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Evaluations of thermocline and half cycle figure of merit of a thermal energy storage tank

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Abstract. Two main criteria that are commonly used to evaluate thermal energy storage systems are thermocline thickness and half cycle figure of merit. For the thermocline thickness, the preference is to achieve as thin as possible the thermocline thickness. While the preference for half cycle figure of merit is to achieve the value of greater than 90 per cent. These two criteria were used to evaluate a thermal storage system at University Teknologi PETRONAS district cooling plant. The capacity of the thermal energy storage tank of the plant is 10,000 RTh. Operating data was used for the evaluation. The values of evaluated thermocline thickness ranges from 2.248 meters to 5.445 meters with an average of 3.251 meters. These values are very much higher in comparison to findings of other studies. One possible reason is due to higher flow rates. For the half cycle figure of merit the evaluated values ranges from 0.9469 to 0.9847, with the average of 0.9698, which are within the acceptable range. For future work a model should be developed which could automatically evaluate both the thermocline thickness and half cycle figure of merit. This would enable both of these parameters to be continuously evaluated.

1 Introduction

Thermal energy storage (TES) is an established technology. It is applied to correct the mismatch that occur between the supply and demand of electrical energy. This is to achieve more efficient utilization of electricity, whereby the off peak electricity is utilize to charge the TES. For effectiveness the TES tank should be stratified [1]. The most commonly used TES system is sensible TES system using water as storage medium.

TES system is widely used in USA, with estimated installed capacity of 353 MW

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for chilled water [2]. In Asia TES systems are installed in Japan, Thailand, Singapore and Malaysia, with Japan having the most installations [3]. In Malaysia stratified TES system is installed at Universiti Teknologi PETRONAS (UTP) [4]. This plant is used as the case study.

The main principle of TES is storing of electrical energy for utilization at a later time. For the case of TES system using electrical energy, the electrical energy is used to cool the water at a thermal storage tank to a temperature of between 6°C to 7°C and the chilled water is then used for air conditioning during the day. Normally the initial temperature of the water is from 12°C to 13°C. The charging of cooling water at the thermal storage tank is done during off peak periods which are normally at night using electric chillers. The off peak is selected to take advantage of cheaper electrical rate, which is the case of district cooling plant for KLIA 2 [5]. For the case of district cooling with gas turbine the excess electricity during the night is used to operate the electric chillers to charge the thermal storage tank. This improved the utilization of electricity [4].

In terms of performance measures of stratified chilled water TES tank, there are three methods of evaluations which are commonly used. The methods are cycle thermal efficiency, half cycle figure of merit (FOM) and thermocline thickness [6, 7, 8, 9].

2 Performance measure

The performance measures used for this study are thermocline thickness and half cycle FOM. These measures were used for performance evaluations of a stratified TES tank at UTP district cooling plant.

2.1 Thermocline thickness

Thermocline thickness indicates the physical barrier that separates the warm and cool water in the TES tank. The thickness determine how well a TES is stratified. The temperature profile of the water during charging is as shown in **Fig. 1 (a)**. Due to the different temperature of the chilled water, the warm water with lesser density forms at the top layer of the tank while cool water with higher density settle at the bottom. Between these two regions, thermocline is formed in the middle [6]. **Fig. 1 (b)** shows the TES system with electric chillers.

The temperature profile of **Fig. 1** is represented by Sigmoid Dose Response (SDR) function as per equation (1) [10].

$$T(X) = T_c+\{(T_h-T_c)/[1+10^{(C-X)S}]\} \tag{1}$$

Equation (1) relates the temperature distribution in the TES to all the variables shown in **Fig. 1 (a)**. T_h and T_c are the warm and cool water temperatures in degrees C, respectively. X is the sensor elevation of the tank. Parameter C determines the thermocline position in the tank. While the parameter S is a constant defining the slope gradient of the thermocline profile.

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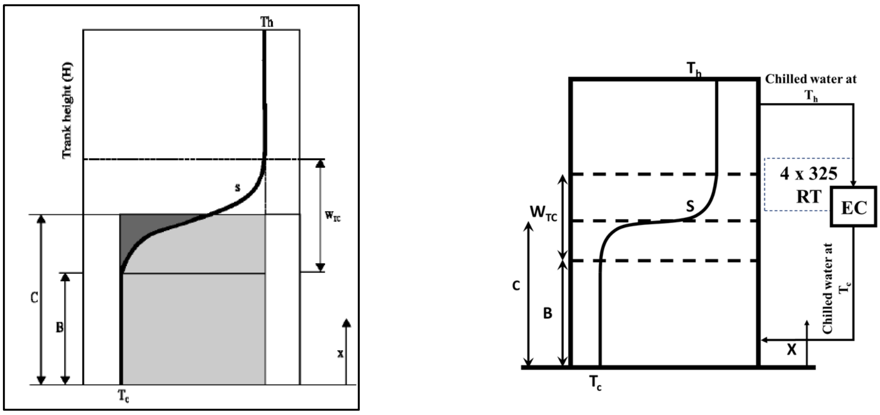

(a) (b)

Fig. 1. : (a) Temperature distribution profile of chilled water in TES tank. (b) TES tank with various parameters and electric chillers for the case study.

To quantify the thermocline thickness, limit points of the thermocline profile required to be analysed by using dimensionless cut-off temperature θ = (T-Tc)/(Th-Tc) [6]. Thermocline thickness, W_{TC}, is calculated using equation (2).

$$W_{TC} = \{[2log(1/\theta - 1)]/S\} \quad (2)$$

2.2 Half cycle figure of merit, ½ FOM

The half-cycle FOM, ½ FOM is the ratio of integrated capacity, C_{int} to theoretical capacity C_{max}, represented by an equal volume of water undergoing a temperature change equal to the difference between the average charged inlet temperatures. Derivation of the ½ FOM is as shown by equations (3) to (5) [9,10].

$$\tfrac{1}{2}\, FOM = C_{int}/C_{max} \quad (3)$$

Where,

$$C_{int} = \{[\rho A C_p(T_h - T_c)]/S\}[log(1+10^{SC}) - log2] \quad (4)$$

$$C_{max} = C\rho A C_p(T_h - T_c) \quad (5)$$

The difference between the integrated capacity and theoretical capacity is the loss of cooling energy in TES, C_{loss}, and is represented by equation (6).

$$C_{loss} = C_{max} - C_{int} \quad (6)$$

Table 1. Hourly temperatures of 14 sensors (S1 to S14) in TES tank, 4th Jan 2016.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
HR	**Temperature, °C**													
0:00	8.0	7.9	7.9	7.9	7.8	7.8	7.7	7.8	7.8	7.7	7.7	7.4	7.5	7.3
1:00	8.0	7.9	7.9	7.9	7.8	7.8	7.7	7.8	7.8	7.7	7.7	7.3	7.5	7.2
2:00	8.0	7.9	7.9	7.9	7.8	7.8	7.7	7.8	7.8	7.7	7.6	7.3	7.4	7.1
3:00	7.9	7.9	7.9	7.9	7.8	7.8	7.7	7.8	7.8	7.6	7.5	7.3	7.3	7.0
4:00	7.9	7.9	7.9	7.9	7.8	7.8	7.7	7.8	7.8	7.6	7.5	7.2	7.2	7.0
5:00	7.9	7.9	7.9	7.8	7.8	7.8	7.6	7.8	7.7	7.5	7.4	7.2	7.1	7.0
6:00	7.9	7.9	7.9	7.8	7.8	7.8	7.6	7.7	7.7	7.4	7.4	7.1	7.1	6.9
7:00	8.1	7.9	7.9	7.8	7.8	7.8	7.6	7.7	7.7	7.4	7.4	7.1	7.1	7.0
8:00	12.2	7.9	7.9	7.8	7.8	7.8	7.6	7.7	7.7	7.5	7.5	7.2	7.2	6.9
9:00	13.8	10.2	7.9	7.8	7.8	7.8	7.6	7.8	7.8	7.7	7.6	7.3	7.4	7.0
10:00	14.0	13.8	10.5	7.9	7.9	7.8	7.7	7.8	7.8	7.7	7.8	7.5	7.5	7.1
11:00	14.0	14.0	13.9	10.2	7.9	7.9	7.7	7.8	7.9	7.8	7.9	7.7	7.7	7.4
12:00	14.1	14.1	14.0	13.9	11.3	8.0	7.8	7.9	7.9	7.8	7.9	7.8	7.9	7.5
13:00	14.3	14.2	14.2	14.1	14.0	12.5	8.3	7.9	8.0	7.9	7.9	7.8	8.0	7.7
14:00	14.5	14.5	14.4	14.2	14.1	14.0	13.4	9.9	8.0	7.9	8.0	7.8	8.0	7.9
15:00	14.6	14.5	14.5	14.4	14.2	14.1	13.9	13.9	11.6	8.2	8.0	7.9	8.1	7.9
16:00	14.6	14.6	14.5	14.5	14.4	14.3	14.0	14.1	14.1	13.2	9.5	8.0	8.1	8.0
17:00	14.6	14.6	14.6	14.5	14.4	14.3	14.1	14.2	14.1	13.9	12.3	8.2	8.1	8.0
18:00	14.6	14.6	14.5	14.4	14.3	14.2	14.0	14.1	14.0	12.4	8.6	8.2	8.2	8.1
19:00	14.6	14.5	14.5	14.3	14.2	14.2	13.9	14.0	12.2	8.5	8.3	8.1	8.3	8.1
20:00	14.5	14.4	14.3	14.2	14.1	14.0	13.8	11.8	8.5	8.2	8.2	8.0	8.2	8.1
21:00	14.4	14.3	14.2	14.1	14.0	13.9	11.4	8.3	8.2	8.0	8.1	8.0	8.1	8.0
22:00	14.3	14.2	14.2	14.1	13.9	11.2	8.1	8.1	8.1	7.9	8.0	7.9	8.1	8.0
23:00	14.2	14.2	14.1	14.0	12.2	8.4	8.0	8.0	8.0	7.9	8.0	7.8	8.0	7.9

3 Results and discussion

Thermocline thickness and ½ FOM were used for evaluations of TES at UTP District Cooling plant. The TES tank at the plant is with 10,000RTh capacity. There are 14 temperature sensors within the tank. January 2016 data was used for analysis. The hourly temperatures at the 14 sensors data for the 4th Jan 2016 is as shown in **Table 1**. The plot of hourly temperature profiles for the 14 sensors is shown in **Fig. 2 (a)** for 4th January 2016, while **Fig. 2 (b)** shows the plot for 6th January 2016. **Table 2** are the calculated SDR fitting temperature distribution on 4th Jan 2016 and 6th January 2016 respectively.

From **Fig. 2 (a)** and **Table 2** it is observed that the values of midpoint C of the thermocline on 4th January 206 were increasing as the charging hour increases. This indicates that the position of the thermocline was moving upward while the warm water drawn out and chilled water added into the TES tank. The increased in the portion of chilled water in the TES tank during the charging period resulted to increased cooling capacity of the TES tank. Since the values R2 in **Table 2** are greater than 0.99, this indicate the recorded temperature fitted well to SDR function.

For the case of 6th January, the C values increases from 18:00 to 12:00 as per **Table 2**. The plot for S-curve, fitted well during this period as shown in **Fig. 2 (b)**. However, it is not for the case of 01:00 and 02:00. The recorded temperatures did not fit the SDR function. The thermocline thickness for whole month of January 2016 were also evaluated. Plot of the values of the thermocline thickness is as shown in **Fig. 3 (a)**. The values range from 2.248 meter to 5.445 meter, with an average of 3.251 meter. These values are very much higher than that was obtained by [4] and [11], and the result close to that was obtained by [10]. One possible reason is due to higher flow rates in comparison to [4].

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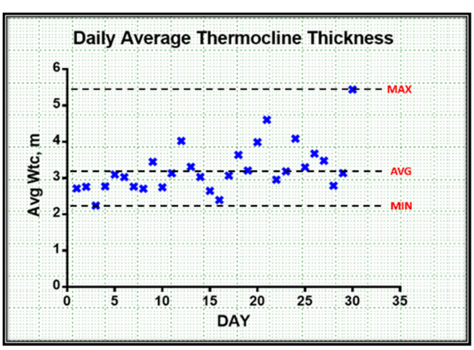
(a) **(b)**

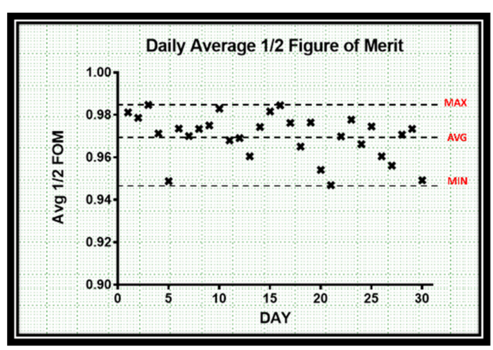
Fig. 2. Plot of hourly temperatures from 6 pm to 2 am on **(a)** 4th January 2016 & **(b)** 6th January 2016 by 14 temperature sensors within the TES tank.

Table 2. Calculated SDR fitting of temperature distribution on 4th & 6th January 2016.

Initial Condition: ϴ= 0.01								
Date: 4th January 2016								
Hr	Tc	Th	C	S	R^2	Wtc(m)	1/2FOM	Remark
18:00	8.14	14.32	4.267	1.376	0.9959	2.90	0.9487	Accepted
19:00	8.18	14.29	5.32	1.437	0.9962	2.78	0.9606	Accepted
20:00	8.12	14.23	6.377	1.209	0.9978	3.30	0.9609	Accepted
21:00	8.05	14.19	7.456	1.335	0.9989	2.99	0.9697	Accepted
22:00	8.00	14.18	8.494	1.499	0.9992	2.66	0.9763	Accepted
23:00	7.95	14.15	9.274	1.422	0.9996	2.81	0.9771	Accepted
0:00	7.94	14.13	10.23	1.485	0.9993	2.69	0.9801	Accepted
1:00	7.92	14.06	11.02	1.738	0.9981	2.30	0.9842	Accepted
2:00	7.93	14.10	11.67	1.546	0.9965	2.58	0.9833	Accepted
Date: 6th January 2016								
Hr	Tc	Th	C	S	R^2	Wtc(m)	1/2FOM	Remark
18:00	8.10	14.36	5.921	1.285	0.997	3.11	0.9604	Accepted
19:00	8.28	14.38	7.132	1.219	0.9974	3.27	0.9653	Accepted
20:00	8.26	14.32	8.222	1.459	0.9977	2.74	0.9749	Accepted
21:00	8.20	14.27	9.256	1.322	0.998	3.02	0.9754	Accepted
22:00	8.18	14.25	10.23	1.333	0.9976	2.99	0.9779	Accepted
23:00	8.13	14.18	11.19	1.251	0.9966	3.19	0.9785	Accepted
0:00	8.14	13.98	12.14	1.37	0.9941	2.91	0.9819	Accepted
1:00	8.10	~	~	~	0.9851	Undefined	Undefined	N.P.S.C
2:00	7.67	~	~	~	0.896	Undefined	Undefined	N.P.S.C

***N.P.S.C = Not perfect S-Curve.*





(a) **(b)**

Fig. 3. Plot of **(a)** thermocline thickness & **(b)** ½ FOM for January 2016.

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Since thermocline thickness might varies over a wide range, depending on tank dimension and operating temperatures, flow rates and diffuser designs, the magnitude of thermocline thickness could not be strictly compared.

For the half cycle FOM, the values obtained range from 0.9469 to 0.9847, with an average of 0.9698. The plot of the values is as shown in **Fig. 3 (b)**. Since the half cycle FOM are greater than 90%, the values are meeting the standards [6].

4 Conclusion

Thermocline thickness and ½ FOM were used for evaluations of TES at UTP District to assess the performance of the TES system. Results obtained indicate the TES tank performance is acceptable in terms of half cycle FOM but not for the thermocline thickness. The thermocline thickness are very much higher in comparison to other findings. One possible reason was due to higher flow rates. However, it is noted that due to a wide range of tank configurations and operating parameters, the magnitude of thermocline thickness could not be strictly compared. For continuously operating TES tank the performance monitoring should also be continuously evaluated. It is recommended that a model to be developed which could automatically evaluate both of these parameters. This would be enable continuous monitoring of these parameters.

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