Asian Journal of Scientific Research

ISSN 1992-1454

Asian Journal of Scientific Research 6 (3): 546-554, 2013
ISSN 1992-1454 / DOI: 10.3923/ajsr.2013.546.554

Assignment Model for Charging of Thermal Energy Storage by Electric Chillers Using Zero-one Programming Approach

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ABSTRACT
Thermal Energy Storage (TES) system is commonly installed at District Cooling plant for storing of chilled water (CHW). The stored CHW is used to support requirement of chilled water during day time. Charging of the TES tank by the electrical chillers (EC) is done during off-peak hours. For the case of TES tank at Universiti Teknologi PETRONAS, the charging of TES tank is done from 6 p.m. to 6 am. To ensure optimum TES charging, the operations of EC need to adhere to an optimum scheduling strategy. To address this requirement, an assignment model using transportation model is proposed. The model is formulated as a zero-one programming model. Spreadsheet is used for solving the model. Results from analysis indicate that maximum production of chilled water depends on the generating capacity of the EC. Results from three case studies indicate that all EC were operated at below rated capacity. Based on the weekly data, the maximum operated capacities of EC1, EC2, EC3 and EC4 are 308, 288, 295 and 270 RT, respectively. This is below rated capacity 325 RT of the EC. The outcome is that TES is not charged to full capacity during off peak period. From the sensitivity analysis using the proposed model, TES could be fully charged during the off peak period. An example, if three of EC are operated to full capacities for specified off peak period, TES could be fully charged. The model could be useful for the UTP District Cooling plant to schedule EC for charging of TES during off peak hours.

Key words: Assignment model, thermal energy storage, zero-one programming, electrical chillers, capacity peak period

INTRODUCTION
District Cooling (DC) plant is a centralized energy plant generating chilled water (CHW) for air conditioning within a district. This system is adopted by Universiti Teknologi PETRONAS (UTP) for campus cooling. The UTP DC system consists of two units of steam absorption chillers (SAC), four units of EC and one unit of TES. The plant is required to supply 4000 RT per hour to UTP. The plant is operated on 24 h basis. The SAC are operated from 5 a.m. to 11 p.m. everyday and four of EC are operated during off peak to charge the TES tank. The CHW produced by SAC is directly supplied to UTP campus. The CHW from TES is used to supplement the daytime requirements of CHW (Sulaiman and Majid, 2011).

Records indicate the charging capacity is usually less that the nominal storage capacity of the TES. This has affected the performance of the plant. One alternative to increase the performance of the plant is to ensure the operation schedule need to be revised (Khushairi *et al.*, 2011). A number of researchers have undertaken studies related to this scope. Chilled water storage is based in maintaining a thermal separation between cold charged water and return water. Gretarson *et al.* (1994) have developed a time step model to study the performance of cool storage. The operation of chillers can thus be minimized during peak cooling periods which is also the period of highest cost electrical energy. The chillers should then be operated during non-peak cooling periods, to recharge the storage medium. It is anticipated that TES will reduce the peak cooling load demand by approximately 30-40% and the peak electricity demand by approximately 10-20% (Boonnasa and Namprakai, 2010).

Figure 1 shows the schematic flow diagram of charging cycle of TES system. Each of the EC is design with capability to produce 325 RT while each of absorption chillers has a capacity of 1250 tons of refrigerant (RT). The storage capacity of the TES tank is designed to be 10000 RT. Figure 2 shows TES tank capacity daily during November 2011. It is noted that the TES tank supplement CHW for 6 to 7 h. The charging of the TES was from about 6 p.m. to 6 a.m. as shown in Fig. 3.

Figure 4 shows typical chilled water daily demand in UTP. This Fig. 4 also illustrates the use of thermal energy storage and clearly demonstrates how the peak load can be shifted to the

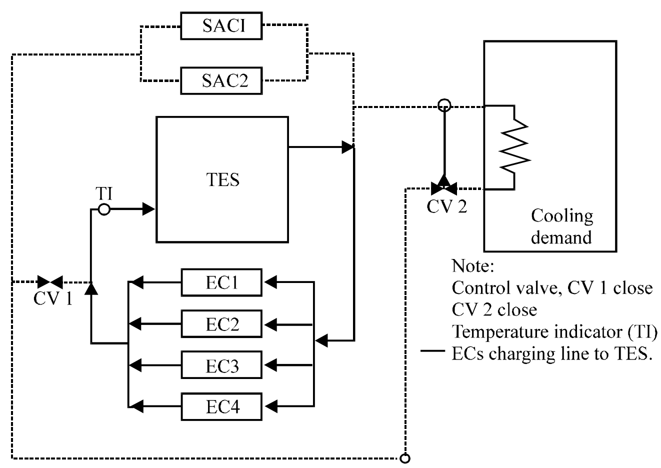

Fig. 1: Schematic of the GDC cooling system at UTP GDC plant

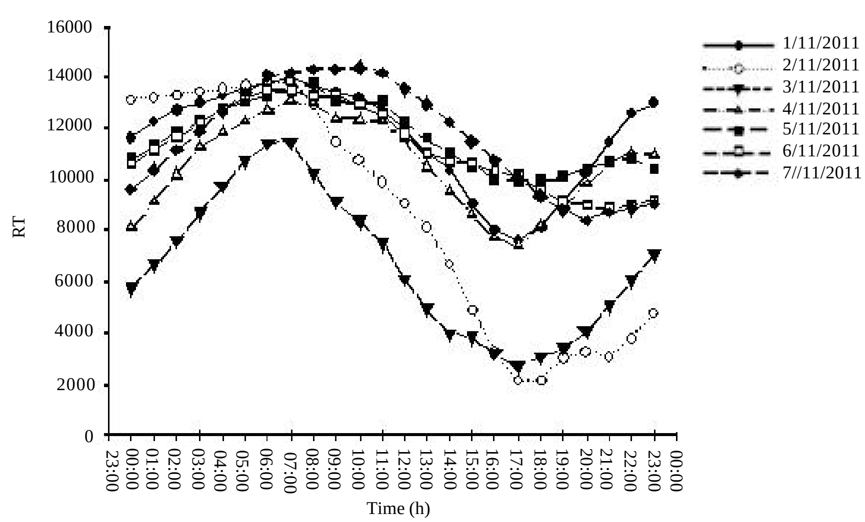

Fig. 2: TES capacity daily report on Nov. 2011

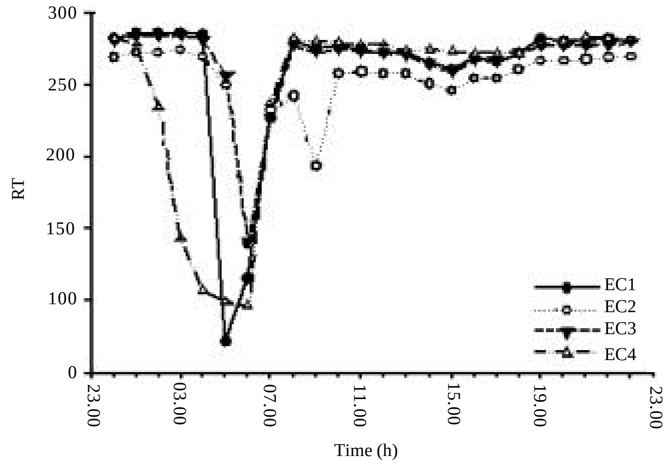

Fig. 3: EC operating hour daily

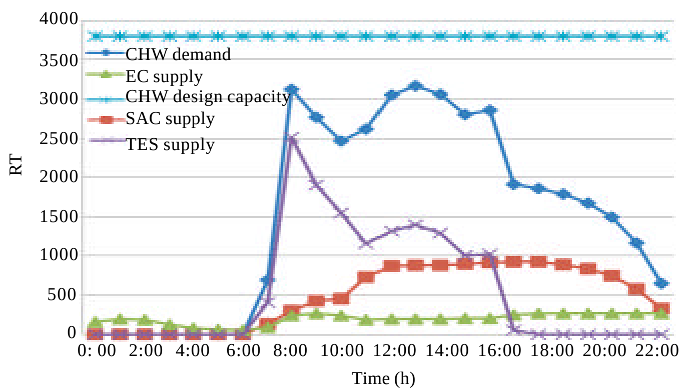

Fig. 4: Typical CHW daily demand in 2010

off-peak. Besides shaving the peak load, TES has many other benefits. Since, off-peak period is much longer than peak period, so that chillers can run at full capacity during charging the storage tank. As chillers run at night time, when outside temperature is lower than daytime, chiller cycle efficiency is higher.

At the UTP DC plant, during the night four EC produced chilled water to charge the TES tank. The duration of charging process is 12 h per day. During daytime chilled water from the TES tank is circulated through the cooling coil to achieve the required comfort level for the buildings. Historical records on charging of TES indicate that most of the time, TES was not charged to the full capacity. Hence, there is a requirement to study and to develop an improved scheduling strategy for charging of TES.

APPROACH AND METHODS

The proposed model is to ensure balanced operation of EC and at the same time TES is charged to maximum capacity during off peak period i.e. during the night. Based on the historical records as shown in Fig. 4, it is noted that TES is charged from 6.00 p.m. to 6.00 a.m. Hence, the model is based on 12 h charging period. The capacity of EC is taken by taking the average of the data from 1/11/2011 to 7/11/2011.

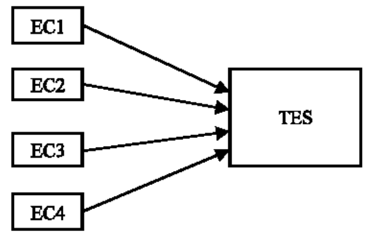

Fig. 5: Network model of TES charging

Zero-one programming model is developed for this scheduling policy. In this 0-1 programming model the decision variables will be either "AZERO" or "AONE". The "AZERO" value of the decision variable may be represented as "AOFF" condition of EC and value "AONE" as "AON" condition of the EC during charging. Figure 5 shows the EC network model for the TES charging.

Assignments involved determining the total hours each EC should be operated to charge the TES. The available time for charging is from 6.00 p.m. to 6.00 am. The main objective is to achieve maximum capacity of the TES.

Decision variables: There are 48 decision variables, representing number of hours each EC will be operated. The decision is represented by x_{ij} = hour of EC i operated, where i = 1, 2, 3 and 4 and j = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12. It is an integer either 0 or 1.

Objective function: The objective function is to maximize the production of chilled water per day:

$$\text{Maximize, } Z = \sum_{i=1}^{i=4} \sum_{j=1}^{j=12} c_i x_{ij} \tag{1}$$

where, i = 1, 2, 3 and 4.

For each i where j = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12:

$$Z = \sum_{i=1}^{i=4} \sum_{j=1}^{j=12} c_i x_{ij}$$

is obtained from historical data. It is the average of the production each EC from 1/11/2011 to 7/11/2011.

Supply constraints:

$$X_{ij} = 0 \text{ or } 1 \tag{2}$$

Demand constraints:

$$\sum_{i=1}^{i=4} \sum_{j=1}^{j=12} c_i x_{ij} \le 10000 \tag{3}$$

Table 1: B data for electric chillers scheduling problem

Hour	Time period	EC1 c1	EC2 c2	EC3 c3	EC4 c4
1	6.00 p.m. 7.00 p.m.	x_{11}	x_{21}	x_{31}	x_{41}
2	7.00 p.m. 8.00 p.m.	x_{12}	x_{22}	x_{32}	x_{42}
3	8.00 p.m. 9.00 p.m.	x_{13}	x_{23}	x_{33}	x_{43}
4	9.00 p.m. 10.00 p.m.	x_{14}	x_{24}	x_{34}	x_{44}
5	10.00 p.m. 11.00 p.m.	x_{15}	x_{25}	x_{35}	x_{45}
6	11.00 p.m. 12.00 am	x_{16}	x_{26}	x_{36}	x_{46}
7	12.00 a.m. 1.00 a.m.	x_{17}	x_{27}	x_{37}	x_{47}
8	1.00 a.m. 2.00 a.m.	x_{18}	x_{28}	x_{38}	x_{48}
9	2.00 a.m. 3.00 a.m.	x_{19}	x_{29}	x_{39}	x_{49}
10	3.00 a.m. 4.00 a.m.	$x_{1\,10}$	$x_{2\,10}$	$x_{3\,10}$	$x_{4\,10}$
11	4.00 a.m. 5.00 a.m.	$x_{1\,11}$	$x_{2\,11}$	$x_{3\,11}$	$x_{4\,11}$
12	5.00 a.m. 6.00 a.m.	$x_{1\,12}$	$x_{2\,12}$	$x_{3\,12}$	$x_{4\,12}$

X_{ij} is either 0 or 1

Table 2: Spreadsheet formulation of the scheduling problem

Time period	Hour	EC 1	EC 2	EC 3	EC 4	Volume	No. of chiller running
6.00 p.m.-7.00 p.m.	1	0	1	1	1	975	3
7.00 p.m.-8.00 p.m.	2	1	1	1	0	975	3
8.00 p.m.-9.00 p.m.	3	1	1	1	0	975	3
9.00 p.m.-10.00 p.m.	4	0	1	1	1	975	3
10.00 p.m.-11.00 p.m.	5	1	1	1	0	975	3
11.00 p.m.-12.00 a.m.	6	1	1	1	0	975	3
12.00 a.m.-1.00 a.m.	7	1	1	1	0	975	3
1.00 a.m.-2.00 a.m.	8	0	1	1	1	975	3
2.00 a.m.-3.00 a.m.	9	1	1	1	0	975	3
3.00 a.m.-4.00 a.m.	10	1	1	1	0	975	3
4.00 a.m.-5.00 a.m.	11	1	0	1	1	975	3
5.00 a.m.-6.00 a.m.	12	1	1	1	0	975	3
Total volume of CHW						11700	
Total production of CHW	9	11	12	4			
Available time	12	12	12	12			

Capacity of EC: 325

Zero-one programming solution: Table 1 presents the formulation of the model as a tabular format. This format is used to develop spreadsheet format for the problem. The use of spreadsheet is to assist in solving the problem.

Table 2 shows the spreadsheet formulation assuming all EC are running at designed capacity of 325 RT. The strategy adopted is to have only three EC operating simultaneously at the same time.

RESULTS AND DISCUSSION

Case 1: Data was collected on 1/11/2011 to 7/11/2011. The average of RT during charging TES for each EC was used for the value of c_1. Table 3 show data for EC Average hourly capacity.

Premium Solver was used to obtain the maximum schedule. Table 4 shows that on 1/11/2011, EC2 should be off because of the lowest capacity itself.

The result shown the maximum CHW is 6084 RTh for 1/11/2011 when three chillers are running. While EC1, EC2 and EC4 are operating for 12 h to charge TES.

Table 3: Data for EC Average hourly capacity

	RT			
Date	EC1 c1	EC2 c2	EC3 c3	EC4 c4
1/11/2011	164	161	171	172
2/11/2011	121	170	139	130
3/11/2011	270	288	295	270
4/11/2011	308	208	113	200
5/11/2011	256	140	0	0
6/11/2011	183	247	117	0
7/11/2011	272	197	253	0

Table 4: Premium solver results on 1/11/2011

Time period	Hour	EC 1	EC 2	EC 3	EC 4	Volume	No. of chiller running
6.00 p.m.-7.00 p.m.	1	1	0	1	1	507	3
7.00 p.m.-8.00 p.m.	2	1	0	1	1	507	3
8.00 p.m.-9.00 p.m.	3		0	1	1	507	3
9.00 p.m.-10.00 p.m.	4	1	0	1	1	507	3
10.00 p.m.-11.00 p.m.	5	1	0	1	1	507	3
11.00 p.m.-12.00 a.m.	6	1	0	1	1	507	3
12.00 a.m.-1.00 a.m.	7	1	0	1	1	507	3
1.00 a.m.-2.00 a.m.	8	1	0	1	1	507	3
2.00 a.m.-3.00 a.m.	9	1	0	1	1	507	3
3.00 a.m.-4.00 a.m.	10	1	0	1	1	507	3
4.00 a.m.-5.00 a.m.	11	1	0	1	1	507	3
5.00 a.m.-6.00 a.m.	12	1	0	1	1	507	3
Total volume of CHW						6084	
Total production of CHW	12	0	12	12			
Available time	12	12	12	12			

Capacity of EC: 164

Case 2: In case II, the maximum capacity of each EC was assumed in order to obtain the maximum capacity of CHW. Table 5 shows the results by running Solver.

Results in Table 5 show maximum capacity of CHW produced by EC during charging hours is 10692 RTh. Since, EC 4 produced the lowest capacity, EC4 should be off.

Case 3: The model was used to run two EC with full capacity i.e., 325 RT for each hour. Results obtained by the Solver shown in Table 6.

For the alternate sequence hourly, only two EC are running hourly. Result show the maximum capacity obtained is 7800 RTh.

Sensitivity analysis: Table 7 shows the results of CHW production from Premium Solver from historical data dated from 1/11/2011 to 7/11/2011. The production varies from 4752 to 10236 RTh. The maximum RTh produced is on 3rd Nov 2011.

Figure 6 shows the distribution of EC's capacity running daily. The maximum rate of capacity is 308 RT on 4/11/2011 from EC1. The minimum rate is zero from EC4. The figure also indicate that EC4 was down for three days.

Table 5: Premium solver results using maximum capacity of each EC

Time period	Hour	EC 1	EC 2	EC 3	EC 4	Volume	No. of chiller running
6.00 p.m.-7.00 p.m.	1	1	1	1	0	891	3
7.00 p.m.-8.00 p.m.	2	1	1	1	0	891	3
8.00 p.m.-9.00 p.m.	3	1	1	1	0	891	3
9.00 p.m.-10.00 p.m.	4	1	1	1	0	891	3
10.00 p.m.-11.00 p.m.	5	1	1	1	0	891	3
11.00 p.m.-12.00 a.m.	6	1	1	1	0	891	3
12.00 a.m.-1.00 a.m.	7	1	1	1	0	891	3
1.00 a.m.-2.00 a.m.	8	1	1	1	0	891	3
2.00 a.m.-3.00 a.m.	9	1	1	1	0	891	3
3.00 a.m.-4.00 a.m.	10	1	1	1	0	891	3
4.00 a.m.-5.00 a.m.	11	1	1	1	0	891	3
5.00 a.m.-6.00 a.m.	12	1	1	1	0	891	3
Total volume of CHW						10692	
Total production of CHW	12	12	12	0			
Available time	12	12	12	12			

Capacity of EC: 308

Table 6: Results using alternate sequence hourly

Time period	Hour	EC 1	EC 2	EC 3	EC 4	Volume	No. of chiller running
6.00 p.m.-7.00 p.m.	1	1	0	1	0	650	2
7.00 p.m.-8.00 p.m.	2	0	1	0	1	650	2
8.00 p.m.-9.00 p.m.	3	1	0	1	0	650	2
9.00 p.m.-10.00 p.m.	4	0	1	0	1	650	2
10.00 p.m.-11.00 p.m.	5	1	0	1	0	650	2
11.00 p.m.-12.00 a.m.	6	0	1	0	1	650	2
12.00 a.m.-1.00 a.m.	7	1	0	1	0	650	2
1.00 a.m.-2.00 a.m.	8	0	1	0	1	650	2
2.00 a.m.-3.00 a.m.	9	1	0	1	0	650	2
3.00 a.m.-4.00 a.m.	10	0	1	0	1	650	2
4.00 a.m.-5.00 a.m.	11	1	0	1	0	650	2
5.00 a.m.-6.00 a.m.	12	0	1	0	1	650	2
Total volume of CHW						7800	
Total production of CHW		6	6	6	6		
Available time		12	12	12	12		

Capacity of EC: 325

Table 7: CHW Production capacity from assignment modeling

	RT				
Date	EC1 c1	EC2 c2	EC3 c3	EC4 c4	Total capacity
1/11/2011	164	161	171	172	6084
2/11/2011	121	170	139	130	5268
3/11/2011	270	288	295	270	10236
4/11/2011	308	208	113	200	8592
5/11/2011	256	140	0	0	4752
6/11/2011	183	247	117	0	6544
7/11/2011	272	197	253	0	8664

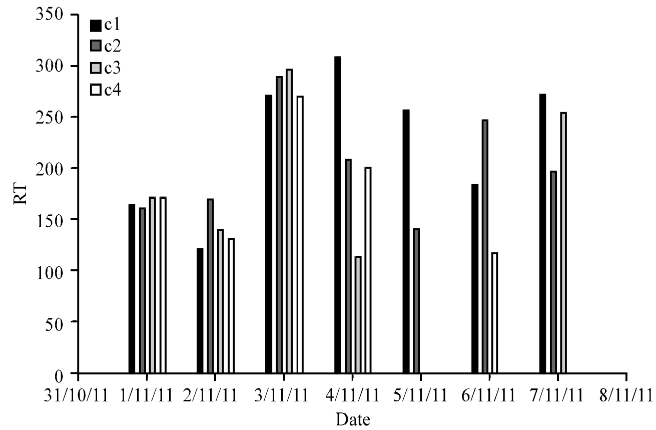

Fig. 6: Capacity of EC running daily

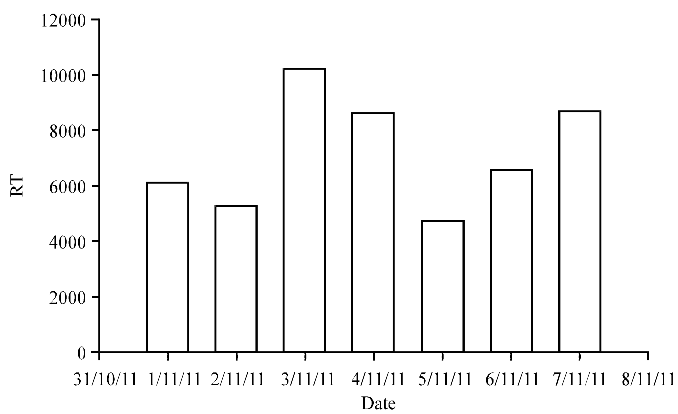

Fig. 7: CHW production daily in November, 2011

Figure 7 shows the total of CHW production daily with the capacity of EC as listed in Table 7.

Figure 7 shows the maximum capacity is 10236 RTh on 3/11/2011. The maximum capacity achieved when all EC operating with the high capacity.

During 1/11/2011 to 7/11/2011, the maximum capacity from all ECs is 308 RT. The average of capacity of EC1, EC2, EC3 and EC4 are 225, 201, 155 and 110 RT, respectively. Thus all EC were operated at below rated capacity. Results from the study indicate that EC4 is running at the lowest capacity and often shut down for operation.

When two ECs were running in one hour and followed by two other ECs, the capacity of CHW produced is low which is 7800 RTh compared to maximum three ECs running per hour with the capacity of CHW is 11700 RTh.

From 1/11/2011 to 7/11/2011, the highest capacity of CHW generated by the cooling system is 10236 RTh with three EC are running. Compared to the previous study done by Gilani *et al.* (2006) which that the output of CHW from 10/1/2005 to 16/1/2005 was 10688 RTh with four EC running. This is lower than the output obtained by the model. This meant that by using the assignment model for scheduling of the EC, the production of CHW can be increased. This could also improved the Coefficient of Performance, COP of the EC as only three EC will be operating hourly.

Based on the results, it is noted that the capacity of CHW obtained depends on the capacity of EC and the numbers of EC operating at the same time. This is in agreement finding by K. T. Chan when the chiller contains equality of sized chillers the implementation of chiller sequencing is based entirely on the load conditions of individual chillers (Chan and Yu, 2004).

CONCLUSION

Due to limited time available to charge the TES during off peak hours, the scheduling of operating EC for charging is important. Analysis on the use of the proposed model indicate the model could assist to address the issue. Hence, the model would be useful for the UTP GDC plant to schedule daily charging assignment for the EC.

ACKNOWLEDGMENT

The authors would like to express their appreciation to the assistance and support by University Teknologi PETRONAS (UTP) and also to the UTP-GDC Operator for the access to the GDC operating data.

REFERENCES

Boonnasa, S. and P. Namprakai, 2010. The chilled water storage analysis for a university building cooling system. Applied Therm. Engin., 30: 1396-1408.

Chan, K.T. and F.W. Yu, 2004. How chillers react to building loads. ASHRAE J., 46: 52-57.

Gilani, S.I.H., M.A.A. Majid and C. Rangkuti, 2006. Chillers operating strategies of a thermal energy storage system: Case study of a gas district cooling plant. Proceedings of the International Conference on Energy and Environment, June 12-15, 2006, Kajang, Selangor, Malaysia.

Gretarson, S.P., C.O. Pedersen and R.K. Strand, 1994. Development of a fundamentally based stratified thermal storage tank model for energy calculation. ASHRAE Trans., 100: 1213-1220.

Khushairi, M.M., H. Abdullah and H. Hazran, 2011. A study on the optimization of control strategy of a thermal energy storage system for building air-conditioning. Procedia Engin., 20: 118-124.

Sulaiman, S.A. and M.A.A. Majid, 2011. Gas District Cooling in Malaysia: Leveraging Abundant Cleaner-Burning Natural Gas. LAP Lambert Academic Publishing, Germany, ISBN: 3846554413, Pages: 124.