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Study of Energy Consumption of Air Conditioning System in Container Energy Storage System

Yabo Wang[1], Changjiang Fu[1], Xueqiang Li[1], Zhongyao Zhang[1], Hailong Li[1,2*]

1 Tianjin Key Laboratory of Refrigeration Technology, Tianjin University of Commerce, Tianjin 300134, China

2 School of Sustainable Development of Society and Technology, Mälardalen University, Västerås 72123, Sweden

ABSTRACT

In this paper, the temperature mathematical model and compressor model are established to study the effect of different charge/discharge rates on air conditioning energy consumption. The results show that with the increase of the charge/discharge rate, the air conditioning starts earlier and runs longer, and the energy consumption of the air conditioning system also increases. This method considers different charge/discharge rates of batteries and combines with the energy consumption analysis of air conditioning systems, which is of great value for improving the safety and efficient utilization of energy storage systems.

Keywords: Lithium-ion battery, battery energy storage system, air conditioning system, energy consumption

NOMENCLATURE

Abbreviations	
BESS	Battery Energy Storage System
ACS	Air Conditioning System
CFD	Computational Fluid Dynamics
Symbols	
C	Capacity coefficient of air-conditioned rooms (kJ/°C)
T_n	Air temperature in air-conditioned rooms (°C)
G	Air delivery volume (kg/s)
C_p	Specific heat capacity of air (kJ/kg·°C)
T_s	Supply air temperature (°C)
q_n	Heat dissipation in air-conditioned rooms (kW)
T_w	Outdoor air temperature (°C)
r	Thermal resistance of air-conditioned room envelope (°C/kW)
T	Time constant (s)
R	Thermal resistance of air-conditioned rooms (°C/kW)
K	Amplification coefficient
T_f	Change of indoor and outdoor disturbance amount converted to supply air temperature (°C)
A	Step function
q_m	Mass flow rate (kg/s)
η_v	Volumetric efficiency
q_v	Theoretical volumetric gas delivery capacity (m^3/h)
v_1	Suction volume (m^3/kg)
λ_v	Volumetric coefficient
λ_p	Pressure coefficient
λ_T	Temperature coefficient
λ_l	Leakage coefficient
λ_h	Reflux coefficient
c	Relative clearance of air cylinder
P_k	Condensing pressure (kPa)
p_e	Evaporation pressure (kPa)
κ	Expansion process index
P	Power of compressor (W)
h_1	Inspiratory enthalpy (kJ/kg)
h_2	Exhaust enthalpy (kJ/kg)
η_{el}	Electrical efficiency
η_i	Indication efficiency
η_m	Mechanical efficiency
η_{mo}	Motor efficiency
ε	Theoretical pressure ratio
n	Multivariate process index
ε'	Actual pressure ratio
S	Air conditioning start-stop state
T_{set}	Air conditioning set temperature (°C)
δ	Difference between the critical temperature of air conditioning state switching and the set temperature (°C)

1. INTRODUCTION

With the gradual depletion of fossil energy, people are facing a serious energy crisis and environmental pollution [1], and the demand for environmental protection is increasingly urgent, new energy has been widely concerned and developed rapidly. The output power of renewable energy is affected by the natural environment, which will produce random and intermittent fluctuations [2]. Energy storage technology has a positive significance in improving the absorption capacity of new energy, regulating the peak and valley of electricity consumption, and improving the quality of electricity consumption [3,4].

Nowadays, lithium-ion battery technology provides one of the most important approaches for large-scale electricity storage. Compared with other rechargeable electrochemical batteries, lithium-ion batteries have the advantages of high energy density, high efficiency [5], long life, and low self-discharge rate [6]. However, a large amount of heat will be generated during the battery charging and discharging process. If the heat cannot be dissipated effectively, the accumulated heat in the battery system will increase the battery temperature. Once it exceeds the appropriate operating temperature range, the life and service performance of the battery will be affected. Therefore, an effective battery thermal management system is essential to regulate the operating temperature of the battery and ensure its performance, life, and safety.

Gas cooling, typically air cooling [7], is one of the most common approaches, as effective cooling can be achieved by simple equipment arranged in a constrained space. Therefore, the container energy storage system mostly adopts air cooling.

The existing literature on battery container thermal management mainly focuses on the problem of airflow distribution. Xu et al. [8] investigated the flow pattern and temperature distribution of the container-type BESS via CFD; they proposed a solution to improve the cooling performance by installing a guide plate at the flow path. The new design reduces the average temperature of the battery by 4.57 °C, and the maximum temperature difference is reduced by 3.65°C. Zhu et al. [9] proposed several optimization schemes for the air supply system, including the location and number of air intakes, and the number and angle of baffles. The results show that the airflow uniformity is better when the baffles are added at the entrance and the bottom of each riser duct than at other locations. Lin et al. [10] proposed a solution to improve the airflow distribution of the battery energy storage system. The proposed solution is a rearrangement of the layout by repositioning the air supply and return vent. After modification, the maximum temperature difference of the battery decreased from 31.2°C to 3.5°C, and the average temperature decreased from 30.5°C to 24.7°C.

Forced air cooling uses air conditioners for cooling, which can meet the heat dissipation requirements of the energy storage system and is the most commonly used heat dissipation method for container battery energy storage systems. However, there are few researches on the energy consumption of air conditioning systems during the process of thermal management. The existing articles mainly focus on energy consumption and control of building air conditioning systems. Fasiuddin et al. [11] used Visual-DOE software to simulate the energy consumption of the main design and operation parameters of different types of air conditioning systems for a commercial building, and the results showed that a maximum energy saving of 30% could be achieved by choosing the right air conditioning system and operating mode while maintaining an acceptable comfort level. Shan et al. [12] proposed an optimal intermittent operation mode that achieves both goals (energy saving and indoor thermal comfort). The results show that the power consumption of intermittent operation mode is reduced by 11% compared with traditional operation mode. Mu et al. [13] calculated the corresponding energy consumption indexes of various energy consumption systems. The results show that the air-conditioning system and lighting system are the two most energy-consuming systems in the office building.

However, the battery heat generation has the characteristics of irregular change of charge/discharge rates and long time, and the energy storage container is greatly affected by the external environment. Therefore, this paper studies the indoor temperature and the energy consumption of the air conditioning system of the energy storage container in one day under different charge/discharge rates and different ambient temperatures, to provide a reference for the efficient utilization of the energy storage system.

2. MODEL BUILDING

2.1 Mathematical model of battery cabin temperature

When establishing the mathematical model, the room temperature object is treated as a centralized parameter without considering the lag time. According to the law of energy conservation, the mathematical equation of the air-conditioned room is [14]:

$$C\frac{dT_n}{dt} = \left(GcT_s + q_n\right) - \left(GcT_n + \frac{T_n - T_w}{r}\right) \tag{1}$$

Eq. (1) can be written as:

$$\frac{C}{Gc+\frac{1}{r}}\frac{dT_n}{dt} + T_n = \frac{Gc}{Gc+\frac{1}{r}}\left(T_s + \frac{q_n + \frac{T_w}{r}}{Gc}\right) \tag{2}$$

Assumptions:

$$T = RC = \frac{1}{Gc + \frac{1}{r}} C \tag{3}$$

$$K = \frac{Gc}{Gc + \frac{1}{r}} \tag{4}$$

$$T_f = \frac{q_n + \frac{T_w}{r}}{Gc} \tag{5}$$

Then Eq. (2) can be organized as:

$$T \frac{dT_n}{dt} + T_n = K\left(T_s + T_f\right) \tag{6}$$

Eq. (6) is the differential equation of the change of the output parameter and the change of the input parameter of the air conditioning room.

Assuming that the supply air temperature is stable, Eq. (6) is a first-order linear non-homogeneous differential equation with constant coefficients, and the solution of the equation is:

$$T_n = KA\left(1 - e^{-\frac{t}{T}}\right) \tag{7}$$

The above equation shows that the temperature of the air-conditioned room varies exponentially.

2.2 Compressor model

The role of the compressor in the refrigeration system is realized by the migration of refrigerant. Therefore, for the simulation model of the compressor system, it is most important to calculate the mass flow rate through the compressor. The compressor model is as follows [15]:

$$q_m = \frac{\eta_v q_v}{v_1} \tag{8}$$

$$\eta_v = \lambda_v \lambda_p \lambda_T \lambda_l \lambda_h \tag{9}$$

Volumetric efficiency (η_v) represents the use level of cylinder working volume, which can be expressed as the product of volumetric coefficient (λ_v), pressure coefficient (λ_P), temperature coefficient (λ_T), leakage coefficient (λ_l), and reflux coefficient (λ_h). The calculation method or value range of the specific coefficient is as follows:

$$\lambda_v = 1 - c\left[\left(\frac{p_k}{p_e}\right)^{\frac{1}{\kappa}} - 1\right] \tag{10}$$

The volumetric coefficient (λ_v) represents the influence of the clearance volume. The pressure coefficient (λ_P) represents the influence of inspiratory pressure loss on gas transmission, which can be approximately equal to 1. The temperature coefficient (λ_T) is the loss of gas transmission caused by the heating of the inhaled gas, usually ranging from 0.82 to 0.95, the value decreases with increasing pressure ratio. The leakage coefficient (λ_l) is the influence of cylinder leakage, which is mostly given by the empirical value. In this paper, the value is 0.94. The reflux effect of the rotor compressor is very small, and the reflux coefficient (λ_h) can be approximately equal to 1.

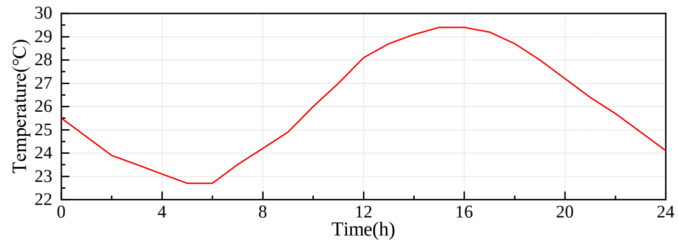

Fig. 1 Outdoor temperature

The outdoor temperature affects the condensing temperature, which is corresponding to the condensing pressure. Considering the change of outdoor temperature with time, we assume that the outdoor temperature is constant for a certain period of time, and its change curve is shown in Fig. 1.

The power of the compressor can be calculated by the ratio of the isentropic power to the electrical efficiency (η_{el}) of the compressor, and the calculation formula can be expressed as:

$$P = \frac{q_m\left(h_2 - h_1\right)}{\eta_{el}} \tag{11}$$

$$\eta_{el} = \eta_i \eta_m \eta_{mo} \tag{12}$$

The electrical efficiency (η_{el}) reflects the consummation degree of the motor input power used in the compressor and is the product of indicating efficiency (η_i), mechanical efficiency (η_m), and motor efficiency (η_{mo}).

$$\eta_i = \frac{\lambda_T \lambda_l \frac{\kappa}{\kappa - 1}\left(\varepsilon^{\frac{\kappa-1}{\kappa}} - 1\right)}{\frac{n}{n-1}\left(\varepsilon'^{\frac{n-1}{n}} - 1\right)} \tag{13}$$

Indicating efficiency (η_i) represents the magnitude of aerodynamic loss in the process of pressurizing air and heat exchange loss in the process of compression, which is calculated according to Eq. (13). The mechanical efficiency (η_m) is the size of the friction loss, which depends on the viscosity of the mixture of oil and refrigerant. It is difficult to give a specific calculation formula, and the value is 0.95 in this paper. The motor efficiency (η_{mo}) reflects the loss of motor, usually, the motor efficiency of commercial refrigeration machines is less than 0.8, and the value is 0.78 in this paper.

2.3 Two-position control law

The two-position control law is that when the indoor temperature reaches the upper limit of the controller, the compressor starts and begins to supply air to the cabin, at which time the indoor temperature begins to fall; when the indoor temperature reaches the lower limit of the controller, the compressor stops working and no longer supplies air to the cabin, at which time the indoor temperature will slowly rise.

The relationship between the compressor start-stop state and indoor temperature can be expressed as follows:

$$S = \begin{cases} 1, & T_n \geq T_{set} + \delta \\ 0, & T_n \leq T_{set} - \delta \end{cases} \quad (14)$$

3. RESULTS AND DISCUSSIONS

3.1 Effect of different charge/discharge rates on indoor temperature

Fig. 2, Fig. 3, and Fig. 4 show the change of indoor temperature at different charging and discharging rates. With the increase of charge/discharge rate, the time for the indoor temperature to rise from the lower limit (33°C) to the upper limit (35°C) gradually decreases. When the charge/discharge rate increased from 0.5C to 1C or 2C, the indoor temperature rise time decreased by 78.67 minutes and 87.21 minutes, and the phenomenon is the most obvious when 2C rate charged/discharged. On the other hand, with the increase of charge/discharge rate, the total opening time of air conditioning in a day increased. At 2C and 1C rates, the increase time is 17.77 minutes and 17.07 minutes compared with that at 0.5C.

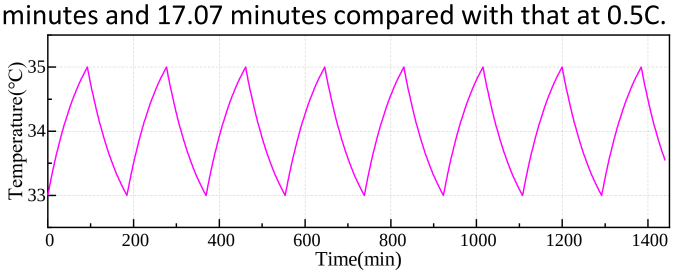

Fig. 2 Indoor temperature (0.5C)

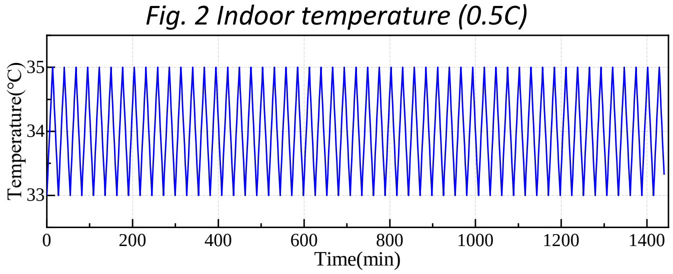

Fig. 3 Indoor temperature (1C)

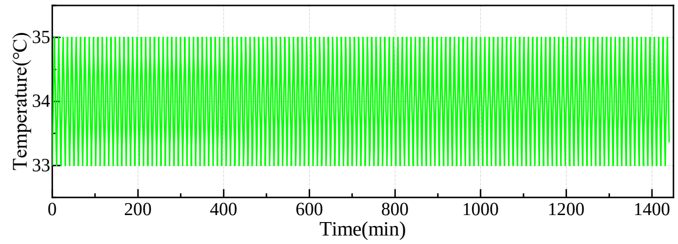

Fig. 4 Indoor temperature (2C)

Considering that the charge/discharge rate of the battery is not constant, the temperature variation of the battery in a cycle of 0.5C-1C-2C for one day is added, as shown in Fig. 5. In this case, the total opening time of the air conditioner is the shortest, which is reduced by 52.97 minutes, 70.04 minutes and 70.71 minutes compared with that at 0.5C, 1C, and 2C.

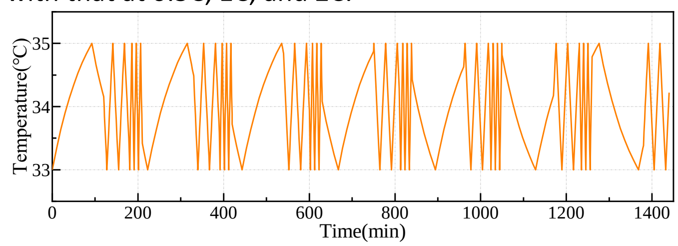

Fig. 5 Indoor temperature (0.5C-1C-2C)

3.2 Effect of different charge/discharge rates on compressor power

When the air conditioning system is running, the compressor provides power for the whole system and consumes the most electricity in the whole system. Therefore, when analyzing the energy consumption of the system, the main calculation is the power consumption of the compressor. Fig. 6, Fig. 7, Fig. 8, and Fig. 9 show the changes of compressor power at different charge/discharge rates. The results show that with the increase of the charge/discharge rate, the number of air conditioner starts increases (summarized in Table 1), which leads to an increase in compressor power consumption. In addition, the change curve is consistent with the outdoor temperature change curve, because with the increase (or decrease) of the outdoor temperature, the condensation temperature also increases (or decreases), and the power consumption of the air conditioning system increases (or decreases) accordingly.

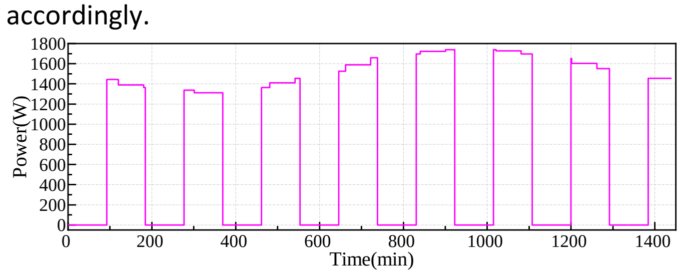

Fig. 6 Compressor power (0.5C)

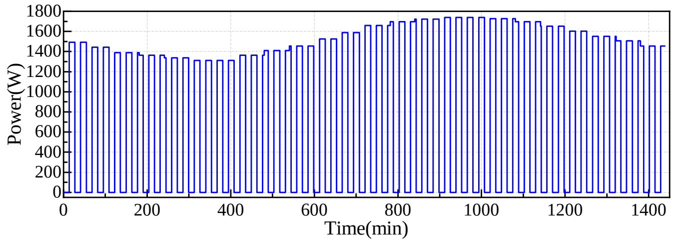

Fig. 7 Compressor power (1C)

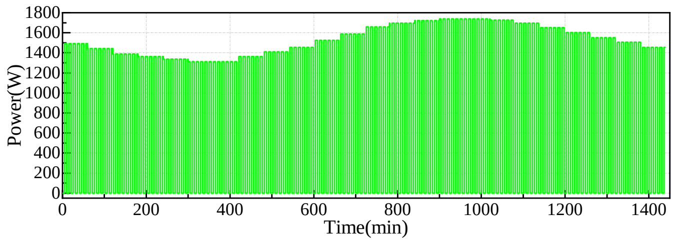

Fig. 8 Compressor power (2C)

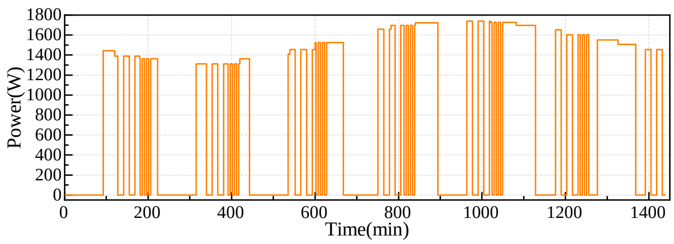

Fig. 9 Compressor power (0.5C-1C-2C)

Table 1 Number of air conditioner starts

Charge/discharge rate	Number of air conditioner starts
0.5C	7.6
1C	52.8
2C	141.8
0.5C-1C-2C	38

The results of opening time and power consumption of the air conditioning system at different charge/discharge rates are listed in Table 2. As can be seen from the table, when the cycle is 0.5C-1C-2C, the values of these two parameters are the minimum. When the charge/discharge rate increases from 0.5C to 1C and 2C, the number of air conditioning starts increases, in addition, the power consumption of the air conditioner increased by 458.32Wh and 472.67Wh, respectively.

Table 2 Opening time and power consumption

Charge/discharge rate	Opening time	Power consumption
0.5C	701.76min	17884.3Wh
1C	718.83min	18342.62Wh
2C	719.53min	18356.97Wh
0.5C-1C-2C	648.79min	16711.18Wh

4. CONCLUSION

In this paper, mathematical models of temperature and compressor are established respectively to study the indoor temperature and compressor power consumption. The power consumption of the compressor is closely related to indoor and outdoor temperatures. With the increase of the battery charge/discharge rate, the start time of the air conditioner is advanced, so that more power is consumed in a day, the main findings are as follows:

(1) Due to the control policy, the air conditioner is turned off when the indoor temperature does not reach the upper limit. Under the condition of low rate charge and discharge at 0.5C, the opening time of the air conditioning system is reduced by 17.77 minutes compared with 2C. Therefore, the operation mode with smaller charge/discharge rate should be adopted to reduce the opening time of the air conditioner.

(2) The charge/discharge rate affects the power consumption of the compressor. The air conditioning power consumption at 0.5C-1C-2C cycle operation is the smallest, reducing 1173.12Wh, 1631.44Wh, 1645.79Wh than at 0.5C, 1C, and 2C rates. Therefore, the optimal charge/discharge rate should be found to reduce the power consumption of the air conditioning system.

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