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A Thermoelectric Coupling Dynamic Energy Consumption Model of Data Center in MATLAB/SIMULINK Environment

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ABSTRACT

Energy consumption model is the key for energy demand reduction in data center, but existing models are usually static, which cannot well represent the dynamic coupling characteristics of energy consumption in each component and fluid change. To address this issue, this paper constructs a dynamic energy consumption model (named the DECM) to simulate the energy consumption dynamic process in MATLAB/Simulink platform. The DECM mainly includes two energy-consumption components of data center, namely information technology (IT) equipment and cooling equipment. For the IT equipment, a polynomial based general modeling method is proposed by fitting real data from the SPECpower_ssj2008 benchmark, so as to improve the modeling accuracy in data center. For the cooling equipment, a dynamic model consisted of server fan, computer room air conditioning (CRAC), chilled water pump, refrigeration chiller and cooling tower is developed, and the cooling system is coupled with IT equipment. Finally, taking a data center with 100 racks and having 10 servers in each rack as an example, simulation results illustrate the effectiveness of the proposed DECM while ensuring the internal temperature of data center at an accept able value to some extent.

Keywords: data center, dynamic energy consumption model (DECM), energy efficiency, SPECpower_ssj2008.

1. INTRODUCTION

Data center, as a key infrastructure for processing massive data, has been growing rapidly in the number and scale to accommodate the informatization development of the society. Correspondingly, more energy consumption is needed to maintain the data center operation [1]. As a result, energy consumption reduction has gained widespread concerns and become an active topic in research and engineering. The primary work on energy reduction for data center is to model accurately the energy consumption characteristics of data center equipment. The data center mainly include information technology (IT) & cooling equipment, and the energy consumption of them accounts for more than 90% of the total energy consumption in data center and is the focus of this study [2].

IT equipment consists of servers, network equipment and power distribution equipment, and the server is the main component [3]. At present, the similarity of common server modeling methods is the usage of linear model taking the server utilization as only parameter, which has an inferior modeling accuracy. In this regard, some works to improve the model accuracy have been reported [4-6]. [4] models servers' power consumption as a linear function of processor utilization, network equipment, and memory modules. [5] divides the server utilization into two parts caused by server self-applications and the service turning on the server. In [6], model servers power consumption based on CPU die temperature, server utilization and server cooling fan's revolution speed. The work in [4-6] present a good performance at model accuracy by considering more parameters in modeling process. However, [4-6] have two main limitations as follows: 1) The models are almost developed for homogeneous servers, which make the modeling of heterogeneous servers in modern data centers less accuracy and reliable; 2) Small number of models have been only validated on few different types of servers by real data, resulting in a lack of credibility [7].

For cooling equipment modeling, some works can be found in the literatures. In [8], the energy consumption of cooling system is effectively analyzed through performing thermodynamic static modeling of each component. A detailed thermodynamic mathematical

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model is constructed in [9] to predict the energy consumption and energy efficiency of various components in data center cooling system. In [10], a complete energy consumption model of data center is established, in which the cooling system is modeled by thermodynamic formulas. In summary, the main works in [8-10] are to construct a mathematical static model for cooling system. However, the static model is unable to reflect the real-time power consumption and the fluid change. In addition, the above work in [4-10] did not consider the coupling dynamic characteristics of IT equipment and cooling equipment, which will reduce the accuracy of the model to a certain extent.

To address the aforementioned problems, this paper proposes a thermoelectric coupling dynamic energy consumption model of data center. The remainder of the paper is organized as follows. Section 2 proposes the polynomial model of IT equipment based on the least-squares method. Section 3 establishes a dynamic model of cooling equipment coupled with IT equipment so as to form the DECM of data center in MATLAB / Simulink environment. In section 4, the accuracy and efficiency of the proposed method are validated on a data center with 100 racks and 10 servers in each rack. Finally, conclusion is drawn in Section 5.

2. IT EQUIPMENT ENERGY CONSUMPTION MODELING AND ANALYSIS IN DATA CENTE

2.1 Energy consumption modeling of IT equipment

Studies have shown that the power curve and the CPU utilization curve of server are nearly consistent [11], so we use CPU utilization as the parameter to estimate servers' power consumption. This paper divides server power model into linear model, power function model, non-linear model and polynomial model, and as shown in Table 1, the corresponding model in common use are selected for analysis. P_{server} is the server power; P_{idle} and P_{max} are server idle power and peak power, respectively; u_{server} is the CPU utilization; *a*, *b*, *c*, *d*, *e*, *f* and *r* represent model parameter values needed to be fitted according to the actual data respectively.

For the power modeling of network and power distribution equipment in data center, the time-by-hour power consumption evaluation method is shown in [3]. Network equipment is responsible for transmitting data between servers and between servers and external data centers. Power distribution equipment mainly includes PDUs and UPSs. And UPS is responsible for transmitting power to PDUs, then PDUs transform the high-voltage power distributed throughout the data center into a voltage level suitable for servers.

TABLE 1 The functional form of four power models

Power Model	Function Expression
Linear Model	$P_{server}(t)=P_{idle}+(P_{\max}-P_{idle})\times u_{server}(t)$
Power Function Model	$P_{server}(t)=P_{idle}+a\times u^{b}{}_{server}(t)$
Non-linear Model	$P_{server}(t)=P_{idle}+(P_{\max}-P_{idle})\times(2\times u_{server}(t)-u^{r}{}_{server}(t))$
Polynomial Model	$P_{server}(t)=c+d\times u_{server}(t)+e\times u^{2}{}_{server}(t)+f\times u^{3}{}_{server}(t)$

As indicated above, the overall energy consumption model of IT equipment is as shown in Eq. (1).

$$P_{IT}(t)=P_{server}(u_{server}(t))+P_{network}(C_{network}(t))+P_{dist}(u_{server}(t)+C_{network}(t)) \quad (1)$$

where P_{IT}, $P_{network}$ and P_{dist} are the power consumption of IT equipment, network equipment and power distribution equipment, respectively; $C_{network}$ is the time-variant network traffic load.

2.2 Validation and analysis of different energy consumption models for servers

2.2.1 The SPECpower_ssj2008 benchmark and evaluation index

The SPECpower_ssj2008 benchmark is the first industry benchmark to measure performance and power of volume server class computers using graduated load levels [12]. And the evaluation index in this paper is R-Squared (coefficient of determination), RMSE (root mean square error) and MAPE (mean absolute percentage error). The R-Squared value is used to test the predicted models and shows how well their predicted results fit the actual value. The RMSE value represents the expected value of the square of the error between the predicted value and the actual value. While MAPE value represents the average error between the predicted value and the actual value, and it is often used to measure the forecast accuracy. Different evaluation index are as follows:

$$\begin{cases} \bar{y}=\frac{1}{n}\sum_{i=1}^{n}y_i \\ SSD=\sum_{i=1}^{n}(y_i-\bar{y})^2 \Rightarrow R^2=1-SSR/SSD \\ SSR=\sum_{i=1}^{n}(y_i-f_i)^2 \end{cases} \quad (2)$$

$$RMSE=\sqrt{\sum_{i=1}^{n}(y_i-f_i)^2/n} \quad (3)$$

$$MAPE=(\sum_{i=1}^{n}|(f_i-y_i)/y_i|\times 100\%)/n \quad (4)$$

where $\bar{y}$, y_i, f_i and *n* are the mean of data, the actual value, the predicted value and the number of data, respectively; SSD and SSR are the sum of squares of deviations and residual respectively.

2.2.2 Validation & analysis of server energy consumption model

In this paper, SPECpower_ssj2008 benchmarks of Q1, 2008 to Q1, 2020 are performed to verify the accuracy of power model of different servers shown in Section 2.1. This paper first obtains corresponding coefficients and power model values of different server models that fit the actual server data best in the least-squares method, then analyze the accuracy of models through regression evaluation indexes and use the cumulative distribution function (CDF) to express the distribution of models, and finally this paper selects the model with the highest accuracy as the calculation model. The R-Squared, RMSE and MAPE value distribution diagrams of different models and the corresponding CDF diagrams under different evaluation indexes are shown in Figs. 1-3.

As shown in Fig.1 (a), R-Squared values of almost all polynomial models are greater than 0.95, which are also greater than other models, indicating that the model is acceptable and fits the data better than other models. From Figs. 2 (a)-3(a), the RMSE and MAPE values of the polynomial model are relatively the minimum, that is, the error relative to the actual value is the minimum. As can be seen from CDFs shown in Figs. 1(b)-3(b), the polynomial model fits the servers' power consumption best, with better fitting degree and smaller error. In conclusion, all the results show that the polynomial server model fits the power consumption of servers best.

Therefore, a polynomial based energy consumption model of IT equipment with high accuracy as shown in (5) is proposed.

$$P_{IT}(t)=[c+d\times u_{server}(t)+e\times u^2{}_{server}(t)+f\times u^3{}_{server}(t)] \\ +P_{network}(C_{network}(t))+P_{dist}(u_{server}(t)+C_{network}(t)) \quad (5)$$

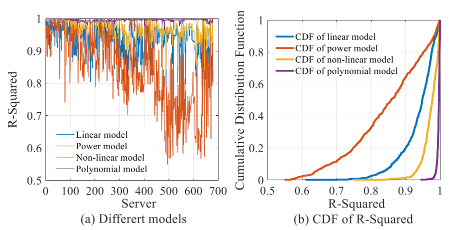

Fig 1 R-squared and CDF of R-squared of different servers' models

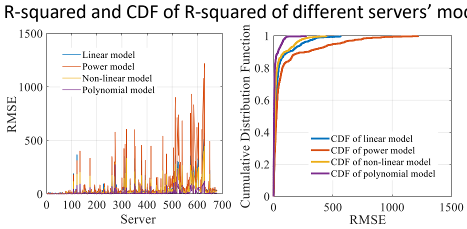

Fig 2 RMSE and CDF of RMSE of different servers' models

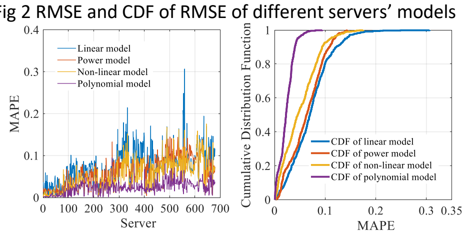

Fig 3 MAPE and CDF of MAPE of different servers' models

3. COOLING EQUIPMENT DYNAMIC ENERGY CONSUMPTION MODELING IN DATA CENTE

Almost all of the electricity consumption in data center is dissipated in the form of heat. The obvious consequence of the increase in energy consumption is a corresponding increase in the energy demand for cooling equipment. In the standard cooling equipment design, the main energy consumption components usually include the server fans, the computer room air conditioning (CRAC) unit, the chilled water pump, the refrigeration chiller, and the cooling tower. In this section, the dynamic modeling of cooling equipment will be carried out based on MATLAB/Simulink environment.

3.1 Server fans power consumption modeling

Fans in server are used to provide necessary airflow to send the cool air from the floor vent into the front of the server rack, and to exhaust the hot air out of the rear of the server rack. For the calculation of the work done by the server fan, the fan is assumed to work in isentropic mode. The fan power consumption expression is:

$$P_{fan}=dW_{fan}/dt=(dm_{fan}/dt)\times(h_{out\_fan}(t)-h_{in\_fan}(t)) \quad (6)$$

$$dm_{fan}/dt=m_{fan\max}\times \mathrm{ctrl}_1(t) \quad (7)$$

where P_{fan} and W_{fan} are server fans' power consumption and work done, respectively; dm_{fan}/dt and m_{fanmax} are the mass flow rate and maximum mass flow rate of server fan, respectively; $ctrl_1$ is the control signal value of server fan flow rate; h_{in_fan} and h_{out_fan} are the enthalpy of input and output fluids of server fan, respectively.

3.2 CRAC unit power consumption modeling

Hot air from the IT racks will eventually flow into the CRAC. Since the main obstacles of pressure loss when fluid flows in CRAC are heat exchanger coils, chilled water pipe and so on, which can be counteracted by air-pumping function of the blower [9]. Therefore, the main energy consumption in CRAC comes from blower, and the corresponding model is as follows:

$$C_{CRAC}=C_{CRAC\_int}\times(1+\beta_{CRAC}) \quad (8)$$

$$P_{CRACblower}=dW_{blower}/dt=(dm_{blower}/dt)\times(h_{out\_blower}(t)-h_{in\_blower}(t)) \quad (9)$$

$$dm_{blower}/dt=m_{blower\max}\times \mathrm{ctrl}_2(t) \quad (10)$$

where C_{CRAC_int} is the pressure loss coefficient inside the CRAC; β_{CRAC} is the factor to account for under floor and tile pressor drop; $P_{CRACblower}$ and W_{blower} are the blower power consumption and work done, respectively; dm_{blower}/dt and $m_{blowermax}$ are the blower mass flow rate and maximum mass flow rate, respectively; $ctrl_2$ is the control signal value of blower flow rate; h_{in_blower} and h_{out_blower} are the enthalpy of blower input and output fluids, respectively.

3.3 *Chilled water pump power consumption modeling*

The two devices thermally coupled to the chilled water pump (CWP) are CRAC and evaporator of refrigeration unit. The CWP is used to pump the chilled water in the evaporator to the CRAC unit at a suitable flow rate to achieve the heat exchange inside the CRAC, during which the CWP consumes power to compensate the pressure drop of the evaporator and CRAC heat exchanger coil, interconnecting piping and other components. The CWP modeling expression is:

$$\begin{aligned}&(dm_{CWP}/dt)\times(h_{in\_CWP}(t)+0.5v^2{}_{in\_CWP}(t))\\&=(dm_{CWP}/dt)\times(h_{out\_CWP}(t)+0.5v^2{}_{out\_CWP}(t))+dW_{CWP}/dt\end{aligned} \quad (11)$$

$$\begin{aligned}(dW_{CWP}/dt)/(dm_{CWP}/dt)&=(h_{out\_CWP}(t)-h_{in\_CWP}(t))/\eta_{CWP}\\&=(p_{out\_CWP}(t)-p_{in\_CWP}(t))/(\eta_{CWP}\times\rho_{water})\end{aligned} \quad (12)$$

$$dm_{CWP}/dt=m_{CWP\_\max}\times ctrl_3(t) \quad (13)$$

$$P_{CWP}=dW_{CWP}/dt=((dm_{CWP}/dt)\times\Delta p_{CWP})/(\rho_{water}\times\eta_{CWP}) \quad (14)$$

where $h_{\text{in\_CWP}}$ and $h_{\text{out\_CWP}}$ are the enthalpy of input and output fluids, respectively; $v_{\text{in\_CWP}}$ and $v_{\text{out\_CWP}}$ are input and output velocity, respectively; dm_{CWP}/dt and $m_{\text{CWP\_max}}$ are the mass flow rate and maximum mass flow rate of CWP, respectively; $p_{\text{out\_CWP}}$ and $p_{\text{in\_CWP}}$ are pressure of outlet and inlet of CWP, respectively; η_{CWP} is the CWP efficiency; ρ_{water} is the water density; $ctrl_3$ is the control signal value of CWP flow rate; P_{CWP} and W_{CWP} are the CWP power consumption and work done, respectively.

3.4 *Refrigeration chiller power consumption modeling*

The chiller includes four components: evaporator, compressor, condenser and expansion valve. Its working principle is: The normal temperature and pressure liquid refrigerant flows into the expansion valve and throttles into the low-temperature and low-pressure wet steam. The wet steam flows into the evaporator to absorb the heat of the chilled water from the CRAC, and then evaporates into gas refrigerant. The gas refrigerant flows into the compressor and is compressed into high-temperature and high-pressure gas refrigerant, which is then condensed into a normal temperature and pressure liquid refrigerant, and finally it flows into the expansion valve to repeat the above steps to achieve the purpose of refrigeration [13]. The power consumption expression of refrigeration unit is expressed as follows.

$$P_{chiller}=(dW_{chiller}/dt)=(dm_{compressor}/dt)\times(h_{out\_compressor}(t)-h_{in\_compressor}(t)) \quad (15)$$

$$dm_{compressor}/dt=m_{compressor\max}\times \mathrm{ctrl}_4(t) \quad (16)$$

$$P_{Chiller}=Q_{evaportor}/COP_{chiller} \quad (17)$$

where P_{chiller} and W_{chiller} are the chiller power consumption and work done, respectively; $dm_{\text{compressor}}/dt$ and $m_{\text{compressormax}}$ are the mass flow rate and maximum mass flow rate of compressor, respectively; $ctrl_4$ is the control signal value of flow rate; $h_{\text{in\_compressor}}$ and $h_{\text{out\_compressor}}$ are the enthalpy of compressor input and output fluids, respectively; $Q_{\text{evaportor}}$ is the evaporator heat load; COP_{chiller} is the coefficient of performance.

3.5 *Cooling tower power consumption modeling*

The main energy consumption components of cooling tower are cooling tower pump (CTP) and cooling tower fan (CTF). The main energy consumption of cooling tower comes from the energy required by water and air side pumps and fans, and the energy consumption model is similar to the CWP and server fan. Limited to space, this paper will not repeat [8].

Thus, the total electrical power consumed used for cooling the data center facility is expressed as follows.

$$P_{cooling}=P_{fan}+P_{CRACblower}+P_{CWP}+P_{chiller}+P_{CTP}+P_{CTF} \quad (18)$$

where P_{CTP} and P_{CTF} represent the power consumption of the CTP and the CTF, respectively.

In this paper, the temperature control strategy is that the compressor speed is controlled to make the evaporator outlet chilled water temperature as a fixed value, and the CRAC blower speed is controlled to change the cooling capacity to adjust the room temperature to an appropriate value.

To sum up, the power consumption model of IT equipment and cooling equipment in sections 2 and 3 are called dynamic energy consumption model (DECM) of data center load.

4. MODEL SIMULATION AND VERIFICATION

To simulate the operating characteristics and coupling relationship of data center while verifying the practicability of the DECM, the DECM is applied to a data center with 100 racks and 10 servers in each rack, and the FUJITSU Server PRIMERGY TX1320 M4 in SPECpower_ssj2008 data is assumed as the case study object. The server's IT equipment specification follows [3] and the cooling equipment parameters used in this paper are shown in Table A1 of Appendix A. The server CPU utilization and network traffic load follow the SDSC Blue Horizon data with approximate number of processors and EDU2 data center data with similar number of servers [3], respectively.

In MATLAB/Simulink environment, the proposed DECM and the temperature control strategy are applied to the above data center to construct the coupling dynamic model of IT equipment and cooling equipment, and then analyze the simulation results.

4.1 *Load characteristics energy consumption analysis of data center*

4.1.1 IT equipment model validation and energy consumption analysis of data center

Through the simulation modeling of FUJITSU Server PRIMERGY TX1320 M4, the results are shown in Fig. 4. It can be seen that the polynomial server model's power consumption almost coincides with the actual power consumption. In summary, the polynomial model is best for predicting the server power consumption through CPU utilization with high accuracy and small error, thereby improving the IT equipment modeling accuracy.

Therefore, the server energy consumption expression is as follows:

$$P_{server}(t) = 20.7961u^3{}_{server}(t) - 5.6698u^2{}_{server}(t) + 24.1174u_{server}(t) + 16.3379 \tag{19}$$

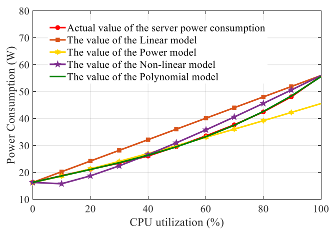

Fig 4 Comparison diagram of server power consumption

4.1.2 Energy consumption analysis of IT equipment and cooling equipment in data center

Based on DECM, the real-time energy consumption of data center can be estimated, the dynamic energy consumption proportion of each component relative to the total IT equipment or cooling equipment can be calculated, and the results are shown in Fig. 5. At this time, the average proportion of each component relative to the data center energy consumption is shown in Fig.6.

Generally, the energy use of IT equipment and cooling equipment consume around 60% and 30% of total electricity use of data center respectively. And the energy consumption of servers, network equipment and power distribution equipment in IT equipment are account for 70% to 80%, 7% to 20%, and 10% to 20%, respectively [3]. As can be seen from Figs. 5-6, for the IT equipment, the average energy consumption proportion of each component in IT equipment are 77.61%, 7.5% and 14.89% respectively, which is within the range of the proportions mentioned above, indicating that the estimated results are reasonable. For the cooling equipment, the refrigeration chiller and CRAC unit energy consumption accounts for 51.30% and 35.01% of the total energy consumption of cooling equipment respectively, which is in line with the actual operating conditions. Therefore, the energy proportion of each component meets the proportion range, which verifies the rationality of DECM and demonstrates that the DECM can be applied to the actual data center.

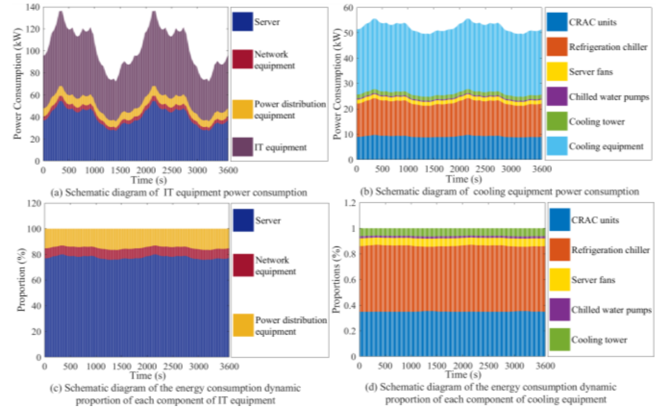

Fig 5 Schematic diagram of the data center IT equipment & cooling equipment

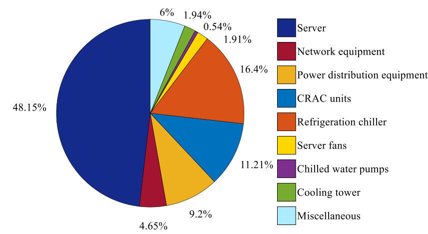

Fig 6 Power consumption breakdown for the data center

4.2 Data center load coupling characteristics analysis

In the MATLAB/Simulink environment, IT equipment and cooling equipment are coupled with each other. As shown in Fig. 7, the inlet and outlet temperature and enthalpy value of chilled water in CRAC unit, and the inlet and outlet temperature and enthalpy value of various components of refrigeration chiller and cooling tower can be obtained through the simulation. It can be concluded that the DECM can reflect the real-time fluid change of data center. At the same time, the energy is always balanced during the coupling heat transfer process, which verifies the accuracy of the DECM.

In summary, from the analysis of simulation results in Section 4, it can be concluded that the DECM can be used to model the actual data center load.

5. CONCLUSION

This paper constructs a dynamic energy consumption model (DECM) of the data center load in MATLAB/Simulink environment. The main contributions are summarized as follows:

(1) A high-precision polynomial-based IT equipment energy consumption model and a detailed cooling equipment model are proposed, which can achieve more accurate IT equipment & cooling system energy consumption estimation.

(2) Through effective coupling modeling of cooling equipment and IT equipment, the DECM is formed. And the DECM is verified to effectively predict the actual energy consumption and reflect the fluid changes of the data center components.

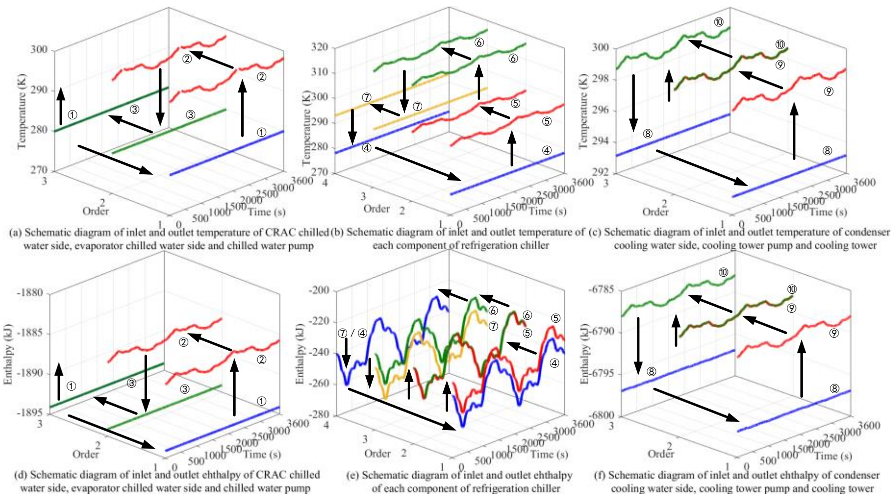

Fig.7 Schematic diagram of inlet and outlet temperature and enthalpy of different components in data center

(3) The proposed temperature control strategy can ensure the data center temperature at an acceptable value to some extent.

Therefore, the DECM established in this paper can be used for data center in a variety of configuration scenarios, and can also be used as a verification platform for energy management and resource planning.

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APPENDIX A

The cooling equipment parameters used in this paper are shown in Table A1, respectively.

TABLE A1 Specification of the cooling equipment in data center

Component	Parameter description	Value
Server fan	Efficiency of server fan	80%
	Maximum mass flow rate	3000 g/s
CRAC units	Efficiency of blower	80%
	Pressure loss coefficient term for CRAC internals	4.1648e-5 Pa/(g/s)^2
	Thermal mass for CRAC internals	8360 J/kg
	Maximum mass flow rate	275 g/s
Chilled water Pump	Efficiency of CWP	80%
	Maximum mass flow rate	237.8 g/s
Chiller	Efficiency of compressor	98%
	Maximum mass flow rate of compressor	259.65 g/s
Cooling Tower	Efficiency of CTP	80%
	Maximum mass flow rate of CTP	475.6 g/s
	Efficiency of CTF	80%
	Maximum mass flow rate of CTF	5000 g/s
other	Specific heat of water	4179 J/kg K
	Specific heat of air	1007 J/kg K
	Mass density of water	995 kg/m^3
	Mass density of air	1.16 kg/m^3