

Construction of Joint Simulation Platform and Model Identification for Water Storage Air Conditioning System



Yong-Shun Wang^{1*}, Dong Wei¹, Kun Liu¹

¹ Department of Electrical and Information Engineering, Beijing University of Civil Engineering and Architecture
13051392873@163.com

² Beijing Key Laboratory of Intelligent Processing for Building Big Data

Received 13 January 2019; Revised 6 March 2019; Accepted 12 March 2019

Abstract. The predictive model is a main topic in the modeling predictive control(MPC) of the HVAC control field. According to Shenzhen Guoying building, the water storage air conditioning system was studied and modeled. This paper proposes a modeling method that combines the TRNSYS and MATLAB to model the water storage air conditioning system. The MPC method demonstrates good performance on the control of the water storage air conditioning system. And the MPC method requires a predictive model of the controlled object. So this paper focuses on the modeling of the water storage air conditioning system. A joint simulation platform of TRNSYS and MATLAB is built. Using rapid development function of TRNSYS build the models of the water tank and plate heat exchangers. The model of the water storage air conditioning system is identified by using artificial neural networks and the collected operation data through the joint simulation platform. Simulation results show that the prediction model match well the test data. The model identified has high accuracy and strong generalization ability.

Keywords: artificial neural networks, joint simulation platform, plate heat exchanger, predictive model, TRNSYS, water storage air conditioning system

1 Introduction

As the economy grows, society's demand for energy is also increasing, and social power consumption is on the rise. In particular, air conditioning power adds a lot of load to the grid. The water storage air conditioning technology emerged from the development of the times and scientific and technological progress [1]. Its promotion and application play a role in reducing the peak-valley imbalance of the grid and meeting the needs of social development. Wei Dong and Liu Kun [2] obtained that the MPC method demonstrates good performance on the control of the water storage air conditioning system, while the MPC method requires a precise predictive model of the controlled object. We applied TRNSYS and MATLAB to build a joint simulation platform, and used artificial neural networks to identify the model of water storage air conditioning system.

2 Co-simulation Platform Construction

This paper mainly uses the air conditioning system module library provided by TRNSYS and the water tank and plate heat exchanger module developed by TRNSYS development module. The water storage system based on TRNSYS and MATLAB is constructed. The air conditioning system joint simulation platform lays the foundation for the analysis and research of subsequent modeling data acquisition and control strategies as demonstrated [3].

* Corresponding Author

2.1 MATLAB and TRNSYS Co-simulation

Nicholas De Forest [4] points out that TRNSYS can connect the .m file with Type155 module, which makes TRNSYS and MATLAB connect smoothly. TRNSYS can be used for transient simulation of the system, where most air conditioning system equipment can be found and operated. In order to realize the simulation test of the whole system, this paper comprehensively considers the advantages of the two softwares, and creates a co-simulation platform. In this paper, the rapid development function of the module provided by TRNSYS is used to create the sink and plate heat exchanger module, and the predictive control algorithm is written into MATLAB and called by TRNSYS to jointly complete the control system simulation.

2.2 Mathematical Model of Water Storage Equipment

The water tank in the research project located in the cooling station on the third floor of the building. TRNSYS failed to cover the dynamic module of the sink [5]. Although the software contains a plate heat exchanger module, the module is non-dynamic [6]. In order to be able to perform predictive control simulation experiments, it is necessary to establish dynamic modules for both. Firstly, based on the mathematical mechanism of the water tank and the plate heat exchanger, the mathematical dynamic model is established, and the dynamic module of the water tank and the plate heat exchanger is prepared by the module development function of the TRNSYS.

2.2.1 Water Storage Equipment Tank Modeling

This paper uses a temperature-stratified cold storage tank. The water inside the water tank flows along the axial direction. The tank can be layered, with the upper layer being the warm water layer (12 °C) and the lower layer being the cold water layer (4 °C). 11 temperature sensors are evenly arranged along the vertical height of the water tank to measure the water temperature in the water tank; the water tank is a part of the closed hydraulic circuit, and the quality of the cold water flowing out is equal to the quality of the warm water flowing into the water tank.

The internal temperature of the water tank is set to Z_a , and the cold water height is set to Z_b . The height of the cold water and hot water in the water tank, $Z_a + Z_b$ is a fixed value, which is equal to the height of the water tank Z_{tank} . The average temperature of the upper layer of warm water inside the water tank is set to T_a , and the average temperature of the lower layer of cold water is set to T_b . There are two working conditions for the water tank, namely cold storage conditions and cold storage conditions. When the cold is released, the following dynamic model of the sink can be established.

$$\dot{H}_a = (\dot{m}_c - \dot{m}_{CHWS}) C_p T_{cmp,r} \quad (1)$$

$$\dot{H}_b = (\dot{m}_{CHWS} - \dot{m}_{cmp,s}) C_p T_b \quad (2)$$

$$T_{CHWR} = T_{cmp,r} \quad (3)$$

$$T_{cmp,s} = \frac{T_{CHWS} \dot{m}_{CHWS} - T_b (\dot{m}_{CHWS} - \dot{m}_{cmp,s})}{\dot{m}_{cmp,s}} \quad (4)$$

$$\dot{z}_b = \frac{(\dot{m}_{CHWS} - \dot{m}_{cmp,s}) / \rho}{\pi r_{tank}^2}, \dot{z}_a + \dot{z}_b = 0 \quad (5)$$

$$\dot{U}_a = \dot{H}_a + \dot{Q}_{b>a} + \dot{Q}_{Amb>a} \quad (6)$$

$$\dot{U}_b = \dot{H}_b + \dot{Q}_{a>b} + \dot{Q}_{Amb>b}$$

$$\begin{aligned} U_a &= m_a C_p T_a \\ U_b &= m_b C_p T_b \end{aligned} \quad (7)$$

$$\begin{aligned} \dot{Q}_{Amb>a} &= (T_{amb} - T_a)(2\pi r_{tank} z_a) k_1 \\ \dot{Q}_{a>b} &= (T_a - T_b)(\pi r_{tank}) k_2 \end{aligned} \quad (8)$$

Where the flow rate of the cold machine is \dot{m}_{CHWS} , \dot{m}_{emps} is the flow rate supplied to the cold end of the plate heat exchanger, H_a and H_b are the flow rate of the enthalpy of the warm water and the cold water respectively. C_p is the specific heat capacity of the water. $T_{cmp,s}$ and $T_{cmp,r}$ are the water temperature providing to the plate heat exchanger and the return water respectively. ρ is the density of the water. r_{tank} the radius of the water tank. U_a and U_b are the internal energy of the warm water and the cold water in the water tank, respectively. $\dot{Q}_{Amb>a}$ and $\dot{Q}_{Amb>b}$ are the heat transferred to the warm water and the cold water in the ambient temperature. $\dot{Q}_{a>b}$ is the heat transferred to the cold water in the warm water in the water tank. $\dot{Q}_{b>a}$ is the heat transferred to the warm water in the cold water in the water tank. k_1 and k_2 are the thermal conductivity.

2.2.2 Plate Heat Exchanger Modeling

The plate heat exchanger in the project is a heat exchange device for the cold water supplied by the water tank and the chilled water return water of the air conditioning system. This work about predictive control of water storage air conditioning system focuses on stabilizing the hot end outlet temperature of the plate heat exchanger at 5.5 °C, and adjusting the cold end flow of the plate heat exchanger to achieve the purpose of controlling the hot end flow. The author of [7] proposed that the inlet of the hot end of the plate heat exchanger is disposed on the same side as the outlet of the cold end, and the outlet of the cold end and the outlet of the hot end are disposed on the other side. A countercurrent plate heat exchanger is used in this project. Fig. 1 shows the direction of energy transfer inside the plate heat exchanger. The energy transfer process consists of six parameters, a mass flow rate of the hot end \dot{m}_h , the inlet temperatures T_{hi} , The outlet temperatures T_{ho} , a mass flow rate of the cold end \dot{m}_c , the inlet temperature T_{ci} and the outlet temperature T_{co} .

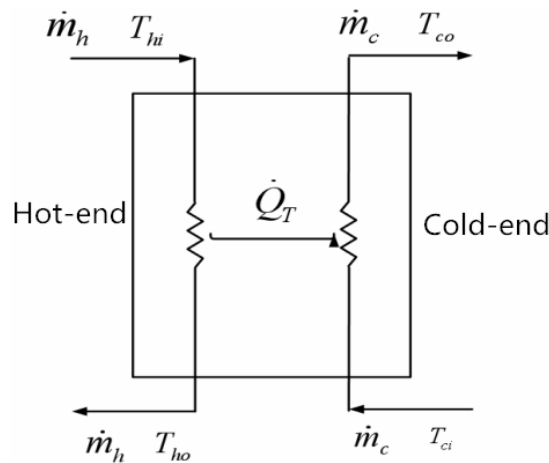


Fig. 1. Schematic diagram of energy transfer of plate heat exchanger

The total heat exchange area of the plate heat exchanger is expressed as A , and the heat exchange efficiency is U , which can obtain

$$\frac{1}{U(t)} = a + \frac{C}{[\dot{m}_h(t)]^b} \quad (9)$$

$$\dot{m}_c C (T_{ci} - T_{co}(t)) + AU(t) \left\{ \frac{T_{hi} - T_{co}(t)}{2} + \frac{T_{ho}(t) - T_{ci}}{2} \right\} = \frac{M_c C dT_{co}(t)}{dt} \quad (10)$$

$$\dot{m}_h C (T_{hi} - T_{ho}(t)) + AU(t) \left\{ \frac{T_{hi} - T_{co}(t)}{2} + \frac{T_{ho}(t) - T_{ci}}{2} \right\} = M_c C \frac{dT_{co}(t)}{dt} \quad (11)$$

$$\dot{m}_h \dot{Q}_T = AU(t) \left\{ \frac{T_{hi} - T_{co}(t)}{2} + \frac{T_{ho}(t) - T_{ci}}{2} \right\} \quad (12)$$

Where C is the specific heat capacity J (kg °C) of water, and the above formula can be discretized:

$$\frac{1}{U_k} = a + \frac{C}{[m_{h(k-1)}]^b} \quad (13)$$

$$m_{ck} C_p (T_{cik} - T_{co(k-1)}) + AU_{(k-1)} \left\{ \frac{T_{hik} - T_{co(k-1)}}{2} + \frac{T_{ho(k-1)} - T_{cik}}{2} \right\} = M_c C_p (T_{cok} - T_{co(k-1)}) \quad (14)$$

$$m_{hk} C_p (T_{hik} - T_{ho(k-1)}) + AU_{(k-1)} \left\{ \frac{T_{hik} - T_{co(k-1)}}{2} + \frac{T_{ho(k-1)} - T_{cik}}{2} \right\} = M_c C_p (T_{cok} - T_{co(k-1)}) \quad (15)$$

$$\dot{m}_h \dot{Q}_T = AU(t) \left\{ \frac{T_{hi} - T_{co}(t)}{2} + \frac{T_{ho}(t) - T_{ci}}{2} \right\} \quad (16)$$

When it is in the k -th sampling period, it can indicate the outlet temperature of its cold end and hot end

$$T_{cok} = \frac{T_{co(k-1)} + \left\{ m_{ck} C_p [T_{ci(k-1)} - T_{ho(k-1)}] + AU_{(k-1)} \right\}}{M_c C_p} \quad (17)$$

$$T_{hok} = \frac{T_{ho(k-1)} + \left\{ m_{hk} C_p [T_{hi(k-1)} - T_{co(k-1)}] + AU_{(k-1)} \right\}}{M_h C_p} \quad (18)$$

Adjusting the cold end inlet flow rate \dot{m}_c and the hot end inlet flow rate \dot{m}_h , the temperature of the cold end and hot end outlet will also change dynamically. The chiller operates in a constant temperature differential flow mode (this paper requires the temperature difference between the cold end and the hot end to be 8°C). When the cold and hot end flow of the plate heat exchanger is changed, the outlet temperature will also change. And the hot and cold ends will affect each other, so that the flow rate can be changed by changing the flow rate.

This paper requires that the cold-end outlet temperature of the plate heat exchanger be controlled at 12°C, and the hot-end outlet temperature should be controlled at 5.5 °C.

2.3 TRNSYS Sink Module Development

The module parameters that have been developed in TRNSYS are divide into three categories, input parameters, output parameters, and characteristics parameters of the module. The sink model can be expressed as

$$X_k = f(u, X_{(k-1)})$$

Where X_k is the state variable of the current time of the sink; $X_{(k-1)}$ is the state variable of last moment; u is the control variable of the sink, that is, the outlet flow of the sink per unit time.

The program is written in TRNSYS using the mathematical dynamic model of the sink. After determining the input, output and characteristic parameters of the sink, the mathematical model of the sink is written in the VF6.0, and the newly developed module program is saved in the TRNSYS root directory, after which the newly created sink module can be called by the TRNSYS module database.

2.4 Construction of MATLAB and TRNSYS Co-simulation Platform

By using the air conditioning equipment model and the new water tank and plate heat exchanger modules in TRNSYS 17, the equipment module can be connected and parameterized to build a simulation platform for the water storage air conditioning system. On this basis, the predictive control algorithm written in MATLAB is called to optimize the equipment operating parameters in real time.

According to the actual project equipment, the double-working mainframe and plate heat exchanger are connected in series on the TRNSYS platform. When the load changes, the outlet temperature of the plate heat exchanger is controlled to 5.5 °C under the premise of meeting the load requirements. The inlet temperature of hot end of the plate heat exchanger is constant at 13.5 °C. The inlet flow rate of the hot end changes according to the load. The cold end inlet of the plate heat exchanger and cold water outlet of the sink are connected together, so that we can master the valve opening to adjust flow rate to control the output of cooling capacity.

3 Predictive Model Identification

The rolling optimization in the predictive control algorithm is to perform the optimization calculation using the error between the prediction model output and its set value [8]. Therefore, Wei Dong in [9] draw the conclusion that establishing an accurate prediction model is the key to predictive control. The neural network method is used to establish the prediction model of the water storage air conditioning system. The operation data collected by the joint simulation platform is used to train the neural network to construct the prediction model of the water storage air conditioning system.

3.1 Neural Network Parameter Selection

The cold end outlet (inlet) of the plate heat exchanger is connected to the return pipe (outlet) of the water tank. For simplicity, we assume: (1) The cold end outlet flow rate and temperature of the plate heat exchanger are the same as the inlet flow rate and temperature of the water tank; (2) the inlet flow rate and temperature of the cold end are the same as the outlet flow rate and temperature of the water tank. The chiller works under the condition of constant temperature difference and flow change. When the flow rate at both ends of the model changes, the outlet temperature at both ends will change, and the cold and hot ends are coupled to each other. The cold junction outlet temperature of the plate heat exchanger is required to be controlled at 12 °C, and the hot end outlet temperature is controlled at 5.5 °C.

In summary, it can be determined that the input parameters of the prediction model include cold end inlet flow \dot{m}_c , hot end inlet flow \dot{m}_h , cold end inlet temperature T_{ci} , current hot end outlet temperature T_{ho} , and current time load Q . The neural network structure of the water storage cooling air conditioning system prediction model is shown in Fig. 2.

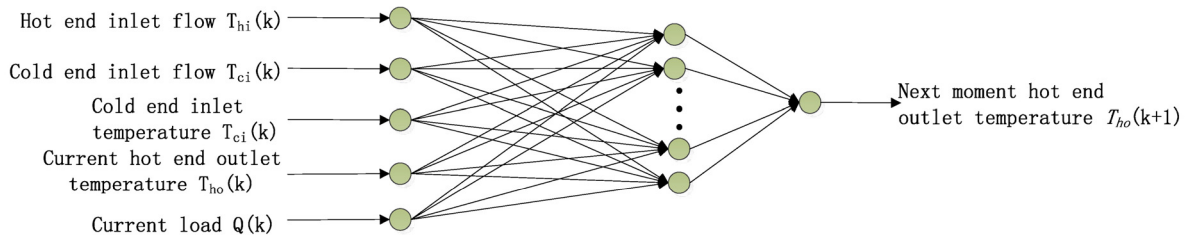


Fig. 2. Neural network structure of water storage cooling air conditioning system prediction model

3.2 Sample Data Collection

This section uses the co-simulation platform to collect the system operation data, and obtain the state-output sample data. According to the data of sample input and output, the neural network is trained to find the nonlinear mapping relationship between the input and output data, and save it in the form of weights and thresholds.

The data sampling scheme for the platform is as follows: There are 8760 hours in a year. The data is collected in the air conditioning summer cooling season, which is between 3624 and 5088 hours in one year. The running simulation step of the data acquisition model is 1s. The data acquisition module of TRNSYS is used to collect samples of system operation data, and the data acquisition time interval is 10 min.

3.3 Analysis of Prediction Model Identification Results

Predictive models are identified in the MATLAB environment. The corresponding changes of each parameter in the experiment process are shown in Fig. 3. The gradient parameter curve represents the gradient change of the error surface, and μ represents the range of the weight error adjustment; The different values of the μ represent different learning styles, namely Newton's learning method and gradient learning method. At the same time, μ are also used as judgment variables. When $\mu > \mu_{max}$, the training is stopped.

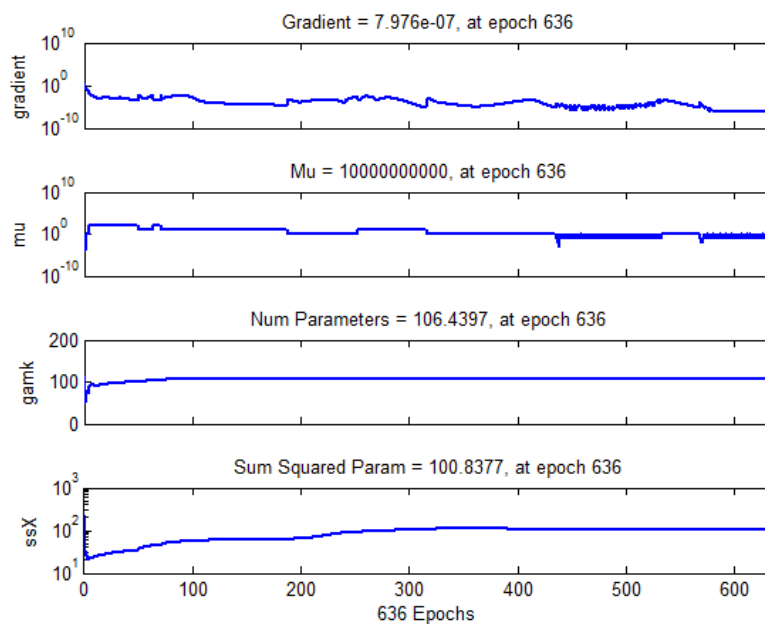


Fig. 3. The change of parameters in the prediction model of water storage and cooling air conditioning system

We divide the sample data into two parts. The sample data in the first 700 groups is used for neural network training, and the remaining 700 sets of sample data are used to test and verify the trained prediction models. When testing the prediction model, the model test output error curve shown in Fig. 4

is obtained. The abscissa is the 700 sample data for this test, and the ordinate indicates the error value between the test and target output. As Fig. 5 shown, the output error data is mostly distributed between -0.04 and 0.05. This error range is within an acceptable range for practical engineering. From the perspective of identification error, the model identified has high precision when it is used to reflect the nonlinear relationship of input-output sample data pairs.

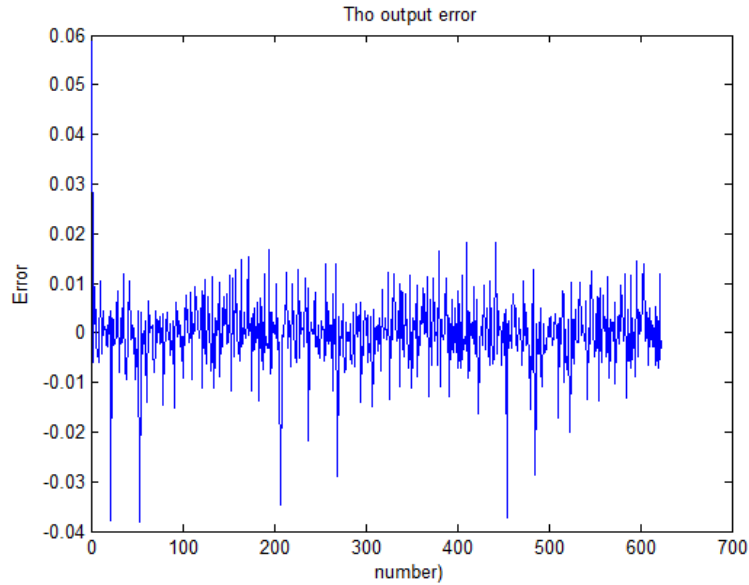


Fig. 4. The results error of the test samples

Fig. 5 is a graph showing the relationship between the model output and the target output. It can be seen that the linear correlation between the model output and the target output is $R=0.9953$, and the linear correlation is high, which indicates that the recognition effect is good. The prediction model can better fit the nonlinear relationship between the hot end outlet temperature of the plate heat exchanger and related influencing factors.

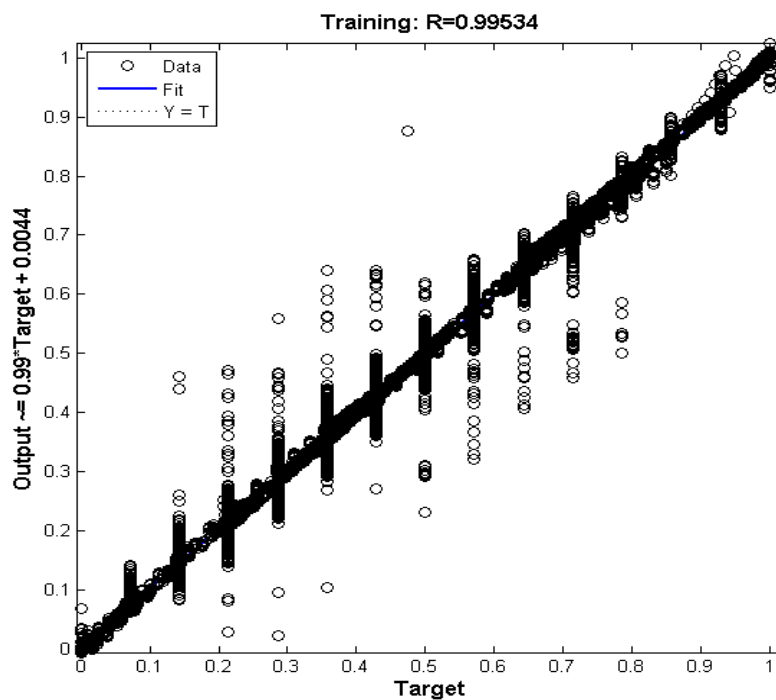


Fig. 5. Network output and expected linear regression graph of water storage cooling air conditioning system

The water storage air conditioning system modeling method of this paper is simple, avoiding the tedious mathematical derivation. Only by inputting 5 parameters, the relationship between the hot end outlet temperature of plate heat exchanger and influencing factors can be found with higher precision. The model can be used for predictive control strategy research.

4 Conclusions

In this paper, the sink and plate heat exchanger modules are built using TRNSYS, and a joint simulation platform is built. The BP neural network was used to identify the water storage air conditioning system and analyze the results. The linear correlation between the output of the established neural network prediction model and the output of the controlled object reaches 0.9953. Therefore, the prediction model has higher accuracy and higher generalization ability.

References

- [1] M. Molina-Solana, M. Ros, M D. Ruiz, Data science for building energy management: a review, *Renewable & Sustainable Energy Reviews* 70(2017) 598-609.
- [2] D. Wei, K. Liu, Model predictive control of a large temperature difference refrigerating station with ice cold thermal energy storage, in: *Proc. China Automation Conference & Intelligent Manufacturing International Conference*, 2017.
- [3] E. Asadi, M.G.D. Silva, C.H. Antunes, A multi-objective optimization model for building retrofit strategies using TRNSYS simulations, *GenOpt and MATLAB. Building & Environment* 56(10)(2012) 370-378.
- [4] D.F. Nicholas, M. Goncalo, S. Michael, Optimal deployment of thermal energy storage under diverse economic and climate conditions. *Applied Energy* 119(2014) 488-496.
- [5] M Maasoumy, M. Razmara, M. Shahbakhti, Handling model uncertainty in model predictive control for energy efficient buildings, *Energy & Buildings* 77(7)(2014) 377-392.
- [6] L. Magnier, F. Haghighat, Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and Artificial Neural Network, *Building & Environment* 45(3)(2010) 739-746.
- [7] L. Seneviratne, Potential of cool thermal storage for an air conditioning system in a records repository building, [dissertation] Diyagama, Sri Lanka: University of Moratuwa, 2015.
- [8] A. Afram, F. Janabi-Sharifi, A.S. Fung, Artificial neural network (ANN) based model predictive control (MPC) and optimization of HVAC systems: a state of the art review and case study of a residential HVAC system, *Energy & Buildings* 141(2017) 96-113.
- [9] D. Wei, K. Liu, Study of an algorithm to predict future building cooling load with neural networks, *Journal of Computers* 28(6)(2018) 57-268.