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Design and optimization of a hybrid air conditioning system with thermal energy storage using phase change composite

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ABSTRACT

This paper evaluates the use of a phase change composite (PCC) material consisting of paraffin wax (n-Tetradecane) and expanded graphite as a potential storage medium for cold thermal energy storage (TES) systems to support air conditioning applications. The PCC-TES system is proposed to be integrated with the vapor compression refrigeration cycle of an air conditioning (AC) system. The use of this PCC material is novel because of its unique material and thermal characteristics as compared to ice or chilled water that are predominantly used in commercial TES systems for air cooling applications. The work of this paper proposed and tested a hypothesis, which suggests that integrating a conventional AC with a PCC-TES would result in significant benefits concerning compressor size, compressor efficiency, electricity consumed and CO_2 emissions. The proposed integration would also contribute to reduce electricity demand during peak hours and reduce necessity to build more expensive power plants and distribution lines. To test the hypothesis, a simulation model in Aspen Plus® software was prepared. However, Aspen Plus® does not have a built-in library to predict PCC's melting and solidification behaviors. Therefore, an analytical heat transfer model was written as a system of equations in Fortran code into Aspen Plus® calculation block to simulate the phase change behavior and associated characteristics. The overall simulation model, which was designed specifically for this research work, consists of two main parts that communicate with each other. The first part simulates the AC's refrigeration loop using the built-in Aspen Plus® components and the second part implements the PCC heat transfer model written within the calculation block of Aspen Plus®. The simulation model was validated by crosschecking the calculated results with actual experimental data from an actual 4 kWh PCC-TES benchtop thermal storage system. Very good agreement was observed between the simulations and laboratory data. Simulated performance of the proposed integration between the AC and the PCC-TES indicated the potential to (1) downsize the compressor by 50%, (2) lower electrical consumption by the compressor by 30%, (3) lower CO_2 emissions by 30%, and (4) double the compressor efficiency during off and mid peak hours. The present work is a conceptual design and optimization study and does not account for integration inefficiencies, energy losses, real-world operation complexity, and added capital cost of TES integration with AC systems.

1. Introduction

A large portion of electricity consumptions in the US and all over the world is associated with air conditioners especially during summer seasons. According to the US Department of Energy, air conditioners annually cost homeowners around 29 billion dollars and release 117 million tons of CO_2 to the air [1]. A recent study [2] revealed that approximately one fifth of the electricity consumption in Austin Texas during peak hours is attributed to air conditioners operated in single-family residential homes. A similar study conducted in Spain revealed that air conditioners are responsible of more than one third of the electricity consumption during peak hours in Madrid [3]. Likewise, a study of Saudi Arabia's electricity consumption [4] revealed that air conditioners account for 50% of the increase in peak demand during summer months. The air conditioner (AC) units in the US and around the world are mostly oversized to meet peak cooling load during hot summer days. The underutilized capacity of oversized AC units wastes significant amount electricity during cooler hours/days of the year and increases carbon emissions. Moreover, high demand of electricity during peak hours drives up the transient price of electricity. In the US,

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List of abbreviations

$A_{(eff\text{-}tube)}$	effective area of heat transfer fluid tubes (m^2)
AC	Air Conditioning
A_{PCM}	Surface area of the phase change material (m^2)
COP	Coefficient of Performance
C_p	Specific heat of the phase change material (kJ/kg K)
Cp_{eff}	Effective specific heat of the phase change material (kJ/kg K)
Cp_l	Specific heat of the phase change material in liquid phase (kJ/kg K)
Cp_s	Specific heat of the phase change material in solid phase (kJ/kg K)
d_i	Inside diameter of the heat transfer fluid tube (m)
d_o	Outside diameter of the heat transfer fluid tube (m)
EG	Ethylene Glycol
h_{fluid}	Heat transfer coefficient of the heat transfer fluid (kJ/s m^2 K)
ΔH	Latent heat or Energy content per mass (kJ/kg)
Δh	Energy content per volume (kJ/m^3)
m	Mass of the phase change material (kg)
Δm	Fraction melted (or solidified) during phase change
PCC	Phase change composite
PCM	Phase change material
ρ	Density (kg/m^3)
Q	Cumulative heat or thermal energy (kJ)
s	Depth or (location) of moving phase boundary in z-direction (m)
t	Melting duration of the PCM (seconds)
TES	Thermal energy storage
T_f	Final temperature of the PCM (°C)
T_i	Initial temperature of the PCM (°C)
T_m	Melting temperature of the PCM (°C)
λ_{PCM}	Thermal conductivity of the PCM (kJ/s m K)
λ_{wall}	Thermal conductivity of tube wall material (kJ/s m K)

for example on year 2016, Southern California Edison Electric utility company applied time of usage (ToU) electricity charges during peak hours which was 0.235 $/kWh from 12 pm to 6 pm plus a demand charge of $9.5/MAX kW for each billing cycle. The company also applied $0.191/kWh and $0.064/kWh electricity ToU charges for mid-peak and off-peak hours, respectively. The ToU charges for year 2018 are almost 30–40% higher [5,6]. Furthermore, at some parts of the world, high electricity demand at once during peak hours may even lead to power outages.

On the production side, utility companies are adopting various energy efficiency programs and energy storage technologies to offset carbon emissions and avoid building new additional power plants and distribution lines to meet the peak electricity demands. On the demand side, residential and commercial customers are motivated to avoid ToU electricity charges and demand charges by opting for alternative technologies that are available or emerging in the market. A thermal energy storage (TES) system is a good alternative solution for demand-side management to shift the AC electricity usage from peak hours to off-peak hours, thereby also reducing the overall carbon footprint compared to a conventional air conditioning system.

A typical TES system cools the building during peak hours (when electricity prices are high) by absorbing heat from the incoming hot air for the spaces that need to be cooled. At night (when electricity prices are low), the TES then rejects the stored heat by exchange with the refrigeration loop of a conventional AC. The TES system will be integrated with an AC unit such that the TES system can provide additional cooling to the building during peak hours by completely or partially shifting the cooling load.

TES systems integrated with AC can be generally classified into groups; sensible heat versus latent heat. A sensible heat storage system utilizes liquid or solids to store energy on the basis of heat capacity over a range of temperatures. A latent heat TES system, on the other hand, stores energy at the temperature of (or within a narrow band of temperatures covering) a phase transition, either solid-liquid or solid-solid. Both cases have been described as phase change materials (PCM), although henceforth in our application we shall mean solid-liquid. Solid-liquid transitions have wider range of materials and applications as compared to limited to variety in solid-solid phase change materials. Solid-solid transitions are discussed by several researchers [7–14]. Latent heat is much larger than sensible heat, so latent heat systems are typically more compact than sensible heat systems

The concepts of exploring phase change materials and integrating cold thermal energy storage (TES) into an air conditioning (AC) system have been widely evaluated in the literature [15–28] aiming to partially or completely shift electricity demand from peak hours to off-peak hours.

As examples of latent heat versus sensible heat systems, respectively, ice and chilled water have been popularly used for commercial cold (TES) applications integrated into a conventional air conditioning system [22,24,25,27,29]. However, ice-TES systems also have some disadvantages such as super cooling issues, low thermal conductivity and low melting temperature [29]. Thus, they need to be oversized to accommodate more of the (highly conductive) tubes to speed up the thermal response. Alternately, the vapor compression refrigeration loop can be upsized to speed up solidification within the limited night hours. But this partially negates the purpose of integrating TES and reduces overall operating efficiency of the ice-TES by 30–40% [29]. Clearly, neither oversizing refrigeration loop that cools the ice-TES system nor using extremely large number of highly conductive tubes is a cost effective solution. Chilled water TES, on the other hand, is a very mature system to divert electricity consumption from day to night [25]. Given the relatively low thermal capacity of sensible heat (compared to latent heat), chilled water systems need very large equipment sizing to operate efficiently [25]. They are only economical for very large loads – typically 7000 kWh or higher [27].

In light of the aforementioned deficiencies with ice and chilled water TES systems, a wide variety of (organic and inorganic) PCMs evaluated in the literature possess certain strengths and weaknesses depending on the intended application. However, only few of those evaluated PCMs are feasible candidates for cold latent heat TES storages. For commercial rooftop air conditioning applications, the optimum melting temperature of a PCM should be in the range of 5–10 °C [29] and the latent heat and thermal conductivities should be relatively high. PCMs also need to be chemically stable, uniform during melting/solidification (i.e., producing no phase segregation), non-toxic, non-corrosive, and readily available at low cost [19,23,30–33].

Among the variety of inorganic materials, hydrated salts are among the highly potential storage medium materials for thermal energy storage because of their abundance & availability, good energy density (> 200 kJ/kg) and cheap cost as studied by [32,34–39]. However, disadvantages like low thermal conductivity, phase segregation, sub-cooling issues and corrosion are still pending major breakthroughs [19,32,34,40–42]. Thicking agents were proposed to reduce phase segregation issues, however it is proved to reduce thermal conductivity [19,42]. Furthermore, the use of nucleating agent can assist in minimizing sub-cooling issues with the aid of thinking agent while negatively impacting enthalpy by 20–35% [43].

Among the organic paraffin family, n-Tetradecane ($C_{14}H_{30}$) and n-Hexadecane ($C_{16}H_{34}$) are the most appropriate paraffin waxes for cold storage applications [28,30]. $C_{14}H_{30}$ has a melting temperature of