IMPROVEMENT OF TEMPERATURE CONTROL PERFORMANCE FOR ELECTRIC HEATING WATER TANK

by

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Temperature control is an important factor which influences the accuracy of refrigerant heat transfer experimental results. In this paper, the three temperature control methods for the electric heating water tank (EHWT) in the single tube heat transfer experimental rig are investigated. The error of proportional-integral-derivative (PID) controller is ±1 °C and the stability time is 390 seconds. The control performance is not satisfactory. A fuzzy controller and a fuzzy PID controller are designed to improve temperature control performance. The designed controllers are simulated by MATLAB/SIMULINK and the results prove that the designed controllers is suitable for EHWT. The experimental results show that the performance of the designed controllers are improved concerning. The error of two controllers is ±0.1 °C. Compared to the PID controller, the stability time of the fuzzy controller and the fuzzy PID controller are decreased by 14.9% and 43.1% and the overshoot of the two controllers are reduced by 100% and 62.5%, respectively. The results and the control method have great significance for the refrigerant heat transfer experiment.

Key words: *EHVT, fuzzy controller, fuzzy PID controller, temperature control*

Introduction

Precise control of temperature is an important factor in various industrial tasks [1]. Temperature control is usually achieved by the heater and the precision of the heater temperature control depends on the accuracy and sensitivity of its controllers [2]. The PID controllers are used widely in industrial control owing to their simplicity and adaptability [3]. The accuracy of PID controllers is a bit lower because their parameters are constant. The control performance of PID controllers for processes with large time delays is undesirable in the presence of process noise or the presence of non-linear operating conditions [4].

Temperature control is a typical time delay case. It is well known that time delay have a negative influence on the performance of control systems [5]. The PID controllers are limited in industrial control applications because of their disadvantages. Therefore, the improvement of PID controller performance has become a research issue. Fuzzy logic control greatly

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reduces computation time and memory because of its ability to simplify functions and rules. This advantage makes fuzzy logic control suitable for temperature control systems for heating, ventilation and air conditioning [6]. The experimental studies have proved that the fuzzy logic control combined with PID control had good performance in temperature control [7]. Another advantage of fuzzy logic control is the ability to include a great number of variables and rules at the same time. It has been shown that fuzzy logic control is suitable for temperature control of different systems [8].

Fuzzy PID controllers for temperature control have been used in many fields. Liang *et al.* [7] controlled the temperature of the vehicle climate by a fuzzy PID controller. The experimental results showed that the designed controller reduced the stability time, overshoot and downshoot. The time-averaged temperature error was reduced for both high and low temperature tests. Jia *et al*. [9] used an improved smith fuzzy PID controller to control the temperature of heating boilers in power plants, the improved controller enhanced the stability and balance of the system. Li *et al.* [10] studied the control of coolant temperature in the reactor core power control system. The experimental results showed that the errors with both fuzzy controller and fuzzy PID controller were acceptable. Zhang *et al.* [11] controlled the orchard temperature by a fuzzy PID controller to provide a comfortable growth environment for fruits. Experiments showed that the designed controller can effectively control the temperature difference between day and night. Liu *et al.* [12] used fuzzy PID controller and PID controller for segment control when conducting the test. Under the same test conditions, the test results become more accurate and the whole test time become shorter due to the better control of the fuzzy PID controller compared to the PID controller. Hu *et al.* [13] studied the temperature control of the injection machine. The fuzzy PID controller was superior to the PID controller in all aspect. Ćojbašić *et al*. [14] proposed intelligent optimization method for temperature controller to increase control performance and energy efficiency. Fuzzy PID controller has shown excellent performance in other areas such as automotive industry [15], animal husbandry [16], an electromechanical actuator system [17], cold storage [18], and heating, ventilation and air conditioning system control [19]. In terms of energy consumption, fuzzy control was superior to PID controllers, reducing energy consumption by 30-70% [20].

In this paper, the effective temperature control of EHWT in the experimental rig is investigated. In the first part, the control performance of the existing PID controller is tested. It is found that the existing PID controller does not perform well in controlling the temperature of the EHWT through experiments. In the second part, a fuzzy controller and a fuzzy PID controller are designed by LabVIEW software based on fuzzy control rules. The designed controllers are verified to be suitable for the EHWT by MATLAB/SIMULINK simulation. Last, the experimental investigation of the two designed controllers is carried out to finish the temperature control performance analysis.

Experimental rig

The system schematic fig. 1(a) and the physical diagram fig. 1(b) of the single tube heat transfer experimental rig are shown in fig. 1. The experimental rig is composed of the control system, water system and refrigerant system. The EHWT is located in the water circulation system. The test section is a double-tube. Water flows in the outer pipe and refrigerant flows in the inner pipe. The conditions that can be changed are the refrigerant pump frequency, the pump frequency, the water tank heating power and the valve opening. A flowmeter is installed in each closed pipe. Temperature and pressure measurement units are installed before and after the test section, respectively. The required cooling capacity of the experimental rig is provided by the chiller.

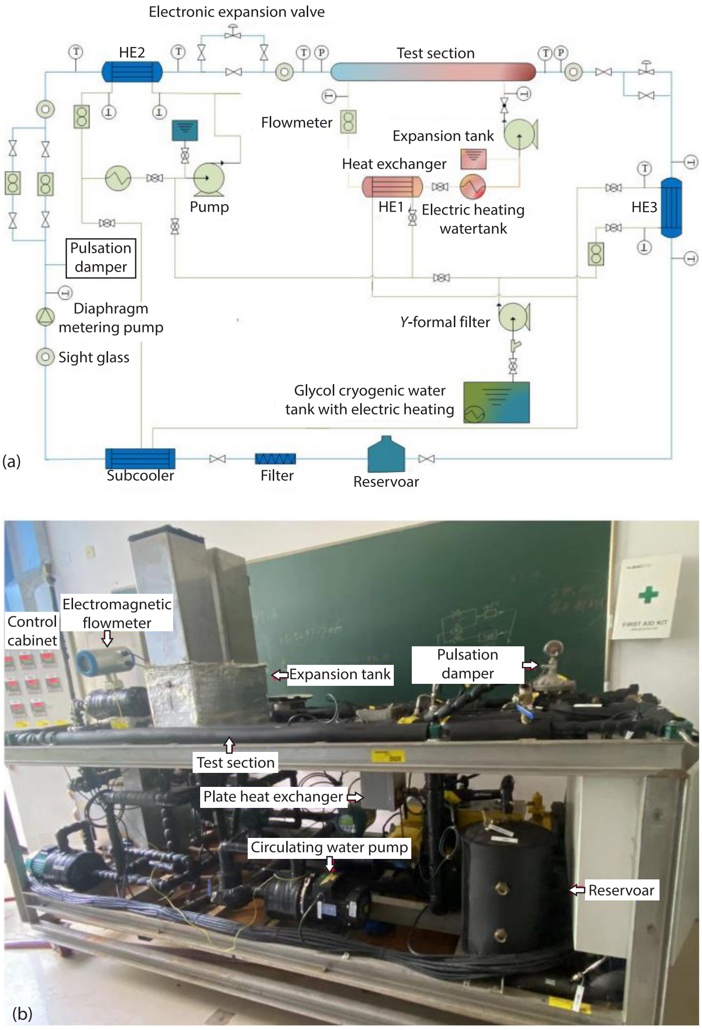

Figure 1. The system schematic (a) and the physical diagram (b) of the experimental rig

The structure of the EHWT is shown in fig. 2. Length, width, and height are 51 cm, 13 cm, and 38 cm, respectively. The EHWT is mainly consisted of rubber-plastic and steel. The main materials of rubber-plastic insulation material are rubber and polyvinyl chloride (NBR/PVC). The thickness of the rubber-plastic and steel just mentioned are 25 mm and 1.2 mm, respectively. There are three heating tubes inside the EHWT, and the maximum power of each heating tube is 500 W. The water flows in from the inlet at the lower part of the EHWT and out from the outlet at the upper part.

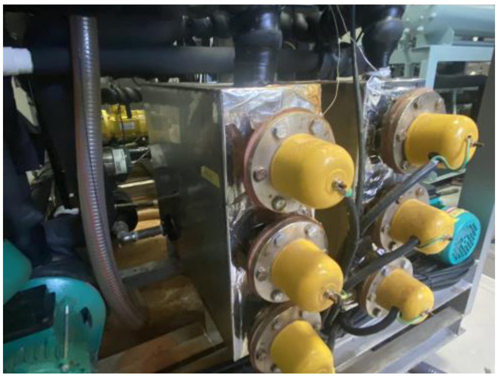

Figure 2. The structure of the EHWT

The water temperature is measured with a platinum resistor. A current signal is generated by the sensor to indicate the measurement, from 4-20 mA (corresponding to –40-60 °C). Then the electrical signal is delivered to a PLC module. After analyzed by a control algorithm, the current signal is output by the module to the power controller of the EHWT.

The temperature control of the water side inlet of the test section is especially significant and is the core part of the whole experiment rig. The precise temperature control not only contributes to the accuracy of the experiment, but also reduces energy consumption. The control of the outlet temperature of the EHWT (inlet temperature of the water side of the test section) is discussed in the next section.

Experimental rig control and control algorithm

The PLC-HMI based monitoring system has been designed for the experimental rig [21]. The operator can monitor and control the experiment rig remotely through the monitoring system. The monitoring system can be optimized for more intelligent control. The EHWT is equipped with a conventional PID controller. Conventional PID controller is first used to control the temperature of the EHWT. The output of the PID controller:

$$u(t)=K_P\left[e(t)+\frac{1}{T_i}\int_0^t e(t)\,\mathrm{d}t+T_d\frac{\mathrm{d}e(t)}{\mathrm{d}t}\right]\tag{1}$$

where $u(t)$ is the power output, $e(t)$ – the deviation between set temperature and current temperature, K_P – the proportional gain, T_i – the is the integral time, and T_d – the derivative time.

The PID parameter setting

Parameter setting is one of the core issues in PID controller applications. Various PID parameter setting methods have been proposed in industry. In this paper, the parameters of the PID controller are set by the critical proportion method [22]. In the case of pure proportional regulation, K_P is decreased from large to small until the temperature curve equal amplitude oscillation is occurred according to the critical proportion method. By this step, K_P and T_K are obtained, where T_K is equal amplitude oscillation time. The common critical proportion method is expressed by δ:

$$\delta=\frac{1}{K_P}\tag{2}$$

where δ is proportionality.

The equation for solving the PID parameters is shown in tab. 1.

Table 1. Controller parameters are set according to the critical proportion method

Controller type	δ	T_i	T_d
P	$2\ \delta$	∞	0
PI	$2.2\ \delta$	$0.833\ T_k$	0
PID	$1.7\ \delta$	$0.5\ T_K$	$0.125\ T_K$

From the steps described previously, there is a constant amplitude oscillation at $K_P = 0.45$. The oscillation curve is shown in fig. 3. As shown in the figure, $\delta = 2.5$ and $T_K = 119$ seconds are obtained.

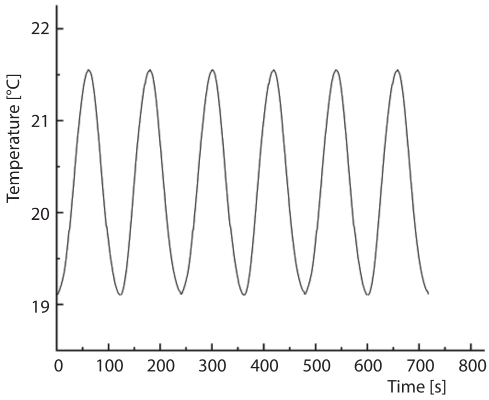

Figure 3. Schematic diagram of equal amplitude oscillation

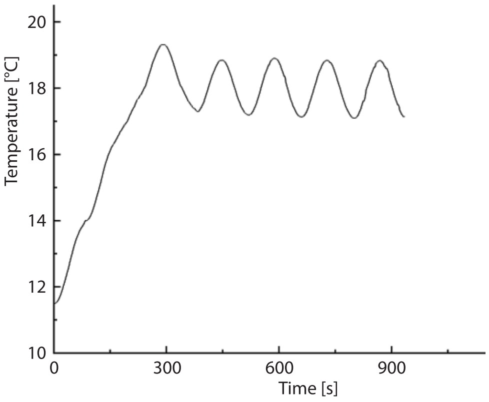

Figure 4. Temperature change by PID control

The PID control test

According to tab. 1, the parameters of the PID controller are $\delta = 4.3$, $T_i = 59.5$ seconds, and $T_d = 14.9$ seconds. The control performance of the EHWT by PID controller is tested. The relevant data of the experiment are the power of the EHWT is set to 450 W, the opening of the electronic expansion valve is set to 50%, the frequency of the refrigerant pump is set to 15 Hz and the frequency of the test pump is set to 50 Hz. These are nominal values for system operation. The experiment is conducted at room temperature. The temperature variation of EHWT is shown in fig. 4.

It is obvious that the PID controller is not as effective as it could be. The experimental results shows that the stability time of the PID controller is 390 seconds. The error after stabilization is ±1 °C. The overshoot is 7% of the set value. Such control performance will have a great impact on the accuracy of the experimental results.

The control of the chiller is on/off. There is a fluctuation of ±2 °C in the outlet water temperature. The temperature of the refrigerant after subcooling is also unstable due to the aforementioned reason. It leads to unstable heat transfer between refrigerant and water. Further, it affects the outlet temperature of the EHWT. The PID controller cannot realize the real-time change of parameters. Conventional PID controller is not suitable for the temperature control of the EHWT in the experiment rig. A more intelligent control method is needed to improve the control performance since the existing PID controller is not effective.

Fuzzy controller and Fuzzy PID controller

Improvement of control performance by combining other intelligent algorithms with PID control was proven to be feasible. For example, fuzzy PID control. Hu *et al.* [23] proposed a fuzzy PID control regulation method for the temperature control of screw shaft with an oil cooling cycle that can reduce the temperature variation by about 3 °C. Chu *et al.* [22] carried out four control methods for the temperature control of the experimental platform. The results showed that the controller with the best performance is the proposed fuzzy PID. It had less overshoot and shorter setting time.

In order to improve the control performance, a fuzzy controller and fuzzy PID controller are designed based on NI LabVIEW software for the temperature control of EHWT. The controllers designed based on NI LabVIEW software can communicate with PLC through OPC protocol to realize remote control of the experimental rig.

Fuzzy logic control is a control method based on fuzzy set theory, fuzzy linguistic variables and fuzzy logic reasoning [24], which is proposed by professor Zadeh. The fuzzy rules are written based on expert experience as well as system characteristics. The whole fuzzy control is composed of the following parts: the signal is first fuzzified as an input to the fuzzy controller. Then defuzzification is carried out according to the written fuzzy rules. At last, the output values are transferred to the actuator after completing fuzzy inference. The basic schematic of fuzzy logic control is shown fig. 5. Currently, fuzzy logic control combined with PID control is widely used as a more effective control method. The shortcomings of traditional PID control can be compensated by fuzzy logic control. The system control accuracy is more accurate and responds more rapidly under fuzzy PID control [25].

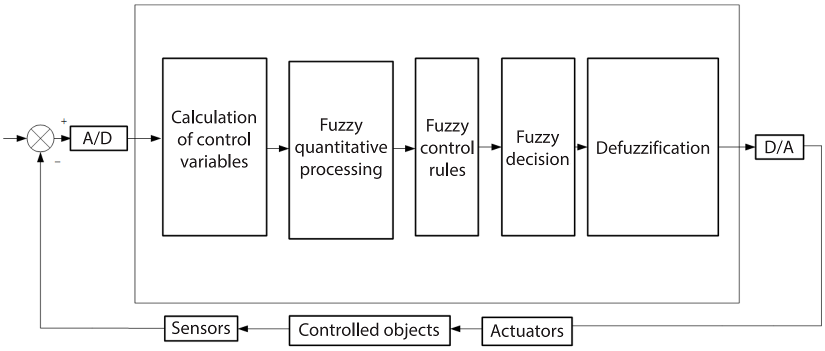

Figure 5. Basic schematic of fuzzy control

Fuzzy controller

The temperature error, E, and the rate of error, EC, are used as inputs to the fuzzy controller. The power output, u, of the EHWT is used as the output. The physical domains of E, EC, and u are set to [–1, 1]. The fuzzy subsets are set as {NB, NM, NS, ZO, PS, PM, PB} [26]. In this paper, the membership function used is a triangle. The setting of fuzzy rules is the key to the fuzzy control algorithm, which directly influences the performance of the controller. The form formed is an if-then statement. The fuzzy rules table is obtained based on the logical reasoning of AND-OR. Fuzzy rules are set based on previous engineering experience. An output value is determined by two input values. There are 49 fuzzy rules in the fuzzy controller [22]. The output u function curve of the fuzzy controller and the correspondence surface of input and output are shown in figs. 6(a) and 6(b).

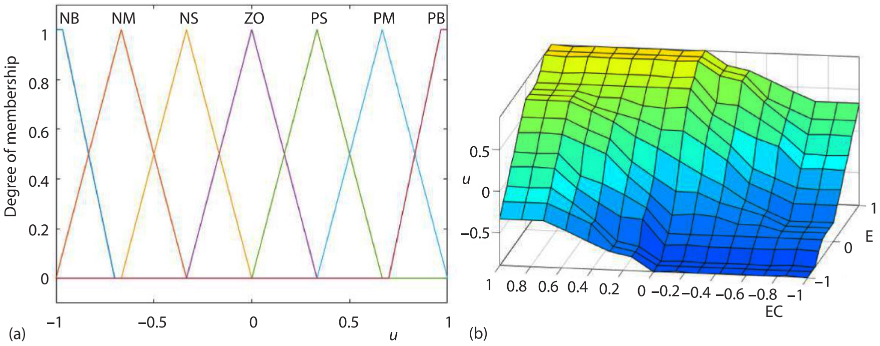

Figure 6. Membership function curve (a) and input and output correspondence surface (b) of fuzzy controller

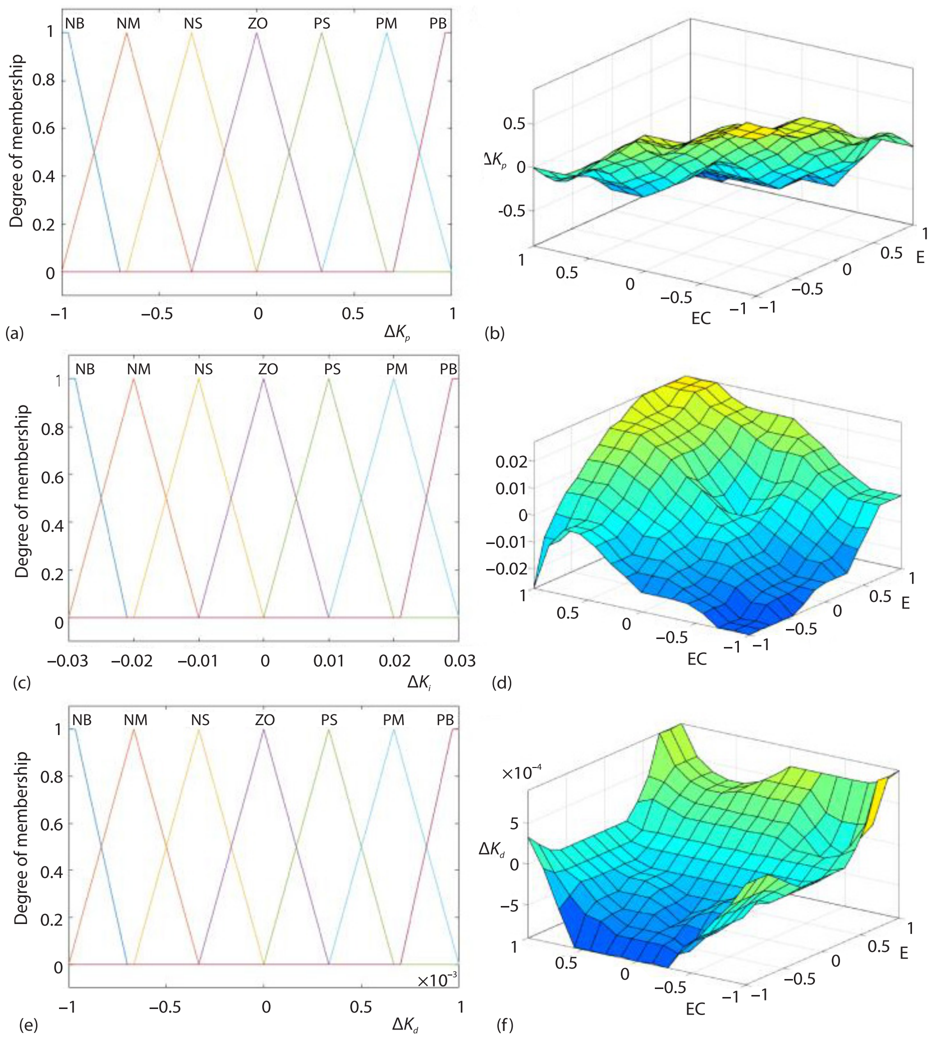

Figure 7. (a), (c), and (e) Membership function curve of ΔK_P, ΔK_i, and ΔK_d, respectively; (b), (d), and (f) input and output correspondence surface of ΔK_P, ΔK_i, and ΔK_d, respectively

Fuzzy PID controller

The E and EC are used as inputs to the fuzzy PID controller. The three parameters of the PID are used as outputs of the fuzzy PID controller. The current E and EC are collected and analyzed when the controller is operating. The three parameters of the PID are also adjusted online by fuzzification and fuzzy inference. The physical domain of E, EC, and ΔK_P are set to [–1, 1], the physical domain of ΔK_i is set to [–0.03, 0.03] and the physical domain of ΔK_d is set to [–0.001, 0.001] based on experience. The fuzzy subsets are set as {NB, NM, NS, ZO, PS, PM, PB}. Three different output values are determined by two input values. There are 147 fuzzy rules in the fuzzy PID controller [22]. The three output function curves of the fuzzy PID controller and the corresponding surface of the input and output are shown in fig. 7.

The designed fuzzy PID controller improves the control performance while maintaining the simple structure of the PID controller. Fuzzy PID controller can improve performance without modifying any hardware part of the PID controller. The fuzzy PID controller is based on the system characteristics to identify the fuzzy relationship between the three outputs and the two inputs. Then the three parameters are adjusted online by the set fuzzy control rules to achieve better dynamic stability performance of the controlled object [27].

Simulation test

Simulation model

In order to verify the suitability of the designed controllers for EHWT control in this experimental rig, the designed controllers are simulated by using MATLAB/SIMULINK. The block diagrams of the fuzzy controller and fuzzy PID controller are shown in fig. 8. The key step in the simulation is to establish the transfer function. It is essential to simplify the transfer function since many factors are involved in the heating of the water tank. Therefore, the transfer function is described as a first-order transfer function:

$$G(s) = \frac{K}{T_s + 1}\mathrm{e}^{-\tau s} \tag{3}$$

where K is the static amplification factor, T – the time constant, and τ – the pure delay time.

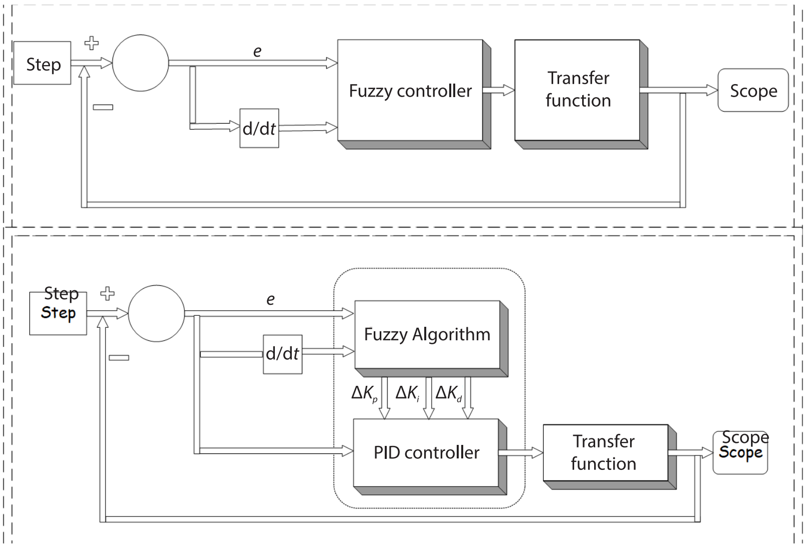

Figure 8. Block diagrams of the fuzzy controller and fuzzy PID controller

In this paper, the step disturbance response method is used to establish the transfer function of the simulation model. The power and outlet temperature of the EHWT are used as the input and output of the model, respectively. According to the common experimental conditions, the input control data is chosen to be 30% (input power of the heating rod is 450 W and total power is 1500 W). The step response curve of temperature-time is obtained as shown in fig. 9.

The relevant value of the controlled subject is represented by dimensionless form:

$$y^*(t) = \frac{y(t) - y(0)}{y(\infty)} \tag{4}$$

where $y(t)$ is the EHWT outlet temperature value at t time obtained and $y(\infty)$ – the maximum temperature of EHWT and $y(0)$ is the initial temperature of EHWT. According to temperature-time curve $y(\infty)$ is 46.25 °C. From the temperature curve: t_1 = 200 seconds, t_2 = 380 second, $y(t_1) = 26.78$, and $y(t_2) = 37.12$:

$$\begin{aligned} y^*(t_1) &= 0.43 \\ y^*(t_2) &= 0.65 \end{aligned} \tag{5}$$

The parameters of the transfer function are accessed by the following equation, where $T = 360$, $\tau = 20$, and $K = 1.962$:

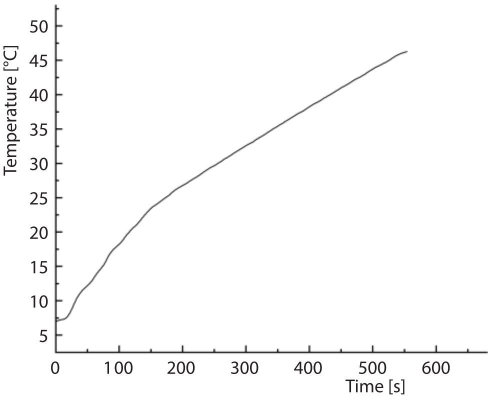

Figure 9. The temperature-time curve

$$\begin{aligned} T &= 2(t_2 - t_1) \\ \tau &= 2t_1 - t_2 \\ K &= \frac{y(\infty) - y(0)}{\tau} \end{aligned} \tag{6}$$

Hence the first-order transfer function is represented as:

$$G(s) = \frac{1.962}{360_s + 1} e^{-20s} \tag{7}$$

Simulation results

The simulation results of the designed controllers are shown in fig. 10. The temperature of the controller is set to 18 °C. From the figure, it is observed that the error of the fuzzy PID controller is 0 °C and there is an overshoot of 12.8%. The error of the fuzzy controller is 0.1 °C with no overshoot. From the simulation results, it is clear that the performance of the two designed controllers is improved compared to the PID controller. So the fuzzy controller and the fuzzy PID controller can be used to control the temperature of the EHWT.

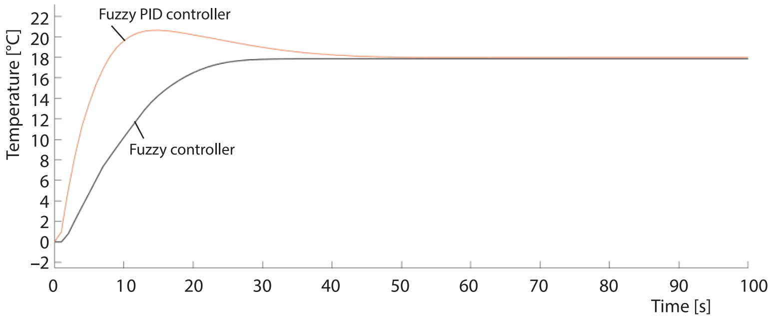

Figure 10. Simulation results of the fuzzy controller and the fuzzy PID controller

Experimental results and discussion

In order to confirm the actual control effect of the two designed controllers, experiments are carried out at the target temperature of 18 °C and 30 °C, respectively. The environmental temperature is room temperature. Regarding the experimental steps are:

- The instrument is checked for normal display.
- The valves of refrigerant pipe-line and water pipe-line are opened.
- The water pump and refrigerant pump are turned on in turn. The frequencies of the water pump and refrigerant pump are set to 50 Hz and 15 Hz, respectively.
- The electric heater of the water tank is turned on and the target temperature is set.
- The designed controller is run. The data is recorded after the temperature stabilization.
- The electric heating tank, refrigerant pump and water pump are turned off in turn.

The experimental results of the fuzzy controller and fuzzy PID controller are shown in figs. 11 and 12, respectively. The actual regulation trend of both controllers are the same compared with the simulation results. Increased stability time and reduced overshoot of the fuzzy PID controller, which due to the simplified transfer function. From the experimental results, the error of the fuzzy PID controller are ±0.1 °C in the experiments where the set temperature are 18 °C and 30 °C, respectively. The stability time is 222 seconds and 237 seconds, respectively. The overshoot are 0.04% and 0.02%, respectively. The error of the fuzzy controller are ±0.1 °C in two experiments, respectively. The stability time are 332 seconds and 338 seconds in two experiments, respectively. The fuzzy controller has no overshoot.

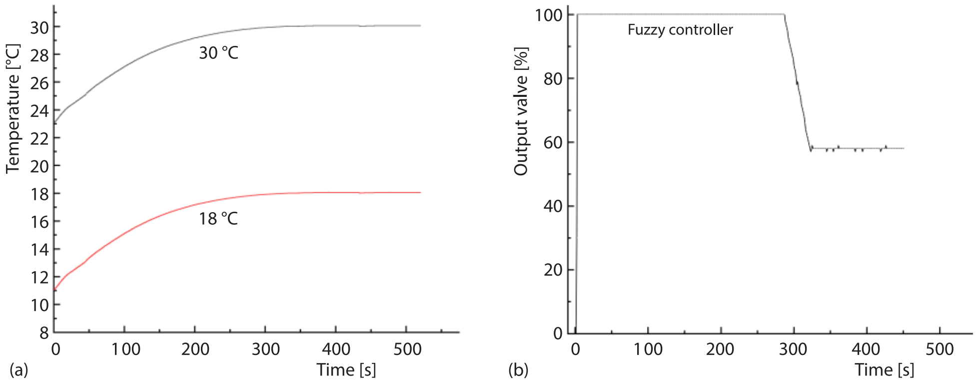

Figure 11. Temperature change (a) and control signal (b) of fuzzy controller

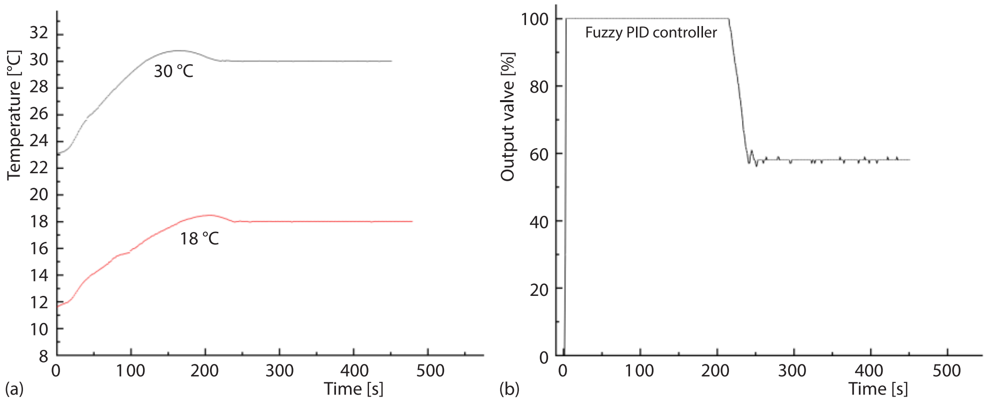

Figure 12. Temperature change (a) and control signal (b) of fuzzy PID controller

At the condition of the set temperature of 18 °C, the control performance comparision of the three controllers are finished. In terms of accuracy, the error of the three controllers are

±1 °C, ±0.1 °C, and ±0.1 °C, respectively. The accuracy of the two designed controllers are improved by 90% compared to the PID controller. The stability time of fuzzy controller and fuzzy PID controller are 222 seconds and 332 seconds, respectively. Compared to PID controller, the stability time of the two designed controllers are reduced by 14.9% and 43.1%, respectively. The improvement of the fuzzy PID controller is significant. Better performance of the stability time provides the fuzzy PID controller with a faster response time when the experimental conditions of the system are changed. In terms of overshoot, the overshoot of the fuzzy PID controller is 0.04% and the fuzzy controller has no overshoot. In general, the control performance of the designed controllers is improved in each aspect compared to the existing PID controller. Based on the aforementioned study, the fuzzy PID controller is more suitable for the equipment with high requirement of stability time. The fuzzy controller is more suitable for equipment with high requirements of low overshoot. The fuzzy controller and the fuzzy PID controller can be applied for one equipment and intelligent selection of the controller depends on the specific situation. Considering the experiment time, because the overshoot of fuzzy PID controller is allowed, the fuzzy PID controller is recommended for the experimental rig.

Conclusions

The temperature control of the EHWT in the single tube heat transfer experimental rig is investigated to improve the accuracy of the experimental results of refrigerant heat transfer in this paper. The following results are obtained based on the previous experimental studies.

- A fuzzy controller and a fuzzy PID controller are designed for the temperature control of the EHWT. A model for the heating process is established and the suitability of the designed controllers are verified by MATLAB/SIMULINK simulation.
- The experimental results show that the performance of the two designed controllers are improved compared to the existing PID controller. The stability time of the fuzzy PID controller has greater decline. The overshoot of the fuzzy controller has bigger decrease.
- The overshoot of the fuzzy PID controller is allowed for the temperature control of the EHWT. In order to shorten the experimental time, the fuzzy PID controller is recommend for the temperature control of the EHWT in the experimental rig.

Acknowledgment

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Nomenclature

E – temperature error, [°C]
EC – error rate of change
$e(t)$ – input function
$G(s)$ – transfer function
K – static amplification factor
T – time constant, [second]
T_d – derivative time, [second]
T_K – equal amplitude oscillation periods, [second]
T_i – integral time, [second]
u – output power
$u(t)$ – output function
ΔK_d – derivative gain
ΔK_i – integral gain
ΔK_P – proportional gain

Greek symbols

δ – proportional band
τ – pure delay tim, [second]

Acronyms

EHWT – electric heating water tank
HMI – human machine interface
NB – negative big
NBR – nitrile butadiene rubber
NM – negative medium

NS – negative small
OPC – ole for process control
PB – positive big
PID – proportional-integral-derivative
PLC – programmable logic controller
PM – positive medium
PVC – polyvinyl chloride
ZO – zero

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