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Thermal energy storage with phase change material—A state-of-the art review

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ABSTRACT

Recently, thermal energy storage (TES) has received increasing attention for its high potential to meet cities' need for effective and sustainable energy use. Traditionally, energy was stored in the form of sensible heat which requires large volume of storage material. The storage volume can be significantly reduced if energy is stored in the form of latent heat and thus can benefit enormously practical applications. The existing approaches in the design, integration and application of phase change materials (PCMs) in domestic hot water tanks (HWT) and transpired solar collector (TSC) using water/air as the heat transfer media are reviewed. Crucial influencing factors are considered, including thermo-physical properties of different PCMs, different configurations of PCMs in HWT and TSC, and the limitations of each technique. This paper also discusses the existing simulation, design tools and experimental studies related to PCMs usage in HWT and central thermal storage.

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1. Introduction

Building sector contributes immensely to the total energy consumption, particularly for its space conditioning and domestic hot water. Energy use and emissions result from both direct sources (on site use of fossil-fuels) and indirect sources (heating, electricity, cooling and energy embodied in different construction materials). Pérez-Lombard, Ortiz, and Pout (2008) reported that primary energy has grown by 49% and CO_2 emissions by 43%, with an average annual increase of 2% and 1.8%, respectively. Based on the International Energy Agency (IEA) reports on energy consumption trends and promoting energy efficiency investments, it is estimated that the building sector in developed countries is consuming over 40% of the global energy with 24% of greenhouse gas emissions. The growing peak demand of today's energy consumption for heating or cooling contributes significantly to a portion of utility-wide total demand and may lead more often to brown or black outs. During peak energy demand periods, the cost of generating, distributing and maintaining electricity by the utility companies is higher compared to non-peak periods (Agyenim & Neil, 2010). This cost is likely to increase due to the increase demand of improved thermal comfort and emerging techniques such as electronic gadgets and electric cars. Moreover, it is estimated that every day, over 2 million people immigrate to cities and thus more mega cities packed with densely high-rise buildings are needed to accommodate this population.

The highly packed built urban environment influences the heat dissipation (Urban Heat Island) and pollution (Urban Pollution Island) due to the reduction of airflow, city ventilation (Haghighat & Mirzaei, 2011). Impact of urban heat island (UHI) and urban pollution island (UPI) on mortality rate and heat related diseases are extensively addressed in the literature (Hayhoe, Sheridan, Kalkstein, & Greene, 2010; Kinney, O'Neill, Bell, & Schwartz, 2008). Hajat, Kovats, Atkinson, and Haines (2002) reported an increase of 3.34% in death for every 1 °C temperature increase above 21.5 °C. This implies that cities are expecting more fatalities during heat waves, and preparing urban-wide programs to confront beforehand prognosis solutions (Ng, 2009). Energy generated from fossil fuels is extensively used in buildings for domestic hot water, space heating and/or cooling applications resulting in millions of tons of carbon dioxide (CO_2), climate change and related greenhouse gas emissions. The growing concern about environmental problems and the high costs of new power plants calls for new approaches to building technologies to stop this growth in electricity (ASHRAE handbook-HVAC Application, 1991). This has promoted the need for a reduction in CO_2 emissions via significant increase in energy efficiency of buildings. To offset related greenhouse gas emissions, renewable energy sources must make a significant contribution to global energy production, storage and usage of which solar energy is a major contributor (Kalogirou, 2004a,b). Renewable energy resources have massive energy potential but are not always fully accessible, can be diffused, or are regional, variable and intermittent. To sustain economic growth, issues relating to the supply

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and efficient use of energy must be addressed in the design of low energy buildings and sustainable cities. Nkwetta, Smyth, Lo, and Mondol (2008) reported that future energy systems require some combinations of retrofitting and adaptiveness, since no single source of energy is capable of optimizing for all applications. To achieve the European Union targets of 2020, it is necessary to encourage the retrofitting of existing buildings using local incentives and policies (Dall'O', Galante, & Pasetti, 2012). Dall et al. (2012) provided a methodology for evaluating the potential energy savings of retrofitting residential building stocks and reported that by using the envelope retrofitting alone it is possible to reduce the energy used in the residential sector by up to 24.8% by 2020. Rosa, Cumo, Garcia, Calcagnini, and Sferra (2012) reported an energy consumption reduction of 14–16% resulting from corrective interventions on the buildings using recycled non-toxic local materials and reduced environmental impact throughout their life cycle.

Gu, Sun, and Wennersten (2013) reported that the existing technologies for renewable energy are not yet sufficiently economically efficient and thus prevent the replacement of fossil fuels. They also reported it is impossible to generate enough energy using solar technology at the local sites and thus the needs not to overlook energy efficiency. They concluded that the two main contributors to domestic energy consumption in the city are the household and transport energy uses. They recommended that energy issues should not be considered as single element (notwithstanding the high performance) but be considered from a systems perspective point of view. This is because the high performance of single systems may not produce the same efficiency/performance when integrated and functioning as a system. The economical and successful application of renewable energy technologies to improve energy use and energy efficiency of buildings and offset related greenhouse gas emissions depends on efficient energy storage options.

2. The need for energy storage

In regions with extreme weather conditions, a lot of variations in energy demand and consumption are related to domestic hot water demand, space heating and/or cooling applications and vary drastically from day to night as well as seasonally. Changing energy demand and consumption results in peak and off-peak energy usage, leading to variation in energy prices offered by majority of the utility companies with higher electricity rates being imposed during peak-power demand (reflecting the cost of electricity provided during peak periods) compared to off-peak power demand (Agyenim & Neil, 2010; Lacroix, 1999). Wang and Yang (2012) reported on enhancing the intelligence of the multi-zone building during its operations using particle swarm optimization (PSO). They concluded PSO to be useful for maintaining the high comfort level in a building environment when the total energy supply is in a shortage. The mismatch between the energy supply and energy consumed and the need to store excess energy that would otherwise be wasted as well as shifting peak power demand calls for the need for thermal energy storage for different application areas (hot water, space heating and air-conditioning). Thermal energy storage (TES) systems enable greater and more efficient use of these fluctuating energy sources by matching the energy supply to the energy demand. This would greatly help to achieve a substantial reduction in fossil-based energy utilization and subsequent reduction in UHI and UPI phenomena, and would help in the design of sustainable cities. Two common methods of storing thermal energy are sensible and latent heat storage. While the majority of practical applications make use of sensible heat storage methods, latent heat storage such as phase change materials (PCM) provides much higher storage density, with very little temperature variation during the charging and discharging processes and thus proving to be efficient in storing thermal energy.

Domestic hot water is mostly provided using electric or gas heaters which are simple, but they have very low efficiency of energy usage. Long and Zhu (2008), reported that electric resistance water heaters are convenient for both installation and operation, but their overall efficiency in converting energy of fossil fuels to electric energy and then to thermal energy is quite low and also results in tons of greenhouse gas emission. The performance of water heaters depends mostly on the position and the number of the thermal elements, energy delivery to the fluid stream, the inlet/incoming water temperature, the size and the aspect ratio of the tank, flow rate, and the location of the inlet and outlet of the water heater (Bourke & Bansal, 2012). The main challenge is that the system should be designed to be efficient, compact and economical with minimum impact on the environment. TES systems are widely used for building applications and could be easily integrated with a solar or a heat pump system, or be charged with purchased electricity during off-peak periods. Techniques to improve the performance of TES using PCM have been investigated and include improving heat transfer through the application of fins, enhancing thermal conductivity, application of tube-in-shell TES, and application of micro-capsulation (Agyenim, Eames, & Smyth, 2009; Akgun, Aydin, & Kaygusuz, 2008; Cabeza, Ibáñez, Solé, Roca, & Nogués, 2006a). Energy storage does not only improve the performance and reliability of energy systems but plays an important role in conserving the energy and reducing the mismatch between energy supply and demand.

2.1. *Applications and advantage of phase change materials (PCM) in HWT*

Water has been used and is currently being used as a storage medium (sensible heat storage) in most of the low temperature applications. In such systems, as the energy is stored in the storage medium, the temperature of the storage material (water) increases. Latent thermal storage on the other hand, in which energy is stored in the material due to phase change, has attracted considerable interest in recent times due to its operational advantages. Hasnain (1998a,b) reported that thermal energy storage technologies can play an important role in re-shaping patterns of electricity use for both hot water, and space heating and cooling. He further highlighted that thermal storage systems can be applied in most buildings with significant heating needs, and thus electricity rates can allow thermal storage to be competitive with other forms of heating. Domanski, El-Sayed, and Jaworski (1994) and Fuqiao, Maidment, Missenden, and Tozer (2002) reported that PCM thermal storage technology, due to its high latent heat storage density and compactness, allows for greater flexibility in choosing a location for the storage system. Some of the operational advantages; smaller temperature swing between day indoors and night outdoors, smaller size and lower weight per unit of storage capacity with high energy storage density were reported (Fuqiao et al., 2002). Regin, Solanki, and Saini (2008) provided a detailed classification of the phase change process and reported that the storage capacity depends on the PCM latent heat value and specific heat capacity.

In addition, these systems are not only reliable and flexible but can reduce electrical demand and utility charges, use less and or at least no more energy than conventional systems, and cost no more than non-storage systems. According to Hasnain (1998a,b) the economic aspect of TES in buildings is easily noticed where cooling demands significantly contribute to high demand charges. In the phase transformation of the PCM, the solid–liquid phase change of material is of interest in thermal energy storage applications due to the high energy storage density and capacity to store energy as

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