












## Review Article

# Phase Change Materials in Metal Casting Processes: A Critical Review and Future Possibilities

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Phase change materials are the category of materials that release or absorb enough energy during phase change transformation to provide heating or cooling. Divided into two principal classes of organic and inorganic, these materials find a wide range of uses in commercial applications of casting where stable temperature and heat storage are a requirement. In this research work, application of inorganic phase change materials having significantly elevated temperature zone, especially within metal casting processes, has been discussed. Phase change material with high enthalpy of fusion and high melting point can be used for metal casting, but in a limited temperature range (between 200°C and 1300°C). In sand casting, inorganic PCM has the potential to be used as chills to provide directional solidification. Despite having advantages, inorganic PCM comes with major disadvantages, that is, toxicity, corrosivity, supercooling, and low thermal expansion. Few solutions to overcome these problems have been discussed in this research paper. Future research is required to reduce the disadvantage to a low level, so that PCM can be used in application where elevated temperature is achieved.

## 1. Introduction

There is a looming crisis surrounding us today: the ever-growing consumption in energy and its subsequent harms. Energy consumption is growing across all its uses [1]. Manufacturing industries are one of the leading consumers of energy [2]. With the increase in energy production, the levels of greenhouse gases also increase substantially. Elevated levels of greenhouse gases harm our environment and result in various long-term adverse effects to the climate and natural resources. It is imperative then, in the face of increasing climate change concerns, that we find efficient ways to generate, produce, and

store the energy we use that are also sustainable in the longer run. On the lookout for better ways to store energy, phase change materials show a promising future [3]. PCMs (phase change materials) can be widely classified into three parts, based on their chemical structure: organic, inorganic, and eutectic [4]. Organic PCMs are composed of paraffin and nonparaffin [5], and inorganic phase change materials include salt hydrates and metals. Eutectic PCMs consist of combinations of inorganic and organic phase change materials. Because of their high storage capacity which is achieved using thermochemical reactions involving adsorption, they are well suited to provide solutions to the problem of energy storage.

PCMs are currently used in under floor heating systems, ceiling boards, and off-peak electricity storage systems [6]. They are used in various heating and cooling applications [7], including the production of beverages like coffee, milk, and wine along with heat pump systems and solar power plants [8, 9]. Their use also extends to cooling in computers and production of textiles used in clothing. Amongst all manufacturing processes, metal casting is the most widely used. Every product we use today has been made, in the initial stages, by some form of casting. Metal casting has rightly been described as a modern process having ancient origins. The basis of all types of metal casting process is similar, that is, forming metal shapes by pouring hot molten metal into mold cavity and solidifying it to obtain the desired shape. Contestably, metal casting is the most influential and ancient industrial process dating back around 6000 years that is still in use today. The basic metal casting tools used for this process are classified into hand tools, mechanical tools, and containers. Hand tools consist of tool such as rammer, shover, riddle, and vent wire. Mechanical tools are used in automated foundries in modern days.

This metal casting process is done in industries known as foundry. Foundry is the largest contributor of recycling manufacturing as tonnes of metals are melted and remoulded every day in these factories. Metal casting takes place over a series of steps that includes mold making, pouring molten metals in these molds in foundry, removing the solidified metal from its mold (shakeout), removing runners, gates, risers (degating), heat treatment, surface cleaning, and finishing.

## 2. Processes of Metal Casting

Metal imitation is a modern process with ancient seats. In the metal molding process, the final mold is produced by pouring molten metal into the mold hole, where the molten metal cools and the final extract is extracted from the skin. It is used to make many metal objects that are used in our daily lives: car tires, train wheels, light poles, school buses, and much more. In addition, steel foundations also rely on the recycling of iron as a viable source of underdeveloped material, which greatly reduces waste disposal that ends up in the landfill.

### 2.1. Types of Metal Casting

**2.1.1. Sand Casting.** The most common way to make castings is to use a sand mold. Sand mold is made of ramming sand in metal or wooden containers. Figure 1 shows the Schematic representation of sand casting. The basic sequence of operations required for sand formation is

- (i) pattern making,
- (ii) mold and core making,
- (iii) melting of metal and pouring the metal,
- (iv) cooling and solidification,
- (v) cleansing of castings and inspection.

In the process of sand casting, liquid metal is poured into a hollow sand mold, where it solidifies as it cools down. The mold is made up of sand particles held in position with an inorganic binder. After the metal has cooled to ambient temperature, the sand mold is opened to remove the casting. Figure 2 shows a flowchart representation of process of sand casting. The main merit of sand casting is the extremely modest cost of the mold, which is a crucial factor in casting processes. The process is suitable for small-series production of filigree shaped castings, but it does not allow high tolerances. The mechanical properties of the casting are low because of the coarse-grained structure caused by the relaxed cooling rate [10].

Solidification in specific portion of metal casting mold is promoted by using chills. Solidification which occurs from the farthest end of casting towards the sprue is known as directional solidification. Chills are used when directional solidification is prevented from occurring naturally because of the geometry of mold. These chills are placed in a strategic manner to help the directional solidification. These are of two types: internal and external [11].

**2.1.2. Investment Casting.** Investment casting or lost foam casting is a fabrication process in which a pattern is made up of wax or a suitable polymer. [12] The first step is dipping the wax patterns in a slurry of refractory material. After the refractory material lining has hardened, the dipping process is repeated multiple times to increase the lining's strength and thickness. The mold is then further cured (by a process called sintering) to achieve proper strength. Once the final coating has cured, the pattern covered with refractory material is heated which results in melting of wax and leaving the refractory material. After this, the molten metal is poured into the hollow cavity created by the wax model. After the metal solidifies in the mold, the casting is separated by breaking the refractory mold. Figure 3 shows a flowchart representation of process of investment casting. This casting process can cast extremely high melting temperature materials because of the refractory mold. Extremely accurate dimensions and high surface finish can be achieved in the process of investment casting. The cost of tooling of investment casting is high, and thus this process is used for high volumes of production or for specific requirements of intricate shapes or casting of high melting point material [13].

**2.1.3. Die Casting.** This is the process by which the molten metal is poured or pressed into steel molds. Die casting is a permanent mold manufacturing process. The forms, also called tools or dies, are made of steel and specially developed for each project. This allows each component to be created with precision and repeatability. The pressure die casting process is the most common casting for Al, Zn, and Mg castings (low melting point). The liquid metal is injected into the mold under high pressure and allowed to solidify at high pressure. The molten metal is forced into the die cavity at pressures ranging from 0.7 MPa to 700 MPa. After filling the mold with liquid metal, the pressure is sustained until the

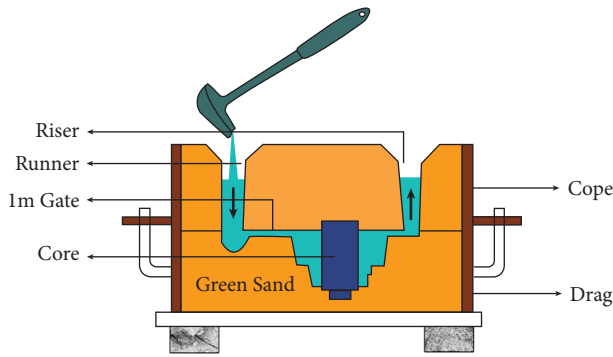


FIGURE 1: Schematic representation of sand casting process.

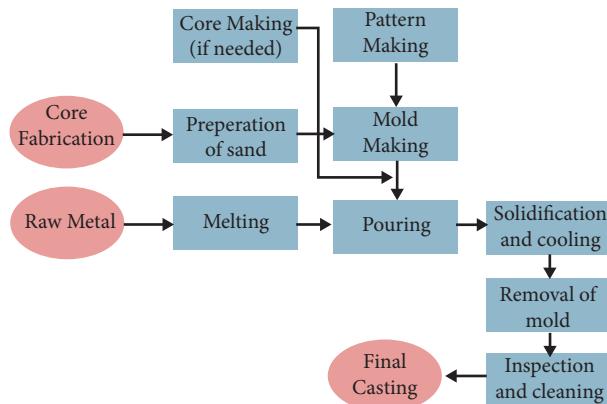


FIGURE 2: Sand casting process.

casting hardens. There are two different types of pressure cushions used: low-pressure die cast and high-pressure die cast. Figure 4 shows a schematic representation of die casting process. Large production volumes can be achieved through the pressure distribution process with limited imitation control. Wearing dies can be problematic due to high pressure and constant exposure to hot gradients from molten metal. In a well-maintained process, the die can remain a large amount of use before it needs to be replaced [14].

**2.1.4. Centrifugal Casting.** It is a casting process typically used to cast thin-walled cylinders. Unlike most other casting processes, centrifugal casting is primarily used to produce rotationally symmetrical starting materials in standard sizes for further processing, and not castings tailored to a specific application. The schematic representation of centrifugal casting is shown in Figure 5. It is often used to melt materials such as metals, glass, and concrete. The casting is free from defects. In the centrifugal casting process, the molten metal is poured at the centre of a rotating mold or die. Because of the centrifugal force, the lighter impurities are crowded towards the centre of the case. For producing a hollow part, the axis of rotation is placed at the centre of the desired casting. The speed of rotation is maintained high to produce a centripetal acceleration. The centrifuge action segregates the less dense nonmetallic inclusions near to the centre of

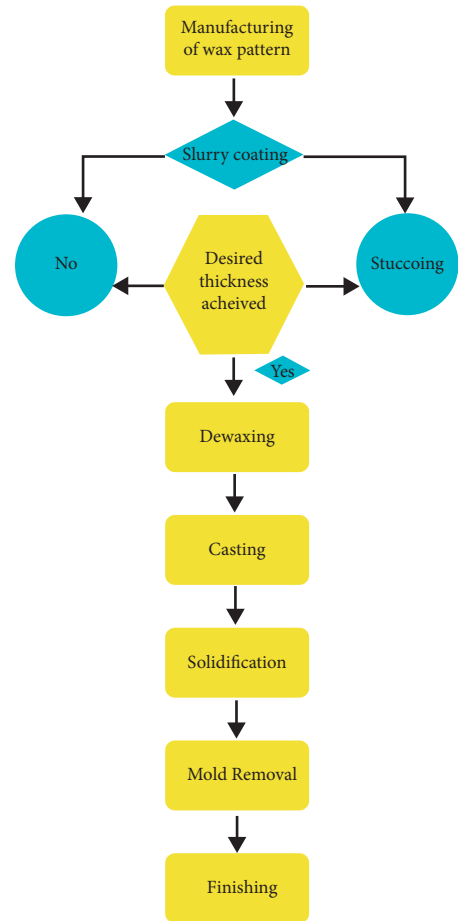


FIGURE 3: Process of investment casting.

rotation that can be removed by machining a thin layer. Final castings manufactured by centrifugal casting have a dense metal structure with all impurities forced back to the centre from, where frequently they can be machined out. Moreover, any metal can be cast by this process. One disadvantage of the centrifugal casting process is that all castings cannot be made centrifugally since there are definite size and shape limitations. True centrifugal casting, semi-centrifugal casting, centrifuging, vertical centrifugal casting, and horizontal centrifugal casting are types of centrifugal casting [10].

**2.1.5. Shell Molding.** Shaping a shell is like scattering sand. A mechanical pattern made of grey metal or aluminium was used in this process. The pattern can be heated to 250°C to 260°C and a mixture of sand mortar is poured over it. The hot pattern melts resin forming bonds between sand grains. After some time, the pattern and sand are turned, and the extra sand is removed. The mold is now made of solid sand shell. The mold is then heated to a preheated oven so that it can continue to be cured. So, a built-up shell forms one part of the mold. Two such halves are placed on top of each other to form a perfect mold. Sands used in the shell molding process are generally better than those used for sand molding. Figure 6 shows a schematic representation of shell

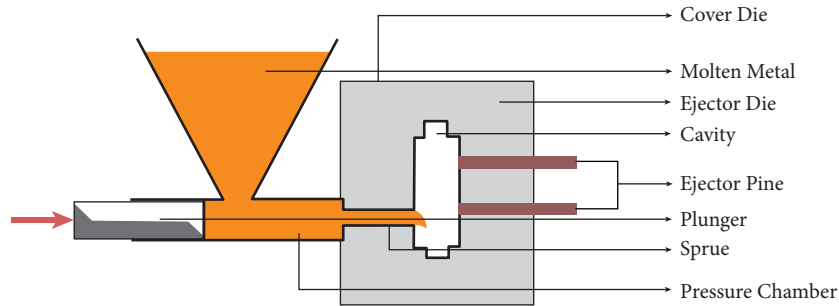


FIGURE 4: Schematic representation of die casting.

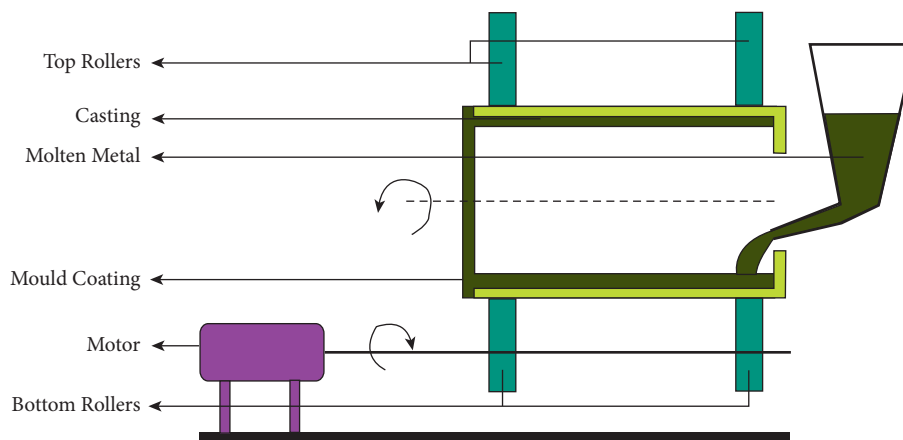


FIGURE 5: Centrifugal casting.

molding process. This process is suitable for medium-sized parts with complex shapes. Subsequent machine operations have also been reduced due to increased accuracy of size. The mold formation of the shell allows its use in both stainless steel and nonferrous metals, usually using cast iron, carbon steel, alloy steel, stainless steel, aluminium alloys, and copper alloys [15].

### 3. Phase Change Materials Properties: A Metal Casting Perspective

PCMs belong to a lineage of chemical substances having higher heat values of joining and solidification. PCM releases or absorbs sufficient energy when the substance undergoes phase transformation (liquid to solid or vice versa). The energy absorbed or released should be sufficient to be used for heating or cooling [16]. PCMs can store/release massive amount of energy compared to sensible heat storage by melting and solidifying at PCT. Figure 7 shows a relation between temperature and energy content in PCM. Widely used in commercial sectors that require energy storage or stable temperatures, PCM materials find wide usage in heating pads and items of clothing. Sometimes, microencapsulation is done on PCM, and that allows the material to remain in solid form even after melting the PCM core [17, 18].

Specific heat capacities and latent heat of fusion of PCM are extremely high and high, respectively [19]. The melting

point of PCMs is near to required operational temperature of TES, and it is required that supercooling during freezing is least.

Phase change materials have appreciably more densities of thermal energy storage in comparison to materials having sensible heat [20, 21]. With an escalation in the number of effluent gases in the world, scientists are now active on the search for sustainable energy storage forms [22]. This can be used intelligently to decrease the aperture between agronomics of energy while significantly reducing energy consumption [5]. To combat the growing problem of rising energy consumption, researchers are on the lookout for more efficient TES media, which can also be utilised just as efficiently for transfer of heat whenever required [23].

However, the usage of PCM materials is strongly constrained due to their small thermal conductivity coefficient. To overcome this disadvantage, PCMs having low thermal conductivity coefficients metal inserts are used, which are successfully manufactured by using Investment casting [24]. In a research work using aluminium inserts for enhancing heat transfer in PCM accumulator, two types of metal inserts are successfully manufactured, Al-Si structural elements (foams and honeycomb structures) [24, 25].

Phase change materials have been broadly classified into solid-solid PCMs and solid-liquid PCMs [17]. Solid PCMs consist of a variety of natural PCMs and minerals with stable phase modifications such as perovskites coated, dihydric phosphate salts, ammonium thiocyanate, polyatomic

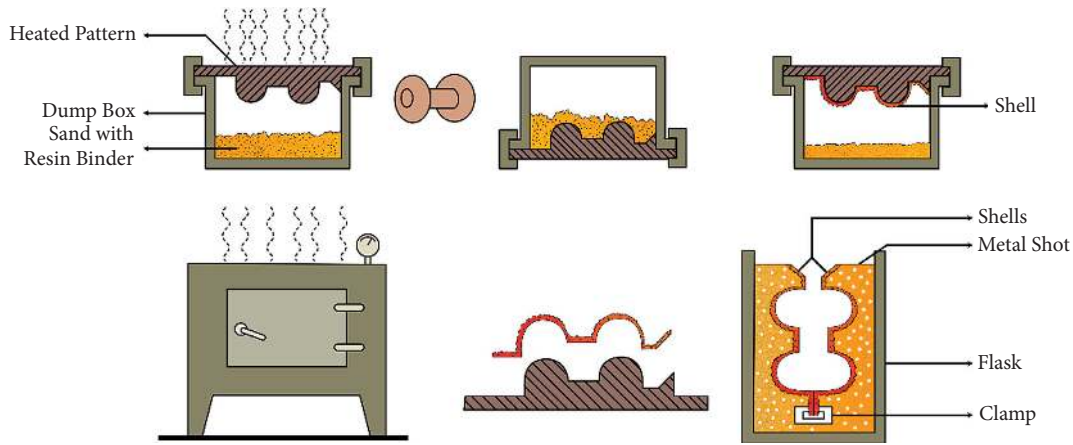


FIGURE 6: Shell molding.

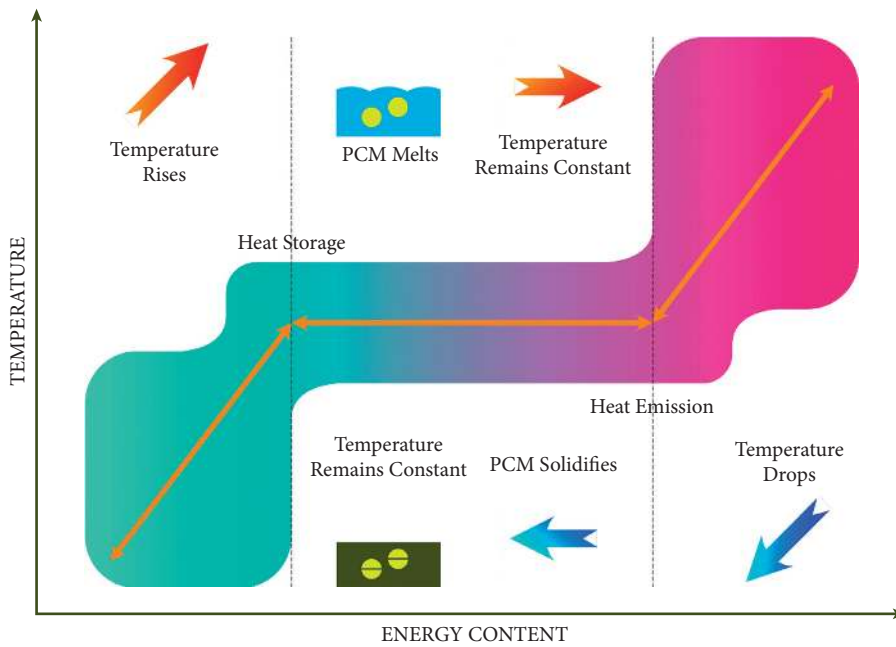


FIGURE 7: Principle of PCM: graph between temperature and energy content for PCM.

alcohols, polyethylene-based crosslinked copolymers, and poly)-grade copolymers supported copolymers [11].

Solid-liquid PCMs with enthalpies change many phases as liquid-phase molecules have a much higher degree of movement than those in solid phase and similar strength. Due to the evolution of the upper class of enthalpies, solid-liquid PCMs are used [17].

Solid-liquid PCMs are divided into 3 types: organic, inorganic, and eutectic [26]. Organic classification materials include paraffin compounds and nonparaffin compounds. Inorganic PCMs are further subdivided into hydrates of salt and iron. Eutectic PCMs are a mixture of organic and nonliving organisms mixed with others: organic-organic, inorganic-organic, and inorganic-inorganic [27]. Different categories of PCM are mentioned in Figure 8.

Various applications of PCMs include under floor heating systems, ceiling boards, and off-peak electricity

storage which are also discussed on several tangents of efficiency, differing performance levels, and their use in reduction of energy consumption of buildings [28–30]. PCM is being widely used in thermal energy storages, especially in latent heat storage [31–33]. PCMs provide a much more capacity of storing which relates with the phase change latent heat and allows a specific driven approach towards releasing temperature being set by the abiding temperature of phase change [34]. While selecting PCMs, a humongous heat of fusion and a particular liquifying or solidification temperature is the primal requirement [35].

On a promising note, many improvements on nanolevel and mechanical are attained, which are expected to escalate the heat transfer rate to further increase performance levels and efficiency of the TES systems [36]. Dependable thermal management for electronic device is promised by heat sinks based on PCMs. A methodical approach for increasing heat

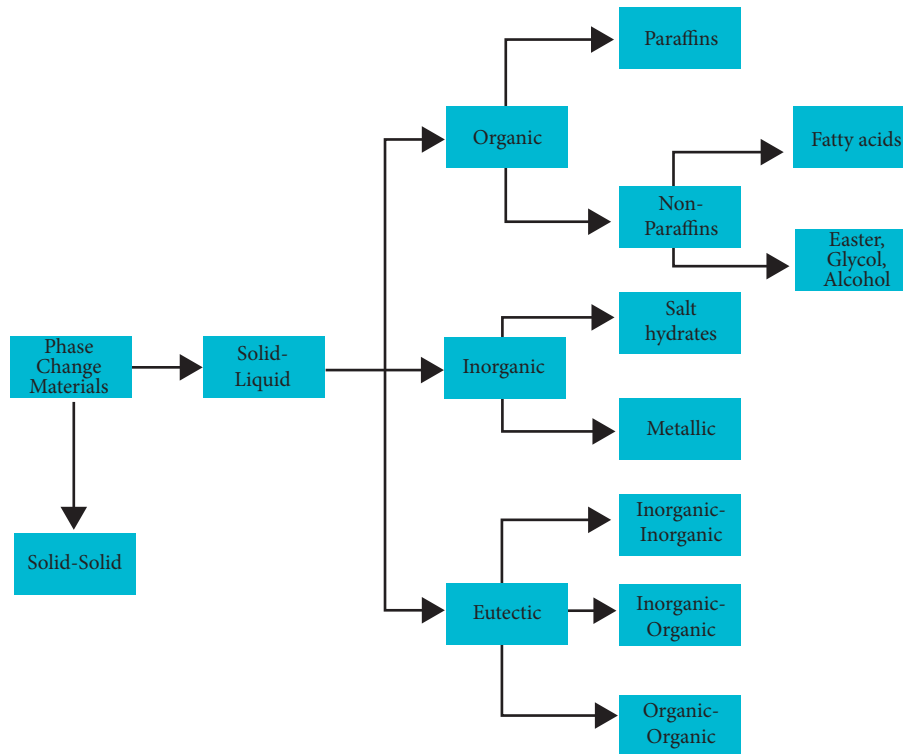


FIGURE 8: Categorizing phase change material.

dispersion in a yielding chilling system would be to embed a phase change material in a permeable matrix [37].

Encapsulation increases the compatibility with various storage materials [38] and increases corrosion resistance of the PCMs [39]. PCMs used are either paraffin waxes, polyethylene glycol, or fatty acids. Figure 9 shows a diagrammatic representation of principle of PCM encapsulation. There is an inherent problem with their use and the limitations they pose in terms of thermal conductivity and melting points, which significantly limits their applications. A novel polymer matrix is proposed which combines paraffinic PCM with a high-performance epoxy matrix [40]. The matrix was then studied for various properties under several tests to obtain results. The freezing and melting temperatures of the blend were established to be stable up to 50 cycles, which promises the growth of a thermally reliable versatile composite material with varying uses. The presence of paraffin was found to lower the flexural strength and elastic modulus of the polymer matrix, thereby showing a significant level of mechanical strength. The results concluded that the matrix could be used to build high-performance fibres [41, 42].

Three distinct categories of heat sinks (filled with MF-PCM and paraffin and empty) with light emitting diodes for heat source were tried out within 4 different extents of power. It was concluded that the PCM-built heat sink could save the heat source from heat flux shocks and could also ensure the safe functioning of the cooling system for a lengthy period. PMFSF has high thermal conductivity and larger specific area, which enhanced the heat transfer to the PCM leading to a lesser heat source temperature.

Encapsulations and nanomaterial additives are observed to be the highest promising approaches towards enhancing PCM properties [43, 44]. Specifically, nanomaterials can be used to enhance the thermal conductivity and specific heat capacity of phase change materials [45–47].

Various TES properties of PEG/diatomite composite were experimentally analysed to decide its suitability to be used in TES applications [48]. Composite PCMs have been prepared by vacuum including PEG in the orifices of diatomite [49, 50]. PEG completely disperses into the pores of diatomite which provides mechanical durability to the composite by retaining its structure. None of the chemical reaction was noted between PEG and diatomite. Since no major changes were noticed in the melting and freezing temperatures, it can be deduced that PCM composite has better thermal reliability, hence making them suitable for use in thermal energy storage applications [51, 52]. TG analysis proved that the PCM composite possesses a good thermal stability, which can be improved by inclusion of expanded graphite in distinct mass fractions [50, 53]. It can be employed to decrease cooling load on constructions [54], thereby decreasing the energy consumption and making it more environmentally friendly [55, 56].

Phase change material (PCM) gives the greatest force by lessening the working temperature of the board. PCM goes under conductive aloof cooling procedures. PCM is a material with enormous fierceness of combination and sharp liquefying point. PCM goes about as inert hotness stockpiling as it can retain or deliver heat when it changes from strong fluid stage as well as the other way around. Although PCM has a high idle fieriness of combination

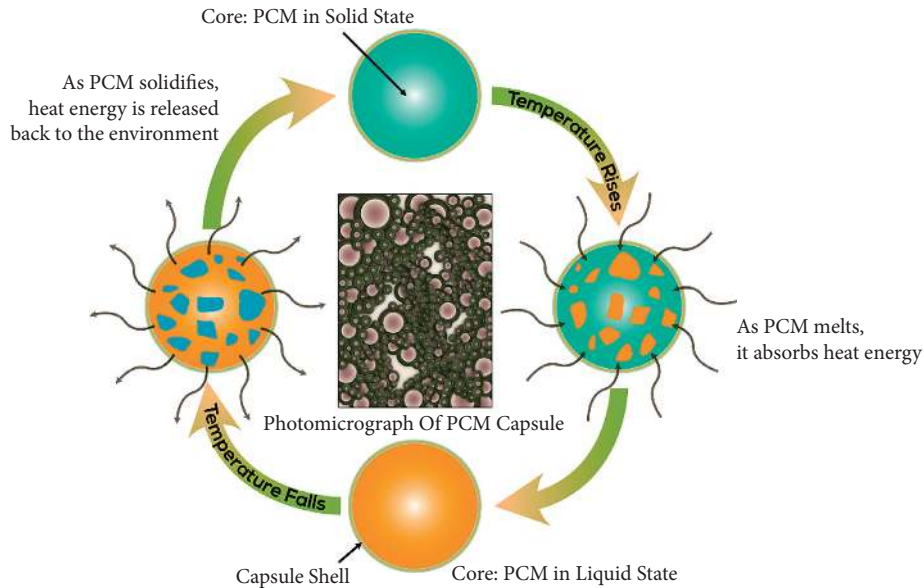


FIGURE 9: PCM capsule.

per unit volume, natural PCMs have low warm conductivity. Nanoimproved PCM gives a less resistive way to warm streams, and consequently it lessens base temperature fundamentally [57]. Be that as it may, on account of a bigger framework, nanomolecule settled in PCM builds the expense. PCM is more useful for open sky environments as the measure of transition episodes on the board during this environment is enormous to create more hotness. One of the significant models for choosing PCM depends on its softening point. PCM with movable softening point is fundamental for sun-oriented applications. The softening place of PCM lies above 15°C and underneath 90°C, which is appropriate for sunlight based warming application and for heat load evening out application. PCM is made by joining a few synthetic compounds, which make PCM change its state during the softening point and move the hotness for keeping up with the temperature at the material's surface. This PCM will store nuclear power as inactive hotness in translucent form. The PCM material makes temperature difference on the outside layer about the PV board although the aluminium sheet was utilised to speed up the pace of dissemination of hotness to the environmental factors [58–60].

**3.1. Features of Phase Change Materials.** The ideal PCMs should meet several bases allied to the desired kinetic, thermophysical, and chemical properties. Thermal properties should include a melting temperature in the desired operating range, high latent phase transition heat per unit volume, high specific heat to provide significantly additional SHS, and high thermal conductivity of both phases.

The physical properties should consist of minor changes in volume during the phase transition, low vapor pressure at operating temperature, consistent melting of PCM, favourable phase equilibrium, and high density [61].

Kinetic properties that are desirable and looked for include a high nucleation rate, no supercooling, and an adequate rate of crystallization.

Long-lasting chemical stability, completely reversible freezing/melting cycle, adherence to building materials, and no corrosion effect on building materials are desirable chemical properties.

In addition, it should be safe, nonflammable, and nonexplosive to ensure safety. PCM should be readily available at large prices at low cost. Table 1 summarizes the properties of various types PCMs. In fact, those processes do not fully integrate with most PCMs. However, recent advances in building and segmenting new energy storage components, including nanomaterials, have opened new opportunities for improved performance and increased health [62].

**3.2. Potential Use of PCM in Metal Casting.** There is an important role of energy storage systems in transforming energy to reduce the gap between demand and supply and to improve its efficiency. Energy conservation is also important to reduce dependence on fossil fuels and thus to contribute to energy efficiency in a more efficient and environmentally friendly manner. The composite material has high thermal fluctuations and about 80% of the subtle fusion temperature per unit weight of each paraffin unit. In thermal energy conservation, the focus is on reducing storage costs, reducing operating costs, and increasing energy efficiency [63]. Due to its large volumetric energy storage capacity, thermochemical substances are as powerful as future thermal energy storage [64, 65].

As energy is collected in the form of subtle fusion temperatures in PCMs, therefore it is used in metal casting processes [25]. In experimental analyses conducted by Wanga and Millago, they concluded that by replacing the traditional metallic mold used in investments, with mold

TABLE 1: Properties of various types of PCMs.

Properties	Organic paraffin	Organic nonparaffin	Inorganic salt hydrate	Inorganic metal eutectic
Heat of formation (kJ/kg)	230–290	120–240	170–340	30–90
Density (kg/m <sup>3</sup> )	~810	900–1800	900–2200	~8000
Thermal conductivity	~0.25	~0.2	0.6–1.2	~20
Thermal expansion	High	Moderate	Low	Low
Congruent melt	Yes	Some do	No	Yes
Supercool	No	No	Must happen	No
Corrosivity	Low	Few are	High	Few are
Toxic	No	Few are	Yes	Few are

made of RP plastic materials integrated with PCM, the process became possible [66].

During the solidification phase, it is very necessary to fill the connection between shrinkage cavity region and riser [67]. In case of loss of liquid connection between these two regions, the shrinkage cavity does not get enough liquid metal which causes a faulty geometry after solidification. We need to a neat solidification to overcome this which can be done by designing the solidification direction of liquid metal inside the mold using directional solidification methods, for example, like incorporating a chill in the sand casting process. In conventional sand casting processes, while manufacturing castings having intricate parts, directional solidification is an important requirement for their proper geometry and dimensional tolerances to be met, as without it, the connection between shrinkage cavity and riser will not be appropriate [68].

Traditionally, for the purpose to cater directional solidification, chills are incorporated in sand casting process [69].

Replacing traditional chill materials made up of the metal being cast with inorganic phase change materials can significantly improve their efficiency of chills while providing directional solidification in the final casting produced. Table 2 shows various inorganic compounds which can be used as PCM.

Colds in the traditional method of sand dispersal cannot function as a heat sink where the heat released during the melting process of the molten metal can be maintained [72]. But PCMs are widely used in areas where heat storage and discharge are required. PCMs have the potential to act as a heat sink [35] in a common cold environment in the normal process of sand distribution at a moderate temperature range. These changes may be helpful because organic phase change materials are not only more expensive but also better at providing better cooling than their traditional counterparts [31]. This is due to their ability to conserve substantial amounts of energy at lesser amounts, making their maintenance costs much lower. In addition, they are easily accessible and do not burn at elevated temperatures.

It is important to note that the temperatures at which the process of casting is carried out should be less than 1200°C as the range of melting point of inorganic PCMs lies between 200°C and 1300°C. Moreover, it should be considered that PCMs can be corrosive in use [73]. However, by making use of microencapsulation technique, this can also be eliminated [17, 74]. It should also be noted with a high degree of

importance that many PCMs are highly toxic in nature. This can make them quite dangerous to use and pose serious threats to human life [75].

To overcome various disadvantages of inorganic phase change materials, these processes can be used [76].

- (a) Microencapsulating PCM is as follows: the thermal performance of small integrated PCMs is expected to surpass conventional PCMs since small PCM particles provide a large heat transfer area with unit volume and will provide a high degree of heat transfer. Microencapsulated PCMs additionally add advantages such as low PCM reaction to container content, as well as the ability to withstand volume changes during phase switching. This process of improving heat transfer has been extensively studied with a combination of PCMs and coating shells. These studies focus mainly on the preparation and classification of microencapsulated PCMs, without extensive comparisons of pure PCM performance with pure PCM, and comparative work is required to evaluate the optimal performance improvement to integrate microencapsulation of widely used PCMs. Such a method requires a lot of testing work, only in the current phase [7].
- (b) Metal carrier structures are made of steel or stainless steel: including metal structures in PCM has been considered as one of the ways to improve thermal flexibility by some researchers, who did investigation of metal structures made up of steel or stainless steel in different geometries, such as cylinder geometry and circle, and with different arrangements. In order to achieve a significant reduction in melting/stabilization time, a significant system capacity is required. Due to the limitations shown in the review, this approach to improving heat transfer does not meet our research interests.
- (c) Scattering of materials that possess a high conductivity within the PCM is as follows: dispersion of high conductivity particles in PCM is an easy way to improve PCM thermal conductivity. Studies involving the disintegration of metal particles such as copper, silver, and aluminium have been performed. Results show that in any given situation, there is a range of high-quality particles, and it is suggested to select low bandwidth values to ensure maximum PCM to increase



TABLE 2: Inorganic compound which can be used as a PCM.

Compound	Heat of fusion (J/g)	Melting temperature (°C)	Ref. no.
LiF	932	868	[70]
LiNO <sub>3</sub>	370	250	[70]
KOH	150	380	[71]
KNO <sub>3</sub>	266	333	[71]
Na <sub>2</sub> O <sub>2</sub>	314	360	[71]
MgCl <sub>2</sub>	452	714	[71]
MgF <sub>2</sub>	936	1271	[70]
LiH	2678	699	[70]
NaNO <sub>3</sub>	172	307	[71]
NaCl	492	800	[71]
Na <sub>2</sub> CO <sub>3</sub>	276	854	[71]
KF	452	857	[71]
AlCl <sub>3</sub>	280	192	[70]
K <sub>2</sub> CO <sub>3</sub>	235	897	[71]
NaF	750	993	[70]
KClO <sub>4</sub>	1253	527	[70]

TABLE 3: Most preferable properties of PCM.

Physical properties	Density variation is low during the phase change High-energy density Supercooling not occurring while freezing
Chemical properties	No synthetic decomposition Chemical stability
Economic factors	Humongous quantities obtainable Low-priced
Thermal properties	PCMs acceptable within the desired operation scope Large specific heat High latent heat unit per mass Large thermal conductivity for liquid phases and solid phases High specific heat

TABLE 4: Properties of inorganic PCM studied in present paper.

Properties	Beneficial for casing process	Potential solution
High enthalpy of fusion	Yes	—
High melting temperature	Yes	—
Corrosive	No	Microencapsulation
Toxicity	No	Future research required
Low thermal expansions	No	Future research required
Supercooling	No	Use of nucleating agents

the amount of energy stored. Therefore, the proper combination of particles of thermal conductivity and particle mass fraction is very important when the conductive particles will be dispersed in PCM to improve unit performance. These results conclude that there are limits to the terms of PCM/particle component that can be used.

- (d) Using materials like carbon fibres and paraffin compounds with high conductivity and low density,

in view of the various issues which arise with the use of PCMs, the implantation of high-conductivity substances in PCMs provides another attractive way to improve heat transfer processes in PCMs. The use of a hollow matrix has gained increasing attention due to its light weight and high specific heat transfer. Hollow structures can even be matrices made of aluminium, copper, and so on or naturally occurring materials such as graphite. As the porous material is embedded in the PCM, the problem of particle separation at the bottom of the TES container is minimized. A major challenge for this approach would be to develop a compatible and effective combination of PCM and porous materials, suitable for high temperature purposes. Specifically, the study should provide appropriate modeling of copper foam structures embedded in selected salts such as PCM. Therefore, the structural and thermomechanical parameters need to be studied in conjunction with the analysis/discharge analysis of PCM foam steel [77].

- (e) Installation of flexible materials with high conductivity, either as foam metal like aluminium, copper, or steel or as flexible as graphite is as follows: high conductivity particles must also be compatible with

all PCMs. According to Fukai et al. [78], not all metal particles are compatible with all PCMs. For example, paraffin and aluminium are compatible, while copper and nickel are incompatible. Similarly, aluminium and copper are not compatible with other saline hydrates. Therefore, there has been a search for low-density high-conductivity supplements that should be compatible with all PCMs. This mechanism to improve heat transfer has been studied extensively, as stated. The revision revealed that both phase modification and/or charge and discharge rate (melting/stabilization) can be significantly increased by adding high conductivity factors. In general, however, these supplements may lead to the loss of the final volume of pure PCM. Loss of storage capacity limits a large fraction/volume of additives [79, 80].

#### 4. Summary

With the ever-growing demand of energy and increasing concerns for the environment, it has become imperative to look for better, more sustainable methods of storing energy. Energy consumption has been growing across the world, and it is one of the major contributors to the problem of climate change. Especially in manufacturing industries, which generate a lot of pollution and consume excessive amounts of energy, there is a need to shift focus and find more efficient ways of storing, producing, and using energy. PCMs can then prove to be quite promising in this regard. Table 3 summarizes properties that are preferable for PCM.

PCMs possess significantly high thermal conductivity, which can increase their areas of usage. Their high melting points allow them to be employed in conditions of elevated temperature ranges in manufacturing industries, which operate in extreme temperatures and in thermal energy storages [81]. Phase change materials are also being popularly used in building fabric to provide good cooling in building [6]. Inorganic phase change materials show a significantly higher melting point than their organic counterparts. They are also inflammable, which also prove to be advantageous in dangerous environments. All these properties make PCMs quite ideal for using it in TES applications, with some added benefit of being economical.

Because of the above-mentioned properties of inorganic PCMs, they show good potential for their use in metal casting. They can be used as a chill in the process of sand casting, acting as a heat sink and promoting directional solidification. It is important to ensure directional solidification in casting as it prevents the formation of dendrites and enhances the mechanical strength of the castings, which is key in engineering applications. However, despite all the potential benefits that the use of phase change materials promise, they also have significant drawbacks in their applications in elevated temperature range conditions such as in the process of metal casting.

Significant loss in latent enthalpy might be caused because it is extremely hard to prevent inappropriate

melting and separation during its cycle. Inorganic phase change materials are corrosive to many other metals [82], which might cause decrease in lifetime and defects in casting process, although this corrosion can be controlled by microencapsulation of PCMs in small quantities using nonreactive plastic [76, 83]. Some mixtures also exhibit high change of volume. PCMs encapsulation method is a method to prevent leakage, phase separation, and volume change [84, 85]. After repeated cycling, necessarily using nucleating agents may become incorporative as super-cooling might cause a problem during solid-liquid transition. Inorganic PCMs are also heavily toxic in nature, posing significant risk to human life upon exposure. This is one of the major drawbacks of using inorganic phase change materials.

Despite the immense ongoing research for using PCMs effectively and efficiently, they are yet to become used for sustainable energy technology. The use of PCMs is currently limited because the harms outweigh the benefits. Future research can be directed to reduce the negative effects of using PCMs specifically in elevated temperature applications and hence bridge the gap between advantages and disadvantages [86–93].

#### 5. Conclusion and Future Directions

This work comprehensively reviews the recent advances in the PCMs and critically analyses use of PCM in the processes of metal casting. The major conclusions of this article are as follows:

- (1) High enthalpy of fusion and high melting point of inorganic PCMs will absorb heat for long time and thus satisfy the elevated temperature requirement of metal casting.
- (2) These inorganic phase change materials have high fusion enthalpy and melting point; hence, they can potentially be used as chills (used to promote directional solidification) in sand casting process. PCMs used here will act like a heat sink.
- (3) Inorganic PCMs are of low cost, which can prove to be economical for their use in small and large industries alike.
- (4) The major limitation of using inorganic PCMs in casting as chills would be that its temperature lies only between 200°C and 1300°C. The temperature of casting should not exceed 1200°C.
- (5) Another drawback of inorganic PCMs is that they cause corrosion, which might lead to defects in casting, or it might defect the pattern of casting. This corrosion can be overcome by an up-and-coming technique known as microencapsulating the PCMs using least reactive plastics.
- (6) Thermal expansion being low is yet another drawback of PCM when used in elevated temperature applications. Because of low thermal expansion, the chills made up of phase changing material would have to be replaced multiple times. Future research

can be directed towards this to combat the problem of thermal expansion.

- (7) One of the major shortcomings of PCM is toxic in nature. It poses serious threats to the personnel handling the equipment; their skin upon exposure can be harmed. This is risky for use and dangerous to human life. Future authors can work on overcoming the issue of toxicity, which will further expand their line of use across various forums.

Future research should be directed towards reducing the various harms of using inorganic PCMs such as toxicity, corrosivity, low thermal expansion, and supercooling. Table 4 concludes the study for this paper.

## Data Availability

All data are included inside manuscript.

## Conflicts of Interest

The authors declare that there are no conflicts of interest.

## Authors' Contributions

All the authors have contributed their part in the research work performed for this article, and results and conclusions were given by the agreement of all the authors.

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