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Energetic evaluation of thermal energy storage options for high efficiency solar cooling systems

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HIGHLIGHTS

- An approach for comparing sensible and latent heat storage materials using dynamic simulations.
- Experimentally validated latent heat storage model used in the numerical simulations.
- Analysis of system design parameters such as storage size, collector area, storage insulation.
- Results show high storage efficiency for latent heat materials due to reduced storage volume.
- Sensible heat based solar cooling system performed with higher annual solar fraction.

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ABSTRACT

Thermal energy storage (TES) plays an important role in ensuring continuous heat supply to solar powered thermal systems such as solar cooling plants. Various sensible and latent heat storage material options are available when designing a solar cooling system. Latent heat materials are known to have higher energy density resulting in lower storage volume. However, it is unclear if there are any energy benefits due to these materials while used in a typical solar cooling application. In this paper we investigate the system performance of different storage materials while delivering cooling to a typical commercial building in Australia. This system uses high efficiency triple effect absorption chiller as the cooling delivery system. Heat requirement for this chiller is provided through parabolic trough collectors delivering heat over 200 °C.

A suitable approach for storage system design that enables direct comparison of sensible and latent heat storage benefits is described in this paper. In order to simulate the latent heat storage system, a new numerical model has been developed, validated with experimental data and implemented in the simulation environment as an external library. Commercially available liquid sensible storage materials have been compared against latent heat materials with a phase change temperatures suitable for triple effect chiller operation. A parametric analysis of the system design parameters such as the collector area, storage volume has been carried out. Results from annual simulations have been presented for fixed cooling load and variable cooling load scenarios.

Latent heat storage systems functioned with high storage efficiency compared to sensible heat storage systems, a reflection of low heat losses due to reduced storage sizes. It is seen that the collectors have higher yield while functioning with a sensible heat storage medium. As a result, for the chosen configuration, the sensible heat storage materials provided higher annual performance than the latent heat material choices.

1. Introduction

Heating, Ventilation and Air conditioning (HVAC) is the largest source of electricity consumption in the building sector [1]. Roof mounted solar thermal collectors can offset a major part of this energy need, by providing heat for winter space heating, hot water requirements, and for cooling during summer months. Thermal

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Nomenclature

A	area of heat transfer (m^2)
a	chiller model coefficient
COP	coefficient of performance (–)
cp	specific heat capacity at constant pressure (J/(kg K))
D	tube diameter (m)
dh	hydraulic diameter (m)
DN	tube nominal diameter (mm)
DSC	differential scanning calorimetry
E	energy (J)
e	enthalpy per unit of volume (J/m^3)
Ev	energy density ($kW h/m^3$)
FVM	finite volume method
H	height (m)
h	convective heat transfer coefficient ($W/(m^2 K)$)
HTF	heat transfer fluid
k	thermal conductivity (W/(m K))
L	tube length (m)
LH	phase change enthalpy or latent heat of phase change (J/kg)
$\dot{m}$	flow rate (kg/s)
N	number of tube (–)
Nu	Nusselt Number (–)
PCM	phase change material
PDE	partial differential equation
Pr	Prandtl Number (–)
Q	capacity (kW)
R	radius (m)
r	radial coordinate (m), chiller model coefficient
Re	Reynolds number (–)
Rth	thermal insulance of storage insulation ($(m^2 K)/W$)
s	chiller model coefficient
SF	solar fraction (–)
T	temperature (K)
t	time (s), average inlet-outlet temperature (°C)
U	overall heat transfer coefficient ($W/(m^2 K)$)
u	velocity (m/s)
V	volume (m^3)
y	axial coordinate (m)

Greek symbols

$\Delta\Delta t$	characteristic temperature function (°C)
ρ	density (kg/m^3)
ε	storage effectiveness (–)
η	storage efficiency (–)
γ	laminar to turbulent Reynolds number ratio

Subscripts

AC, ac	absorber and condenser
aux	auxiliary
bot	bottom
c	cooling
charg	charging
disch	discharging
E, e	evaporator
env	environment
G, g	generator
i	inner
ini	initial
lam	laminar
liq	liquid
loss	losses
nom	nominal
o	outer
pc	phase change
pcm	phase change material
sol	solid
st	stored
top	top
bot	bottom
turb	turbulent
tube	tube

absorption chillers driven by solar energy have been evaluated as a viable option for meeting building cooling demand over the past 20 years [2,3]. High temperature absorption chillers (double- and triple-effect chillers), are a suitable choice due to their higher performance coefficients, and concomitant reduction in solar collector foot print [4].

Thermal storage in a solar cooling plant provides a way to overcome solar intermittency and provides on demand availability of cooling based on the end user need. As a result, there have been plenty of successful demonstrations and studies of solar cooling systems with thermal storage using single effect chillers [5–9]. Water is the predominant storage medium and the heat transfer fluid in these installations due to its low cost and potential to transfer heat from solar collector to the chiller without any secondary heat exchanger. However, double effect (heat inlet in the range of 160–180 °C) and triple effect (heat inlet temperature of 200–230 °C) absorption chiller based solar cooling system design requires careful consideration of storage medium choice, driven by the following factors:

- *Simple and cost effective system design:*

Hot water storage for high temperature applications requires use of pressure vessels and the additional costs of handling of high pressure in the piping. For example, a triple effect chiller operating with 200 °C heat input might need the storage vessel and the piping to be designed for 35 bar. An alternative heat transfer fluid and thermal storage media is thermal oil. Thermal oil has been commonly used as a heat transfer fluid in parabolic trough power plants [10]. Thermal oil can be used at atmospheric pressure for double and triple effect chiller applications. Unfortunately, the cost of thermal oil is significantly higher than that of water. Solid storage media such as reinforced concrete is also a potential candidate due to its low cost and high strength. Concrete has been evaluated as a potential storage material up to 400 °C [11]. However, use of solid storage media will require additional heat exchangers to transfer the heat from the collector loop to the storage material and from the storage material to the chiller.

- *Minimise heat losses and match the storage to given application:*

Due to heat storage at high temperatures, thermal losses from the storage tank can be significant. As a result, a compact thermal store that uses a high volume density storage material, can provide considerable energy saving benefits. Phase Change Materials (PCM) with high latent energy storage density and phase change temperature matching the solar cooling heat requirement could be suitable for high temperature solar cooling applications. Gil et al. [12,13] evaluated the suitability of latent heat storage with PCM with heat inlet temperature of 150 °C to 200 °C. Fan et al. [14] and Gil et al. [15] have assessed hydroquinone as suitable phase change material for double effect chiller applications.