

The Testing System of Thermal Performance of Heating Radiators Based on ZigBee Wireless Sensor Network Technology

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Abstract: Based on Zigbee Wireless Sensor Network technology and fuzzy control technology, a design scheme of the testing system of thermal performance of heating radiators is put forward, which is no wiring, low-cost and high precision. The project adopts Zigbee wireless communication technology to transmit temperature data, and is no wiring, temperature measuring points can be laid out flexibly. By adopting piecewise polynomial fitting nonlinear soft correction technology, Zigbee wireless network and RS-485 bus to transmit digital temperature signals, transmission error is reduced and temperature measuring accuracy is improved. By adopting Fuzzy-PID control, the control precision of temperature and flow rate are improved, the control precision of temperature is $\pm 0.1\%$, the control precision of flow rate is $\pm 1\%$. Experiments prove that the system has a fast response, a stable control process, the high measuring and control precision to meet the requirements of national standard. Copyright © 2013 IFSA.

Keywords: Thermal performance of heating radiators, ZigBee Wireless Sensor Network, Soft correction, Fuzzy-PID control, RS-485 communication, CC2530.

1. Introduction

Thermal performance of heating radiators has a direct impact on the level of energy consumption of the heating system, adopting better heating radiator is one of major technical measures to heating energy saving. According to the GB/T13754-2008 “test methods of thermal output of heating radiator”, the test bench for thermal performance of heating radiators is used for testing thermal performance of heating radiator. The testing needs to collect the temperature of more than 20 measurement points,

and requires high measuring and control accuracy of temperature and flow rate. The existing systems often use a cable to transmit analog signals, the control scheme is “thermocouple – transmitter – cold end compensation – linear processing – a long distance transmission – multiple conversion – A/D conversion – PLC – IPC”, more conversion link, complex circuit, field wiring clutter, low accuracy, high failure rate, the large amount of maintenance, long time of testing. Networking technology is on the rise and has been widely used in various fields, by adopting the ZigBee wireless sensor network and fuzzy PID

control, a scheme of test system of thermal performance of heating radiators is put forward in this paper, which is no wiring, low-cost, high-precision.

2. Test Principle

The test of thermal output of heating radiator must be on the basis of stable heat transfer, steady state conditions mainly include temperature steady-state and flow steady-state. By controlling the heating medium and cooling systems, when the flow rate and temperature of the heating medium system, the supply air temperature of air-conditioning system and test chamber temperature field (space temperature and wall temperature) to reach steady state constant, keep the heating radiator water flow stable, then measure the inlet and outlet water temperature and the reference air temperature in the three conditions of high middle and low temperature respectively, then calculate excess temperature, thermal output and thermal transmittance to create a standard characteristic equation of the radiator [1]:

$$Q = K_M \cdot \Delta T^n, \quad (1)$$

where Q is the thermal output of heating radiator, unit W; ΔT is the excess temperature, unit K; K_M , n is the constant for radiator models. Taking the logarithm on both sides of the equation we get:

$$\ln Q = \ln K_M + n \ln \Delta T \quad (2)$$

set: $\ln Q = y$; $\ln \Delta T = X$, then we get a linear equation:

$$y = \ln K_M + nX \quad (3)$$

A linear regression on the regression equation, using the method of least squares solving $\ln K_M$ and n , so we get the characteristic equation of this kind of heating radiator thermal output.

3. System Overall Design

The test device mainly consists of a heat medium system, cold air system, the test chamber, automatic control detection system. The heat medium system mainly consists of high water tank, low water tank, the secondary heating tank, radiator, water re-cooler, rotameter, electronic scales, pumps, filters, etc. The cold air system mainly consists of air conditioning units and compensation heater. The automatic detection system is composed by ZigBee wireless sensor network, the gateway node, RS-485 bus, IPC four parts, and is divided into two major sections of PC monitoring and wireless sensor networks detecting on the whole, as shown in Fig. 1. IPC-810B

is used as the host computer, Kingview is taken as the platform to design and development monitoring interface. IPC communicates with gateway node, interlayer sensor nodes and electronic scales through RS-485 interface to complete system monitoring, data display, alarm and management work [2]. The gateway node which takes the CC2530 as the core collects the temperature data that collected by the sensor nodes, then back to the IPC via RS-485 communication. IPC controls electric heaters, air conditioning units, flow control valve and other equipment to stabilize the flow rate and temperature of the heat medium system, and the temperature of the test chamber can be made maintain at the required value.

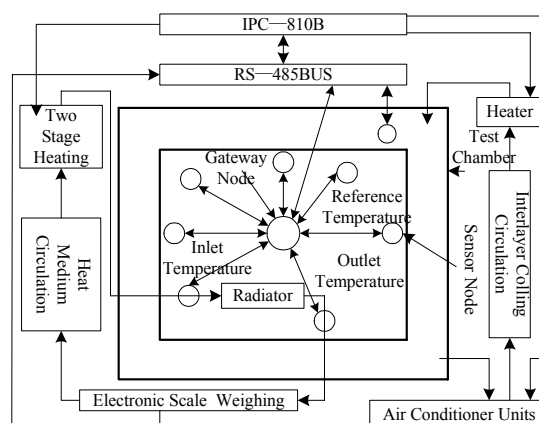


Fig. 1. System overall block diagram.

The system adopts two level two network networking model, the underlying is the Zigbee-WSN two level subnet, composed of sensor nodes and gateway nodes, adopting the star network topology to complete the acquisition of the temperature data, the gateway node is a wireless sensor network coordination controller. The upper is RS-485 backbone network which includes the IPC, interlayer sensor nodes and electronic scale, using a bus network topology, complete the features that control and display the temperature and flow and input interactive [3].

4. Sensor Node Design

The sensor node is mainly responsible for the acquisition of the temperature data, and sent it to the collection node by CC2530 RF transceiver, and mainly consists of the platinum resistance, current transducer XTR105, I/V converting circuit and CC2530, hardware block diagram shown in Fig. 2 [4]. PT1000 platinum resistance detect the temperature of measuring points, current transducer XTR105 transform the temperature changes to 4~20 mA current signal, the current signal is converted into the voltage signal of 0.6 V to 3 V by

the I/V converting circuit which is composed by precision resistance, The voltage signal is converted by the A/D converter integrated in CC2530, then the actual temperature value obtained by the MCU after non-linear compensation.

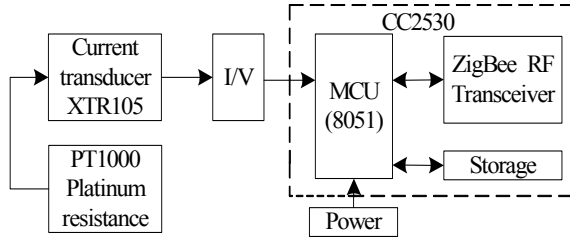


Fig. 2. Hardware block diagram of sensor node.

Non-linear relationship exists between the thermal resistance of the platinum resistance and the temperature, it is more serious especially in the high-temperature side, to achieve high-precision temperature measuring, it is necessary to do the non-linear calibration for the test data [5]. The correction method combining software with hardware is adopted, hardware adopts a three-wire connection to eliminates measurement error caused by wire resistance of platinum resistance, adopts the current transducer XTR105 with the precision current source which converts resistance changes to current, after I/V conversion the voltage signal is converted into digital signal by 12-bit ADC integrated in CC2530; software adopts the piecewise polynomial fitting nonlinear correction, fitting formula is:

$$t = a_0 + a_1x + a_2x^2 + \dots + a_mx^m = \sum_{j=0}^m a_jx^j \quad (4)$$

where $a_0, a_1, a_2, \dots, a_m$ are the unknown coefficients.

The higher degree of the polynomial, the higher accuracy of the fitting, but the greater amount of calculation. Considering the characteristics of platinum resistance and the system temperature measuring range of 0°C to 100°C , a quadratic polynomial is adopted, mean $m=2$, the least square method for each coefficient is used, so that minimize the sum of errors square Q .

$$Q = \sum_{i=1}^n (t_i - \sum_{j=0}^m a_jx_i^j)^2 \quad (5)$$

$$\frac{\partial Q}{\partial a_k} = -2 \sum_{i=1}^n (t_i - \sum_{j=0}^m a_jx_i^j)x_i^k = 0 \quad (6)$$

There are equations:

$$\begin{cases} \frac{\partial Q}{\partial a_0} = -2 \sum_{i=1}^n (t_i - a_0 - a_1x_i - a_2x_i^2) = 0 \\ \frac{\partial Q}{\partial a_1} = -2 \sum_{i=1}^n (t_i - a_0 - a_1x_i - a_2x_i^2)x_i = 0 \\ \frac{\partial Q}{\partial a_2} = -2 \sum_{i=1}^n (t_i - a_0 - a_1x_i - a_2x_i^2)x_i^2 = 0 \end{cases} \quad (7)$$

Set:

$$\begin{cases} \theta_{(k)} = \sum_{i=1}^n x_i^k & (k = 0, 1, 2, 3, 4) \\ y_{(k)} = \sum_{i=1}^n t_i x_i^k & (k = 0, 1, 2, 3) \end{cases} \quad (8)$$

Have equations

$$\begin{cases} a_0\theta_{(0)} + a_1\theta_{(1)} + a_2\theta_{(2)} = y_{(0)} \\ a_0\theta_{(1)} + a_1\theta_{(2)} + a_2\theta_{(3)} = y_{(1)} \\ a_0\theta_{(2)} + a_1\theta_{(3)} + a_2\theta_{(4)} = y_{(2)} \end{cases} \quad (9)$$

Set the matrix θ, A, Y respectively is:

$$\begin{cases} \theta = \begin{bmatrix} \theta_{(0)} & \theta_{(1)} & \theta_{(2)} \\ \theta_{(1)} & \theta_{(2)} & \theta_{(3)} \\ \theta_{(2)} & \theta_{(3)} & \theta_{(4)} \end{bmatrix} \\ A = [a_0 \ a_1 \ a_2]^T \\ Y = [y_{(0)} \ y_{(1)} \ y_{(2)}]^T \end{cases} \quad (10)$$

Use Matlab software to solve matrix equation:

$$\theta A = Y \quad (11)$$

After solving vector A the fitting curve polynomial coefficients a_0, a_1, a_2 can be determine.

The variable x can be the resistor R or voltage U , dividing the temperature measuring range of 0°C to 100°C into five sections, the polynomial fitting takes once every 20°C . Each section takes 20 measuring temperature points to measure (temperature interval is 1°C), and each point continuous takes sample 12 times, and remove the maximum value and the minimum value in the resulting sampled data, then take average of the remaining 10 sampled data to obtain the best polynomial fit equation of temperature and the resistance or temperature and voltage. By using double correction of hardware and software, it achieves a higher temperature measuring accuracy, temperature resolution is 0.01°C and measurement error is less than $\pm 0.1^\circ\text{C}$ between the temperature measuring range 0°C to 100°C .

5. Communication Protocol

The gateway node communicates with sensor node using ZigBee protocol, ZigBee protocol stack consists of four parts: the physical layer (PHY) and medium access control sublayer (MAC), network layer (NWK) and application layer (APL) [6]. The format of ZigBee protocol frame is shown in Table 1. Among them: the frame sequence number field is for the order number of the sender, sequence number field value pluses 1 when each send a data; Address field includes the network ID of the destination node, destination address and the network ID of the source node, source address, which is 64 IEEE long address or 16-bit short address; Data payload field is valid data, which length is variable, measurement and control command and the temperature data contained in the data payload.

Table 1. Format of ZigBee protocol frame.

Description	Code	Length
Leading code	Preamble	4 bytes
Start flag of frame	SFD	1 byte
Frame length field	Length	1 byte
Frame control field	FCF	2 bytes
Frame sequence number	DSN	1 byte
Address field	ADDR	0~20 bytes
Data payload	Payload	variable
Frame check code	FCS	2 bytes

Table 2. Format of ASCII communication protocol frame.

Description	Code	Length
Prefix	40H	1 byte
Device address	Addr	1 byte
Flag	Flag	1 byte
Data address	DataAddr	2 bytes
Data length	DataNum	1 byte
Data	Data	≤100 bytes
Exclusive or	CRC	1 byte
CR	0x0d	1 byte

KingView communicates with the gateway node through the serial interface using communication protocol of ASCII code type. In order to achieve the communication between the gateway node and KingView, the communication parameters set by KingView must be consistent with MCU communication parameters, such as baud rate: 9600 bps, 8 data bits, 1 stop bit, no parity check. The device address format set by KingView is: # # #. The first two characters is a device address (0 ~ 255), this address is the address of the MCU; the last character is the packaged flag: "0" for not packaging, "1" for packaging. The master device transmits information

with the slave device using the frame as the basic unit, and the data frame format of the communication protocol is shown in Table 2 above. In the data which PC send to the MCU, all bytes are ASCII codes except the prefix and suffix and one byte is represented by two ASCII codes. Among them, the signs: a byte is two ASCII codes (bit 0 to bit 7), when bit0 = 0 means to read; when bit0 = 1 means to write; when bit1 = 0 means not to package, when bit1 = 1 means to package; when bit3bit2 = 00 means data type is bytes; when bit3bit2 = 01 means data type is words; when the bit3bit2 = 1x means data type is floating point data [7]. Data is ASCII codes which are converted into by the actual data and its number is 2 times the number of bytes. CRC code is the XOR value from the device address to the XOR byte front, and XOR value is converted into two ASCII codes.

6. Control Strategy

The measurement and control system mainly consists of three parts: the reference point temperature control (test chamber temperature control), inlet temperature control and heat medium flow control. Reference point temperature control is achieved through controlling the supplying air temperature of the wall cooling system, it is completed by air conditioning refrigeration units and compensation heater, supplying air temperature and air flow can be adjusted, there is a compensation heater in front of the entrance of the small room of the cold air duct, the amount of heating of heater is automatically adjusted by the fuzzy PID controller [8]; Radiator supplying water temperature is adjusted by two stages of heating, the high level water tank has a rough heater, the reheating water tank has a fine heater, they constitute a cascade control structure adopting adaptive fuzzy PID control strategy; Heating medium flow is detected by the weighing method, 31002 electronic scale has the RS-232 serial communication interface and the maximum relative error is 0.01 %, the computer can directly read the weighing data, then calculate the flow of the heating medium in accordance with the measurement time, heat medium flow control is achieved by controlling the flow of circuit adjusting the variable frequency pump.

Thermal performance test bed is such a controlled object with a large time delay, nonlinear, time-varying, and requires a high control precision. Requirements of national standard: Inlet water temperature control accuracy: $\pm 0.1^{\circ}\text{C}$, water flow control accuracy: $\pm 1\%$, reference point temperature control accuracy: $\pm 0.1^{\circ}\text{C}$ and only using the conventional PID control or fuzzy control will not achieve good control effect [9], therefore, this paper uses fuzzy PID controller, combining the high control accuracy advantage of conventional PID control with the strong adaptability advantages of fuzzy control, real-time online to adjust the PID parameters to obtain the desired control performance.

6.1. Fuzzy PID Controller Structure

Fuzzy PID controller mainly consists of two parts: the conventional PID control section and the fuzzy inference section. The conventional PID controller completes the direct control of the system and the fuzzy inference achieves online automatic correction on three PID control parameters [10]. The fuzzy inference section is essentially a two inputs and three outputs fuzzy controller, with temperature deviation E and error change rate EC as input variables and ΔK_p , ΔK_i , ΔK_d as output variables. Fuzzy PID control is to find out the fuzzy relations between the three PID parameters and the deviation E and error change rate EC, detecting E and EC continuously in running, the three parameters of PID controller are online modified based on fuzzy control rules to meet the different requirements of the control parameters when E and EC are different, and conditions are different [11], its structure is shown in Fig. 3.

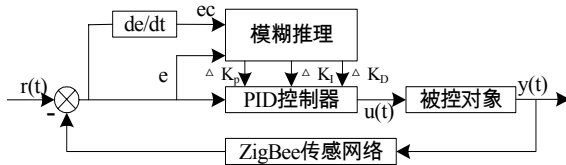


Fig. 3. Structure diagram of Fuzzy PID Controller.

6.2. Fuzzy Linguistic Variables and its Membership Function

Fuzzy controller input linguistic variables are the deviation E (The difference between the actual temperature and set temperature) and the deviation change rate EC, output linguistic variables are the amount of correction ΔK_p , ΔK_i , ΔK_d of three PID parameters K_p , K_i , K_d . The basic domain of the deviation E is $[-5^\circ\text{C}, +5^\circ\text{C}]$ and the basic domain of the deviation change rate EC is $[-1,1]$. Define the fuzzy subset of the input E and the EC and output amount ΔK_p , ΔK_i , ΔK_d : {NB, NM, NS, ZO, PS, PM, PB}, the fuzzy domain: $\{-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6\}$, the elements NB, NM, NS, ZO, PS, PM, PB in the set respectively mean: negative big, negative medium, negative small, zero, positive small, positive median, positive big [12]. The trigonometric function is chosen as membership function of the fuzzy subsets, as shown in Fig. 4.

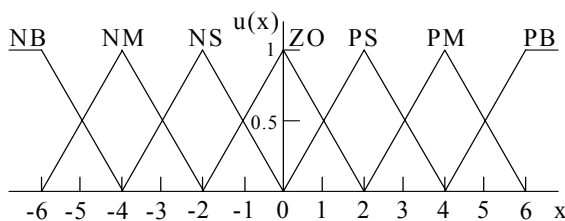


Fig. 4. Membership function of the fuzzy variables.

6.3. The Establishment of Fuzzy Control Rules

Based on PID algorithm, for different $|e|$ and $|ec|$, K_p , K_i and K_d setting principle is as follows[13, 14]:

(1) When $|e|$ is larger, to make the system has a good fast-track performance, K_p and should be larger and K_i should be smaller, at the same time in order to avoid the greater overshoot of system response, integral action should be limited, usually $K_i = 0$.

(2) When $|e|$ is in a medium-sized, to make the system response has small overshoot, the K_p should be smaller, the value of K_d has a greater impact on the system, the value of K_i should be appropriate.

(3) When $|e|$ is smaller, to make the system has good steady-state performance, K_p and K_i should be larger, in order to avoid system oscillations around the set value, taking into account the anti-jamming performance of the system, the choice of the K_d value should be based on EC, when $|ec|$ is smaller, the K_d value should be greater, it is usually taken as a medium-sized; when $|ec|$ is larger, K_d value should be smaller.

Combining with the control law above, in the summary of the experience of the experts and the engineering and technical personnel, the fuzzy control rule table of the three parameters ΔK_p , ΔK_i , ΔK_d is established, as shown in Table 3, Table 4 and Table 5.

Table 3. Fuzzy control rule table of ΔK_p .

EC	E						
	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	PS	ZO
NM	PB	PB	PM	PM	PS	ZO	ZO
NS	PM	PM	PS	PS	ZO	NS	NS
ZO	PM	PS	PS	ZO	NS	NS	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	ZO	ZO	NS	NM	NM	NM	NB
PB	ZO	NS	NS	NM	NM	NB	NB

Table 4. Fuzzy control rule table of ΔK_i .

EC	E						
	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NB	NM	NS	ZO	ZO
NM	NB	NB	NM	NM	NS	ZO	ZO
NS	NM	NM	NS	NS	ZO	PS	PS
ZO	NM	NS	NS	ZO	PS	PS	PM
PS	NS	NS	ZO	PS	PS	PM	PM
PM	ZO	ZO	PS	PM	PM	PB	PB
PB	ZO	ZO	PS	PM	PB	PB	PB

Table 5. Fuzzy control rule table of ΔK_p .

EC	E						
	NB	NM	NS	ZO	PS	PM	PB
NB	PS	PS	ZO	ZO	ZO	PB	PB
NM	NM	NS	NS	NS	ZO	PS	PM
NS	NB	NM	NM	NS	NS	PS	PM
ZO	NB	NM	NM	NS	NS	PS	PM
PS	NB	NM	NS	NS	NS	PS	PS
PM	NM	NS	NS	NS	ZO	PS	PS
PB	PS	ZO	ZO	ZO	ZO	PB	PB

6.4. Fuzzy Reasoning and Decision-Making

According to the fuzzy control rule table of the ΔK_p , ΔK_i , ΔK_d , with reasoning of Mamdani inference method and clear computing of the weighted average method, we can offline calculate the fuzzy control query table of ΔK_p , ΔK_i , ΔK_d , and it is stored in the memory of the controller [15]. According to error E and error change rate EC, we will find out in real time the ΔK_p , ΔK_i , ΔK_d from the control query table, then add them to the initial setting value of PID parameter K'_p , K'_i , K'_d , we will be able to get the PID regulator control parameters K_p , K_i , K_d , these parameters are taken into the recursive formula of PID control positional control algorithm (12), the amount of actual control calculated can be used for real-time control the temperature and flow.

$$\begin{aligned}
 u(k) &= u(k-1) + \Delta u(k) \\
 &= u(k-1) + K_p[e(k) - e(k-1)] + K_i e(k) \\
 &\quad + K_d[e(k) - 2e(k-1) + e(k-2)]
 \end{aligned}
 \tag{12}$$

ActiveX control method increases fuzzy PID algorithm for the KingView. We first make ActiveX control of the fuzzy PID algorithm by VC, then embed the control in the configuration software, then make data connection and set the corresponding parameters between variables in the control and configuration software, so that we can use it [16]. The flow chart of fuzzy PID algorithm is shown in Fig. 5.

7. Experimental Results

In a laboratory environment, we test the performance of the system by detecting the thermal output and the thermal transmittance of some an aluminum radiator. Heating medium is hot water, water supply temperature of 3 kinds of conditions selected are 95 °C, 75 °C, 60 °C, and the reference air temperature of the test chamber is set to 18 °C. KingView runs conventional PID control algorithm and fuzzy PID algorithm respectively, the

temperature control experimental curve of reference point can be obtained as shown in Fig. 6.

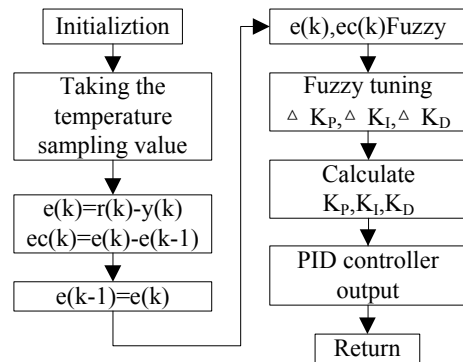


Fig. 5. Flow chart of Fuzzy PID algorithm.

As can be seen from the two groups of curves in Fig. 6, PID control has a fast response, but has a larger overshoot, the poor system suitability of different mathematical models; fuzzy PID control has a smaller overshoot, a smoother response process, a shorter adjustment time and a better robust performance than the conventional PID control, its static and dynamic performance specifications can meet the control requirements and superior to PID control, fuzzy PID control steady-state error is less than ± 0.1 °C.

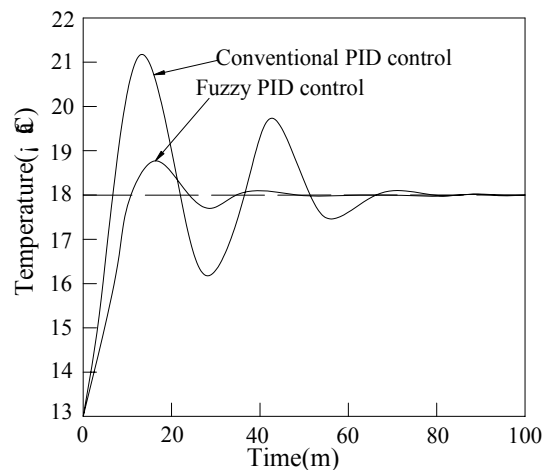


Fig. 6. Reference point temperature control curve.

The fuzzy PID algorithm program is run by the KingView. When the system reaches steady state conditions, the experimental data of three kinds of conditions and the calculated results of thermal output Q and thermal transmittance K of the radiator each condition are shown in Table 6. Seen from the table, the temperature measuring and control precision of the system can reach ±0.1 °C, and all the indicators meet the requirements of national standard.

8. Conclusions

Based on Zigbee wireless sensor network technology, taking computer as control means, fuzzy PID control as control strategy, a set of high-precision testing system with adaptive of thermal performance of heating radiators is designed in this paper. Compared with the traditional control scheme, the system adopts Zigbee wireless network and RS-485 bus to transmit digital temperature signals, intermediate links are lessened, to avoid the errors caused by wire resistance and field interference in the

transmitting analog signal with long wire and long-distance.

By adopting piecewise polynomial fitting nonlinear correction, the temperature measuring accuracy is improved. By adopting Fuzzy-PID control, the control precisions of temperature and flow rate are improved. Experimental results show that the control system has a fast response, a stable control process, a high control precision to meet the requirements of national standard fully, the test efficiency and self-control level is increased dramatically, and has a higher practical value.

Table 6. Experimental data of three kinds of conditions.

	$t_1/^\circ\text{C}$	$t_2/^\circ\text{C}$	$t_r/^\circ\text{C}$	$\Delta T/\text{K}$	Q/W	$K/(\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1})$
1	94.96	69.98	18.04	64.42	874.3	4.99
2	75.04	55.68	18.05	47.31	677.6	5.27
3	59.95	45.53	18.02	34.72	504.7	5.34

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