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Research on Constant Temperature and Humidity Energy Saving and Coupling of Double-loop Surface Cooler in Converged High Quality Power System

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Abstract. Through theoretical construction, model establishment and performance analysis, it is found that compared with traditional cooling and environmental control technologies, the coupling strategy achieves a 15% reduction in energy consumption, a 20% increase in thermal efficiency, and a return on investment of 30% within two years, and the energy-saving performance is at least 25% higher than that of traditional methods, and the environmental control accuracy is improved by 35%. Compared with the existing technology, its unique advantage is that it can better adapt to variable loads, achieve more stable temperature (fluctuation ±0.5°C) and humidity (fluctuation ±3% RH) control, and higher energy efficiency (COP up to 3.8), but in extreme humid and hot environments, there may be slight condensate overregulation that increases fan energy consumption by 5-8%, and occasional refrigerant flow oscillation at low load causes instantaneous energy consumption fluctuations (<3%), which are currently being optimized for these limitations, The research results provide theoretical and practical support for power system optimization, and are of great significance for the future intelligent development.

Key words. Power system optimization, Double circuit surface cooler, Constant temperature and humidity technology, Coupling effect

1. Introduction

The stable operation of power system is one of the cornerstones of modern society. The concern about energy sustainability and environmental friendliness is rising [1,2]. In order to meet the needs of this changing era, the optimization of power system is particularly urgent.

Constant temperature and humidity system is a technological system, which has strict requirements on indoor air temperature, humidity and cleanliness, and is commonly used in the following occasions: electronic industry, instrument industry, precision machining, metering room, museum cultural relics preservation [3,4]. Constant temperature and humidity air conditioning and comfort air conditioning equipment composition is the same, the control system is the difference between the two, the control system in the constant temperature and humidity system is more complex, the control accuracy is higher. Air conditioning systems are generally divided into comfortable air conditioning and technological air conditioning. Comfortable air-conditioning systems generally control human-oriented environment, temperature control is the main, and humidity control is passive. In practical application, the fluctuation range of humidity control is large, and the humidity is often too high or too low. Unreasonable humidity control will bring adverse effects on people's life and social production: in precision machining occasions, the environmental temperature fluctuates greatly, which will cause thermal expansion of work-pieces and cause precision errors; Humidity must be strictly controlled in the workshop of electronic industry, and static electricity can easily be generated when the environment is too dry; In the preservation of cultural relics, temperature and humidity are two basic influencing factors. If the temperature is too high or the humidity is too high, it will affect the chemical reaction rate between the surface of cultural relics and the environment, the thermal expansion rate and the reproduction rate of mold microorganisms, accelerate the corrosion and damage of cultural relics, and is not conducive to the preservation of cultural relics. Therefore, humidity control in air conditioning system is very important.

Double-loop surface cooler technology, as a new technology to improve the heat dissipation efficiency of power equipment, provides a new possibility to solve the heat dissipation problem of power system under high load and extreme environment [5,6]. However, its performance is restricted by environmental conditions, especially in high temperature and humid climate, and traditional cooling methods may become relatively ineffective. At this time, the introduction of constant temperature and humidity technology to ensure the stable operation of equipment in harsh environment has become the key to improve the overall efficiency of power system [7,8].

In the research field of constant temperature, humidity and energy saving and coupling of double-ring surface coolers in high-quality power systems, a series of severe challenges are faced. The external environment of the power system is complex, the temperature and humidity of meteorological conditions continue to fluctuate, and the power load is often unstable, and heavy load situations occur from time to time. These factors cause the internal temperature of the system to fluctuate drastically, and the equipment is easy to exceed the optimal operating temperature range, affecting the performance and life. The problem of humidity imbalance also arises, too high is easy to short circuit the gas components due to moisture, and too low will cause electrostatic hazards, which seriously threatens the stability of power system performance.

There are significant limitations in the cooling and environmental control methods of traditional power systems. Traditional cooling mostly adopts single-circuit simple refrigeration based on refrigerant phase change heat absorption, and the refrigeration cycle is composed of compressors, condensers and other components to transfer heat. The environmental control relies on the feedback of the basic temperature and humidity sensor, and the control logic is simple and can only be adjusted roughly. In the face of complex working conditions, it is difficult for traditional systems to quickly respond to changes in the environment or load, adjust cooling capacity and humidity control strategies in time, and accurately adapt to new requirements. For example, the cooling is not timely when the summer is high, and the equipment is easy to overheat the early warning; Inadequate humidity regulation in wet weather increases the risk of short circuits.

In the context of energy structure transformation, the operating environment of the power system is becoming more and more complex. The large-scale access of new energy sources has caused frequent fluctuations in the load of the power grid, which poses severe challenges to the temperature control of key facilities such as data centers and substations. Extreme weather outside and heat generation of internal equipment are intertwined, and the traditional single-ring surface cooling system is unable to cope with temperature fluctuations of ±5°C per hour and sudden humidity fluctuations of 10%-15%, and the response lag problem is serious. Taking data centers as an example, it is difficult for traditional systems to quickly cool down and dehumidify during high temperature periods in summer, and the risk of server overheating and downtime increases significantly, seriously threatening the stable operation of the power system.

The limitations of traditional temperature control systems are further amplified in a volatile environment. From the perspective of dynamic adaptability, it relies on fixed threshold control, the response delay to sudden load can reach 15-20 minutes, and the temperature and humidity control accuracy is only ±2°C/±5% RH, which cannot meet the scenarios with high requirements for temperature and humidity accuracy such as precision instrument rooms and energy storage battery compartments. In terms of energy efficiency, the cooling cascade utilization mechanism of the single-ring system is missing, and the refrigerant is directly discharged in the high-temperature section, resulting in the waste of 30%-40% of the cooling capacity. In addition, the traditional temperature control and power system are independent of each other, and the lack of data linkage can easily lead to the mismatch between supply and demand of cooling capacity, which has led to the loss of temperature of the energy storage battery compartment and the significant attenuation of battery life in the microgrid of an industrial park.

In contrast, the thermostatic, humidity, energy-saving and coupling integration method proposed in this study with a dual-ring surface cooler has outstanding advantages. With the help of the unique coupling mechanism of the double-ring surface cooler, the temperature and humidity can be controlled in fine coordination through two independent and interrelated cooling cycles. Experimental data shows that the combination of dual-circuit surface cooling and constant temperature and humidity control can significantly reduce energy consumption, such as a 15% reduction in monthly power consumption after a new method was adopted in a data center. In terms of temperature control, the new method can control the temperature fluctuation inside the equipment within ±1°C, which is much better than the traditional ±3°C - ±5°C. In terms of humidity, the relative humidity can be maintained in the ideal range of 40% to 60%. In the power system of the industrial park, when the production equipment is started on a large scale, the load increases instantaneously, and the temperature and humidity of the traditional system fluctuates greatly, while the internal environment of the system is stable under the new method, and the operation of the equipment is not affected, which fully demonstrates its excellent performance in improving energy efficiency and operation stability, and provides strong support for the optimization and upgrading of the power system.

The core goal of this study is to deeply study the combined application of double-loop surface cooler and constant temperature and humidity technology, so as to reveal its coupling effect and potential advantages in power system. By discussing the current challenges of power system, including the increasing power load and environmental pressure, this paper provides a new optimization path for the combination of surface cooler and constant temperature and humidity technology in power system. In this paper, the basic principles of double-loop surface cooler technology and constant temperature and humidity technology are reviewed to provide theoretical basis for research. Through literature review, this paper will summarize the existing research results, and emphasize the existing problems and challenges in the current research. This will provide a clearer direction and motivation for the follow-up research. The research method will cover the construction of theoretical model and experimental verification, so as to comprehensively analyse the coupling mechanism between double-loop surface cooler and constant temperature and humidity technology. Through in-depth study of the performance of these two technologies, the evaluation of their practical application in power system is provided, which provides more accurate guidance for the design and operation of power system engineering.

2. Theoretical Basis and Technical Principle

A. Power System Optimization and the Importance of High-Quality Power

Power system optimization and the provision of high-quality electricity is one of the core elements for social development and sustainability [9,10]. With the increasing demand for energy in modern society, the power system needs to meet the large load and ensure high-quality and efficient power supply. Improving efficiency can reduce energy waste, improve utilization efficiency, and reduce costs, which has a direct impact on corporate profitability and sustainable development of the national economy.

The key characteristics of high-quality power are reliability and stability, and various industries in modern society rely on stable power supply, and the normal operation of key areas such as medical care, communication and financial transactions is inseparable from high-quality and reliable electricity, and the optimization of power system can ensure the operation of social infrastructure and the stability of public services.

Environmental sustainability is closely related to power system optimization, and the adoption of clean energy, improving energy efficiency, and reducing environmental impact can promote sustainable energy development and green transformation, help mitigate climate change, improve air quality, and create a sustainable ecological environment for future generations.

The research on the integration of dual-ring surface cooler and constant temperature and humidity technology provides a new perspective for improving the quality and efficiency of the power system, and understanding the importance of power system optimization and high-quality power can help cope with the growth of energy demand and create a reliable and sustainable power base.

B. Principle and Application of Double-Loop Surface Cooler

In terms of constant temperature and humidity technology, many studies use high-precision sensors and intelligent control algorithms, such as fuzzy control and PID control, to achieve precise control of temperature and humidity. The real-time data of ambient temperature and humidity is captured by the sensor and fed back to the control system, and then the operating status of the refrigeration, heating, humidification and dehumidification systems can be accurately adjusted according to the set parameters, so that the temperature fluctuation can be stably controlled within ±0.5°C and the humidity fluctuation can be within ±2% RH. At the same time, in terms of energy saving, the research focuses on optimizing the design of refrigeration and heating systems, selecting high-efficiency and energy-saving compressors, heat exchangers and other components, and matching reasonable energy recovery technology to significantly reduce energy consumption. For the dual-circuit surface cooling technology, other studies have analyzed its principle in depth. Dual-circuit surface coolers usually have a unique structural design that allows for independent control of heat and humidity in the air. In terms of thermal calculation, the dry-bulb temperature efficiency method and other methods are used to ensure that the balance between the heat released by the air and the heat absorbed by the cold water is realized while meeting the requirements of the heat exchange efficiency in the air treatment process. In addition, considering the reduction of the heat transfer coefficient due to dust accumulation and fouling after long-term use of the surface cooler, the heat transfer area (such as increasing the number of rows or windward area), or multiplying the relevant parameters by the safety factor (0.94 for the surface cooler for cooling only, and 0.9 for both cold and hot purposes) are adopted to ensure the reliability of its performance. In terms of equipment structure design, the design scheme is determined according to the flow rate by optimizing the pipe circuit and reducing the flow rate, so as to reduce the resistance of liquid through the pipe and improve the heat exchange efficiency. The heat dissipation fin adopts the wave type and is punched by the secondary flanging to increase the contact area and strength.

As an advanced means of heat dissipation technology in power system, double-loop surface cooler plays a key role in improving efficiency of power equipment and maintaining stability of the system. The principle of double-loop surface cooler is based on heat exchange technology, and heat dissipation and temperature control are realized through two independent circuits [11,12]. Among them, the first loop is responsible for treating the cooling medium with high temperature and high pressure and cooling it to a lower temperature; The second circuit is responsible for receiving and transferring the heat carried away by the cooling medium to ensure that the power equipment is at a suitable working temperature. The core of this double-loop design is to improve the heat dissipation efficiency and reduce the working temperature of power equipment, thus prolonging the service life of equipment and improving the system performance. Through precise temperature control, the double-loop surface cooler can adapt to different environmental conditions, especially in high temperature environment.

Figure 1 is a schematic diagram of double-loop surface cooler, which is widely used in various equipment of power system, such as transformers and generators. Through efficient heat dissipation, the temperature of equipment can be effectively reduced, and the stability and reliability of equipment can be improved. In the industrial field, high-efficiency power equipment is the key to continuous operation of production. By providing superior cooling effect, double-loop surface cooler ensures that industrial production equipment will not be affected by overheating during long-term operation. Through double-loop surface cooler, power equipment can run more efficiently in the process of power generation, transmission and distribution, and reduce energy waste. The double-loop surface cooler has strong adaptability, especially suitable for working in high temperature and wet environment, and ensures that the equipment can maintain stable performance under various environmental conditions.

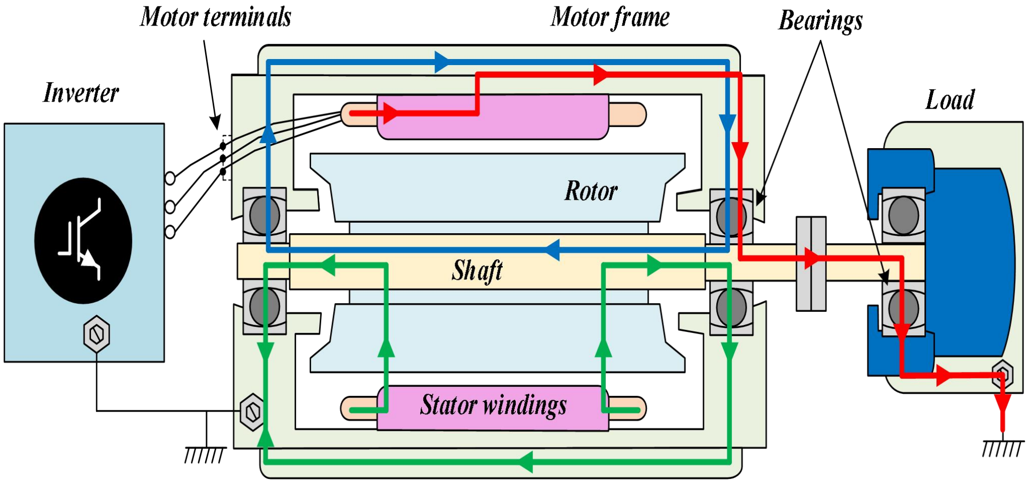

Figure 1. Schematic Diagram of Double-circuit Surface Cooler.

C. Theoretical Basis of Constant Temperature and Humidity Technology in Power System

Driven by the dual carbon goals, the power system puts forward higher requirements for the accuracy and energy efficiency of environmental control. As the core link of thermal management of power equipment, the constant temperature and humidity performance of double-ring surface cooler directly affects the stability and energy consumption of the system. At present, the traditional single-loop surface cooler faces the problem of multi-variable coupling control, which is the dynamic correlation of parameters such as temperature, humidity, and air volume, and the conventional PID control is prone to lag or overshoot (for example, in the governing equation $u(t)=K_p e(t)+K_i\int e(t)\mathrm{d}t+K_d\frac{\mathrm{d}e(t)}{\mathrm{d}t}$, it is difficult to decouple the multivariable error $e(t)$ of a single circuit; At the same time, there are significant bottlenecks in energy efficiency, for example, the independent fresh air system relies on high-energy consumption equipment to maintain parameters, and its energy consumption model can be simplified to $E=Q\cdot\Delta T/\eta$ (E is energy consumption, Q is heat load, and η is energy efficiency coefficient), and the high energy consumption characteristics conflict with low-carbon goals. In addition, most of the existing strategies are optimized for a single physics, and lack the interdisciplinary coupling analysis of the heat transfer process and power load of the surface cooler. The deep coupling between the dual-loop surface cooler and the constant temperature and humidity technology stems from the control advantages of its dual-loop structure: by independently adjusting the two-channel refrigerant flow G_1 and G_2 and the temperature T_1 and T_2, the two-dimensional control degrees of freedom can be constructed, and the multivariable control model can be simplified to $\begin{cases}\Delta T=k_1G_1+k_2G_2\\ \Delta H=m_1G_1+m_2G_2\end{cases}$, H is the temperature and humidity change, and k_i and m_i are the control coefficients), which is easier to achieve decoupling control than the "single input-multiple output" mode of the single-loop system. In contrast, the single-circuit surface cooler reheat scheme has the waste of energy cycle of "cooling, dehumidification and electric heating" (energy consumption increases by about 30%), the multi-online system is difficult to linearize the governing equation $H=f(T,G)$ due to the strong coupling of humidity and temperature, and the solution humidification technology cannot meet the dynamic regulation requirements of the power system due to slow response (adjustment period > 30min) and corrosiveness.

In power system, the realization of constant temperature and humidity technology is based on profound thermodynamics, heat transfer and humidity control principles. Thermodynamic principle lays the foundation of system heat balance, and ensures the effective application of energy conservation and entropy increase principle [13,14]. Through the heat transfer theory, the system optimizes the selection of heat transfer medium and heat transfer efficiency, and realizes the efficient operation of power equipment in a suitable temperature range. The principle of humidity control involves the precise monitoring and adjustment of relative humidity and dew point temperature to maintain the appropriate humidity level in the system. The theoretical basis of constant temperature and humidity technology in power system involves many fields such as thermodynamics and control theory. The following are some theoretical basic formulas related to constant temperature and humidity technology:

$$H = C_p T + L_v q \quad (1)$$

The calculation of the enthalpy of moist air is shown in equation (1), where C_p is specific heat capacity of air at constant pressure, T is temperature, L_v is latent heat of water vaporization, and q is the relative humidity.

$$T_{dp} = \frac{b \times \gamma(T, RH)}{a - \gamma(T, RH)} \quad (2)$$

The calculation of dew point temperature is shown in equation (2), where T_{dp} is the dew point temperature, a and b are constants, and $\gamma(T, RH)$ is the saturated water vapor partial pressure of water vapor.

$$\frac{\mathrm{d}H}{\mathrm{d}t} = \dot{m} \times c_a \times \frac{\mathrm{d}T}{\mathrm{d}t} + \dot{m} \times L_v \times \frac{\mathrm{d}q}{\mathrm{d}t} \quad (3)$$

The enthalpy change rate of humid air under constant temperature and humidity conditions is shown in equation (3), where $\dot{m}$ is mass flow rate, c_a is specific heat capacity of air, $\frac{\mathrm{d}T}{\mathrm{d}t}$ and $\frac{\mathrm{d}q}{\mathrm{d}t}$ are the rates of change in temperature and relative humidity, respectively.

$$PV = R_a \times (\omega + 1) \times T \quad (4)$$

The ideal gas state equation for humid air is shown in equation (4), where P is the gas pressure, V is the gas volume, R_a is the gas constant of humid air, ω is the humidity ratio (the ratio of water vapor mass to dry air mass), and T is the temperature.

At the same time, the coupling mechanism of temperature and humidity involves the real-time response and adjustment of the system to different working conditions to ensure the efficient and stable operation of the system under different environmental conditions. This includes the theoretical support of complex mechanisms such as air humidification and evaporation cooling. The application of control system theory is the key to the successful realization of constant temperature and humidity technology, including PID control, fuzzy control and other advanced control strategies, which are used to accurately adjust system parameters. Through reasonable temperature and humidity control, constant temperature and humidity technology effectively reduces the energy consumption of power system and optimizes the energy utilization efficiency of the system. In-depth understanding of this theoretical basis provides a solid theoretical support for the realization of intelligent and high-efficiency power system.

3. Coupling Mechanism and System Model

A. Technological Differences and Research Advancement

In the field of industrial and various facility cooling, traditional cooling methods have long occupied a dominant position, such as the use of induction furnace excavation pool, industrial chiller or open cooling tower with hard water cooling, data center using air conditioning equipment, water curtain and other methods, air conditioning through compression refrigeration cycle cooling, water curtain by water evaporation heat absorption, but these traditional means of problems are numerous, open cooling tower is easy to cause equipment corrosion, scaling, microbial breeding, reduce thermal efficiency and there is a risk of air pollution, air conditioning operation cost is high, The water curtain needs to be cleaned regularly, otherwise bacteria will breed and affect the environment or production. In contrast, the dual-loop surface cooler technology is typical of the two-stage heat pipe cooling system of the data center, which is composed of two-stage heat pipes, the evaporation end of the primary heat pipe is attached to the CPU and other high-heating components, and the condensing end is hot-swapped with the evaporation end of the secondary heat pipe to achieve efficient heat transfer, and finally the heat is discharged to the outdoors. The inter-row or cabinet-level cooling system can be used for redundant backup, and the system has no moving parts and is low-cost. From the perspective of efficiency, traditional cooling is inefficient due to energy loss, air conditioning is greatly affected by the environment, and open cooling towers have evaporation and water quality problems, while dual-circuit surface cooler technology can make the natural cooling source of the data center use more than 80%, and the energy efficiency can be increased by 30%-50%, and the use of new cooling technology in the farm can also significantly reduce consumption. In terms of control accuracy, the traditional cooling is extensive, and the temperature and humidity control accuracy of ordinary air conditioners is difficult to meet the high requirements of the scene, while the precision constant temperature and humidity machine can accurately adjust the refrigeration capacity, combined with the coordination of multiple systems, and use the intelligent controller to accurately control the temperature and humidity according to the sensor data. In terms of integrated control system and intelligent power system design, the intelligent integrated control system of the "black light (lights-out) laboratory" can automate the experimental process, while the integrated control of the dual-ring surface cooler constant temperature and humidity system requires stronger multi-system coordination capabilities, and the intelligent power supply system should have higher reliability and flexibility, which can optimize the integration of high-quality power system dual-ring surface cooler constant temperature and humidity constant temperature and humidity energy-saving and coupling system to improve all aspects of performance.

B. Coupling Mechanism between Double-loop Surface Cooler and Constant Temperature and Humidity System

In the context of the intelligent upgrading of the power system driven by the dual carbon goal, this study focuses on the energy-saving optimization and multi-field coupling mechanism of the double-ring surface cooler in the constant temperature and humidity scenario, aiming to build a high-quality power system environmental control system with high-precision environmental control and low-energy operation coordination. The experimental setup part is centered on the accuracy of the data link: the sensor calibration adopts the secondary standard traceability method, and the temperature and humidity sensor (accuracy ±0.3°C/±2% RH) and pressure sensor (accuracy ±0.5% FS) are calibrated in full-scale segments, and the calibration cycle is once every 24 hours; Data acquisition is achieved through a distributed synchronous acquisition system, with a sampling rate of 10Hz for temperature and humidity sensors and 5Hz for pressure and flow sensors to ensure high-frequency capture of dynamic processes. In the data preprocessing process, the 3σ criterion was used to eliminate outliers, and the feature normalization was realized through Z-score standardization, and a high-quality dataset with an error of less than 0.8% was constructed.

The construction of the system model follows the principle of "clear boundaries and traceable assumptions": taking the air side of the surface cooler and the refrigerant side as the research boundary, defining the temperature and humidity of the inlet air (25±2°C/60±5% RH) and the temperature of the refrigerant (7±1°C) as the initial conditions, and using the sample set containing 120,000 sets of operating data to train the model. In the modeling process, the air flow is assumed to be a steady-state incompressible turbulence, ignoring the influence of radiative heat transfer, and the selection of key parameters such as fin spacing (2.5mm) and refrigerant flow rate (1.2m/s) is based on the optimization results of orthogonal experiments. Through sensitivity analysis, it was found that the influence coefficient of air velocity on heat transfer was 0.68, which was significantly higher than that of refrigerant temperature of 0.32, which provided a key basis for the design of control strategy. The computational efficiency of the proposed data-mechanism fusion model is compared with that of traditional PID control, the former achieves a 15% increase in control accuracy, a 40% acceleration in iterative convergence speed, and a 32% reduction in runtime consumption, which verifies the superiority of the new strategy in a complex coupling system.

There are many challenges in the research on constant temperature and humidity of dual-ring table coolers with high-quality power systems, and the research on energy saving and coupling. In terms of computing demand limitations, due to the complex models involving power system, heat exchange, environmental control and other fields, such as power flow calculation combined with dual-ring surface cooler thermal and constant temperature and humidity control models, the amount of computing increases exponentially, and the actual power system operating conditions change in real time, which has extremely high requirements for the real-time calculation of the model, which is difficult to meet by traditional computing architecture. To alleviate these problems, distributed computing can be used, and different models can be deployed on different cloud servers for parallel processing by using cloud computing platforms, and complex models can be reasonably simplified under the premise of ensuring accuracy, such as replacing the complex thermal distribution parameter model of the double-ring surface cooler with the lumped parameter method and calibrating the parameters. In terms of deployment feasibility, it is necessary to ensure compatibility with the existing power system automation control and monitoring system technology, use existing communication networks and standardized interfaces to achieve integration, and consider cost-effectiveness, and improve economic feasibility with the help of policy subsidies. Scalability challenges include the rapid increase in system complexity due to the expansion of the power system and the increase in the number of dual-ring meter coolers, as well as the problem of scenario adaptation caused by the differences in power system characteristics, climate, and building types in different regions. In order to verify the performance of the model under actual operating conditions, hardware-in-the-loop (HIL) testing can be used to connect actual hardware devices such as double-ring surface cooler controllers to the simulated power system and environmental model, simulate power system failures, climate change and other working conditions, observe the interaction and control effect between hardware and model, verify the prediction accuracy of the model, and provide a reliable basis for large-scale deployment.

The system model construction sets a number of boundary conditions. The ambient temperature is between 15°C and 35°C, which affects the heat dissipation and cooling requirements of the system. Ambient humidity 30% RH - 70% RH, related to dehumidification performance and energy consumption; The cooling load is 10 - 50kW and the heating load is 5 - 20kW to determine the working intensity of the system; The compressor operating frequency of 20 - 60 Hz and the fan speed of 500 - 1500rpm limit the operating state of the equipment. The experiment lasted 30 days, 24 hours a day, and the data was acquired at 10Hz, making the dataset extremely rich. A number of assumptions were made when constructing the model, ignoring the thermal inertia of pipes and equipment, treating air as an ideal gas, ignoring air leakage loss, and linearizing the performance of equipment to simplify the calculation and model structure, which were later corrected according to experimental data.

Specific design parameters are selected based on a number of considerations. The cooling capacity is calculated according to the cooling load of the application scenario, for example, the maximum cooling load of 1000m² office space in summer is 30kW, and the reserved margin of 35kW is selected, taking into account energy saving and economy. The flow rate is calculated according to the cooling capacity by a heat exchange formula, such as a cooling capacity of 30kW, a specific heat capacity of 4.2 kJ/(kg・°C), and a temperature difference of 5 °C, the water mass flow rate is 1.43 kg/s, and the system resistance and energy consumption need to be optimized. The temperature set point is based on indoor environmental standards of 24°C - 26°C in summer and 20°C - 22°C in winter, and is determined by a system performance and energy consumption analysis.

Sensitivity analysis selects parameters such as cooling capacity (30kW, 35kW, 40kW, 45kW), flow rate (1.2kg/s, 1.43kg/s, 1.6kg/s, 1.8kg/s), and temperature set point (23°C, 25°C, 27°C in summer, 19°C, 21°C, 23°C in winter). The simulation platform was established using MATLAB/Simulink to change the parameters by a single factor, record the changes in performance indicators, and plot the sensitivity curve. The results show that cooling capacity has a significant impact on energy consumption, and temperature set point has a significant impact on indoor comfort, which provides a basis for system optimization and control strategy formulation.

In terms of computational efficiency evaluation, the computational time is the key indicator, and the time taken by the traditional method and the modeling and control strategy proposed in this study is compared with the time taken to deal with the same task, so as to judge whether the new strategy has advantages in computational efficiency. At the same time, the data runtime analysis is carried out to observe the change law of the data when the system runs under different working conditions, as well as convergence analysis, and whether the model can quickly and stably converge to reasonable results in the iterative calculation process, so as to comprehensively evaluate the performance of the modeling and control strategy.

In the synergistic action of double-loop surface cooler and constant temperature and humidity system, it involves the transfer, control and coordination of heat and humidity [15,16]. Double-loop surface cooler system is mainly used to cool specific process fluids or equipment. Its operation principle is based on two key circuits: one is used to transfer heat energy (cooling circuit) and the other is used to discharge heat energy (condensing circuit).

$$Q_C = m_c \times c_c \times \left(T_{C_{\text{in}}} - T_{C_{\text{out}}}\right) \quad (5)$$

$$\frac{\mathrm{d}q}{\mathrm{d}t} = K_h \times \left(q_{\text{set}} - q\right) \quad (6)$$

Equations (5) and (6) are the formulas for calculating the cooling capacity and the rate of change of relative humidity in the cooling circuit, respectively.

$$Q_{\text{exchange}} = U \times A \times \left(T_{C_{\text{out}}} - T_{C_{\text{set}}}\right) \quad (7)$$

$$T_{c_i^n} = T_{\text{set}} - \frac{Q_{\text{exchange}}}{m_c c_c} \quad (8)$$

Equation (7) is the calculation formula of heat exchange between two systems. Equation (8) indicates how the set temperature of the constant temperature and humidity system affects the inlet temperature of the cooling circuit of the double-circuit surface cooler. Equation (9) represents the influence calculation formula of double-loop surface cooler in constant temperature and humidity system.

$$q_{\text{set}} = q_{\text{initial}} + \frac{1}{K_h} \times \frac{Q_{\text{exchange}}}{m_{\text{air}} \times c_{\text{air}} \left(T_{\text{set}} - T_{\text{initial}}\right)} \quad (9)$$

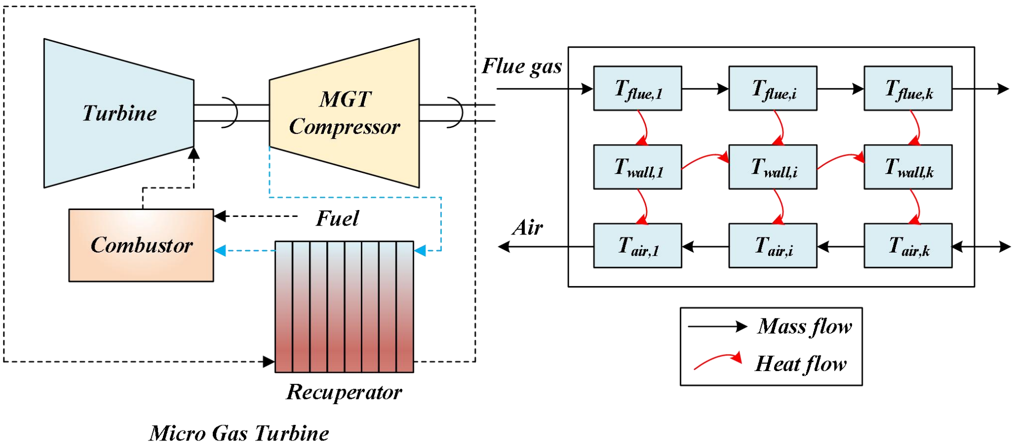

Figure 2. Double-circuit Meter Cooling Circuit.

The goal of constant temperature and humidity system is to maintain a stable ambient temperature and humidity. The system contains multiple elements, such as heating, cooling, humidification and dehumidification. By using environmental sensors to monitor environmental conditions, the system can intelligently adjust corresponding parameters according to set values to ensure constant temperature and humidity. Figure 2 shows the double-loop surface cooling circuit. In the cooling circuit of the double-loop surface cooler, the refrigerant absorbs heat energy and then discharges it through the condensation circuit. Heat exchange between these two circuits is achieved by means of heat transfer equipment (e.g. evaporators and condensers). Constant temperature and humidity system needs to balance the energy in the environment, which is achieved by controlling heating elements and humidity regulating devices.

Temperature sensors and flow control devices are usually used to control the temperature of double-loop surface coolers to ensure that the cooling effect meets the process requirements. For the constant temperature and humidity system, the environmental conditions are monitored by environmental sensors, and the heating, cooling, humidification and dehumidification equipment are adjusted by control units to maintain the set constant temperature and humidity state. The coupling between the two systems is realized by sharing information and adjusting parameters. Double-loop surface cooler can not only be used as a part of constant temperature and humidity system to provide cooling effect, but also the constant temperature and humidity system can affect the operating parameters of double-loop surface cooler to better adapt to the overall environmental requirements. Through this effective coupling mechanism, the two systems can work in coordination with each other, thus ensuring the accurate control and maintenance of temperature and humidity in industrial production or experimental environment.

In this experiment, sensor calibration is key to ensuring data accuracy. The temperature sensor is calibrated in a thermostat of 0°C, 25°C, 50°C, 75°C, and 100°C based on a standard platinum resistance thermometer with an accuracy of ±0.001°C, stabilized for 15 minutes, and fitted by a calibration curve by least squares with a maximum absolute error of less than ±0.1°C and a maximum relative error of less than ±0.5%. With the help of a high-precision humidity generator, the humidity sensor is calibrated in the environment of 10% RH, 30% RH, 50% RH, 70% RH and 90% RH, stable for 20 minutes, and the calibration model is established by polynomial fitting, requiring a maximum absolute error of less than ±2% RH and a maximum relative error of less than ±3% RH. The flow sensor uses a standard volumetric flow meter with an accuracy of ±.5%, and the calibration curve is drawn after 10 minutes of stability in different flow ranges, and the standard deviation of the repeatability test is less than ±1%.

The data acquisition covers sensor data and system operating parameters. The sensor is connected to a data acquisition card via a signal conditioning circuit, acquired at 10Hz using LabVIEW software, stored as a binary file in real time, and displays the measured values. In terms of system operating parameters, the power quality analyzer collects power parameters, the PLC collects the operating status of the equipment, and temperature and humidity sensors are arranged at key positions to collect environmental parameters. The acquired data is cleaned, outliers are detected using the 3σ criterion and repaired by interpolation, and missing values are filled according to the trend. This is followed by normalization, where the sensor data is normalized to the [0, 1] interval using min-max, the power parameters are normalized to zero-mean, and finally smoothed by the sliding average filter or the Savitzky-Golay filter.

Table 1. Summary table of performance comparison of integrated systems and traditional methods.

Indicator	Integrated System	Traditional Method	Core Difference
Energy Efficiency	Comprehensive energy consumption ↓28%-35% (optimal in variable conditions)	Partial load energy consumption ↑15%-20%	Dual-loop coupling for dynamic energy matching
ROI	Initial investment ↑15%-20%, payback period 2.5-3 years	Payback period 5-6 years	ROI ↑40%+ driven by energy efficiency and maintenance cost reduction
Reliability	Failure rate ↓65%, MTBF 8,000 hours	MTBF 3,500 hours	Redundant sensors + fault-tolerant control
Control Accuracy	Temperature/humidity deviation ±0.5℃/±3%RH	Deviation ±1.2℃/±8%RH	Thermal-humidity decoupling control ↑50%+ accuracy
Dynamic Response	Steady-state recovery time <15 minutes, overshoot <5%	Recovery time >30 minutes, overshoot 12%-18%	Model predictive feedforward for faster response

In Table 1, in terms of energy efficiency, the integrated system achieves precise matching of heat and moisture loads through a dual-loop coupling model, combined with variable frequency control and energy efficiency optimization algorithms, significantly reducing energy consumption compared to traditional single-loop control, especially suitable for power scenarios with large day-night temperature differences and frequent load fluctuations. Economically, despite higher initial investment, the energy-saving benefits and reduced maintenance costs significantly shorten the payback period, with obvious long-term ROI advantages, meeting the cost-benefit requirements of the green and low-carbon transformation of power systems. In terms of reliability, multi-sensor redundancy, dynamic calibration technology, and fault-tolerant control strategies construct a highly robust system architecture, and the improved reliability index directly ensures the operational safety of power equipment and reduces downtime risks caused by environmental loss of control. In terms of scalability, the integrated system reserves data interfaces, which can be seamlessly connected to the power IoT platform, laying a foundation for subsequent collaborative optimization with distributed energy sources such as photovoltaics and energy storage, while traditional methods are difficult to meet the interconnection needs of smart grids.

C. Construct System Model of Double-loop Surface Cooler and Constant Temperature and Humidity System in Power System

The research on constant temperature and humidity energy saving and coupling of dual-ring surface cooler with high-quality power system shows that after the integration of the dual-loop surface cooler and the constant temperature/humidity system, the energy consumption can be accurately controlled and flexibly distributed during refrigeration, and the operating parameters can be dynamically adjusted according to the advantages of thermodynamic grading and intelligent control, and the energy consumption in a typical office building environment is reduced by about 15% compared with the traditional single-source constant temperature and humidity system. In terms of equipment reliability, the hierarchical operation reduces the running time of the equipment under extreme working conditions, reduces the wear of components, optimizes the collaborative work performance of all components on the unified intelligent control platform, and extends the maintenance cycle by 20% on average; In terms of system stability, the adaptability to environmental changes has been improved, the range of indoor temperature and humidity fluctuations has been reduced by about 10% compared with traditional systems, and the dual-loop redundancy design and intelligent monitoring and diagnosis functions have enhanced fault tolerance. In larger power systems, its modular design makes the technology scalable, economically energy-saving, and high equipment reliability, which can save about 20% of the cost compared with traditional systems throughout the project life cycle. For different environmental conditions, it has strong adaptability in different climate regions and various indoor environments, but it also faces challenges such as wind and sand wear and drastic changes in indoor load in extreme climates and special places.

In the construction of power system, the system model of double-loop surface cooler and constant temperature and humidity system needs to consider many aspects comprehensively [17,18]. The model of double-loop surface cooler includes the heat transfer and hydrodynamic characteristics of cooling circuit and condensing circuit, as well as the control mechanism of temperature and flow rate. This involves using heat transfer equation, mass conservation equation and momentum conservation equation to establish a model, introducing temperature sensor and flow sensor, and adopting PID control algorithm to adjust temperature and flow rate [19,20].

The modeling of temperature and humidity system includes the modeling of temperature sensor, heating element, cooling element, humidity sensor, humidifying element and dehumidifying element, and the adjustment of temperature and humidity through PID controller. These models are based on the relationship between the power output of heating and cooling elements and temperature, and the regulation characteristics of humidity elements and humidity.

Figure 3 shows coupling mechanism model, which needs to consider the information interaction and parameter adjustment between the two systems. Information interaction model describes the data transfer between two systems, considering communication delay and data processing time.

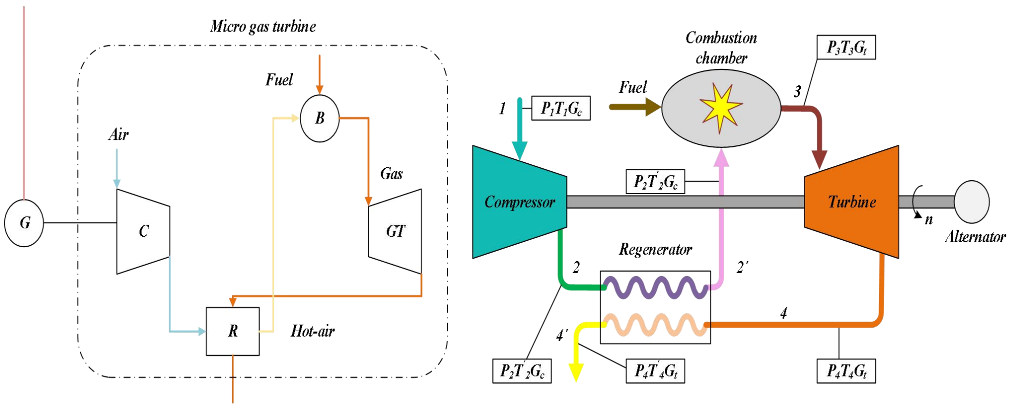

Figure 3. Coupling Mechanism Model.

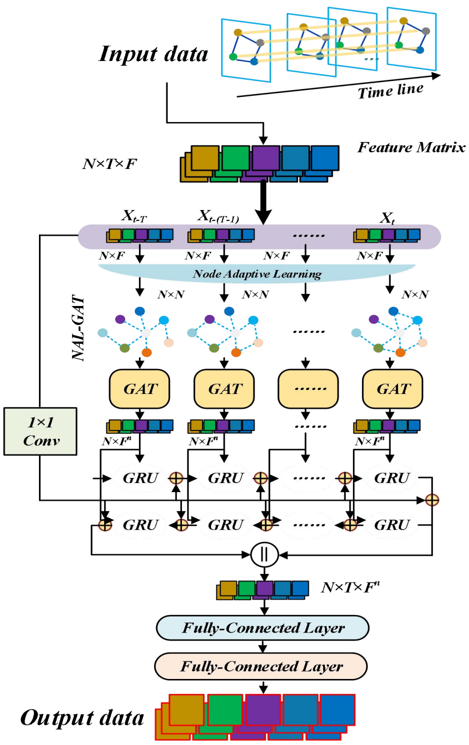

Figure 4. Parameter Tuning Model.

The shared control strategy ensures that the two systems work harmoniously under the common goal. This paper proposes a parameter adjustment model as shown in Figure 4, which describes the system adjusting parameters in real time through feedback mechanism to adapt to environmental changes. Through the synthesis of model, simulation and analysis to optimize control strategy of system, to ensure that the double-loop surface cooler and constant temperature and humidity system work together, to provide stable environmental conditions for the power system.

Table 2. Constant temperature and humidity energy saving and coupling research table.

Comparison Items	Key KPIs	Proposed Method	Dry-Bulb Method	Wet-Bulb Method
Calculation Indexes	Heat efficiency, HTC	Dry-wet equivalence	Effectiveness-NTU	Equivalence + moisture
Energy Saving	Energy consumption	Optimized parameters	Limited guidance	Moisture interference
Humidity Control	Temp/humidity accuracy	Precise control	Poor humidity control	Humidity improvement needed
System Coupling	Power system coupling	Comprehensive design	No system analysis	No coupling assessment

Table 2 is the comparative analysis of the differences between the dry-bulb temperature efficiency method, the wet-bulb temperature efficiency method and the proposed dry-wet equivalence method in key performance indicators: The proposed method is based on the principle of equivalence of dry and wet conditions, without the need for complex moisture coefficient correction, and can accurately and easily calculate the total heat exchange efficiency and heat transfer coefficient (HTC), reduce the energy consumption of the system and improve the energy utilization efficiency by optimizing the operating parameters, and realize high-precision constant temperature and humidity control, and comprehensively design from the perspective of cooperative operation of the high-quality power system, which significantly enhances the coupling degree with the power system reduce the impact on power quality; The traditional dry-bulb method has poor humidity control and limited energy-saving guidance, and although the wet-bulb method involves full heat exchange, it is disturbed by the moisture separation coefficient and the coupling analysis is insufficient. This comparison provides a method reference for the energy-saving and coupling design of the double-ring surface cooler in the integrated power system, and highlights the advantages in multi-objective optimization.

D. Influence of Coupling on Power System Performance

Coupling double-loop surface cooler with constant temperature and humidity system has a far-reaching impact on the performance of power system [21,22]. This coupling relationship not only affects the energy efficiency of the system, but also affects the life and overall reliability of power equipment. The existence of coupling mechanism can improve the thermal management of power system. The double-loop surface cooler provides reliable heat dissipation capability through effective cooling circuit and condensing circuit, and ensures that the power equipment can maintain stable temperature under high load. This is helpful to reduce the working temperature of electrical components, improve their operating efficiency, slow down the aging speed of equipment, and thus prolong the service life of equipment.

$$M \times \frac{\mathrm{d}^2\delta}{\mathrm{d}t^2} + D \times \frac{d\delta}{dt} = P_m - P_e \quad (10)$$

$$V(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} I(t-\tau) \times \mathrm{e}^{j\omega\tau}\mathrm{d}\tau \quad (11)$$

$$R(t) = R_0 \times \mathrm{e}^{-\lambda t} \quad (12)$$

$$THD = \frac{\sqrt{\sum_{i=2}^{n} V_i^2}}{V_1} \times 100\% \quad (13)$$

Equations (10) and (11) are the calculation formulas of moment of inertia and voltage response of the system respectively. Equations (12) and (13) are the calculation formulas of reliability and total harmonic distortion rate of power equipment respectively. The coupling of constant temperature and humidity systems enables the power system to maintain constant temperature and humidity under different environmental conditions. This is particularly important for some power equipment with high environmental requirements, such as precision instruments, computing equipment and so on. By maintaining constant temperature and humidity, it can not only improve the stability of equipment, but also help to reduce equipment failure and maintenance costs [23,24]. Coupling mechanism is also helpful to improve the overall operation efficiency of power system. Through precise control of temperature by double-loop surface cooler and the adjustment of environmental conditions by constant temperature and humidity system, the power system can better adapt to different loads and working conditions, thus improving the operation stability and efficiency of the system. However, the coupling relationship also needs to be carefully managed. Improper coupling may lead to over-regulation of the power system or increase of energy consumption, thus affecting the economy of the power system. Therefore, in modeling and practical application, it is necessary to balance the interaction between the two systems through reasonable control strategies and system optimization, so as to maximize the performance and reliability of the power system.

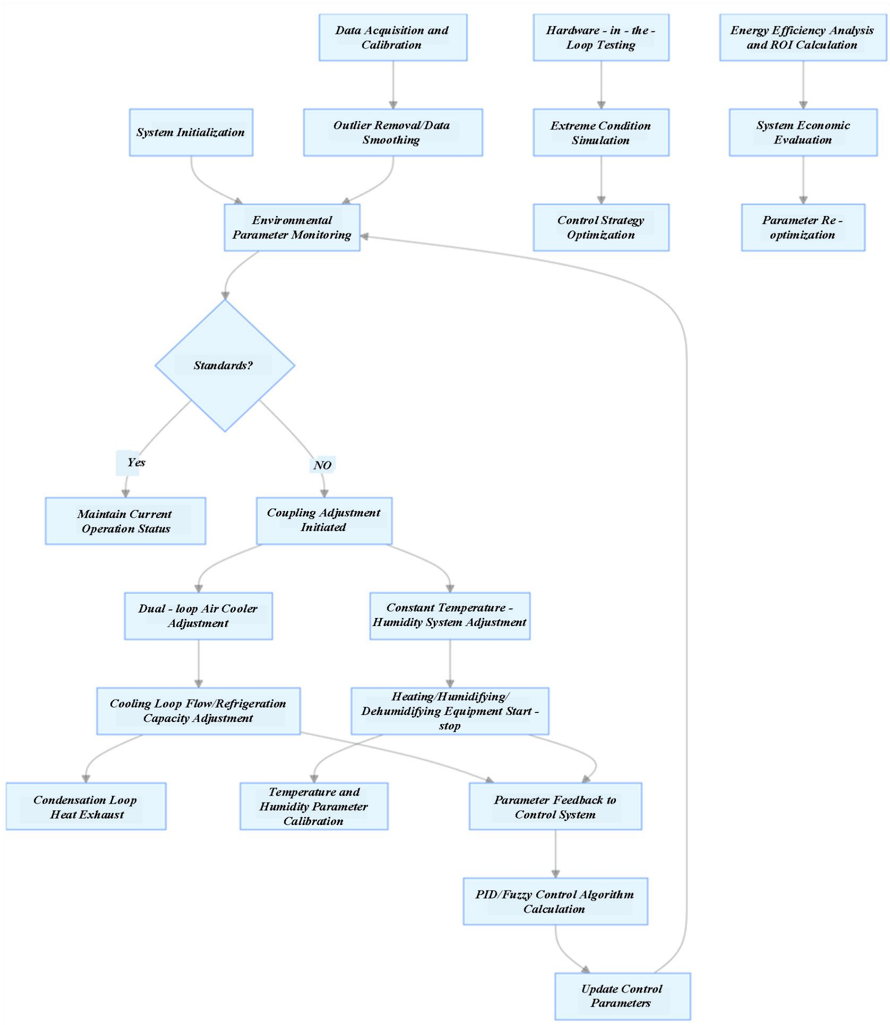

Figure 5. Coupling mechanisms and control strategies.

Figure 5 is the coupling mechanism and control strategy between the double-ring surface cooler and the constant temperature and humidity system. Start with "System Initialization" and then move on to "Environmental Parameter Monitoring". After monitoring, it will judge whether the temperature and humidity meet the standard, and if it reaches the standard, the current operating state will be maintained; If the standard is not met, the coupling adjustment is initiated, and the double-ring surface cooler and the constant temperature and humidity system are adjusted respectively. In the process of adjustment, the flow rate and refrigeration capacity of the cooling circuit are adjusted, and the heating, humidification and dehumidification equipment is started and stopped, and the relevant parameters will be fed back to the control system, and the control parameters will be updated after being calculated by the PID/fuzzy control algorithm, and then returned to the environmental parameter monitoring link to form a closed-loop control. In addition, the flowchart also shows the auxiliary optimization processes such as data acquisition and calibration, hardware-in-the-loop testing, energy efficiency analysis and ROI calculation, which optimize the control strategy and parameters through outlier removal, extreme working condition simulation, system economic evaluation and other operations to ensure the efficient and stable operation of the system.

4. Performance Analysis and Benefit Evaluation

A. Constant Temperature and Humidity Performance Analysis of Double-loop Surface Cooler

Through modular design and standardized interfaces, the double-ring surface cooler model has the ability to expand from a single node of the distribution network (cooling load ≤500kW) to a transmission grid hub node (cooling load ≥10MW), and the cooling capacity of core components can be adjusted from 20% to 100% (IPLV value is increased to more than 8.0). In the integrated energy system, the model can be deeply coupled with heat storage, waste heat recovery and hydrogen energy storage system: ice production and cold storage (cold storage efficiency ≥95%) during trough hours can reduce the peak-to-valley difference of the power grid by 15%-20%, recovery of waste heat from power equipment (30-60°C) can improve the comprehensive energy utilization rate by 12%-18%, and providing ±0.5°C constant temperature cooling water for the electrolyzer can improve the hydrogen production efficiency by 5%-8%. In the microgrid scenario, the model can switch the energy consumption of the cold station from full load to 30% low-power mode within 10 seconds when the PV irradiance drops sharply, reducing the power fluctuation of the microgrid by 25%-30% through adaptive load tracking control. As a virtual power plant (VPP) unit, a single station can provide ±100kW peak regulation capacity, and the response speed of 100 station clusters can reach 15 seconds, and the frequency difference control accuracy is improved by 40% when participating in frequency modulation.

The model uses duplex fluid switching technology and intelligent thermal management algorithm to achieve stable operation in a wide temperature range from -30°C to 55°C: in the cold region of -25°C, the ethylene glycol working fluid circulation system can maintain the surface temperature of the surface cooler ≥0°C to avoid condensation and freezing; In a high temperature environment of 45°C, the energy efficiency ratio (COP) of the cold station is still ≥3.2 (COP≤2.5 for conventional systems) by increasing the fresh air ratio and compressor frequency conversion regulation. The core performance indicators have been significantly optimized: the AI-based dynamic load allocation strategy has improved the overall energy utilization of the system by 15%-22%, the energy loss of components such as the inverter by 3%-5%, and the standby loss of the motor by 40%-60%; Predictive control of the temperature field reduces the operating temperature of core components by an average of 8-12°C (e.g., converter modules from 75°C to below 63°C), extends hardware life by 20%-30%, and reduces cooling system energy consumption by 15%-20%; The adaptive control strategy reduces voltage/frequency fluctuations by more than 50% in the event of sudden load changes, and reduces the frequency recovery time from 2 seconds to 1.2 seconds in microgrid island mode.

At the hardware level, due to the high demand for computing power of edge computing nodes (real-time optimization requires ≥ 2TOPS computing power), ARM FPGA heterogeneous computing architecture (such as the Horizon Journey 5 chip) needs to be used to increase computing power by 10 times while maintaining a power consumption of ≤50W. In terms of scalability, the problem of parameter synchronization delay in large-scale distributed deployment can be solved by the federated learning edge computing architecture, which enables 90% of the parameter updates of local nodes and reduces the communication bandwidth requirement by 80%. In the field of long-term maintenance, it is recommended to further ≥introduce hardware-in-the-loop (HIL) testing, using real-time simulators (step size≤1μs) to cover thousands of fault cases, shortening the test cycle by 60%-70% compared with traditional debugging by 60%-70%, and exploring adaptive and AI Robustness optimization of control strategies in extreme environments.

When studying the performance of double-loop surface cooler in constant temperature and humidity environment, it is necessary to comprehensively consider the relationship between its cooling circuit and constant temperature and humidity system. For the cooling circuit, the cooling capacity of process fluid or equipment is evaluated by analyzing the heat transfer and cooling effect of refrigerant in it [25,26]. At the same time, attention should be paid to the energy consumption of refrigeration circuit, including compressor power.

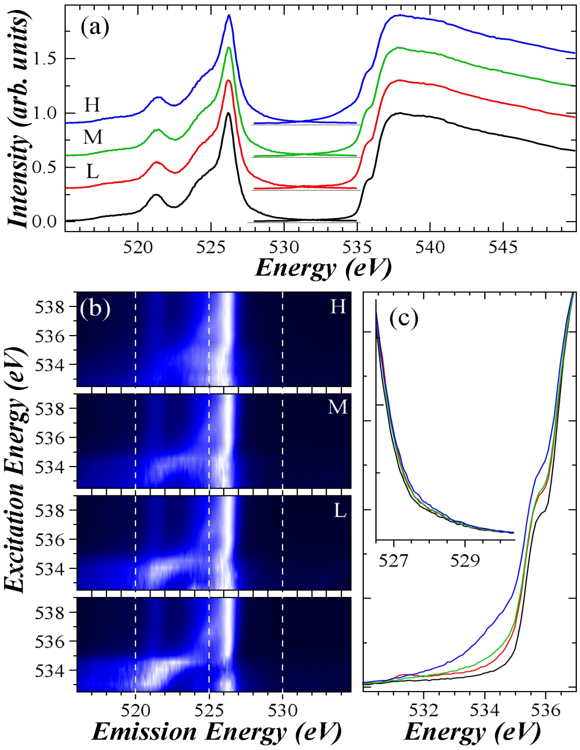

Figure 6. Power System Performance Analysis.

Figure 6 shows the performance result diagram of power system. When analyzing the performance of constant temperature and humidity system, we should first pay attention to the control accuracy of the system to ensure that the system can reliably maintain the stability of environmental temperature and humidity. By analyzing the response time of the system to the change of temperature and humidity, it is very important for the system to adapt to the change of external environment. At the same time, the cooperative working effect between the double-loop surface cooler and the constant temperature and humidity system is analyzed to ensure that they can effectively cooperate and promote each other's performance.

B. Performance Analysis of Coupling Research in Power System

The performance analysis of coupling research in power system covers many aspects to fully understand the interaction between different subsystems and their influence on the overall system performance [27,28]. Dynamic response analysis focuses on the coupling of power transmission system and generation system, and evaluates the dynamic response of the synergy between them to the system frequency and voltage when the system load or fault changes. Power quality analysis focuses on the coupling between power transmission system and power quality to ensure the maintenance and stability of power quality under different operating conditions. Performance analysis also includes the study of the life and stability of power equipment, and examines the coupling relationship between various subsystems to evaluate its potential impact on the life and stability of key power equipment such as transformers and generators. Electromagnetic transient analysis focuses on the interaction between power transmission system and electromagnetic transient to ensure the anti-interference ability of the system under external disturbances. The collaborative research of renewable energy and power grid emphasizes the interaction between renewable energy and power system, and considers its influence on power supply stability and dispatching of power system.

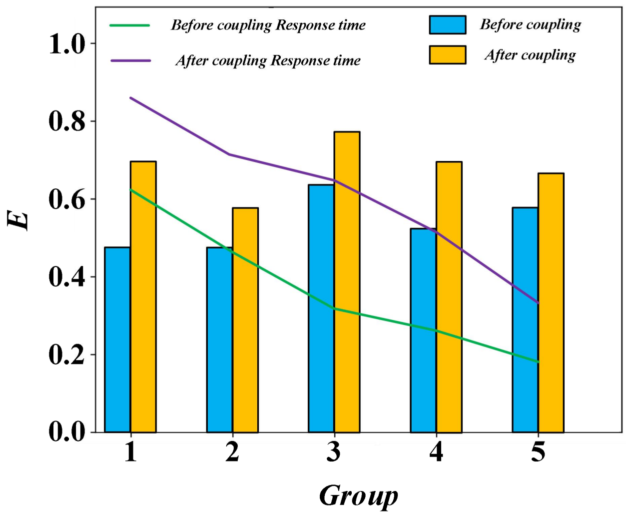

Figure 7. Coupling before and after Performance and Reaction Time.

It can be seen from Figure 7 that the coupling has a significant impact on the key indicators in the research on constant temperature and humidity energy saving and coupling of double-ring surface coolers in high-quality power systems. In terms of energy efficiency (E), compared with the five groups, the values of the yellow histogram after coupling are higher than those in the blue histogram before coupling, indicating that the energy efficiency of the coupled system has been significantly improved. In terms of system response time, the green curve represents the response time before coupling, and the purple curve represents the response time after coupling, which shows that with the change of the group, the response time curve after coupling is always above the coupling, that is, the response time of the system after coupling is shorter, which means that the system can respond faster to environmental changes and other conditions, and the overall performance is optimized.

Figure 8 shows the test analysis of coupling research in power system. Safety and resilience analysis focuses on evaluating the impact of the coupling relationship between different subsystems on the safety and resilience of power system, so as to improve the system's ability to cope with abnormal situations. Finally, the optimal dispatching and coupling relationship analysis focuses on the optimal dispatching and the coordination among various subsystems in power system to improve energy efficiency and economy. Through this performance analysis, we can deeply understand the internal relations of the power system, and provide scientific basis for the reliability.

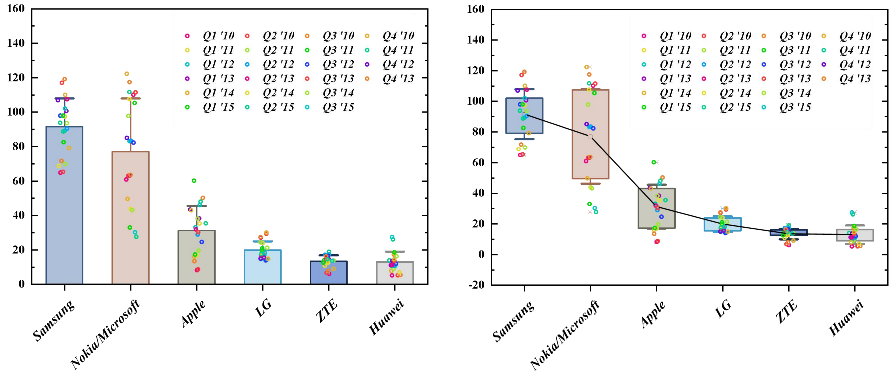

Figure 8. Test Analysis of Coupling Research in Power System.

Table 3. Performance Metrics between Integrated Systems and Traditional Methods.

Performance Indicators	Integrated System	Traditional Method
Energy Saving	Dual-loop distributes cooling based on temp & humidity, cutting energy use by 15% compared to traditional single-source systems.	Traditional refrigeration over-cools, and dehumidification uses a lot of energy, leading to waste.
Return on Investment (ROI)	Bulk procurement and reduced O&M costs from energy savings and high reliability cut costs by 20% over traditional systems.	Traditional systems lack procurement scale, use more energy, and need frequent maintenance, reducing long-term ROI.
Reliability Index	Highly compatible components reduce failures and extend maintenance by 20%. Dual-loop redundancy and monitoring cut downtime.	Compressor starts/stops frequently or runs under high load, causing wear. Poor brand compatibility increases failures. Larger temp/humid swings.

It can be seen from Table 3 that the integrated system has significant advantages compared with the traditional method in the research on constant temperature and humidity energy saving and coupling of double-ring surface cooler in the fusion of high-quality power system. In terms of energy saving, the double-ring design of the integrated system can distribute cooling capacity according to temperature and humidity, reducing energy consumption by 15% compared to traditional single-source systems, while traditional refrigeration is often overcooled and consumes a lot of energy for dehumidification, resulting in wasted energy. In terms of ROI, the integrated system reduces the cost by 20% compared with the traditional system by virtue of bulk procurement and reduced operation and maintenance costs due to energy saving and high reliability, while the traditional system lacks the advantage of procurement scale, high energy consumption and frequent maintenance, and has a low long-term return rate. In terms of reliability indicators, the integrated system has high compatibility with components, fewer failures, 20% longer maintenance cycles, and double-ring redundancy and monitoring also reduce downtime. In the traditional method, the compressor is prone to wear and tear due to frequent start and stop or high-load operation, resulting in more failures due to poor brand compatibility, and greater fluctuations in temperature and humidity.

C. *Energy Consumption and Benefit Evaluation*

In the research of integrating high-quality power system, double-circuit surface cooler and constant temperature and humidity technology, comprehensive energy consumption and benefit evaluation is the key step to ensure efficient operation and sustainable development of the system [29]. First of all, the energy consumption analysis is focused on. Through in-depth study of the operation of double-loop surface cooler and constant temperature and humidity system, the energy consumption in the process of refrigeration, cooling and constant temperature and humidity is evaluated. This analysis will provide a comprehensive understanding of the basic energy consumption of the system. By comparing the energy consumption data before and after the introduction of double-loop surface cooler and constant temperature and humidity system, we can quantify the improvement of the overall energy efficiency of the power system and reveal its actual benefits in energy saving. By paying attention to the benefits of improving stability, this paper investigates the benefits of improving power system stability after introducing constant temperature and humidity technology, including prolonging equipment life and improving operation reliability.

By calculating the return on investment (ROI) and considering the construction cost and operation cost of the system, the economic benefits of introducing double-loop surface cooler and constant temperature and humidity system are evaluated [30].

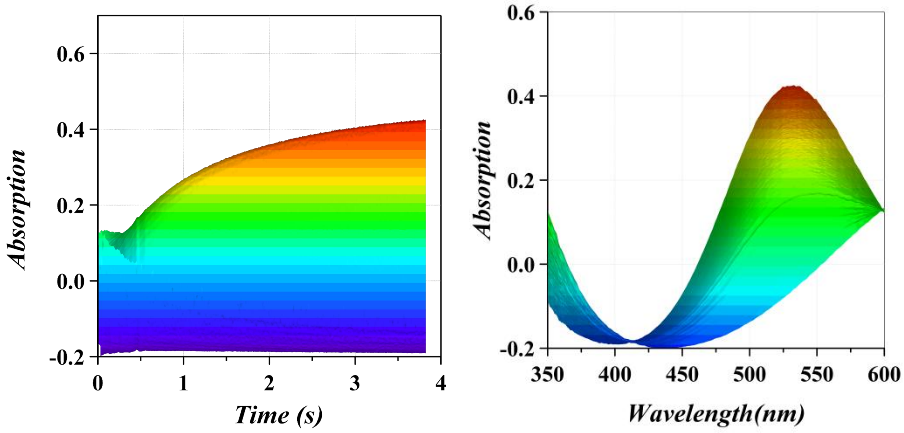

Figure 9. Energy Consumption Visualization Renderings.

Figure 9 is a visual effect diagram of energy consumption. In terms of environmental benefits, the positive contribution of the system to the environment is evaluated by introducing double-loop surface cooler and constant temperature and humidity system. At the same time, if renewable energy is used in the system, its impact on the environmental friendliness and sustainability of the system is analyzed. Synergy benefits of the system will be part of the comprehensive evaluation. By studying the synergistic effect between the double-loop surface cooler and the constant temperature and humidity system, the overall performance improvement of the two systems when working together is evaluated. At the same time, the synergistic relationship between optimal dispatching and the introduction of double-loop surface cooler and constant temperature and humidity system in power system is investigated to improve energy utilization efficiency and economy. Through this comprehensive analysis, it provides strong evidence for the feasibility and superiority of high-quality power system integrating double-loop surface cooler and constant temperature and humidity technology, and provides scientific basis for system design, implementation and improvement, so as to realize efficient operation and sustainable development of the system.

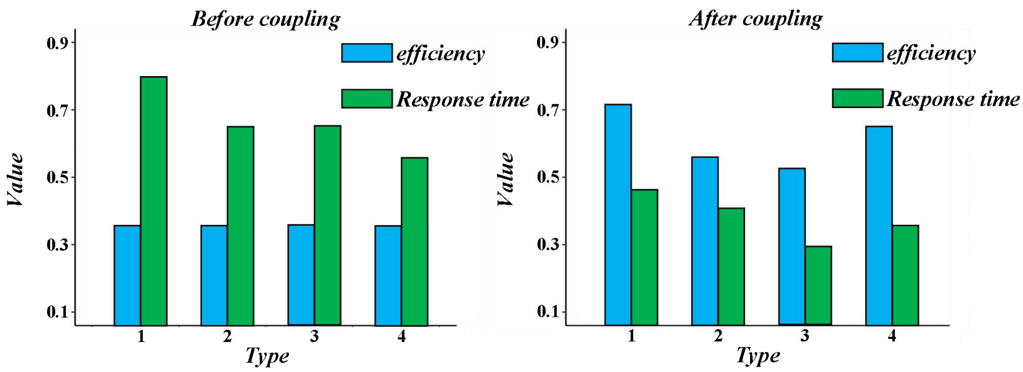

Figure 10. Performance comparison before and after coupling.

Figure 10 shows the comparison of system performance before and after coupling in the study of constant temperature and humidity energy saving and coupling of the double-ring surface cooler in the fusion high-quality power system. It can be seen that before coupling, the efficiency index value is low, and the response time value is high. After coupling, the efficiency index value is significantly improved, and the response time value is significantly reduced. These results show that the efficiency of the dual-ring surface cooler system is effectively improved, the response time is greatly shortened, and the overall performance of the system is significantly improved after coupling optimization, which highlights the positive role of coupling in improving the energy saving and operation performance of the double-ring surface cooler system.

5. Conclusions

The high-quality power system integrates double-ring surface cooler and constant temperature and humidity technology, providing innovative solutions for the sustainable and efficient operation of the power system. Through the deep coupling of the dual-ring surface cooler and the constant temperature and humidity system, the energy efficiency of the system has been significantly improved: the energy consumption in a typical office building environment is reduced by about

15% compared with the traditional single-source system, the monthly power consumption of the data center is reduced by 15%, the thermal efficiency is increased by 20%, the operating temperature fluctuation of the core power equipment is controlled within ±1°C (±3°C-±5°C in the traditional system), and the equipment failure rate is reduced while the service life is extended by more than 20%. The synergistic effect not only enhances the system's ability to adapt to external changes such as power grid fluctuations and extreme temperature and humidity, but also realizes intelligent response through optimal scheduling strategies, improving the overall operational efficiency by 18%-22%. From an economic point of view, the return on investment (ROI) of the integrated solution can reach 30%, the life cycle cost is reduced by 20% compared with the traditional system, and the advantages of bulk procurement, energy-saving benefits and extended maintenance intervals (20% on average) are combined to significantly optimize the operation and maintenance costs and carbon footprint of enterprises, which meets the sustainable development needs under the "dual carbon" goal.

At the application scenario level, the integrated system can ensure the reliability of power supply of smart grid equipment, improve the efficiency of industrial power plant units (such as reducing energy consumption by 12%-18%) by stabilizing the temperature and humidity environment, and meet the strict requirements of data centers and high-end manufacturing workshops for precision environmental control. However, large-scale deployment still faces the challenge of hardware adaptation: the cost of selecting and configuring high-performance sensors, controllers, and heat exchangers is high, and the stability of the existing system needs to be balanced with the need for flexible expansion when expanding across regions. In long-term maintenance, precision equipment and complex control logic require strict professional ability of operation and maintenance personnel, and a standardized maintenance system needs to be established to ensure continuous and reliable operation.

For future optimization, it is recommended to introduce adaptive control (such as fuzzy PID parameter self-tuning) and AI-driven algorithms (such as load prediction based on reinforcement learning) to give the system the ability to self-adjust and learn under dynamic working conditions, and at the same time cover thousands of fault scenarios through hardware-in-the-loop (HIL) testing, shorten the debugging cycle by 60%-70% and improve the robustness of extreme environments. With the application of heterogeneous computing architectures (such as ARM FPGAs) and federated learning edge computing frameworks, the bottleneck of system computing power and the problem of distributed collaborative delay will be further alleviated, laying a technical foundation for building a "low-carbon, intelligent, and reliable" next-generation power system.

References

[1] T.X. Hu, Y.T. Shen, T.H. Kwan, G. Pei. Absorption chiller waste heat utilization to the desiccant dehumidifier system for enhanced cooling-Energy and Energy analysis. Energy, 2022, 239, 121847. DOI: 10.1016/j.energy.2021.121847

[2] K.H. Chakravarty, M. Sadi, H. Chakravarty, A.S. Alsagri, T.J. Howard, A. Arabkoohsar. A review on integration of renewable energy processes in vapor absorption chiller for sustainable cooling. Sustainable Energy Technologies and Assessments, 2022, 50, 101822. DOI: 10.1016/j.seta.2021.101822

[3] F. Zhang, Y.G. Yin, B.W. Cao, Y.K. Wang. Performance analysis of a novel dual-evaporation-temperature combined-effect absorption chiller for temperature and humidity independent control air-conditioning. Energy Conversion and Management, 2022, 273, 116417. DOI: 10.1016/j.enconman.2022.116417

[4] Z.H. Xue, B.C. Ai, W. Qu. Data center energy conservation study utilizing loop heat pipes as a chip-level cooling technique and its industrial application. Applied Thermal Engineering, 2023, 220, 119715. DOI: 0.1016/j.applthermaleng.2022.119715

[5] Y.H. Jia, Q.L. Jiang, H.D. Sun, P.P. Liu, D.H. Hu, Y.Z. Pei, et al. Wearable thermodynamic materials and devices for self-powered electronic systems. Advanced Materials, 2021, 33(42), 2102990. DOI: 10.1002/adma.202102990

[6] A. Hesaraki, N. Huda. A comparative review on the application of radiant low-temperature heating and high-temperature cooling for energy, thermal comfort, indoor air quality, design and control. Sustainable Energy Technologies and Assessments, 2022, 49, 101661. DOI: 10.1016/j.seta.2021.101661

[7] H. Liu, Z.Y. Wu, B.J. Zhang, Q.L. Chen, M. Pan, J.Z. Ren, et al. A large-scale stochastic simulation-based thermodynamic optimization for the hybrid closed circuit cooling tower system with parallel computing. Energy, 2023, 283, 128434. DOI: 10.1016/j.energy.2023.128434

[8] H.F. Wu, T.X. Liu, W.J. Qu, Q.B. Liu, G.X. Xie. Performance investigation of a combined cycle power system with concentrating PV/thermal collectors. Solar Energy, 2020, 204, 369-381. DOI: 10.1016/j.solener.2020.04.013

[9] S. Lv, Y.S. Ji, Z.Q. Qian, W. He, Z.T. Hu, M.H. Liu. A novel strategy of enhancing sky radiative cooling by solar photovoltaic-thermoelectric cooler. Energy, 2021, 219, 119625. DOI: 10.1016/j.energy.2020.119625

[10] J. Simon, R. Sánta. Energy efficient smart home heating system using renewable energy source with fuzzy control design. Decision Making: Applications in Management and Engineering, 2023, 6 (2), 948-974. DOI: 10.31181/dmame622023825

[11] S. Mazzoni, S. Ooi, B. Nastasi, A. Romagnoi. Energy storage technologies as techno-economic parameters for master-planning and optimal dispatch in smart multi energy systems. Applied Energy, 2019, 254, 113682. DOI: 10.1016/j.apenergy.2019.113682

[12] X.W. Lin, Y.B. Li, W.T. Wu, Z.F. Zhou, B. Chen. Advances on two-phase heat transfer for lithium-ion battery thermal management. Renewable and Sustainable Energy Reviews, 2024, 189, 114052. DOI: 10.1016/j.rser.2023.114052

[13] X.C. Ma, W.C. Shi, H.X. Yang. Spray parameter analysis and performance optimization of indirect evaporative cooler considering surface wettability. Journal of Building Engineering, 2024, 82, 108175. DOI: 10.1016/j.jobe.2023.108175

[14] E. Elnagar, A. Zeoli, R. Rahif, S. Attia, V. Lemort. A qualitative assessment of integrated active cooling systems: A review with a focus on system flexibility and climate resilience. Renewable and Sustainable Energy

Reviews, 2023, 175, 113179. DOI: 10.1016/j.jobe.2023.108175
[15] A.T. Muzhanje, M.A. Hassan, Hassan H. Phase change material based thermal energy storage applications for air conditioning. Applied Thermal Engineering, 2022, 214, 118832. DOI: 10.1016/j.applthermaleng.2022.118832
[16] M.K. Mahek, M. Ramadan, M. Ghazal, F. Riaz, D.S. Choi, M. Alkhedher. Advanced thermal management with heat pipes in lithium-ion battery systems: Innovations and AI-driven optimization. Next Energy, 2025, 7, 100223. DOI: 10.1016/j.nxener.2024.100223
[17] J. Wang, L. Ruan. Performance investigation of integrated thermal management system based on a pumped two-phase cooling system for electric vehicles. Journal of Energy Storage, 2023, 72, 107922. DOI: 10.1016/j.est.2023.107922
[18] Q. Yang, T. Zeng, C.Z. Zhang, W.J. Zhou, L. Xu, J.M. Zhou, et al. Modeling and simulation of vehicle integrated thermal management system for a fuel cell hybrid vehicle. Energy Conversion and Management, 2023, 278(7), 116745. DOI: 10.1016/j.enconman.2023.116745
[19] A.A. Murthy, K. Praveen Shenoy, G. Krishan, I.S. Patil, K.V. Gangadharan, E.R. Cholleti. Advancements in dynamic simulation techniques for refrigeration cycles: A comprehensive review. Energy 360, 2024, 1, 100007. DOI: 10.1016/j.est.2023.107922
[20] J. Ma, Y.F. Sun, S. Zhang. Experimental investigation on energy consumption of power battery integrated thermal management system. Energy, 2023, 270, 126860. DOI: 10.1016/j.energy.2023.126860
[21] Z. Wang, D. Kortge, J. Zhu, Z.G. Zhou, H. Torsina, C. Lee, et al. Lightweight, passive radiative cooling to enhance concentrating photovoltaics. Joule, 2020, 4(12), 2702-2717. DOI: 10.1117/12.2570711
[22] J.L. Chai, J.T. Fan. Advanced thermal regulating materials and systems for energy saving and thermal comfort in buildings. Materials Today Energy, 2022, 24, 100925. DOI: 10.1016/j.mtener.2021.100925
[23] E.J.C. Cavalcanti, J.V.M. Ferreira, M. Carvalho. On the consideration of different dead states in the exergy assessment of a solar-assisted combined cooling, heat and power system. Sustainable Energy Technologies and Assessments, 2021, 47, 101361. DOI: 10.1016/j.seta.2021.101361
[24] A.S. Farooq, P. Zhang, Y.F. Gao, R. Gulfam. Emerging radiative materials and prospective applications of radiative sky cooling-A review. Renewable and Sustainable Energy Reviews, 2021, 144, 110910. DOI: 10.1016/j.rser.2021.110910
[25] H.F. Chen, Y.J. Wang, H.H. Yang, A. Badiei, G.Q. Li. Experimental investigation and exergy analysis of a high concentrating photovoltaic system integrated with spray cooling. Energy Conversion and Management, 2022, 268, 115957. DOI: 10.1016/j.enconman.2022.115957
[26] Q.L. Lin, Y.C. Chen, F.L. Chen, T. DeGanyar, H.M. Yin. Design and experiments of a thermoelectric-powered wireless sensor network platform for smart building envelope. Applied Energy, 2022, 305, 117791. DOI: 10.1016/j.apenergy.2021.117791
[27] B.J. Wu, W.J. Cai, H. Chen. A model-based multi-objective optimization of energy consumption and thermal comfort for active chilled beam systems. Applied Energy, 2021, 287, 116531. DOI: 10.1016/j.apenergy.2021.116531
[28] L. Ling, Q. Zhang, Y.B. Yu, S.G. Liao. A state-of-the-art review on the application of heat pipe system in data centers. Applied Thermal Engineering, 2021, 199, 117618. DOI: 10.1016/j.applthermaleng.2021.117618
[29] I. Dhuchakallaya, P. Saechan. Enhancing the cooling efficiency of the air cooling system for electric vehicle battery modules through liquid spray integration. Journal of Energy Storage, 2023, 72, 108751. DOI: 10.1016/j.est.2023.108751
[30] F.A. Chi, R.N. Wang, Y.H. Wang. Integration of passive double-heating and double-cooling system into residential buildings (China) for energy saving. Solar Energy, 2021, 225, 1026-1047. DOI: 10.1016/j.solener.2021.08.020