

PERFORMANCE OF A COOL THERMAL STORE FILLED WITH BALLS CONTAINING WATER

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ABSTRACT

A cool thermal storage (CTS) system can be integrated with an A/C system in order to reduce power consumption during a period of high demand. Investigator conducted experiments to investigate the performance of a CTS during charging and discharging processes. The rectangular 1.65 m³ CTS enclosed 1080 plastic balls, with each having a diameter of 11 cm and ¾ full of water. All balls were immersed totally in a 40% ethylene glycol solution. The solution circulated through the store during charging and discharging processes at a speed of 0.417 kg/sec by entering the store at the top and leaving at the bottom. A chiller was used to charge the store with cool energy and an electric heater was used to discharge it. Temperatures of selected balls at different locations and temperatures of entering and leaving solution were recorded. A sharp drop in temperature of balls was observed generally during the first four hours of every charging process, followed by a gradual but slow decrease in temperature. Temperature inside some balls reached -6 to -8°C. It increased to 3°C after one and half-hours of a discharging process. Ball temperatures generally remained constant at around 3.5°C during most of a discharging process. Experiments reveal that CTS has a potential of handling a cooling load.

KEY WORDS: Cool Thermal Store, Charging and Discharging, Ethylene Glycol, Peak Load Reduction, Chiller and Heater.

1. INTRODUCTION

Space cooling in Arabian Gulf countries during the summer consumes as much as 80-90% of the total energy produced by Utilities [1 & 2]. Peak electricity demand, which occurs during the summer due to cooling loads, increased from

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7317 MW in 1415H to 8219 MW in 1418H (12.3% increase), according to SCECO East annual report [3]. Residential, commercial, and governmental sector electricity consumption during 1418H was 29% of the total power provided by SCECO East [3]. A major portion of this load is caused by space cooling requirements of buildings. It is expected that K. S.A. will require 70,000 MW of electricity after two decades.

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 energy storage. Storage of cool energy in a volume of water for air conditioning purposes is used to reduce peak electricity demand. It is a relatively new technology (it surfaced during the late seventies) that is used in some countries to reduce electricity consumption for air conditioning of large buildings during peak periods. A lot of research was conducted ever since to increase awareness among scientists and engineers about theory and practice of cool energy storage [4 to 19].

Cool energy, of a vapor-compression cycle, could be either used directly or stored in a fluid by reducing its temperature to near or below zero. In the later case the evaporator coils are impeded inside a tank containing the cool energy storage fluid. Cool energy can be also stored in a third medium that is kept separate from the refrigerant cycle. A fluid serves as an agent between the medium and the refrigerant. On leaving the evaporator the agent fluid enters a cool energy store, releases part of the cool energy it collected, and returns to the evaporator to absorb more cool energy. Cool energy, released in the store, is absorbed by water or a similar liquid encapsulated in special containers (balls, plates, etc.) that are always submerged in the agent fluid.

When the stored cool energy is needed later, the fluid in the store is pumped to a cooling coil where it absorbs heat from air and returns to the store to be cooled again. 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 if a high demand exists.

2. RESEARCH OBJECTIVES

This research investigates the performance of a cool energy store that uses water encapsulated in hollow spheres, which are submerged in a solution, as the energy storage medium. Several charging and discharging experiments were conducted,

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but only one charging and one discharging experiment is presented in this paper. One aim of the research is to prove the concept of peak load reduction by a cool energy store. Another aim is to present the method of storing cool energy in a storage medium of the type used in this paper. Research also shows that location and initial conditions affect the amount of cool energy stored in a ball.

3. APPARATUS DESCRIPTION

The experimental rig consisted of a rectangular cool thermal store (CTS) connected to a chiller (Figure 1). The condenser shown in Fig.1, which is larger in size than the evaporator, is located above the evaporator while the compressor is located at the bottom right corner of the photo. Both the condenser and the evaporator of the chiller were counter-flow shell-and-tube heat exchangers. The evaporator operated with refrigerant on the tube side and ethylene glycol solution on the shell side. The condenser used water from mains to reject heat.

An electric immersion heater with a capacity of 7.5 kW The vertical white column shown to the right of the apparatus in Figure 1 provided the load on the store during a discharging process. It was located outside the store to avoid any effect on the store performance. It could be switched on and off to simulate different load profiles.

The CTS was made of an inner metallic tank, a middle 10cm thick polystyrene insulation, and an outer plywood container. The inner metallic box, made of galvanized steel, was 0.94 meter high, 1.54 meter wide, 1.14 meter deep. It enclosed energy storage balls, which were fully immersed in an ethylene-glycol solution, and solution-distribution and solution-collection pipe networks (Figure 2). The insulation surrounded the top and all four sides of the metallic box in order to reduce the effects of the surroundings. The outer plywood box was 1.14 meter high, 1.74 meter wide, and 1.34 meter deep.

There were 1080 plastic balls in the CTS, each of 11 cm diameter. Figure 3 shows a sample ball with a thermocouple wire extending from the top. The insulated thermocouple wire was housed in a steel capillary tube (Figure 4). The mass of water inside each ball was 0.557 kg, occupying almost two thirds of the ball volume to provide room for water expansion during freezing.

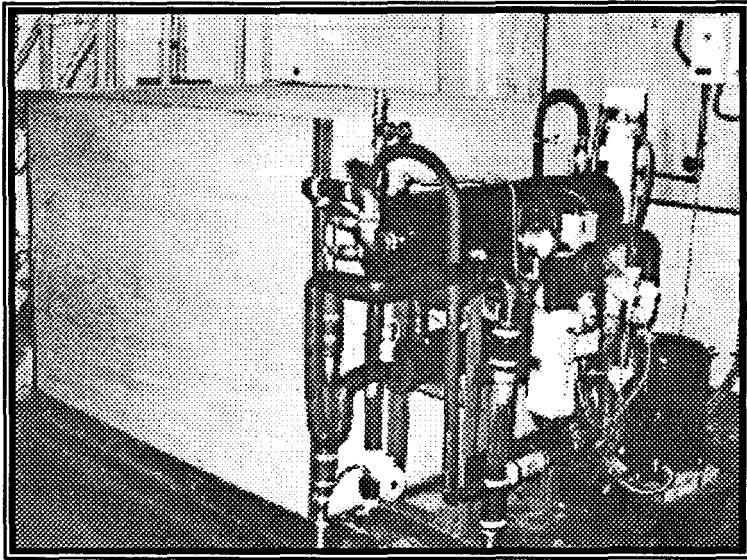


Fig. 1. Cool energy store and refrigeration

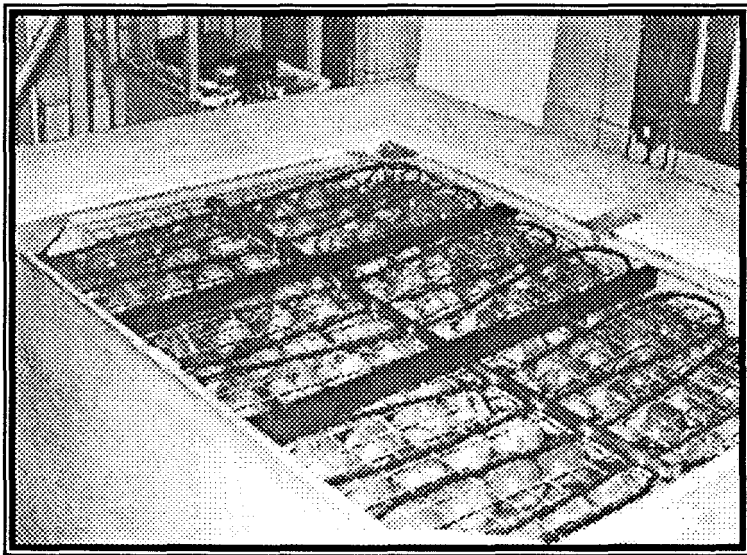


Fig. 2. Energy storage balls and solution machine distribution pipe network

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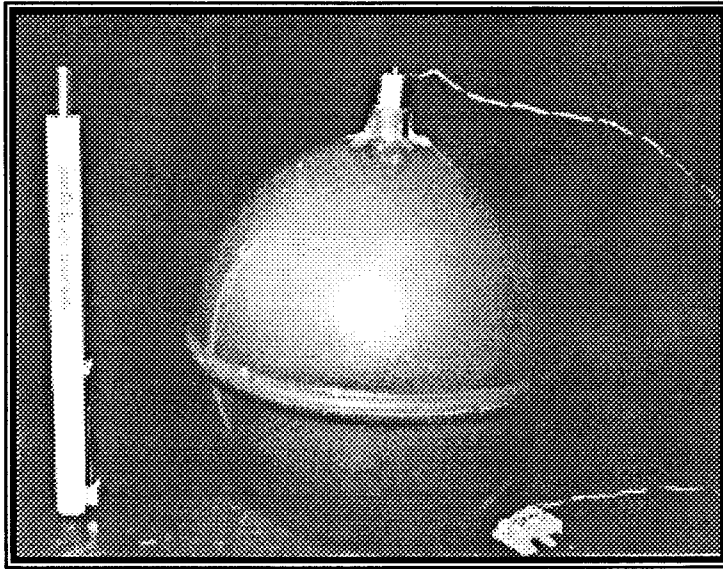


Fig. 3. A cool thermal storage ball Figure

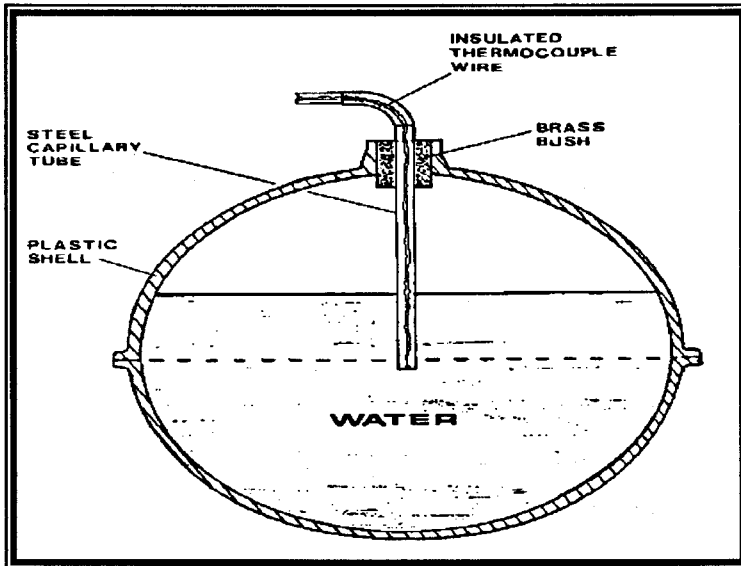


Fig. 4. Cross-section of a ball

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The plastic balls were arranged horizontally in nine layers. The first 8 layers from top had 119 balls in each. The 9th layer had 128 balls. Temperature was recorded in four balls in each of three layers. The layers selected were the uppermost, middle, and bottom layers. Locations of selected balls were the same in each one of the three layers (Figure 5-a). Numbers assigned to every ball location are shown in Figure 5-b.

The energy-transfer fluid used in the experiment was a 40% ethylene glycol (automobile antifreeze) solution with a specific heat of $3.5 \text{ kJ/kg } ^\circ\text{K}$. 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 both charging and discharging processes through a one inch diameter copper tube and 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. The mass flow rate of the ethylene glycol-solution was set at 0.417 kg/sec during all the experiments conducted.

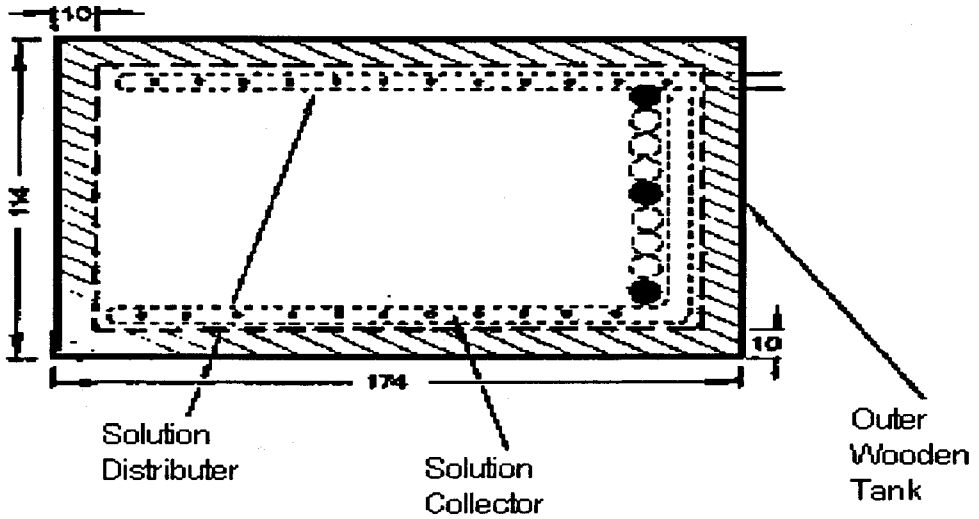
Temperatures were measured by K type thermocouples (Nickel-Chromium vs. Nickel-Aluminum alloy), recommended by the American Society of Testing and Materials (ASTM) for continuous use at temperatures within a range of -250 to 1260°C in oxidizing or inert atmospheres [20]. It is classed as one of the base-metal couples. It is more resistant to oxidation, and gives less conduction error than other thermocouples of the same diameter.

Compensating cables were used to connect a data logger with the thermocouples. Thermocouples measuring solution inlet and exit temperatures were inserted inside the tubes leading into and out of the store. All pipes outside the store were insulated to reduce outside effects. Flow paths of antifreeze, refrigerant, and main water are shown in Figure 6.

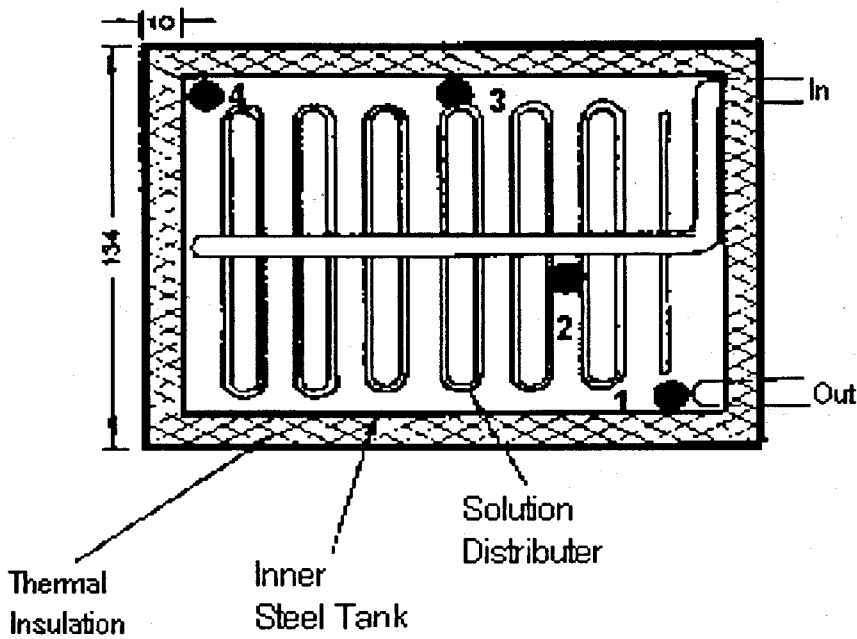
4. DATA OF A CHARGING EXPERIMENT

Several charging experiments were conducted with a duration time of 3 to 12 hours for each. There was a ten-minute interval between each two successive readings. A charging process continued until all balls indicated negative temperatures. The store exit solution temperature was in the range from -5 to -9°C near the end of each experiment.

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(a)



(b)

Fig. 5. Locations of balls for data (a) store cross-section and (b) store top-view [Dimensions in centimeters]

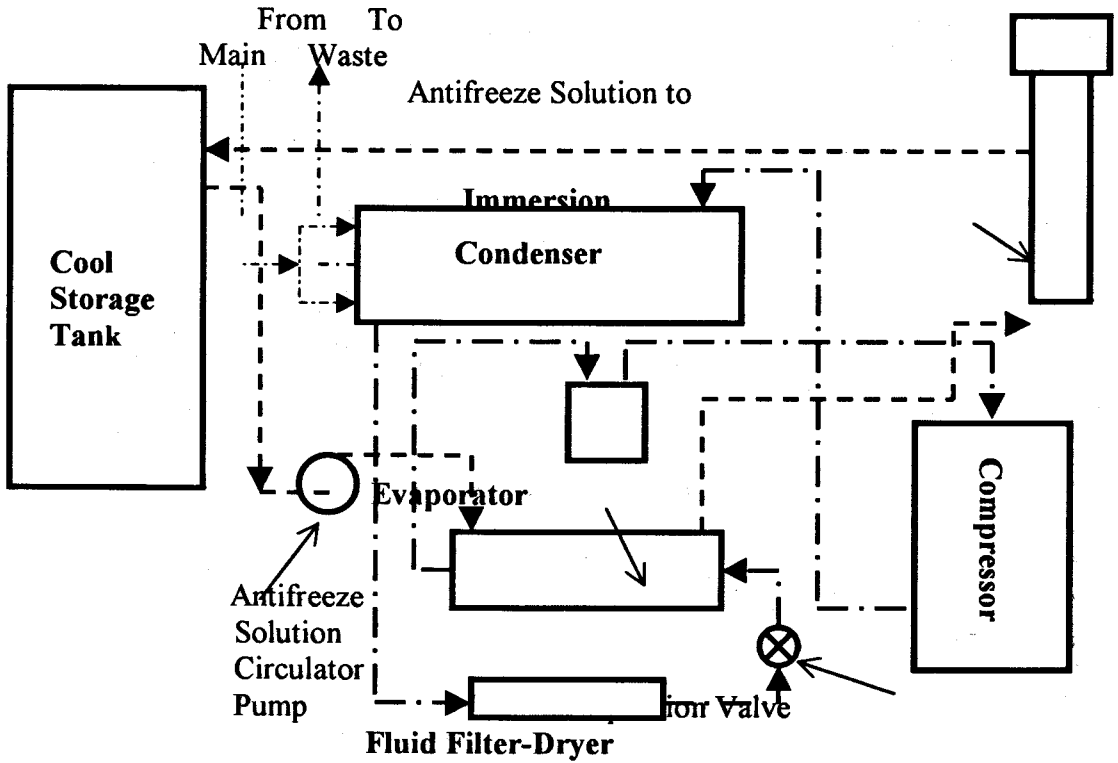


Fig. 6. Solution flow diagram for refrigerant (- - - - -), antifreeze solution (- . - . - . -), and main water (.) Sizes of elements shown in the figure are not actual.

A sample of a set of collected data for a charging experiment is shown in Figures 7 to 9. The charging process lasted three continuous hours. Figure 7 shows temperatures of solution at inlet and exit of the store. Both temperatures decreased with time. Exit solution temperature was always higher than entering solution temperature, an indication that both solution and balls inside the store absorbed cool energy. Energy in kJ stored inside the store can be calculated by the equation,

$$\text{Stored energy} = m c_p \Delta t$$

where m is solution mass flow rate in kg/s, c_p is solution specific heat in kJ/kg °K, and Δt is difference between inlet and exit solution temperatures. If data is substituted in the above equation then the stored energy becomes

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Stored energy = $1750 \Delta t$.

Figure 8 presents results of above equation for the duration of the experiment. It is evident that the amount of the energy added to the store decreases with time due to the decrease of uniform solution temperature inside the store.

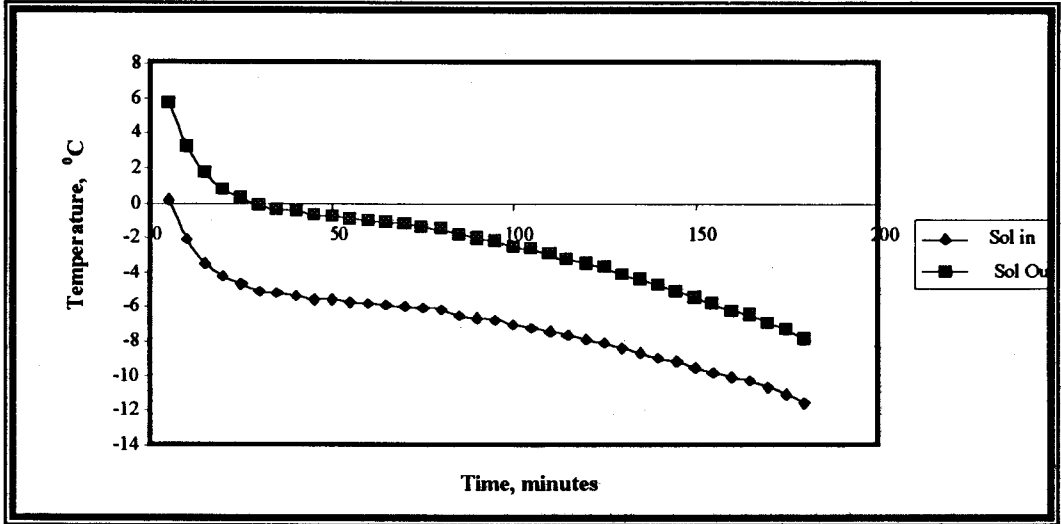


Fig. 7. Measured inlet and exit solution temperature

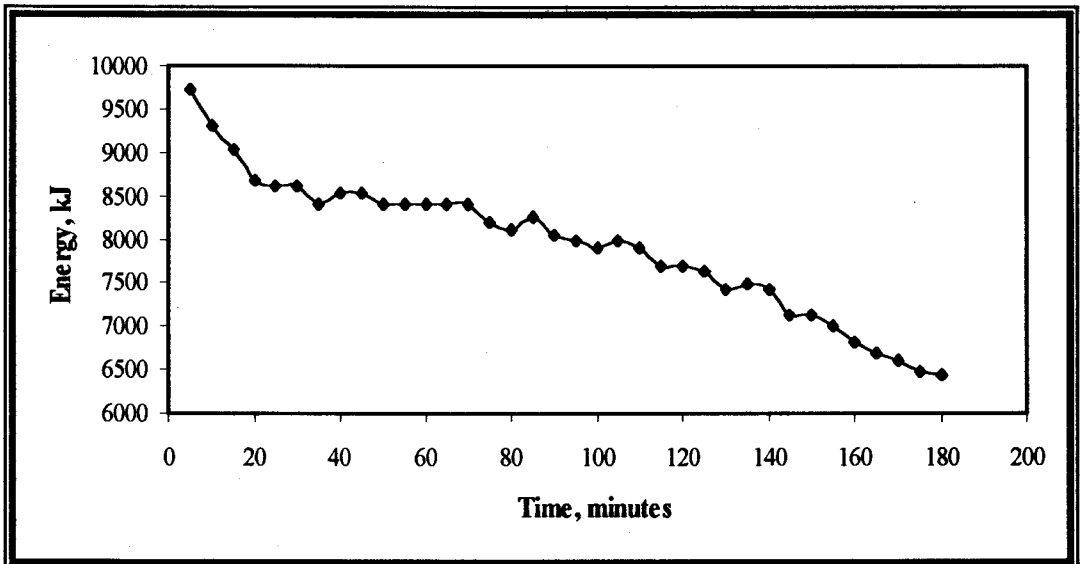


Fig. 8. Calculated stored energy in the store at ten minute interval, kJ

Figures 9, 10, and 11 show changes in temperature of water/ice in balls at top, middle, and bottom layers, respectively. It is noticed that performance of every ball is unique, both within every layer and within the store, even though a general trend is evident. Discrepancies could be due to different initial and boundary conditions from one ball to another and due to differences in solution temperature. The

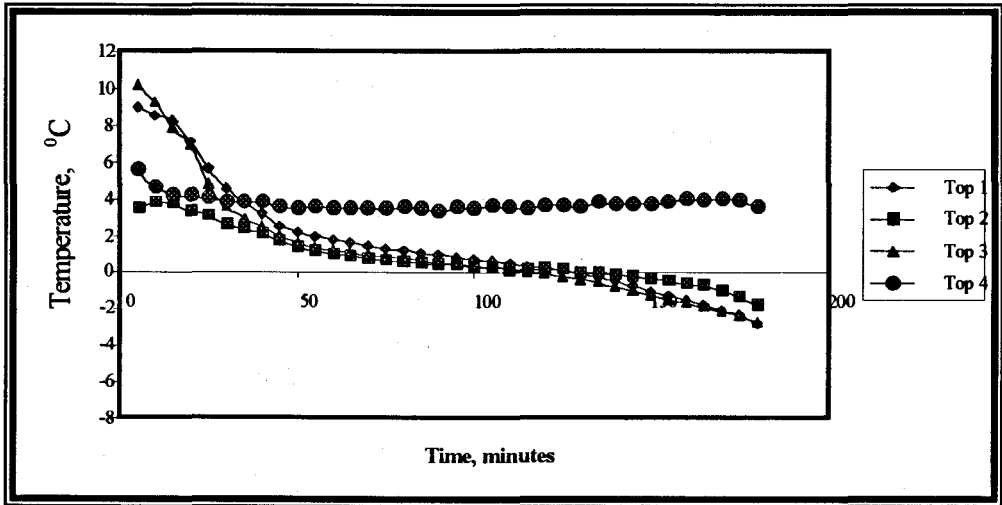


Fig. 9. Temperatures of balls at top layer for a charging process, °C

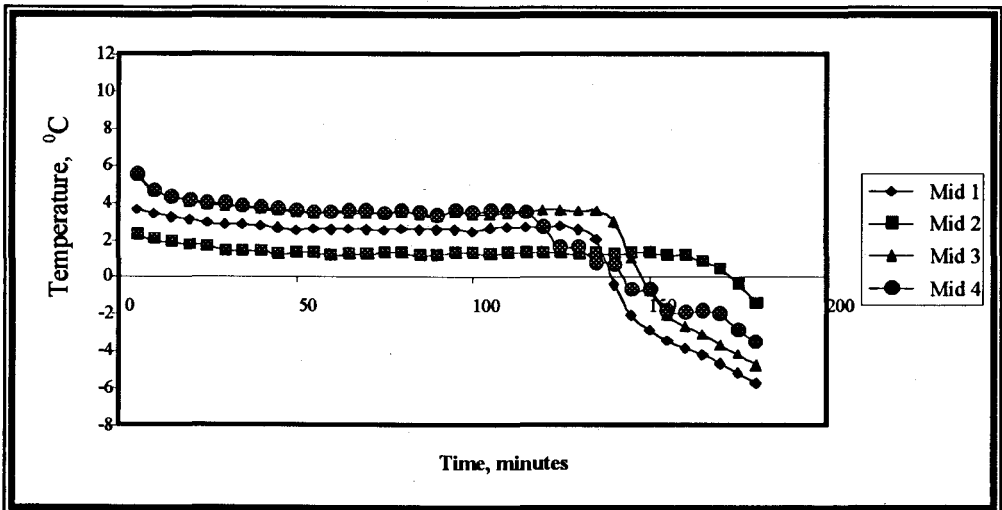


Fig. 10. Temperatures of balls at middle layer for a charging process, °C

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behavior of balls, within each layer, is roughly similar. Rate of temperature decrease in the bottom layer is higher than in upper layer, due to the presence of cooler solution at the bottom of the store. Latent energy from water to ice phenomena occurs, in most cases, at temperatures between 2 and 4°C. Duration of a latent temperature change is shorter in the bottom layer. The sample data present how balls, in different locations behave differently during freezing. Similar trends were observed in all other charging experiments.

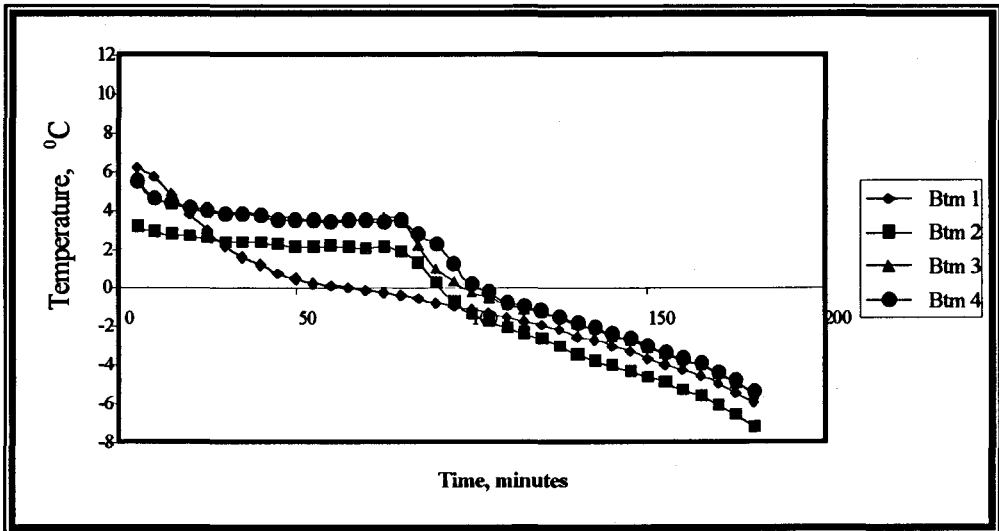


Fig. 11. Temperatures of balls at bottom layer for a charging process, °C

Average ball temperature, for each of the three layers, is calculated and presented in Figure 12. Average bottom ball temperature is the lowest at the end of the experiment because colder solution settles at the bottom of the store. If more time was given to the experiment then the average middle ball temperature would become the second lowest.

5. SAMPLE DATA OF A DISCHARGING EXPERIMENT

The chiller was switched off during a discharging process. After leaving the store the antifreeze solution passed through the redundant evaporator, into the immersion heater where it absorbed heat, and back to the store where heat got delivered to the balls and solution.

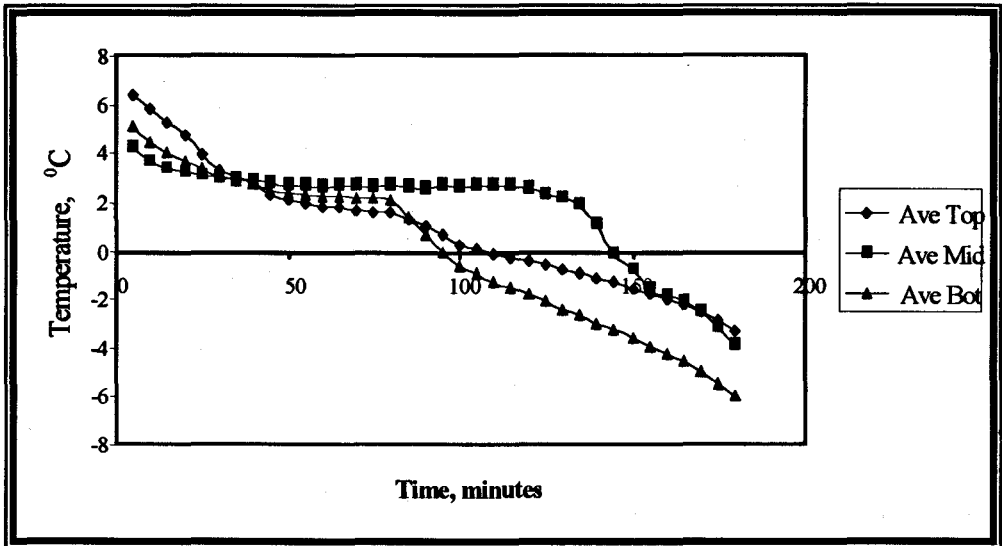


Fig. 12. Average ball temperature at each of the three layers, °C

Temperature of the incoming solution during a discharging process changed gradually from a temperature below zero to a maximum temperature of about 12°C. This maximum was chosen as it provided an exit solution temperature of about 5°C, the recommended temperature for a cooling coil. No attempt was made to start the discharging process with a sudden high temperature. This was the case in all experiments because it was difficult to do it otherwise. Some time elapsed before the heater could provide high temperatures.

The heater was turned on and off to simulate different types of demand during a discharging process. Nine discharging experiments were conducted in order to simulate different demand types, with duration time between 3 to 9 hours. A sample discharging experiment data is presented in Figures 13 to 16.

Figure 13 presents inlet and exit solution temperature data for the discharging experiment, which lasted for 5.5 hours. The heater was switched off two times during the discharging process. Exit solution temperature was always less than inlet one, due to the release of cool energy by balls and solution inside store.

Figures 14, 15, and 16 present the history of selected ball temperatures at top, middle, and bottom layers, respectively. Figure 14 indicates that only one ball, at the top layer had a negative temperature at the beginning of the experiment, while other three balls had above freezing temperatures. A nearly constant temperature is

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a result of change in phase from ice to water. Most of other balls showed a sensible increase in temperature during the first two hours followed by a latent change (Figures 15 & 16).

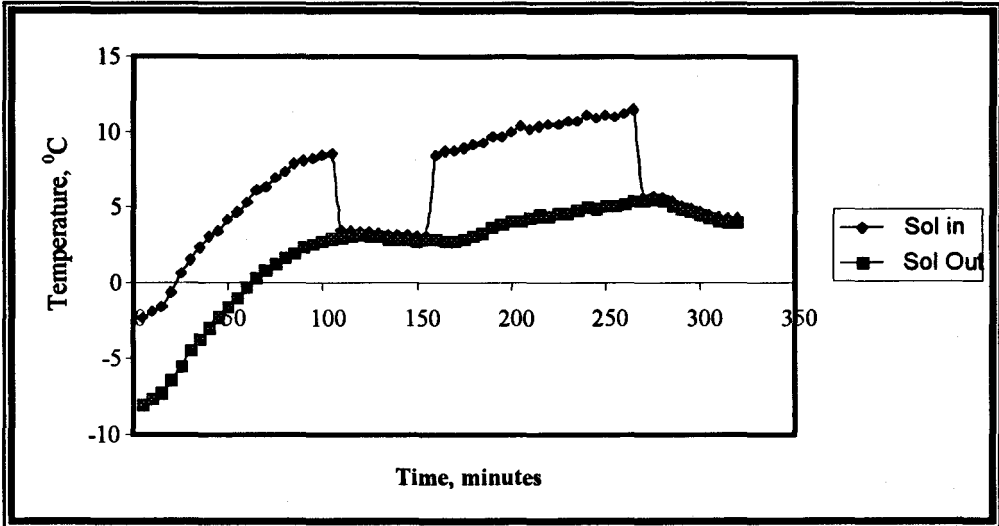


Fig. 13. Inlet and exit solution temperature for a discharging process, °C

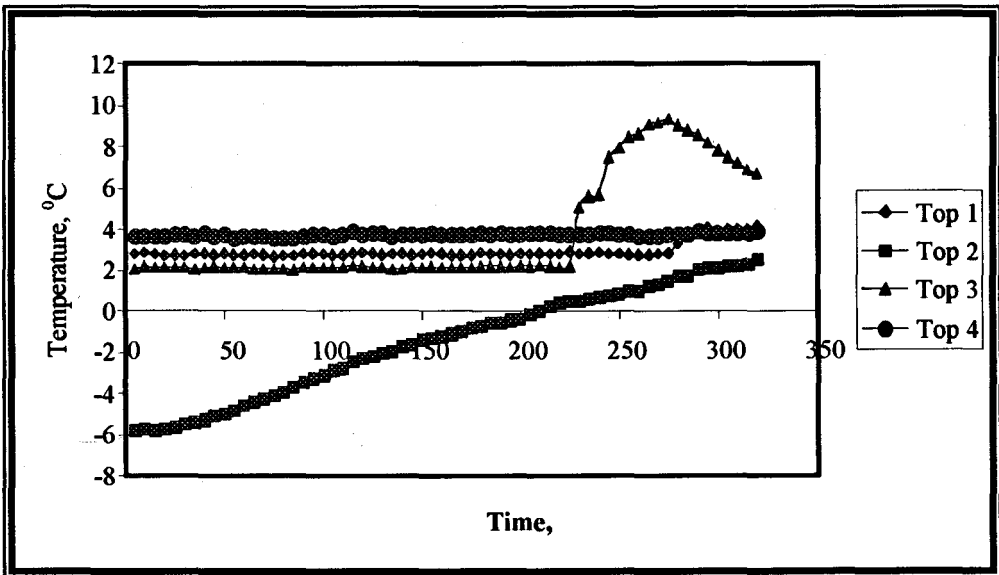


Fig. 14. Temperatures of balls at top layer for a discharging process, °C

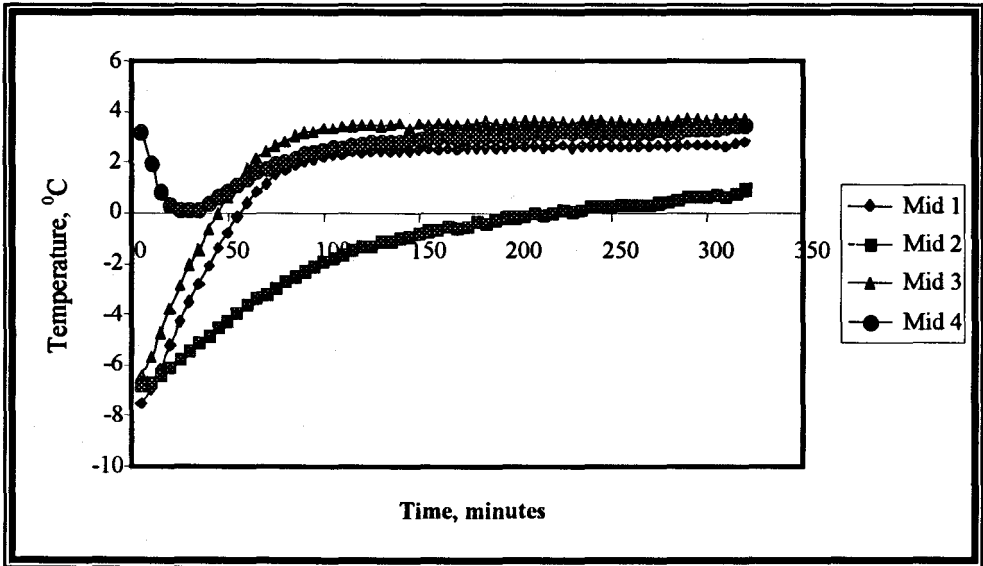


Fig. 15. Temperatures of balls at middle layer for a discharging process, °C

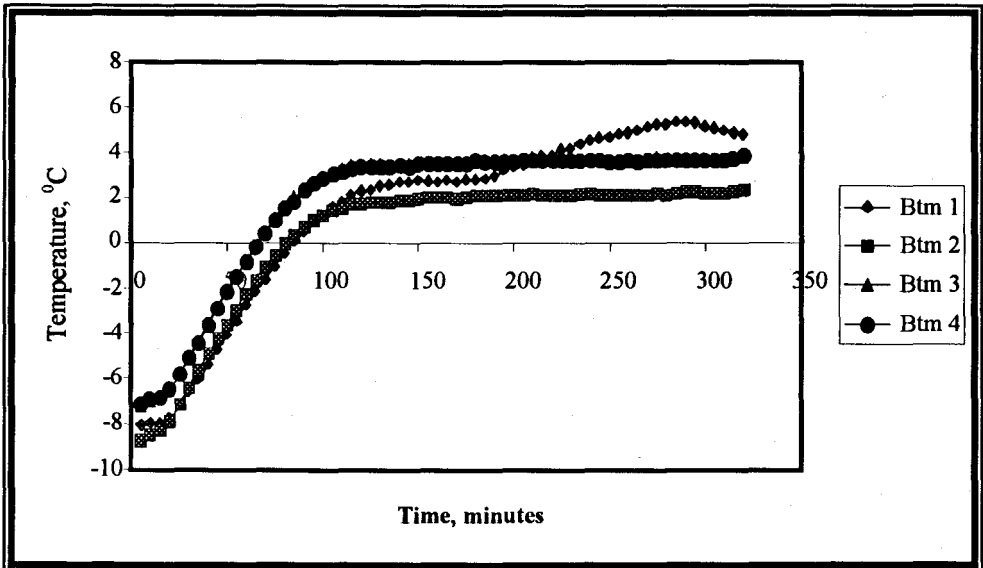


Fig. 16. Temperatures of balls at bottom layer for a discharging process, °C

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The average ball temperature at each layer is calculated and presented in Figure 17. Average ball temperature at the bottom was the coldest at the beginning of the experiment but it became higher after two hours.

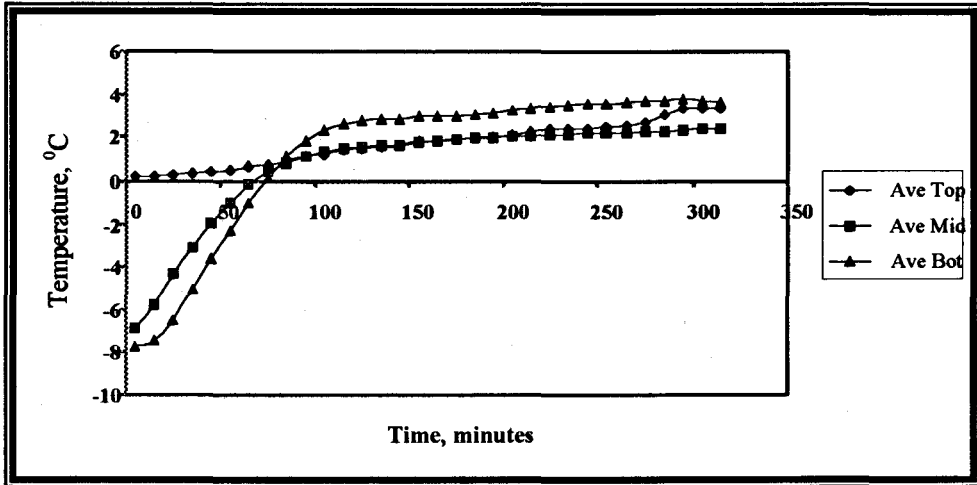


Fig. 17. Average ball temperature at three layers for a discharging process, °C

6. CONCLUSIONS

Inspection of data collected during several charging experiments, within restrictions imposed by experimental set-up, lead to the following conclusions and observations. There was a sharp drop in temperature of water inside the balls during the first four hours of every charging experiment. This was a sensible decrease in temperature. During the subsequent latent storage of cool energy the temperature decreased slowly.

- 1) Temperatures of some balls during most charging processes got to below freezing but for others it was 2 to 4°C above freezing, mainly for balls in the top level and near container walls but not the center.
- 2) Temperatures of balls in the middle column were, on the average, less than temperatures of other balls along the side or at the corners of the store. This was due to the absence of wall and tube effects on inner balls.
- 3) Temperature of some of the balls was irregular in some experiments. The reason could be the formation of an air bubble around the thermocouple

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junction. The temperature recorded was that of the air bubble which was higher than the ice temperature.

- 4) In some experiments, a possible formation of an air bubble around the thermocouple lead to a nearly constant above freezing temperature. In some cases this phenomenon persisted but in others a later sharp drop was noticed due to a sudden removal of the bubble.
- 5) Difference between inlet and exit solution temperatures decreased slowly with time during all charging experiments. This was due to the fact that solidification process of water continued to absorb cool energy. If enough time was permitted then less energy would be absorbed and as a result the difference in temperature would decrease more.
- 6) Temperatures of balls, in bottom layer, were the coldest in most experiments due to higher density of colder solution.

Data collected for discharging experiments revealed similar trends for different balls in similar layers. Observations and conclusions can be summarized in the following points.

- 1) Of all the conducted experiments only 42% of upper balls temperatures were below freezing at the start of the experiments compared to 61 and 100% of middle and bottom balls temperature, respectively. For frozen balls, the temperatures were between -6 & -8°C at the beginning of discharge. For these balls the temperature increased steadily during the first one and a half-hour to around 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.
- 2) The differences between exit and inlet solution temperatures during the heater-off period were around one degree or less. These differences were caused by the continuous antifreeze solution flow, picking up some of the energy still present in the heater element.
- 3) Differences between inlet and exit solution temperatures in a continuous discharging experiment 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 ice in the balls.

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