International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 10 Issue 9 ǁ September 2022 ǁ PP. 636-642

Research on model of fin-and-tube heat exchanger based on experimental data

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Abstract
A modeling method of fin-tube heat exchanger based on "experimental data" is proposed, and relevant heat exchanger experiments are carried out according to the table requirements given by the model, and a steady state model of the heat exchanger is established; the model data table is calculated according to the formula, The output value of the heat exchanger under the corresponding input conditions can be obtained. Through relevant experiments, the model is verified, and the required air temperature of the heat exchanger is obtained within 0.6 °C of the actual system error.

Keywords:*experimental data; ship simulation;heat exchanger*

Date of Submission: 15-09-2022 Date of acceptance: 30-09-2022

I. INTRODUCTION

For the experimental study of the finned tube heat exchanger, due to its complex structure, difficult processing, and troublesome determination of its local characteristic parameters, the object of previous experimental research is mainly the enlarged model of the heat exchanger entity. By arranging the relevant data of heat transfer and pressure drop of various structural heat exchanger amplification models, experimental correlations with predictable heat transfer and resistance coefficients are obtained.

Kim et al. [1] experimentally studied the influence of factors such as the fin spacing, the number of tube rows and the tube arrangement on the heat transfer coefficient of air. The reduction of the number increases the heat transfer coefficient on the air side. The heat transfer coefficient of the tubes in the fork row is 10% higher than that in the straight row. At the same time, the experimental correlation formula of heat transfer coefficient is also drawn up. Meyer et al. [2] studied the inlet flow loss of nine kinds of finned tube radiators by experimental method, and found that the inlet loss decreases with the increase of the inclination angle of the air inlet, which has nothing to do with the average velocity of the fluid. At the same time, the arrangement of the tubes the method also has an effect on the inlet flow loss of the air. Japanese scholars Xi, Ebisu et al. [3] explained the difference between two-dimensional and three-dimensional numerical simulation results by studying the surface characteristics of two-row tube-fin heat exchangers. The simulation found that the two-dimensional model can be used for qualitative analysis in the case of limited computing space. Fluid flow and heat transfer, but the numerical simulation results of the 2D model are larger than the 3D model in terms of the simulation results. Bakaya et al. [4] simulated the natural convection heat transfer process of straight fins with different fin spacing, fin height, and fin length. The results show that each variable has an impact on heat transfer. In order to obtain the best heat transfer for performance, the cross-connection between all parameters must be considered, not just one or a few parameters, and compared with the experimental data in the previous literature, the numerical calculation results are more accurate at high Rayleigh numbers.

The heat exchanger studied in this paper mainly studies the influence of the input parameters of the simulation system on the output parameters of the heat exchanger, that is, the outlet air temperature. Therefore, according to the modeling method based on "experimental data", the relevant exchange is carried out according to the table requirements given by the model. The heat exchanger experiment is carried out to establish a steady state model of the heat exchanger; the model data table is operated according to the formula, and the output value of the heat exchanger under the corresponding input conditions can be obtained. Through relevant experiments, the model is verified, and the required air temperature of the heat exchanger is obtained within 0.6 °C of the actual system error. This has important implications for engineering practice.

II. Laboratory introduction

2.1 Optimization analysis of tube row number performance in evaporator

The research of this paper relies on the simulation laboratory of full-scale marine variable air volume air conditioning system in a research institute in Shanghai.

The schematic diagram of the laboratory is shown in Figure 1. The laboratory contains 12 simulatedcabins, and the six sides of each cabin are made of 150mm polyurethane warehouse board, which has goodthermal insulation performance and is little affected by external environmental factors. The cabin rooms are equipped with simulated load generators, which can generate dynamically changing room heat and humidity loads. The air supply duct in the cabin is connected to the VAV end of the circular air outlet, which is equipped with a micro-perforated plate muffler and has a 2kW electric heating function. The 12 cabins in the laboratory are grouped in groups of three, which are connected to the static pressure box of the air outlet of the air handling unit (air conditioning box) through four main air pipes. The air-conditioning box is a three-section structure of mixing section, coil section and fan section. The fresh air load generator connected to the fresh air outlet of the mixing section can generate pre-defined simulated fresh air heat and humidity loads and can simulate allcommon fresh air conditions. The built-in fin tube heat exchanger in the coil section is provided with constant temperature water by two 65kW variable frequency chillers, which can heat or cool the air and dehumidify. The fan section adopts a backward inclined direct-connected variable frequency centrifugal fan, which can provide sufficient power for the air supply system.

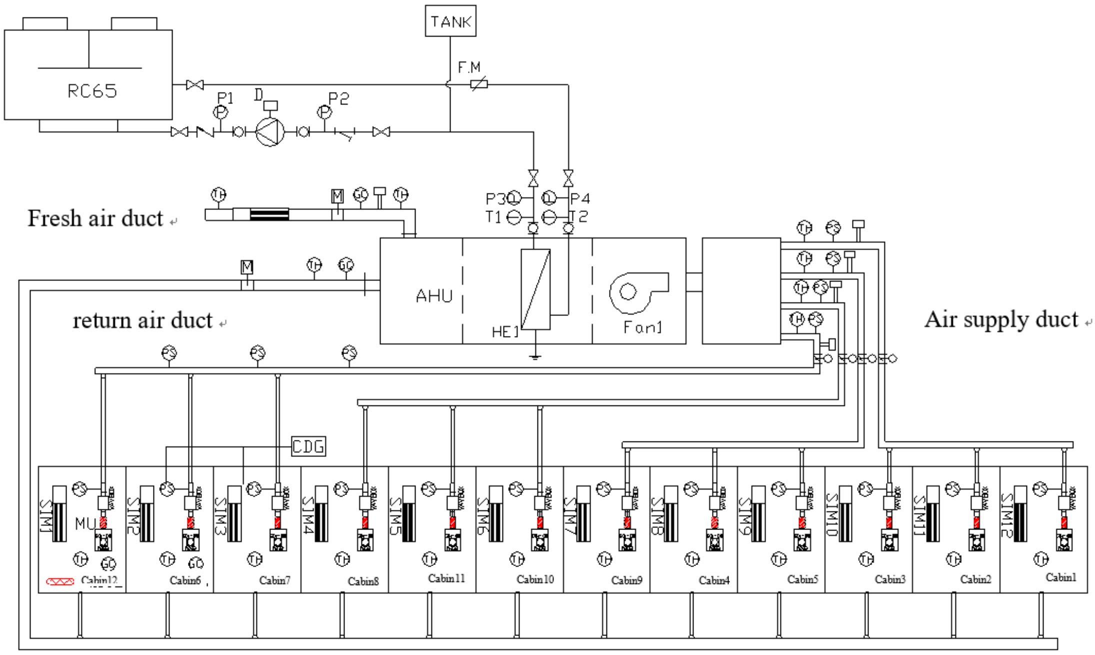

Figure 1: Schematic diagram of full-scale marine VAV air conditioning laboratory system

2.2Acquisition control system

The topological diagram of the control and acquisition system in the laboratory is shown in Figure 2, including terminal device control board, cabin control board, fresh air simulated load control board, inverter water machine control board, air-conditioning box PLC (air handling unit) and other terminal acquisition control boards, serial server, network switch, central control board and other relay equipment, and a Windows computer for monitoring. All lower computer acquisition boards and centralized control boards communicate with each other through the serial port protocol, and the serial port server accepts commands from the local area network or uploads the acquisition analog data of the serial port device to the local area network. The function of the centralized control board is the same as that of the serial server, the difference is that the centralized control board can connect multiple serial devices at the same time. The host computer uses the TCP/IP protocol to accept the devices in the local area network to upload data or issue control commands.

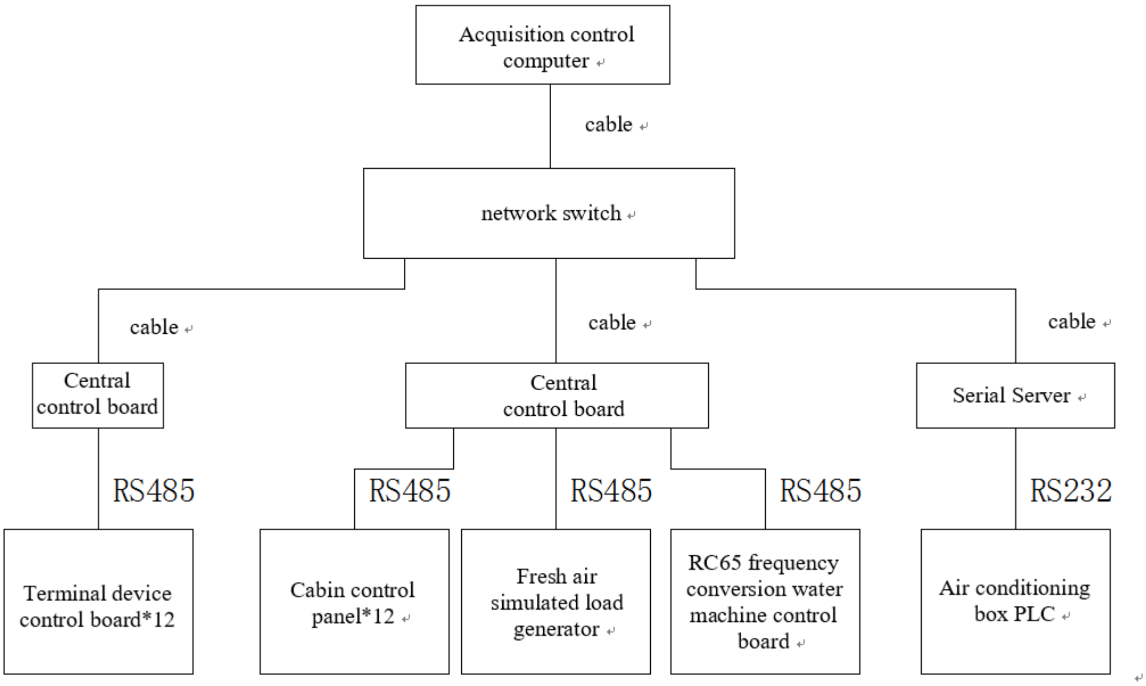

Figure 2:Laboratory Acquisition System Topology

III. Mathematical model of fin-and-tube heat exchanger

There are many kinds of heat exchangers and different forms. The actual laboratory uses water coils (that is, finned tube heat exchangers) as heat exchange equipment for marine variable air volume air conditioning systems. The finned tube heat exchanger cools and dehumidifies the air flowing over its surface in summer and heats it in winter. The water supply temperature, water supply volume and air supply volume of the heat exchanger play an important role in the temperature and humidity regulation of the air-conditioned cabin.

For the finned tube heat exchanger, a large number of literatures [5] [6] [7] introduced the thermodynamic modeling method, and obtained the heat exchanger model through the related theory of heat transfer. There are many parameters that need to be considered in this modeling method. Different pipe diameters, fin spacing and other factors will affect the heat exchange efficiency of the model; the established model will be affected by actual factors such as the actual manufacturing process and service life, and there will be deviations; and the modeling process still makes a considerable number of assumptions and approximations that will affect the results. Although the thermodynamic modeling method can be used in the modeling of the variable air volume air conditioning system, it is too cumbersome and requires a lot of theoretical calculations, and the verification process requires a lot of energy.

Furthermore, the purpose of the model established in this chapter is to study the variable static pressure control logic of the system, and the accuracy of the coil model is not high, and the control law is not affected. Therefore, a method based on experimental data proposed in this paper is used in the actual modeling.

Experimental data modeling is one of the commonly used modeling methods [8]. Compared with mechanism modeling, experimental data modeling does not require knowledge of the physical principles of the research object, and has higher applicability to complex objects. When modeling, it is necessary to carry out a series of experiments according to the characteristics of the object to obtain relevant experimental data, and obtain the mathematical model of the object through the method of linear regression.

When establishing the model of the heat exchanger based on the experimental data, the following assumptions are made: the input variables of the heat exchanger are independent of each other, and the coupling between them is not considered.

For a specific finned tube heat exchanger, after the size and shape of the heat exchanger are determined, the main factors affecting the finned tube heat exchanger are: tube side inlet water temperature Twi, tube water flow L, coil inlet air volume Vair, Inlet air temperature Tai, inlet air humidity Wi (relative humidity). Through the idea of controlling variables, experiments are carried out on each influencing factor in turn, and the corresponding outlet air temperature Tao, outlet air moisture content Wo (relative humidity), pipe side outlet water temperature Two, and wind side resistance Rcoil are obtained by measuring or calculating the results. summarized in Table 1.

Table 1:Heat exchanger model table based on experimental data

	enter					output			
serial number	Inlet water temperature °C	Water flow kg/s	Air volume m³/s	Inlet air temperature ℃	moisture content g/kg	Outlet air temperature ℃	moisture content g/kg	Outlet temperature	wind resistance Pa
0. Baseline group	T_{wi0}	L	V_{air0}	T_{ai0}	W_{i0}	T_{ao0}	W_{o0}	T_{wo0}	R_{coil0}
1. Inlet water temperature	T_{wi1-a}	L	V_{air0}	T_{ai0}	W_{i0}	T_{ao1-a}	W_{o1-a}	T_{wo1-a}	$R_{coil1-a}$
	T_{wi1-b}	L	V_{air0}	T_{ai0}	W_{i0}	T_{ao1-b}	W_{o1-b}	T_{wo1-b}	$R_{coil1-b}$
2. water flow	T_{wi0}	L_{2-a}	V_{air0}	T_{ai0}	W_{i0}	T_{ao2-a}	W_{o2-a}	T_{wo2-a}	$R_{coil2-a}$
	T_{wi0}	L_{2-b}	V_{air0}	T_{ai0}	W_{i0}	T_{ao2-b}	W_{o2-b}	T_{wo2-b}	$R_{coil2-b}$
3. Air volume	T_{wi0}	L	V_{air3-a}	T_{ai0}	W_{i0}	T_{ao3-a}	W_{o3-a}	T_{wo3-a}	$R_{coil3-a}$
	T_{wi0}	L	V_{air3-b}	T_{ai0}	W_{i0}	T_{ao3-b}	W_{o3-b}	T_{wo3-b}	$R_{coil3-b}$
4. Inlet air temperature	T_{wi0}	L	V_{air0}	T_{ai4-a}	W_{i0}	T_{ao4-a}	W_{o4-a}	T_{wo4-a}	$R_{coil4-a}$
	T_{wi0}	L	V_{air0}	T_{ai4-b}	W_{i0}	T_{ao4-b}	W_{o4-b}	T_{wo4-b}	$R_{coil4-b}$
5. moisture content	T_{wi0}	L	V_{air0}	T_{ai0}	W_{i5-a}	T_{ao5-a}	W_{o5-a}	T_{wo5-a}	$R_{coil5-a}$
	T_{wi0}	L	V_{air0}	T_{ai0}	W_{i5-b}	T_{ao5-b}	W_{o5-b}	T_{wo5-b}	$R_{coil5-b}$

The state of the coil design condition is used as the input parameter of the benchmark group to conduct experiments, and the corresponding output parameters are obtained; the five input parameters are adjusted up and down on the basis of the benchmark group in turn, and the corresponding output parameters are obtained through the experiment. The upper and lower limits of each experimental group are listed in the table. The output parameters corresponding to any input parameters within the range specified in the above table can be calculated by the following formula (1):

$$n = n_0 + \sum_{i=1}^{5} \left(\frac{dn_i}{dm_i} \cdot \Delta m_i\right) \quad （1）$$

In the formula,n is the model output parameter,n_0 is the value of the desired output parameter in the benchmark group, $\frac{dn_i}{dm_i}$is the slope of the i-th input-output function, and $\Delta m_i$is the deviation of the i-th input from the corresponding benchmark.

An example of the above model:

Let the input $(T_{wi}，L，V_{air}，T_{ai}，W_i)^T = (T'_{wi}，L'，V'_{air}，T'_{ai}，W'_i)^T$, and the input is smaller than the benchmark group.

Then the outlet air temperature T_{ao} is calculated according to formula (2) as follows:

$$T_{ao} = T_{ao0} + \left[\frac{T_{ao1-a} - T_{ao0}}{T_{wi1-a} - T_{wi0}} \times (T'_{wi} - T_{wi0}) + \cdots + \frac{T_{ao5-a} - T_{ao0}}{W_{i5-a} - W_{i0}} \times (W'_i - W_{i0})\right] \quad （2）$$

The advantages and disadvantages of the heat exchanger modeling method based on the experimental data are shown in Table 2.

Table 2:Analysis table of advantages and disadvantages of heat exchanger modeling based on experimental data (compared to theoretical modeling of heat transfer)

Advantage	disadvantage
Small amount of calculation, fast calculation speed, no errors in production and use, easy to program	Experiments are required, and the cycle is long. There is a large error in the data that deviates from the benchmark. The scope of application is small, and it is only suitable for a single type of heat exchanger.

IV. Heat Exchanger Model Validation

Modeling using experimental data is one of the commonly used modeling methods, which generally uses regression analysis to establish a model based on experimental data. The second chapter of this paper proposes a relatively simplified method. This chapter designs relevant experiments to verify the method.

The experimental design is described as follows:

1. By setting the outlet water temperature and water flow rate of the RC chiller in the experimental system, the inlet water temperature and water flow rate of the coil heat exchanger in the air-conditioning box are controlled;
2. Set the air valves at the end of all rooms to be fully open, and adjust the total air supply volume by adjusting the fan frequency, that is, the air volume passing through the heat exchanger;

3. During the experiment, close the return air valve of the mixing section of the air-conditioning box, open the fresh air valve, and control the temperature and humidity of the incoming air by controlling the fresh air simulated load generator.

4. Record the outlet air temperature, relative humidity and outlet water temperature of the heat exchanger in the experiment, and calculate the average value within 5 minutes after the experiment is stable, and summarize them in Table 3.

Table 3:Heat Exchanger Model Parameter Table

serial number	set value					Measurements		
	Inlet water temperature℃	water flow m^3/h	Air volume m^3/h	Inlet dry bulb temperature℃	Inlet wet bulb temperature℃/ Relative humidity%	Outlet air temperature℃	Relative humidity%	Outlet temperature℃
0.Baseline group	8	10	4000	30	22.00/49.4	8.76	95.6	12.24
1. Inlet water temperature	5	10	4000	30	22.00/49.4	5.90	94.7	9.91
	11	10	4000	30	22.00/49.4	11.60	95.7	14.50
2. water flow	8	7	4000	30	22.00/49.4	9.10	95.9	13.94
	8	13	4000	30	22.00/49.4	8.60	95.5	11.29
3. Air volume	8	10	2000	30	22.00/49.4	8.08	96.3	10.20
	8	10	6000	30	22.00/49.4	9.92	89.2	13.94
4. Inlet air temperature	8	10	4000	25	22.00/77.1	9.01	97.4	12.24
	8	10	4000	35	22.00/31.1	8.64	93.7	12.20
5.moisture content	8	10	4000	30	17.00/25.0	8.24	96.2	10.51
	8	10	4000	30	27.00/79.3	9.60	97.7	14.30

The above table is the model based on the experimental data established for the heat exchanger of the air-conditioning box of the experimental system. The output of the heat exchanger under any input state within the range specified in the above table can be obtained by formula 3.1. The experimental conditions shown in Table 4 were selected, and the verification experiments were carried out according to the above experimental methods.

Table 4:Heat Exchanger Model Experiment Verification Operating Conditions Table

serial number	Inlet water temperature℃	water flow kg/h	Air volume m^3/h	Inlet air temperature℃	Relative humidity %
1	6.00	10.00	3000	27.00	35.0
2	6.00	10.00	3000	27.00	65.0
3	6.00	10.00	3000	33.00	35.0
4	6.00	10.00	3000	33.00	65.0
5	6.00	10.00	5000	27.00	35.0
6	6.00	10.00	5000	27.00	65.0
7	6.00	10.00	5000	33.00	35.0
8	6.00	10.00	5000	33.00	65.0
9	10.00	10.00	3000	27.00	35.0
10	10.00	10.00	3000	27.00	65.0
11	10.00	10.00	3000	33.00	35.0
12	10.00	10.00	3000	33.00	65.0
13	10.00	10.00	5000	27.00	35.0
14	10.00	10.00	5000	27.00	65.0
15	10.00	10.00	5000	33.00	35.0

16	10.00	10.00	5000	33.00	65.0

In the verification experiment, 16 sets of representative heat exchanger operating conditions were selected, and the corresponding experimental measurement results were obtained; the simulation results under the corresponding operating conditions were obtained through the established model simulation, and the errors of the two were summarized as follows: Table 5.

Table 5:Error summary table of heat exchanger model simulation results and experiments

Experiment number	Measurements			Analog value			error		
	Outlet air temperature ℃	Relative humidity %	Outlet temperature ℃	Outlet air temperature℃	Relative humidity %	Outlet temperature ℃	Outlet air temperature℃	Relative humidity%	Outlet temperature ℃
1	6.20	96.0	8.24	6.24	96.9	8.21	-0.64%	-0.91%	0.26%
2	6.49	96.9	9.63	6.80	96.7	9.98	-4.72%	0.15%	-3.68%
3	6.31	96.0	9.41	6.29	94.4	9.08	0.44%	1.72%	3.49%
4	6.77	96.9	11.35	7.23	96.1	11.55	-6.82%	0.81%	-1.73%
5	6.82	89.9	9.57	7.16	93.3	10.09	-4.97%	-3.80%	-5.45%
6	7.73	94.0	11.69	7.72	93.2	11.86	0.23%	0.90%	-1.40%
7	7.27	89.5	11.43	7.20	90.8	10.95	0.92%	-1.42%	4.14%
8	8.67	93.6	14.37	8.15	92.5	13.42	6.01%	1.10%	6.60%
9	10.08	97.5	11.52	10.04	97.5	11.28	0.39%	-0.03%	2.14%
10	10.38	97.4	12.91	10.60	97.4	13.05	-2.08%	0.02%	-1.05%
11	10.23	96.5	12.70	10.08	95.0	12.14	1.46%	1.58%	4.41%
12	10.66	97.5	14.64	11.03	96.7	14.61	-3.49%	0.80%	0.21%
13	10.39	94.8	12.45	10.95	94.0	13.15	-5.45%	0.87%	-5.63%
14	11.34	94.3	14.54	11.51	93.8	14.92	-1.50%	0.47%	-2.61%
15	10.96	90.6	14.29	11.00	91.5	14.01	-0.40%	-0.98%	1.91%
16	12.27	94.0	17.21	11.95	93.2	16.48	2.63%	0.84%	4.20%

For the research content of this topic, the output variable of the heat exchanger that needs to be verified is the outlet air temperature, and the relative humidity and outlet water temperature are temporarily out of the scope of the topic. For the outlet air temperature of the heat exchanger, a comparison between the experimental and simulation results is made in Figure 3.

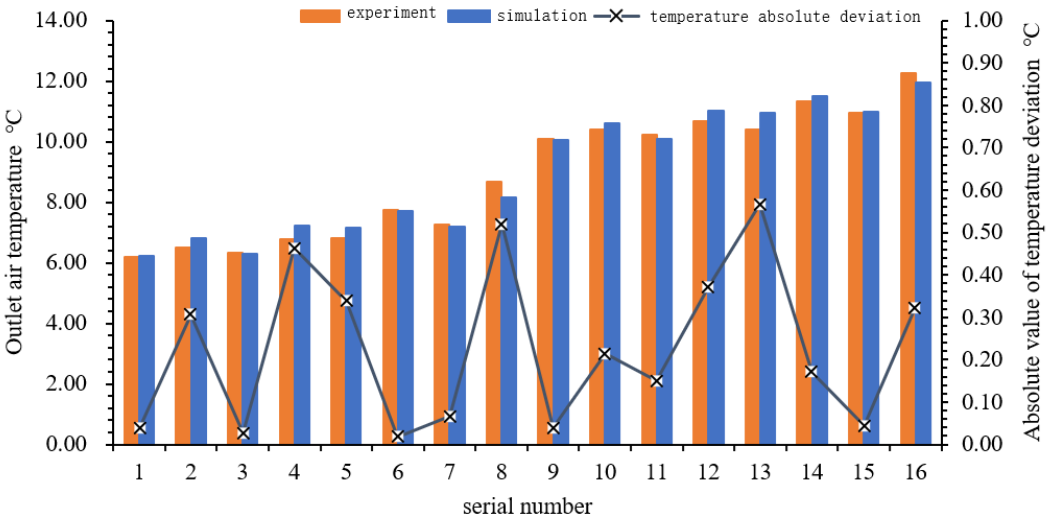

Figure 3:Comparison of experimental and simulated coil outlet air temperature deviations

As can be seen from the figure, the experimental and simulated results are relatively close, and the maximum deviation is about 0.6 °C.

V. CONCLUSION

A method of establishing a heat exchanger model based on experimental data is proposed. This method does not need to know the specific size and parameter performance of the heat exchanger. Using the working conditions and calculation formulas given in the paper, the corresponding experiments and calculations can be obtained. The data of the heat exchanger during steady-state operation saves the complicated calculation process and improves the overall simulation speed of the variable air volume system.

The established simulation model is verified by the actual laboratory system, the relevant model parameters are determined, the parameters of the heat exchanger model are determined through experiments, and a set of verification conditions are designed to verify the model. The final experimental and simulation results are relatively close, and the maximum deviation is about 0.6 °C, which fully demonstrates the reliability of the simulation model proposed in this paper.

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