DISCHARGING EXPERIMENTS OF A COOL THERMAL STORE FILLED WITH BALLS CONTAINING WATER

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ABSTRACT

Cool thermal storage (CTS) systems remove heat from a thermal storage medium during periods of low cooling demand. Stored cool energy is used later, during high demand period, to meet an air-conditioning or process cooling load. Decoupling chiller operation from instantaneous loads is a major advantage of a CTS system. The investigator conducted two experiments to investigate the performance of a CTS during discharging processes. The rectangular CTS used in the experiments enclosed 1080 plastic balls. All balls were submerged totally in a 40% ethylene glycol solution .They were arranged in nine layers. The hot solution circulated through the store by entering the store at the top and leaving at the bottom. Initial solution and ball temperatures and experiment duration time of each experiment were different. Temperatures of twelve selected balls, four at each of three layers (top, middle, and bottom), and temperatures of entering and leaving solution were recorded every ten minutes. Average ball temperatures at each layer were calculated for each experiment.All temperatures increased differently with time, but with similar general trend. Data of ball temperatures against time were fit into fourth-degree polynomial, which can be used to predict the performance of the store with similar initial conditions. It evident that a CTS can be used to cover a cooling requirement.

Keywords: *Cool thermal Store, Reduce Power Consumption of Chillers, Ethylene-Glycol Solution Platic Balls, Solution and Ball Temperatures, Discharging Process*

الملخص

تزيل أنظمة التخزين الحراري البارد الحرارة من وسط تخزين حراري خلال أوقات حاجة منخفضة للتبريد. يستفاد من هذه الطاقة الباردة المخزنة لاحقاً، خلال فترة طلب مرتفع، لتلبية حمل تكييف هواء أوعملية تبريد. إن الفائدة الكبرى من انظمة التخزين الحراري هي فصل أداء المثلج عن احمال التبريد الفورية. اجري الباحث تجارب عديدة للتحقق من طبيعة اداء خزان حراري بارد خلال عمليات تفريغه من الطاقة الباردة، لكن هذه الورقة تحتوي على نتائج تجربتين فقط . إحتوى الخزان المستطيل الشكل المستخدم في التجارب ١٠٨٠ كرة مصنوعة من البلاستيك وثلاثة ارباع حجمها مملوء بالماء . كانت جميع الكور مغمورة تماما في محلول إيثيلين جلايكول وقد تم توزيعها ضمن تسع طبقات . تم تدوير المحلول عبر الخزان بحيث يدخل الخزان من أعلاه ويخرج من أسفله. تميزت كل تجربة أجريت بدرجات حرارة أولية مختلفة للمحلول والكور. المعطيات التي جمعت كل عشر دقائق كانت درجات حرارة المحلول قبل دخوله الخزان

وبعد خروجه منه بالإضافة الى درجات حرارة الماء في إثنى عشرة كورة موزعة على ثلاث مستويات (علوي، وأوسط، وسفلي) داخل الخزان، أربع منها في كل مستوى . حسب المؤلف بعد ذلك متوسط درجات حرارة الكور بمعلومية الزمن عند كل مستوى. إرتفعت هذه المتوسطات عند نهاية التجربة الأولى التي استمرت زهاء ثلاث ساعات . استمرت التجربة الثانية أربع ساعات حيث إرتفعت متوسطات درجات حرارة الكور عند نهاية التجربة الى ٧ و ٤،٥ و ٥°م بالترتيب. استخدم برنامج حاسوب لإيجاد معادلة جبرية من الدرجة الرابعة تربط بين متوسط درجات حرارة الكور في كل مستوى وبين الزمن . من الواضح امكانية استخدام خزان حراري بارد في تخفيض استهلاك الكهرباء خلال وقت الذروة.

1. INTRODUCTION

Space cooling in Arabian Gulf countries during the summer consumes as much as 80-90% of the total energy produced by Utilities [Bahel et al., 1985 & Ayyash, 1983]. Residential, commercial, and governmental sector electricity consumption during 1418H was 29% of the total power provided by SCECO East [SCECO, 1997/98]. This number jumbed to 32% in 1420H [SCECO, 1999/2000], as shown in Figure 1. A major portion of this load is caused by space cooling requirements of buildings.Peak electricity demand, which occurs during the summer due to cooling loads, increased from 7317MW in 1415H to 8219MW in 1418H (12.3% increase), according to SCECO East annual report [SCECO, 1997/98]. In 1420H peak demand reached 8332 MW [SCECO, 1999/2000], an increase of 8.4% compared to 1416H figures (Figure 2).

Given such high electricity consumption figures and the need to make more rational use of the world's energy resources it has become necessary to investigate every avenue for saving primary energy without reducing building occupants comfort standards. One such avenue is cool thermal store (CTS). Storage of cool energy in a volume of water for air conditioning purposes is used to reduce peak electricity demand. It is a technology that is used in developed countries to reduce electricity consumption for air conditioning of large buildings during peak periods. Early research on cool storage started during the late sevevnties of the last century [Gusman et al., 1979]. A lot of research was conducted ever since to increase awareness and experience among scientists and engineers about theory and practice of cool energy storage [Grumman et al., 1988; Fiedler, 1988; Knebel et al., 1989; Cottone, 1990; Bakenhus, 2000; Silvetti, 2002]. Several books were written on planning, design, and operation of cool thermal storage projects [Elleson, 1997; Dorgan et al., 1993]

CTS systems remove heat from a thermal storage medium during periods of low cooling demand. Stored cool energy is used later, during high demand period, to meet an air-conditioning or process cooling load. CTS medium can be chilled water, ice, or a eutectic salt phase-change material. Benefits of a CTS system are enormous. Decoupling chiller operation from instantaneous loads is one advantage. Other advantages are higher chiller operation efficiency, less intial system cost, more operation flexibility, and lower supply air and supply water temperatures. A study on the performance of the store is required for optimum operation of the system. Cooling requirements and load pattern must be known in order to size the cool store accurately. An over-sized store is a poor investment and an under-size store will fail to meet cooling requirements.

Author conducted research on charging and discharging a CTS that uses water encapsulated in hollow plastic spheres, which are submerged in a solution, as the cool energy storage medium [Hariri, 1991]. General results of some charging and discharging experiments were presented in an earlier paper [Hariri, 2000]. Deatails of two charging experiments were discussed in another paper [Hariri, 2002]. This paper investigates results of two discharging experiments only. One aim of this paper is to show the concept of peak load reduction by a cool energy store. Another aim is to present the method of releasing cool energy from a storage medium of the type used in this paper. Research also investigates effects of ball location inside the store on ball performance. Fourth order algebraic equations are used to correlate data of balls temperature with time.

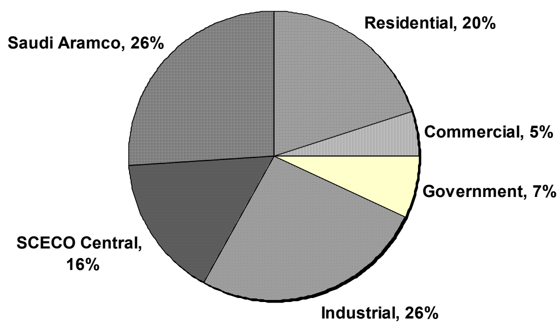

Figure 1. SCECO Power Consumption By Sectors During 1999/2000

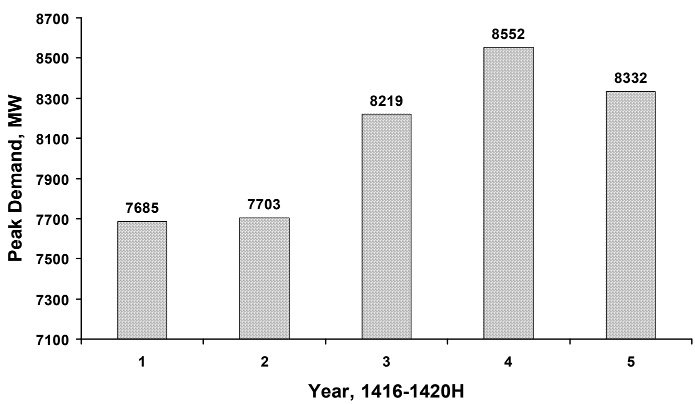

Figure 2. SCECO Peak Demand During 1416-1420H

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2. APPARATUS DESCRIPTION

The experiment rig consisted of a rectangular CTS connected to an electric immersion heater with a capacity of 7.5 kW (the vertical white column shown to the right of the apparatus in Figure 3). This heater provided the load on the store during a discharging process. It could be switched on and off to simulate different load profiles. The CTS was made of an inner metallic tank, a middle 10-cm thick polystyrene insulation surrounding top and all four sides of the metallic box, and an outer plywood container. The metallic box enclosed energy storage balls (fully immersed in an ethylene-glycol solution), and solution-distribution-collection pipe networks (Figure 4). The inner box, made of galvanized steel, was 0.94 meter high, 1.54 meter wide, and 1.14 meter deep. The outer plywood box was 1.14 meter high, 1.74 meter wide, and 1.34 meter deep.

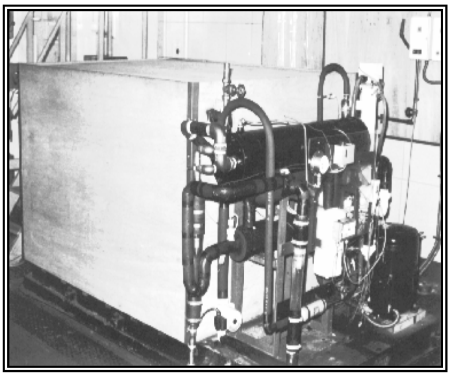


Figure 3. Cool energy store and heater

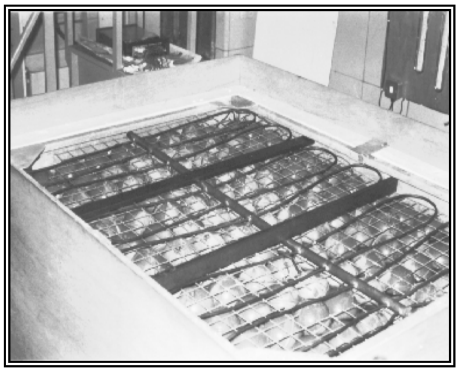
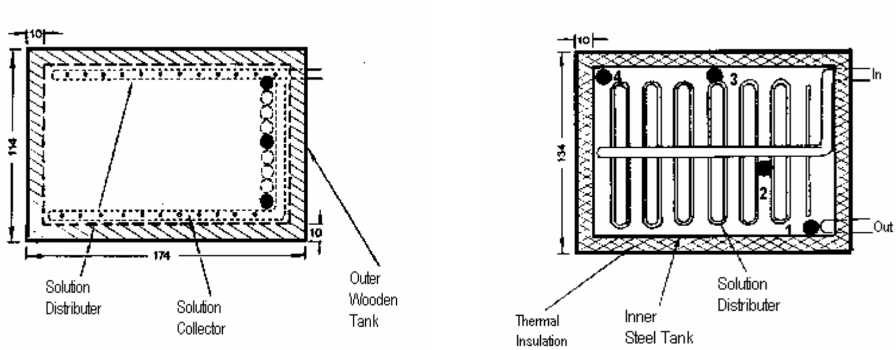


Figure 4. Energy storage balls and solution distribution pipe network



(a) Cross-Section

(b) Top-View

Figure 5. Dimensions [in centimeters] of store and locations of balls where data is collected

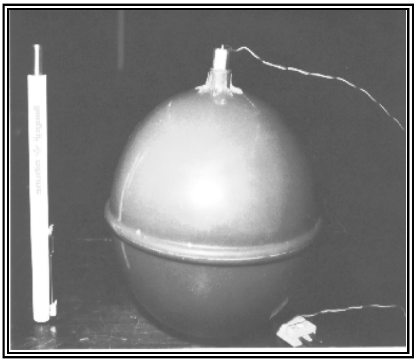


Figure 6. A cool thermal storage ball

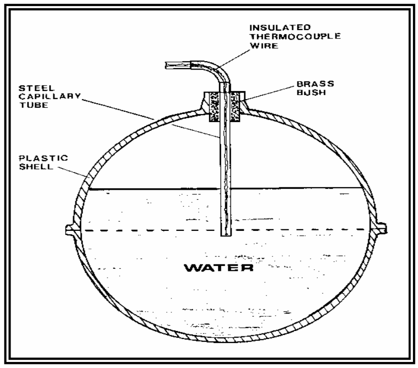


Figure 7. Cross-section of a ball

The 1080 plastic energy storage balls, each of 11 cm diameter, filled the store. Figure 5-a shows how the balls were arranged horizontally in nine layers . The first 8 layers from top had 119 balls in each, a total of 952 balls. The 9th bottom layer had 128 balls. Temperature was recorded in four balls in each of three layers (Figure5-b). The layers selected were the uppermost, middle, and bottom layers. Locations of selected balls were the same in each one of the three layers. A thermocouple wire extended from the top of selected balls (Figure 6) to a data logger. Figure 7 shows a cross section of a ball with the insulated thermocouple wire housed in a steel capillary tube. The mass of water inside each ball was 0.557 kg, occupying almost two thirds of a ball volume.

The energy-transfer fluid used in the experiment was a 40% ethylene glycol solution with a specific heat of 3.5 kJ/kg K. It filled up the CTS, with a mass of 500 kg, so as to have all the balls immersed. The ethylene glycol solution entered the CTS during a discharging process at a mass flow rate of 0.417 kg/s through a one inch diameter copper tube. It got distributed by the horizontal solution-distribution pipe network of a smaller diameter. A similar pipe network collected the solution at the store bottom, which then got pumped out through a vertical pipe that extended along the height of the store and exited at the top.

Temperatures were measured by type K thermocouples (Nickel-Chromium vs. Nickel-Aluminum alloy). Compensating cables connecting thermocouples with data logger extended from the balls, through the store, and into the data logger. The thermocouple measuring the solution inlet temperature was positioned inside the tube leading into store in a location just before the solution enters the store.

3. RESULTS AND DISCUSSION

The immersion heater was turned on during discharging processes. After leaving the store the antifreeze solution passed through the redundant evaporator, into the immersion heater where

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it absorbed heat, and back to the store where heat got delivered to the balls and solution. There was a ten-minute interval between each two successive readings. Temperature of the incoming solution during a discharging process increased gradually from a temperature below zero to a maximum temperature of about 12^{o}C. This maximum was chosen for it provided an exit solution temperature of about 5^{o}C, the recommended temperature for a cooling coil.

Inlet and exit solution temperature data for the first experiment, which lasted for 2 hours and 50 minutes, are presented in Figure 8. Initial exit solution temperature was -9^{o}C. It increased steadily with time. Sharper increase during the first 30 minutes is noticed. Exit solution temperature was always less than inlet solution temperature, due to the release of cool energy by balls and solution inside store.

Figure 9 presents history of average ball temperatures at top, middle, and bottom layers for the first experiment. This average is the nean of the four readings obtained for balls at every level. Balls at the bottom were the coldest at the beginning of the experiment because colder solution is more dense than less cold solution. Ball temperature in top layer increased sensibly during the first twenty minutes of the experiment. Latent change followed afterwards for eighty minutes. Snesible increase in temperature followed untill the end of the experiment. A nearly constant temperature is a result of change in phase from ice to water. Balls in the top layer became hotter faster than balls in middle and bottom layers.

Middle and bottom layer ball temperatures allways increased, but at a slower rate after fourty minutes. Afterwards, bottom layer ball temperature was higher than middle layer ball temperature. For twenty minutes, bottom layer ball temperature was even higher than top layer ball temperature. Such a result contradicts with the fact that a colder solution is more dense than a less cold solution.

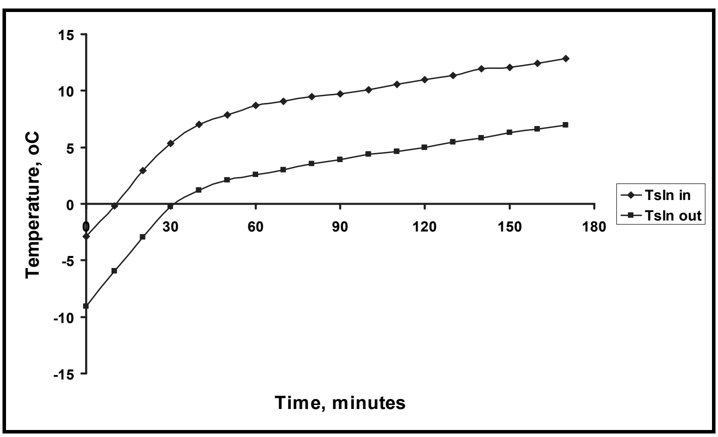

Figure 8. Inlet and exit solution temperatures for the first experiment vs time

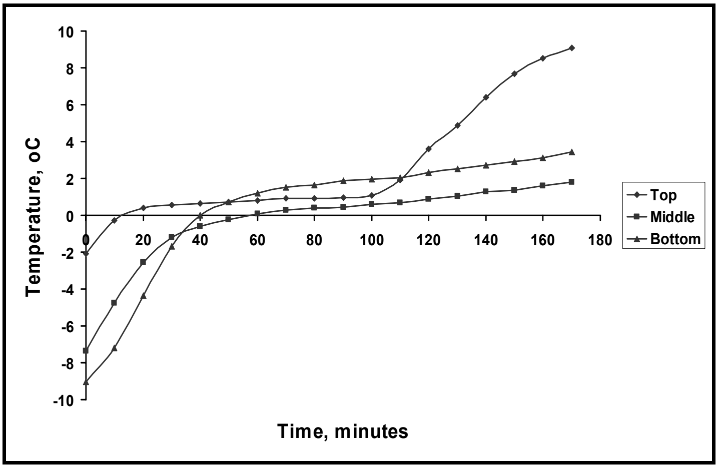

Figure 9. Average temperatures of balls at three layers for the first experiment vs time

The second experiment, with different initial temperatures, lasted for 4 hours and 10 minutes. Inlet and exit solution temperature data are shown in Figure 10. Similar to the first experiment, exit solution temperature was always less than inlet solution temperature. Nevertheless, the difference between the two is greater in the second experiment. The reason could be the greater intial temperatures of balls in the second expeiment. Figure 11 presents history of average ball temperatures at top, middle, and bottom layers for the second experiment. Observations similar to the first experiment can be seen. Ball temperature at the bottom was the coldest at the beginning of the experiment. If Figures 9 and 11 are compared then it can be seen that middle layer balls become hotter than bottom layer balls toward the end of the two experiments.

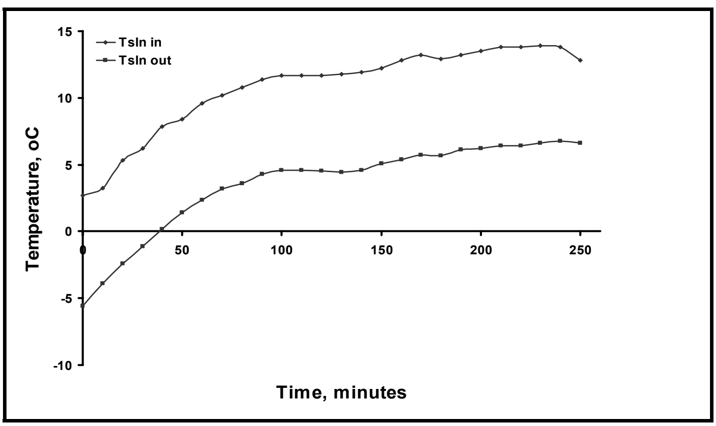

Figure 10. Inlet and exit solution temperatures vs time for the second experiment

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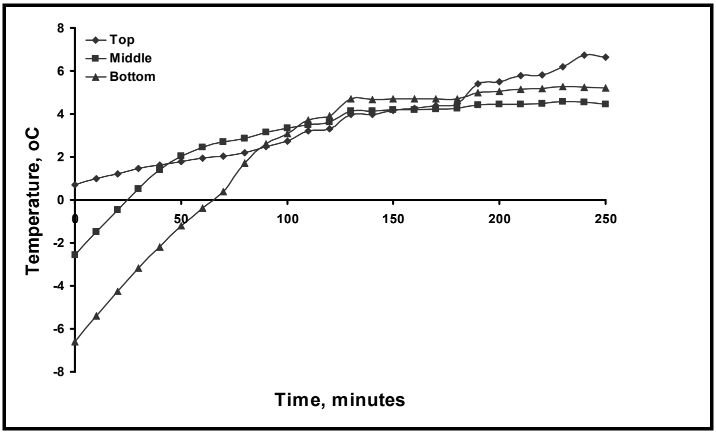

Figure 11. Average temperatures of balls at three layers for second experiment vs time

A mathematical software (MATLAB) was used to correlate average ball temperatures and time. Collected data for ball temperatures (***T:*** °C) at the end of each time interval (***t***: minutes) are fit into fourth order polynomials. Three equations for average top, middle, and bottom ball temperatures are obtained for each experiment (Table 1). Dimention of the first correlation coefficient is $^{o}C/min^4$. The second correlation coefficient has a dimension of $^{o}C/min^3$. The third correlation coefficient has a dimension of $^{o}C/min^2$. The fourth correlation coefficient has a dimension of °C/min. The constent has a dimension of °C. These equations can be used to predict a ball temperature at later times which provides a wider picture of store performance. The correlation coefficient was calculated for every polynomial equation. It was found that all had a rounded value of unity (Table 1), an indication of excellent fit.

	Correlation Equations	**Corrln Coefft**
First Experiment	$T_{top}(t) = -1.237\times10^{-7}\, t^4 + 4.643\times10^{-5}\, t^3 - 5.194\times10^{-3}\, t^2 + 0.216\, t - 2.119$	0.9988
	$T_{mid}(t) = -6.859\times10^{-8}\, t^4 + 3.007\times10^{-5}\, t^3 - 4.646\times10^{-3}\, t^2 + 0.311\, t - 7.314$	0.9991
	$T_{bot}(t) = -3.927\times10^{-8}\, t^4 + 2.194\times10^{-5}\, t^3 - 4.300\times10^{-3}\, t^2 + 0.367\, t - 9.641$	0.9986
Second Experiment	$T_{top}(t) = -2.767\times10^{-10}\, t^4 + 8.029\times10^{-8}\, t^3 + 2.124\times10^{-5}\, t^2 + 0.018\, t + 0.786$	0.9901
	$T_{mid}(t) = -6.759\times10^{-9}\, t^4 + 4.453\times10^{-6}\, t^3 - 1.117\times10^{-3}\, t^2 + 0.135\, t - 2.631$	0.9866
	$T_{bot}(t) = 9.504\times10^{-9}\, t^4 - 4.005\times10^{-6}\, t^3 + 1.604\times10^{-4}\, t^2 + 0.110\, t - 6.565$	0.9977

Table 1. Correlation equations of ball temperature and time and corresponding correlation coefficient for first and second experiments

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4. CONCLUSIONS

The concluding remarks can be summarized as follows,

1) Initial ball temperatures were between -2 and -9°C at the beginning of discharging processes. The temperature increased sharply during the first hour to around 2-3°C due to liberation of sensible heat. From there on the increase in temperature was gradual and slow, an indication that energy supplied was consumed in changing phase. Faster increase in temperature was observed towards the end of the experiments, especially in upper layer.

2) Differences between inlet and exit solution temperatures were slightly less at the beginning of the process than at later times. As time progressed the difference increased due to more cool energy released by cold water in the balls.

3) Fourth order algebraic equations are used to correlate average ball temperature with time. The correlation coefficient of every equation is amost unity, an indication of excellent fit. These equations can be used to predict history of average ball temperature at later times and can be used in other experiments with similar initial conditions.

4) Average bottom ball temperature becomes higher than average middle ball temperature at later times of both experiments, in contradiction with expectations and earlier temperatures.

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