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Research Article

Design and Research of a New Thermostatic Valve

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Abstract: This study designed a new type of intelligent thermostatic mixing valve which could keep the temperature and flux of the outlet water constant by the adaptive controller. It firstly established mathematical model of the valve about angle-flux and angle-temperature and then it applied the “Fluent” software to numerical simulation of the valve about flow field based on the two-equation turbulence model. Finally, it designed the intelligent controller hardware and developed the controlling software of the valve. With the controller and it finished experiments with the thermostatic valve prototype. The results of simulation and experiments prove that the correctness of the theoretical research and they can be used to improve designing of the thermostatic valve.

Keywords: CFD, intelligent control, modeling, simulation, thermostatic valve

INTRODUCTION

Thermostatic mixing valve is designed for supporting products of the hot water system, which are widely used in electric water heater, solar water heater and geothermal heating water system. Thermostatic valves, such as manual adjustable mixing valve and mechanical thermostatic valve with thermal sensor (Luo *et al*., 2008; Cai and Yu, 2009) have defects in controlling precise and response speed and need to be improved greatly.

Manual adjustable mixing valve is difficult to control and keep the temperature and flux constant of the outlet water, which greatly causes waste of the water and electricity. The thermostatic valve with thermal sensor is a kind of mechanical thermostatic valve in essence; the thermal sensor can be divided into two kinds: memory of titanium alloy and thermal paraffin. The control accuracy and response speed of this kind thermostatic valve depends on expansion performance of the thermal sensor. The references (Wu *et al*., 2004; Matsui *et al*., 1995; Ohkata and Tamur, 1997) have studied for expansion properties of the memory of titanium alloy and proved the driving characteristics of the memory of titanium alloy is difficult to realize micro adjusting displacement and output big driving force of the thermostatic valve. The references (Li *et al*., 2006; He *et al*., 2008; Wang *et al*., 2003) have studied for expansion properties of the thermal paraffin and the results prove the thermal expansion interval of the thermal paraffin will become larger with the melting process change, so the flux is difficult to keep constant.

In this study, it designed an intelligent thermostatic mixing valve based on the fuzzy control and STC of the single chip microcomputer. Users can adjust the temperature of the outlet warm water according to their need and the controller can make the temperature quickly achieve the preset value and keep stably, which ensures the temperature of the outlet warm water constantly and it is not affected by the temperature, pressure and flux.

In this study, it firstly establishes the mathematical model of the thermostatic valve and then comprehensive analysis on the characteristics of the thermostatic valve by the numerical simulation and experimental research.

MATHEMATICAL MODEL OF THE THERMOSTATIC VALVE

Structure and working principle of the thermostatic valve: The structure of the thermostatic valve is shown in Fig. 1. The study principle of the valve is: when the

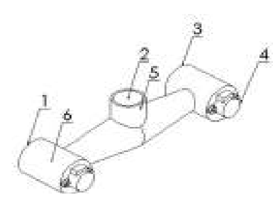

Fig. 1: The structure of the thermostatic valve
1 cool water inlet; 2 warm water outlet; 3 hot water inlet; 4 stepping motor; 5 temperature sensor; 6 valve body

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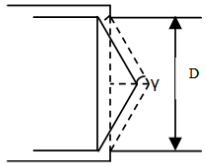

Fig. 2: Structure diagram of the ventileinheit

temperature of the outlet warm water is higher or lower, the temperature sensor can real-time monitor it and give feedback the measured temperature signal of the outlet warm water to the valve controller. According to the signal, the controller will generate controlling signal to drive the stepping motor to rotate and then drive the ventileinheit to move through the screw structure, which can change the axis rotate angle of the stepping motor to the linear displacement of the ventileinheit. When users need to change the flux of the outlet warm water, stepping motor will drive the ventileinheit to open (increasing water flux) or close (decreasing flux), thus realize the flux adjustment of the outlet warm water.

Flow models: The ventileinheit of the thermostatic valve is designed for cone (Fig. 2), which is connected with the stepping motor by a screw structure. When the liquid flow through the ventileinheit, the change of the through-flow sectional area will cause the change of the outlet warm water flux and the flux of the valve can be calculated as:

$$Q_m = \alpha \cdot A\sqrt{2\rho \Delta p} \tag{1}$$

where,
Q_m = The flux of the outlet water
α = The flux coefficient
A = Area of the valve port
Δp = The differential pressure of inlet and outlet of the valve
ρ = Density of the water

Through the screw driving, the rotation angle θ of the stepping motor can be transformed to the linear displacement ΔL of the ventileinheit, which can be calculated as:

$$\frac{2\pi}{\theta} = \frac{l}{\Delta L} \tag{2}$$

where,
l = The pitch of the screw
θ = Rotate angle of the stepping motor
ΔL = Displacement of the ventileinheit

According to Fig. 2, the through-flow sectional area can be calculated as (Chen *et al*., 2008):

$$A = \frac{\pi}{4}\left[D^2 - \left(D - 2\Delta L \cdot \tan\gamma\right)^2\right]\cos\gamma \tag{3}$$

where,
D = Outlet diameter of the valve
γ = The cone ventileinheit angle of the valve

According to the flow continuous equation and the conservation of mass, the flux of the outlet warm water can be calculated as:

$$\begin{aligned} Q_m &= Q_{m_1} + Q_{m_2} \\ &= \alpha \cdot \frac{\pi}{4}\cos\gamma \cdot \sqrt{2\rho}\left\{\left[D^2 - \left(D - \frac{l\tan\gamma}{\pi}\cdot\theta_1\right)^2\right]\sqrt{\Delta p_1} + \left[D^2 - \left(D - \frac{l\tan\gamma}{\pi}\cdot\theta_2\right)^2\right]\sqrt{\Delta p_2}\right\} \end{aligned} \tag{4}$$

where,
Q_{m_1} = The flux of inlet hot water
Q_{m_2} = The flux of inlet cool water
Δp_1 = The differential pressure of inlet hot water
Δp_2 = The differential pressure of inlet cool water

From Eq. (4), it is known that the flux of the outlet warm water is not only related with the pressure differential Δp, but also with the stepping motor angle θ. Therefore, even if the inlet water pressure of the valve is unstable which leads to change of the differential pressure, it can also ensure the flux of the outlet warm water constantly through controlling the rotate angle of the stepping motor.

Temperature model: According to the energy conservation law, it is known that the release heat of hot water is equal to the absorbed heat of cool water in the blending process. And because of the quality is equal to the mass flux Q_m multiplies by time t, therefore, when the ventileinheit of the hot and cool water open at the same time, the heat balance equation can be expressed as:

$$c \cdot Q_{m_1} t \cdot \left(T_1 - T\right) = c \cdot Q_{m_2} t \cdot \left(T - T_2\right) \tag{5}$$

where,
c = The specific heat capacity
T = Absolute temperature of the outlet warm water
T_1 = Absolute temperature of the inlet hot water
T_2 = Absolute temperature of the inlet hot water

According to Eq. (2), (3) and (5), the absolute temperature T of the outlet warm water can be calculated as:

$$T = \frac{\left[D^2 - \left(D - \frac{l\tan\gamma}{\pi}\cdot\theta_1\right)^2\right]\sqrt{\Delta p_1}\cdot T_1 + \left[D^2 - \left(D - \frac{l\tan\gamma}{\pi}\cdot\theta_2\right)^2\right]\sqrt{\Delta p_2}\cdot T_2}{\left[D^2 - \left(D - \frac{l\tan\gamma}{\pi}\cdot\theta_1\right)^2\right]\sqrt{\Delta p_1} + \left[D^2 - \left(D - \frac{l\tan\gamma}{\pi}\cdot\theta_2\right)^2\right]\sqrt{\Delta p_2}} \tag{6}$$

Table 1: Results of the numerical simulation

Serial number	Absolute temperature of inlet hot water T_1/K	Absolute temperature of inlet cool water T_2/K	Hydraulic diameter of inlet hot water D_1/mm	Hydraulic diameter of inlet cool water D_2/mm	Iterations times	Absolute temperature of outlet warm water T/K	Flow of warm water outlet Q_m/Kg/s
1	320	295	10	4	600	312.7	1.09
2	320	300	9	5	870	313.1	1.01
3	325	295	8	6	950	312.9	0.97
4	350	300	6	8	900	313.0	0.91
5	360	305	5	9	880	313.3	1.01
6	370	310	4	10	600	312.7	1.09

According to Eq. (6), it is known that the temperature of the outlet warm water is not only related with the hot and inlet cool water temperature, but also related with the differential pressure $\Delta\rho$ and the stepping motor angle θ. Therefore, even if the inlet hot water temperature decreases in the water heater with using, the valve controller can adjust the angle θ of the stepping motor to ensure the temperature of the outlet warm water constant.

NUMERICAL SIMULATION AND ANALYSIS

In order to validate the correctness of the theoretical temperature model, analyze the relationships between the pressure, temperature, flux of the inlet cool and hot water with the outlet warm water, it applies the "Fluent" software to numerical simulation about the flow field of the thermostatic valve.

In order to reduce the simulation calculation and maintain the flow field really, it adopts the reasonable simplified treatment to the physical model according to the structure of the valve. The simplified model is similar to the tee (Fig. 3).

Where it chooses boundary conditions as and then begins to simulate. From the simulating data shown as Table 1, it can easily find out that even if the different temperature conditions of the inlet hot and cool water, the corresponding hydraulic diameter (area) of the inlet hot and cool water can keep the temperature and flux constantly of the outlet warm water. Figure 4 is the curve of the outlet warm water about area-weighted average static temperature.

Figure 5 is the flux distribution nephogram of $z = 0$ section and the simulating parameters are T_1= 360K, T_2 = 305K, D_1 = 5, D_2 = 9.

According to the Table 1, it is known that it will have the corresponding hot and inlet cool water diameter to keep the temperature of the outlet in approximately 313.0 K (40ºC for the human body the most comfortable shower temperature) and keep the flux in approximately 1.01 kg/s (6 L/min) under the different hot and inlet cool water temperature. In the error allow range, it can explain that the temperature and flux of the outlet warm water is constant. At the same time, it can demonstrate the validity of the theoretical analysis that the actual value of the outlet warm water temperature and flux can be consistent with the set value through the thermostatic valve and controller adaptive adjust under the different hot and inlet cool water temperature.

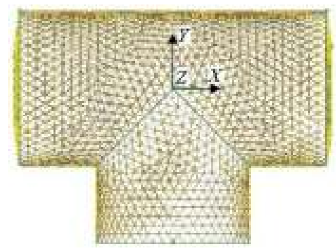

Fig. 3: Simplified model of the valve

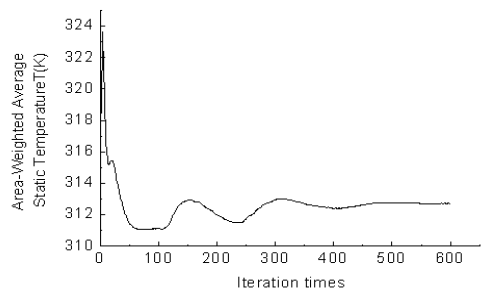

Fig. 4: Curve of the outlet warm water about area-weighted average static temperature

In order to validate the correctness of the mathematical model about the thermostatic valve, it compares the simulation values with the calculated values. According to Eq. (1) and Eq. (12), take as α = 0.8, ρ =1×10^3 kg/m^3 and the differential pressure Δp about water flowing through the ventileinheit, it can easily calculate out the flux and temperature of the outlet warm water of the valve. Figure 6 is the contrast curve of the simulation value and the calculated value about the flux of the outlet warm water. Figure 7 is the contrast curve of the simulation value and the calculated value about the temperature of the outlet warm water. According to Fig. 6 and 7, the variation tendency of the CFD simulation results and the calculated value is consistently, which proves that the mathematical model of the thermostatic valve is correct.

DESIGN INTELLIGENT CONTROLLER OF THE VALVE

The controller uses STC90C52RC as the controlling core chip and the hardware system mainly constitutes with five parts: temperature acquisition circuit module, preset circuit module, power supply

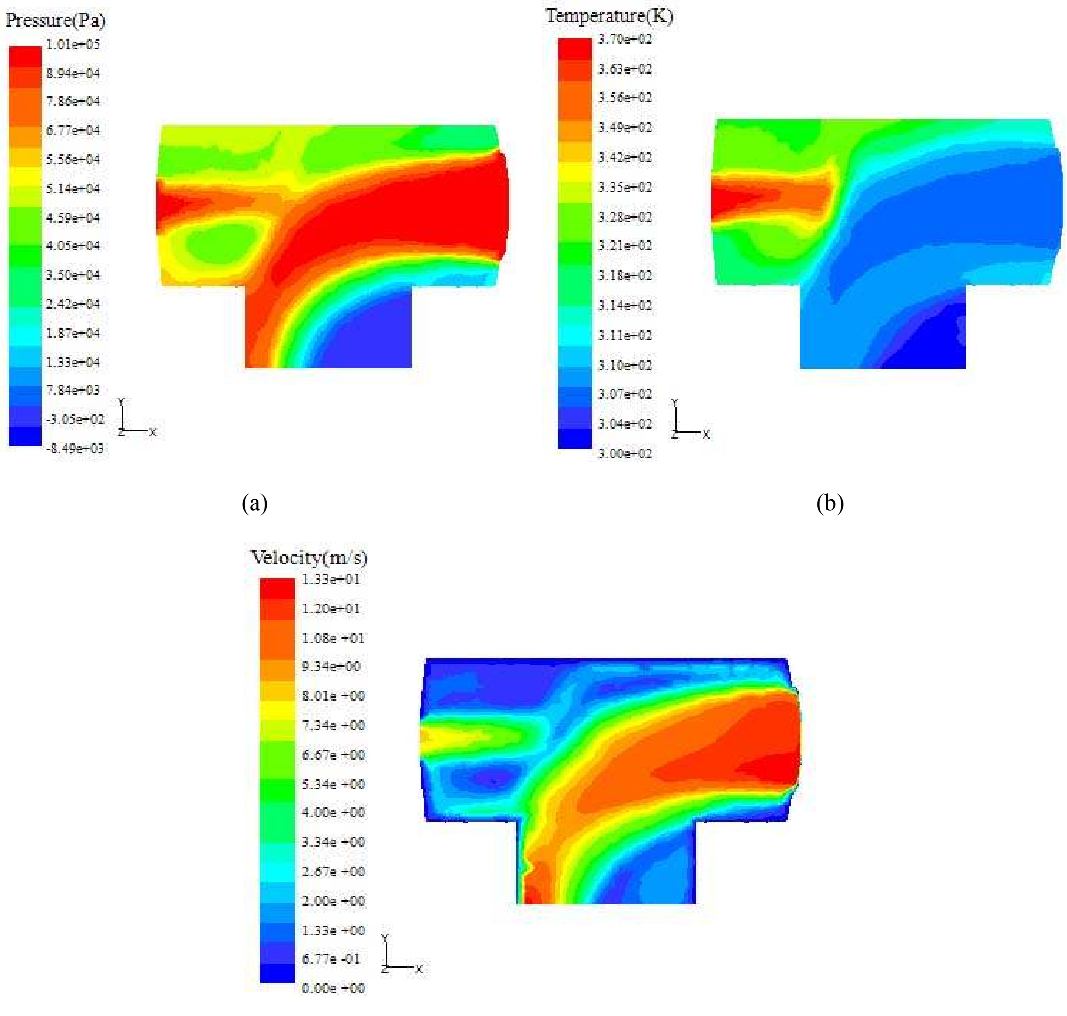

Fig. 5: Flow distribution nephogram of the $z = 0$ section; (a) Pressure distribution nephogram of $z = 0$ section; (b) Temperature distribution nephogram of $z = 0$ section; (c) Velocity distribution nephogram of $z = 0$ section

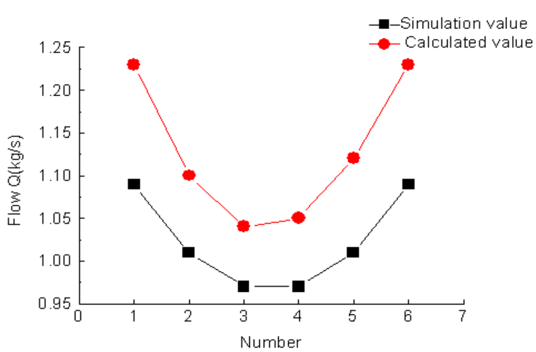

Fig. 6: Contrast curve of the flux

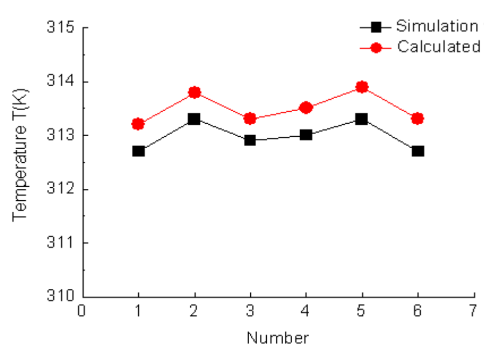

Fig. 7: Contrast curve of the temperature

module, display module and control circuit module. The controller principle diagram is shown as Fig. 8.

Design intelligent controller hardware: The temperature sensor is installed in the outlet of the valve to measure the temperature of the warm water and is isolated by a rubber ring. Temperature acquisition module is achieved by DS18B20, which has characteristics of high performance, low power consumption and strong anti-jamming. The temperature

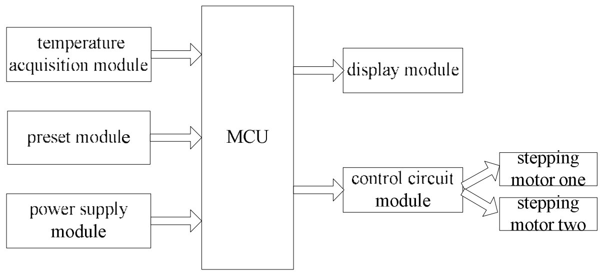

Fig. 8: Controller principle diagram

measure range of the sensor is from -55°C and 5ºC and the accuracy is 0.0675°C, which can completely satisfy the valve working temperature range from 5°Cto 75°C.

The keyboard has five independent keys. The keys are respectively defined as "start", "close", "flux gear", "temperature increase", "temperature decrease". According to the most appropriate temperature, the controlling system sets the default temperature as 40ºC. If the shower wants to change the temperature, he/she can operate the corresponding key on the operation panel board.

The stepping motor can change the electrical pulses signal into angular displacement. It uses two stepping motors of four phase eight pats to drive the ventileinheit of the valve. When the driver receives pulse signals from the MCU, it will drive the stepping motor to rotate according to the step angle. When the stepping motor receives a series of continuous control pulse signal, it can rotate continuously. Because the output signal of the MCU is not big enough, an amplifier is designed with ULN2003 chips. The controller circuit diagram is shown as Fig. 9.

Design intelligent controller software: The controller uses STC90C52RC as the controlling core chip and it uses the fuzzy control algorithm to realize intelligent control. The control system flow diagram is shown as Fig. 10. From the Fig. 10, the controller firstly finishes initialization according to the keyboard input value and then it will operate with the set value according to intelligent controller program until the temperature and flux of the outlet warm water are constant.

The fuzzy control algorithm: In the process of the software design, this study uses the modular programming based on the fuzzy control algorithm. As the temperature of the outlet warm water exist pure lag, result in imprecise measure. It is very difficult to establish the valve accurate mathematical model to realize the control of the temperature. Therefore, this design uses the fuzzy control algorithm to realize constant temperature control.

In the set of temperature and flux, the input of the fuzzy controller is the deviation E of the measure temperature and the set temperature ($E = t_0 - t$, where t_0 is the set temperature, t is the measured temperature) and the change of deviation ($\Delta E = t_i - t_{i-1}$, where t_{i-1} is the i-1 time measured temperature, t_i is the i time measured temperature), the output is the rotation angle and direction of the stepping motor. E is divided into six fuzzy subset PB (positive broad), PM (positive median), PS (positive small), NS (negative small), NM

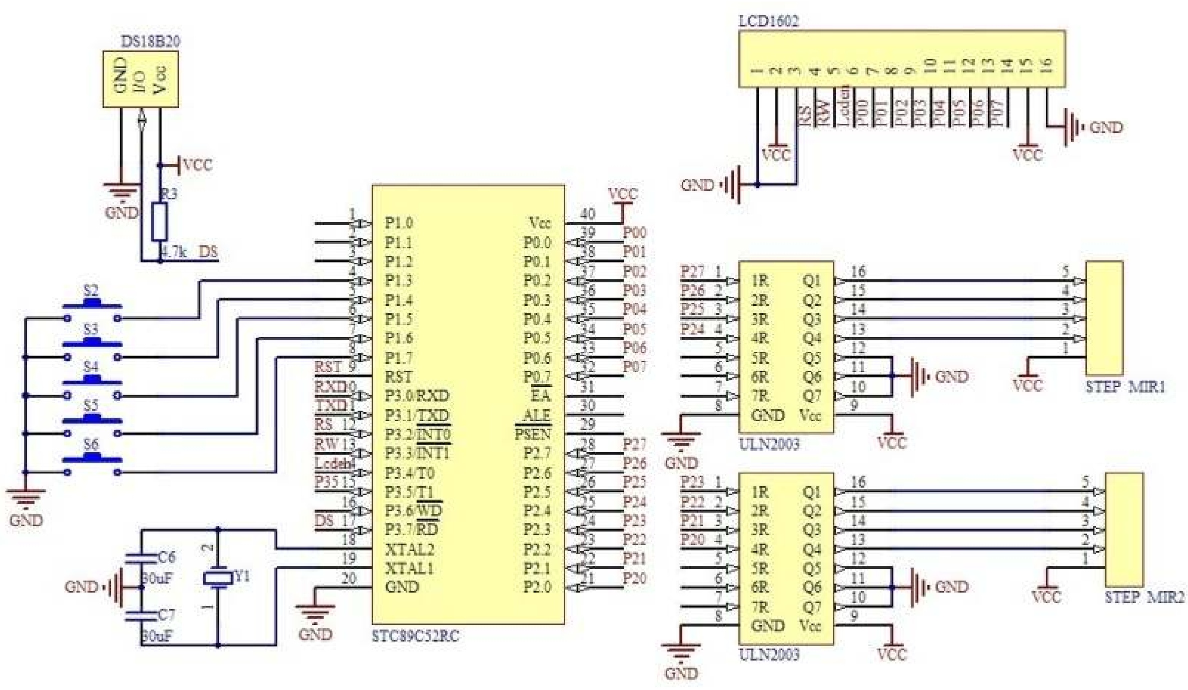

Fig. 9: Controller circuit diagram

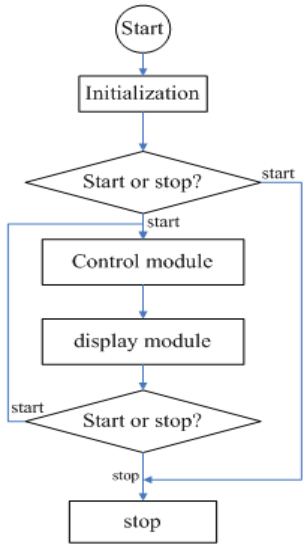

Fig. 10: Control system flow diagram

Fig. 11: Thermostatic valve physical prototype diagram

Table 2: The fuzzy control rules

E/ ΔE	P	Z	N
PB	NB	NB	NB
PM	NM	NM	NS
PS	NS	NS	Z
NS	Z	PS	PS
NM	PS	PM	PM
NB	PB	PB	PB

Table 3: The experimental results

Serial number	Temperature of inlet hot water T_1/°C	Temperature of inlet cool water T_2/°C	Response time t/s	Temperature of hot water outlet T/°C
1	50	10	7.85	40
2	55	10	7.78	40
3	60	10	7.02	40
4	65	10	6.98	40
5	70	10	7.08	40
6	75	10	7.14	40
7	80	10	7.35	40
8	85	10	7.55	40
9	90	10	7.68	40

(negative median) and NB (negative broad), the corresponding temperature deviation is: PB>TM1°C, TM2°C < PM < TM1°C, 0°C < PS < TM2°C, TM3°C < NS < 0°C, TM4°C < NM < TM3°C, NB < TM4°C (TM4 < TM3 < 0 < TM2<TM1). ΔE is divided into three fuzzy subset P (positive), Z (zero), N (negative), the corresponding deviation change: $t_i - t_{i-1} > A_0$, $-A_0 < t_i - t_{i-1} < A_0$, $t_i - t_{i-1} > A_0$, $(A_0 > 0)$. According to the direction and the size of the rotation angle, the stepping motor which cool and hot water ventileinheit correspond can be divided into PB, PM, PS, Z, NS, NM, NS. The fuzzy control rules are shown as Table 2.

EXPERIMENTS AND ANALYSIS

After the structure design, intelligent control system design and simulation analysis of the thermostatic valve are completed, this study manufacture the thermostatic valve prototype (Fig. 11) for test the actual control effect. The test purpose is: it makes that the outlet temperature and flux of the actual value and the set value are consistent through the thermostatic valve and controller adaptive adjusts in the different inlet hot and cool water temperature; it tests the correctness of the program controller and the speed of response at the same time. The test results are shown as Table 3. According to the experimental data with different inlet hot and cool water temperature, it verifies the consistency of the design, simulation and experimental results. And the response time can keep in 7 seconds or so, it verifies the temperature of the inlet hot water almost no influence to the ability of the thermostatic valve respond.

CONCLUSION

- It introduces the structure and working principle about a kind of new intelligent thermostatic mixing valve and it established mathematical model about angle-flux and angle-temperature of the valve.
- According to the numerical simulation results about the valve flow field, it proves that the temperature and flux of the outlet warm water can keep constantly with the valve, which demonstrates the validity of the theoretical analysis.
- According to the experimental data with different inlet hot and cool water temperature, it verifies the consistency of the design, simulation and experimental results. And the response speed of the temperature sensor is very quickly and the outlet temperature can keep coincidence with shower setup.

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