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Performance enhancement of solar absorption cooling systems using thermal energy storage with phase change materials

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HIGHLIGHTS

- A novel analytical methodology to size thermal storage in solar absorption systems.
- The analytical methodology compares water and Phase Change Materials.
- Analytical results are verified against a validated numerical system model.
- The analytical method is valid for a variety of limited temperature applications.

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ABSTRACT

Thermal energy storage has been shown to improve the efficiency of solar absorption cooling systems by capturing excess insolation during peak to meet cooling demand in low insolation periods. While water is the most commonly used thermal storage medium in solar cooling applications, the small operating temperature range of solar cooling systems limits its energy density. In contrast, Phase Change Materials maintain a high energy density under limited temperature ranges, and are ideally suited for such applications. Methods to select and size appropriate thermal storage technologies in solar cooling applications vary between studies with no standard methodology being utilized across the literature. Moreover, there is limited quantification of the influence of thermal storage on system performance to motivate the additional capital investment in these systems. This study provides an analytical framework to quantify the benefit of the thermal energy storage. Predictions from the analytical model are compared to the results from a validated transient system simulation. The paper gives an engineering approach for predicting the expected benefit from both water and phase change materials based thermal storage for applications with limited temperature ranges.

1. Introduction

Space cooling represents a significant portion of electrical energy consumption in many climates, accounting for 20% of a typical US household annual electrical bill [1]. Electricity is required to drive a conventional compressor-based vapor cooling system, a major contributor to electric power demand peaking, causing annual peaks to occur during the summer for many climates (e.g. California [2], Ontario [3], Saudi Arabia [4]). In electrical transmission systems, peak electrical demand is generally met by fossil-based power plants capable of responding quickly and on-demand. Fossil-based electrical generation is a major contributor of CO_2 emissions. Thus, reducing summer cooling peak would have a substantial impact on reducing CO_2 emissions from the electrical generation sector. In Ontario, summer peak can result in a 250% increase in grid CO_2 emissions per generated kW h [5,6].

Solar thermal driven absorption cycle systems provide an opportunity to offset peak electrical demand by utilizing solar radiation to provide cooling. Due to the temporal variation in incident solar radiation, thermal energy storage (TES) is typically utilized in these systems to improve the system performance. This study presents a novel analytical approach to assess the benefit of TES on the system performance. The framework can also be used to quantify the required storage volume, and compare volume reduction when using advanced thermal storage techniques that incorporate phase change materials (PCM).

2. Background

At the system level, experimental and numerical investigations in solar cooling systems generally focus on finding the combination of chiller, collector, and thermal storage type and capacity that is capable

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Nomenclature

f	solar fraction
q_V	volumetric energy density (kJ/m^3)
C_p	heat capacity (kJ/kg·K)
ρ	density (kg/m^3)
Q	total energy stored (kJ)
V	storage volume (m^3)
h_f	heat of fusion (kJ/kg)
T_{max}	maximum system temperature (°C)
T_{min}	minimum system temperature (°C)
ΔT	temperature difference (°C)
τ	integration time period (hours)
Q	total energy integrated over time period τ (kJ)
$\dot{Q}$	instantaneous energy throughput (kW)
COP	coefficient of performance
$\dot{S}(t)$	incident solar radiation profile (kW/m^2)
	collector area (m^2)
e_c	collector efficiency
$f_{V=0}$	solar fraction when no thermal storage is used
$f_{V=\infty}$	maximum allowable solar fraction with thermal storage

Acronyms

TES	thermal energy storage
PCM	phase change material

of maximizing system performance while minimizing investment costs. Critical details of numerous experimental investigations are discussed in Section 3.1 of this paper and summarized in Table 1. Although they vary in many key aspects, these experimental systems provide case studies for a specific set of equipment type and size at a specific climate and application. In such experiments it is difficult, however, to change the size of storage while keeping all other parameters constant in order to fully investigate the impact of thermal energy storage. These studies provide points for validating system models, and insight into the real complexities that arise for full installations. These experiments do not quantify the impact of one parameter (e.g. storage capacity) on the performance of the system while keeping all other conditions constant.

Numerical system models (discussed in Section 3.2 and Table 2) have the flexibility of simulating several different storage sizes under the same conditions. Confidence in the system model results is obtained through careful validation of components and their interactions. System simulations can be used to quantify the benefit of thermal energy storage on solar cooling performance, as is the aim of this study. However, the numerical simulations assume a case study with specifics regarding building cooling load, solar insolation profile, chiller and collector performance curves, control strategies, and other system specific characteristics.

In the current state of the art there is no standard method to appropriately select the type and size of thermal energy storage for solar absorption cooling systems. This paper presents a novel generalized analytical framework, presented in section 4, to assess the influence of thermal storage on system performance. This analytical framework was verified by comparing it to a validated system simulation code, presented in section 5. The generalized approach is able to provide quantitative storage design guiding principles that are applicable to a variety of solar cooling system sizes and boundary conditions.

A typical solar cooling system, depicted in Fig. 1, consists of a solar collector array used to capture solar radiation thermally through a coolant and deliver it to an absorption chiller. The hot coolant is used to drive an absorption cycle and provide cooling to a chilled water loop.

The absorption cycle consists of several components as shown in Fig. 1. The hot coolant from the thermal storage tank is delivered to the generator which is an evacuated chamber containing a binary solution. The hot coolant is used to raise the temperature of the solution and extract dissolved vapor which flows to the connected condenser. The condenser uses the cooling tower to eject heat and condense the refrigerant vapor to liquid, which then passes through an expansion valve to the evaporator producing a cooling effect to the chilled water. The vapor then enters the absorber which mixes it with the solution from the generator while heat is rejected to the cooling tower. The solution is then returned through a recuperating heat exchanger back to the generator for the cycle to be repeated [7].

Fig. 2 shows the energy flows across the absorption chiller unit along with typical temperatures at key points of the cycle. The performance of the chiller system is related to the temperatures of the cooling tower, generator, and evaporator through a coefficient of performance (COP).

$$COP_{thermal} = \frac{Q_{in\ Evaporator}}{Q_{in\ Generator}} \tag{1}$$

The COP increases when the generator and the evaporator temperatures are high and the cooling tower temperatures are low while still within the design range of the unit. The design point for the evaporator temperature, ranging between 4 and 7 °C, is such that humidity control is possible by reaching the dew point. The cooling tower temperature, designed to be maintained between 30 and 35 °C, is based on typical absorption chiller specifications [8] and substantially impacts the COP. The highest temperature in the chiller is at the generator, and the COP increases as the generator temperature increases up to a maximum, which typically ranges between 60 °C and 185 °C, depending on the type of absorption chiller (Table 1).

While many climates will be able to utilize solar cooling systems during peak hot summer days, it is most economically effective for climates in which substantial year-round cooling is needed [9–11] (discussed in detail in Section 3). In most installations, the solar cooling system is used as a supplement to an existing conventional system, and solar fractions (f) ranging from 0% to 100% have been reported (Table 1). The value of f represents the cooling power provided by the solar cooling system over the total amount of cooling required.

$$f = \frac{Q_{Cooling\ Solar}}{Q_{Cooling\ Demanded}} \tag{2}$$

Solar fraction can be increased by including thermal storage into these systems to allow for cooling during periods of low solar radiation. The role of TES in solar absorption cooling systems is to bridge the temporal mismatch between when thermal energy is available and when it is required. The optimal size of storage depends on the daily total available thermal energy and the degree of mismatch in time between when this energy is captured and when it is to be used. Water is typically used as the thermal storage medium with experiments utilizing tank sizes varying between 0 to 34 m^3 for chillers providing nominally 4.5–174 kW of cooling power (Table 1). The addition of thermal storage of this size allows for a daily storage of energy, and the opportunity to provide evening/night cooling.

Thermal energy can be stored in sensible, latent, or chemical forms. While sensible energy storage requires the temperature of the medium to increase in order to store energy, latent energy storage through phase change allows for storage and release of energy at near constant temperatures [12].

The temperature of the fluid in the collector and storage tank influences the collector efficiency and the chiller COP. It also impacts the energy storage requirements since the volumetric energy density of a sensible medium is described by: