 10** [30].

3. Bottlenecks, recommendations and design standards for PWTCs

The fabrication of PWTCs is simple until investigated recently; nonetheless thermo-physical bottlenecks of the paraffin waxes still exist. For example, their inert features do not allow chemical reactions, so the utilization of chemical methods for fabrication of PWTCs can be overlooked. Thus, physical methods are only viable options for the fabrication of PWTCs. However, physical methods can also be wet or dry, for example, mixing the melted paraffin waxes with thermal reinforcement is the dry-physical method, while dissolving the paraffin wax into a solvent and then mix with thermal reinforcement is the wet-physical method or encapsulating the paraffin wax in the capsules is also the wet-physical method. Meanwhile, the shape-stabilization can be achieved via both methods, but thermal conductivity improvements have abundantly been reported based on dry-physical methods. Besides, thermal conductivity of PWTCs prepared via dry-physical methods is not sufficiently high, leaving a wide research roam and urging to put rigorous efforts into this serious matter. However, the PWTCs with increased thermal conductivity suffer from another challenge which consists of a short and uprising isothermal zone, indicating the reduced duration of temperature-control capacity. The uprising isothermal zone dictates that the temperature-control capacity of PWTC is not perfectly constant, but nearly constant and fast. A case-study describing this standpoint can be seen above in **Figure 7**.

Thus, either maximum or minimum, threshold limit of the thermal reinforcements is very important in PWTCs, which is however not standardized yet. Thermal reinforcements always demand the equal replacement of base material in PWTCs, signifying that the equivalent reduction in latent heat storage capability [12]. In such a situation, the design parameters of PWTCs should be adjusted according to the target applications. For example, thermal management of photovoltaic panel is required to be done through PWTC. In this case, the liquid drainage of the PWTC may not be considered a design parameter of the primary importance because the mechanical enclosure can assist in controlling the liquid drainage, meaning that the form-stability of PWTC can be neglected. However, the heat accumulation at the interface of PV and the hot-spots in the PWTC body are altogether supposed to be the primary design parameters. Therefore, thermal reinforcements for such applications should solely be the TCEs that can help fabricate the duplex PWTCs. Counter-institutively, Another case can be discussed regarding the thermal management of buildings where PWTCs should capable of ensuring prolonged temperature-control capacity as well as adequate shape-stability. So, thermal reinforcements for such applications should solely be the SSs, but the SSs needs to conform the property prerequisites of the building ingredients like cement, sand, and clay, etc., which altogether leads to the triplex PWTCs. In between these two scenarios, special applications such as thermal management of satellites, robots, and astronauts can be put forth, where the total quantity of PWTC emerges is another design parameter together with consideration of temperature-control capacity and shape-stabilization.

PWTCs can also suffer from the challenge of saturation energy storage limit which is dependent on the total thermal energy storage (sensible heat + latent heat)

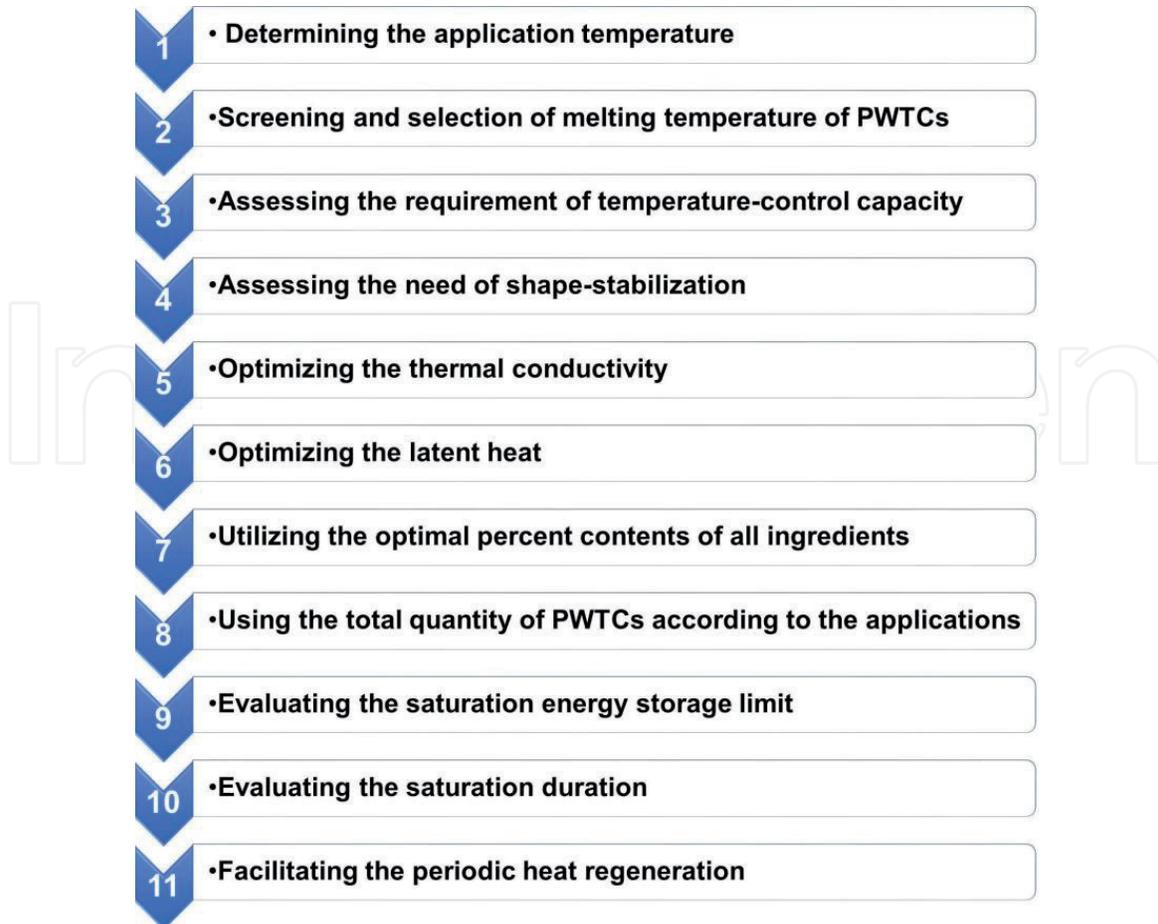


Figure 11.
Proposal of design standards for PWTCs.

of paraffin wax. This challenge is expected to emerge in all kinds of applications. Therefore, it is strongly recommended to evaluate the total saturation duration that can anticipate saturation energy storage limit. Accordingly, the periodic heat regeneration of PWTCs, i.e., extracting the stored thermal energy, becomes essential to keep the whole thermal management system fresh for the coming cycles. The possible methods for periodic heat regeneration encompass the natural convection or forced convection achieved either via air or water for which deep design considerations of the whole thermal management systems are required.

Among thermal reinforcements, EG can act both as TCE and SS [29, 31], pointing out that duplex PTWCs can be fabricated for thermal management with high charging/discharging rates. Therefore, EG is declared to be the most effective carbonic thermal reinforcement.

Although the design standardization of the optimal PWTCs is complicated, the parameters as-proposed in **Figure 11** may serve as the preliminary design principles.

4. Conclusions

The research paradigm on PWTCs has recently been shifted from duplex thermal composites to triplex thermal composites, which however lacks of the design standards. It is therefore stressed that the fabrication of PWTCs should be reported conforming with the screening requisites of specific applications, because proclaim is that every PWTCs is not applicable everywhere. Shape-stability is the design standard, but it may be essential only for a few applications, most importantly including thermal management of buildings and fabrics. Instead of shape-stability, high thermal energy storage capability and high thermal conductivity are the most important parameters for thermal management of heat-emitting devices and systems where mechanical enclosures are essential, helping in controlling the liquid drainage threats. Thus, shape-stabilizers should be carefully employed. In all, attention should be paid on thermal reinforcements such that the optimal PWTCs can be created. Most importantly, the focus should be asserted on the thermal interface between paraffin waxes and thermal reinforcement which is the backbone allowing the development of well-defined thermal paths for higher thermal conductivities of PWTCs. On the whole, three main hypotheses should be carefully checked for an ideal PWTC strictly depending on the target application: (i) preservation of optimal latent heat, (ii) maintenance of the trade-off between thermal conductivity enhancement and latent heat reduction, (iii) achievement of the optimal shape-stability.

Acknowledgements

The support provided by IntechOpen is highly acknowledged.

Conflict of interest

The authors declare no conflict of interest.

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