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Energy Management through Encapsulated PCM Based Storage System for Large Building Air Conditioning Application (December 2006)

R. Velraj, M. Cheralathan* and S. Renganarayanan

Abstract - *A detailed study done on the phase change material based cool thermal energy storage (CTES) system integrated with a large building air conditioning system is presented in this paper. The major focus of this study is to provide the technical information about the encapsulated phase change material (PCM) based storage system for air conditioning application and the importance of careful design load calculation. The economic benefits of load shift operations are highlighted. It has been found that the PCM based storage system reduces the monthly demand charges of INR 1.2 million. It is also estimated that cost saving of INR 2.26 million per annum through energy management by scheduling the chiller operation.*

Keywords - **Building air conditioning, Cool storage, Demand side management, Encapsulated storage.**

1. INTRODUCTION

A Cool Thermal Energy Storage (CTES) technique "Storing low temperature energy for later use in order to bridge the time gap between energy availability and energy use" can be considered as a useful tool to achieve peak load management in large building air conditioning system. This concept attracts the attention of the electric power utilities as a viable strategy to reduce the high peak demand load placed on their systems.

Braun [1] investigated the magnitude of cost savings and peak electrical energy usage reduction through proper control of the building's thermal storage. Braun [2] and Simmonds [3] have compared ice storage system for minimum energy costs, minimum demand charges, chiller priority and simple load limiting strategy. The use of phase change materials for energy savings and management in greenhouses has been widely studied by Kürklü [4, 5]. Sawers et al. [6] developed guidelines for achieving capital cost economics in the application of cool thermal storage. Siddhartha Bhatt [7] developed an analytical tool for energy conservation measures and techno-economic evaluation of the various options.

Dincer and Rosen [8] states that using thermal energy storage system, substantial energy saving up to 50 percentages can be obtained when implementing appropriate demand side management strategies. Several methods were identified for lowering the energy consumption in air conditioning of buildings [9-14]. A study on phase change material (PCM) based thermal storage system for building air conditioning system was carried out by Velraj et al. [15]. A review on cool thermal storage technologies as a demand side management tool for electrical load management and a supply side management tool for efficient and economical power production was done by Hasnain [16]. Most of the above studies are related with ice on coil and latent heat energy storage system. The quantitative approach on energy management and cost saving details were scarcely reported.

The present study was carried out on a cool thermal energy storage system integrated with a large building air conditioning system located at Chennai, India. The air conditioning plant was designed based on a typical office building cooling load profile that usually exists between 8.00 a.m. and 7.00 p.m. and considering no load during the remaining hours. Fig. 1 shows cooling load profiles of the building.

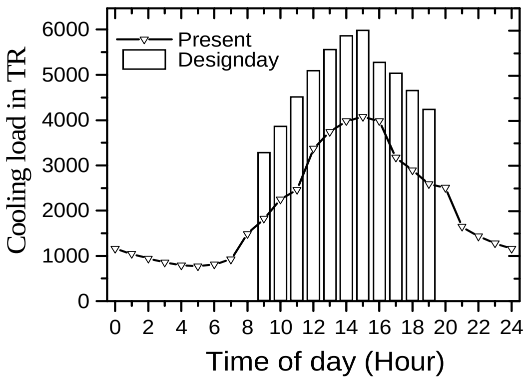

Fig. 1. Cooling load profiles

The design day profile has a peak load to average load ratio of 2.8, which is ideal for CTES operation. But as per the present operation cooling load is extended to 24 hours due to change in occupancy schedule of various software companies. Hence there is a deviation between design day and present cooling load profiles. In addition the seasonal ambient temperature variation and fluctuating weather conditions have significant effect on the cooling load profile. Hence, the building services need sufficient flexibility for load shifting and energy usage controls in order to achieve the most economical operation. The main objectives of this study are to provide technical information on CTES system operated in large building air conditioning application,

R. Velraj and S. Renganarayanan are attached to Institute for Energy Studies, Anna University, Chennai 600 025, India.

* M. Cheralathan is attached to School of Mechanical Engineering, SRM Institute of Science and Technology, Deemed University, Chennai 603 203, India. Tel.: + 91 - 44 -27452270;+91-44- 22311719; Fax: + 91 - 44 - 27452343.E-mail address: cheralathanm@yahoo.co.in

importance of careful design load calculations and energy cost saving measures through effective utilization of storage system.

2. BUILDING ENERGY CONSUMPTION PATTERN

The building considered in the present study is a large software office complex where 10000 software professionals work during different office hours and the details are given in Table 1. The air-conditioning systems of this building incorporate a large PCM based energy storage system, which is the largest in the South Asia region and the third largest in the world.

Table 1. Building details

Description	Values
Carpet area (m^2)	93000
No. of floors	12
No. of occupants	10000
Annual energy consumption (kWh)	3.6×10^7

The electrical energy consumption pattern of the building is shown in Fig. 2. It was found that air conditioning forms the major load accounting to 53.28% of total energy consumed. Fig. 3 shows the monthly KVA peak demand variation for one year from October 2004 to September 2005. The cool thermal energy storage system with a capacity of 24000 Ton-hr, reduced the installation requirement of centralized air conditioning system from 6000 TR to 3000 TR.

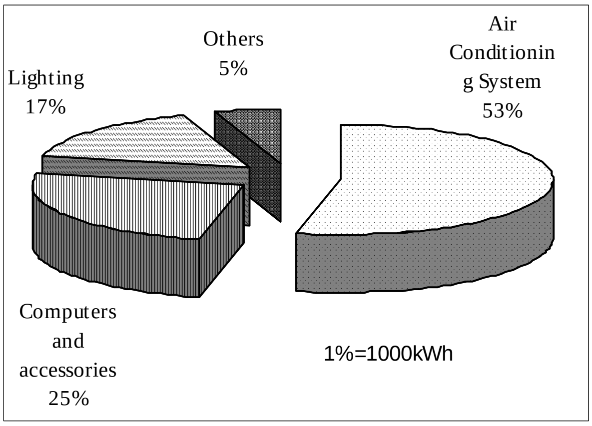

Fig. 2. Electrical energy consumption pattern in the building.

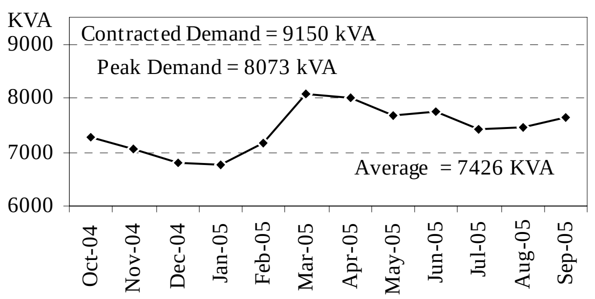

Fig. 3. KVA peak demand variation – month wise details.

Each ton of refrigeration demands approximately 1.3 KVA and the monthly demand charge is INR 300 / KVA (The electricity tariff in India includes demand charges and consumption charges). This reduces the monthly demand charges of INR 1.2 million for 4000 (3000×1.3) KVA.

3. SYSTEM DESCRIPTION

The schematic layout of the air conditioning system integrated with PCM based cool energy storage system is shown in Fig. 4. The maximum capacity of the air-conditioning system is 3000 TR. This total capacity is split into four parallel paths by chiller banks named as A, B, C, D. Each of the 750 TR capacity chiller banks is provided with 3 numbers of 250 TR refrigeration units. All the chiller banks of the air-conditioning unit are connected to three plate heat exchangers (PHE) of 2000 TR capacity each and the system can deliver a maximum cooling load of 6000 TR through the PHE. The installed capacity of the cool thermal energy storage system is 24,000 Ton-hr. This is provided by four cool energy storage tanks each of 6000 Ton-hr capacity. All the storage tanks are connected in parallel to the four chiller banks, so that each tank can be charged by operating the corresponding chiller bank. Normally the charging of one storage tank requires the operation of chiller bank for about 9 hours (i.e. 3×250 TR chillers $\times$ 9 hrs of operation). The plate heat exchangers are located in the ground floor and the refrigeration units are located at a height of 10 meters from the ground. Each 250 TR refrigeration unit consists of one chiller, four screw compressors (C1, C2, C3, and C4), two air cooled condensers (CR1, CR2) and one expansion valve (EV). The chiller is a shell and tube evaporator where the cool energy from the refrigerant is transferred to the heat transfer fluid -mono ethylene glycol (Brine solution). The pump P1 circulates heat transfer fluid from the chiller to the plate heat exchanger. The valve V1 regulates the flow rate of cool heat transfer fluid passing through the plate heat exchanger. During off peak period and nighttime the storage tank is charged. The valve V2 regulates the flow of heat transfer fluid to the storage tank.

The storage tanks are cylindrical in shape; 4 meter in diameter and 30 meter in length made of 14 mm thick mild steel plates with a design pressure of 20 bar [17] and are installed in a horizontal manner. The tanks are fitted with upper manholes for filling the tank with spherical nodules, lower manholes for emptying the tank and internal headers with holes to attain better flow distribution and for uniform heat transfer throughout the tank. The tanks are insulated with polyurethane foams (PUF) of 100 mm thickness. The photographic view of storage tanks is shown in Fig. 5.

The commercial phase change material [17], C00 (salt hydrates) is filled in the spherical nodules of 100 mm diameter. The spherical nodules are made of high-density polyethylene material. The number of spherical nodules in a tank is approximately 4,65,000. During the discharge, the heat transfer fluid (HTF) is allowed to pass through the storage tank and thereby cool energy is transferred from the PCM to the HTF.

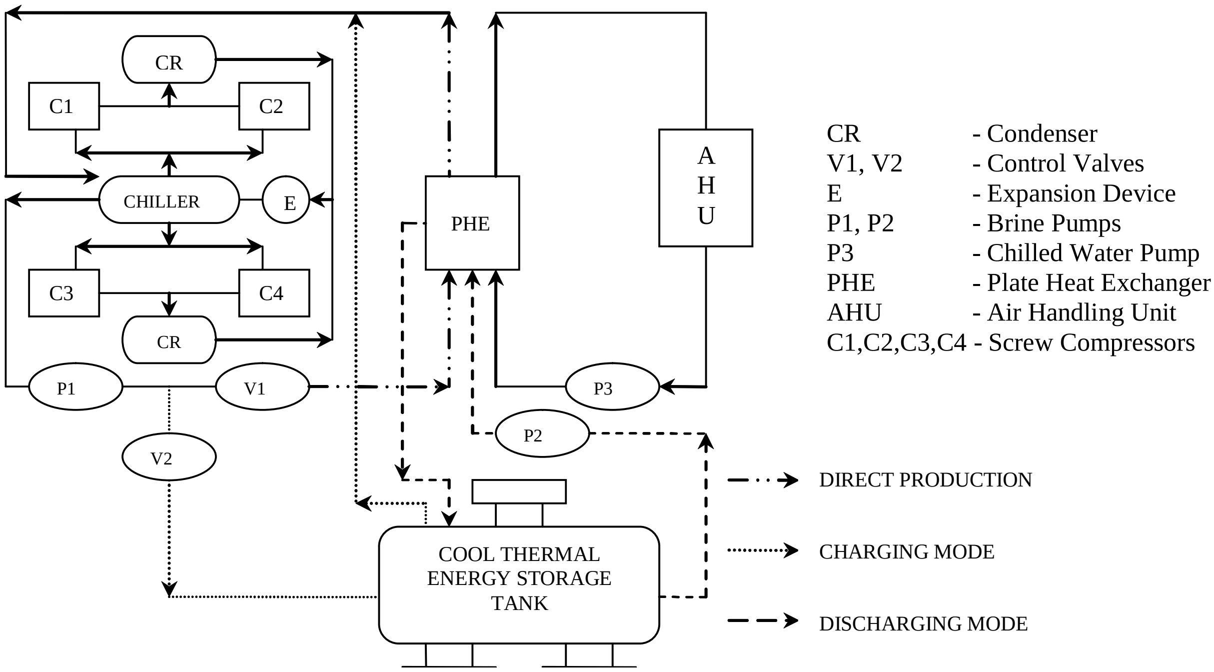

Fig. 4. Layout of 250 TR air-conditioning system integrated with CTES system

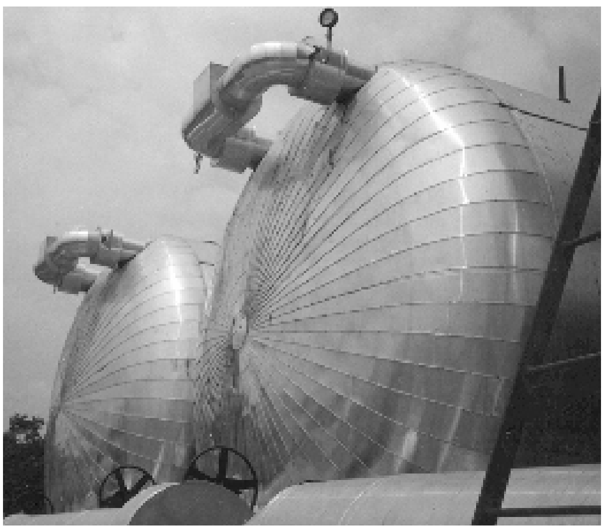

Fig. 5. Photographic view of cool thermal energy storage tanks.

The heat transfer fluid is then circulated through the PHE to exchange the cool energy to water. This chilled water is supplied to air handling units (AHU) in the building and it cools the air. About 334 numbers of AHUs with different rating (25 TR, 20 TR, 15 TR, 10 TR) are installed in various floors to meet the cool air requirement of the building. The technical specifications of chiller circuit are given in Table 2.

Table 2. Technical specifications of chiller circuit and storage

Utilities / Devices	No’s	Rated capacity (Each)
Compressor	48	65.5 kW
Brine pump primary	16	7.5 kW
Brine pump secondary	4	45 kW
Chilled water pump	4	10 kW
Plate heat exchanger	3	2000 TR
Thermal storage tank	4	6000 Ton-hr

Modes of Operation

The storage system must accept excess cool energy as available from the refrigeration system and supply energy to the system load elements as needed. This is achieved by proper controls and the controls determine the interaction between the refrigeration system, storage system and the load at the end use. The plant comprises three flow circuits viz. the HTF circulation between chiller and PHE, chiller and CTES tank and CTES tank and PHE. These flow circuits are properly controlled for 4 modes of operation to enable efficient energy management.

(i) Direct mode (Chiller mode)

When the cooling demand is lower than the installed chiller capacity, the chiller alone satisfies the demand. There is no flow through CTES tank. During this direct production, the valve V1 regulates the flow of HTF passing through the PHE and the valve V2 is closed.

(ii) Charging mode

During the nighttime the chiller is used to store cool energy in the storage medium. HTF temperature in the range of – 6°C is circulated around the nodules causing crystallization of the PCM. During the charging mode valve V1 is closed and the pump P1 pumps the flow of chilled HTF through the regulating valve V2 to CTES tank. The bulk of the stored energy is, therefore, stored at constant temperature as latent heat during the liquid-solid transition.

(iii) Discharging mode

During the discharge mode the chiller is stopped and pump P2 draws chilled HTF from the CTES tank to PHE and return the fluid to the storage tank. The rate of energy release from the storage is controlled by the three-way valve to match the system demand.

(iv) Combined mode (Direct and discharging mode)

When the cooling demand is greater than the installed chiller capacity, the cool energy requirement is met directly from the chiller and also from the CTES tank. During this mode valve V2 is fully closed and valve V1 regulates the chilled HTF flow between chiller and PHE and pump P2 circulates the fluid from CTES tank to the PHE. The chiller works at full capacity with the storage providing the shortfall.

4. PERFORMANCE STUDY ON CHILLER PLANT

The performance studies were carried out for three chiller banks namely A, C, D under direct mode of operation. Mass flow rates of brine solution, temperatures at various locations, energy consumption of compressors, fans, pumps were measured at hourly interval for a typical day. Using these values performance parameter like coefficient of performance (COP), specific energy consumption (SEC) and hourly ton of refrigeration (TR) were calculated for the direct mode operation. Similar studies were done for one chiller bank (C) during charging and discharging operation mode. To quantify the energy and cost savings, the average SEC of one chiller bank (C) under direct and charging modes are calculated.

5. RESULTS AND DISCUSSION

The hourly cooling load is calculated, based on the field measurement data for various months in winter and summer. This cooling load varies with respect to building occupancy schedule and ambient conditions during day and nighttime. The variations of the cooling load profile in a day for various months are given in Fig. 6.

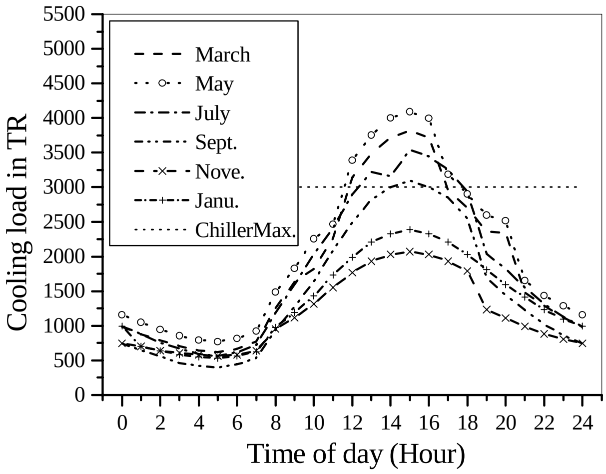

Fig. 6. Cooling load profile for various months in TR.

It is seen from the figure that the cooling load never reaches the maximum design day load (6000 TR) due to the present variation in the occupancy schedule. It is observed that the chiller load during winter months varies from 533 TR in the night to as high as 2388 TR during daytime and during summer it varies from 771 TR in the night to as high as 4090 TR during daytime. From the previous record (plant log book) it is observed that utilization of cool thermal energy storage system is almost nil during winter and it is utilized to the maximum extent in the summer.

Energy Management by CTES Utilization

In order to achieve better load management in the power plant production and distribution, many countries and some of the states in India are offering more than 50% reduction in electricity tariff during the off peak hours. This offer is being exploited by many industries by different ways by having night shift operation and performing the energy intensive operation only during off peak hours. In large commercial establishments where air conditioning load is very high this tariff benefit offer is being exploited by shifting the chiller operation from on peak electric hours to off peak electric hours by chiller operation management combined with CTES systems.

During the charging process the set temperatures in the evaporator should be maintained at a very low temperature. This reduces the COP of the system and consequently the SEC of the system will increase. Hence, the benefit achieved by the tariff difference should be much better than the increase in cost incurred by the decreased COP operation of the chiller system. However, since the charging is done during the night hours the favorable ambient conditions helps to improve the performance of the system.

The COP and SEC of the chiller at direct and charging mode is shown in Fig. 7. It is observed from the result that the average SEC for direct operation of the chiller is 1.306 kW/TR and during charging mode the specific energy consumption is increased to 1.429 kW/TR, due to reduction in COP by lowering the evaporation temperature. The actual air conditioning plant cooling load during winter and summer season for 24 hours were studied in detail to implement most favorable operating strategy.

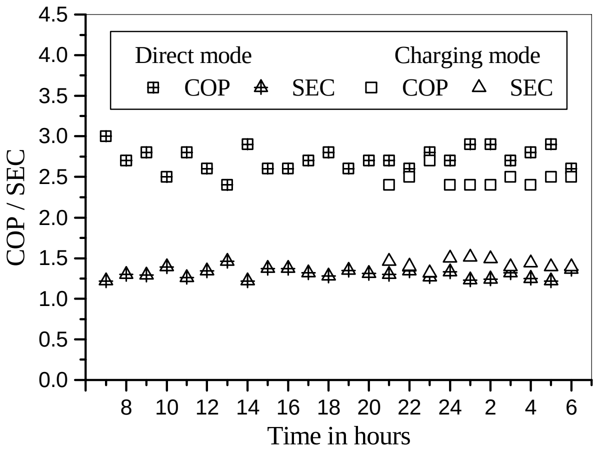

Fig. 7. Performance comparison of chiller plant during direct and charging mode.

(i) Scheduling of chiller operation on winter season

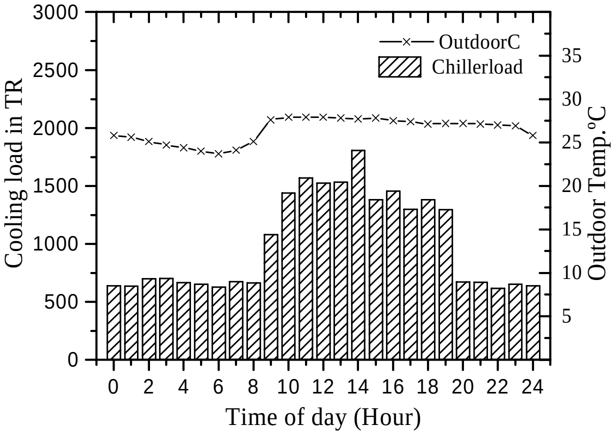

Fig. 8. Hourly cooling load on a winter day with reference to outdoor temperature.

Figure 8 shows the hourly cooling load profile on a typical winter day with reference to outdoor dry bulb temperature.

The chiller plant has a peak load of 1811 TR and the total cooling load requirement of the day is 24440 Ton-hr. The peak load is much lower than the total chiller capacity. It is observed from the load profile that 20.8 % of the load falls during peak hours. This can be met directly by chiller. However to reduce the energy cost, peak hours cooling load is to be shifted to off peak hours. Figure 9 illustrates the recommended operating strategies of chiller and storage on a winter day. One bank of chillers with a total 750 TR capacity is used for charging the storage system from 9 p.m. to 6 a.m. (9 hours charging). This stored energy is discharged during on peak hours of the next day. Hence by the above said operation it is possible to shift 5085 Ton-hr (which is 20.8 % of the load during peak hours) from peak hours to off peak hours. The use of multiple chillers in the present application increases the flexibility of the system scheduling and optimal control of operation in meeting the various load conditions.

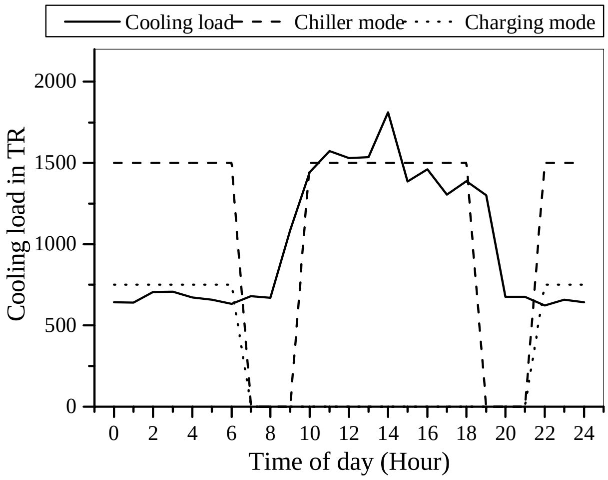

Fig. 9. Operating strategies of chiller and storage on a winter day.

(ii) Scheduling of chiller operation on summer season

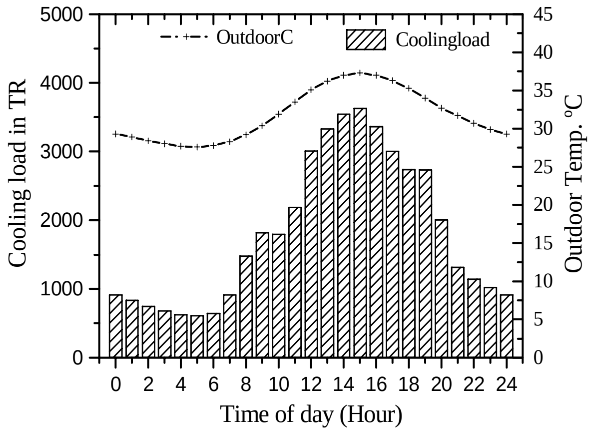

Fig. 10. Summer day hourly cooling load profile with reference to outdoor temperature.

The peak summer day hourly plant cooling load profile with outdoor dry bulb temperature is presented in Fig. 10. The chiller plant has a peak load of 3636 TR and the total cooling requirement of the day is 44252 Ton-hr.

Figure 11 illustrates the effect of the load shifting operation on building energy profile during a summer day. The chiller is not allowed to operate during the peak hours of 6 a.m. to 9 a.m. and 6 p.m. to 9 p.m. daily. The CTES alone is operated to meet cooling need of the building during these hours.

Therefore 10306 Ton-hr cooling energy is to be discharged from CTES tank during peak hours of the day. During 12 noon to 5 p.m. the plant cooling load exceeds the total capacity of chiller (3000 TR). This excess load is to be discharged from CTES system. Hence the combined mode of operation is recommended and chiller should be operated at maximum capacity and remaining excess load (1920 Ton-hr) is to be obtained from storage. During the remaining 9 hours (from 10 p.m. to 6 a.m.) the chiller should be operated at full capacity and the excess energy is to be used to charge the storage tank. Hence by the above said operation it is possible to shift 10306 Ton-hr from peak hours to off peak hours. This accounts 23 % of total plant energy consumption.

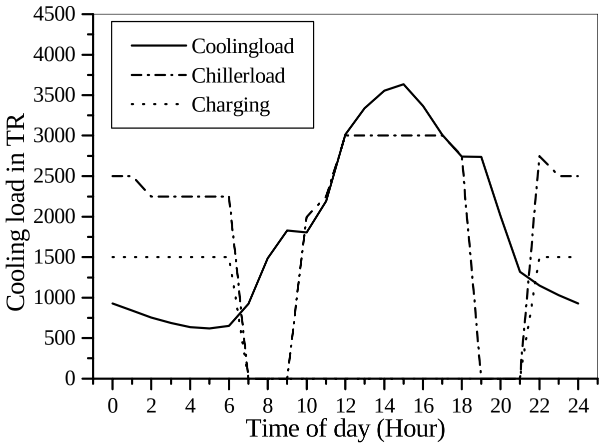

Fig. 11. Operating strategies of chiller and storage on a summer day.

Economics of the Load Shift Operation

To quantify the energy saving due to the above said operation for Chennai weather where the building is located, it is assumed that the winter condition prevails for 4 months and summer condition prevails for 8 months. The economics of load shift operation is given below. The electric energy cost for the peak (during 6 a.m. to 9 a.m. and 6 p.m. to 9 p.m.) and off peak (night time during 10 p.m. to 6 a.m.) hours are INR 4.2 and 3.325 per unit respectively.

Energy cost saving for winter season (4 months) in INR
1.306(SEC) × 4.2(Peak Tariff)
× 5085 × 120 = 3347069

1.429(SEC) × 3.325(Off peak Tariff)
× 5085× 120 = 2899320

Energy cost saving in winter operation = 447749

Energy cost saving for summer season (8 months) in INR
1.306(SEC) × 4.2(Peak Tariff)
× 10306 × 240 = 13567313

1.429(SEC) × 3.325(Off Peak Tariff)
× 10306 × 240 = 11752365

Energy cost saving in summer operation = 1814949
Annual energy cost saving through storage operation **= 2262697**

Hence using the CTES operation management, by shifting the on peak hour energy requirement to off peak hour the annual saving will be INR 2.26 millions.

6. SUMMARY

A detailed study has been done on the existing large PCM based storage systems integrated with building air conditioning system. The existing system has the following advantages:

1. Reduction in monthly demand charges of INR 1.2 million for 4000 KVA. Further, there are additional savings through reduced size of refrigeration system components and piping, which resulted in significant savings in capital and operating costs.
2. Air conditioning plant has 12 numbers of chiller units with each 250 TR capacity. The use of multiple chillers in the present application, compressors are running at full load all the time which gives better efficiency for the compressors.
3. The tariff difference during peak hours and off peak hours is only 25% in Tamilnadu. The additional expenditure incurred due to this charging and discharging is calculated around 15%. From the analysis it is found that a cost saving of INR 2.26 million per annum (by considering sample day winter and summer load) is possible through energy management by scheduling the chiller operation in winter and summer season. Hence it is strongly recommended to exploit the benefit without any additional investment. In places where the tariff difference is higher between the peaks and off peak hour operation the benefit will be much better than the present situation.

From the study it is found that the advantages of PCM based CTES system are many. The integration of cool thermal storage system with refrigeration unit requires careful design based on the proposed load pattern. In order to explore the same technology for other applications the study carried out in the present research work will be very useful.

7. CONCLUSIONS

The advantages of cool thermal storage system integrated with refrigeration plant for building air conditioning are many and the capacity of the storage system should be based on the expected load pattern. Hence the design of the cool thermal storage system requires careful attention before the installation for optimum benefit. The load shift operation by CTES will not only provide benefit to the consumer and it decreases the burden for the government to reduce the capital investment on power plant sector and helps the existing power plant to achieve maximum load factor that in turn helps for clean environment. The cool thermal storage system concept can be extended for other applications like food preservation (cold storage) and dairy industries.

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NOMENCLATURE

AHU	air handling unit
COP	coefficient of performance
CR	condenser
hr	hour
HTF	heat transfer fluid
PHE	plate heat exchanger
PUF	polyurethane foams
INR	Indian rupees
SEC	specific energy consumption (kW/TR)
TR	ton of refrigeration

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