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Research Article

Application of Thermal Energy Accumulators Based on Paraffin Phase Change Materials in Convective-Vacuum Impulsive Drying Units: A Brief-Focused Overview of Characteristics and Thermal Conductivity Enhancement Techniques

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ABSTRACT

Researchers worldwide are studying thermal energy storage with phase change materials because of their substantial benefits in the enhancement of energy efficiency of thermal drying systems. A two-stage convective-vacuum impulsive drying plant is a technology for the manufacturing of chemical and food products with high quality and low energy costs. Energy consumption during the drying process is the main indicator in terms of economy. In this paper, a brief and focused review of the peculiarities of TEAs with PPCMs and opportunities of their application in such drying systems is done and discussed. The paper described the mentioned manufacturing system. The advantages of paraffin wax and thermal conductivity improvement techniques were demonstrated for their use as heat storage materials in CVID drying units. The results of similar previous studies were presented. The results of the experimental studies conducted by the researchers proved that the use of heat accumulators with PCMs increased the overall energy efficiency of drying systems. Finally, integration of TEAs based on modified PPCMs in the CVID system was recommended to intensify thermal energy, reduce thermal influence on the main indicators of the vacuum pump during the evacuation process, and decrease production costs.

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1. INTRODUCTION

1.1. General background

Drying is a traditional preservation technique for the preservation of food products and the processing of various chemical materials. It is a process of dehumidification from substances. It is a time-consuming and energy-intensive process (Azzouz et al., 2018; Iqbal et al., 2019). The energy needed to remove moisture content can be procured from traditional and non-traditional sources (Aktaş et al., 2016; Malakar and Arora, 2022). Reliance on fossil fuels as a source of energy (heat) during the drying process of raw materials leads to major environmental problems. Currently, preserving the environment and finding alternative energy sources are among the most important issues in developing countries (Bahari et al., 2020; Srinivasan et al., 2021). In most industrial and technological processes, the operation of machines and devices is accompanied by the release of heat, which is poorly used, hence heat loss. The application of thermal accumulators based on phase change materials with various thermal performance improvement techniques works to manage the thermal energy in the drying system and increases the drying speed, thus reducing energy costs (Ahmadi Mezjani et al., 2022; Babapoor et al., 2015; Babapoor et al., 2022; Bahari et al., 2020; Srinivasan et al., 2021). In this review, a beneficial insight is provided on the main characteristics of PCMs with a focus on paraffin waxes and methods for improving thermal conductivity as materials for storing heat energy during thermal processing of raw materials to intensify the thermal energy consumed by a two-stage Convective-Vacuum Impulsive Drying (CVID) plant. The aim of this paper is to study the potential of thermal energy storage and recirculating stored heat depending on the TEAs with PPCM to be integrated in CVID units.

1.2. Working principle description of convective-vacuum impulsive drying unit

The convective-vacuum impulsive drying plant is a two-stage drying technology used for the manufacturing of products with high quality and low energy consumption in the food and chemical industries (Didone and Tosello, 2016; Zubov and Khamitova, 2011; Nikitin et al., 2021). The first stage is the processing of materials using the traditional hot air convective dryer (Figure 1a) to remove the free moisture content from the external surface of the material. It involves two main processes.

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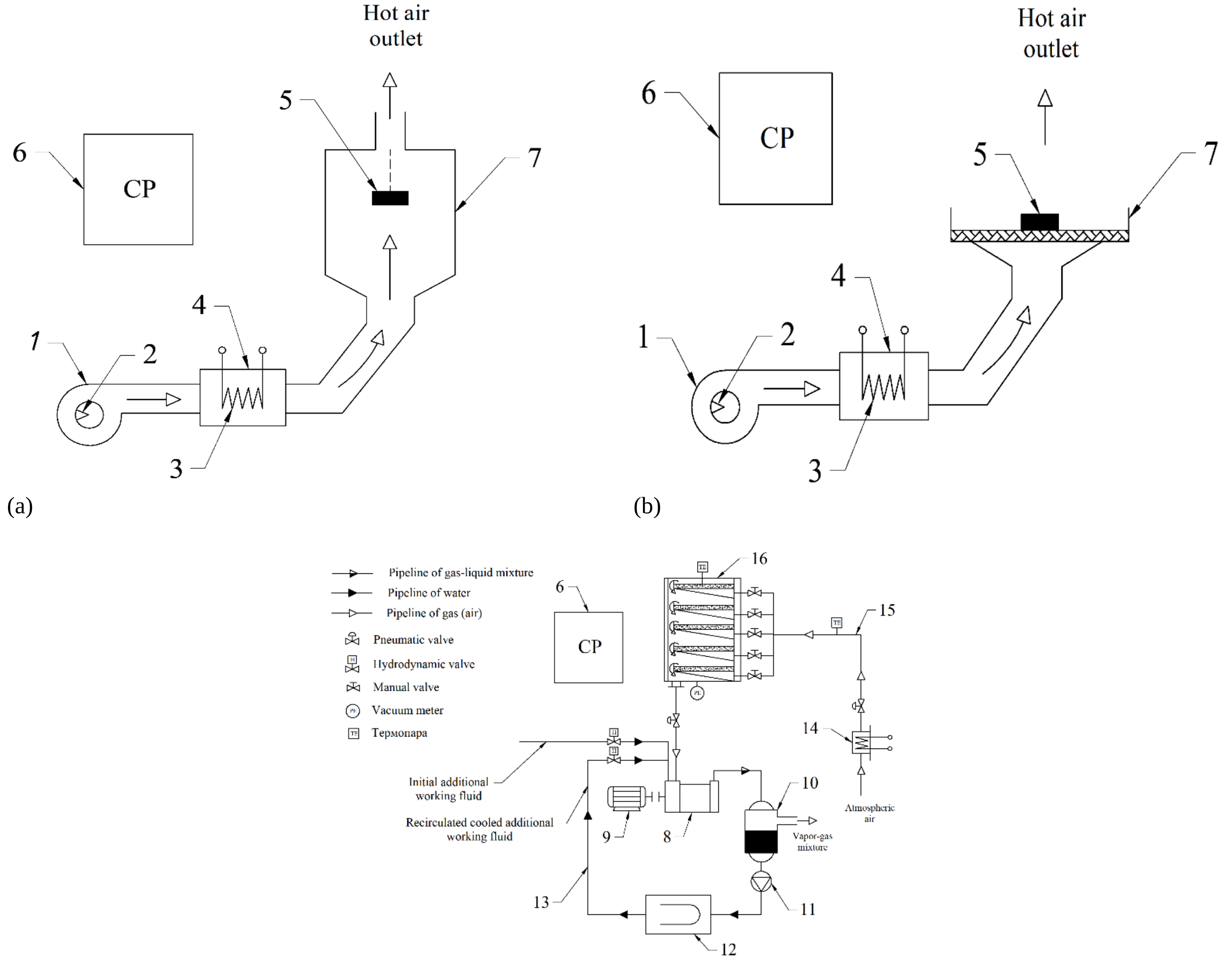
The first is transfer (supply) of the thermal energy from the surrounding environment to the materials (solid) (5). The hot air heated by heater (3) to a desired temperature is provided using blower (1). Regulator (2) controls the flow rate of the supply air. The second process is the transfer of humidity from within the materials (removing moisture) in the drying chamber (7). The control panel (6) contains devices to control and display the main parameters of the drying process. As a result, it may be thought of as a simultaneous process of mass and heat transmission. It is worth noting that convection drying for the first stage can be done using a tray dryer as shown in Figure 1b. The second stage is the removal of bound moisture from the substance by means of vacuum impulsive cabinets with auxiliary equipment (Figure 1c). In this technology, the evacuation process takes place at a lower temperature and a higher mass transfer rate; as a result, the energy consumption during drying is reduced. The mechanism of action consists of the following periods: The first period is the heating of the material placed in the drying cabinet (9) through heated air by an electric heater (7) at a desired drying temperature. In this period, the temperature of substance and drying rate is constant. The second period is the removal of bound moisture by vacuumization using a liquid ring vacuum pump (LRVP) (1). The control panel (10) with needful controllers is used to adjust the parameters of the drying process. The pneumatic valves are employed to regulate the flow rate in air pipelines. The hydrodynamic valves are applied to controlling the indispensable working fluid for the normal operation of the LRVP. A chiller (5) is employed to cool the recirculated working fluid and to prevent liquid evaporation in the working cavity of LRVP. The set temperature and periods of heating and evacuation depend on the characteristic of products to be dried. The cycle is repeated until the required moisture content of the product is obtained. Figure 2 presents the 3D of the CVID system.



(a)

(b)

(c)

Figure 1. Schematic diagram of a two-stage drying plant (Zorin, 2019): (a) the first stage of hot air convective dryer with a suspended swirling layer; (b) the first stage of hot air convective tray dryer; (c) the second stage of vacuum impulsive cabinets with recirculation of working fluid of LRVP: 1 – blower, 2 – air flow regulator, 3 – electric heater, 4 – heating unit, 5 – sample of material, 6 – control panel, 7 – drying chamber, 8 – LRVP, 9 – electric motor, 10 – gas-liquid phase separator, 11 – water circulation pump, 12 – chiller for cooling of recirculated working liquid, 13 – water pipeline, 14 – electric heater (resistance), 15 – air pipeline, and 16 – drying cabinet.

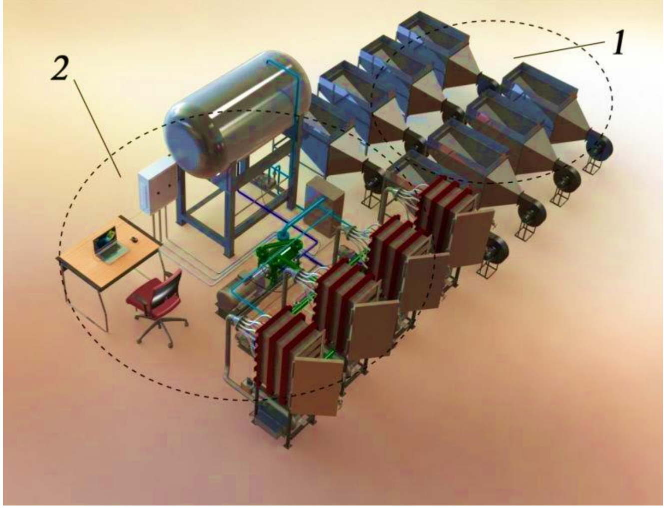


Figure 2. 3D configuration of a two-stage CVID (Petrovna, 2016): 1 – The first stage of hot air convective tray dryers, 2 – The first stage of vacuum impulsive cabinets with auxiliary equipment.

2. THERMAL ENERGY ACCUMULATORS

Thermal Energy Accumulators (TEAs) are units or apparatuses that are used to temporarily store thermal energy for use at a later time (Zorin, 2019). The energy demand varies with time according to thermal drying system requirements. This change can be controlled through the integration of TEAs with PCMs (Socaciu, 2012). The selection of TEAs for a drying plant depends on many factors, such as supply temperature requirement, economics, storage duration, heat losses, storage capacity, and available space (Ibrahim and Marc, 2011). There are two main kinds of TEAs: sensible and latent. Sensible TEA systems accumulate TE by modifying the temperature of the utilized storage medium, like soil, brine, water, rock, etc. Latent systems accumulate TE by phase change, e.g., the storage of heat through melting paraffin waxes and cold storage water/ice. In addition, TAs can be performed through chemical reactions (Abedin, 2011; Socaciu, 2012). Figure 3 illustrates the categories of TEA units (Sarbu and Sebarchievici, 2018).

2.1. Phase change materials

PCMs are latent heat storage materials that have been used in many thermal applications due to their thermo-physical peculiarities (Du et al., 2018). Heat is mostly accumulated during the phase change process and is directly connected to the substance's latent heat. The application of TEAs with PCMs is considered an efficient and desirable technology because they provide isothermal and high thermal energy storage (Sarbu and Sebarchievici, 2018). PCMs are classified into several types, as shown in Figure 4. TEAs with PCMs typically involve three stages: charging, storing, and discharging. They are a reliable technology dependent on the storage of latent heat energy (Mondal, 2008), where PCM absorbs or releases heat with time during the charging and discharging process (phase change period), with a high heat of fusion (Ghoneim, 1989; Morrison, 1978), as shown in Figure 5.

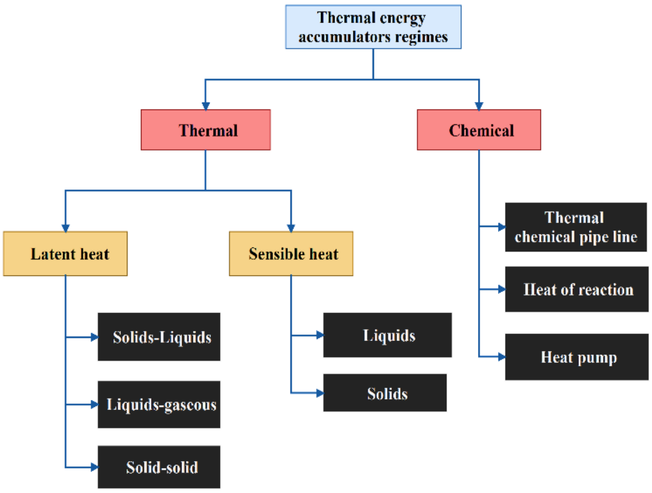


Figure 3. Classifications of the thermal energy accumulator regimes (Sarbu and Sebarchievici, 2018).

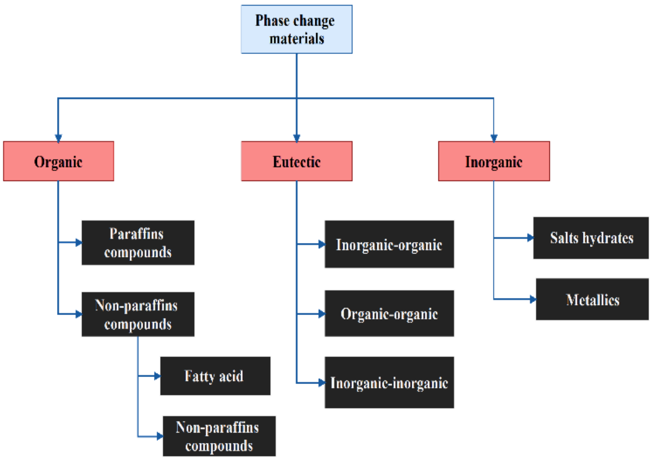


Figure 4. Classifications of PCMs (Sarbu and Sebarchievici, 2018).

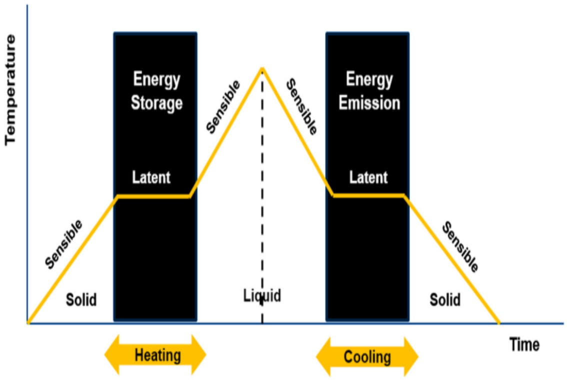


Figure 5. Regime representation TEAs-PCMs, cycle of charging, storing and discharging in case of cooling and heating (Du et al., 2018).

The amount of stored sensible heat depends on the average specific heat of the medium, the quantity of storage material, and the temperature change. The sensible heat for various materials can be calculated as follows (Kumar and Shukla, 2015):

$$Q_s = c_p\, m \int_{T_i}^{T_f} dT = c_p\, m\,(T_f - T_i) \qquad (1)$$

where Q_s is the amount of sensible heat stored in, J; c_p is the specific heat of the materials, J/kg.°C; T_f, T_i are the final and initial temperatures, °C. The accumulated latent heat via PCMs can be calculated using the following equation (Kumar and Shukla, 2015):

$$Q_{LHS} = \int_{T_i}^{T_m} m_{PCM}\, c_{ps}\, dT + m_{PCM}\, q_{hf} + \int_{T_m}^{T_f} m_{PCM}\, c_{pl}\, dT \qquad (2)$$

$$Q_{LHS} = m_{PCM}\left[c_{ps}\left(T_m - T_i\right) + q_{hf} + c_{pl}\left(T_f - T_m\right)\right] \qquad (3)$$

where m_{PCM} is the mass of PCM medium, kg; T_m is the melting temperature, °C; c_{pl} is the average specific heat of the liquid phase between T_m and T_f, J/(kg·K); q_{hf} is the latent heat of fusion (J/kg) at the temperature of phase change T_{pc}; c_{ps} is the average specific heat of the solid phase between T_i and T_m, kJ/(kg·K). The reported advantages and disadvantages for several PCMs are tabulated in Table 1 (Pahamli and Valipour, 2021). In thermal energy storage applications, paraffins, fatty acids, and hydrated salts are the most common widespread used materials (Sarbu and Sebarchievici, 2018). Ice water is frequently utilized in cold storage, as well (Sarbu and Sebarchievici, 2018). The important thermophysical properties of some indispensable PCMs are presented in Table 2.

2.2 Paraffins as latent PCMs

2.2.1. General overview

Among many types of PCMs currently available, paraffin waxes have been used in many types of thermal applications. They belong to groups of organic PCMs with greater processing options than the other types illustrated in Figure 4. Furthermore, because of their widespread accessibility, safe operation, and low cost, they are a remarkable choice to enhance the thermal efficiency of the drying system (Srinivasan et al., 2021). Paraffin is a hydrocarbon combination and is derived basically from waste products of the petroleum. Depending on the number of carbon atoms, the state of the phase is distinguished. They are in a gaseous state under room conditions with a number of carbon atoms ranging from 1 to 4 and carbon atoms from 5 to 17 being in a liquid state and waxes with a number of carbon atoms more than 17 (Al-yasiri, 2021). Typical paraffin properties are listed in Table 3. Figure 6 presents the appearance of paraffin available in local markets.

Table 3. General properties related to paraffins (Hamad, 2021).

Property	Liquid phase	Solid phase
Boiling point	> 370 °C	
Melting temperature	57 °C	57 °C
Thermal conductivity	0.25 W/m °C	0.23 W/m °C
Specific heat capacity	1.6 kJ/kg °C	2 kJ/kg °C
Latent Heat of Fusion	2.1 kJ/kg °C	
Chemical formula	C_nH_2n+2	
Appearance	According to source of paraffin and composition	

Figure 6. Appearance of paraffin wax (Al-yasiri, 2021).

Table 1. Advantages and disadvantages of PCMs (Pahamli and Valipour, 2021).

Indicator	Organic Material	Inorganic Material	Eutectic Material
Advantages	- Good chemical and thermal stability, - Non-corrosive, - Low vapor pressure, - No supercooling, - High heat of fusion, - Nontoxic.	- Inexpensive, - Nonflammable, - Good thermal conductivity, - High heat of fusion.	- Wide range of phase change temperature, - Good chemical and thermal stability, - High heat capacity, - No or little supercooling.
Disadvantages	- Low thermal conductivity, - Low phase change enthalpy, - High changes in volumes during the phase transition.	- Corrosion, - Phase decomposition, - High supercooling effect, - Loss of hydrate throughout the process, - Insufficient thermal stability, - Weight problem.	- Leakage during the phase transition, - Low thermal conductivity.

Table 2. Properties of the main PCMs (Sarbu and Sebarchievici, 2018).

PCM	Melting enthalpy (kJ/kg)	Melting Temperature (°C)	Density (g/cm^3)
Ice	333	0	0.92
Na-acetate trihidrate	250	58	1.30
Paraffin	150 - 240	- 5 - 120	0.77
Erytritol	340	118	1.30

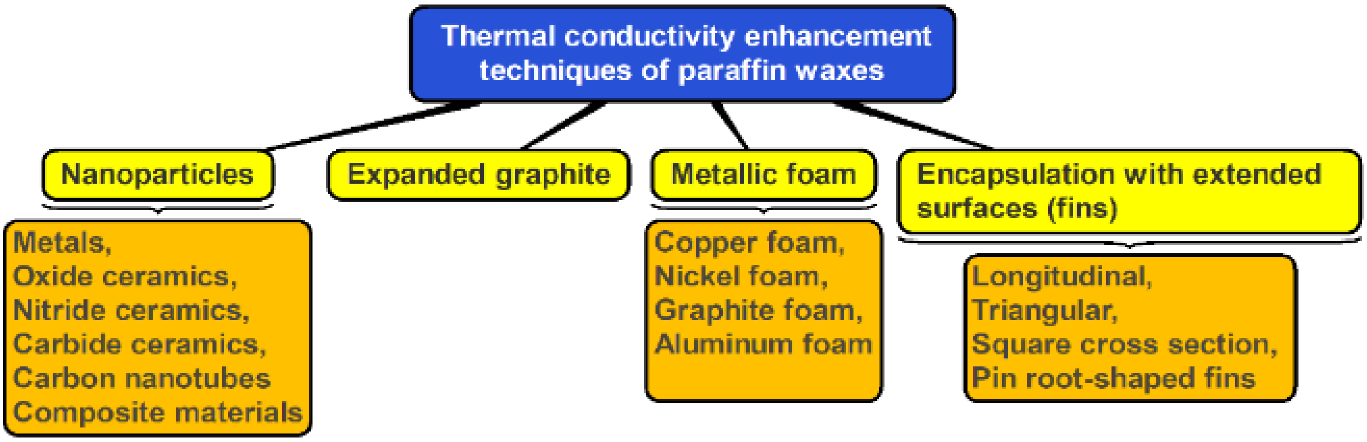


Figure 7. TC enhancement methods of paraffin PCM.

2.2.2. Thermal conductivity enhancement techniques of paraffin

Despite the many advantages of paraffin such as no sub-cooling, non-toxic, low-cost, high latent heat, eco-friendly, non-corrosive, and chemical stability (Sharma et al., 2009), they are renowned for their poor thermal conductivity (TC), causing melting and solidification to take longer and have an influence on thermal performance of convective and TVID plant. Five known methods exist to improve the TC of paraffin, as shown in Figure 7. Recently, nanoparticles (NPs) have been used to increase the TC of paraffin. In this regard, many studies have been conducted in depth and the results are attractive (Wang et al., 2019; Zhang, 2020). The use of NPs with paraffin activates the charging and discharging time, which is positively reflected on the thermal system performance. Modified paraffin by NPs is manufactured in the same way as nanofluids (Al-yasiri et al., 2021; Sundar et al., 2017). Figure 8 shows the manufacturing stages of PPCM-NPs. The other method is to use expanded graphite (EG) as a supplement material with paraffin to increase the TC (Kenisarin et al., 2019). It is a novel approach to improving the TC of paraffin. As the mass fraction of EG increases, the TC of paraffin increases (Zhang et al., 2020). The steps of PPCM-EG are shown in Figure 9. Metallic foam is another important way to improve the TC of PPCM. High TC of the base materials makes metallic foams an excellent choice. Moreover, their better properties, such as long-term stability and lower density, make them preferred over NPs (Qureshi et al., 2018). The effectiveness of metallic foams is determined by the density of the pores, the size of the pores, and the type of foam material (Tauseef-ur- Rehman, 2018). Figure. 10 illustrates the stages of preparation. The TC of PPCM can considerably improve by encapsulating it in finned containers (internal and/or external fins). This technology is a cost-effective solution that has demonstrated significant improvement when used with high-TC materials like stainless steel aluminum, and copper. Fins speed up the melting and solidification processes, reducing the time required to complete the cycle. Different characteristics of fins, such as size, type, spacing, and the number of fins, affect the thermal performance of PPCM (Shehzad et al., 2021; Zayed et al., 2020). The different shapes and designs of the fins utilized for the PPCM TC improvement are shown in Figure. 11.

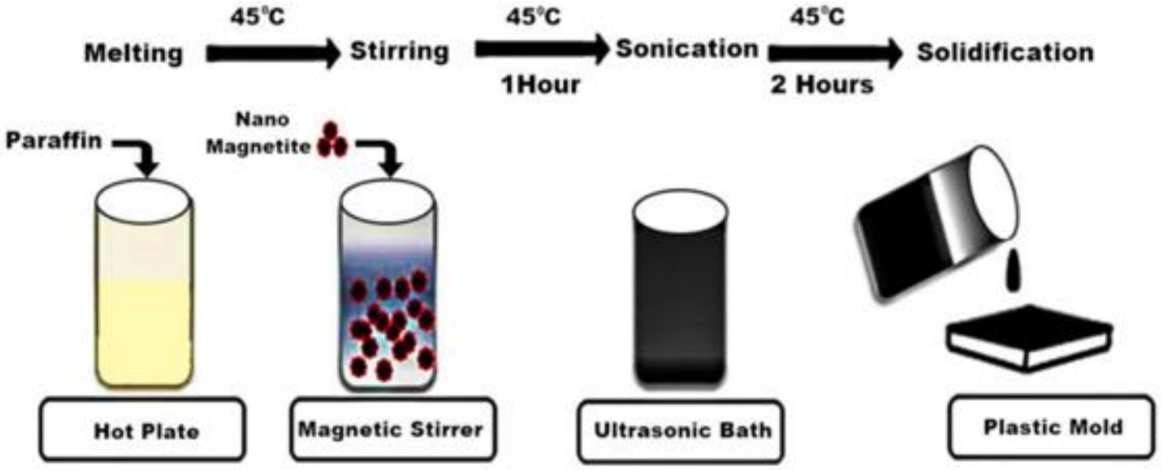


Figure 8. Preparation steps of PPCM-NPs (Mohammad et al., 2019).

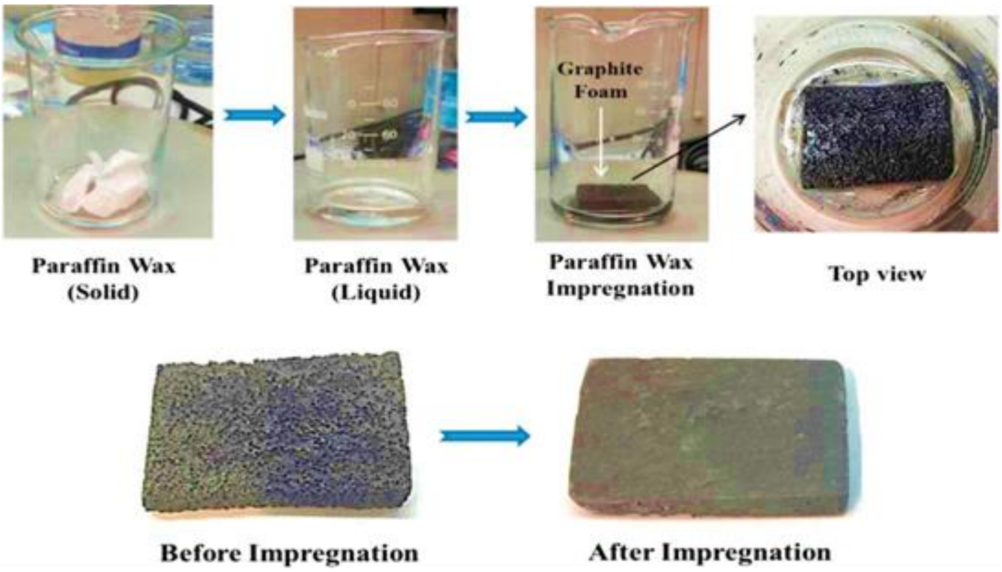


Figure 9. PPCM-EG preparation steps (Karthik et al., 2017).

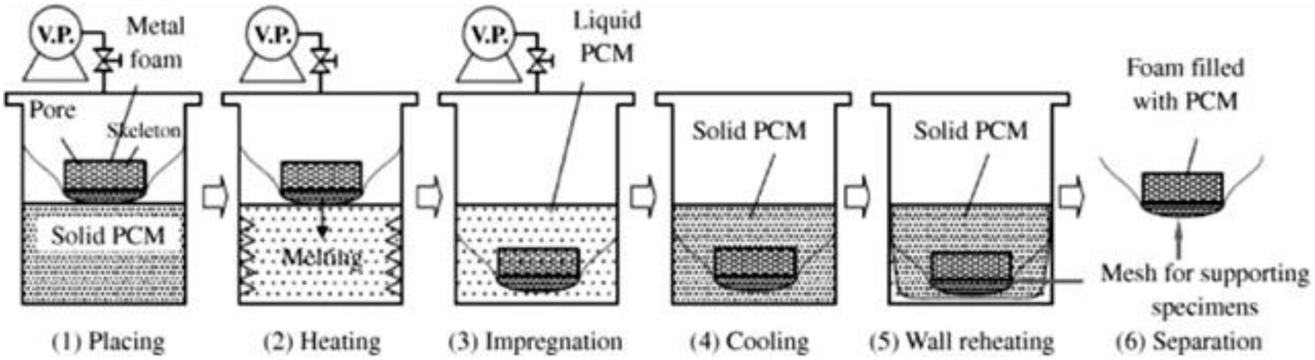


Figure 10. Preparation of PPCM-metal foam (Xiao et al., 2013).

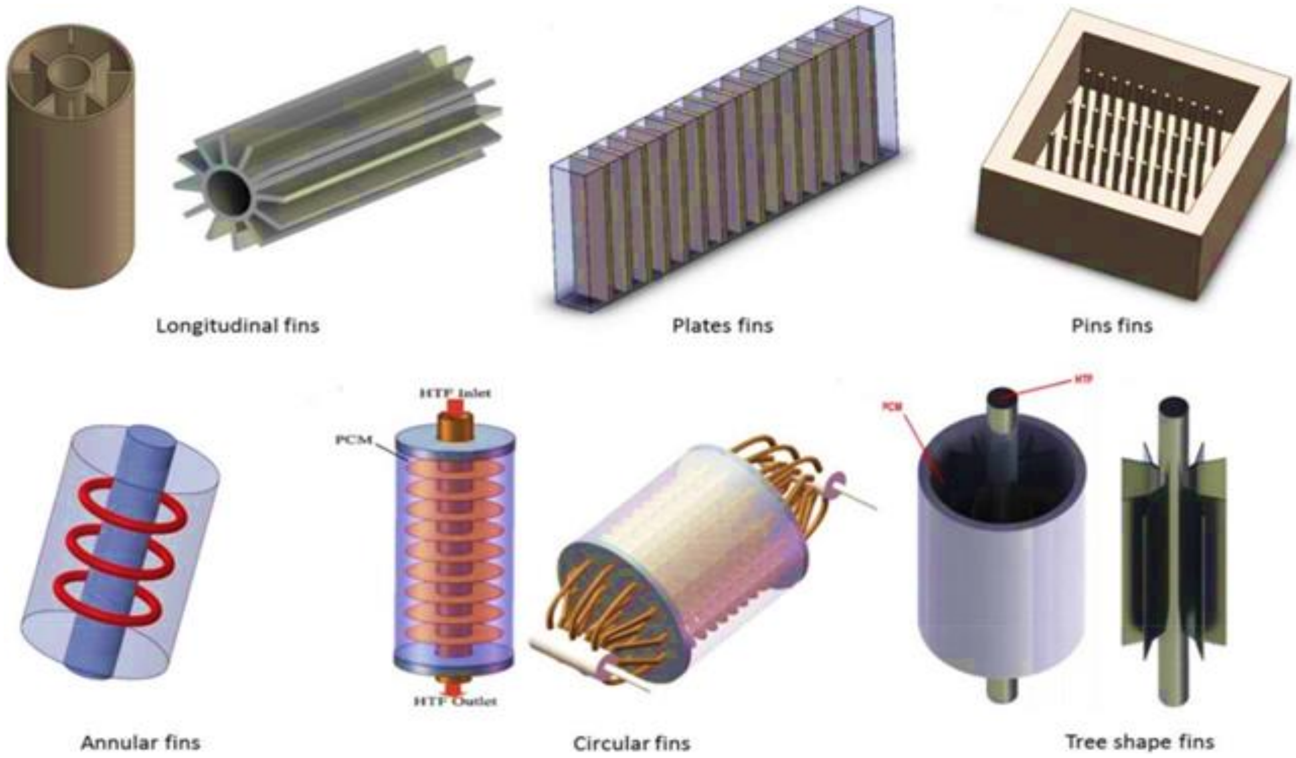


Figure 11. Various types of TEAs/containers encapsulated with external and internal fins (Al-yasiri, 2021; Wu et al., 2021).

3. RECENT RELEVANT STUDIES AND EXPERIMENTS

In connection with the topic of the current article, this section presents and discusses the reported investigations. Due to the large volume of published research on the use of TEAs with PCMs in drying systems, this review focuses on the relevant and strong works published in recent years. Hamad, 2021, were applied PCMs to solar air drying and air conditioning systems for energy saving. An experimental setup was developed to investigate two PCMs: paraffin wax and RT-42 in different locations. The findings showed a considerable increase in energy saving. For the first PCM1 (paraffin wax) and PCM2 (RT-42), complete melting occurred during the charging cycle at temperatures of 57-60°C as well as 38-43°C. When two PCMs were used, the overall energy saving was higher by around 29.5% and 46.7% than the application of PCM1 and PCM2, respectively. Poonia et al., 2022, investigated a solar dryer with and without PCMs to dry arid fruits. They employed an experimental approach to test the use of polyethylene glycol (PEG) 600 as a heat storage material during drying. The results revealed that the moisture content of the product decreased from 80% to 22% in seven days in the case of PCM and in 9 days without PCM. In date palm fruit, MC was reduced from 65 to 20% in 6 and 8 days with and without PCM, respectively. The thermal efficiency was 18% with PCM compared to 15% without PCM. Mahdavi Nejad, 2020, studied the drying process of paper with PCM. The drying efficiency was enhanced by about 45%. Bhardwaj et al., 2021, evaluated the thermal performance of the solar dryer using PCM. They used paraffin RT-42 as PCM during the experimental test. The outcome of study indicated that the products were dehydrated to a value of 9% from preliminary MC of 89% and it took 120 (216) hours with (without) use of PCM. The mean values of the exergy and energy efficiencies of the SAC without (with) PCM were calculated to be 0.14 (0.81%) and 9.8 (26.2%)%, respectively. Rodionov et al, 2020, integrated TEA-based PCMs to enhance the energy efficiency of a two-stage combined vacuum impulsive drying for plant materials. They introduced nano modified PPCM as a material to store the heat during their experimental studies. Utilized TEAs reduced electricity losses by 20%-25%. In this regard, they (Zorin et al, 2019), were awarded a patent.

4. CONCLUSION AND FUTURE PERSPECTIVE

This study investigated the application characteristics of TAs with PPCM and thermal conductivity improvement techniques to be used in the CVID unit. From the results of previously reported studies, the following conclusions can be derived.

1. The use of TEAs with PPCM is a successful method to reduce the time consumed in the drying process of materials in CVID system;
2. The design of TEAs based on PCMs is a complex issue when inserted in such systems;
3. Paraffin waxes are most commonly used as a heat storage material. Their main disadvantage lies in the low thermal conductivity;
4. Many techniques for improving the thermal conductivity of PPCM are reported in the literatures. A cost-effective method is encapsulating it in finned containers (internal and/or external fins).

Currently, work is underway to use TEAs based on paraffin waxes or modified paraffin as a heat storage material/cooler and temperature regulation in a CVID technology. Considering the characteristics of TEAs with PPCMs presented in this paper, it is recommended to design liquid ring vacuum pumps units with integration of TEAs with PPCMs to prevent the deformation of form of liquid ring (evaporation of liquid) in the working cavity during their use in heat and mass transfer devices/processes such as drying and evaporation. Studies such as suitable design of TEAs and the possibility of recirculation of stored heat are candidate.

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NOMENCLATURE

PCM/ PCMs	Phase change material/ materials
TEA/TEAs	Thermal energy accumulator/ accumulators
CVID	Convective-vacuum impulsive drying
TE	Thermal energy
TC	Thermal conductivity
NPs	Nanoparticles
PPCM	Paraffin phase change materials
EG	Expanded graphite
LRVP	liquid ring vacuum pump
TVID	Thermo-vacuum impulsive drying

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