Investigation of performance parameters of building thermal battery

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Abstract. The concept of a building thermal battery refers to storing the supplied heat and releasing it the next day through radiation and convection. The introduction of building thermal battery performance has created a more convenient solution to the problems of building load estimation, control and optimization, building-grid integration, etc. Some literatures have expanded the original definition of building thermal batteries, including PV RE (photovoltaic renewable energy), HVAC and other units. Starting from the building body, this investigation studies a building energy system. With reference to the performance parameters of traditional rechargeable batteries, the corresponding performance parameters of building thermal batteries are developed. The RC model is further used to model the performance parameters of the building thermal battery respectively. Among them, the corresponding parameter values of the RC model are obtained by parameter identification. Finally, the heat storage and heat release characteristics of the building integrated energy system are obtained. It makes the application of buildings as batteries more flexible in the urban energy network.

1 Introduction

As an important part of the urban energy flow network, buildings can adjust the cooling and heating load within a certain range without affecting the thermal comfort of the human body due to the thermal storage characteristics of the envelope structure and indoor thermal mass, thereby decreasing building energy consumption [1-3]. The heat storage in buildings can be used to reduce the mismatch between the supply and demand of cold and thermal, in order to improve the energy efficiency of the building [4-6]. Therefore, the building thermal system has energy saving potential. Although the thermal storage characteristics of the building have significant advantages in model predictive control and demand response analysis, it still faces many difficulties. How to efficiently and accurately utilize the heat storage of the building body is a challenge faced.

In some existing studies, the research on the thermal mass of the whole single building is mostly qualitative. There are many studies on thermal mass, but few detailed studies combine thermal mass and air conditioning system, etc. to define and correspondingly analyze building thermal battery parameters. Panão [7] et al. explored the ‘building as battery’ (BaB) concept and presented measured and simulated performance of BaB systems. The results showed that, for apartments with high thermal mass, thermal insulation is the key driver of BaB system thermal efficiency. Tahersima [8] et al. proposed that the concept of a thermal battery refers to storing the supplied radiant heat and releasing this heat the next day through radiation and convection.

An approach was introduced to examine the idea of thermal battery in thick concrete flooring using the earth as a heat source. Starting from heat and mass, Braun [9] et al. had demonstrated significant savings potential for use of building thermal mass in commercial buildings. They also attempted to provide an assessment of the state of the art in load control using building thermal mass and to identify the steps necessary to achieve widespread application of appropriate control strategies.

This work starts from the traditional rechargeable battery performance parameters and adopts the method of thermoelectric analogy to construct the performance parameters of the thermal battery. Building thermal system is constructed based on a thermal resistance-capacitance (RC) model. Using the method of parameter identification, after obtaining the specific thermal parameter values of the building RC model, the parameter values of the building thermal battery are quantitatively calculated and analysed. The characteristic parameters of building thermal battery obtained in this study can make the application research of building model predictive control and demand response more refined and improve the matching degree of building thermal control strategy and urban energy control strategy.

2 Definitions

This section refers to the performance parameters of analogous traditional rechargeable batteries, combined with the relevant knowledge in the field of heat transfer,
to construct the parameter system of building thermal batteries. The required performance parameters of the building thermal battery analogous to the traditional rechargeable battery include [10-11]: Thermal resistance (R), Thermal capacity (C), Rated temperature difference, Rated capacity, Thermal storage and release rate, State of charge (SoC), Self thermal release rate, State of Health (SOH), Depth of discharge (DoD), Time constant.

### 2.1 Mathematical Formulation

1) **Thermal resistance (R)**

Thermal resistance represents the resistance to heat transfer. The thermal resistance of the building thermal battery is composed of the thermal resistance of all elements in the heat exchange process according to the series-parallel principle of thermal resistance.

For example, the thermal resistance between the envelop and the outdoor environment is:

$$ R_{\text{env-ext}} = \frac{1}{K_{\text{env-ext}}} \quad (1) $$

where $K_{\text{env-ext}}$ is the heat transfer coefficient between the envelope and the outdoor environment (W/K).

2) **Thermal capacity (C)**

Thermal capacity is a physical quantity that characterizes the heat storage capacity of an object. The heat capacity of a building thermal battery is the sum of the heat capacities of all elements in the building.

3) **Rated temperature difference ($\Delta T$)**

The rated voltage of a traditional rechargeable battery refers to the typical working voltage of the battery at homoeothermy. Referring to the traditional battery, the rated temperature difference of the building thermal battery refers to the difference between the theoretical optimal value of the indoor set temperature, which is the optimal temperature range for human thermal comfort.

$$ \Delta T = T_{\text{max}} - T_{\text{min}} \quad (2) $$

where $T_{\text{max}}$ is the maximum set indoor temperature (K) and $T_{\text{min}}$ is the minimum set indoor temperature (K).

4) **Rated capacity ($Q_r$)**

The rated capacity refers to the minimum capacity that the battery can release under the actual specified conditions. The rated capacity of the building thermal battery refers to the minimum energy that can raise the room temperature from the lowest temperature to the highest temperature, and all thermal storage units fully store heat.

$$ Q_r = \sum_{i=1}^{n} C_i (T_{\text{max}} - T_{\text{min}}) + \sum_{i=1}^{n} Q_{i} \quad (3) $$

where $C_i$ is the thermal capacity of the envelop and indoor thermal mass (kJ/K) and $Q_i$ is the thermal storage of other thermal storage units (Phase change heat storage, heat storage water tank) except the envelope structure and indoor heat mass (kJ).

5) **Heat storage and release time ($h$)**

The thermal storage and release rate are expressed as the thermal storage and release time, and the value is equal to the number of hours obtained by dividing the rated capacity of the building thermal energy battery by the heat storage and release heat flux density.

$$ h = \frac{Q_r}{q} \quad (4) $$

where $Q_r$ is the rated capacity (KJ) and $q$ is the heat flux (KJ/h).

6) **State of charge (SoC)**

State of charge also known as remaining power, represents after being used for a period of time or left unused for a long time the ratio of the remaining capacity of the battery to the capacity of the fully charged state.

$$ \text{SoC} = \frac{Q_{\text{re}}}{Q_{\text{max}}} \quad (5) $$

where $Q_{\text{re}}$ is the residual thermal storage (kJ), and $Q_{\text{max}}$ is the maximum thermal storage (kJ).

7) **Self-discharge rate ($\rho_{\text{loss}}$)**

Self-discharge rate refers to the rate at which the battery loses its capacity during storage. The rate of self-heating is expressed as the percentage of capacity loss due to self-heating per unit storage time to the rated capacity. The self-heating rate of a building thermal battery refers to the corresponding thermal loss due to the temperature difference between indoor and outdoor.

The test is usually performed when the heating system stops working. The energy balance equation of the building thermal battery has the same form as the traditional rechargeable battery. The method of calculating the SoC at the next moment according to the current SoC is as follows [12]:

$$ \text{SoC} + \frac{1}{Q_r} \left[ \left( \eta P_c - \frac{P_d}{\eta} \right) \Delta t - P_{\text{sun}} \Delta t \right] $$

where $\eta$ is the heat storage efficiency, $\Delta t$ is the time step (h), $P_c$ is the heat storage efficiency (kJ/h), and $P_d$ is the heat release efficiency (kJ/h).

When measuring the self-heating rate, it is necessary to turn off all "power" and the value of $P_c$, $P_d$ is 0. Finally get:

$$ P_{\text{sun}} = \frac{Q_{\text{re}} - Q_{\text{re}}'}{\Delta t} \quad (7) $$

8) **State of Health (SOH)**

SoH refers to battery capacity, health, and performance status. Simply, it is the ratio of the performance parameters to the nominal parameters after the battery has been used for a period of time. The new battery is 100%, and the complete scrap is 0%. Generally speaking, there is a certain difference in rated capacity and maximum capacity for all new batteries,
3. Thermal parameter identification and performance parameter calculation

3.1 RC modelling

When determining the performance parameters of the building thermal battery, we must first determine the type of the building model. Among all feasible models, the physically interpretable model be better, the so-called grey-box model. Another requirement for the model is that we need a linear or linearizable model with a short simulation time, because the model needs to be used for the quantification of the parameters. Therefore, thermal resistance and thermal capacitance model was selected. In this study, the structure of the model needs to be examined first to determine the best accuracy for constructing thermodynamic simulations. First-order models (where all elements in a building are concentrated at a temperature node) are not accurate enough to predict for shorter time steps [13]. The improvement of the first-order structure is the second-order structure. It uses one heat capacity to represent the heat capacity of the building structure and another to represent the heat capacity of the indoor air or internal thermal mass [14-15]. A simple 2R2C model [7] was used in this study, as shown in Fig. 1, which is concern with the internal mass and the heating system. Its complete differential-algebraic equation system is as follows. A parameter with a (*) superscript indicates that the parameter is unknown which needs to be identified.

\[
C_1' \frac{dT}{d\tau} = \frac{T_i - T_m}{R_1} + \frac{T_m - T_r}{R_2} + \phi_i
\]  

(11)

\[
C_2' \frac{dT_m}{d\tau} = \frac{T_m - T_{in}}{R_2}
\]  

(12)

where \(C_1'\) is the short-term heat capacity (time scale of minutes) that brings together the thermal responses of the air and other light elements in the room (JK\(^{-1}\)). \(C_2'\) is the long-term heat capacity (time scale of hours) that brings together the thermal response of the maintenance structures in the room and all other exposed interior masses (JK\(^{-1}\)). \(R_i\) is the total thermal resistance between the indoor air, \(T_i\), and the outdoor air, \(T_0\) (KW\(^{-1}\)) (aggregates all indoor and outdoor heat exchange due to thermal conduction and infiltration/ventilation effects). \(R_m\) is the total thermal resistance between the room air, \(T_m\), and the exposed room thermal mass, \(T_{in}\) (KW\(^{-1}\)). \(\phi_i\) is the heat source term (characterizes the convective heat source that affects the indoor air temperature node).

![Fig. 1. 2R2C representation of the building model structure.](image_url)

3.2 Parameters identification approach

After the structure of the RC model is determined, the most critical task is to determine the value of the building thermal parameters, so as to quantify the performance parameter values. Therefore, parameter identification is required to find the optimal parameter set by minimizing the objective function. That is to minimize the error between the output value of the RC model and the measurement value as the function value of the objective function Eq.(13) [16], in order to obtain the specific values of thermal resistance and thermal capacitance in Eq.(11) and Eq.(12).

\[
\theta^{opt} = \arg \min_{\phi} \left[ \int_0^{T_P} \left( \phi_{i}^{act} - \phi_{i}^{opt} \right)^2 \, d\tau \right]
\]  

(13)

where \(\phi_{i}^{act}\) is the true value obtained by measuring , \(\phi_{i}^{opt}\) is the simulated output value and \(TP\) is the training period.

Modelica, a building dynamic simulation tool, was chosen based on model complexity, reusability, simulation speed and accuracy. Models in Modelica are mathematically described by differential, algebraic, and
discrete equations with enough information to automatically determine specific variable values. The external simulation tool used Dymola for evaluating the objective function and searching for the value of the objective function in the Genopt software. Genopt is an optimization software designed to solve computationally expensive optimization problems. During the identification process, it is used to specify the trajectory according to the search algorithm and iteratively calculate new parameters. Genopt provides many optimization algorithms, here choose the PSO and HJ optimization algorithm to optimize the search for the objective function [16].

In the PSO optimization algorithm. The initial phase, the PSO optimization algorithm launches N particles and places them randomly in the search area. Each particle iteratively evaluates the objective equation using its influence parameters. And its position and step size are upgraded. In each generation, each particle can remember the best position found so far. The iteration stops after reaching the specified number of generations. The HJ optimization algorithm is a structured search algorithm. After a set of relevant parameters of an initial base point is given, the exploration steps include the positive direction and search step. After checking all parameters, a new base point is generated.

The PSO optimization algorithm sweeps the search space. It is likely to converge the objective function to an acceptable minimum value instead of the global optimal solution. The HJ optimization algorithm intervenes to closely examine the surrounding area and find the minimum value, which is the global optimal solution. Since the HJ optimization algorithm is very sensitive to the initial value, here we assume that the initial point of the PSO optimization algorithm is a good starting point.

Above optimization process can be done automatically in Genopt. The RC model is built separately in the Dymola, which can read input parameter values saved in a text file and return the simulation results to the objective function. In the process of parameter identification, according to the result of the objective function, the parameter set of the RC model is iteratively updated through the GenOpt search algorithm.

Based on the above method, reasonable parameter values can be ensured. The method of parameter identification can carry out reasonable parameter initialization search. The searched parameters are also normalized based on the initial value.

### 3.3 Performance parameter calculation

According to the building RC model in Section 3.1 and the parameter identification method given in Section 3.2, the measured data of the passive house described in the literature [7] is used as the basic data for the calculation, including outdoor temperature, indoor temperature, wall temperature, heat supply, and building area. The obtained RC model identification parameters consistent with [7] are listed in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Identified value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>$423.8$ kJ/K</td>
</tr>
<tr>
<td>$C_2$</td>
<td>$4498.8$ kJ/K</td>
</tr>
<tr>
<td>$R_1$</td>
<td>$0.02045$ K/W</td>
</tr>
<tr>
<td>$R_2$</td>
<td>$0.002378$ K/W</td>
</tr>
</tbody>
</table>

Due to space limitations, this paper only presents the results of a few simple parameters.

### I. Thermal resistance ($R$)

For the structure of the room shown in Fig. 1, the total thermal resistance of the room is treated as a series of thermal resistance $R_1$, which between the indoor air and the outdoor air and $R_2$, which between the room air exposed room thermal mass.

$$R = R_1^* + R_2^* = 0.02045 + 0.002378 = 0.022828$$ kJ/K (14)

### II. Thermal capacity ($C$)

The heat capacity of the entire room is the sum of the short-term heat capacity $C_1^*$ and the long-term heat capacity $C_2^*$.

$$C = C_1^* + C_2^* = 423.8 + 4498.8 = 4922.6$$ kJ/K (15)

### III. Rated temperature difference ($\Delta T$)

According to the research on human thermal comfort [17-20], the optimal value of indoor temperature is set as the lowest indoor set temperature, $T_{\text{min}} = 291$ K. Indoor maximum set temperature is $T_{\text{max}} = 299$ K. According to Eq.(2), the rated temperature difference of 8 K is specified.

### IV. Rated capacity ($Q_f$)

According to Eq.(3), it can be obtained that the rated capacity of the building is 39380.8 kJ when the rated temperature difference is 8 K and the indoor heat capacity is 4922.6 kJ/K.

### V. Time constant ($\tau$)

To determine of time constant is required that all power is turned off and the building thermal battery stops the charging process. It is assumed that the outdoor temperature is constant at 262 K and the initial temperature in the room is 299 K. Calculation of the RC model is carried out from hours 1 to 24 with a 60 second output interval using the Dassl solver with a tolerance of $10^{-6}$. The thermal dynamic behavior of the building is modeled using the data in Table 1. The variation of indoor temperature is shown in Figure 2.
The indoor temperature continued to drop from 0 h to 24 h and reached 63% (289.38 K) of the initial temperature of 299 K after 6.5 h, which is as the time constant. It is consistent with the actual situation.

4 Conclusions

In this work, the definition of building thermal battery performance parameters is proposed. The performance parameters of the building thermal battery corresponding to the traditional rechargeable battery, include Thermal resistance ($R$), Thermal capacity ($C$), Rated temperature difference, Rated capacity, Thermal storage and release rate, State of charge ($SoC$), Self thermal release rate, State of Health ($SOH$), Depth of discharge ($DoD$), Time constant. Through a simple RC model, several parameter values of building thermal parameter were obtained by using minimizing the error between the measured and simulated values for calculating of building thermal battery parameters. The thermal resistance of the entire building as a simple example is 0.022828 kJ/K, the thermal capacity is 4922.6 kJ/K, the rated capacity is 39380.8 kJ, and rated temperature difference is 8K, and time constant is 6.5 h. They provide basic parameters for quantitative analysis of thermal performance, flexible control, and demand response analysis of buildings.

This study integrates a complex building thermal system into a single thermal battery. Other thermal battery performance parameters and independent heat storage units will be more abundant and in-depth in future research.

References