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Latent Heat Storage: An Introduction

Hebatallah Teamah

Abstract

This chapter includes an introduction to thermal energy storage systems. It lists the areas of application of the storage. It also includes the different storage systems; sensible, latent, and chemical. It concentrates on the concept and the application of latent thermal storage. A detailed overview of the energy storage capacity of latent systems is discussed. The motivation and the challenge to incorporate phase change materials in the storage system are highlighted. Next, a classification of different phase change materials (PCMs) and their applicability in different temperature ranges of operations are analyzed. A thorough review will be presented for its industrial applications.

Keywords: storage, latent, phase change material, organic, inorganic, solar

1. Introduction

The aim of the current chapter is to provide the reader with basics related to thermal energy storage. It highlights the need for storage, different types of storage, and the applicability of each. It mainly focuses on the latent heat storage from the prospective of its integration to different applications. It includes a comprehensive summary for different phase change material classifications. It articulates the efforts that has been reported within different scholarly articles in the research community.

2. The need for thermal storage and its types

Thermal energy storage is inevitably needed when the energy source is characterized by its intermittency. For example, it is crucial for a solar thermal system. **Figure 1** shows how the solar irradiation curve typically looks like. It shows the incident solar radiation, the useful collected solar gain, and the load if this system is used in residential heating applications. The useful collected gain is less than incident radiation because of collector absorbance properties. The figure shows that there are times of the day where there is excess solar supply relative to the demand. However, there are other times where there is deficient supply relative to the demand. The storage in this case is indispensable to even out this mismatch between the supply and the demand. It ensures that the residential demand is supplied whenever needed. The optimization of needed storage sizing is a tedious process. It needs to take into account a robust control mechanism to allow for stable operation.

Figure 1.
Mismatch between supply and demand [1].

Energy storage systems have numerous classifications in literature. The most common one is to classify it to the broad category of thermal and chemical storage (**Figure 2**) [2]. The thermochemical storage stores heat as a part of chemical reaction. This kind of storage is out of scope of this book. Our focus is directed towards the thermal storage. It is subcategorized into the sensible, and the latent types. For the sensible storage, storage material preserves its condition as a solid or a liquid. The stored energy is manifested through the sensible increase in temperature of the material. The most common sensible storage material are water and rocks. On the other hand, latent storage is mainly dependent on phase change from solid to liquid and vice versa. Phase change materials (PCMs) change their phase at constant temperature (melting or solidification temperature). It stores the heat as the latent heat of change in phase is very high compared to the sensible heat. The temperature range of operation is important to choose the proper system. Sensible system shows an advantage with the wider temperature range. Latent system outperforms the sensible one in the narrow ranges of operation.

To show the difference in energy storage capacity between sensible and latent storage. Two storage media are chosen; water as a sensible medium, and lauric acid as a latent medium. Lauric acid changes its phase at 42°C. **Figure 3** shows a comparison of energy storage density between them when different operating temperature ranges are considered [1]. The first considered range is a narrow one of 10°C, and the second is a wide range of 40°C. In the wide range of operation, the energy stored in lauric acid is 70% higher than that of water. In the narrow operating range, the energy stored in lauric acid increases to 400% relative to water. This shows that phase change materials are more beneficial in narrow operating ranges.

Figure 2.
Different thermal energy storage systems [2].

Figure 3.
Energy stored in lauric acid compared to water [1].

Especially as most of them possess poor thermal properties (density, and specific heat capacity). Latent heat storage attracted the research consideration through the past four decades. During the energy crisis at that time, PCMs were extensively studied in residential heating applications. There has been also a lot of efforts to maximize the benefits of latent storage and reduce the challenges that face its wide implication.

The special feature of high storage density of PCM, increased its integration in vast range of applications. Those applications include electronic cooling, smart buildings, and waste heat recovery. Most recently it was included in the water and space heating applications [3–9]. A typical heating system needs a stable temperature to maintain a good level of indoor comfort conditions. This can be achieved when latent storage is considered.

PCM classification is given in **Figure 4**. Different combination of probable phase change are shown. It might be from solid to liquid and vice versa as a common mode [10]. They are further subcategorized to; organic, inorganic, and composites. The inorganics have been dominant in the residential applications. They are less toxic and less corrosive. Their density does not change that much with phase change.

Figure 4.
PCM classification [2].

However, they are relatively more expensive with lower thermal conductivity. A family of organic fatty acids has been common as their melting point covers a wide temperature range (from 16–65°C). The inorganics especially salts are used in high temperature applications like solar concentrators.

Water is the most common sensible storage. A good way to make sense of PCM thermal properties is to compare them to water. Organic PCMs possess a specific heat capacity that is around 50% of that of water. The density is almost 80%. Their average latent heat of transformation is $\sim 150 \text{ MJ} / \text{m}^3$. For inorganic PCM, the density is $\sim 60\%$ more than water. The specific heat capacity is half of water. However, the latent heat of fusion can be double the corresponding of an organic PCM.

Paraffins are considered a promising candidate for phase change materials. It is a hydrocarbon of high molecular mass. The melting point of paraffins differ with the number of atoms that can range from 12 to 40. The melting temperature includes a vast range from 6–80°C. This makes it suitable for several applications due to the wide range of melting temperature.

Paraffins have a high thermal storage capacity and the material freezes with marginal supercooling. It is highly stable under numerous cycles of melting and freezing. It is considered non corrosive in addition it is non-reactive to insulation material. This makes its encapsulation a straight forward process.

Hybrid thermal storage systems have shown a great promise in different applications. Those systems contain both water and PCMs. They combine the advantages of sensible and latent media. They also minimize the disadvantages of both of them. It should be taken into account that the configuration of heat exchanger is crucial for efficient energy storage. In addition, the PCM encapsulation should be carefully designed especially if the chosen PCM is of low conductivity. Spherical and cylindrical PCM encapsulations have shown a superior performance relative to rectangular ones [1].

The most common type of heat exchangers in hybrid storage is the shell and tube. Some researchers put the PCM in tubes and others put it in the shell. If water in the hybrid system is to be used in domestic applications, it is common to put PCM in tubes. Experiments can be done on this configuration in addition to numerical models. The numerical models account for phase change using different approaches.

The phase change process is tricky to model. The numerical model is nonlinear and transient throughout the process. Dutil et al. [11] summarized various numerical methods that has been reported to model phase change. The first most common one is the fixed grid. Such method presents a solution on unchanged grid through the entire numerical solution process. The second method that is not that common is the adaptive mesh. In such method, the mesh is varying throughout the solution. In the common fixed grid method, there are two subcategories. Those include the enthalpy porosity and specific heat capacity. The enthalpy porosity method is considered more stable. It adds an enthalpy term that is function of phase change percent. The main challenge of this method is to account for stagnation that that happens due to the solidification. This have been remedied by introducing the liquid fraction term [12]. This fraction is equal to unity when PCM is fully liquid and zero when PCM is solidified. It ranges from 0 to 1 throughout the rest of the process. The solution gets even trickier when convection dominated melting is considered [13–15]. There has been few approaches to take it into account. The straightforward one is the concept of equivalent thermal conductivity. Correlations are deployed to calculate its value. The higher the effect of convection, the higher the value of equivalent thermal conductivity. This causes it to deviate from the PCM conductivity and makes conduction dominated melting an invalid assumption.

The second fixed grid method is the heat capacity method. The heat of fusion is taken into account as a large effective heat capacity in a narrow phase change range [16–20]. This numerical method is easier to code relative to the enthalpy porosity method. However, there is numerical instability that arises from the narrow temperature range and selected integration procedure. This causes a difficulty in getting a converged solution. This has been overcome by using commercial software packages like COMSOL. They have developed a robust algorithm to account for the phase transition using the heat capacity method.

The configuration of latent and hybrid storage differs according to the application. The most common one is the shell and tube configuration. PCM can be put in either shell or tube. When the system is used in water heating application, PCM is put in tubes. Teamah et al. [21, 22] provided a detailed modeling for the operation of a shell and tube system (**Figure 5**). There is a parallel axial flow of water along PCM tubes. Melting considers both conduction and convection using correlations. One form to assess the feasibility of PCM integration is to compare energy storage gain. It is the stored energy in a hybrid system relative to a water based system. A nondimensional map has been concluded that is a function of design and operating parameters. The nondimensional map (**Figure 6**) shows that when Stephan number increases in wide temperature ranges, the system gains decrease. Gains also decrease if the heat capacity of PCM is lower than water. Better gain can be fulfilled if the charging period is longer. Similarly, it is higher if the thermal resistance of PCM modules is lower. The increase in velocity or packing ratio of PCM, results in a higher gain as the Reynold's number is augmented. Finally, the optimum selection of PCM temperature can increase the system gains significantly. It must be ensured that PCM is fully molten by the end of the charging period.

Phase change materials have been dominating different markets other than domestic heating. As it modulates temperature around the melt temperature, they have been included in the envelope [23–27]. It also suppresses losses from thermal bridging as the indoor temperature is more uniform. It has been also included in the power generation owing to the large latent heat [28]. It has been also used in space cooling [29–31] and air conditioning [32, 33]. When PCM melt temperature is carefully selected, heating/cooling loads are reduced [34, 35]. The high storage capacity of phase change which accumulates during the day is discharged during the night.

High storage capacity of latent storage has motivated researchers to further exploit this capability. This was fulfilled by a multi-PCM configuration. This configuration can divide the whole operating range to narrow bands. This will increase

Figure 5.
Hybrid storage studied by Teamah et al. [21]. (a) whole problem domain, and (b) considered element.

Figure 6. Nondimensional map that correlates gain to various operating parameters (Teamah et al. [1, 21]).

the energy storage capacity. The investigation of multiple PCMs has emerged since the 1980s. There are different arrangements for such a system (**Figure 7**) [36]. It can be either in parallel or in series. However, the series arrangement is the one that harness the potential of temperature range division and higher storage potential. Michels and Pitz-Paal [37] performed a detailed comparison for single PCM system, and multi-PCM systems. They also compared it to water-based system. They considered the application of PCMs in concentrated solar power applications where the melting point is high. The multiple PCM configuration is shown in **Figure 8** [36]. They quantified that the energy storage potential is 74% higher in the multiple PCM case. The multiple PCM configuration accelerates charging and discharging of system and promotes exergy of the system [38]. A study was done on a heat exchanger with multiple PCM [39]. The PCM is in the tubes and water flows in the shell. They highlighted that the careful choice of PCMs melt temperatures is crucial. The majority of the PCM needs to be molten by the end of the charging period. If this is not guaranteed, the potential of multi-PCM decreases drastically.

Teamah et al. [40] investigated the incorporation of multiple fatty acids in cascaded tanks (**Figure 9**). They found that the multiple PCM configuration can

Figure 7. Multiple phase change material systems arrangement [36]. (a) parallel configuration, and (b) series configuration.

Figure 8.
Multiple PCM arrangement in Michels and Pitz-Paal [36] work.

Figure 9.
Multi-tank configuration investigated by Teamah et al. [40].

increase the energy storage three times compared to the water-based system. Comparison between direct and indirect system has been performed. When water is admitted indirectly to the tank, the charging occurs through coil heat exchangers. Direct system is proven to be more efficient than indirect one. The energy stored in the direct system is also higher than the indirect system.

3. Conclusion

The introductory chapter of the book has presented the reader with basic knowledge needed to be an expert in the thermal energy storage field. It focused on the comparison between sensible and latent storage. The sensible storage is useful if the operating temperature range is higher. Latent storage system presents a great opportunity for storing heat in the narrow operating ranges. Phase change materials are used in variety of applications in the residential and commercial sector. It can stabilize the operation of different systems. Lastly multiple phase change materials can be deployed to magnify the energy storage potential.

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