Development Simulation Model for Charging of Stratified Thermal Energy Storage Tank in Cogeneration Plant

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Abstract: Currently, cogeneration plants technology have been used widely in the world since its advantageous prospect in generating the extra thermal energy from waste heat of gas turbine chimneys. Stratified thermal energy storage tank is used incorporated to cogeneration plant for shifting energy by charging the thermal energy during off-peak and discharging during the on-peak demand. The other advantage utilization tank stratified thermal energy tank is reducing the size of thermal equipment on the cogeneration plant. However, performance of stratified thermal energy storage tank is still carried out using an estimation method that has drawback of its inaccurate result and has difficulties on the measurement. One method used to overcome the drawbacks is formulation based on temperature distribution that gives beneficial in having characterization precisely and capable to be solved analytically. This research is aimed to develop a simulation model based on formulation method on the charging of stratified thermal energy storage tank. The simulation model is enhanced using non linear regression of the temperature distribution. The model is used to determine the important parameters in the charging of stratified thermal energy storage tank namely thermocline thickness, empty and full capacity, cumulative cooling capacity as well as half cycle Figure of Merit ($FoM_{1/2}$). Validation of the model uses temperature distribution profile, parameters similarity and statistical test. Simulation results show that the simulation model is enable representing the performance characteristic and accepted satisfactorily. The model is not only capable for determining the thermocline thickness, empty - full capacity, cumulative cooling capacity and half cycle Figure of Merit ($FoM_{1/2}$) but also can be used to determine the charging duration of stratified thermal energy storage tank exactly. Further, the simulation model is ready to be implemented for design and operation monitoring of stratified thermal energy storage in a cogeneration plant.
Keywords: *simulation model, performance parameters, stratified thermal energy storage tank*

1. Introduction

Stratified thermal energy storage (TES) tank is addressed to increase energy utilization in cogeneration plant. In the district cooling plant, the stratified thermal energy storage is used for shifting energy, by charging the TES during off-peak demand and discharging during on-peak demand. In the charging cycle, cool water temperature from absorption chiller is circulated to be stored in the TES and is withdrawn during discharging cycle. The sratified TES tank has beneficial in reducing the size of refrigerator equipment, and has capability in fullfiling the demand during on-peak periods effectively [1].

Charging cycle holds an important role in the operation of stratified TES tank. Determination of charging parameters accurately offers beneficial to increase energy utilization in the district cooling of a cogeneration plant. Characterization of the stratified TES is carry out based on the temperature distribution inside of the tank. There are two methods for analyzing temperature distribution namely estimation and formulation. The first method, estimation, is noted has drawback of its less accuracy [2,3]. The formulation method is developed with advantage of having more precise results producing from analytical solution. Using this method, the impartant parameters in the charging of stratified TES tank is derived based on

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Sigmoid Dose Response [4,5].

In this study, temperature distribution analysis is utilized to perform simulation model for charging of stratified TES tank in cogeneration plant. The simulation model is carried out to determine temperature distribution growth, full capacity of the charging cycle, charging duration, cumulative cooling capacity as well as determination of haf-cycle Figure of Merit ($FoM_{1/2}$). Validation of the model is carried out through evaluation of coeficient determination of the temperature distribution and temperature parameter similarities. Statistical test is also performed to endorse the acceptance of the model.

2. Methodology

2.1. Temperature Distribution Function

Temperature distribution function in this study adopted Sigmoid Dose Response (SDR) function [6]. This function is enabling of representation water temperature distribution in the stratified TES tank. The SDR function takes form as

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

Where T_c and T_h are average cool and warm of water temperatures. C expresses cool water depth, whereas S identifies the slope gradient of temperature profile. In the purpose of developing simulation model, the SDR function is extended to determine several important parameters as the following.

(a). Bottom limit points.

Bottom limit point identifies the position of lower thermocline edge where water exists at cool water temperature. Determination of bottom limit point (B) based on SDR function refers to the following:

$$B = C - \frac{\log(\frac{1}{\Theta} - 1)}{S} \tag{2}$$

Where Θ is dimensionless cut-off temperature by Musser (1998) [4] which takes forms as:

$$\Theta = (T - T_c)/(T_h - T_c) \tag{3}$$

(b). Full capacity of charging.

Full capacity is determined by equalizing of bottom limit point (B) to upper nozzle elevation (N_T). Hence cool water depth at full capacity (C_F) can be formulated as follows.

$$C_F = N_T + \frac{\log\left(\frac{1}{\Theta} - 1\right)}{S} \tag{4}$$

(c). Charging duration

Charging duration is defined as time duration to reach final condition of cool water depth (C_F) from initial condition (C_E). Charging duration, designated as t_{CF}, therefore takes form as:

$$t_{CF} = \frac{C_F - C_E}{V_C} . A \tag{5}$$

(d). Cumulative cooling capacity

Cumulative cooling capacity (Q_{cum}) which expresses the quantity of cooling energy stored in stratified TES tank is determined based on SDR function. This formula is obtained by integral solution of formulae derived from the basic concept in the stratified TES tank [7].

$$Q_{cum} = \frac{\rho.A.C_p.(T_h - T_c)}{S}\left\{\log\left(\frac{(1+10^{SC})}{(1+10^{S(C-H)}}\right)\right\} \quad (6)$$

Where ρ is density of water (kg/m^3), Cp is specific heat (kJ/kg.^{o}C)and H is effective depth of stratified TES (m) occupied by the water.

(e). Half Cycle Figure of Merit ($FoM_{1/2}$)

Half cycle Figure of Merit ($FoM_{1/2}$) is thermal performance in the charging of stratified TES tank. The half cycle Figure of Merit ($FoM_{1/2}$) is calculated as ratio of internal capacity (C_{Int}) and maximum capacity (C_{Max}).

$$C_{Int} = \frac{\rho.A.C_p.(T_h - T_c)}{S}\left\{\log\left(\frac{1+10^{SC}}{2}\right)\right\} \quad (7) \qquad C_{Max} = \frac{\rho.A.C_p.C.(T_h - T_c)}{S} \quad (8)$$

2.2. Model Development

The simulation model is developed as an open system where charging of stratified TES is performed by introducing cool water from absorption chiller at lower nozzle, whereas the upper nozzle withdraws the warm water. The outlet charging water is not re-circulated into the lower nozzle. Schematic illustration of the open charging system is presented in Figure1 that illustrates the empty and full condition in the charging cycle.

The conditions and assumptions on the charging model of stratified TES tank are as follows:

i. The inlet temperature of charging is equal to average cool water temperature of T_c.
ii. Charging has constant flow rate of V_c
iii. Temperature distribution has similar profile during its passage. Hence, parameters of average cool and warm water temperatures as well as slope gradient (T_c, T_h and S) are constant.
iv. Cool water depth (C) increases with respect to time. Increased cool water depth is calculated proportional to charging flow rate (V_c) over cross sectional area (A), therefore it takes form as
$\Delta C = V_C/A$.

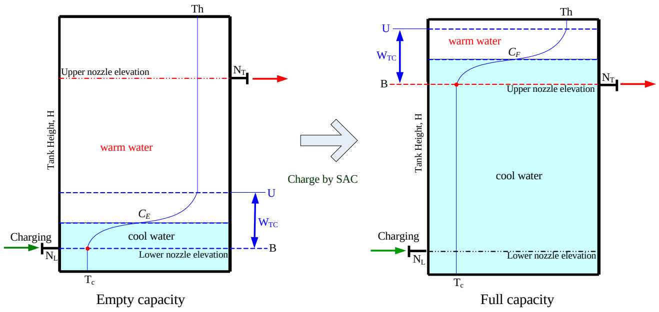

Figure 1. Schematic of charging model of stratified TES

2.3. Validation of the Model

In order to validate the model, the temperature distribution data from an operating stratified TES tank of cogeneration plant in Universiti Teknologi Petronas are acquired for this study. The district cooling in the cogeration plant are equipped with 2 absorption chillers and 4 electric chillers. The TES tank configuration of 22.3 m diameter, effective water depth is 14 m, lower and upper nozzles elevations are 1.824 m and 14 m, respectively. The schematic flow diagram of the system is shown in Figure 2.

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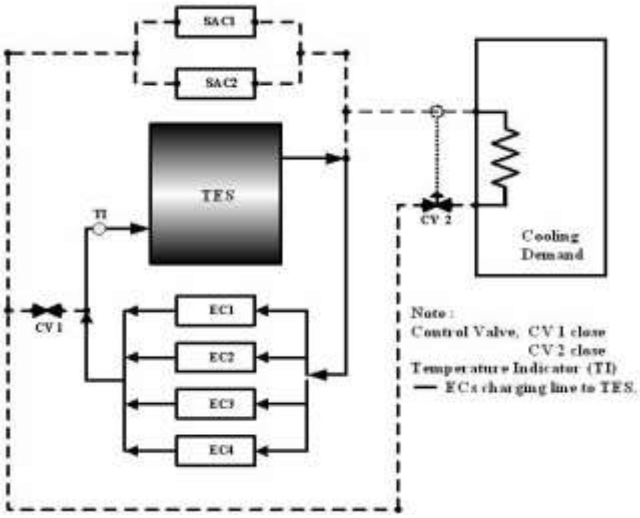

Figure 2. Schematic flow diagram of charging stratified TES in a cogeneration plant

Temperature distribution data are obtained from the data of September 11, 2008 with charging operation from hours 18.00 to 03.00. The data are recorded at constant flow rate charging of 393 m3/hr, using 14 temperature sensors installed at 1 m interval, with the lowest elevation at 0.51 m inside of the tanks. The plotting of temperature distribution is presented in Figure 3.

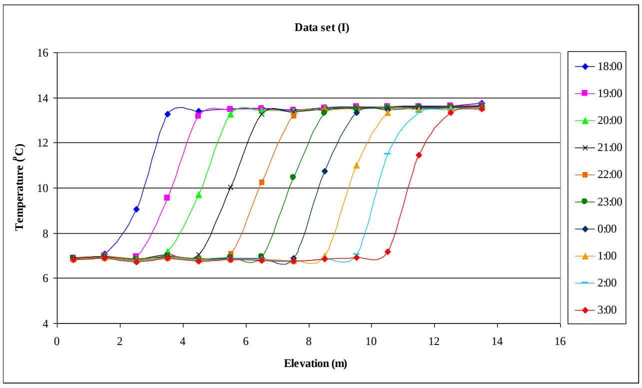

Figure 3. Temperature distribution

Validation of the simulation model is conducted through three evaluations criteria namely temperature value similarities, temperature parameter similarities and statistical test acceptance.

(i). Temperature data similarities.

Temperature data similarities are evaluated using coefficient of determination (R^2). It is carried out by comparing each hourly temperature of the observed data and the model.

(ii). Temperature parameters similarities.

It is conducted by comparing SDR parameters i.e T_c, T_h, C and S of hourly temperature distribution. The evaluation is used to observe the parameters pattern as well as determining of parameter deviations.

(iii). Statistical test acceptance.

In order to verify that the model is significantly similar with the observed data the t-statistical test is implemented. The Null hypothesis of the test is no data difference between the model and observed data.

Null hypothesis Ho: $y_i^1 - y_i^2 = 0$

Alternative hypothesis Ha: $y_i^1 - y_i^2 \neq 0$

The t-statistical value for the test is as follow:

$$t = \frac{y_i^1 - y_i^2}{\sqrt{\sigma_{y_i^1}^2 + \sigma_{y_i^2}^2}} \quad (9)$$

3. Result and Discussion

3.1. Temperature Distribution

Prior to the analysis, the observed data is fitted with non linear regression to determine its SDR parameters. Fitting SDR function to the data is presented in Table 1. Referring to Table 1, it is obviously shown that cool water temperature has constant trend during the charging cycle. This is suitable with that on assumption of the simulation model. It is also shown that all R2 are approaching to value of 1, means that temperature distributions are fitted well to SDR function.

Table 1. Parameters from fitting SDR function to the Data

Chrg. Hrs.	Tc (°C)	Th (°C)	C	S	R^2
18:00	6.9	13.6	2.7	1.6	0.999
19:00	6.9	13.6	3.6	1.4	0.999
20:00	6.9	13.6	4.6	1.4	1.000
21:00	6.9	13.5	5.5	1.5	1.000
22:00	6.9	13.5	6.5	1.4	1.000
23:00	6.9	13.5	7.5	1.7	1.000
0:00	6.9	13.5	8.4	2.0	1.000
1:00	6.8	13.5	9.4	1.8	1.000
2:00	6.8	13.5	10.3	1.8	1.000
3:00	6.8	13.5	11.3	1.6	1.000

The model is then developed using parameters T_c, T_h, S and C from initial temperature at hours of 18.00 at Table 1. Hence the model has initial conditions with values of 6.9, 13.6 and 1.6, for T_c, T_h and S respectively. The initial cool water depth is obtained equal to 2.7. Hourly additional cool water depth as flow rate over area of the tank, resulting 393/390.73 = 1 m. Temperature distribution of the model is generated with that parameters based on SDR function, in Equation (1). The generation of temperature distribution with 9 hours charging from the model is shown in Figure 4.

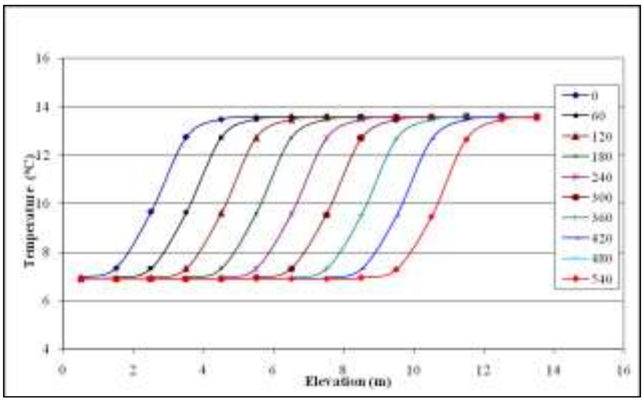

Figure 4. Temperature distribution generated from the model

3.2. Model Validation

3.2.1. R^2 between the model and observed data

The goodness relationship between temperature distribution of the model and observed data is evaluated using coefficient of determination (R^2). It is conducted by comparing temperature distribution of the observed data and model as shown in Figures 3 and 4, respectively. The R^2 result is presented in Table 2.

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Table 2. R^2 between model and observed data

Data Chrg. Hrs.	to	Simulation Chrg. Min.	R^2
18:00	-	0	1.000
19:00	-	60	0.997
20:00	-	120	0.997
21:00	-	180	0.996
22:00	-	240	0.995
23:00	-	300	0.991
0:00	-	360	0.986
1:00	-	420	0.979
2:00	-	480	0.963
3:00	-	540	0.958

From Table 2, it can be seen that R^2 values of the model and observed data are higher than 0.95. It indicates that both temperature distributions are similar.

3.2.2. Temperature parameters similarity

Temperature profile similarity is carried out by comparing SDR parameters of the observed data and model. Temperature parameters of the observed data are obtained from Table 1, whereas temperature parameters of the model are obtained by following step (iii) and (iv) on the model development. Comparison of temperature parameters of T_c and T_h between the model and observed data is presented in Figure 5, and S and C are compared in Figure 6. The parameter deviations between the two data are presented in Figure 7.

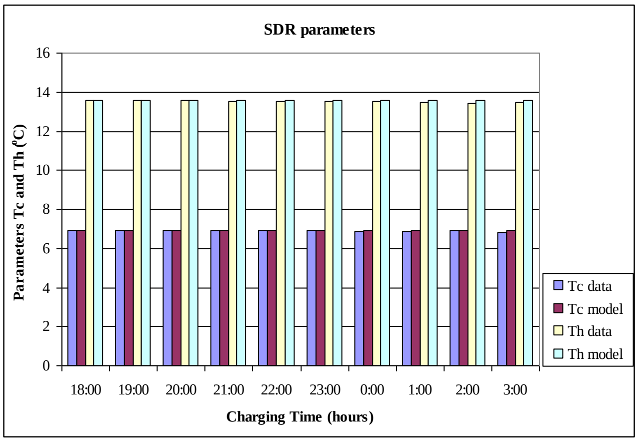

Figure 5. Comparison of parameters T_c and T_h

Referring to Figures 5 and 6, it can be seen that parameters of T_c, T_h and S have constant trends within the charging periods, whereas C increases linearly with respect to charging hours. Both observed data and model has similar of the trend. As seen in Figure 7, smaller deviation occurred in the parameter of T_c and T_h, and relatively higher in the parameters of C and S. Deviation of the parameters is found below 5%.

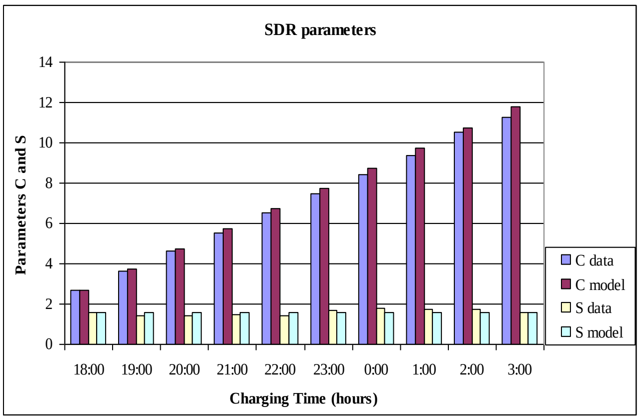

Figure 6. Comparison of parameters C and S

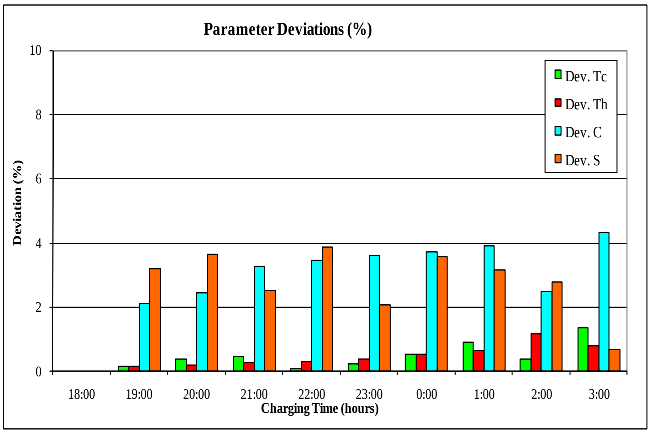

Figure 7. SDR parameters deviation

3.2.3. *Statistical test*

Statistical test is used to justify whether the observed and model are similar or not. Result of t-computed values between the two data is presented with respect to charging hours in Figure 8.

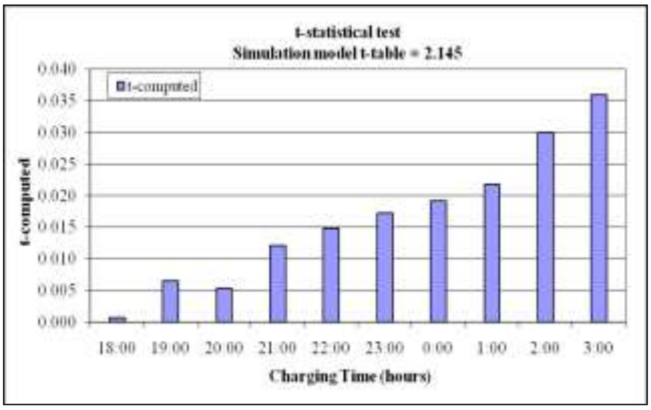

Figure 8. t-computed of verification

It can bee seen from Figure 8 that t-computed of the data are relatively small compared to t-table (= 2.145) obtained with confidence level of 95% and 14 number of data. It indicates that the null hypothesis is accepted, the two data are similar. Hence, the charging model is statistically accepted. Based on results in the three evaluations, it is noted that temperature distribution during the charging cycle a stratified TES tank has constant profile of T_c, T_h and S. It indicates that temperatures are relatively not degraded in its charging passage. This is due to initial condition exist above the lower nozzle elevation. Hence, mixing effect as the main degradation factor does not obstruct the stratification of temperature distribution.

3.2.4. Cumulative Cooling Capacity (Q_{cum})

Cumulative cooling capacity of the data is obtained from recorded data of the operating cogeneration plant, whereas in the model is calculated based on equation (6). The cumulative cooling capacity of the model is calculated using ρ = 1000 kg/m^3 and C_p = 4.12 kJ/kg.^{o}C. Comparison of cumulative cooling capacity between data and model is presented in Table 3.

Table 3. Cumulative cooling capacity

Data		**Simulation Model**			**Deviation (%)**
Charging time	Q_{cum}	Charging time	Cool Water Depth (C)	Q_{cum}	
(hours)	(kWh)	(min)	(m)	(kWh)	
18:00	11,432.3	0	3.92	11,675.2	2.08
19:00	14,092.0	60	4.92	14,557.5	3.19
20:00	16,938.5	120	5.92	17,439.9	2.87
21:00	19,704.8	180	6.92	20,322.3	3.03
22:00	22,564.5	240	7.92	23,204.8	2.76
23:00	25,477.3	300	7.92	26,087.2	2.34
0:00	28,361.1	360	8.92	28,969.5	2.12
1:00	31,126.7	420	10.92	31,850.7	2.27
2:00	34,080.1	480	11.92	34,720.9	1.84
3:00	37,061.9	540	12.92	37,483.7	1.12

From Table 3, it is shown that the cumulative cooling values of the model are approaching to that on the data. The deviation of cumulative cooling capacity is less than 3.1 %.

3.2.5. Parameters on Full Capacity

The charging duration of the data is obtained using extrapolation to have outlet water temperature equal to 7.36^{o}C. As a result, charging duration are obtained at 587.3 minutes and 580.5 minutes, for the data and model, respectively. Accordingly, cumulative cooling capacity and cool water depth at full capacity are calculated as well. The obtained parameters of full capacity are presented Table 4.

Table 4. Parameter values in full capacity of data and model

Parameters	**Data**	**Model**
Charging duration (min)	587.3	580.5
Cool water depth (m)	-	13.73
Q_{cum} (kWh)	39,377.3	38,212.0

From Table 4, it is shown that cumulative cooling capacity of the data is higher than that in the model. It is due to averaging of non linear regression fitting as a part of model processing. The other reason, since heat transfer losses to surrounding is ignored on the model. From comparison between data and model, it is noted that cumulative cooling capacity deviations are less than 3.2% and deviations of charging duration below 1.2%.

3.2.6. Half-cycle Figure of Merit ($FoM_{1/2}$)

Performance evaluation during the charging cycle is half cycle Figure of Merit which represents thermal efficiency due to conduction and mixing losses. The half-cycle Figure of Merit growth within charging period is presented in Figure 9.

The parameter $FoM_{1/2}$ is calculated using Equation (8). Referring to Figure 9, it is noted that half-cycle

Figure of merit ($FoM_{1/2}$) increases polynomial in value with increased of cool water depth during the charging cycle. $FoM_{1/2}$ during the charging periods has value of 93.06 % to 98.60 %. The increased trend of half-cycle figure of merit is understood due to the increasing of C_{Max} in the charging cycle.

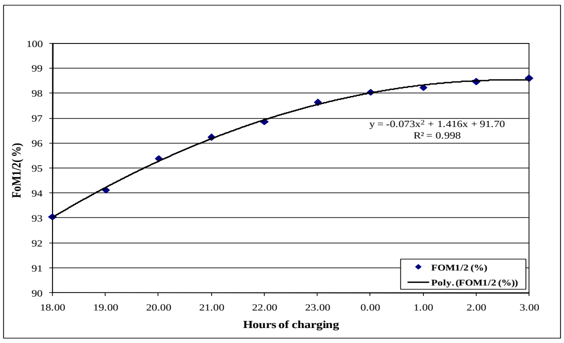

Figure 9. Growth of half-cycle of Figure of Merit ($FoM_{1/2}$)

3. Conclusion

Simulation model for charging stratified TES has been developed based on temperature distribution analysis. The model was developed using mathematical formulation so that gives advantage for determination of the parameters analytically. Validation of the model was carried out using coefficient determination and similarities temperature distribution parameter. Endorsing of the acceptance criteria of the model was carried out using statistical analysis. Validation results showed that the model has coefficient of determination more than 99.5% has SDR parameters deviation less than 5 %. On the comparison of cumulative cooling capacity and charging duration, the deviations are less than 3.2 % and 1,2 %, respectively. From statistical test, it is highlighted that the simulation model is accepted. The simulation have advantages for determination of charging parameters exactly, namely determination of cool water depth, generating of periodical temperature distribution, cumulative cooling capacity and half cycle Figure of Merit ($FoM_{1/2}$). Further simulation model is enabling for calculation of empty capacity, full capacity as well as charging duration effectively. The simulation model offers a beneficial to be utilized effectively on the design and operation of stratified thermal energy storage tank incorporated to cogeneration plant.

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