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ABSTRACT

To mitigate the variation in demand on the electric grid, thermal energy storage (TES) is an alternative to electric batteries and constructing new peaking power plants. The aggressive carbon reduction goals of the United States are accelerating the electrification of building equipment. If space heating and cooling in the US were electrified using conventional heat pump technologies, the winter electric grid peak would approximately double. Integrating TES with heat pump (HP) enables electrification of space cooling and heating devices without overtaxing the grid.

This paper evaluates the benefits of a novel phase change material (PCM) integrated heat pump configuration via simulation. A one-dimensional PCM heat exchanger model which discretizes the PCM tank and refrigerant tubes into small control volumes is developed. Each control volume can have different PCM temperatures, PCM properties, and heat transfer coefficients. The PCM tank is charged by a wrapped tank condenser and discharged by an internal refrigerant coil. The PCM heat exchanger model is integrated into DOE/ORNL Heat Pump Design Model for heat pump system simulation.

To demonstrate the performance of the PCM integrated heat pump, a case study in Chicago was performed. A Time-of-Use utility structure-based control strategy is implemented to schedule the PCM tank charging and discharging mode switching. Compared with a conventional electric heat pump, the PCM integrated heat pump shows superior performance on load shifting and utility cost reduction. As a result, the proposed system demonstrates 24.6% utility saving for cooling application and 25.8% utility saving for heating application.

Key words: Thermal energy storage, Phase change material, Heat pump, Demand reduction, Load shifting

1. INTRODUCTION

To mitigate the variation in demand on the electric grid, thermal energy storage (TES) is an alternative to electric batteries or installing new peaking power plants. The aggressive carbon reduction goals set by the United States are increasing the need for thermal energy storage (TES) technologies. TES is an important way to buffer the temporal variations of renewable energy electricity generation. The intermittent availability of renewable sources can result in rapid fluctuations in power supply to the electric grid, and TES can address this issue by storing thermal energy when electricity production exceeds demand and reinjecting energy into the system when supply is short. Since periods of peak demand normally occur in extreme thermal conditions that require large cooling or heating loads on buildings, TES provides an excellent means to buffer imbalances in the supply and demand of electric power. Furthermore, TES can be more cost effective than electrical storage with batteries. Besides, the retirement of coal-fired power plants throughout the United States could present new opportunities for TES.

Adding TES to building HVAC systems usually involves integrating the heat pump system with a TES component to shift most of the electricity used for space cooling and heating from peak to off-peak periods. Taking space cooling as an example, TES systems produce ice chiller water or phase change material (PCM) during off-peak periods and then discharge the cooling capacity during peak periods. Commonly used PCMs include paraffin wax, ice, and salt hydrates. Taking advantage of the thermal energy storage ability, a number of feasible PCM application schemes have been proposed to reduce the energy consumption of buildings (De Gracia and Cabeza (2015)). Most schemes are designed to utilize the thermal storage ability in a passive way by exploiting the diurnal ambient temperature swings. For instance, in building space-cooling applications, paraffin wax is integrated into building walls and provide passive cooling by solidifying overnight and then slowly absorbing heat throughout the day (Sharma et al. (2009)). An alternative solution to address the load shifting on the power grid is to add actively integrated PCM with building equipment (Skach et al. (2017)). However, most of the previous PCM integration approaches were developed for new buildings (Jacobson et al. (2018)), or require significant modifications on the existing envelope.

This research evaluates a novel PCM integrated heat pump (PCM-HP) system via simulation to reduce the residential HVAC electrical demand using a Time-of-Use based control strategy to help building end-users shift the use of electricity to low-cost period. The proposal PCM-HP system for heating and cooling can enable year-round demand flexibility for the power grid.

2. METHODOLOGY

2.1 Discretized PCM Heat Exchanger (PCM-HX) Model

A one-dimensional PCM tank model, which discretizes the PCM tank and refrigerant tube into small control volumes was developed as shown in Figure 1. Each control volume can have different PCM temperatures, properties and heat transfer coefficients as model inputs. The PCM tank is charged by a wrapped tank condenser and discharged by an internal refrigerant coil. The model accounts for the PCM heat conduction between adjacent nodes. The PCM mixing and natural convection between adjacent control volume are neglected for simplicity.

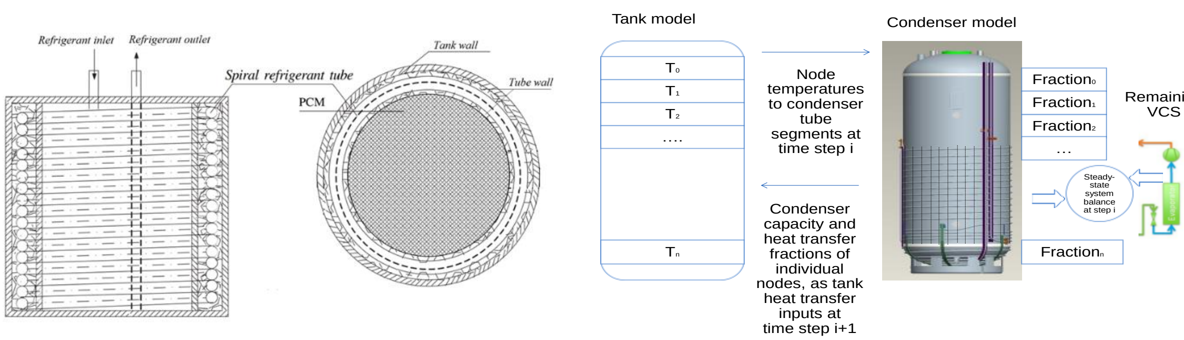

Figure 1: One-dimensional wrapped tank PCM-HX model

The properties of the graphene enhanced PCM used in this study is listed in Table 1 .

Table 1: Properties of PCM Material (Qiao *et al.* (2020))

Properties	Unit	Value
Melting temperature	°C	37
Latent heat	kJ/kg	210
Thermal conductivity	W/m*K	0.15 (liquid), 0.25 (solid)
Density	kg/m^3	840 (liquid), 920 (solid)
Specific heat	kJ/kg*K	2.63 (liquid), 2.21 (solid)

Figure 2 shows the PCM heat transfer coefficient at the outer surface of the tube is a function of PCM melt fraction.

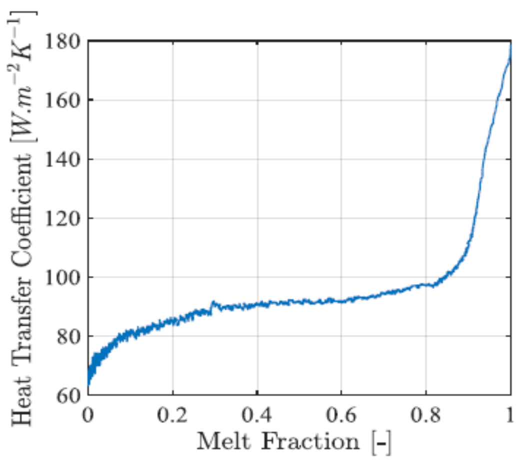

Figure 2: PCM side heat transfer coefficient versus PCM melt fraction (Qiao *et al.* (2020))

To demonstrate the simulation capability of the PCM heat exchanger model, Figure 3(a) shows the heat pump charging process. Different node represents different control volumes. The charging heat is not uniform among different control volumes at the starting phase (as shown by the scattering points), but the heat is balanced out via heat conduction through the charging process. Figure 3(b) shows that heat pump COP decreases with the increase of the PCM temperature during PCM melting process.

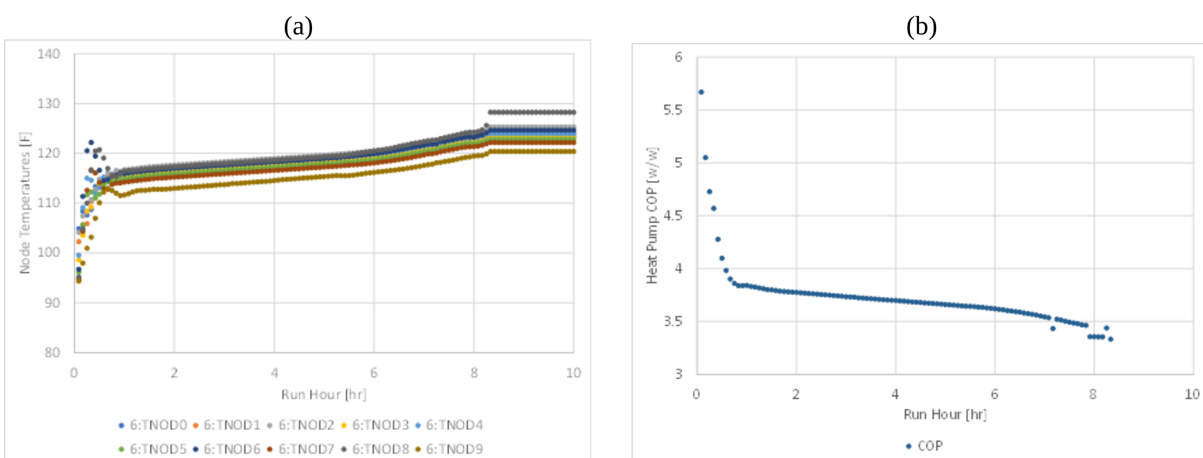

Figure 3: (a) Transients of PCM tank charging process; (b) Transients of PCM integrated heat pump COP during charging process.

The PCM integrated heat pump is to be operated under continuous switching between charge and discharge modes. Figure 4 shows the temperatures of PCM control volumes during continuous charge and discharge operations.

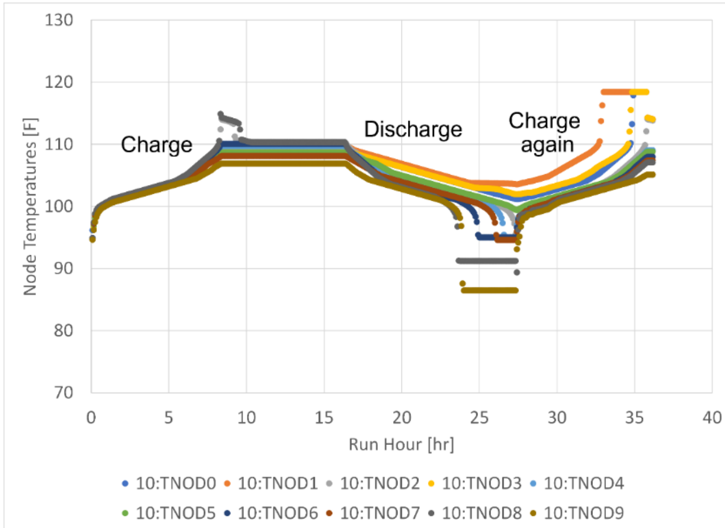

Figure 4: PCM node temperatures during continuous charge and discharge operations

2.2 System Simulation

The PCM heat exchanger component model described in previous section was added to the component library of the DOE/ORNL Heat Pump Design Model (HPDM)). HPDM allows user to integrate this PCM heat exchanger model with other component models to assemble a PCM integrated heat pump system. Figure 5 shows the system configuration of PCM integrated heat pump simulated in this study. For instance, when the system is operated in heating charge mode, the heat in sub-cooler is used to melt PCM. When the system is operated in heating discharge mode, it elevates stored heat for space heat at low ambient temperatures and bypass the outdoor coil.

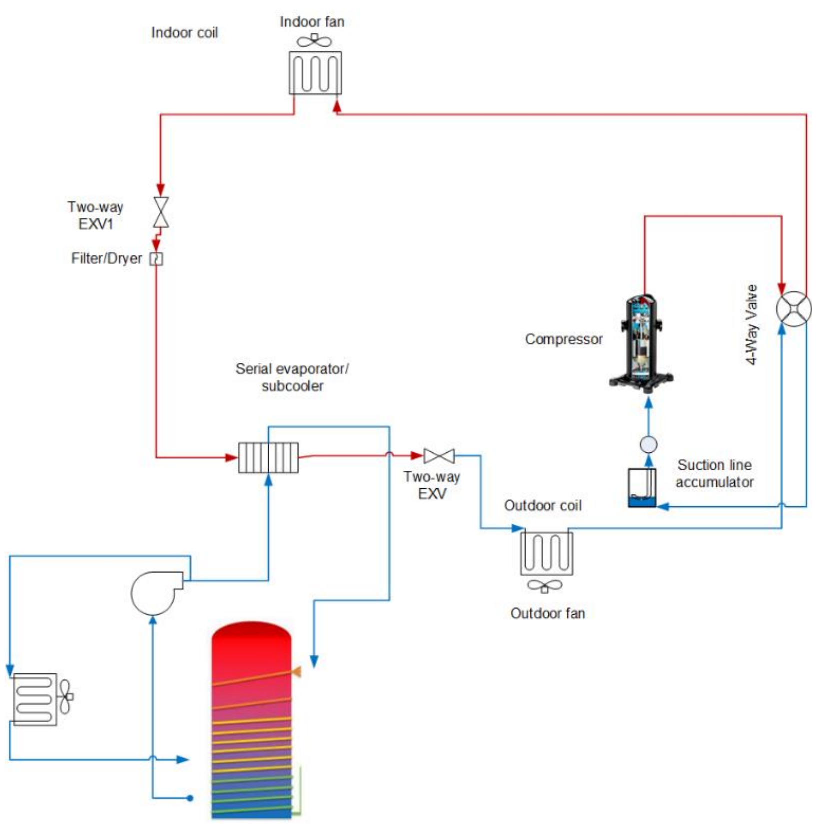

Figure 5: System configuration of PCM integrated heat pump

In addition to the PCM-HP, a 4.5-ton single-stage heat pump was simulated as the baseline for comparison. The baseline direction expansion system has rated EER of 13.0, and HSPF of 9.0 per AHRI 210/240 test standard (AHRI (2008)), and was calibrated using the manufacturers product specification.

For the PCM integrated heat pump, four modes, i.e., cooling charge, cooling discharge, heating charge, heating discharge, were modelled. Since the response of PCM tank are much slower than the heat pump, the PCM integrated heat pump simulation can be treated as quasi-steady-state or steady-state simulation. This is a widely accepted assumption, for example, the heat pump water heater model in EnergyPlus is a quasi-steady-state model (Crawley *et al.* (2001)).

To size the PCM tank, The coldest day in December 2019 and the the hottest day in August 2019 in Chicago are used to calculate the required PCM capacity to maintain 4-hour 50% peak load reduction. The resulting capacity of PCM tank is 14.78 kWh.

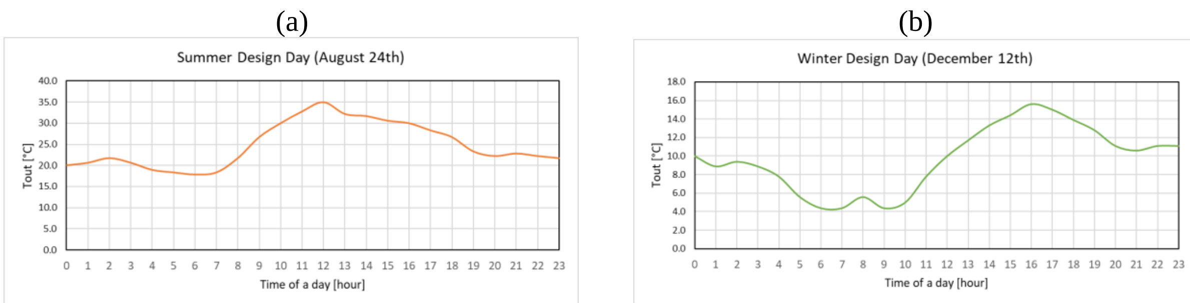

Figure 6: Sizing PCM tank capacity using (a) summer design day; (b) winter design day

2.3 Time-of-Use based Control Strategy

Different pricing schemes are available for demand response in different utility companies. Among all the schemes in Figure 7 (adapted from Baatz (2017)), TOU pricing is the most common scheme for utility companies. Therefore, this study used TOU utility rate as a representative to demonstrate utility cost savings obtained from PCM-HP.

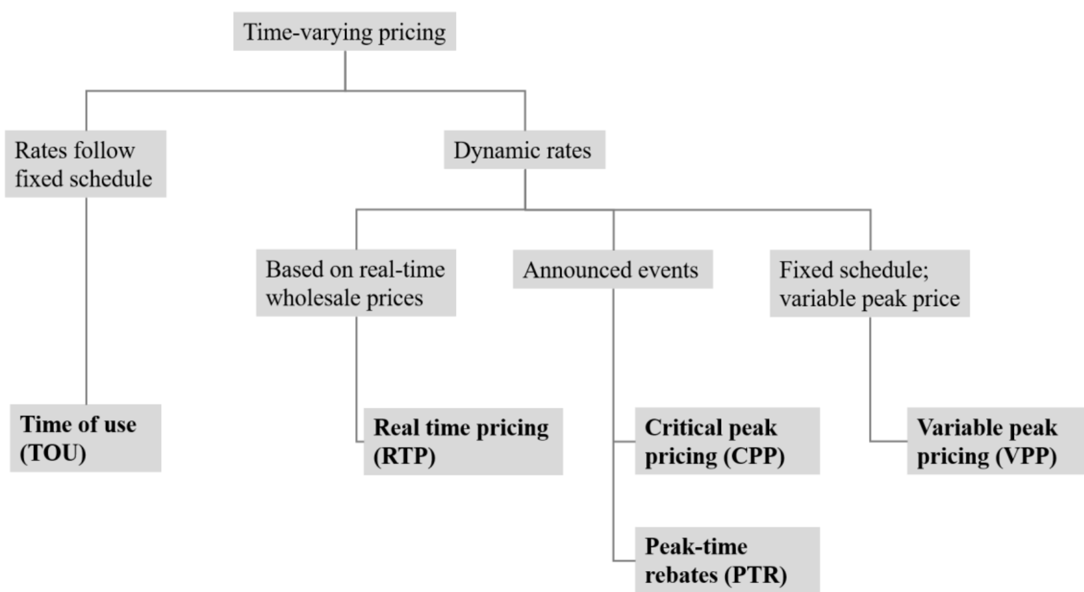

Figure 7: Common utility pricing schemes adapted from Baatz (2017).

To schedule the mode switching of PCM-HP, the system is operated under discharge mode during utility peak hours until the PCM tank is exhausted. Once the stored energy in PCM tank is exhausted, the system switches to charge mode, meanwhile, offer space cooling in summer or space heating in winter.

3. CASE STUDY

To obtain the building load, EnergyPlus is used to simulate a 2,500 ft^2 single-family home which is selected from the EnergyPlus library of template buildings. The case study adopts weather data in Chicago and a sample utility TOU structure in ComEd utiltiy company to demonstrate the efficacy of the PCM integrated heat pump system. It is assumed that the for both baseline direction expansion system and the PCM integrated system, the indoor heat exchanger capacity always satisfies the building load. For summer application, the indoor set point is specified as 80 °F. Figure 8 shows the electricity consumption for cooling mode application during August 17th to August 20th, 2019. The red shaded area represents the grid peak. The PCM integrated heat pump shows significnat demand reduction during grid peak under discharge mode. During off-peak hours, PCM-HP consumes more power than the baseline system when it is operated under charge mode.

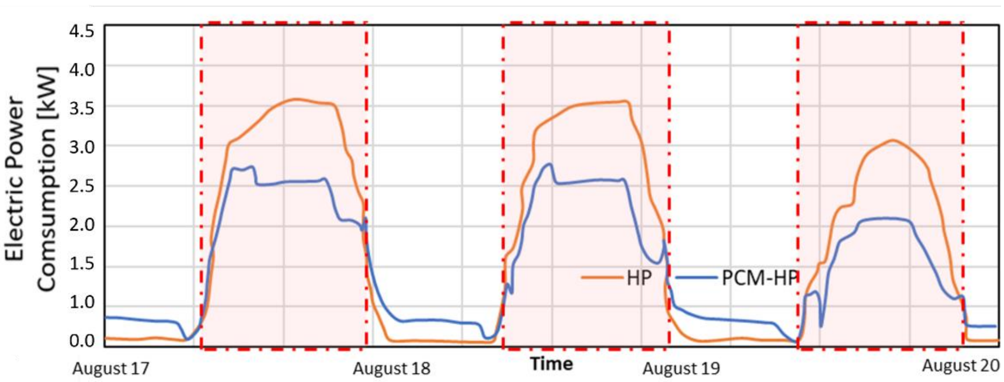

Figure 8: Power consumption of PCM-HP vs DX-baseline August 17-20th, 2019, Chicago (summer application).

For winter application, the indoor set point is specified as 70 °F. Figure 9 shows the electric power consumption of PCM integrated heat pump and the baseline direct expansion heat pump for heating application from December 5th to 9th, 2019. Similar to the cooling application, the PCM-HP consumes less power than baseline system during peak hours and the PCM-HP has more electric consumption during the off-peak hours when it is operated in charge mode.

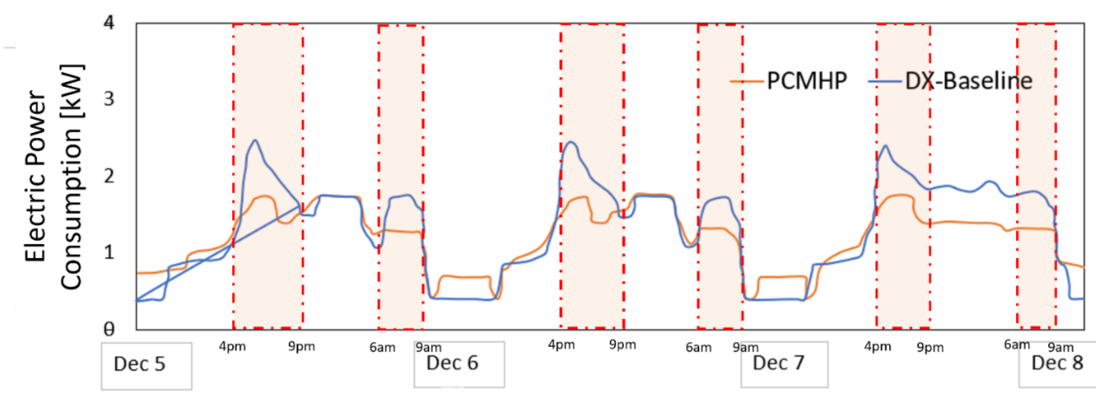

Figure 9: Power consumption of PCM-HP vs DX-baseline, December 5-8th, 2019, in Chicago (winter application)

Table 2 shows the overall utility cost using PCM-HP and the baseline system in August 2019 and December 2019. The utility saving is 24.6% for cooling application and 25.8% for heating application.

Table 2: Monthly utility cost in Chicago using PCM-HP and baseline in August and December 2019

	Operation Mode	
	August 2019, Cooling Mode	**December 2019, Heating Mode**
Baseline DX system	\$ 110.98	\$ 194.21
PCM-HP	\$ 83.6 (24.6%↓)	\$ 144.94 (25.8%↓)

4. CONCLUSION

In this paper, the potential for using phase change material (PCM) as a thermal storage medium to enable grid-responsive control of heat pump (HP) system is evaluated. The objective of this research is to design a novel and practical PCM integration with existing heat pump system. High-fidelity models for building, heat pump and PCM heat exchangers are developed. A Time-of-Use utility structure-based control strategy is implemented to regulate the PCM tank charge and discharge mode switching. Compared with a conventional electric heat pump, the PCM integrated heat pump shows superior performance on load shifting and utility cost reduction. It demonstrates 24.6% utility saving in a summer month and 25.8% utility saving in a winter month.

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