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Modified Smith fuzzy PID temperature control in an oil-replenishing device for deep-sea hydraulic system

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ABSTRACT

With the characteristics of large inertia, large time delay and time-varying parameters, it is difficult to control accurately the oil heating process in an oil-replenishing device for deep-sea hydraulic system. Four temperature control methods are presented and compared in this paper, i.e. proportional–integral–derivative controller(PID controller), fuzzy PID controller, Smith fuzzy PID controller and modified Smith fuzzy PID controller which adds a first order filter in the Smith predictor. They are simulated in MATLAB/SIMULINK based on the cases of transfer function matching and mismatching between the theoretical and the actual model. The results show that, in both cases, the step response curve of the modified Smith fuzzy PID controller has neither the significant oscillation nor the overshoot and requires the minimum time to achieve stabilization as well. Furthermore, this paper applies those four control methods in actual oil heating temperature control process through PIC16F877A micro controller unit (MCU). The experimental data demonstrate that the oil heating system controlled by the modified Smith fuzzy PID controller could stabilize at the expected temperature with nearly no overshoot, which further proves that the modified Smith fuzzy PID controller is able to sufficiently meet the challenges of industrial applications containing varying system parameters.

1. Introduction

Hydraulic system has been widely used in deep-sea devices due to its long service life, stable and reliable performance. However, the impurities in hydraulic oil such as water and air bubbles could seriously damage the quality of hydraulic oil (Phillips, 2006) and result in significant reduction of oil bulk modulus as well as mechanic motion precision, which would yield the control error for deep-sea hydraulic equipment thereafter. We have developed an oil-replenish device (Hao, 2013), which has multi-functions of oil suction, filtration, degasification, dehydration and oil replenishing. It is used to process the oil treatment and replenish the deep-sea hydraulic system with the treated oil. The whole device works in the laboratory base.

It is known that through vacuum filtration and heating operation, water and air bubbles in hydraulic oil could be effectively removed. Because of the characteristics of large inertia, large time delay and time-varying parameters of hydraulic oil heating system, it is difficult to control accurately the oil temperature during heating process. Under work condition, if the oil temperature exceeds 55 °C, the service life of hydraulic oil would be shortened by half when the temperature increases 8 °C (Hao, 2013). The oil temperature control still remains a challenge.

Temperature control is a process of measuring, detecting and adjusting temperatures to achieve a desired value. It is widely used in industry sectors, such as food processing and transportation, central heating, chemical engineering, etc. Temperature control is a typical time delay case. It is known that time delays have a deleterious effect on both the stability and performance of controlled systems and are generally harder to control unless the lag compensated (Udwadia et al., 2003). So far, two methods are acknowledged feasible to handle time delay. One is model-based control, such as PID controller, Smith predictor, robust control, and the other is model-free adaptive control, such as Smith fuzzy controller, intelligent control (Zhang, 2012). For temperature control in various occasions, different control approaches were applied to eliminate the time delay phenomenon. For temperature control of a central heating system, a PD plus PI controller was proposed feeding back the environment temperature and the temperature of the heated room (Koumboulis

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and Kouvakas, 2010). A joint design method of closed-loop identification and IMC (Internal Model Control) for the cooling temperature control system with input time delay was presented (Abe et al., 2003). An expert system for the humidity and temperature control in HVAC systems was brought forth, using ANFIS (Artificial Neural Fuzzy Interface System) and optimization with fuzzy modeling approach (Soyguder and Alli, 2009). However, with regard to the oil temperature control during the heating process, to the author's knowledge, little research has been done so far especially to tackle this challenge.

In our research, to avoid the damage to oil quality caused by high temperature and to ensure the effective filtration as well, four oil temperature control methods of an oil-replenishing device are simulated and analyzed, i.e. the PID controller, the fuzzy PID controller, the Smith fuzzy PID controller and the modified Smith fuzzy PID controller. With its advantages of simple structure and easy operation, PID controller is widely used in industrial production (Zhang et al., 2011; Esfahani et al., 2015; Skjong and Pedersen, 2016). Fuzzy PID controller combining the conventional PID and the fuzzy rules identifies the fuzzy relation between PID controller parameters and system error, error change rate (Fadaei and Salahshoor, 2008), then tunes the PID controller parameters by fuzzy rules. Smith predictor control, proposed by O.J.M Smith in 1957(Feliu-Batlle et al., 2013), deals with the problem of large time delay of system and connects a compensation link to the original controller in parallel in order to compensate pure lag process. Modified Smith predictor has structural improvement by adding a first-order filter to Smith predator. S. Uma and A. Seshagiri Rao proposed a modified Smith predictor, which consists of a set-point tracking controller and a disturbance rejection controller, for the purpose of enhancing control of non-minimum phase unstable second order time-delay processes with/without zero (Uma and Rao, 2016). Based on two-degree-of-freedom control structure, Yin proposed a modified Smith predictor scheme for a class of unstable processes with time delay (Yin et al., 2014). The modified Smith predictor used in this paper was proposed by Yang et al. (Yang, 2005), adding a first order filter to the original Smith control loop to overcome the interference caused by inaccurate model and further to enhance the robustness of control system.

In this paper, the oil heating process is simulated based on the above-mentioned four controllers and their corresponding step response curves are obtained thereafter in the cases of model matching and mismatching. After analyzing and comparing the curves through four indicators, i.e. rise time, settling time, steady-state error and maximum overshoot, the modified Smith fuzzy PID controller is proved to have the best control effect. Furthermore, through PIC16F877A MCU, these four control methods are applied to the actual oil temperature control system in the oil-replenishing device. The experimental data of oil temperature changing over time also verifies that the modified Smith fuzzy PID controller is able to meet the challenges of the oil temperature control process.

After a brief introduction, the remainder of this paper is organized as follows: in Section 2, the structure of oil-replenishing device is introduced. In Section 3, the mathematic model of the oil heating control system is presented and the relevant parameters are defined and set. Four control methods are illustrated and their simulation results are obtained, compared and analyzed in Section 4. The experimental process is described and the results analysis is carried out in Section 5 followed by the conclusions in Section 6.

2. Oil-replenishing device

The device structure and entity are shown in Fig. 1.

The oil-replenishing device consists of a vacuum pump, a high-precision oil filter, an immersion electrical heater and a vacuum tank with the capacity of 60 L oil. The heater located near the bottom of tank has the maximum power of 2 kW to be adjusted by a designed program. To let the oil be heated evenly, the inner circulation is switched on during the heating process. The steps of oil purification process are specifically listed as follows:

a) Connect the oil inlet pipe to an external oil tank; open the vacuum pump and vacuumize the vacuum tank; the internal and external pressure difference would cause the oil from the external oil tank to pass the high precision oil filter where the solid particles are filtered, into the vacuum tank.
b) Close the inlet valve once the volume of oil in the vacuum tank reaches the set value; keep the vacuum pump running to maintain a low pressure in the vacuum tank.
c) Start the electric heaters and heat the oil according to the preset control program.

In the heating and vacuum environment, air nucleons would develop into air bubbles and deviate from oil quickly. Meanwhile, compared with hydraulic oil, water reaches first the saturated vapor pressure and thus could also be separated from oil. In real operations, only through controlling relay on and off it is hard to control the oil temperature rising speed and to maintain it at the expected value due to the large inertia, large time delay and time-varying parameters of oil heating system. In the operation process, the oil temperature trends to deviate from the set value. However, excessive oil temperature would lead to oil molecules polymerize and thus further generate impurities, which not only shortens oil service life but also spoils its quality (Lou, 2014). On the other hand, if oil temperature is lower than the set value, air nucleus would develop inadequately resulting in air bubbles rising

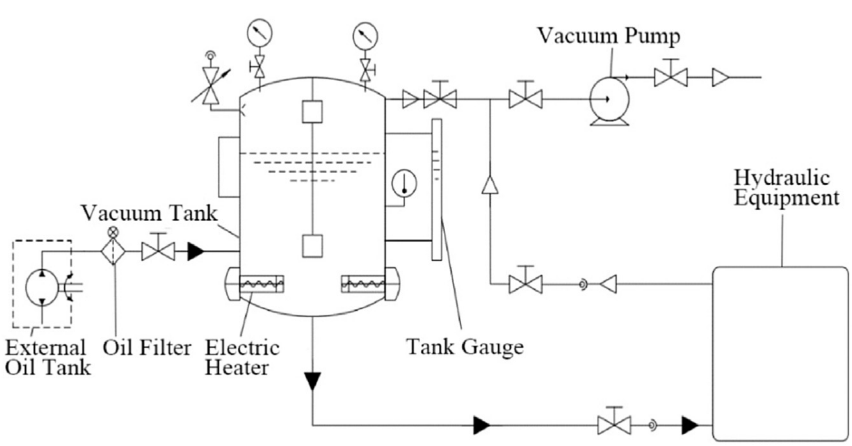

Fig. 1. Structure of oil-replenishing device.

slowly and water hardly being evaporated from oil. Therefore, to ensure the effective filtration as well as high oil quality, the oil temperature needs to be controlled accurately by an intelligent control method.

3. The mathematical model of oil heating system

3.1. The system transfer function

Since the mathematical model of the industrial process is often a high-order model, it is challenging to apply to controller design. To simplify it to a first or second order transfer function while reserving the main characters of controlled system is more preferred (Rivas-Perez et al., 2014). In a control system of residual oil outlet temperature in a coke furnace (Wu et al., 2014), Wu chose a general first order plus dead time model formulation obtained by a step response as its transfer function. Sun established a temperature control mathematical model by applying heat transfer theory, a first order transfer function as well with pure lag (Sun et al., 2015). In this paper, the oil heating system is taken as the controlled object and has non-vibration and self-balance under step input. Its transfer function could be described as a first order transfer function $G(s)$ shown in Eq. (1) with a time-delay(Yang, 2005; Wang and Shi, 2011), which not only reserves the main features of controlled object but also facilitates the theoretical analysis and the real control operation.

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

where K is amplification factor; T is time constant; τ is pure delayed time. In this paper, the parameters are obtained by step response method (Li, 2014).

3.2. System step response curve

Taking the electrical heater power $P(t)$ as the system step input, and the oil temperature $f(t)$ as the system output, we get the oil temperature-time curve. The environment temperature in the laboratory is 22 °C. The power of the heaters used to heat the oil is set at 1 kW with 20 L oil in the tank. The temperature-time data is shown in Table 1. In order to remove air and water more effectively, the expected temperature is set at 60 °C in the research during oil purification process.

The curve shown in Fig. 2 is plotted from the data in Table 1. The initial temperature is set 19.9 °C as the coordinate origin so as to solve the parameters of the system's mathematical model conveniently.

3.3. Identification of transfer function parameters

The first order approximation method was applied (Zheng et al., 2014) in this paper and the system step response curve was used to identify the transfer function parameters. The equations are shown in Eqs. (2) and (3).

$$\begin{cases} f(t_1) = 0.39h(\infty) \\ f(t_2) = 0.63h(\infty) \end{cases} \tag{2}$$

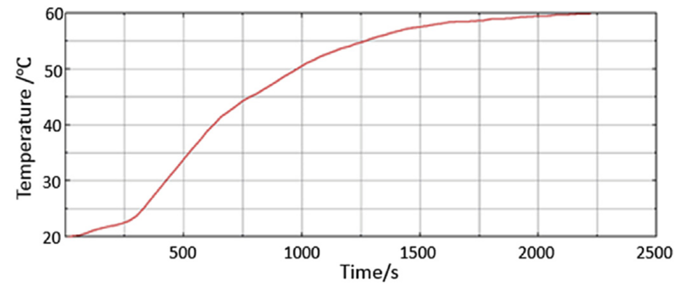

Fig. 2. The temperature change curve of oil heating process.

where $f(t)$ is the oil temperature-time curve shown in Fig. 2, and $h(t)$ is the oil temperature-time curve obtained by the mathematical model of system. Setting $h(\infty) = f(\infty) = 59.8$ °C, according to system step response curve, it could be obtained that $f(t_1) = 23.32$, $f(t_2) = 37.67$ and $t_1 = 303.03$, $t_2 = 528.95$.

$$\begin{cases} T = 2(t_2 - t_1) \\ \tau = 2t_1 - t_2 \\ K = \dfrac{h(\infty) - h(0)}{P(\infty) - P(0)} \end{cases} \tag{3}$$

$T = 451.85$, $\tau = 77.11$ and $K = 22.8$ are obtained from Eq. (3), and these parameters are verified in Eq. (4).

$$\begin{cases} t_3 = 0.8T + \tau \\ t_4 = 2T + \tau \\ f(t_3) = 0.55f(\infty) \\ f(t_4) = 0.87f(\infty) \end{cases} \tag{4}$$

where $t_3 = 438.59$,$t_4 = 980.81$ and $f(t_3) \approx 0.55f(\infty)$, $f(t_4) \approx 0.87f(\infty)$. The verification condition is satisfied and the transfer function of hydraulic oil heating system is shown in Eq. (5).

$$G(s) = \frac{22.8}{451.85+1}e^{-77.11s} \tag{5}$$

4. The system controller research and simulation

4.1. PID controller

PID controller is the basic and the most used module in discrete control system. Over 90% control loops were designed with PID method (Yin et al., 2014; Akbari-Hasanjani et al., 2015). PID controller consists of proportional unit (P), integral unit (I) and differential unit (D). The basic equation of PID controller is shown in Eq. (6):

$$u(t) = Kp\left[e(t) + \frac{1}{Ti}\int e(t)dt + Td\frac{de(t)}{dt}\right] \tag{6}$$

Table 1
Measurement data of hydraulic oil heating temperature with time.

Time(s)	0	50	100	150	200	250	300	350
Temperature(°C)	19.9	20.2	20.9	21.4	21.9	22.4	23.6	26.4
Time(s)	400	450	500	550	600	650	700	750
Temperature(°C)	28.4	31.2	34.1	35.9	38.7	41.2	42.4	43.2
Time(s)	800	850	900	950	1000	1050	1100	1150
Temperature(°C)	45.2	46.4	48.5	49.3	50.4	51.5	52.6	53.3
Time(s)	1200	1250	1300	1350	1400	1450	1500	1550
Temperature(°C)	53.8	54.7	55.4	56.0	56.6	57.2	57.4	57.8
Time(s)	1600	1650	1700	1750	1800	1850	1900	1950
Temperature(°C)	58.1	58.3	58.4	58.5	58.8	58.9	59.0	59.2
Time(s)	2000	2050	2100	2150	2200	2220		
Temperature(°C)	59.3	59.5	59.5	59.6	59.7	59.7		

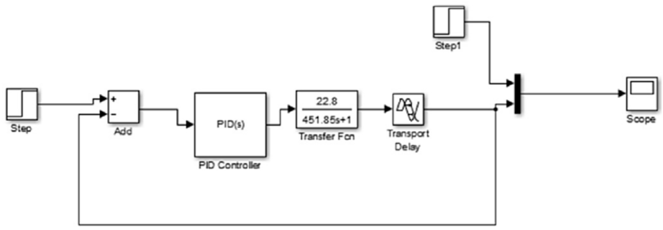

Fig. 3. The simulation model of temperature control system based on PID controller.

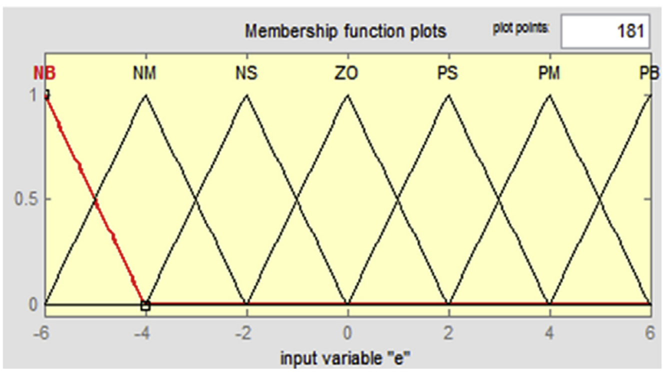

Fig. 4. Membership function.

Table 2
Fuzzy control rules.

e	e_c NB	NM	NS	ZO	PS	PM	PB
NB	PB NB PB	PB NB NS	PM NM NB	PM NM NB	PS NS NB	ZO ZO NM	ZO ZO PS
NM	PB NB PB	PB NB NS	PM NM NB	PS NS NB	PS NS NB	ZO ZO NM	ZO ZO PS
NS	PM NB ZO	PM NM NS	PM NS NM	PM NS NS	ZO ZO NS	NS PS NS	NS PS ZO
ZO	PM NM ZO	PM NM NS	PS NS NS	ZO ZO NS	NS PS NS	NM PM NS	NM PM ZO
PS	PS NM ZO	PS NS ZO	ZO ZO ZO	NS PS ZO	NS PS ZO	NM PM ZO	NM PB ZO
PM	PS ZO PB	ZO ZO NS	NS PS PS	NM PS PS	NM PM PS	NM PB PS	NB PB PB
PB	PB NB PS	PB NB NS	PM NM NB	PM NM NB	PS NS NB	ZO ZO NM	ZO ZO PS

where *e(t)* is deviation signal; T_i is integral time constant; T_d is differentiating time constant. Setting $K_I = K_p/T_i$, $K_d = K_p{*}T_d$, K_P, K_I and K_D represent proportionality coefficient, integral coefficient and differential coefficient respectively.

In this paper, the simulation model controlled by PID controller is established by MATLAB/SIMULINK, shown in Fig. 3, where $K_P = 0.2098$, $K_I = 0.000386$ and $K_D = 3.505$.

4.2. Fuzzy PID controller

Fuzzy PID controller tunes PID three parameters by fuzzy controller. Consider the oil temperature error *e* and error change rate *ec* as input variables, and ΔK_P *(correction proportional gain)*, ΔK_I *(correction integral gain)*, ΔK_D *(correction derivative gain)*, which adjust the values of PID parameters, as output variables. Thus the whole fuzzy controller is a two-input and three-output system. The fuzzy domain of *e*, *ec*, ΔK_P, ΔK_I and ΔK_D are selected from −6 to 6. The fuzzy subsets of input and output variables are {NB,NM,NS,ZO,PS,PM,PB}, where NB represents negative big; NM is abbreviation of negative middle; NS is negative small; ZO is zero; PS is positive small; PM is positive middle; PB is positive big.

This paper adopts the mean of maximum method (Zheng et al., 2014) to clear the fuzzy results, and the membership function of input and output variables are all triangular displayed in Fig. 4. The fuzzy control rules are demonstrated in Table 2.

The fuzzy controller in this paper adopts Mamdani fuzzy (Guo et al., 2016) inference algorithm to reason and applies weighted mean method to deblur. The fuzzy PID controller simulation model is shown in Fig. 5.

4.3. Smith fuzzy PID controller

The Smith predictor is used to correct the lag of the system (Sun et al., 2015). At a given signal, it estimates the dynamic characteristics of system under disturbances in advance and then compensates by the predictor to reduce system's overshoot and to shorten the adjustment process (Guo and Liu, 2003). Through introducing the compensation link in system feedback loop, Smith predictor separates the pure lag link of controlled object from the other parts of control system. The structure diagram of Smith predictor is shown in Fig. 6.

Where $R(s)$ is expected value of system; $Y(s)$ is measured value of system; $G_C(s)$ is the controller transfer function; $e^{-\tau_m s}$ is pure lag link; $G_p(s)$ is mathematical model of system; τ is lag time; $G_m(s)$ is the mathematical model of Smith predictor. The function of Smith predictive compensation is expressed as $G_m(s)(1-e^{-\tau s})$. The transfer function of the control system is shown in Eq. (7).

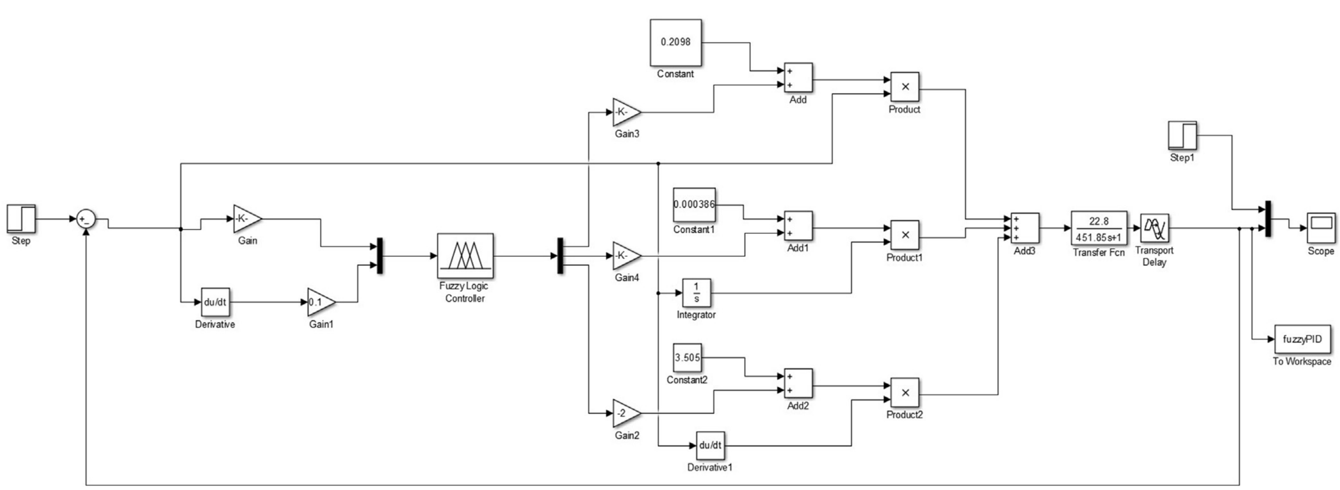

Fig. 5. The simulink model of temperature control system based on fuzzy PID controller.

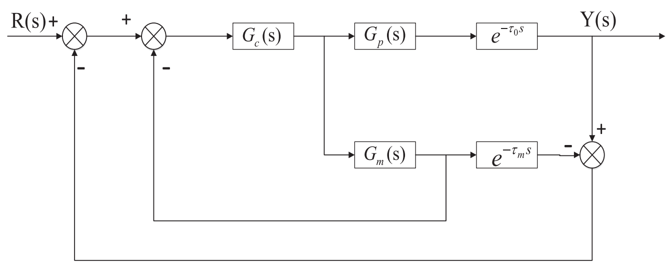

Fig. 6. System of Smith predictor.

$$\frac{Y(s)}{R(s)} = \frac{G_C(s)G_p(s)e^{-\tau s}}{1 + G_C(s)G_m(1 - e^{-\tau_m s}) + G_C(s)G_p(s)e^{-\tau s}} \tag{7}$$

if $G_p(s) = G_m(s)$, $\tau = \tau_m$, then Eq. (7)could be rewritten as:

$$\frac{Y(s)}{R(s)} = \frac{G_C(s)G_p(s)e^{-\tau s}}{1 + G_C(s)G_p(s)} \tag{8}$$

Since the closed-loop part of Eq. (8) does not contain the pure lag link $e^{-\tau s}$ after the Smith estimated compensation, it no longer affects the characteristic equation of the system. This control method has good control effect.

Fig. 7 shows the structure diagram of temperature control system based on Smith fuzzy PID controller, which combines the fuzzy PID controller and Smith predictor. This system not only possesses the fuzzy PID controller's advantage of good dynamic performance, but also is able to compensate the system's time-lag part by Smith predictor. Consequently, it is capable of enhancing the robustness of oil heating system and improving system's control performance (Sun et al., 2010).

The simulation model of Smith fuzzy PID controller is shown in Fig. 8. However, if $G_p(s) \neq G_m(s)$, $\tau \neq \tau_m$, the item with time-delay factor in the closed-loop part of Eq. (7) would severely damage the control effect. The compensation effect of Smith predictor heavily depends on accurate mathematical model of system (Feliu-Batlle et al., 2009). If there is margin error between the estimated model and the real model, the control quality would deteriorate and even diverge (Duan, 2010). For control system which lacks accurate mathematical model or has pure lag link and time-varying parameters, like oil heating processes, Smith predictor fails to obtain satisfactory control effect.

4.4. Modified Smith predictor fuzzy PID controller

The previous analysis shows that the conventional Smith predictor can only effectively eliminate the negative effect of large time delay by obtaining an accurate mathematical model of controlled system. For an oil heating system with large inertia, large time delay and time-varying parameters (Yamada et al., 2010), it is difficult to obtain the accurate mathematical model. In order to further reduce the requirement of model accuracy and achieve better control effect, a first-order filter is added to the original Smith control loop to improve the control system's robustness and adaptability.

The structure diagram of modified Smith predictor is shown in Fig. 9, where $\frac{1}{T_f s+1}$ is the form of the first-order filter, $T_f = \frac{T_m}{K_c K_m}$ is the filter time constant, T_m is the predictor constant, K_c is $G_C(s)$ gain, K_m is Smith predictor gain. The closed-loop system transfer function is shown in Eq. (9).

$$\frac{Y(s)}{R(s)} = \frac{G_C(s)G_p(s)e^{-\tau s}}{1 + G_C(s)G_m(s) + G_C(s)\left(G_p(s)e^{-\tau s} - G_m(s)e^{-\tau_m s}\right)\frac{1}{T_f s+1}} \tag{9}$$

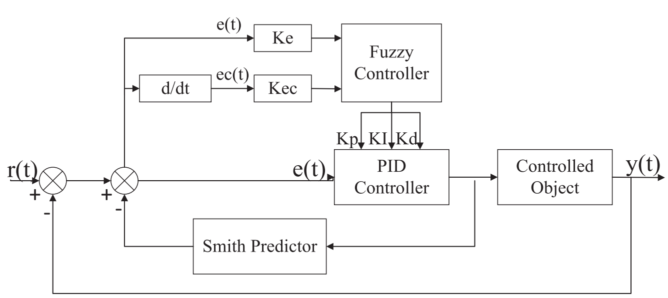

Fig. 7. Schematic diagram of temperature control system based on the Smith fuzzy PID controller.

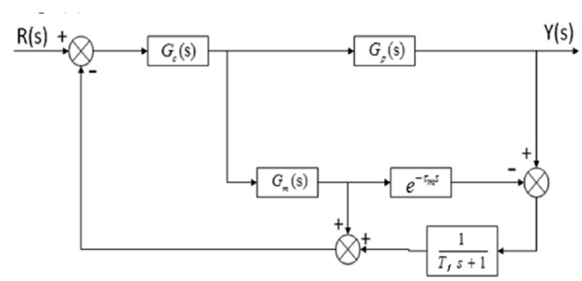

Fig. 9. Schematic diagram of temperature control system based on the modified Smith fuzzy PID controller.

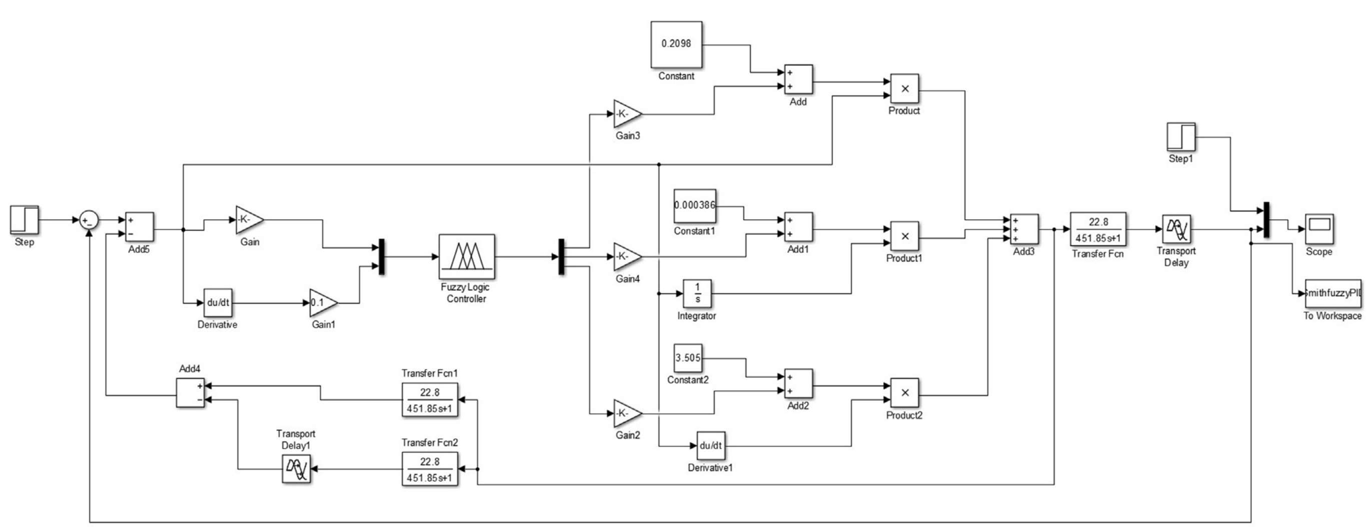

Fig. 8. The simulink model of temperature control system based on Smith fuzzy PID controller.

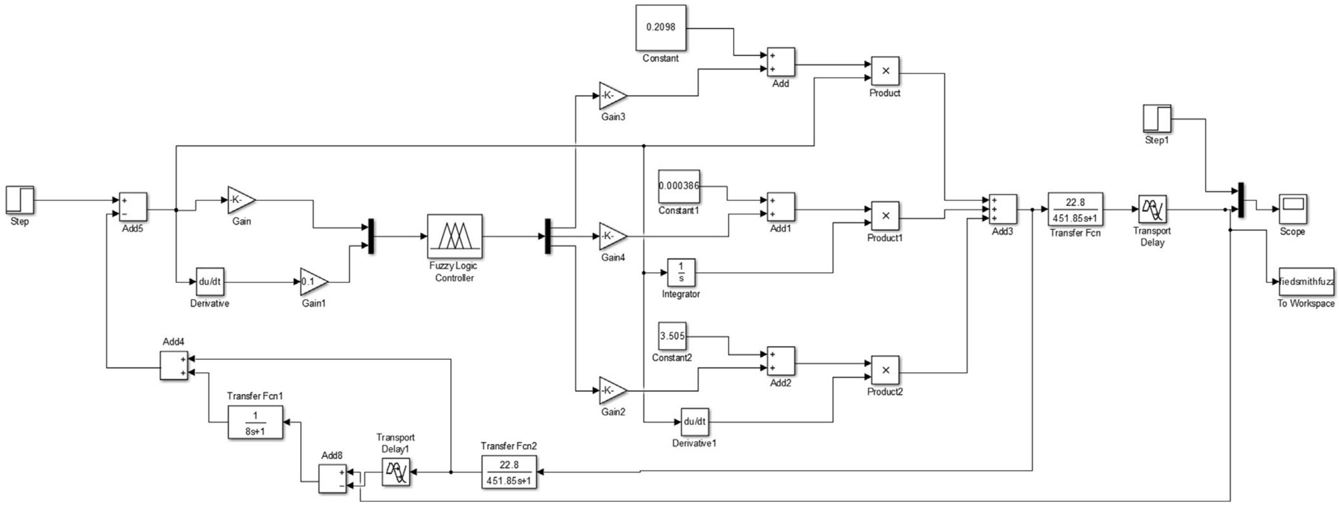

Fig. 10. The simulink model of temperature control system based on modified Smith fuzzy PID controller.

if $G_p(s) = G_m(s)$, $\tau = \tau_m$, Eq. (9) is the same as the conventional Smith predictor control program and the improved program has no effect on the system, only the output response shifted by a pure lag time. If $G_p(s) \neq G_m(s)$, $\tau \neq \tau_m$, a first-order inertial link, $\frac{1}{T_f s+1}$ is introduced to the main feedback channel. It functions as a buffer to mismatch predictor model. T_f could be adjusted to change the characteristic equation roots and therefore the performance of the control system could be improved accordingly, benefitting to system stability (Yang, 2005). When $T_f = 0$, the system is equivalent to the conventional Smith predictor control system (Chen and Yang, 2007). The simulation model of modified Smith fuzzy PID controller is shown in Fig. 10, where the value of T_f is 8 by adjusting.

4.5. Analysis of simulation results

In this paper, the simulation results of PID controller, fuzzy PID controller, Smith fuzzy PID controller, modified Smith fuzzy PID controller are presented and compared. The initial oil temperature is 19.9 °C and the oil temperature is expected to be 60 °C, thus, the step size is 40 °C. The total simulation time is 2220 s. The simulation results obtained by four control methods are illustrated by the step response curves shown in Fig. 11. Their corresponding specific parameters are listed in Table 3.

The controlled system's performance of rapidity, stability, accuracy and oscillation amplitude are reflected by four indicators, i.e. rise time, settling time, steady-state error and maximum overshoot. The stability

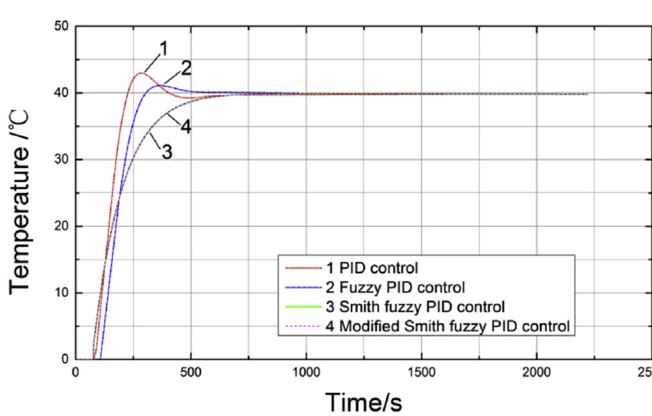

Fig. 11. The step response curves under precise model.

Table 3
Performance indexes of four control methods in the case of model match.

	Rise time (s)	Settling time (s)	Steady-state error(°C)	Maximum overshoot (%)
PID controller	290	1683	0.03	7.9
Fuzzy PID controller	300	1367	0.02	3.3
Smith fuzzy PID controller	734	1154	0.01	0.4
Modified Smith fuzzy PID controller	735	1152	0.01	0.4

and accuracy of the controlled system are primarily concerned in the research because the actual oil temperature needs to be set as certain value in order to steadily heat the system and sufficiently remove air and water in the oil. Meanwhile, the overshoot reflects the system stability and thus significant as well. Excessive overshoot means that the oil temperature in the control process is prone to yielding overheating, which would not only threaten the system safety but spoil the quality of hydraulic oil.

In real hydraulic oil heating processes, due to the complex oil heating system, its corresponding accurate mathematical model is hardly obtained. Furthermore, since the ambient temperature and the working conditions vary over time, the mathematical model itself tends to change, which may lead to the mismatch between the theoretical model and the actual one in the control process. Therefore, it is necessary to analyze the actual control effect of different control methods in the case of model mismatch. Here, we simulate and analyze a case which is most difficult to control accurately, where $K_p > K$, $T_p > T$ and $\tau_p > \tau$ (Zhang, 2012). The actual parameters of mathematical model in oil heating process is $K_p = 30$, $T_p = 381.85$ and $\tau_p = 85$. The step response curve is shown in Fig. 12. The corresponding four performance indicators are displayed in Table 4.

In the case of model match, Smith fuzzy PID controller and modified Smith fuzzy PID controller can not only keep the advantage of dynamic performance of fuzzy PID control, but also have the advantage of compensation for pure lag link. The time required to reach steady state is 1152 s, and the overshoot amount is only 0.4%, which satisfy the requirement of small overshoot in this system. In the case of model mismatch, after increasing the numeric value of K_P and τ_p, the maximum overshoots of both PID controller and fuzzy PID controller have climbed up dramatically, from 7.9% to 37.2% and from 3.3% to 24.2% respectively. Meanwhile, from the settling time perspective, the step response curves of PID controller and fuzzy PID controller have relatively significant oscillation compared with the corresponding ones in the case of model match. Thus, they require longer time to reach the steady stage.

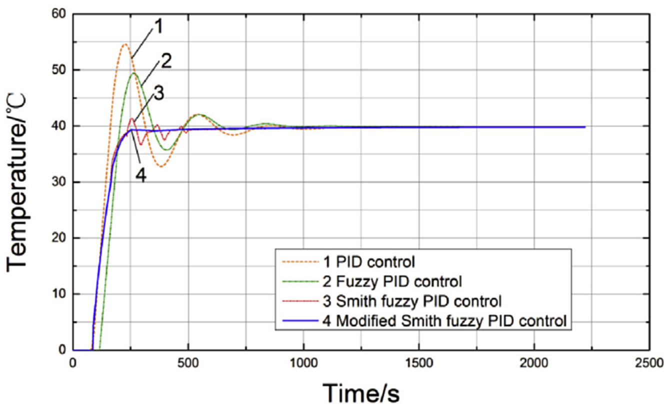

Fig. 12. The step response curves under imprecise model.

Table 4
Performance indexes of four control methods in the case of model mismatch.

	Rise time (s)	Settling time (s)	steady-state error(°C)	Maximum overshoot (%)
PID controller	163	1801	0.03	37.2
Fuzzy PID controller	177	1462	0.02	24.2
Smith fuzzy PID controller	240	1367	0.02	3.9
Modified Smith fuzzy PID controller	1143	1143	0.02	0.4

However, the modified Smith fuzzy PID controller with a first-order filter could effectively reduce the model mismatch interference on the control effect and the time to reach a steady stage is 1143 s. Its corresponding curve in Fig. 12 has little oscillation as well and the overshoot amount is 0.4%. Therefore, the control system based on modified Smith fuzzy PID controller has the minimum overshoot and the settling time with the best robustness among four control methods and is able to meet the requirement of high precision oil filter in this equipment.

5. Experiment

5.1. Hardware and software design

In this section, PIC16F877A MCU is used to implement the intelligent control of oil heating process in an oil-replenishing system. Two electric heaters are used to heat the oil, and their heating power is taken as the system input signal. Through controlling the heating power, MCU controls the oil heating rate to avoid uneven heating. The selected JCJ100ZB screw fixed temperature sensors are positioned at different places of the vacuum tank. The measured temperature is averaged and converted into an analog signal and fed back to the control system. Hydraulic oil vacuumizing and heating is carried out in a vacuum tank which is made of stainless steel 304 with a nominal wall thickness of 5 mm. The hardware components and oil heating process are shown in Figs. 13 and 14.

In order to verify the control effect, four controllers are applied to the oil temperature control process separately in experiments. Taking the relatively complicated modified Smith fuzzy PID controller as an example, the software structure of the heating system is shown in Fig. 15.

The flowcharts of fuzzy PID control algorithm realized by MCU and the combination of fuzzy PID and modified Smith predictor are displayed in Figs. 16 and 17 respectively.

Fig. 14. Hydraulic oil heating devices in experiment.

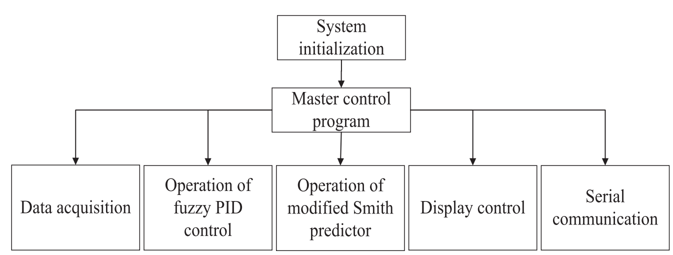

Fig. 15. The software structure of the heating system.

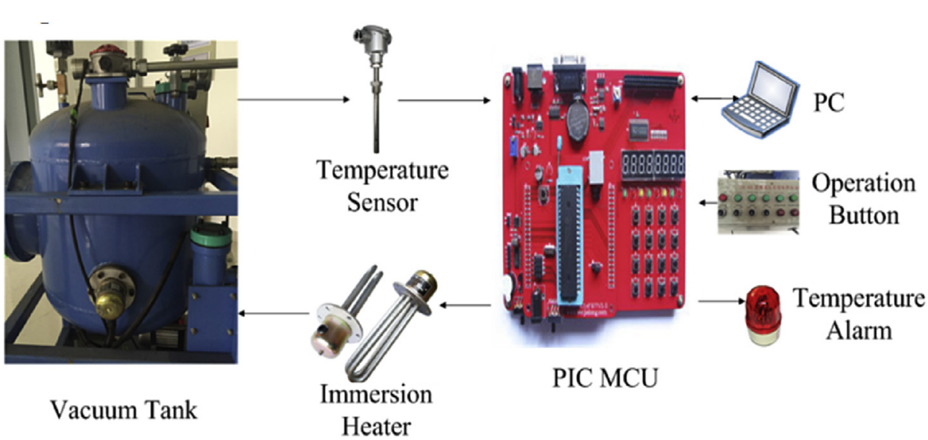

Fig. 13. Hardware components of hydraulic oil heating system.

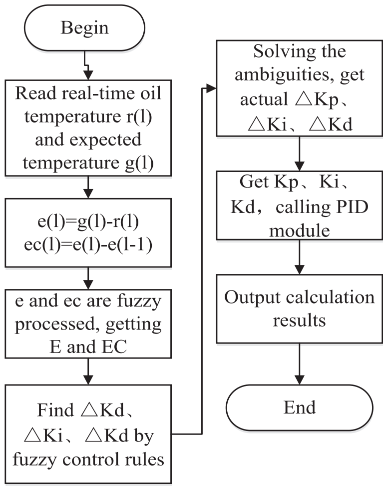

Fig. 16. Fuzzy PID control method.

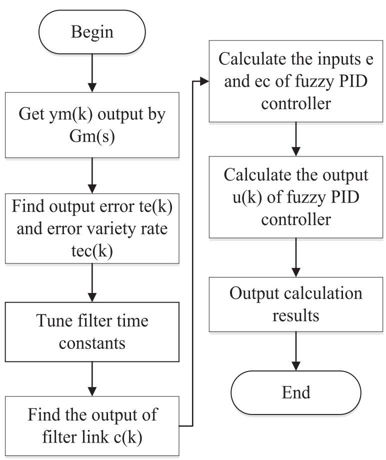

Fig. 17. Modified Smith fuzzy PID control method.

5.2. Experimental process and results analysis

The oil-replenishing device utilizes vacuumizing and heating methods for oil purification. Specific steps are explained as follows:

a) Connect the oil inlet pipe with an external oil tank; open the vacuum pump to vacuumize the vacuum tank; through internal and external pressure difference, lead the oil from the external oil tank to pass the high precision oil filter where the solid particles are filtered, into the vacuum tank.
b) Close the inlet valve once 20 L oil is available in the vacuum tank; the vacuum pump keeps working, so that the vacuum pressure in the vacuum tank maintains at −0.06 MPa.
c) Switch on the electric heaters and heat the oil according to preset program.

Considering the possible external disturbances to the measured value, the oil temperature was measured and collected and its average value was taken. The initial oil temperature is around 20 °C. Fig. 18 shows the change of oil temperature with time under four different controllers and the relevant indexes are displayed in Table 5.

As shown in Table 5, during oil heating process, PID controller has the largest settling time and overshoot, indicating that only a single PID controller is less effective. The indexes of both fuzzy PID and Smith fuzzy vary slightly, which imply that the compensation effect of Smith

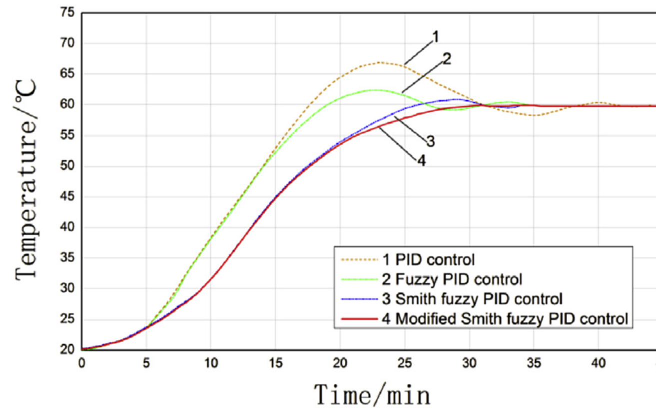

Fig. 18. The change of oil temperature with times.

Table 5
Performance indexes of four control algorithms in real oil heating process.

	Rise time (s)	Settling time (s)	steady-state error(°C)	Maximum overshoot(%)
PID controller	1057	2493	0.3	11.5
Fuzzy PID controller	1120	2096	0.2	4
Smith fuzzy PID controller	1157	2034	0.2	2
Modified Smith fuzzy PID controller	1789	1845	0.2	0.3

predictor is not predominant in the case of model mismatch. On the other hand, the modified Smith fuzzy PID has the minimum overshoot of 0.3% and the shortest time of 1845 s to achieve stability, proving that the first order filter the minimum could reduce the error interference and benefit the stability of this system. The experiment results also verified that the modified Smith fuzzy PID controller has the best control effect for the oil heating system in this oil-replenishing device.

6. Conclusions

For an oil-replenishing device, this paper established the mathematical model of its oil heating system by first order approximation method. By comparing PID controller, fuzzy PID controller, Smith fuzzy PID controller and modified Smith fuzzy PID controller those four control methods, we have simulated the oil heating process in the cases of both model match and mismatch. It is found that in both cases, the step response curves of modified Smith fuzzy PID controller could achieve the expected value in the shortest time with the minimum overshoot among four curves, which indicates its best stability and accuracy. Therefore, it is believed safely to draw the conclusion that the control system under modified Smith fuzzy PID controller possesses the best robustness.

Moreover, this paper has built the hardware system of oil-replenishing system and applied those four control methods into the oil heating process as well. The experimental results show that under modified Smith fuzzy PID control, the actual oil temperature could be stabilized at the expected value, and there is hardly any overshoot during the heating process. It is verified that modified Smith fuzzy PID controller is able to meet the challenge of large inertia, large time delay and time-varying parameters of oil heating system in this oil-replenishing device and accomplish the accurate oil temperature control.

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