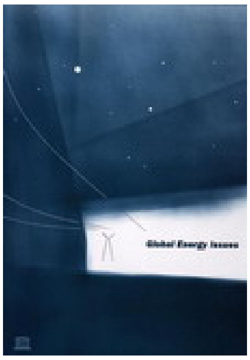

International Journal of Global Energy Issues

ISSN online: 1741-5128 - ISSN print: 0954-7118
https://www.inderscience.com/ijgei

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Yuanhua Li

DOI: 10.1504/IJGEI.2023.10051073

Article History:

Received:	01 July 2021
Accepted:	29 September 2021
Published online:	13 December 2022

Study on load estimation method of HVAC system in large public gymnasium

Yuanhua Li

College of Physical Education,
Central South University of Forestry and Technology,
Changsha 410004, China
Email: yuanhua@mls.sinanet.com

Abstract: This paper proposes a load estimation method for HVAC system of large public gymnasium. The operation data of HVAC system in large public gymnasium are collected and processed by principal component analysis. According to the data processed, this paper analyses the influencing factors of HVAC system, constructs the linear regression estimation model of system load, and optimises the objective function of load estimation by using genetic algorithm to obtain the optimal solution. Experiments show that the method has strong robustness good adaptability to the model parameters, high fitting degree between the load estimation results and the actual values, and the maximum running time is less than 12.8 s. It can complete the load estimation efficiently and has good performance in practical application.

Keywords: HVAC system; load; linear regression model; model parameters; estimate.

Reference to this paper should be made as follows: Li, Y. (2023) 'Study on load estimation method of HVAC system in large public gymnasium', *Int. J. Global Energy Issues*, Vol. 45, No. 1, pp.14–25.

Biographical notes: Yuanhua Li received his Master in physical education from Hunan Normal University in 2010. Currently he is a lecturer in the College of Physical Education of Central South University of Forestry and Technology. His research interests include volleyball training, sports training.

1 Introduction

Because of the rapid development of social and economic level, large public gymnasiums and other buildings have huge energy consumption, which has become an important research content of environmental protection (Dubey, 2020). Due to the large internal building space of large public gymnasiums, the indoor temperature changes significantly (Harmath, 2020). In order to maintain a more suitable temperature environment, the HVAC system needs to operate continuously. Therefore, the HVAC system accounts for a large proportion of building energy consumption, and the load research and energy saving of HVAC system are widely concerned by the society (Cho et al., 2018). However, the energy consumption of air conditioning in public buildings is increasing year by year, accompanied by the contradiction between supply and demand in the daytime, resulting in serious energy waste (Wang et al., 2020). In order to solve this problem, it is necessary to estimate the load of HVAC system, so as to seek optimal control measures, reduce the load of HVAC system on the premise of ensuring the stability of indoor temperature, and solve the contradiction between supply and demand in the daytime, reduce the energy consumption of large public gymnasiums, better protect the ecological environment (Li et al., 2019).

In Li et al. (2018), the deformation method is used for downscaling, and the short-term, medium-term and long-term hourly meteorological data of typical meteorological years are obtained. Taking office, residential, hotel and store buildings as simulation objects, the HVAC system loads of different buildings are predicted. The results show that the climate change caused by global warming will reduce the energy use of winter heating. In summer, refrigeration is used more, and load is the main basis to guide the air-conditioning equipment. This method is not detailed enough for the load forecasting process of HVAC system, resulting in inaccurate parameter calculation results. Singh et al. (2020) point out that heating, ventilation and air conditioning loads contribute most of the energy consumed by buildings. But the effect of this method is not good. Therefore, this paper uses integrated learning method to treat the load model as a black box. The historical meteorological data is used as input to model the load of HVAC system, this paper can better predict the dynamic information of HVAC load, but it takes a long time to run. In Kim et al. (2018), a control method of terminal unit based on load forecasting model is introduced. HVAC system is used to predict the indoor environment. The dynamic simulation program trnsys17 is used to compare with the traditional control method in indoor and energy consumption. Experiments show that this method can effectively reduce the energy consumption of air conditioning system, but the calculation accuracy is not high.

Due to the slow speed and low accuracy of traditional load estimation model for HVAC system of large public gymnasiums, this paper introduces genetic algorithm to design a new load estimation method for HVAC system of large public gymnasiums:

1. Improving the processing effect of load estimation parameters of the air-conditioning system in large public gymnasiums, the operation data of HVAC system in large public gymnasiums are collected, so as to solve the problems of low accuracy, poor fitting and long time-consuming of load estimation effect of HVAC system.

2. To improve the accuracy of air conditioning system load estimation, linear regression model is used to estimate the load and reduce the complexity of model construction. Genetic algorithm is used to optimise the objective function of load estimation to obtain the optimal solution. In order to complete the research on load estimation method of HVAC system in large public gymnasium

3. The accuracy, fitting degree and time-consuming of load estimation of air-conditioning system are taken as experimental comparison indexes, and the proposed method is compared with Li et al. (2018), Singh et al. (2020) and Kim et al. (2018).

2 Research on load estimation method of HVAC system in large public gymnasium

2.1 Data pre-processing of air conditioning system operation

Due to the diverse data types of HVAC system, significant differences between different data and different dimensions (Li and Siegel, 2020), it is easy to slow down the network convergence speed or unable to converge in the calculation and analysis of these data fusion, so it is necessary to pre-process the data (Santos et al., 2020). In this paper, the data of HVAC system completed by principal component analysis is pre-processed to eliminate the data dimension, improve the unity and effectiveness of data operation, accelerate the network convergence speed, and better complete the problem analysis (Park et al., 2020). Generally, there is a certain linear correlation between HVAC data (Santoso et al., 2020), so the linear function normalisation method is used here to process the data, and the formula is as follows:

$$y = \frac{x - x_{min}}{x_{max} - x_{min}} \tag{1}$$

In the above formula, x_{min} and x_{max} represent the minimum and maximum values of a certain the data is concentrated on the HVAC data set.

The normalised data is dimensionless, but it can't reflect the real state of the original data, so it needs to be denormalised.

$$z = y_{min} + (y_{max} - y_{min})\ y \tag{2}$$

In the above formula, z is the data after inverse normalisation.

2.2 Data acquisition of air conditioning system operation

This study firstly collects and pre-processes the operating data of HVAC system in large public gymnasium to provide basic data support for load estimation of HVAC system. Water flow and temperature sensors are installed on the pipes of HVAC system equipment to monitor and collect the water flow and temperature of the air conditioner in real time with a collection interval of half a minute. The energy consumption on different supply branches can be calculated conveniently through data collection (Al-Falahi et al., 2020).

The sensor data acquisition choose to cologne, Germany brand flow sensor (Huang et al., 2018), Honeywell brand of temperature sensor, using the data obtained from the sensors including large public stadium indoor and outdoor temperature, humidity, air conditioning air conditioning compressor power consumption, and air conditioning water supply temperature, etc., various types of data, the characteristics of each different (Ning and Zaheeruddin, 2019). Therefore, in order to efficiently utilise the collected HVAC system data, the principal component analysis method is adopted to analyse the data, and fewer variables are used to explain the main problems, so as to improve the data processing efficiency of HVAC system.

Select a set of data from the data collected and recorded as samples. Set to $\left(x_1, x_2, ..., x_n\right)$, among $x_1 = \left(x_{i1}, x_{i2}, ..., x_{in}\right)$. From this, an observation matrix of sample data is formed. Note it as follows X:

$$X = \begin{bmatrix} x_{11} & x_{12} \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} \cdots & x_{nm} \end{bmatrix} \tag{3}$$

In the above formula, the x represents a data model sample .the rows of the observation matrix represent the types of data, and the columns represent the data collected according to time series.

The observation matrix is standardised to form a new matrix (Piselli et al., 2020), which is described as follows.

$$F_{ij} = \frac{X}{n-1} \sum_{i=1}^{n} \sum_{j=1}^{n} \left(x_i - \overline{x}\right)\left(x_j - \overline{x}\right) \tag{4}$$

$$E_{ij} = \frac{F_{ij}}{\sqrt{F_{ii}}\sqrt{F_{jj}}} \tag{5}$$

In the formula, F_{ij} represents a prediction argument variable, E_{ij} is the correlation coefficient matrix, and $\overline{x}$ is the data mean value.

The data eigenvalue of the above covariance matrix is calculated to solve the principal component data of the HVAC system operation. Constructing a new data set based on the principal component means that the principal component analysis of the HVAC system data is completed, and the newly determined variables can be used for subsequent data calculation operations.

Through the above process, the data pre-processing and data acquisition of air conditioning system operation are completed, the overall quality of HVAC system load estimation in large public gymnasiums is improved, and the foundation is laid for the effective realisation of HVAC system load estimation function based on genetic algorithm.

3 Load estimation function of HVAC system based on genetic algorithm

The load estimation model of HVAC system in large public gymnasium is a linear regression model. Solving the model is the key to improve the performance of the model. The least square method is a common parameter identification method (Gianluca et al., 2018). However, the parameters calculated by this method are not accurate enough. In order to improve the accuracy of the load estimation model, the innovation is to optimise the load estimation objective function by using genetic algorithm, so as to obtain the optimal solution. With the advantages of fast search speed, easy operation and less parameter adjustment of genetic algorithm, the algorithm performance is fully improved, and the optimal solution of HVAC load estimation model is calculated (Toub et al., 2019; Hu and Nutaro, 2020). The load model parameters are calculated based on the improved least square method, as follows:

Assuming that the HVAC load is d and the set of influencing factors of HVAC load is $A_i(i=1,2,\ldots,\ n)$, the HVAC load can be expressed as:

$$d = \alpha_0 + \alpha_1 A_1 + \alpha_2 A_2 + \ldots + \alpha_n A_n \tag{6}$$

In the above formula, $\alpha_0, \alpha_1, \ldots, \alpha_n$ represents the model parameters, which can be combined to form the model related parameter matrix α:

$$\alpha = \begin{bmatrix} \alpha_0 \\ \alpha_1 \\ \vdots \\ \alpha_n \end{bmatrix} \tag{7}$$

Based on the set of factors affecting the air conditioning load and the relevant parameter matrix of the load model, the overall load matrix D of HVAC is constructed:

$$D = \alpha \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{bmatrix} = A \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_n \end{bmatrix} \tag{8}$$

In the above formula, A represents the influence factor matrix of the load model. Based on this, the linear regression estimation model D^1 of HVAC system load can be established:

$$D^1 = A \times \alpha \tag{9}$$

Taking the pre-processed data z as the air conditioning object data, the least square method is used to estimate the parameter $\alpha_0, \alpha_1, \ldots, \alpha_n$ of the load estimation model, expressed as $\hat{\alpha}_0, \hat{\alpha}_1, \ldots, \hat{\alpha}_n$. According to the least square estimation of the data, the error between the observed value and the estimated value can be calculated:

$$e = z_i - \hat{z}_i \tag{10}$$

In the above formula, $\hat{z}$ can be called the estimated value of the observed value, and its expression formula is as follows:

$$\hat{z}_i = \hat{\alpha}_0 + \hat{\alpha}_1 x_{i1} + \hat{\alpha}_2 x_{i2} + \ldots + \hat{\alpha}_n x_{in} \tag{11}$$

Calculate the least square sum of the deviations of the observed and estimated values H

$$H = \sum_{i=1}^{n} \left(z_i - \left(\hat{\alpha}_0 + \hat{\alpha}_1 x_{i1} + \hat{\alpha}_2 x_{i2} + \ldots + \hat{\alpha}_n x_{in} \right) \right) \tag{12}$$

According to the basic algorithm requirements of the least square method and the calculation formula of the least square sum of deviations, it is known that the optimal solution can be obtained only when the model parameters meet the following conditions, and the equations that should be satisfied are as follows:

$$\begin{cases} \dfrac{\partial H}{\partial \hat{\alpha}_0} = \sum_{i=1}^{n} \left(z_i - \hat{z}_i \right)^2 = 0 \\ \qquad \vdots \\ \dfrac{\partial H}{\partial \hat{\alpha}_n} = \sum_{i=1}^{n} \left(z_i - \hat{z}_i \right)^2 = 0 \end{cases} \tag{13}$$

Under the condition that the model parameters meet the above equations, the adaptive weight coefficient formula is adopted to make it move continuously with the change of the target function value. The weight estimate method is as follows:

$$\text{s} = \begin{cases} s_{min} - \dfrac{f\left(s_{max} - s_{min}\right)}{f - f_{min}}, f \le f_{avg} \\ s_{max}, f > f_{avg} \end{cases} \tag{14}$$

In the above formula, s_{max} and s_{min} represent the maximum and minimum of the weight respectively, f represent the genetic objective function; f_{avg} and f_{min} represent the average and minimum of the objective function respectively.

Combined with the parameters satisfying the conditions and the calculated weights, assuming that the parameter matrix is of full rank, the estimation matrix $\hat{\alpha}$ can be simplified as:

$$\hat{\alpha} = \frac{s}{\left(z^T z\right)} \tag{15}$$

The optimal solution of the final HVAC load estimation model is obtained:

$$D\left(x\right) = D^1 \hat{\alpha} \tag{16}$$

Based on the above analysis, the load estimation of HVAC system in large public gymnasium is completed.

The above content realises the theoretical research of HVAC load estimation based on genetic algorithm. The practical application effect of the algorithm needs to be further verified by experiments.

4 Simulation experiment analysis

To test the actual application performance proposed load estimation method for HVAC system of large public gymnasium, a simulation experiment is carried out.

4.1 Experimental scheme

Taking a large public gymnasium as the research object, this experiment uses computer simulation technology to simulate, compare and verify the data of gymnasium HVAC system. The stadium has 3000 seats and two floors. The plan is cyclical. It can host table tennis, basketball, volleyball and other sports events. In winter, the temperature of gymnasium is about 20°C and the humidity is about 30°C.

According to the relevant literature and research results, the influencing factors of HVAC are mainly divided into internal factors and external factors. Internal factors include personnel, equipment, etc. there are many kinds of external factors with strong dynamic variability. Through principal component analysis, the main external factors are finally selected as the model parameters, including air temperature, humidity, wind speed and solar radiation.

4.2 Experimental data and indicators

Experimental simulation environment: this experiment is configured with 3.2 ghz CPU, using Intel i7-6700 CPU, windows 10 version of the computer operating system, based on the programming language Python 3.6, running analysis in the experimental platform MATLAB.

Experimental data: collect the field data of the HVAC system operation of the large public gymnasium from January to June 2020, the recording time is from 8:00 a.m. to 20:00 p.m., and the data sampling interval is set to 1 min.

Experimental scheme: Based on the set simulation environment and the collected data, the parameter fitness of load estimation model, the fitting degree of load estimation results and the time-consuming of load estimation are set to test comparison and method in this paper is compared with Kim et al. (2018) and Al-Falahi et al. (2020).

1 Parameter fitness of load estimation model: the more obvious the iterative change effect of the model, the more accurate the parameter value can be found, the better the parameter fitness of the model, indicating that the parameter calculation results are more accurate.

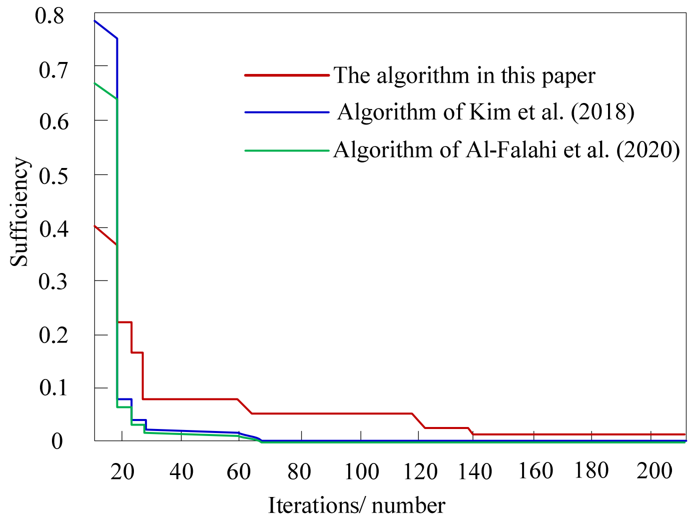
2 Fitting degree of load estimation results: the fitting degree is an index to verify the consistency between the calculation results of the algorithm and the actual results. The higher the fitting degree is, the more accurate the calculation results of the algorithm are.

3 Time consuming of load estimation: time consuming is an efficient index reflecting the performance of the algorithm. If the time consuming is too long, the algorithm will lose its practical application value. In this way, the less time it takes, the better this method is implemented.

4.3 Parameter fitness of load estimation model

To verify the effect of identifying model parameters, these methods are compared with Kim et al. (2018) and Al-Falahi et al. (2020) by taking the fitness of parameters as the index.

Figure 1 Comparative analysis of parameter fitness



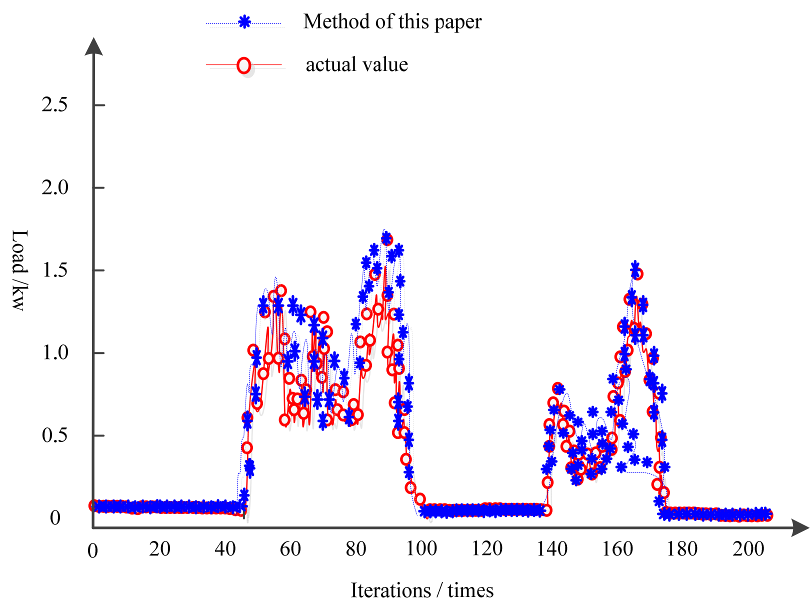
By analysing the model parameter fitness curves of different methods in Figure 1, it can be seen that the iterative effect of the proposed method is obvious. In the whole operation process of the algorithm, the proposed method is in constant iterative change, which is also in the calculation process of constantly seeking the optimal solution. However, after more than 60 iterations, Kim et al. (2018) and Al-Falahi et al. (2020) no longer have obvious iterative change, it can be seen that the parameters of the load estimation model of HVAC system in this paper have good fitness. This is because this paper identifies the parameters based on the improved algorithm to avoid the algorithm falling into the problem of local optimisation, thus improving the fitness of the model parameters.

4.4 Fitting degree of load estimation results

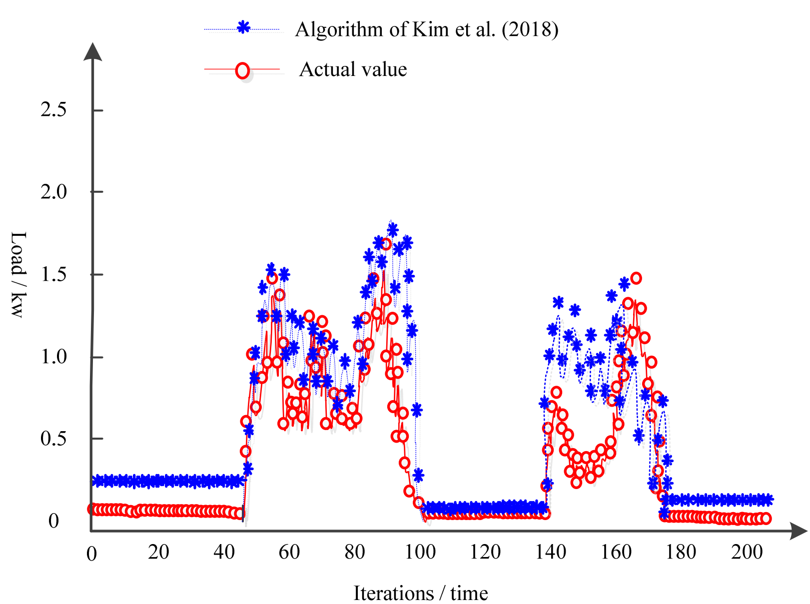
The applicability and practical application performance of the method are verified, the closer the estimated value is to the actual value, the higher the accuracy of the algorithm is, and the better the practical application performance is. Therefore, taking the fitting degree of load estimation results as the index, this paper compares and analyses the method with Kim et al. (2018) and Al-Falahi et al. (2020), and the comparison results are as shown in Figure 2.

According to Figure 2, the load estimation results are compared, although the air-conditioning load calculated by Kim et al. (2018) and Al-Falahi et al. (2020) is close to the actual value, there are still some differences. However, the estimated value calculated by this method is basically consistent with the actual load, with a high degree of coincidence. It shows that this method has good load forecasting ability of HVAC system and strong generalisation ability, and can be applied to the practical application and control management of HVAC system, which provides a good database for the research of reducing energy consumption and carbon emission of HVAC system.

Figure 2 Comparison of fitness of load estimation results

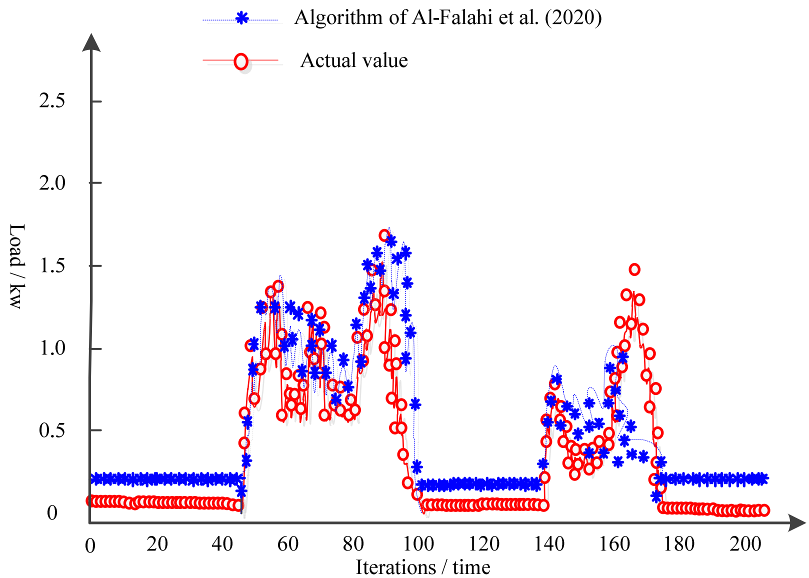


(a) Method of this paper



(b) Method of Kim et al. (2018)

Figure 2 Comparison of fitness of load estimation results (continued)



(c) Method of Al-Falahi et al. (2020)

4.5 Load estimation time

To further verify the advantages of this method, compare the cost of the calculation method with Kim et al. (2018) and Al-Falahi et al. (2020).

The comparison results of the three methods are shown in Table 1.

Table 1 Operation time-consumption comparison

Iterations/times	*Run time/s*		
	Method of this paper	*Method of Kim et al. (2018)*	*Method of Al-Falahi et al. (2020)*
20	9.3	23.5	19.4
40	9.6	23.6	19.7
60	9.9	23.6	19.8
80	10.0	25.0	20.6
100	10.3	25.6	22.3
120	10.5	25.9	22.5
140	11.0	26.3	23.6
160	11.2	26.5	23.8
180	12.5	27.0	24.0
200	12.8	27.1	24.3

From Table 1, with the increase of iteration times, different algorithms show the characteristics of increasing the operation time with the increase of iteration times. According to the comparison data of operation time, its computation time is always slower than other literature methods. In the 200 iterations, the maximum time-consuming of HVAC load estimation is 12.8 s, the maximum time of Kim et al. (2018) is 27.1 s, and the maximum time of Al-Falahi et al. (2020) is 24.3 s, which shows the advantages of short running time of this algorithm. This shows that this method can quickly complete the load estimation of HVAC system in large public gymnasiums, the practical application is good.

5 Conclusion

In order to improve the accuracy of HVAC system load estimation results and reduce operation time, a HVAC system load estimation method for large public gymnasiums is proposed. Its innovation is that it is convenient to calculate the energy consumption on different supply branches through data acquisition. The performance of the proposed method is analysed and verified theoretically and experimentally. The analysis results show that the proposed method has a good effect on the calculation of model parameters, and the load estimation results of the proposed method are basically consistent with the actual values, and the maximum operation time is no more than 12.8 s. Compared with the traditional method, it has significant advantages, which fully shows the effectiveness of the proposed method and can be applied to the actual HVAC system analysis. However, there are still some deficiencies in this study. In the next research, we will consider introducing more intelligent and advanced technical means to explore the law of air conditioning load change, and constantly improve the load estimation method, so as to provide more effective support for HVAC related research and application.

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