PCM Selection for Heat Pump Integrated with Thermal Energy Storage for Demand Response in Residential Buildings

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ABSTRACT

Phase Change Materials (PCM) based Thermal energy storage (TES) is a widespread solution to shift buildings' peak energy demand and add stability to the grid. PCMs can be used for space heating and cooling applications in residential buildings by integrating into the heat pump equipment or building envelope via several possible configurations. The heat pump integrated active PCM storage can provide significant energy savings and reduce peak demand, but the benefits vary substantially depending on the system configuration, storage capacity, and the temperature range of the PCM used. It is critical to provide a review of the materials and their suitability in heat pump integrated PCM systems. This paper will present an analysis of the PCM material selection for heat pump integrated TES in various configurations. The comprehensive review will compare the phase change materials with different melting temperatures, and configurations, corresponding to the energy savings and demand impact reported in the literature. This work is significant to guide the design of high-performance heat pump integrated PCM systems.

Keywords: *Thermal Energy Storage, Phase Change Materials, Heat Pumps, Demand Response, Residential Buildings*

1. INTRODUCTION

Building's energy consumption and peak demand is often attributed to air conditioning applications. More than half of the energy consumed in the residential buildings is used for air conditioning and space heating. According to the DOE report, 54% of the site energy consumption is accounted for space heating and cooling combined, driving major portion of the residential energy demand (U.S. Energy Information Administration EIA, 2015, 2019). The residential buildings can play a major role to reduce energy demand and increase the building flexibility while maintaining the temperature in a comfortable range, by designing a load shifting strategy (Arteconi et al., 2019; Y. Chen et al., 2018; Jensen et al., 2017; Junker et al., 2018). The major electric load from the residential buildings comprises 80% of the total electricity use in the U.S., and 78% of the peak period use during 2-8 PM (Goetzler et al., 2019).

About 80% of American homes are detached single-family houses of an average area of about 2600 ft^2, with an average occupancy of 2.5 (U.S. EIA, 2020). Furthermore, 90% of homes in the U.S. use air conditioning as of 2019, and 75%

of those air-conditioned homes use central units. In 2019, the average annual electricity consumption for a U.S. residential utility customer was about 877 kWh per month. The consumers end up paying additional peak demand charges due to stress on the utility grid.

Though, the energy consumption and demand in the U.S. declined by 14% in response to the COVID-19 pandemic, however, the residential buildings energy consumption rose by 8% due to the increased residential demand shift as a result of working from home (*U.S. Energy Information Administration - EIA - Independent Statistics and Analysis*, n.d.). Power generation grids around the world are undergoing major changes to cope with the increasing energy demand and maintain physical and economic stability in response to the growing need for renewable energy generation (Blum, 2016). The technological advances and flexibility in the design and operation of HVAC systems can allow them to help the grid overcome these new load patterns challenges if properly managed.

Typically, in US residential buildings, there is no mechanical outdoor air exchange, or cross ventilation using natural resources, therefore, heat pumps are important to regulate the humidity inside the house as well as the indoor temperature. It is often cost-prohibitive to rebuild houses or update the conventional methods, but the heat pump systems can be made smart to respond to the peak demand changes. Today’s high-efficiency HVAC and appliance products can provide energy savings, but do not generally help with demand management and grid stress (Sultan et al., 2021).

Thermal energy storage (TES), which has capability to decouple the energy generation from its demand and usage, can be a crucial tool to shift the thermal loads. TES systems can be easily incorporated in small to large single-family or multi-family residential buildings. They are designed to trim the building’s electrical demand profile by reducing the energy usage and high demand costs arising from summer cooling and winter heating needs (Cui et al., 2014). When properly controlled, thermal storage can be useful in an economic or behavioral curtailment scenario for demand response. Major factors influencing an appropriate TES system's choice include the energy storage period and duration, cost and economic feasibility, and operational conditions. The building's thermal load is also dependent on the weather conditions and the thermal quality of the building envelope.

Phase Change Materials (PCMs) are widely used commercial thermal storage materials that could be used for space heating and cooling applications in various configurations. PCM-TES can store and release energy through charging and discharging process, respectively. By utilizing TES to store the energy for later use during peak hours, demand management systems can be designed to take advantage of lower utility rates during off-peak hours.

Researchers have used various configurations to employ the economic and grid benefits of PCM-TES for heating and cooling applications in buildings. The most common configurations are to install the material in building envelope via passive storage where the charging and discharging process is the function of ambient temperature, hence the grid benefits can’t be maximized. Active storage configurations allow real-time control of TES and are proven to be more effective than passive configurations. Active TES systems mechanically transfer the heat and hence can control when to charge or discharge the TES. This allows the TES systems to achieve grid flexibility, making them more suitable for load shifting and demand management. Another benefit of active configuration is the flexibility to be installed in an existing building infrastructure without needing a significant construction. The TES may be separate and removed from the space.

PCM-TES can behave as a standalone isothermal heat exchanger when integrated with heat pump (HP), and can offer advantages by shifting the peak demand while maintaining an adequate internal temperature in comfort range, without excessively using heat pump equipment. HP-TES in an active configuration, can enhance these benefits with a better performance if heat transfer is controlled by the heat pump (Dong et al., 2019).

The key to using TES to provide economic and grid benefits is the development of materials and packaging in optimized configuration and temperature range. Low temperature salt hydrate PCMs with melting point closer to the room temperature have garnered interest for near ambient TES systems because of their high storage density. However, the PCMs in this range often have low thermal conductivity that impacts the storage capacity. As such, modifications are needed to enhance the stability and thermal properties of PCM. Researchers have used single material in passive configurations for both high and low temperature applications but for active configuration, the materials with different melting temperature are selected for each application. Melting temperature for cooling applications is below 10°C, while for heating is above 40°C.

The benefits also vary largely due to other factors such as PCM material and temperature, configuration, and climate zone. Figure 1 below shows the demand impact and load shifting benefits reported in literature for Heat pump coupled passive and active TES. Active TES dominate mostly because the high level of control, allows designing and incorporating effective load shifting strategy.

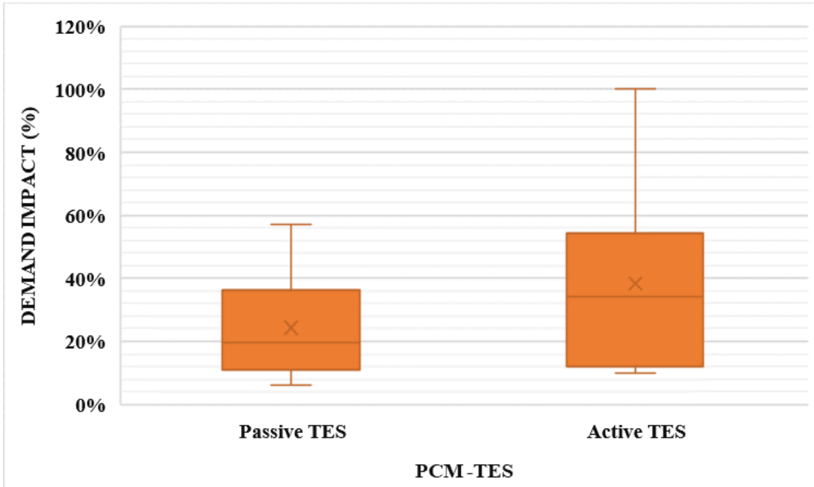

Figure 1: Comparison of load shifting benefits for Active and Passive TES

The focus of this paper is to review the phase change materials used in active heat pump integrated thermal storage systems. Literature review is conducted to evaluate the properties of PCM used in active HP-TES, as well as to compare the different configurations.

Section 2 will discuss the salt hydrate PCMs, focusing on melting temperature and storage capacity. Section 3 explains how PCMs are integrated in heat pump via different configurations. The demand impact is also reported and compared against the PCM types, heat pump configurations, and TES application.

2. PCM FOR HP-TES

Phase change materials (PCM) perform solid-liquid phase changes at temperatures in the operational range of the designated thermal application. When a phase transformation from a solid to a liquid occurs, the energy is absorbed by the phase transitioning material from the surroundings, though maintaining almost the same temperature (Fleischer, 2015). There are generally three classifications of PCMs; organic PCMs, inorganic PCMs, and eutectics. Organic PCMs are attributed to low heat conductivities and are flammable, while inorganic PCMs are relatively inexpensive, easily synthesized, nonflammable and possess high thermal conductivity and high storage capacity (Sarbu et al., 2018).

Any energy storage system should at least possess the following components:

- A PCM with the desired temperature range
- A compatible heat exchanger

This section reviews important factors and parameters for PCM selection to be integrated in heat pump componeents or coupled to the vapor compression system. The salt hydrate PCMs integrated with heat pump for space heating or cooling applications are reviewed.

2.1 PCM Selection

PCM temperature and storage capacity are considerably important to design the TES that can meet the buildings' load and provide necessary comfort. Various approaches can be found in literature to choose the melting point of PCMs to maximize their performance for space conditioning in buildings. Free cooling for continental climates was studied by Medved and Arkar (Arkar et al., 2007), and they found the PCM with a melting point equal to the average temperature of hottest month, most appropriate choice. The melting temperature range 20 and 22 °C was found suitable for passive cooling. Waqas and Kumar (Waqas et al., 2011) demonstrated an optimum PCM storage unit performance by selecting a PCM with the melting point equal to the comfort temperature of hottest month for free cooling.

The PCM temperature optimization studies (Alam et al., 2014; Arıcı et al., 2020; Berardi et al., 2019; Evola et al., 2013; Lei et al., 2016; Markarian et al., 2019; Piselli et al., 2020; Prabhakar et al., 2020; Saffari et al., 2017; Zhu et al., 2021) have commonly utilized passive cooling with organic PCMs. Paraffins are the frequently investigated materials with 20-30 °C melting temperature range. Furthermore, for a given TES, different PCM melting temperatures have been studied for both heating and cooling applications.

Table 1 below reviews salt hydrate PCMs integrated with different types of heat pumps via heat exchangers for space heating and cooling.

Table 1: PCMs for HP-TES

Author	**PCM material**	**Application**	**Heat Exchanger**	**Thermophysical Properties**	**Performance**
(Alkhwildi et al., 2020)	S8, S17, S27 (8 °C, 17 °C, 27 °C)	Geothermal heat pump for heating and peak load shifting	Single U-Tube ground heat exchanger	S27 showed highest savings and had thermal conductivity of 0.540 W/m.K	COP increased from 3.8 to 5.5
(Xin Jin et al., 2021)	Composite modified SAT (47.8°C)	Coupled to air source heat pump for heating	Shell and tube heat exchanger	Latent heat 219.8 kJ/kg (presented longer cycling lifetime)	Heat pump COP increased by 5.1%, 10 year payback period
(Han et al., 2008)	$CaCl_2.6H_2O$ (29.9 °C)	Solar assisted ground source heat pump	U-Tube soil exchanger	PCM thermal conductivity 1.09 W/m.K	COP increased from 3 to 5.95
(Yamaguchi et al., 1995)	$Na_2SO_4.10H_2O$ (32 °C)	Coupled to floor heating system for heating	Tube heat exchanger	PCM thermal conductivity 1.09 W/m.K	COP reported 3.0
(Kaygusuz et al., 1999)	$CaCl_2.6H_2O$ (28°C)	Coupled to solar and heat pump for heating	Fin tube heat exchanger	PCM thermal conductivity 1.09 W/m.K	COP increased to 4.0
(Benli, 2011)	$CaCl_2.6H_2O$ (28°C)	Coupled to ground source heat pump for green house heating	Ground heat exchanger	PCM thermal conductivity 1.09 W/m.K	COP increased to 4.2
(Kelly et al., 2014)	Commercial salt hydrate (48 °C)	Coupled to heat pump for heating	PCM enhanced buffer tank	Thermal conductivity 0.45 W/m.K	COP reduced from 3.0 to 2.4
(Xu et al., 2021)	Sodium Acetate Trihydrate SAT (58°C)	Coupled to condenser for heating	Plate heat exchanger	Thermal conductivity 0.57 W/m.K	COP reported 4.5
(Kumirai et al., 2019)	SP24E, RT27, RT25 (24 °C - 25 °C)	Coupled to ventilation system for cooling	Plate heat exchanger	Thermal conductivity 0.60 W/m.K	Salt hydrate PCM had highest storage capacity
(Alam et al., 2019)	FlatICE PCM (15 °C)	Coupled to chiller for space cooling and peak load shifting	Plate heat exchanger	Thermal conductivity 0.43 W/m.K	Chiller load reduced by 37%. PCM utilized 15% of its storage capacity

Most of the active TES studies reported in literature, as shown in the table above, have selected a melting temperature closer to the typical room temperature. A few of these works have investigated more than one type of PCM and have reported that the salt hydrate PCMs performed better than the organic PCMs in terms of storage capacity, and economic benefits.

3. INTEGRATION IN HEAT PUMP COMPONENTS

Active PCM-TES can be coupled to heat pump in various configurations. Table 1 in previous section described different types of heat exchangers and heat pumps. This section will particularly focus on PCM location within the heat pump and charging operation for the configuration. Researchers have reported energy and cost savings, and demand impact benefits for off-peak heating and cooling. Besides the PCM type and melting temperature, the savings and benefits largely depend on how and when PCM has been charged and discharged.

3.1 Heat Pump Integration

PCM-TES can be installed in building envelope, air distribution loops, or the vapor compression system itself. For an active PCM-TES to be installed in the building envelope, a heat exchanger is used and coupled to the air handling unit (Kondo et al., 2006). In the vapor compression system, either the PCM is directly installed in the condenser or evaporator, or coupled via a stand alone storage tank (Bruno et al., 2014; Real et al., 2014). Air distribution system has been the most commonly used configuration where the PCM is installed in the supply or return air ducts (Chaiyat, 2015; Hlanze et al., 2021).

3.2 Application and Configuration

Active HP-TES systems have been investigated for the demand response and load shifting potential. The literature reported in Table 2 and 3 show that the cooling applications are widely explored and peak cooling demand is shifted to off peak hours using different control strategies.

A paraffin PCM was installed in a return air duct coupled with evaporator to enhance the cooling efficiency of air conditioning system (Chaiyat, 2015). The PCM was solidified during nighttime by the cold air from the heat pump. During the daytime, return air from the room was passed through the PCM, liquifying it and reducing the cooling load at the evaporator. The time-of-use TOU tarrif was used and 3 hour load was shifted to off-peak hours. 9% daily energy and cost savings were reported.

Bruno et al. (Bruno et al., 2014) used ice and two salt hydrates PCMs installed in a heat exchanger coupled to chillder. The cooling energy is provided through chiller to either the PCM for solidification, or to the building during off-peak hours. The charging time and duration was optimized depending on the outside temperature to minimize energy usage and the PCM with 10°C melting temperature could save 13% energy.

Table 2 and 3 below compare the energy savings and demand impact for Active TES systems integrated with heat pump via different configurations. PCM melting point and charging operations are reported. Table 2 summarizes the salt hydrate PCMs while Table 3 reviews other PCMs used for HP-TES.

Table 2: Active HP-TES Configurations with Salt hydrate PCMS

Author	**PCM material**	**Application**	**Configuration & HP integration**	**Charging Operation**	**Key Results**
(Real et al., 2014)	S10 (10 °C) S27 (27 °C)	Both heating and cooling	In two storage tanks coupled to HVAC	Cooling energy is stored in cold tank at night using HVAC	18.97% energy saved
(Xu et al., 2021)	Sodium Acetate Trihydrate (SAT) (58 °C)	Space Heating	In storage tank coupled to condenser & electric heater	Heat pump condenser is used to charge PCM during off-peak hours	6 hours of peak load shifted
(Farah et al., 2019)	Salt Hydrate PCM 18T (18°C)	Space Cooling	In storage tank coupled to an air source heat pump	Return air from room passes through PCM before	Peak demand reduced by 32%

				entering the evaporator to increase COP	
(Mosaffa et al., 2016)	S27 (27°C) S25 (25°C)	Space Cooling	In storage tank coupled to vapor type compressor of heat pump	PCM is solidified using air-conditioner during off-peak hours	7-9% energy savings
(Bruno et al., 2014)	S4, S10 (4, 10 °C)	Space Cooling	In heat exchanger coupled to chiller	Chiller provides cooling to PCM during off-peak hours	Peak electric consumption reduced by 36.6%

Table 3: Active HP-TES Configurations with other PCMS

Author	**PCM material**	**Application**	**Configuration & HP integration**	**Charging Operation**	**Key Results**
(Takeda et al., 2004)	35% paraffin GR25 composite (25°C)	Space Cooling	In supply air duct of a ventilation system	PCM is solidified during night using the cool air from AHU	Ventilation load reduced by 62.8%
(Kondo et al., 2006)	Micro capsulate (25°C)	Space Cooling	In ceiling board coupled with AHU	PCM is charged overnight using AHU	9.4% load reduction
(Chaiyat, 2015)	RT20 Paraffin (20 °C)	Space Cooling	In return air duct coupled with the evaporator	Return air from room passes through PCM before entering the evaporator to increase COP	9% energy saved
(X. Chen et al., 2020)	RT11HC Paraffin (10-12°C)	Space Cooling	In storage tank coupled to heat pump	Heat pump directs cold water to solidify PCM	11.28% peak demand charges reduced
(Hlanze et al., 2021)	PureTemp 15T (15 °C)	Space Cooling	In supply air duct of air conditioning system	Cold supply air solidifies PCM during off-peak hours	Peak energy consumption reduced by 20-25%
(Hu et al., 2021)	ATS 30 (28 °C–33 °C)	Space Heating	In supply air system of heat pump	PCM is charged by heat pump at lower utility rates	6.7% energy consumption reduced

4. RESULTS AND DISCUSSIONS

The demand impact reported in the tables 2 and 3 corresponds to peak load shifted, peak electricity consumption reduced, or heat pump cooling and heating loads reduced. This section would discuss the PCM melting temperature and heat pump TES configuration for maximum demand impact. There are still number of factors to be considered such as the ambient climate conditions, size of TES, and heat transfer coefficient. The scope of this paper is limited to PCM material, melting temperature, and heat pump configuration.

4.1 Melting Temperature

Figure 2 shows the range of PCM temperature corresponding to demand impact for space heating and cooling. The PCM materials with the melting temperature ranging from 15 to 27 °C showed the most savings and demand benefits. Majority of the HP-TES systems reported in literature for demand response have investigated a cooling system which shows that cooling demand dominates in the centrally air conditioned residential homes. The PCM melting temperatures reported lie within the narrow range closer to room temperature except the Sodium Acetate Trihydrate (58 °C) which is used for space heating.

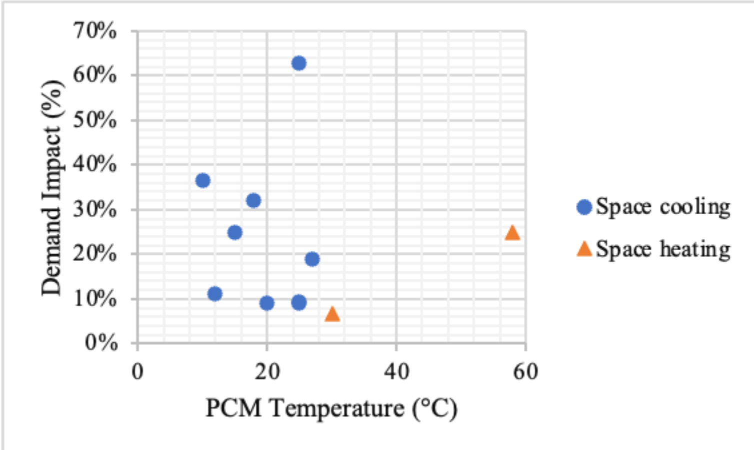

Figure 2: Demand Impact and PCM Temperature

4.2 Configuration

PCM-TES has been integrated with heat pump in various different configurations. Heat exchanger or storage tank containing PCM is coupled to either building envelope or heat pump components. Heat pump components can be on the air-side or the refrigirent-side of the heat pump. The refrigirent-side is referred as vapor compression system components (condenser, evaporator, and compressor), and the air-side corresponds to the air distribution system (supply air duct and return loop). Figure 3 shows that the air-side configurations are the ones most commonly investigated and report maximum demand impact and energy savings.

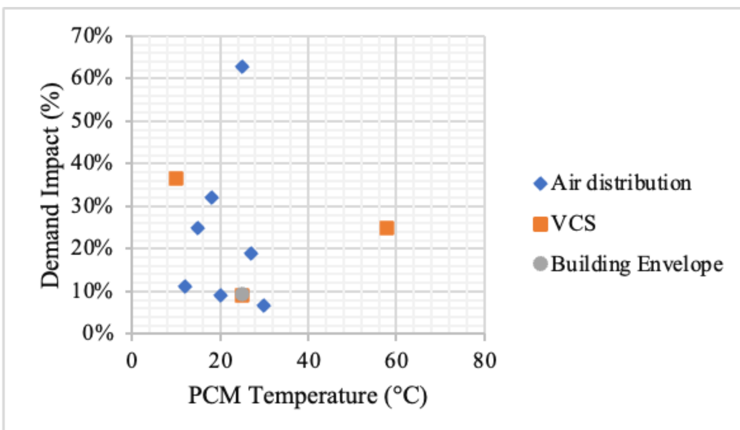

Figure 3: Demand Impact and heat pump configurations

5. CONCLUSIONS

Phase Change Material (PCM) based Thermal energy storage (TES) can provide economic and environmental benefits for grid-interactive residential buildings. The value and performance of TES vary greatly depending on the temperature range and storage capacity of the material, as well as the system configuration and ambient temperature. Active storage configurations allow real-time control of TES and are proven to be more effective than passive configurations, however, the active TES studies found in literature have utilized different materials for both heating and cooling.

This paper reviews the PCM materials, melting temperatures, and heat pump configurations to compare the energy savings and demand benefits of heat-pump integrated TES. The optimum demand impact and energy savings are reported for salt hydrate PCM with melting temperature between 15 and 27 °C integrated via air distribution system of the heat pump.

NOMENCLATURE

PCM	Phase Change Material	
TES	Thermal Energy Storage	
HP-TES	Heat Pump integrated Thermal Energy Storage	
AHU	Air Handling Unit	
TOU	Time of Use	
HVAC	Heating, Ventilation, and Air Conditioning	
HX	Heat Exchanger	
COP	Coefficient of Performance	
VCS	Vapor Compression System	
T	Temperature	(°C)

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