Performance assessment of stratified chilled water thermal energy storage tank at district cooling plant

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Abstract. Thermal energy storage (TES) is the key component of the district cooling (DC) plants. Its performance is important to be analysed. Various works have been carried out to analyse the TES tank performance. Among the methods, the most common are thermocline thickness and figure of merit. In this study nonlinear regression is used to analyse the temperature profiles of a stratified TES tank at DC plant at Universiti Teknologi PETRONAS. The TES performance was also evaluated using thermocline thickness and 1/2FOM. Results indicate curve fitting approach is enabled to plot temperature profiles during charging. The plots assist in understanding the development of thermocline within the TES tank during charging process. Results on the thermocline thickness and 1/2FOM during the understudy charging period indicate increased of thermocline thickness and decreased of 1/2FOM values respectively during the study period. Hence it can be concluded that deterioration occurred to the TES tank during the study period.

1. Introduction

Recently, the stratified thermal energy storage (STES) is getting more popular due to high energy demand. STES is the main component of district cooling (DC) plant and is used to store the cooling capacity during off-peak hours and during on-peak it is used to support the chilled water requirements to the buildings for space cooling [1]. The medium of the storage is water, due to its ease of availability, economic nature and high specific heat [2]. The volume of water having low temperature settle down and the volume of water having high temperature settle on top of the cold water due to density difference [3-5], separated by a transition layer known as thermocline (WTc) [3, 6] as shown in figure 1. Thermocline thickness is one of the accepted performance measures, it is a transition region of the temperature distribution [7]. Thicker thermocline indicates low performance whereas thinner thermocline is sign of high performance [2]. Various numerical and analytical approaches has been proposed and applied to evaluate the performance of TES tank in terms of thermocline thickness [8]. Among the major contributions of performance evaluation of TES tank have been reported by Yoo [8], Homan [9], and Musser and Behnfleth [10]. The definition of thermocline thickness proposed by Musser and Behnfleth [10] remained the most dominant and widely applied. However, this approach still has one drawback, that is, in case of discrete temperature data available this method fails to predict the thermocline thickness accurately [11]. To overcome the issue of fail to predict the thermocline thickness accurately, this paper introduces non-linear regression [11] approach in order to evaluate thermocline thickness.
2. Methodology
In this study, curve fitting method is used which representing mathematical relation between dependent and independent variable for a given set of data. The advantage of using curve fitting is that it enables visualization of data characteristics, to obtain important parameters and to summarize the relationships among variables [11, 13]. Conceptually, fitting a mathematical model on data set is to establish equation that defines the dependent variable as a function of an independent variable with one or more parameters. Temperature data of the TES system of Universiti Teknologi PETRONAS DC plant were acquired for the study, the TES system consists of two 1250 refrigeration ton (RT) of steam absorption chiller and four 325 RT electric chillers and one 54000 m$^3$ storage of TES tank with designed capacity of 10000 RTh. The electric chillers were used to charge the TES during night time. The inlet nozzle of the TES tank is made from 20 inch NPS located at elevation 3.4 meters height, while outlet nozzle is 12 inch NPS at elevation of 12.3 meters. Both nozzles are provided with diffuser on its end-connection in TES tank. Overflow line is connected at elevation of 14.025 meters. The entire tank is extensively insulated. The tank is equipped with 14 temperature sensors, installed at approximately 1 meter vertical interval, to measure the water temperature. The lowest temperature sensor is located at 0.51 meters height. All temperatures are hourly recorded with acquisition data system. Table 1 tabulates design specification of the TES tank. Meanwhile, table 2 shows the example of temperature readings acquired from TES tank by resistance temperature detector (RTD) vertically installed in the tank.

Table 1. Specifications of the TES tank.

| No | Parameter       | Value | Unit   |
|----|----------------|-------|--------|
| 1  | Height         | 15    | m      |
| 2  | Diameter       | 22.3  | m      |
| 3  | Volume         | 5400  | m$^3$  |
| 4  | Mass flow rate | 393   | m$^3$/h|
| 4  | Material       | Steel | -      |
| 5  | Numbers of RTD | 14    | Nos    |
Temperature distribution is an important parameter in performance analyses of TES tanks [14]. From the past researches it is confirmed that the temperature distribution in stratified TES tanks having S-curve profile [8-10]. In this study, the temperature distribution function is considered as the function of the average cold water \((T_c)\), average hot water \((T_h)\), position of thermocline \((C)\) slope of the temperature gradient \((S)\) and sensor elevation \(x\) as shown by equation (1). Since, the data follows the S-curve, the function from S-curve family i.e sigmoid function was chosen to fit the data as shown by equation (2).

\[
T(x) = f(T_c, T_h, C, S, x)
\]

\[
T = T_c + \frac{T_h - T_c}{1 + 10^{(C-x)/S}}
\]

Formulation of thermocline thickness using SDR function was obtained by rearranging equation (2), as shown by equation (3).

\[
\frac{T_h - T_c}{T - T_c} = 1 + 10^{(C-x)/S}
\]

The left term of equation term of equation (3) re-arranged using dimension less cut-off temperature \(\theta = \frac{T - T_c}{T_h - T_c}\) applying the approach of Musser (1998), describing the limit points of thermocline thickness.

\[
\frac{1}{\Theta} = 1 + 10^{(C-X)/S}
\]

Distance from \(C\) to \(X\) express the half-thickness of the thermocline, and represented as follows;

\[
C - X = \log\left(\frac{1}{\Theta} - 1\right)
\]

Therefore thermocline thickness is defined as:

\[
W_{TC} = \frac{\log\left(\frac{1}{\Theta} - 1\right)}{S}
\]
Using the similar analysis, thermocline thickness for 4 parameters sigmoid (FPS) function is determined as:

\[ W_{TC} = 2 \ln \left( \frac{1}{\Theta} - 1 \right) S \]  

(7)

3. Results and discussion

Using historical data of Jan 2016 and Jan 2017 respectively, the data were used to plot temperature profiles for the case of without curve fitting and with curve fitting for three consecutive days in Jan 2016 and 2017. The historical data selected were 28th to 30th Jan for year 2016 and 2017 respectively. The plots were drawn using commercial software GraphPad prism [15]. The temperature profiles using curve fitting indicate clearly that the thermocline for the respective dates compared to the temperature profiles without curve fitting. This assists in visualization the development of thermocline during the charging stage. The charging period being studied was from 6 pm to 3 am. The plots as shown by figure 2(a) to figure 3(b) clearly indicate the stratification process occurred during charging. However, until 3 am the tank still did not achieve full charge. Figure 4(a) and (b) show plot of TES holding capacity (thermal energy status) status at different times during charging for 2016 and 2017.

![Figure 2](image1.png)

Figure 2. Temperature profile for 28 Jan 2016 (a) without curve fitting, and (b) with curve fitting.

![Figure 3](image2.png)

Figure 3. Temperature profile for 28 Jan 2017 (a) without curve fitting (b) with curve fitting.
Table 3 and table 4 indicate the thermocline thickness for month of Jan 2016 and 2017 respectively. Table 5 and 6 show the half cycle figure of merit (1/2FOM) for month of Jan 2016 and 2017. Figure 5(a) and (b) are the plots for the thermocline thickness for year 2016 and 2017 respectively. The average for Jan 2016 the thermocline thickness varies from 2.929 to 4.809 meters. While for Jan 2017 the thermocline thickness varies from 2.338 to 9.076 meters. Year 2016 shows more stable results compared with year 2017. The average daily thermocline thickness was calculated by omitting the thermocline thickness value marked with ‘*’. This was done as the values seem to be out of bound. The evaluated 1/2FOM are included in table 5 and table 6 for 2016 and 2017 respectively. The daily average for 10 days during 2016 varies from 0.95 to 0.98. While for year 2017 the average varies from 0.82 to 0.98. The overall 10 day average for 2016 and 2017 are 0.97 and 0.94 respectively. The decrease in values of 1/2FOM proves deterioration of tank occurred.

The plot of thermocline thickness for year 2016 and 2017 are shown in figure 5(a) and (b) respectively. The 10 days over all average of thermocline thickness for 2016 is 4.192 meters and for 2017 is 4.655 meters. This indicates the performance of tank has deteriorated. It is also noted that the thermocline thickness and the behaviour during charging is similar as noted in the study of Musser [16].

**Table 3. Tabulation of daily maximum thermocline thickness for year 2016.**

| Time  | 21-Jan | 22-Jan | 23-Jan | 24-Jan | 25-Jan | 26-Jan | 27-Jan | 28-Jan | 29-Jan | 30-Jan |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 18:00 | 5.058  | 4.859  | 2.915  | 3.152  | 4.907  | 2.492  | 4.559  | 4.387  | 2.762  | 4.344  |
| 19:00 | 3.999  | 4.212  | 2.985  | 2.365  | 3.274  | 4.188  | 4.196  | 4.000  | 2.583  | 3.877  |
| 20:00 | 3.858  | 4.641  | 3.609  | 4.019  | 3.852  | 3.311  | 4.415  | 3.338  | 2.988  | 3.361  |
| 21:00 | 3.689  | 4.601  | 3.173  | 6.712  | 3.931  | 3.252  | 3.577  | 3.641  | 2.967  | 3.087  |
| 22:00 | 3.390  | 4.434  | 3.265  | 23.57* | 4.361  | 5.619  | 3.317  | 3.585  | 2.867  | 2.766  |
| 23:00 | 3.786  | 4.519  | 2.452  | 18.36* | 3.339  | 38.96* | 2.664  | 2.827  | 2.392  | 2.922  |
| 0:00  | 3.725  | 4.882  | 2.376  | 14.63* | 4.636  | 47.17* | 3.495  | 3.559  | 2.669  | 1.765  |
| 1:00  | 4.360  | 4.725  | 3.281  | 48.03* | 4.079  | 42.83* | 3.457  | 3.117  | 3.189  | 2.355  |
| 2:00  | 5.228  | 6.403  | 2.750  | 28.38* | 4.968  | 33.02* | 4.392  | 3.721  | 2.890  | 2.345  |
| 3:00  | 19.50* | 17.11* | 3.258  | 30.52* | 18.87* | 45.53* | 9.154  | 4.063  | 3.983  | 2.512  |
| Average| 4.121  | 4.809  | 3.006  | 4.062  | 4.150  | 3.772  | 4.323  | 3.624  | 2.929  | 2.934  |

* represents out of bound value
Table 4. Tabulation of daily maximum thermocline thickness for year 2017.

| Time  | Date      | 21-Jan | 22-Jan | 23-Jan | 24-Jan | 25-Jan | 26-Jan | 27-Jan | 28-Jan | 29-Jan | 30-Jan |
|-------|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 18:00 |           | 3.31   | 11.1   | 12.86  | 3.85   | 2.22   | 2.66   | 3.50   | 2.87   | 2.68   | 4.12   |
| 19:00 |           | 3.10   | 10.8   | 13.42  | 3.50   | 2.25   | 3.28   | 3.06   | 2.36   | 3.15   | 5.28   |
| 20:00 |           | 3.02   | 10.0   | 12.94  | 2.21   | 2.31   | 2.95   | 3.50   | 2.34   | 2.32   | 4.32   |
| 21:00 |           | 2.93   | 11.2   | 11.51  | 6.88   | 2.25   | 2.27   | 2.76   | 2.32   | 2.80   | 3.48   |
| 22:00 |           | 2.03   | 9.59   | 9.29   | 49.4*  | 2.27   | 1.72   | 1.85   | 3.18   | 2.57   | 3.00   |
| 23:00 |           | 2.82   | 8.68   | 6.92   | 3.38   | 2.33   | 1.95   | 1.94   | 2.18   | 2.59   | 3.04   |
| 00:00 |           | 2.31   | 8.75   | 4.71   | 5.77   | 4.58   | 1.86   | 4.99   | 2.49   | 2.70   | 4.82   |
| 01:00 |           | 2.54   | 6.89   | 4.78   | 7.06   | 2.49   | 1.98   | 102.5* | 3.20   | 2.25   | 3.87   |
| 02:00 |           | 2.06   | 6.85   | 4.46   | 2.51   | 35.7*  | 221.9* | 0      | 2.33   | 4.95   |
| 03:00 |           | 17.9   | 0      | 6.77   | 4.51   | 3.86   | 35.7*  | 2.91   | 2.84   | 4.81   |
| Average|          | 2.685  | 9.076  | 8.544  | 4.340  | 2.592  | 2.338  | 2.866  | 2.652  | 2.627  | 4.171  |

* represents out of bound value.

Table 5. Tabulation of comparison of half cycle figure of merit (1/2FOM) for year 2016 and year 2017.

| Time  | Date      | 21 Jan | 22 Jan | 23 Jan | 24 Jan | 25 Jan | 26 Jan | 27 Jan | 28 Jan | 29 Jan | 30 Jan | Average | Average of 10 days |
|-------|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|-------------------|
| 18:00 | 0.90      | 0.94   | 0.95   | 0.96   | 0.96   | 0.97   | 0.97   | 0.97   | 0.97   | 0.97   | 0.91*  | 0.96    | 0.97               |
| 19:00 | 0.89      | 0.93   | 0.94   | 0.95   | 0.96   | 0.96   | 0.97   | 0.97   | 0.97   | 0.97   | 0.92*  | 0.95    | 0.97               |
| 20:00 | 0.95      | 0.96   | 0.96   | 0.96   | 0.96   | 0.97   | 0.97   | 0.97   | 0.98   | 0.98   | 0.98   | 0.98    | 0.97               |
| 21:00 | 0.98      | 0.98   | 0.97   | 0.96   | 0.89*  | 0.91*  | 0.93*  | 0.72*  | 0.75*  | 0.74*  | 0.97    | 0.97    | 0.97               |
| 22:00 | 0.95      | 0.97   | 0.97   | 0.97   | 0.97   | 0.97   | 0.98   | 0.98   | 0.98   | 0.97   | 0.92*  | 0.97    | 0.97               |
| 23:00 | 0.98      | 0.97   | 0.98   | 0.98   | 0.97   | 0.97   | 0.97   | 0.98   | 0.98   | 0.98   | 0.98   | 0.95    | 0.96               |
| 00:00 | 0.92      | 0.94   | 0.95   | 0.97   | 0.97   | 0.97   | 0.98   | 0.98   | 0.98   | 0.98   | 0.98   | 0.95    | 0.97               |
| 00:01 | 0.90      | 0.93   | 0.95   | 0.96   | 0.96   | 0.97   | 0.97   | 0.97   | 0.97   | 0.97   | 0.97   | 0.97    | 0.96               |
| 00:02 | 0.95      | 0.96   | 0.96   | 0.97   | 0.97   | 0.98   | 0.98   | 0.98   | 0.98   | 0.98   | 0.98   | 0.97    | 0.97               |
| 00:03 | 0.95      | 0.96   | 0.97   | 0.98   | 0.98   | 0.99   | 0.99   | 0.99   | 0.99   | 0.99   | 0.98   | 0.98    | 0.97               |
| Average| 0.97      | 0.94   | 0.95   | 0.96   | 0.96   | 0.97   | 0.97   | 0.97   | 0.97   | 0.97   | 0.97   | 0.97    | 0.96               |

* represents out of bound value.

Figure 5. Average Daily Maximum Thermocline Thickness for (a) year 2016 and (b) year 2017.
Table 6. Tabulation of comparison of half cycle figure of merit (1/2FOM) for year 2016 and year 2017.

| Date        | Average of 10 days |
|-------------|--------------------|
| Time        |                    |
| 18:00       | 0.96               |
| 19:00       | 0.96               |
| 20:00       | 0.96               |
| 21:00       | 0.96               |
| 22:00       | 0.96               |
| 23:00       | 0.96               |
| 00:00       | 0.96               |
| 01:00       | 0.96               |
| 02:00       | 0.96               |
| 03:00       | 0.96               |

* represents out of bound value.

4. Conclusion
The use of curve fitting assists in visualization of temperature profiles during charging which clearly indicate thermocline development at various stages of charging period. While from the evaluated values of thermocline thickness and 1/2FOM for year 2016 and 2017 indicates the decline in the value of thermocline from 4.19 to 4.65 meters average also 1/2FOM decreased from 0.97 to 0.94 thus deterioration of performance of the TES tank. Hence, maintenance of the tank is required in order to improve the tank performance. Due to escalating gas price the DC plant is current in the process of replacing the two steam absorption chillers with two 1250RT electric chillers and an additional thermal energy storage of same capacity as the current TES i.e. 10,000RTh.

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