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Parameter Sensitivity Analysis of Energy Bus System for Office Buildings

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ABSTRACT

Integrating a variety of renewable energy and waste heat resources, the district energy bus system (EBS) has become a core infrastructure for realizing building heating and cooling in the context of the current low-carbon energy transition. This paper focused on office buildings in hot summer and cold winter areas of China, and developed parameter sensitivity research based on correlation analysis and regression analysis with selected parameters. The results show that the sensitivities are different among the input and output parameters. In general, based on correlation analysis and regression analysis, surface water temperature, outlet temperature of surface water coils are the variables with the highest correlation degree with the output parameters. In addition, the cooling load has a higher correlation with the output parameters than the heating load. The results of this paper can be used for parameter selection in system optimization to help confirm the priority of parameters and reduce the uncertainty of model input and output parameters.

Keywords: Energy Bus System (EBS), 5GDHC, office buildings, parameter sensitivity analysis

NONMENCLATURE

Abbreviations	
CT	Cooling Tower
EBS	Energy Bus System
iGDHC	i-th Generation District Heating and Cooling System
OE	EBS for Office Buildings
SWC	Surface Water Coil
SW	Surface Water
WB	Air Wet Bulb
Symbols	
$\dot{m}$	Water Flow Rate
Q	Load
T	Temperature
W	Energy Consumption

1. INTRODUCTION

1.1 Energy Bus System

In order to meet the energy demand in buildings, district energy systems have emerged. Compared with the traditional energy system, the district heating and cooling (DHC) system combines various energy sources to improve the energy system efficiency, so as to achieve the purpose of energy conservation and emission reduction, and meet the requirements of low-carbon transformation of the energy system.

So far, the DHC system has developed to the fifth generation, which is basically defined as[1]: the fifth generation district heating and cooling system (5GDHC) is a cooling and heating energy system with water or brine as the working medium, the temperature of the medium transported in the pipe network is close to the ambient temperature, making the working medium unsuitable to input directly to users. A thermal station with a distributed water source heat pump can be set up at the user side to further increase the heating temperature or reduce the cooling temperature, and provide heat according to different demands. This definition was proposed in Europe in 2017. In China, the corresponding energy bus system (EBS) was proposed by Long Weiding, Fan Rui and others of Tongji University.

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Several EBS projects have been implemented or operated in Europe, such as Heerlen city energy system in the Netherlands[2], Leuven city energy system in Belgium[3], and energy systems in Germany and Switzerland[4]. The EBS provides cooling and heating at the same time, and the cold water and warm water loops flow in both directions, which greatly promotes the process of low-carbon and smart energy networks.

Marwan Abugabbara et al. illustrated that Modelica language and the Functional Mock-up Interface standard are computational tools opted by the International Energy Agency for simulating building and community energy systems, and analyzed the current status in literature where these tools are utilized in building and energy simulation with focus on district heating and cooling systems. Wang, Fan et al. conducted energy analysis and exergy analysis of EBS according to the first and second laws of thermodynamics, so as to obtain a method to determine the optimal supply temperature[5,6], and established an EBS based on the integration of soil source and surface water source based on shallow geothermal energy utilization in TRNSYS. Liu et al. conducted research on the form of transmission and distribution pipelines in EBS, including the applicability， advantages and disadvantages of different forms of pipe network such as source-load relative position, single-source/multi-source, branch/ring, and single/double-pipe[7].Zhou established a multi-source and multi-sink EBS on the Modelica for residential buildings, compared and analyzed the energy consumption and hydraulic characteristics of the system in terms of the form of the pipe network, the number and location of the sources, and the arrangement of the pumps, and analyzed the economy, energy saving and environmental protection of the EBS[8].

1.2 Aim of the work

In this paper, the sensitivity of EBS parameters was studied. Firstly, taking the office buildings in hot summer and cold winter areas of China as the research object, the EBS model was established based on Modelica. Then the system performance was analyzed, and the typical system operating conditions were extracted. After the simulation data of typical working conditions were obtained, the parameter sensitivity was quantitatively analyzed based on correlation analysis and regression analysis. The input parameters and output parameters were selected according to the characteristics of the system and analyzed based on SPSS software. With the flow rate and outlet temperature of surface water coils and cooling tower, river water temperature, air wet bulb temperature, cooling load and heating load as input parameters, and the average temperature of supply/return water network, heat pump COP, system COP and total energy consumption of system as output parameters, the influence of each parameter was studied, and the optimal parameter results were compared and analyzed.

2. MATERIAL AND METHODS

2.1 Model framework

Due to the low energy consumption, high reliability and flexibility of the multi-source ring-connected system, a dual-source ring-shaped EBS was established. As shown in the figure below, the cooling tower and the surface water coils were selected, and the four office buildings were symmetrically distributed on both sides of the source. A single-stage pump system on the source side was adopted, and the flow rate of each source can be set according to the total load of the users. The operation of the system adopted constant temperature difference and variable flow rate control. The temperature difference between the inlet and outlet of the demand and the source side was set to 5°C, and the flow rate was determined by the cooling and heating load.

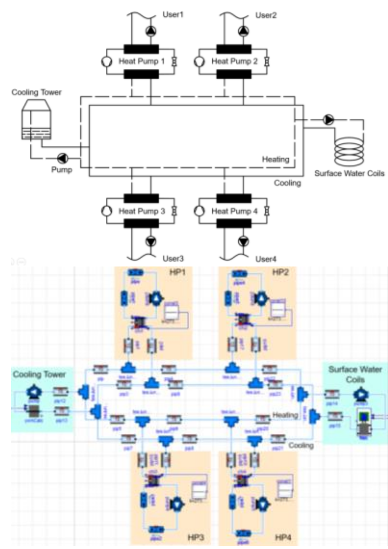

Fig. 1 Schema and simulation model of EBS for office buildings

In the preliminary design, 60% of the cooling load was handled by the surface water coils. In this EBS, DN32 spiral coil with the average heat transfer per unit tube length of 59.35 W/m and the heat transfer coefficient of 105.6 $W/(m^2\cdot°C)$ was selected. The total design flow rate of surface water coils was 90 m^3/h. The cooling tower undertook the remaining 40% of the cooling load of the system, which was about 344 kW. The counterflow closed cooling tower with a rated flow of 100 m^3/h and a rated fan power of 4 kW was selected.

According to the maximum cooling load in July, the screw heat pump was selected. The rated cooling capacity of a single unit is 216.6kW, and the rated COP is 5.4. The specific design parameters are shown in Table 1.

Tab. 1 Data of heat pump for EBS of office buildings

Parameter		Value	
COP		5.4	
Cooling capacity	kW	216.6	
Input power	kW	40.1	
Chilled water flow rate	l/s	8.5	
Cooling water flow rate	l/s	10.0	
Operating conditions	°C	chilled water	12/7
		cooling water	25/30
Pressure loss	kPa	chilled water	31.8
		cooling water	71.9

2.2 Model operation strategy

For the source-side operation strategy of cooling tower and surface water coils system for cooling demand in summer, the start-stop control of the source and the setting of the optimal operating temperature are mostly used. The control strategies mainly include temperature setting strategy, temperature difference setting strategy and opening time control strategy. In the system using the opening time control method, the cooling tower is mostly opened at night when the outdoor temperature is low. However, since the objects of this study were office buildings, it is not necessary to turn on the energy sources for cooling demand at night, so the operation strategy of opening time control was not considered.

For the scheme in which the surface water coils were the main cooling sources, set values of the outlet water temperature of the surface water coils were: 22°C, 23°C, 24°C, 25°C, and 26°C. When the outlet water temperature exceeded the set value, the cooling tower was turned on for supplementary cooling. In order to avoid frequent start-stop of the sources, a temperature threshold of ±2°C was determined. In the temperature difference setting scheme, the difference between the outlet water temperature of the surface water coils and the wet bulb temperature of the cooling tower is set to 1°C, 2°C, 3°C, 4°C, and 5°C.When the temperature difference is greater than the set value, the cooling tower was turned on, and the temperature threshold of ±2°C was determined. In the same way, for the scheme in which the cooling tower was the main cold source, the outlet water temperature of the cooling tower was set to 25°C, 26°C, 27°C, 28°C, and 29°C, with a temperature threshold of ±2°C. In the temperature difference setting scheme, the temperature difference between the outlet water temperature of the cooling tower and the water temperature on the surface water coils was set to 1°C, 2°C, 3°C, 4°C, and 5°C, and set a temperature threshold of ±2°C. The setting conditions of each scheme are shown in table 2:

Tab. 2 Source-side operation strategy scheme of EBS for office buildings

OE-i	main source	auxiliary source	strategy	set value/°C
OE-1	SW	CT	T_{max}	22
OE-2	SW	CT	T_{max}	23
OE-3	SW	CT	T_{max}	24
OE-4	SW	CT	T_{max}	25
OE-5	SW	CT	T_{max}	26
OE-6	SW	CT	ΔT	1
OE-7	SW	CT	ΔT	2
OE-8	SW	CT	ΔT	3
OE-9	SW	CT	ΔT	4
OE-10	SW	CT	ΔT	5
OE-11	CT	SW	T_{max}	25
OE-12	CT	SW	T_{max}	26
OE-13	CT	SW	T_{max}	27
OE-14	CT	SW	T_{max}	28
OE-15	CT	SW	T_{max}	29
OE-16	CT	SW	ΔT	1
OE-17	CT	SW	ΔT	2
OE-18	CT	SW	ΔT	3
OE-19	CT	SW	ΔT	4
OE-20	CT	SW	ΔT	5

2.3 Parameter sensitivity analysis

2.3.1 Correlation analysis

Correlation analysis can characterize the correlation between variables to judge whether the variables are correlated and the degree of correlation between variables. Pearson coefficient was selected in this paper to calculate variable correlation. The formula is as follows:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (1)$$

The value interval of r is [-1,1], r>0 represents positive correlation, r<0 represents negative correlation, r=0 represents no linear correlation, and |r|=1 represents complete linear correlation.

2.3.2 Regression analysis

Correlation analysis represents the strength of the linear relationship between variables, but it isn't able to show the sensitivity of the change of one quantity to the change of another quantity. So linear regression analysis was used to supplement. Regression analysis can fit the regression line of input parameters and output parameters, and the line slope can reflect the contribution of input parameters to the output results. If there is only one input variable, unary linear regression analysis can be used. However, the form of energy system is complex and often involves multiple variables, so multiple linear regression models can be utilized for analysis. The model can be expressed in equation (2), in which the regression coefficient of input variable a_n represents the importance of this variable. Since the input variable unit is different, the data need to be normalized before being introduced into the model.

$$Y = a_0 + a_1X_1 + a_2X_2 + \cdots + a_nX_n + \xi \quad (2)$$

3. RESULTS AND DISCUSSION

3.1 Analysis of operating characteristics of EBS in office buildings

The optimal working conditions in each control scheme were selected, and the performance of these four working conditions was summarized in Table 3. The heat transfer efficiency in the table is defined as:

$$\eta = \frac{T_{si} - T_{so}}{T_{si} - T_e} \quad (3)$$

where, T_{si} is inlet water temperature of source; T_{so} is outlet water temperature of source; T_e is air wet bulb temperature for cooling towers, and water inlet temperature for surface water coils.

Tab. 3 Comparative analysis of performance under optimal conditions of four schemes

		OE-1/2	OE-6	OE-11	OE-16
source side performance	$T_{O,SW}$/°C	25.272	26.384	24.437	24.431
	$T_{O,CT}$ /°C	26.997	26.344	28.628	28.615
	η_{SW}	0.740	0.647	0.862	0.862
	η_{CT}	0.719	0.692	0.597	0.597
	Q_{SW}/kWh	-95678 (*61.6%*)	-127572 (*79.9%*)	-74697 (*43.2%*)	-74779 (*43.3%*)
	Q_{CT}/kWh	-59723 (*38.4%*)	-32061 (*20.1%*)	-98309 (*56.8%*)	-98006 (*56.7%*)
	t_{open_aux}/h	207	101	206	207
pipe network performance	T_{aver_supply}/°C	30.937	31.565	31.930	31.910
	T_{aver_return}/°C	25.881	26.546	27.090	27.072
load side performance	T_{supply_HP1}/°C	26.610	26.725	28.700	28.681
	T_{supply_HP2}/°C	25.350	26.478	25.248	25.227
	COP_{max_HP1}	6.034	5.978	5.562	5.716
	COP_{max_HP2}	6.051	6.013	6.086	6.137
	COP_{aver_HP1}	5.040	5.015	4.579	4.584
	COP_{aver_HP2}	5.401	5.107	5.409	5.416
system performance	W_{pump}/kWh	5596	6436	5506	5505
	W_{fan}/kWh	828	404	828	828
	W_{HP}/kWh	26377	27252	27781	27759
	W_{total}/kWh	32801	34092	34116	34092
	COP_{max_system}	4.791	4.757	4.649	4.719
	COP_{aver_system}	4.187	4.055	4.031	4.035

Compared with OE-6, the outlet temperature of surface water coils in OE-2 was lower, and the outlet water temperature of the cooling tower was higher, but the heat exchange efficiency of the two cold sources was higher than that of OE-6. Compared with temperature control, the heat exchange of surface water coils under temperature difference control improved significantly, the working time of cooling tower reduced to 101h, and the proportion of source side output was only 20.1%, which was much lower than that of temperature control. So, the temperature control method was more reasonable when the main cooling source was used.

In working conditions OE-11 and OE-16, the output ratio of the source side basically maintained at 4:6, and the outlet water temperature of the surface water coils was 4°C lower than that of the cooling tower, resulting in a much higher heat exchange efficiency in the surface water coils than that of the cooling tower. The temperature of the heating pipes and the cooling pipes under the temperature difference control strategy was slightly lower than that of the temperature control. The heat pump COP and the system COP of OE-16 were slightly higher than those of OE-11, indicating that the temperature difference control effect was better when the cooling tower was the main cold source.

Comparing OE-2 and OE-11, it can be seen that the heat exchange efficiency when the cooling tower was the auxiliary cooling source was significantly higher than that when the cooling tower was used as the main cooling source. Similarly, the heat exchange efficiency of the surface water coils as the auxiliary cooling source was also higher than that of the main cooling source.

Based on the above analysis, the cooling method with the surface water coils as the main source and the cooling tower as the auxiliary source combined with the temperature control of 23 °C as the set value was the optimal working condition in this research. Compared with other working conditions, the two cooling sources in this optimal working condition were well utilized, and the heat exchange efficiency was high. After the source-side outlet water was merged into the pipe network, the average temperature of the cooling network was low, resulting in high COP of the heat pump on the user side, high system COP, and low system energy consumption.

3.2 Data sensitivity analysis of EBS of office buildings

3.2.1 Correlation analysis

SPSS was used for correlation analysis. Correlations between the average temperature of the supply/return water pipe network, the COP of the heat pump and the COP of the system, the total energy consumption of the system and the heat exchange of the two sources and input parameters were shown in Figure 2.

	T_{aver_supply}	T_{aver_return}	COP_{HP}	COP_{system}	W_{total}
$\dot{m}_{SW}$	0.819	0.811	0.768	0.765	0.886
$\dot{m}_{CT}$	0.747	0.720	0.676	0.657	0.803
$T_{O,SW}$	0.964	0.958	0.867	0.892	0.720
$T_{O,CT}$	0.942	0.928	0.820	0.843	0.700
T_{SW}	0.956	0.951	0.857	0.881	0.657
T_{WB}	0.911	0.897	0.792	0.819	0.644
Q_H	-0.369	-0.323	-0.233	-0.207	0.131
Q_c	0.858	0.850	0.815	0.816	0.870

-1 1

Fig. 2 Operation data correlation coefficient of EBS in office buildings

According to the analysis results, the input parameters with the strongest linear correlation of the average temperature of water supply network, average temperature of return water network, heat pump COP and system COP were the outlet temperature of surface water coils and cooling tower, water inlet temperature and air wet bulb temperature, followed by cooling load and source flow, and the correlation degree of heating load was low. For the total energy consumption of the system, the variable with the highest correlation was cooling load, surface water coils and cooling tower flow, the four temperature input variables also have a certain correlation, and the correlation of heat load was still the lowest. By analyzing the heat transfer correlation coefficients of the two sources, it can be seen that the most relevant input parameter was cooling load.

From the perspective of input variables, input parameters except for the heating load had a strong linear correlation with output variables. However, since the annual load was dominated by cooling load, the correlation between heating load and output variables was weak. Among all the output parameters, the cooling tower heat transfer was the most correlated with the flow of the two sources, and the water supply and return pipe network temperature were the most correlated with the four temperature input parameters of surface water coils and cooling tower outlet temperature, water inlet temperature and air wet bulb temperature.

3.2.2 Regression analysis

Based on the multiple linear regression theory, the parametric regression model was established and the results are shown in Figure 3.

	T_{aver_supply}	T_{aver_return}	COP_{HP}	COP_{system}	W_{total}
$\dot{m}_{SW}$	1.604	2.597	-1.086	-1.313	-30.390
$\dot{m}_{CT}$	-1.608	-6.466	-1.757	-1.918	5.020
$T_{O,SW}$	1.681	-18.259	-13.788	-11.219	285.210
$T_{O,CT}$	9.108	14.256	-0.626	-0.092	11.620
T_{SW}	1.767	21.092	12.842	10.623	-249.960
T_{WB}	-6.798	-10.349	0.500	0.246	-5.000
Q_H	-0.299	0.562	0.594	0.725	30.520
Q_c	-0.297	7.024	5.952	5.766	39.180

MIN MAX

Fig. 3 Data regression coefficient of EBS in office buildings

According to the analysis results, the regression coefficient can directly represent the contribution degree of each input parameter to the output result since the input parameters have been normalized. Cooling tower outlet temperature had the highest regression coefficient for water supply network temperature, while surface water coils outlet temperature was the most sensitive for heat pump COP and system COP. In general, the output parameters were relatively sensitive to surface water coils outlet temperature, and the sensitivity to cooling load was higher than that of heating load.

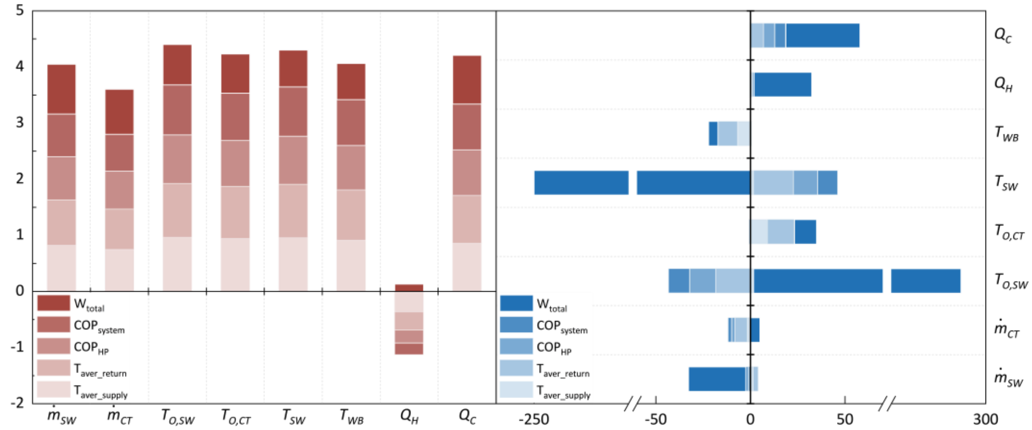

Fig. 4 Sensitivity analysis Comparison of EBS in office buildings

As can be seen from Figure 4, by comparing the above correlation analysis results, it can be seen that the conclusions reached by the two methods were not completely consistent, and comprehensive analysis was required when considering the input parameters.

4. CONCLUSIONS

In this paper, the parameter sensitivity was analyzed quantitatively based on correlation analysis and regression analysis. The input parameters and output parameters were selected according to the characteristics of the system and analyzed based on SPSS software. Then, the optimal parameter results were compared and analyzed. The following conclusions were obtained:

(1) In this case, the cooling method with the surface water coils as the main source and the cooling tower as the auxiliary source combined with the temperature control of 23 °C as the set value is the optimal working condition.

(2) Based on correlation analysis and regression analysis, outlet temperature of surface water coils and surface water temperature are the variables with the highest correlation degree with the output parameters.

(3) The cooling load has a higher correlation with the output parameters than the heating load.

In conclusion, sensitivity analysis can obtain the sensitivity of the output parameters to different input parameters, which can be used for parameter selection in system optimization analysis. With the help of sensitivity analysis, input variables with greater uncertainty can be utilized to help confirm the importance of data collection in subsequent studies and reduce the uncertainty of models.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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