Term Project Report on

Recycled Phase Change Materials for Thermal Energy Storage

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Declaration:

- This report is a collective effort, with equal contribution from all members listed above.
- The report primarily is based on our original work. We have provided due credit by citing original sources, wherever applicable.

Abstract

The current scenario in the world pushes us to look towards adapting new methods to store energy and reuse it while keeping in mind the track of $CO2$ emission for environmental concerns. Thermal Energy Storage(TES) already provided a huge increase in economic balance in industries. The materials which are called as Phase Change Materials(PCMs) are used to increase efficiency & because of their properties, this purpose have been fulfilled upto a large scale. For more advancements, there are methods such as using different waste materials as an alternative which satisfies the material requirement. The different material requirements, properties and examples are discussed. This is a key factor in pollution-less processing.

Introduction

In the modern world, there is an extensive use of Thermal Energy Storage(TES) in the industries. Not only it does overcome the difference in energy supply and demand, it also allows the reuse of waste energy and rational use of thermal energy leading to increased overall efficiency and reliability, better economics and running costs, and less $CO2$ emission. The most important part in a TES are the materials which are called Phase Change Materials(PCMs). These materials have been studied for over decades, and advancements in the materials designs have led to application of this in thermal management and energy storage. For this selection there are certain requirements for the waste materials to be used as PCM, these materials should have large latent heat with a relatively low temperature change which allows them to buffer transient heat loads, balance generation and demand of renewable energy, store grid-scale energy, recover waste heat, and help achieve carbon neutrality. While compared with other energy storage methods such as electrochemical batteries for the purpose, PCMs are attractive for their relatively low cost and ease of integration with readily available energy resources such as solar power, which makes them more reliable for usage in Thermal Energy Storage.
This report will give details about the material used in Thermal Energy Storage, its development, different waste materials that can be used in TES and the requirements for a material to be used in TES, and some examples to support it.

Criteria for Material selection:

Since Phase Change Materials(PCM) has been developed as Thermal Energy Storage(TES) material, it is important to study the properties and behaviour of the PCM so that the suitability of PCM in different types of TES systems can be determined. Now, we should consider a certain criterion in order to produce PCM of good quality.

Criteria to select PCM can be divided based on their thermal, chemical, physical and kinetic properties.

- **Thermal Properties:**

The material should withstand for a longer duration. High density, specific heat and latent heat of fusion are the main characteristics for thermal properties. It should also have a desirable range of phase change temperature to achieve better transfer of heat.

- **Chemical Properties:**

The material should be nontoxic, non corrosive, nonexplosive and nonflammable. The duration of chemical stability is directly proportional to the quality of material. Congruent melting is also one of the important traits.

- **Physical properties**:

During the phase transformation there must be little changes in the volume of the material. Low vapor pressure would result in good quality of material at operating temperatures. High density and specific heat are few of the characteristics.

- **Kinetic properties:**

High nucleation rate and higher rate of crystal growth would be the important factors for PCM with kinetic properties.

Material:

The important parameters for thermal storage are the melting temperature, latent heat, and thermal conductivity of the PCM.

The phase change materials (PCM) have been broadly categorized into:

- **Organic** - It serves as important heat storage media due to their ability to melt congruently, non-corrosiveness , non-toxic and environment friendly characteristics. It has been divided into two types: Paraffin and Non - Paraffin.
- **Inorganic** - It has twice the volumetric latent TES capacity than that of the organic compounds. It has been divided into two types: Salt Hydrate and metallics.

Paraffin:

It has relatively lower cost, is easily available and because of its non-corrosive nature, it is defined as one of the most studied phase change materials in the application of thermal energy storage. The composition of paraffin basically contains a straight long chain of alkanes, the length of the chain determines the melting point and heat release of this paraffin.

Salt Hydrate:

The most extensively studied Phase change material as it has a higher potential because it is relatively less expensive, it has moderately higher thermal conductivity and it is safer to operate. Incongruent melting is one of the major drawbacks of using salt hydrates PCM in TES but to avoid this, we can use a stirrer. NaOH, $NaNO_3$, KOH, KNO_3 and Na_2CO_3 are few of the inorganic salts which have higher energy density, heat of fusion and relatively lower cost due to which they have been used extensively for research purposes.

Metallics:

It has few highly favourable characteristics because of which it has gained the attention of several researchers. These characteristics are: higher heat of fusion per unit volume, also little change in volume during phase change and High thermal conductivity. But because of their cost as well as weight penalties they are mostly not in the final consideration. Though recently these metals are used as additives with the other PCM materials.

Development of Phase Change Materials:

Although normal PCMs can store thermal energy, there are different limitations of different conventional PCMs. Organics paraffins are non corrosive, non toxic, thermally stable but they are expensive, flammable, have low thermal conductivity and the volume change is high upon phase change. Non paraffinic organics compounds like Poly-ethylene glycol have liquid leakage problems. Fatty acids are excellent in nearly all aspects but are very costly. Inorganic PCMs are cheap but have a supercooling effect and incongruous melting. Therefore, fillers are added to improve the properties of PCMs or composite PCMs are formed so that they have improved mechanical, chemical and thermal properties. The formulation of the first C-PCM started in 2012 when copper supported paraffin PCM enhanced the heat transfer of the melting process. In 2015, aluminium foam supported paraffin PCM was used in the Li-ion battery which was used in electric vehicles. It improved the heat storage time and sped up the melting process. Diatomite paraffin composite is also used which improves the thermal stability, energy storage and reduces the liquid leakage. Expanded Perlite is also used as a filler which when combined with carbon nanotube forms a stable Thermal Energy Storage system. Similarly graphite, activated carbon, aluminium and copper powders are some fillers used in formulating C-PCM. But these materials are considered to be expensive and henceforth, to get rid of this problem waste materials are used as a filler which is discussed in the coming section.

Usage of Waste Materials as PCM:

The usage of waste materials as fillers in PCM is highly desired and a lot of research is being done because the usage of waste materials to improve the chemical properties of PCM, greatly help in preserving the environment by reducing the use of land-fills or oceans to dump waste.

Moreover, the recycled materials are usually inexpensive, reducing the overall cost involved in using PCM as TES thereby promoting its usage at an industry level. As an instance, the usage of PCM as a thermal buffer in space and air crafts is highly desired but expensive. The vehicles used for space exploration also need a buffer to protect them from low-temperature limits which is a significant reason for failure in such vehicles.

How to incorporate Waste Materials in TES?

The usage of waste material in energy storage systems is very similar to the conventional PCM,but instead of using conventional fillers or matrices such as ceramic, polymers, graphite or carbon nanotubes, waste materials are incorporated with the base PCM.

Now, we will try to briefly illustrate the usage of blast furnace slag (BFS) as TES to present a clearer idea of utilizing waste materials in the PCM regime.

BFS is a non-metallic by-product from the steel industry, commonly used for construction purposes. Research has shown that BFS can be used as TES in two different ways:

- The usage of vacuum impregnation method to introduce Paraffin (commonly used PCM) into BFS. Here, BFS instead of serving as a filler material serves as the base where paraffin is added to improve its heat capacity.This resulted in the formation of a low-temperature C-PCM.
- BFS could be used to provide the basic structural framework for high-temperature C-PCM by blending three inorganic PCM (Al, Na_2SO_4 and $NaNO_3$) at different operating temperatures. When analyzed, $NaNO_3$ was found to have the best

chemical stability with BFS, producing thermally reliable PCM even after 100 cycles of melting and freezing.

Advantages and Disadvantages associated with PCM:

Advantages	Disadvantages
● The PCM are non-corrosive with very little CO and unburnt hydrocarbon emissions to the environment thereby providing a clean and efficient way of thermal energy storage. ● It is easy to manipulate the properties of PCM by introducing various filler metrics, providing very high thermal energy storage capacity, in the form of sensible heat as well as latent heat. The low thermal conductivity of PCM can be enhanced by introducing metal based fillers.	● PCM as TES materials are not commonly used due to the large number of system-level issues that exist, for example, although the usage of PCM control temperature swings in an electronic circuit, the added mass of PCM in a circuit discourages its usage in most of the small to medium sized circuits. ● The geometry and material limitations due to the unavailability of suitable manufacturing techniques put a constraint on the development of devices that can harness thermal energy stored in recycled phase change materials. Only additive manufacturing techniques coupled with TO (Topology Optimization) present a solution but a lot of research work is still needed.

Sources of Waste Materials:

- **Industrial waste:**

One of the major sources of waste generation is from various industries and usually by-products from these industries are often discarded. However, these can be utilised in making fillers as they possess good thermophysical properties.

By-products from industries such as potash industry and mining industry, can generate high thermal conductivities by converting them into mortar. Treatment of waste by-product before usage further enhances their conductivities.
Steel Slag obtained from the steel making industry, can be used as a TES material in packed bed systems.

- **Activated carbon from agricultural practices:**

The most common ingredient in such kinds of wastes is Carbon. It can be utilized to increase the thermal conductivity and create low density of PCM material. Various carbon based products like graphene and graphite are being used in the preparation of composite PCMs.

Activated Carbons have low density and hence they are cheaper and easier to prepare as fillers. They are also chemically stable.

Rice husk which is often discarded can be used for making Activated Carbon and similarly bone charcoal is also a good alternative.

Example:

Let's take a model cold storage which has an Area of $2m^2$. The temperature outside is assumed to be 45^oC flowing with a velocity of 20m/s and temperature of 5^oC is to be desired. The thickness of the wall is 9 cm, 4 cm of stainless steel and 5 cm of insulation. The pressure is taken to be 1 atm inside and outside the facility. We can find the heat transmission through walls, using $Q = UA(To - Ti)$

Where U is the overall heat transfer coefficient.

$$\frac{1}{U} = \frac{1}{h_i} + \sum_{1}^{n} \frac{x_i}{k_i} + \frac{1}{h_o}$$

h_i = Inside air convective heat transfer coefficient

x_i = Thickness of the materials

k_i = Thermal conductivities of the materials

h_o = Outside air convective heat transfer coefficient

The thickness of stainless steel is taken as 0.035m and its thermal conductivity as 16 $\frac{W}{m\ ^oC}$

The thickness of insulation is taken as 0.05m and its thermal conductivity as 0.023 $\frac{W}{m\ ^oC}$

h_i is calculated using Nusselt Number using properties of air at temperature (5 ^oC) and is taken to be 20 $\frac{W}{m^2\ ^oC}$

h_o is calculated using Nusselt Number using properties of air at temperature (45 ^oC), using the analogy for turbulent flow [$Nu = 0.0296 * Re^{0.8} * Pr^{1/3}$] since Reynolds Number comes out to be $14.283 * 10^5$and h_o is 48.5 $\frac{W}{m^2\ ^oC}$

We find, U = 0.469 $\frac{W}{m^2\ ^oC}$

Heat load comes out to be = 37.52 W

In a cold storage low temperatures less than 5^oC is required. We choose a PCM whose melting point is around this temperature range. Polyethylene glycol 400 is selected as PCM.

If we know the heat load, we can calculate the amount of PCM required.

For a phase change material, Q = mL where L is the latent heat of fusion (at 5 ^oC).
We, find mass rate= 0.015 kg/hr and Volume flow rate= mass/density = 13.32L/hr
In this way, we can determine the volume of PCM required for any device.

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