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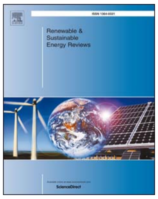

Critical review of latent heat storage systems for free cooling in buildings

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ABSTRACT

Buildings have a major contribution to the global energy consumption. Heating, ventilating and air conditioning systems (HVAC) are responsible for most of the energy use in buildings. Thus, clean and sustainable alternatives such as free cooling of buildings have recently gained much attention as means to reduce the operation hours and capacity of the conventional cooling and heating systems. The free cooling could be provided by collecting the natural cold energy during night time in appropriate thermal storage form and this could be retrieved when needed. Phase change materials are exploited by a number of investigators as a storage medium in free cooling applications, as these substances possess high energy densities, and absorb and release heat at a narrow temperature range, hence, the comfort temperature can be maintained day and night. The objectives of this article are to provide a comprehensive review on recent development on free cooling technologies incorporating latent heat storage and to shit lights on the most significant parameters affecting the performance of these materials in free cooling strategy. The outcomes of this review would be helpful in providing clear insight information on potential improvements that can be applied to the storage materials. All the reviewed studies demonstrated that the night cooling strategy using PCMs has the capacity to maintain the indoor temperature well within the comfort zone whilst providing a considerable reduction in cooling loads in all considered climates.

1. Introduction

The recent concentrations of the greenhouse gases in the atmosphere are vastly higher than at any time before [1]. According to some studies [1–3], the current rates of greenhouse gas concentrations are expected to continue to a very high level in the coming few decades. Accordingly, a substantial consciousness towards energy saving techniques in all kinds of sectors from transportation to buildings has increased [4].

Buildings have the dominant contribution to the global energy use accounting for about 40% of the total energy consumption and are responsible for over 30% of the CO_2 emissions, and a large amount of this energy is exhausted to provide thermal comfort in buildings [5]. According to Pérez-Lombard et al. [6], this situation is expected to augment significantly in future due to the predicted growth in population, growing need for buildings and provision of comfort conditions, and the rise of indoor occupation time due to changing lifestyle.

Heating, ventilating, and air conditioning (HVAC) systems are widely exploited as indoor climate regulators to maintain thermal comfort and improve indoor air quality. These systems utilise a large amount of energy, and hence have many deleterious effects on human health and the natural environment and cause significant problems at peak energy load time [7:p.6]. Thus, alternative sustainable strategies such as thermal energy storage (TES) can be exploited to replace or at least, to mitigate the increasing demand for these systems in buildings by preserving the available energy at a time of surplus to be extracted and used during the unavailability period [8–10]. TES systems are capable of delivering thermal comfort, offering potential energy saving and peak load offset [11–13].

The natural cold energy due to temperature drop at night can be admitted into the building interior to provide instantaneous cooling or it can be stored for later utilisation. The lower the nocturnal air temperature, the more effective the night cooling process will be [14]. The usage of buildings' mass to store the cold energy from the ambient night air is referred to in the literature as night cooling. However, the phenomenon of accumulating the night cold energy in a specialised thermal storage unit to be retrieved when it is needed during the day is referred to as free cooling [15]. Some researches show that free cooling concept is much applicable for locations with a large diurnal temperature variation between 12 and 15 K [16,17].

Thermal Energy Storage (TES) systems can be utilised for both short and long-term storages for high or low-temperature energy [18–20]. In principle, TES mechanisms are classified into sensible heat, latent heat and thermo-chemical energy storages or a combination of these [21:p.2,

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22:p.1]. The recent development in properties and features of the TES have been reported in many published reviews [23,24]. It is also crucial to have an understanding of the different TES technologies and their pros and cons in order to select the most appropriate storage system for a particular application [25].

Thermochemical energy systems (TCES) make use of generation and release of heat during dissociation and synthesizing of chemical compounds in a reversible endothermic chemical reaction [26:p.246]. TCES systems have the advantage of high energy density at a constant temperature, long-term and stable storage, wide temperature ranges, and easy transportation [27,28]. However, some of the disadvantages are poor heat and mass transfer property under high-density conditions. They are also expensive, and there is limited experience on their long-term operation [29:p.63]. The research in reversible thermochemical reactions is still under development and there are some technical and economic barriers that need to be tackled before a wider implementation of the technology [30].

Sensible heat storages (SHS) make use of increasing temperature of a storage substance without any phase change process [31]. The ratio of the heat stored to the temperature rise is the heat capacity of the storage medium [32:p.257]. SHS substances can be classified into liquid SHS such as water and oil or solid SHS such as rocks, metals, and masonry materials. Since gases have a very low heat capacity, they are not usually suitable for cold or heat storage [33:p.257]. Water can be considered the best of all ordinarily used substances, as it has the highest volumetric heat capacity (4187 kJ/m^3 K), which is almost double of that of the concrete and much larger than that of other masonry materials. SHS systems are very well developed and are readily available in the literature. More details about thermal properties of a range of SHS substances commonly used in buildings are available in references [34–37]. The shortcomings are the limited storage capacity, bulkiness, and the non-suitability for most practical applications with a narrow temperature range due to the large temperature variation between the charging and discharging periods [38,39].

Latent heat storages (LHS) on the other hand store energy by making use of the phase changing process of a substance by melting or vaporization without a significant temperature change. Such materials are referred to as phase change materials (PCM) [40:p.141]. The use of LHS as thermal energy storage has attracted vast attention over the past decades owing to the effectiveness and the superiority of these substances compared to other TES materials [41,42]. In general, LHS substances have energy densities greater than SHS and lower by around 5 times than those of the TCES. However, the lower complexity and effective cost make the LHS more practical compared to TCES [43–45]. The latent heat transfer is approximately an isothermal process as PCMs absorb and discharge heat at almost a constant temperature or within a narrow temperature range which is more applicable for maintaining thermal comfort compared to SHS [46,47]. Another important advantage of LHS is their easy integration where other SHS substances are difficult to be installed particularly in existing buildings and light-weight structures [48]. This is because PCMs are capable of enhancing the mass effect with much lighter weight and volume estimated at 5–14 times compared to conventional SHS systems which require a large space for accumulator accommodation [49,50]. Table 1 compares the required weight and volume of some LHS and SHS substances to store 10^6 kJ of energy at a temperature rise of 15 K during heat storage [50,51]. Moreover, LHS can be used as appropriate storage or can be added to enhance the performance of SHS systems [52]. On the other hand, the performance of LHS systems is largely limited by the low thermal conductivity and the lack of thermal stability of PCMs [53]. The cost of PCMs are relatively high at present, nevertheless, they are widely available in various forms and temperature range. The current prices are predicted to drop in the near future due to the extensive research carried out on PCMs nowadays in addition to the increasing number of PCM manufacturers around the world [15].

Table 1
Comparison of required mass and weight of LHS and SHS substances to store 10^6 kJ with ΔT= 15 K [50,51].

	Sensible heat storage		Latent heat storage	
	Rock	Water	Organic PCM	Inorganic PCM
Required weight of storage (kg)	67,000	16,000	5300	4350
Required volume of storage (m^3)	30	16	6.6	2.7

Some of the first studies of exploiting PCM for space cooling and heating were conducted four decades ago by Telkes [54] and Barkmann and Wessling [55]. Nowadays, PCM products are widely available in several forms such as powder, granule or rubber, and in a wide range of container types such as tubes, spheres, and panels. This diversity allows a variety of integration means into buildings such as in construction materials [56–59] and into external and internal building envelope [60,61]. PCMs are also incorporated into other systems such as trombe wall, solar chimneys, PV panels, and solar heating or night cooling of water/air [62:p.133]. Sometimes, PCMs are included in the indoor furniture.

There have been a considerable number of published reviews in the area of LHS [63]. The majority of these articles have focused on reviewing the development of the PCM substances, the heat transfer enhancement, the mathematical modelling developed for the latent heat problem, and the application of PCM in buildings by addressing the integration methods [63–92]. However, there have been few reviews that focused on PCM incorporation in free cooling of building technology, although this area has been investigated for over 25 years and numerous systems have been developed and assessed. Only few review publications have targeted PCM application in free cooling include Raj and Velraj [93], Waqas and Din [15], Kamali [94], Thambidurai et al. [95], Alizadeh and Sadrameli [96] and, Iten et al. [97]. Therefore, this paper focusses on the application of PCM for free cooling in buildings and is expected to complement and update the previous reviews in this area. The objectives of the present review are;

- To provide a comprehensive discussion on the recent progress and development in free cooling systems incorporated latent heat storage.
- To identify the most significant parameters influencing the thermal performance and application of free cooling based PCM storage systems to get a clear picture of possible opportunities and strategies that can be applied to enhance the efficiency of the technology.

The present paper begins with overviewing the latent heat storage systems and highlighting the classifications and the associated advantages and disadvantages. Section 3 addresses the various methods of PCM application in buildings, highlighting on their merits. Section 4 provides a succinct review in a chronological order for the most recent research in free cooling based PCM storage systems. Section 6 discusses the major factors affecting the performance of free cooling systems and the suitable enhancements that can be applied for the required purpose. This paper concludes by summarising the key achievements of application of PCM energy storage in free cooling, based on the reviewed research work.

2. Overview of latent heat storage (LHS) for building application

Latent heat storages (LHS) aim to use the stored heat by altering the physical state of a substance from one state to another by melting or vaporization (solid to liquid or liquid to gas and vice versa) at desired operating temperature range which is almost constant for pure substances, and this one of the advantages of LHS [98–102]. Fig. 1 shows a variation of latent and sensible heat storage with temperature.