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The Impact of Hot and Cold Storages on a Solar Absorption Cooling System for an Office Building

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ABSTRACT

Buildings consume 40% of the total energy in the U.S. and a half of them are used for heating, cooling and hot water usage. Nowadays, people are paying more attention to the energy efficiency and carbon footprints of buildings. Renewable energy-based solar cooling system is regarded as a good candidate, to reduce the energy consumption and CO_2 emissions.

This paper has explored the impact of thermal storage on the energy performance of the solar absorption cooling system for a benchmark medium-sized office building located in Los Angeles, California. The solar cooling system was designed to provide 50% of the total building cooling by $200m^2$ solar collector area. The system selected an absorption chiller at 120kW working with both a hot tank in the solar collection loop and cold storage tanks in the load loop. The sensitivity analyses on the two storages were conducted by varying the volume of the two storages, solar collector area and the nominal capacity of the chiller. The hot storage tank volume was set to $0.01m^3/m^2$ of solar collector area to test the performance of the cold storage with various volumes; and the cold storage tank volume was set to $4m^3$ to test the performance of the hot storage with various volumes. The results indicated that a reasonable sized cold storage tank could reduce the chiller's capacity, but it does not significantly affect the system's energy performance. When the cold storage tank volume varies between $4m^3$ and $22m^3$, the solar fraction only changes about 2%. The solar fraction varies between 51% and 57% when the hot storage tank volume increases from $0.01m^3/m^2$ ($2m^3$) to $0.11m^3/m^2$ ($22m^3$). The sensitivity analyses showed that the solar cooling system is most sensitive to the solar collector area, and followed by the chiller's capacity, hot storage tank volume, and cold storage tank.

1. INTRODUCTION

Buildings in the U.S. are responsible for 41% of the primary energy use and 38% of CO_2 emissions (*Annual energy review, 2008*). According to the U.S. DOE 2006 Building Energy Data Book, of all the energy consumed by buildings, about 50% are consumed by space heating (20%), cooling (18%) and water heating (10%). Due to mounting concerns about climate change and resource depletion, meeting building heating and cooling demand with renewable energy has attracted increasing attention in the energy system design of green buildings. One of these approaches, solar assisted cooling, may be a key solution to addressing the energy and environmental challenges faced by building design, due to the building cooling loads tracking closely with solar irradiation. The most common solar assisted thermal cooling system to date is based on the absorption cycle. Similar to the conventional vapor-compression cycle, the absorption cycle uses a thermal compressor including an absorber, a generator, and a solution pump, instead of a mechanical compressor (*Yunho Hwang, et al. 2008*). Presently, the most promising solar cooling system is the combination of evacuated-tube solar collectors and single-effected LiBr-H2O absorption chillers (*F. Calise, et al. 2010*).

So far, a lot of research work has been done for the solar absorption cooling system design and modeling. *Syed, A. et al. (2005)* and *Zambrano, Darine et al. (2008)* built solar absorption cooling systems with flat-plate collectors, single-effect LiBr-H2O absorption chiller and hot storage tank located between the solar collection loop and the chiller. *Pongtornkulpanich, A. et al. (2008)*, *Ali, Ahmed Hamza H. et al. (2008)* and *F. Calise, et al. (2010)* built the system with both the hot storage tank and cold storage tank. All the system configurations described in these papers are similar, normally including solar collectors, single-effect absorption chiller, hot water or/and cold water storage tanks.

Lots of researchers did simulation and modeling to optimize the system via varying the key parameters of the system, including the storage tank volume. *T. Mateus, A.C. Oliveira (2009)* gave the best hot storage tank volume range was 0.05 to 0.11 m^3/m^2 (of collector area) for the office building. *D.S. Ward and G. O. G. Lof (1978)* introduced that the cold storage tank can prevent the chiller on and off during low cooling demand, and it also can be utilized to combine with smaller nominal capacity chiller. The cold storage tank volume could be determined to minimize the cycling of the chiller and also meeting the cooling demand of the building. *F. Assilzadeh et al. (2005)* simulated a solar absorption cooling system in Malysia, and found a $0.8m^3$ hot water storage tank can minimize the auxiliary heater usage for a 1 ton system consisting of $35m^2$ evacuated solar collectors, which is about $0.02m^3/m^2$ (solar collector area). *N.K. Ghaddar et al. (1997)* determined that the optimal performance of the system was attained at a hot storage tank volume to collector area ratio of 13-19 l/m^2, and the minimum permitted volume to avoid boiling in the system is 11.6 l/m^2 by system modeling and simulation.

To date, few paper discuss the system performance which includes both the hot and cold storage tank. Therefore, this paper aims to explore the hot and cold storage tank impacts on a solar cooling system in the energy performance respect.

2. DESCRIPTION OF SYSTEM LAYOUT

The schematic diagram of the solar cooling system is shown in Figure 1. It mainly consists of solar collectors, a hot storage tank, an auxiliary heater, a single-effect LiBr-H_2O absorption chiller, and the cold storage tank. The solar collectors absorb the solar energy from the sun, and the generated hot water is temporally stored in the hot storage tank. The hot water from the heat source storage tank is pumped to the absorption chiller, which convert the hot water to chilled water. The chilled water transfers the cold energy to the cold water storage tank, which provides the cooling energy to the building side. When the solar energy is not adequate or is not available, a gas-fired auxiliary heater is used to provide heat to the chiller.

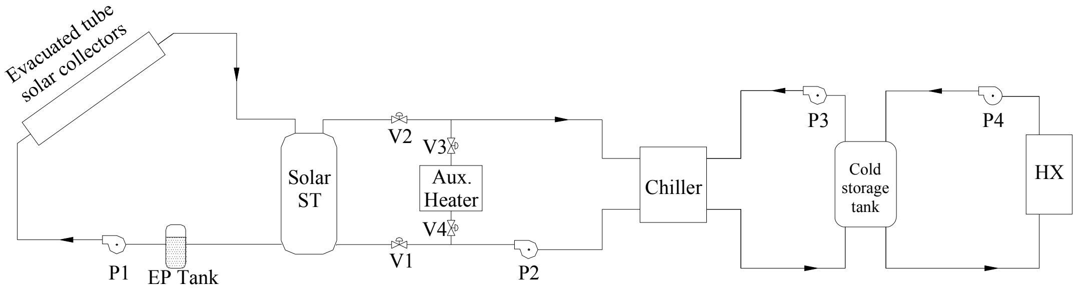

Figure 1: Schematic diagram of solar cooling system

3. SIMULATION MODEL AND CASE STUDY

A case study is conducted to explore the influence of hot and cold storage tank. A low temperature absorption solar cooling system was investigated for a medium-sized office building in Los Angeles, California, which was selected due to its abundant solar resources. The office building was chosen as the building type because its operation schedule matches well with the solar energy profile.

3.1 Meteorological data

Based on the Typical Meteorological Year 2 *(TMY2) data*, the monthly dry-bulb ambient temperature of Los Angeles is between 60°F and 75°F (15.5°C to 23.9°C), as shown in Figure 2. The temperature distribution indicates that cooling is required year around. As shown in Figure 3, the daily global solar irradiation is stable and high throughout a year. Two weather features make Los Angeles an ideal place for solar cooling.

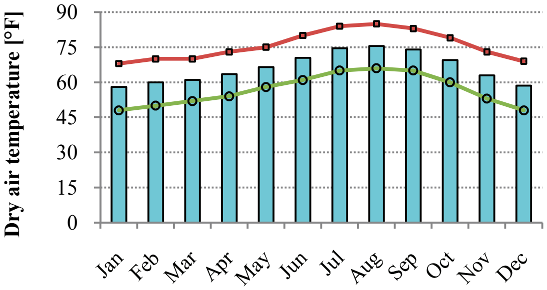

Figure 2: Monthly average temperature for Los Angeles

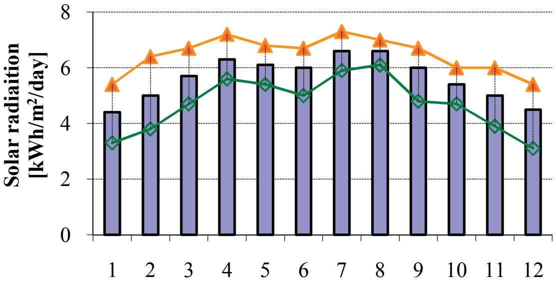

Figure 3: Daily solar irradiation on tilted surface with the latitude angle for Los Angeles

3.2 Building characteristics

The standard benchmark building models for new and existing buildings developed by DOE were used in this research. The standard benchmark building models includes the 15 most representative buildings in the commercial building stock, at 16 locations across all U.S. climate zones and with three vintages (new, pre-1980, and post-1980 construction) *(P. Torcellini, et al.2008)*. All of the models are built in *Energyplus* example input files. The selected building model is a new medium-sized office building. This building is a three-story, rectangular building with a total area of 4,983m^2. Each floor, with a height of 4m, is divided into five thermal zones, including four perimeter zones and one interior zone. The building is south-north facing, the roof is flat, and the walls are steel frame. The characteristics of this building model are shown in Table 1. Figure 4 shows the building cooling load simulation results, which suggest that the building model has a relatively high performance with a peak cooling load of about 40m^2/kW, compared to a peak cooling load of 10m^2/kW for a typical office building *(Bell, A.A, 2002)*.

Table 1: Characteristics of medium-sized office building benchmark model

Name		Medium Office	Note
Floor Area /m^2		4,983	
Number of Floors		3	
Shape		Rectangle	
Aspect Ratio		1.5	
Number of Thermal Zones		15	
Window-to-wall ratio		24.30%	Equal distribution of windows
Infiltration		0.27 ACH	In perimeter zones only
Internal gains	Lights	10.76 W/m^2	
	Elec. Plug loads	8.07 W/m^2	
	Gas plug loads	0 W/m^2	
	people	268 in total; 5.38/100m^2	
Schedule	Occupied	5AM-7PM	Monday-Saturday
Set point	Heating	21°C for occupied, 15.6°C for unoccupied	
	Cooling	24°C for occupied, 30°C for unoccupied	
Humidity		50%	

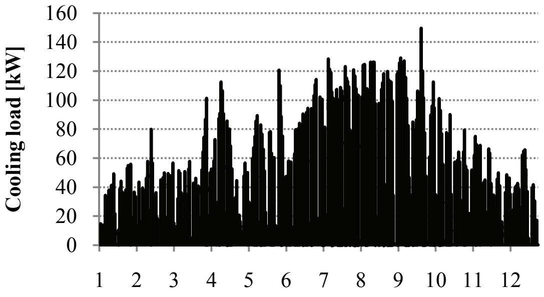

Figure 4: Annual cooling load for Los Angeles, CA

3.3 Sizing of the major equipments in the solar cooling system

The evacuated tube is selected as solar collectors, which is specified in Table 2. Compared to the flat-plate solar collector, the evacuated tube solar collector has higher efficiency and can provide a heat source temperature in the range of 90 to110°C, which is required by the absorption chiller. According to *J.A. Duffie, et al. 2006*, for solar cooling, the optimized tilted angle is the local latitude minus 10°, therefore, a tilted angel of 24° is used in this simulation. 200m^2 solar collector area is selected cover about 50% of building cooling load.

Table 2: Specification of evacuated tube

Parameter	Unity	Evacuated tube collector
Optical collector efficiency (η_0)	-	0.623
Linear heat loss coefficient (a_1)	W $m^{-2}K^{-1}$	1.2297
Quadratic heat loss coefficient (a_2)	W $m^{-2}K^{-2}$	0.00756
Gross area	m^2	1.919m×2.160m = 4.15m^2

120kW nominal capacity chiller is selected to explore the cooling function combined with cold storage tanks. The cold storage tank volume range could be determined based on its two major functions:

1) To meet the daily peak load. As shown in the Figure 5, the cold storage tank volume could be determined based on the area A according to the equation (1) [9].

$$Q_s = \sum_{i=1}^{n} (L_i - Q_o)\Delta\tau_i \qquad if\ L_i > Q_o \tag{1}$$

Where,

Q_s is the thermal capacity of the cold storage, kWh;

L_i is the daily cooling load, kW;

Q_o is the nominal capacity of the chiller, kW;

$\Delta\tau_i$ is the time interval of the simulation, hr;

n is the total operation period.

Therefore, the volume of the cold storage tank could be determined by equation (2) [9]:

$$V = \frac{3600Q_s}{C_p\rho\Delta T_{load}} \tag{2}$$

Where,

V is the volume of the cold storage tank, m^3;

C_p is the specific heat of the water, kJ/(kg-°C);

ρ is density of the water, kg/m^3;

ΔT_{load} is temperature difference of the cold storage tank, °C.

Therefore, the volume of the cold storage tank is calculated equal to $20m^3$.

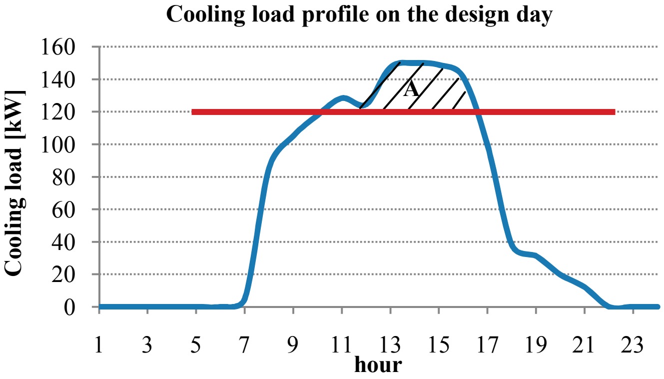

Figure 5: peak daily cooling load

2) To avoid the chiller operating under 20% of chiller's nominal capacity. The cold storage tank should be able to store the cooling energy for the building use when the cooling load is lower than 20% of the chiller's nominal capacity, which is 24kW in this case. Statistic method is applied to determine how large the cold storage tank should be. Figure 6 shows the histogram of the annual cooling load for this building.

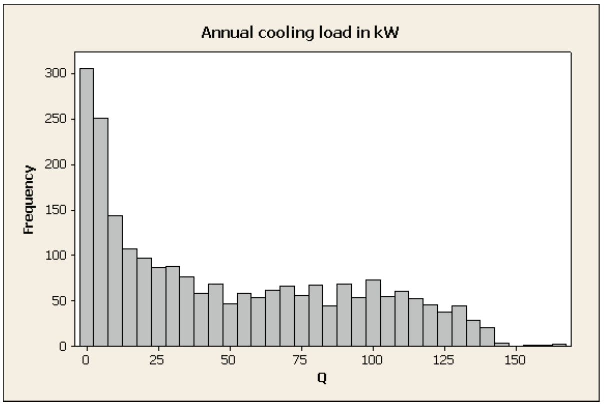

Figure 6: Annual cooling load frequency

According to Figure 6, it is approximately 934 hours which the cooling load is lower or equal to 24kW. And the mean value among this range is 7kW. Since the days between April 15 and October 15 are 183, therefore, it is about 5 hours per day. We can size the cold storage tank when the thermal capacity is equal to 7kW*5hr=35kWh, which represents the cold storage tank volume about 4m^3.Therefore, the cold storage tank volume range is 4m^3 to 20m^3, with the chiller's nominal capacity is 120kW. The specification of a representative chiller available on the market is show in Table 3.

Table 3: Specification of the chiller

Parameter	Unity	Value
Rated COP	-	0.75
Rated Power	kW	150
Chilled water temperature (inlet/outlet)	°C	12.2/6.7
Chilled water flow rate	gpm	103
Heat source water temperature (inlet/outlet)	°C	98/88
Heat source water flow rate	gpm	79
Cooling water temperature (inlet/outlet)	°C	29.4/36.4
Cooling water flow rate	gpm	191
Electrical power	kW	1.8

4. ENERGY SIMULATION RESULTS

Based on the discussion above, the system simulation is conducted by TRNSYS software. The components in the system were built on the basis of the TRNSYS built-in library [12]. Figure 7 shows the solar fraction as a function of cold storage tank volume, when the solar collector area is 200m^2, absorption chiller is 120kW, and the hot storage tank volume ratio is 0.01 m^3/m^2 of solar collector area. The hot storage tank is function as a buffer tank; therefore, its volume is selected at its lower range, in order to eliminate the storage function of the hot storage tank. The cold storage tank volume is in the range of 4m^3 to 20m^3, with the interval of 4m^3. According to Figure 7, the solar fraction change about 2.5% when the cold storage tank volume varies from 4m^3 to 20m^3, and the highest solar fraction occurs when the cold storage tank volume equals 12m^3.

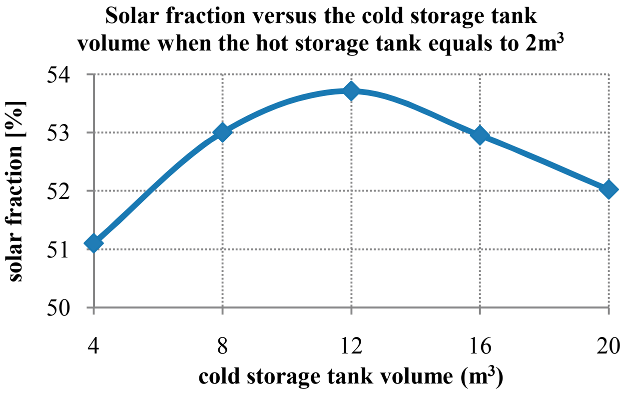

Figure 7: solar fraction and the cold storage tank volume

Figure 8 shows the solar fraction as a function of hot storage tank volume, when the solar collector area equals 200m^2 and absorption chiller nominal capacity is 120kW. As the same principle of selecting hot storage tank, the cold storage tank volume is also selected at its lower range, which is 4m^3. According to Figure 8, the solar fraction varies between 51% and 57% when the hot storage tank volume increases from 0.01m^3/m^2 (2m^3) to 0.11m^3/m^2 (22m^3). Therefore, the solar fraction is more sensitive to the hot storage tank volume compared to the cold storage tank volume. The highest solar fraction occurs when the hot storage tank volume equals about 16m^3.

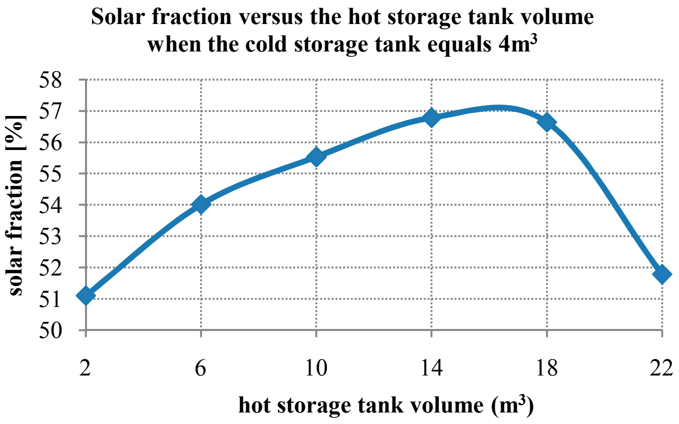

Figure 8: solar fraction as a function hot storage tank volume

5. SENSITIVITY ANALYSIS

In order to examine the sensitivity of the key parameters of the solar cooling system, a base case is selected, and the sensitivity analysis is conducted for the chiller's nominal capacity, hot storage tank volume, cold storage tank volume and solar collector area, by varying ±20% from the base case parameters. According to the results shown in Figure 9, the system is most sensitive to the solar collector area, followed by the chiller capacity, hot storage tank and the cold storage tank.

Table 4: Sensitivity analyses

Key parameters	Chiller capacity	Hot storage	coldstorage	solar collector area	Solar Fraction
Unit	kW	m3	m3	m2	%
Base case	120	14	12	200	55.86
Case1	96	X	X	X	56.51
Case2	144	X	X	X	55.8
Case3	X	11	X	X	55.84
Case4	X	17	X	X	56.45
Case5	X	X	9.6	X	55.8
Case6	X	X	14.4	X	55.92
Case7	X	X	X	160	48.33
Case8	X	X	X	240	68.81

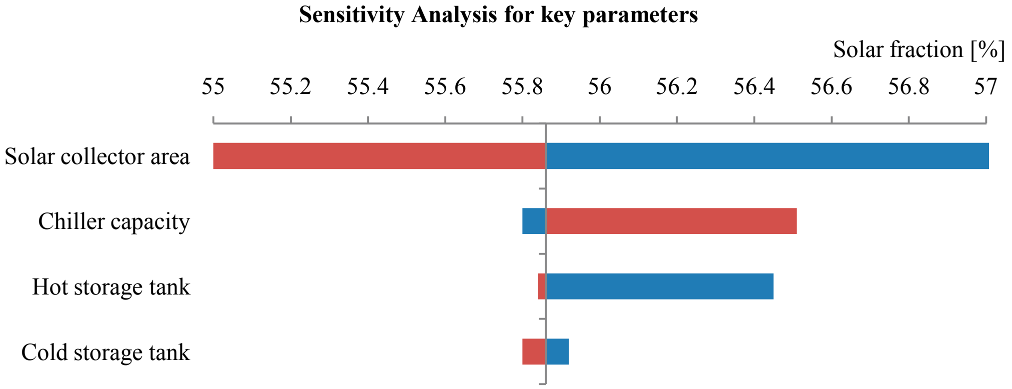

Figure 9: Sensitivity analysis for key parameters

6. CONCLUSION

The hot storage tank is used to store the extra energy from the solar field, and stabilizes the operation of the system. The cold storage tank has two major functions. First is to avoid the chiller running under 20% of its nominal capacity. Therefore, a cold storage tank could stabilize the operation of the system. Besides, a smaller sized chiller with a reasonable sized cold storage tank could reduce the system cost. As we know, the absorption chiller is expensive, especially when the capacity becomes larger. However, the cold storage tank is relatively cheap. The peak cooling load could be met by the cooperation of the absorption chiller with smaller nominal capacity than the peak load and the cold storage tank.

The results showed that a reasonable sized cold storage tank could reduce the chiller's capacity, but it does not affect the system's energy performance a lot. When the cold storage tank volume varies between $4m^3$ and $22m^3$, the solar fraction only changes about 2%. The solar fraction varies between 51% and 57% if the hot storage tank volume increases from $0.01m^3/m^2$ ($2m^3$) to $0.11m^3/m^2$ ($22m^3$). Finally, the sensitivity analysis was also conducted by varying the solar collector area, chiller's capacity, hot water storage tank, and cold storage tank volume. The results showed that the solar cooling system is most sensitive to the solar collector area, and followed by the chiller's capacity, hot storage tank volume, and cold storage tank. This result also matches with the simulation results.

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