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Improvement of the Heat Exchanger Device Based on Advanced Control Algorithms

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***Abstract**: Heat exchangers are vital for industrial heat transfer and recovery. But traditional ones face problems in complex working conditions, with insufficient control accuracy to meet modern industry's high - efficiency and energy - saving needs. This research focuses on optimizing heat exchanger performance using advanced control algorithms. First, it comprehensively analyzes the heat exchanger's working principle, structure, and existing control strategies, highlighting the limitations of traditional control methods. Considering the heat exchanger's non - linear, time - varying, and large - lag features, algorithms like MPC, fuzzy control, and neural network control are chosen for theoretical study. Mathematical and simulation models are built, and MATLAB is used for simulation and comparison. Advanced control algorithms are applied to real - world heat exchanger devices, and an experimental platform is set up for on - site tests. The results show that these advanced algorithms remarkably enhance the heat exchanger's control performance, providing a practical way for its application optimization.*

***Keywords:** heat exchanger; advanced control algorithms; simulation; experiment; performance improvement*

1. Introduction

A heat exchanger is a device used for heat transfer and is widely applied in industrial production and the energy field. It achieves the efficient utilization of energy by transferring heat from one fluid to another. The research and development of heat exchangers have always been an important research area both at home and abroad.

1.1. Domestic Research Status

(1)Material and Structure Optimization: Researchers are committed to developing new materials and optimizing the structure of heat exchangers to improve their heat transfer performance and durability. For example, methods such as using high thermal conductivity materials, increasing the heat transfer area, and improving the fluid flow pattern can significantly enhance the efficiency of heat exchangers. [1]Research institutions and enterprises at home and abroad continue to innovate in heat exchanger materials and manufacturing technologies. For instance, for applications in high-temperature and high-pressure environments, new materials with high temperature resistance and corrosion resistance are developed; advanced manufacturing processes, such as 3D printing technology, are adopted to realize the manufacturing of heat exchangers with complex structures.

(2)Research on Fluid Dynamic Characteristics: Researchers explore the heat transfer and flow characteristics of fluids in heat exchangers through numerical simulations and experimental studies. Studying these characteristics can help optimize the design and operating parameters of heat exchangers, thereby improving their heat transfer efficiency. Researchers keep proposing new performance optimization strategies and energy-saving technologies to improve the heat transfer efficiency and energy utilization rate of heat exchangers. The researchers found that optimizing tube bundle design, fluid flow channels, increasing heat transfer surface area and fluid flow rate, and reducing heat transfer resistance can improve energy utilization [2].

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(3)Energy Conservation and Environmental Protection: With the increasing prominence of energy and environmental issues, researchers have also started to pay attention to the energy conservation and environmental protection performance of heat exchangers. They are committed to developing highly efficient and energy-saving heat exchangers to reduce energy consumption and environmental pollution.

1.2. Foreign Research Status

(1) Application of New Materials: Some foreign research teams are dedicated to developing new materials, such as nanomaterials and composite materials, for the manufacturing of heat exchangers. These new materials have excellent thermal conductivity and mechanical properties, which can further improve the efficiency and durability of heat exchangers. With the progress of science and technology and the change of social needs, the research on heat exchangers in new application fields has also received increasing attention. For example, in the new energy field, researchers explore the application of heat exchangers in renewable energy systems such as solar energy and geothermal energy; in the biomedical field, researchers study the application of micro heat exchangers in fields such as extracorporeal circulation and bioreactors.

(2) Multifunctional Heat Exchangers: Some research focuses on integrating heat exchangers with other functions, such as energy storage, cold storage, heat storage, etc. In this way, more efficient energy utilization can be achieved, and the overall performance of the system can be improved.

(3) Process Integration and Optimization: Researchers are committed to improving the overall energy efficiency of heat exchanger systems through process integration and optimization design. They use advanced optimization algorithms and models to comprehensively optimize the heat exchanger system to achieve the best energy utilization effect. aiming at the problems of fouling accumulation and corrosion that may occur during the operation of heat exchangers, researchers at home and abroad are committed to developing cleaning technologies and maintenance strategies to extend the service life and stability of heat exchangers.

1.3. Research Significance

1) Improving Energy Utilization Rate: Heat exchangers can be used to transfer heat between fluids, enabling the system to use energy more efficiently. By optimizing the design and operation of heat exchangers, energy consumption can be minimized, and energy costs can be reduced. Researchers are committed to improving the heat transfer efficiency and energy utilization rate of heat exchangers to achieve more effective heat transfer and energy conservation.

2) Material and Design Optimization: Researchers explore the performance, thermal conductivity characteristics, and durability of different materials, as well as the influence of different design parameters on the performance of heat exchangers, to find the best material combination and design scheme.

3) Improving Industrial Production Processes: In industrial production, many processes require the control of temperature and heat transfer. Heat exchangers can be used to regulate the temperature of fluids, ensuring that the production process proceeds within an appropriate temperature range, thereby improving production efficiency and product quality.

4) Research on Fluid Mechanics: Through fluid mechanics simulation and experiment, the flow law and heat transfer characteristics of the fluid inside the heat exchanger is understood, and the flow design and structure of the heat exchanger are optimized.

5) Enhancing Environmental Protection Awareness: Through the research on heat exchangers, more environmentally friendly designs and technologies can be developed to reduce the impact on the environment. For example, designing more efficient heat exchangers can reduce the demand for fossil fuels, thereby reducing greenhouse gas emissions.[3]

6) Research on Corrosion Resistance and Cleanliness: Researchers pay attention to the problems of corrosion and fouling accumulation that may be encountered during the use of heat exchangers, and look for material coatings and cleaning technologies to improve the durability and maintainability of heat exchangers.

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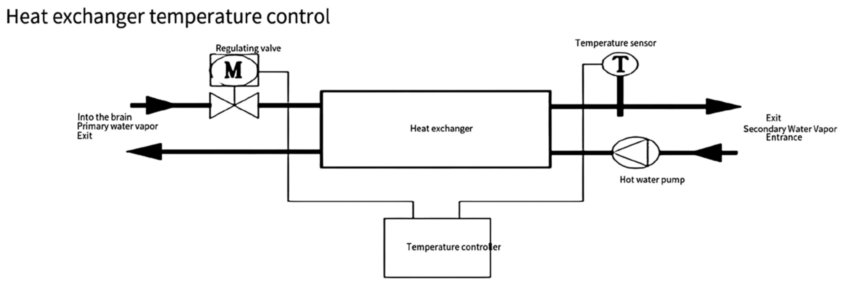
2. Design Scheme

2.1. Upgrade and Transformation Scheme of the Hardware System

2.1.1. Selection and Installation of High - Precision Sensors

(1) Temperature Sensors: High - precision thermocouple or thermal resistance temperature sensors are selected, with a measurement accuracy of up to ±0.1°C. Temperature sensors are installed at the inlets and outlets of both the hot and cold media of the heat exchanger respectively to ensure accurate acquisition of temperature information at each key position. For example, armored thermocouple sensors are adopted, which have the advantages of fast response speed and strong anti - interference ability, and can timely and accurately reflect temperature changes.as is shown in Figure 1.



Serial number	Name	Model
1	Water pipe temperature sensor	HL-SW Series
2	Temperature controller	HL8102 Series/CH402 Series
3	Electric Control Valve	HL series electric control valve

Figure 1. Heat exchanger temperature control

(2) Flow Sensors: High - precision electromagnetic flow sensors or turbine flow sensors are selected, and the measurement accuracy can be controlled within ±0.5% FS (Full Scale). They are installed on the pipelines of the hot and cold media to accurately measure the medium flow. For heat exchanger applications with large flow rates, electromagnetic flow sensors are more suitable because of their characteristics such as no pressure loss and wide measurement range. As is shown in Figure 2.For applications with small flow rates and extremely high precision requirements, turbine flow sensors can provide more accurate measurement results.

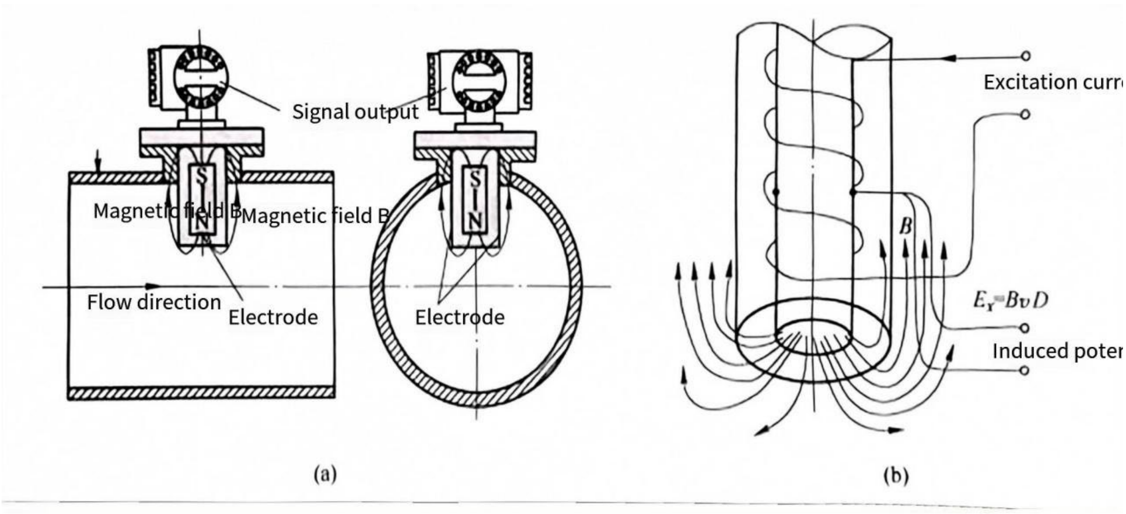


Figure 2. Structure and Measurement Principle of Insertion Electromagnetic Flow Sensor

2.1.2. Configuration of High - Performance Controllers

A programmable logic controller (PLC) or a distributed control system (DCS) is adopted as the core controller. A model with powerful computing capabilities and rich communication interfaces is selected. For example, a high - end PLC from Huachen Zhitong is chosen. It has a high - frequency processor and a large memory capacity, which can quickly handle complex calculation tasks in the model predictive control algorithm and a large amount of data operations in the neural network control algorithm. Meanwhile, this controller is equipped with multiple high - speed communication ports, which can conveniently conduct data interaction with sensors, actuators, and the host computer, ensuring the timely and accurate transmission of control instructions and the rapid reception and processing of feedback data.as is shown in Figure 3.

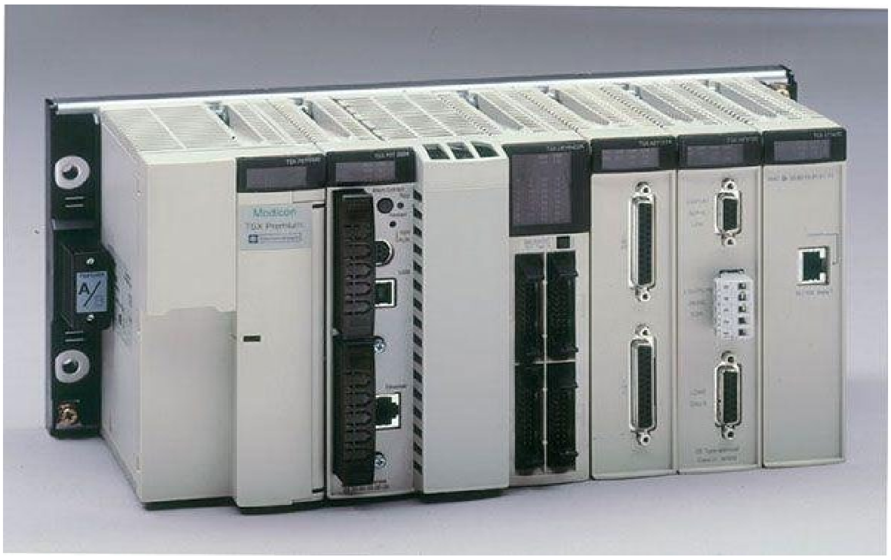


Figure 3. PLC (Programmable Logic Controller)

2.1.3. Construction of a High - Speed and Stable Communication Network

An industrial Ethernet communication network is constructed, and optical fibers are used as the transmission medium to ensure high - speed and stable communication. The network topology can adopt a ring - redundant structure. When a certain link fails, the data can automatically switch to the backup link to ensure uninterrupted communication. The network transmission rate should be no less than 100 Mbps to meet the requirements of a large amount of real - time data transmission. Devices such as switches and routers are set up in the network, and network addresses and subnet masks are reasonably planned to ensure efficient and stable communication between various devices. For example, an industrial - grade fiber optic switch is selected, which has functions such as port isolation and VLAN division, effectively improving the security and reliability of the network.

2.2. Key Points in Software System Design and Development

2.2.1. Programming Implementation of Control Algorithms

Programs for the model predictive control and neural network control algorithms are written in the selected development environment of the controller or the host computer. For model predictive control, based on the previously established mathematical model of the heat exchanger and the optimized objective function, high - level programming languages (such as ladder diagram language, structured text language, or C language) are used. Functional modules such as model prediction, optimization calculation, and control action output are implemented, and the code is optimized and encapsulated to improve the execution efficiency and maintainability of the program. For neural network control, the trained neural network model is converted into a code form that can run in the controller or the host computer. Some specialized neural network conversion tools or library functions can be used to embed parameters such as the weights and thresholds of the neural network into the code, implementing functions such as data input, neural network calculation, and prediction output, so as to generate corresponding control instructions based on the prediction results, as is shown in Figure 4.

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```
real_time_data = preprocess_data(collect_real_time_data())  # Collect and preproce
ss real-time data prediction = model.predict(np.array([real_time_data]))
# Adjust the control variables according to the prediction results, such as adjusting the flo
# An appropriate delay can be added to accommodate the response time of the hardware
time.sleep(1)
```

Figure 4. Cyclic code for real-time data collection and prediction

2.2.2. Design and Function Development of the Human - Machine Interface (HMI)

An intuitive and user - friendly human - machine interface is designed to facilitate operators in monitoring and operating the heat exchanger device. Real - time operating parameters of the heat exchanger, such as inlet and outlet temperatures, medium flow rates, and energy consumption data, are displayed on the HMI. Information like temperature change trends and flow curves is presented in the form of charts, enabling operators to intuitively understand the working status of the heat exchanger. At the same time, a parameter setting area is set up, where operators can set the target outlet temperature of the heat exchanger, adjust weight coefficients in the control algorithm, and other parameters, realizing flexible adjustment of the heat exchanger's control strategy. In addition, the HMI should also have an alarm function. When an abnormal situation occurs during the operation of the heat exchanger (such as excessively high or low temperature, abnormal flow rate, etc.), an audible and visual alarm signal is promptly issued, and corresponding alarm information is displayed to remind operators to take action. For example, a visual programming tool is used to develop the HMI. The interface layout is quickly constructed by dragging and dropping controls and setting attributes, and then corresponding event - handling programs are written to implement functions such as data display, parameter setting, and alarm.as is shown in Figure 5.

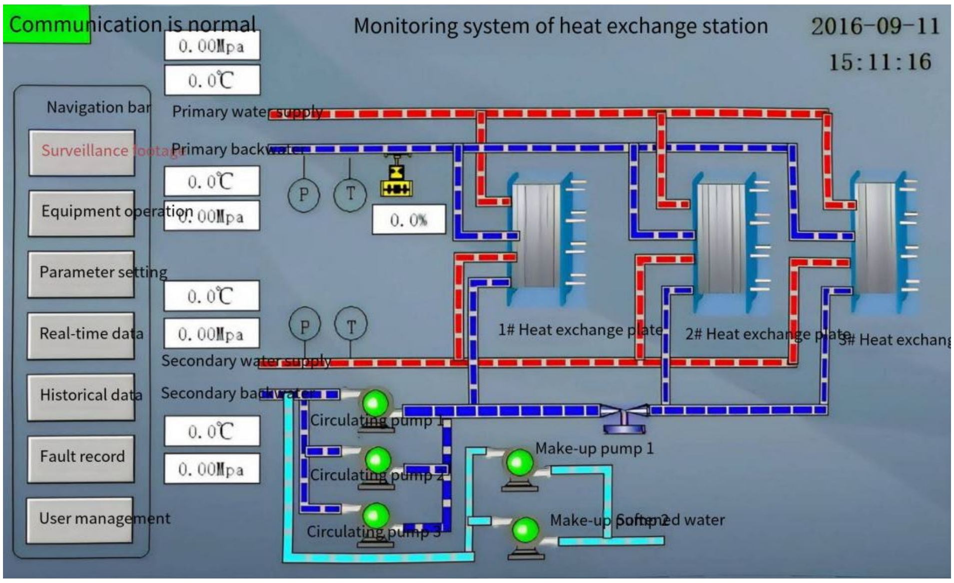

Figure 5. Software operation interface

2.2.3. Construction of the Data Storage and Management System

A database management system for the heat exchanger's operating data is established to store historical operating data, control algorithm parameters, alarm records, and other information. Appropriate database management software, such as a relational database like MySQL or SQL Server, is selected. The database table structure is designed, including a data collection table (used to store real - time collected data such as temperature, flow rate, and energy consumption), a parameter table (used to store various parameter settings of the control algorithm), an alarm table (used to record information such as the time, type, and handling status of alarm events), etc. Database operation programs are written to implement functions such as data insertion, query, update, and deletion. The data in the database is backed up regularly to prevent data loss. The data in the database can also be used for data analysis and report generation, providing data support for the performance evaluation, fault diagnosis, and optimized control of the heat exchanger.

3. Theoretical Design Calculation

In practical application problems, the relationships between variables are hardly simple linear ones but rather nonlinear, which makes the analysis of practical problems quite difficult. To find out the relationships between these variables, nonlinear fitting is required. Selecting an appropriate nonlinear fitting model is particularly important. Common nonlinear fitting models include power function models, exponential function models, polynomial models, etc. Among them, the polynomial model plays an important role in nonlinear fitting analysis. The optimal criterion for polynomial curve fitting is based on the commonly used least - squares principle. The constructed function

P(X)is a polynomial with a degree less than the number of observed values. That is, given ‘n’discrete data points(xj,yji)(i=1,2,3,...,n)a polynomial P(X)of degreem(m⩽n)is constructed:

$$P(x) = a_1^{x^m} + a_2 x^{m_1} + a_3 x^{m_2} + \cdots + a_m x + a_{m+1} \quad (1)$$

The evaluation of curve fitting has two factors: one is the deviation

(residual)**J=(p(xi)-yi)2**of the fitted polynomial at each node; the other is the coefficient of determination **γ2=1-J/S**(where **S** has its specific meaning).For a better fit, the value of **J** should be closer to 0, and the value of **γ2** should be closer to 1. As shown in Table 1, for LA10B, taking the heat - exchange area as the variable, a total of 6 sets of data for the net weight and water - filled weight of the equipment are obtained. However, in engineering design, if the heat - exchange area calculated for model selection is **40m^{2}**, the net weight and water - filled weight need to be calculated through linear interpolation. If the discrete data can be represented by a mathematical function, rapid calculation can be carried out. By using polynomial fitting for the weight data, the discrete data values are converted into a mathematical equation to realize the functions of intermediate data interpolation and data expansion. Taking the LA10B series as an example, as is shown in Table 1, fitting the 6 sets of data in Table 1 results in the quadratic trinomial**y=430+9.41x+3.95e-17x^{2}**the sum of squared residuals**j=1.775e^{-26}**(close to **0**), and the fitting calculation gives**γ2=1**,indicating good simulation accuracy. In the formula, \(x\) is the heat - exchange area parameter on the abscissa, and \(y\) is the net weight data parameter of the equipment. The mathematical equation converts the 6 sets of discrete data into a continuous curve. Using the functional relationship of the curve, by inputting any value of the heat - exchange area in the interactive interface, the corresponding net weight data of the equipment can be calculated.[4]

Table 1. Weight calculation table for LA10B

Design pressure 0.6 MPa		
Heat transfer area/m2	Net weight/kg	Water weight / kg
17	590	680
34	750	930
51	910	1170
68	1070	1420
85	1230	1660
102	1390	1910

4. Working Principle and Performance Analysis

Heat exchangers are crucial in industrial production, and the heat exchanger device based on advanced control algorithms demonstrates excellent performance.

Its working principle mainly includes Model Predictive Control (MPC) and Neural Network

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Control (NN). MPC constructs a mathematical model based on the physical principles of the heat exchanger and establishes a state - space model by comprehensively considering factors such as the flow rates of hot and cold media and the inlet and outlet temperatures. In each control cycle, it predicts the future system output, such as the change in the outlet temperature of the heat exchanger, based on the current state information. Then, it constructs an optimization function by combining multiple objectives, such as minimizing the deviation between the outlet temperature and the set value, the change amplitude of control actions, and energy consumption. Considering constraints such as the upper and lower limits of flow rates and temperature ranges, it uses an optimization algorithm to solve for the optimal control sequence, implements only the first - step control action, and conducts cyclic optimization. NN relies on a large amount of operating data. By collecting various types of data under different working conditions of the heat exchanger, it trains the neural network to enable it to learn the complex non - linear relationship between the input and output. During operation, it inputs real - time data into the trained neural network to predict the outlet temperature and energy consumption, and adjusts control variables such as the flow rates of hot and cold media accordingly.

In terms of performance, the temperature control accuracy is significantly improved. Traditional control methods struggle to handle changes in working conditions, resulting in large temperature deviations. However, MPC can optimize the flow rates in real - time according to the working conditions, and NN can sense the temperature trend in advance. Both enable the outlet temperature to closely track the set value. For example, in chemical production, it can ensure the stable quality of products. Energy consumption is significantly reduced. MPC avoids excessive heating and cooling, and NN intelligently searches for the strategy with the lowest energy consumption. For example, in the application of power condensers, it can reduce the pump power consumption by about 15% - 20%. The system stability is enhanced. Traditional control methods are prone to instability due to variable coupling. MPC coordinates the changes of variables, and NN conducts stable regulation. For example, in chemical heat - exchange networks or pharmaceutical heat - exchange applications, it can reduce oscillations, lower the risk of equipment wear and failure, extend the service life, and reduce maintenance costs, strongly promoting the efficient and stable operation of industrial production.

After the production is completed, the physical appearance photo of the product is shown in Figure 6.

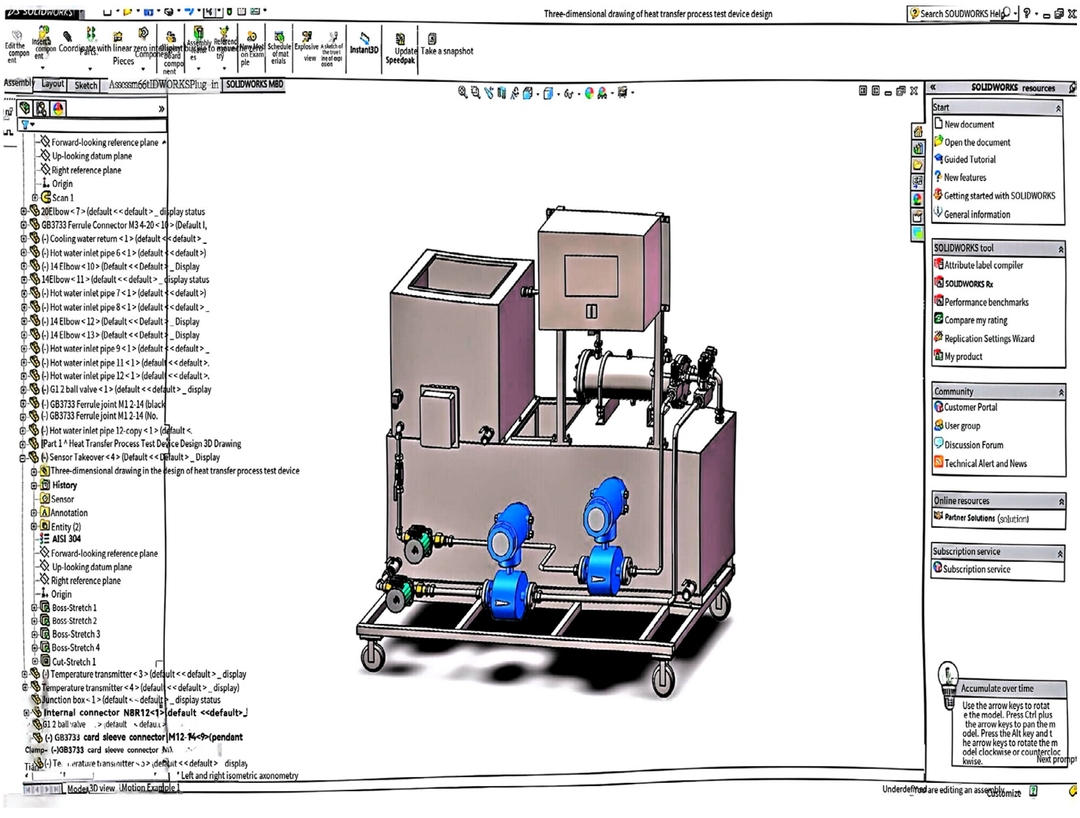

Figure 6. Physical structure diagram of the heat exchanger

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5. Innovations and Applications

A new type of heat exchange device suitable for university laboratories is developed, and advanced control technology research is carried out using this experimental device.

High - efficiency Heat - conducting Materials: New - type high - efficiency heat - conducting materials, such as nanocomposites or advanced alloys, are adopted to significantly improve the heat exchange efficiency. These materials have excellent thermal conductivity and thermal stability and can maintain high - efficiency operation in various complex laboratory environments.

Multi - functionality and Flexibility: The new heat exchange device is designed with multi - functional interfaces and modules, which can be quickly replaced or adjusted according to different experimental requirements to meet the experimental verification of a variety of advanced control technologies. It provides highly flexible parameter settings and control options, supporting complex experimental processes and algorithm verification.

High - precision Measurement and Control: Advanced sensor technology and high - precision measuring elements are used to ensure the accurate measurement and monitoring of key parameters such as temperature and flow rate. Advanced control algorithms are integrated to achieve precise temperature control and heat exchange efficiency optimization.

Realize the automated operation and monitoring of the experimental process, reducing human errors and improving experimental efficiency. It supports remote operation and monitoring, facilitating teachers and students to remotely obtain and analyze experimental data.

Intelligent Control System: An advanced intelligent control system is integrated. By real - time monitoring of parameters such as temperature, flow rate, and pressure during the heat exchange process, the working state of the equipment is automatically adjusted. This helps to achieve precise control and improve heat exchange efficiency and energy utilization rate.

Environmental Protection and Energy Conservation: Emphasis is placed on environmental protection and energy - saving design, and low - energy - consumption and low - emission technical solutions are adopted. For example, heat recovery technology is used to recycle the discharged heat, reducing energy consumption and environmental pollution.

Data Processing and Calibration: Intelligent algorithms and machine learning techniques are used to process and calibrate the data of thermal sensors, improving the accuracy and stability of measurement.

6. Conclusions

In conclusion, this research addresses the problem of insufficient control accuracy of traditional heat exchangers under complex working conditions by optimizing the heat exchanger device using advanced control algorithms. Based on an in - depth analysis of the working principle, structure, and existing control strategies of heat exchangers, algorithms such as model predictive control, fuzzy control, and neural network control were selected for research. Mathematical and simulation models were constructed, and MATLAB was used for simulation and comparison. Meanwhile, an experimental platform was set up to apply advanced control algorithms to actual heat exchanger devices. The results show that these advanced algorithms significantly improve the control performance of heat exchangers. They not only enhance the temperature control accuracy, effectively reduce energy consumption, but also strengthen system stability. In addition, a new type of heat exchange device suitable for university laboratories was developed. This device is innovative in aspects such as the application of high - efficiency heat - conducting materials, multi - functional and flexible design, high - precision measurement and control, and intelligent control. This research provides a practical way for the application optimization of heat exchangers, which is of great significance for promoting efficient heat transfer and energy recovery in industrial production. It is expected to be widely applied in actual industrial production and further promote the technological development in related fields.

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