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Research on the Temperature Control Methods to a Hemodialysis System with Large Inertia and Hysteresis

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Abstract: objective to design a temperature control system for hemodialysis machine. Hemodialysis is a complex process involving multiple components, whereas dialysate temperature is the core performance index, the current control methods are mostly based on experience or fuzzy PID. This article attempted to model accurately the main process. According to the large inertia, hysteresis characteristics of the system, we proposed 3 kinds of control schemes. By comparing, energy model predictive control is a best control method. Adjusting the duty cycle of the PWM to control solid-state relay switch time, achieving temperature control. Experimental results show that this method has a highest control precision, meeting the requirement of thermostatic state.

Key Words: Hemodialysis, Large Inertia, Hysteresis, Temperature Control

1 Introduction

With the development of blood purification technology, Hemodialysis machine was used in chronic renal failure, tissue edema and drug poisoning. In dialysis process (see Fig.1), the patient's blood need to be carried out of body for purification, then return back. This process will cause the loss of quantity of heat, resulting vasoconstriction, spasm complications etc. Generally using heating water system control the temperature of dialysate. In this way, dialysate and cyclic blood in dialyzer can exchange quantity of heat, compensating the lost. Guarding against too hot or too cold causing shiver, hemolysis, arrhythmia, heart failure, a professional temperature control system need to be designed necessarily.

Many delays (dead time) occur in the ducts and balance chambers, and the heater keeps away from dialyzer, therefore, this is a large inertia and hysteresis system. Current control methods are mostly based on experience or fuzzy PID [1]-[3], whose control accuracy is not high and reliability can't be guaranteed. Predictive control as an advanced process control technique was widely used in industrial application [4], we proposed 3 kinds of control schemes, and build accurate mathematic model of hemodialysis process to validate the control effect.

2 Process description

The whole process includes three main parts: heater, balance chambers, long ducts. The long ducts connect other parts together. As in Fig. 1, the reverse osmosis water through a heat exchanger gets pre-heating by the heat exchange with liquid waste. Then the water flows into the heater for a formal heating. Out of heater, the water goes into a long duct. Flowing through the duct, it will pass by A cavity and B cavity respectively, A liquid or B liquid will be injected into the water, because of the amount of AB liquid is small, the thermal affection can be neglected or can be compensated by appropriately raising output temperature of the heater. Finally, the water becomes dialysate, and enters a balance chamber for supplying hemodialysis. The principle of operation of the chambers is introduced in the following section. The dialysate out of the chamber will be

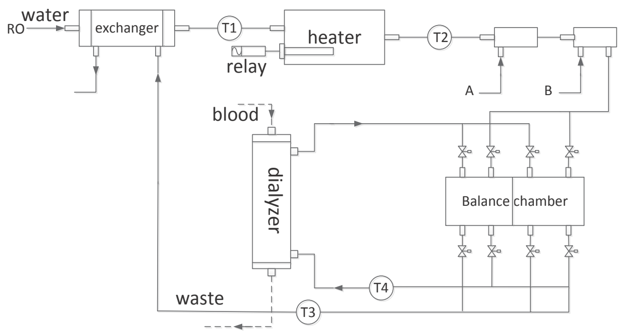

Fig. 1: Hemodialysis temperature control system structure

transported through a duct to the dialyzer for extracting transfer factors. Out of the dialyzer, the dialysate becomes liquid waste. The hot liquid waste flows through a long duct into the heat exchanger for heat exchange with cold inlet water. In the process of this work, there are four temperature sensors T1-T4. T1 and T2 are on the inlet and outlet of the heater respectively, T3 on the end of duct, T4 on the inlet of the dialyzer. The control variable is the pwm of the solid-state relay in the heater, the control target is the dialyzer inlet temperature T_4 . Before the outlet of heat exchanger, temperature hasn't been detected. Only on the subsequent of heat exchanger, T1 is installed. It is easy to consider that the exchanger is only used to preheat inlet water. The whole control process can be considered that basing on inlet temperature T_1 to precisely control temperature T_4. The heat exchanger is ignored. Under the condition of inlet fluid rate is constant, and the ambient temperature is normal and won't

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change a lot, several mathematical models are derived in the follow.

2.1 Heater Model

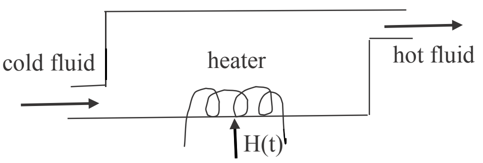

Fig. 2: Liquid heating system

Here is a heating system (see Fig.2), solid-state relay is the executive component, and using PWM method replaces original analog quantity control. Adjusting the on-off time of a solid-state relay in a cycle controls heater's power. The energy of the heater is

$$H = \frac{U^2}{R_L} \cdot \frac{t_{on}}{T} = \frac{U^2}{R_L}\delta \tag{1}$$

Here, $\delta = \frac{t_{on}}{T}$ is heater duty ratio; U is heater operating voltage effective value; R_L is heater resistance.

Consider that the cold fluids move into the box for heating, then flow out. The $T_0, T(t)$ are inlet and outlet temperature respectively. In unit time, the mass of fluid is a constant value m, the mass of fluid in the box is a constant value M, the specific heat capacity is c. The heater in unit time reduces hot energy is $H(t)$ as the input, then in time dt the energy enters the system is

$$\mathrm{d}Q_1 - dQ_2 = dQ_3, \tag{2}$$

then

$$cM\frac{dT}{dt} + cmT - cmT_0 = H, \tag{3}$$

take $T' = T - T_0$, then

$$\frac{M}{m}\frac{\partial T'}{\partial t} + T' = \frac{1}{cm}H, \tag{4}$$

The step response of the heater was done. It is a first order system, the temperature difference T' on the time t was obtained (Fig.3). It confirmed the linearity of the heater.

2.2 Long duct Model

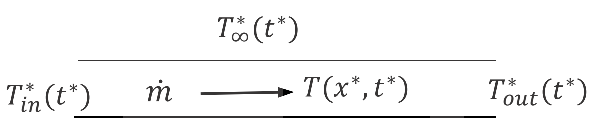

Fig. 4: Flow in duct with heat loss

This is a model of thermal effect in a long duct with a constant flow rate (see Fig.4), the inlet and outlet temperature are $T^*_{in}(t^*)$, $T^*_{out}(t^*)$ respectively, the mass flow rate is $\dot m$. The local fluid temperature is $T^*(x^*, t^*)$, and the ambient temperature is $T^*_\infty(t^*)$. x^* is the longitude coordinate measured from the inlet and t^* is time.

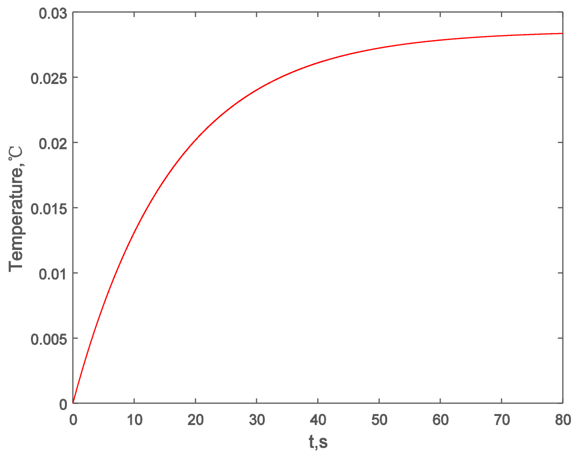

Fig. 3: Step response of temperature difference

Under simplifying assumptions that the flow is one-dimensional and neglecting axial conduction through the fluid and the duct, the governing energy balance per unit length gives

$$\dot m c\frac{\partial T^*}{\partial x^*} + \rho A c\frac{\partial T^*}{\partial t^*} + UP[T^* - T^*_\infty(t^*)] = 0 \tag{5}$$

The duct is subject to energy loss through its surface of the form $UP[T^* - T^*_\infty(t^*)]$ per unit length, U is the overall heat transfer coefficient that is assumed constant, and P is the perimeter at a cross section of the duct.

Using the non-dimensional space, time and temperature variables $x = \frac{x^*}{L}, = \frac{t^*}{\tau}, T = \frac{T^* - \bar T^*_\infty}{\Delta T}$. The equation (5) becomes

$$\frac{\partial T}{\partial x} + \frac{\partial T}{\partial t} + \gamma[T - T'_\infty(t)] = 0, \tag{6}$$

where L is the length of the duct, $\tau = A\rho L/\dot m$ is the time taken to traverse the length of the duct. ΔT is the characteristic temperature difference, the value is arbitrary. $T'_\infty(t) = T'^{*}_\infty(t^*)/\Delta T$. The parameter $\gamma = UPL/\dot m c$ represents the heat loss to circumstance.

Using characteristic method [5], the linear first-order partial differential equation can be reduced to

$$T(x,t) = e^{-\gamma t}\left[f(x-t) + \gamma\int_0^t e^{\gamma s}T'_\infty(s)ds\right], \tag{7}$$

where f is an arbitrary function, $T(0,t) = T_{in}(t)$ and $T(x,0) = T_0(x)$. Using these and at the outlet section $x = 1$, the solution becomes

$$T_{out}(t) = \begin{cases} T_{in}(t-1)e^{-\gamma t} + \gamma e^{-\gamma t}\int_{t-1}^t e^{\gamma s}T'_\infty(s)ds \\ \quad for\ \ t \geq 1 \\ T_0(1-t)e^{-\gamma t} + \gamma e^{-\gamma t}\int_0^t e^{\gamma s}T'_\infty(s)ds \\ \quad for\ \ t < 1 \end{cases} \tag{8}$$

We can see that, after an initial transient, the inlet and outlet temperature are related by a unit delay. The outlet temperature is also affected by the heat loss parameter γ, and the ambient temperature change $T'_\infty(t)$.

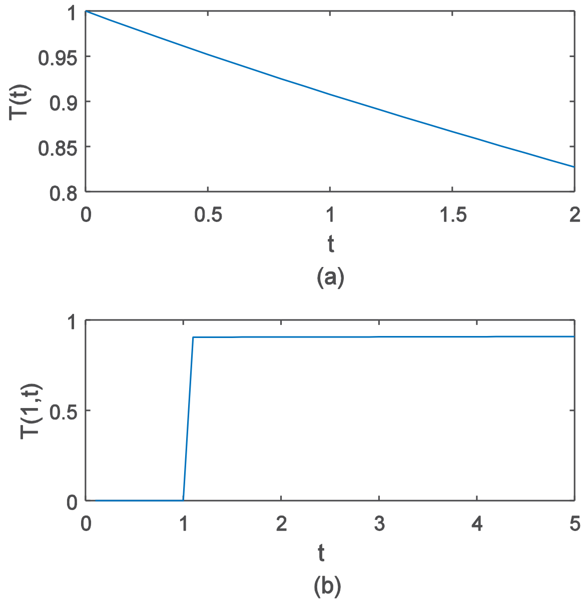

Fig. 5: Temperature for duct, (a) temperature on time t, (b) step response of inlet temperature in outlet

2.3 Balance Chambers Model

In initial condition, BC1 is full of liquid waste, BC2 is full of fresh dialysate. Normal dialysis mode contains two period. In first period (see Fig.6), fresh dialysate flows into BC1, liquid waste is extruded out. At the same time, liquid waste is moved into BC2 by a pump, fresh dialysate is extruded for dialysis. In second period (see Fig.7), reverse. t_f is filling time for chamber filling, t_w is switching time for dialysis supplying. Because of the volume of the two chambers are equal, it can guarantee the inflow and outflow equivalent.

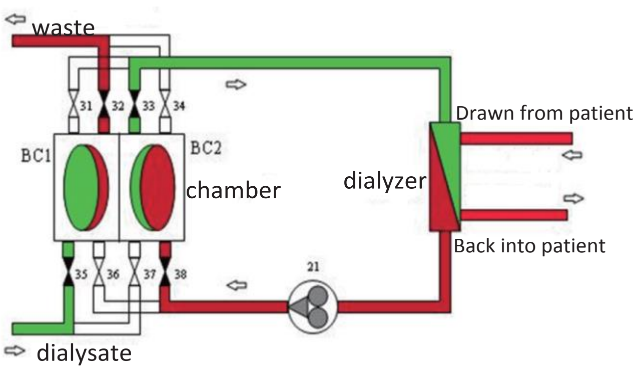

Fig. 6: First period of normal dialysis mode

In the thermal model, under the premise of basic facts, for simplified calculation, assume that

1) Temperature distribution uniformly in left and right half chamber (the chamber volume is small, this assumption is reasonable).

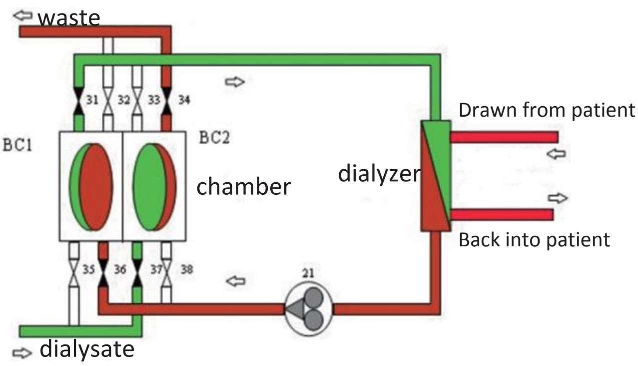

Fig. 7: Second period of normal dialysis mode

2) Diaphragm moves uniformly, frictional heat is negligible.
3) For chamber wall, the part contacting with fluid conducts heat quickly, there is no temperature gradient. The part contacting with diaphragm, the temperature of the two sides are different, existing temperature gradient to conduct heat. We assume it as that in the annular space, one-dimensional axial heat conduction.

2.3.1 Heat conduction equation

Heat through the chamber wall and diaphragm transfers from the heat chamber to cold chamber [6].
Quantity of heat transfer Φ:

$$\Phi = \left(\frac{k_{dia}}{\delta_{dia}} \cdot A + \frac{k_{wall}}{\delta_{dia}} \cdot D \cdot \pi \cdot \delta_{wall}\right) \cdot (T_{H,t} - T_{C,t}) \qquad (9)$$

where Φ is quantity of heat transfer; k_{dia} , k_{wall} is diaphragm and chamber wall thermal conductivity. $T_{H,t}$, $T_{C,t}$ is heat chamber and cold chamber's temperature. A is area of round diaphragm. D is the cross-sectional area of a chamber. δ_{wall} , δ_{dia} is thickness of chamber wall and diaphragm respectively.

In time dt, total conducting heat is

$$\int_{t-dt}^{t} \Phi\, dt \approx \left(\frac{k_{dia}}{\delta_{dia}} \cdot A + \frac{k_{wall}}{\delta_{dia}} \cdot D \cdot \pi \cdot \delta_{wall}\right) \cdot \frac{1}{2} \cdot [(T_{H,t} -$$

$$dT_{H,t}) - (T_{C,t} - dT_{C,t}) + (T_{H,t} - T_{C,t})] \cdot dt \qquad (10)$$

2.3.2 Heat conservation equation

In hot chamber or cold chamber, internal energy at $t - dt$ and at t, the internal energy of fluid bring in and bring out, energy transfer in heat conducting, commonly cause energy change in chamber. According this, we can get that heat chamber's energy equation in time dt

$$\rho \cdot c_v \cdot V_{H,t} \cdot T_{H,t} - \rho \cdot c_v \cdot (V_{H,t} - dV_{H,t}) \cdot (T_{H,t} - dT_{H,t})$$

$$= -\rho \cdot c_v \cdot q \cdot dt \cdot \left(T_{H,t} - \tfrac{1}{2} \cdot dV_{H,t}\right) - \int_{t-dt}^{t} \Phi dt \qquad (11)$$

and cold chamber's energy equation

$$\rho \cdot c_v \cdot V_{C,t} \cdot T_{C,t} - \rho \cdot c_v \cdot (V_{C,t} - dV_{C,t}) \cdot (T_{C,t} - dT_{C,t}) =$$

$$\rho \cdot c_v \cdot q \cdot dt \cdot T_{C,0} + \int_{t-dt}^{t} \Phi dt, \qquad (12)$$

where ρ is fluid's density; c_v is fluid's specific heat capacity; q is volume of flow in unit time; $T_{C,0}$ is temperature of fluid flowing in.

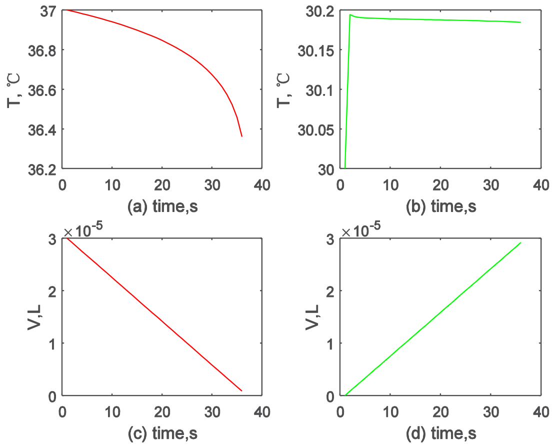

Fig. 8: Temperature in a period for a chamber full of dialysate, (a) and (b) are temperature of dialysate and waste on time respectively, (c) and (d) are volume of dialysate and waste on time respectively

Connected with the three part, the response of whole system is shown on Fig.9.

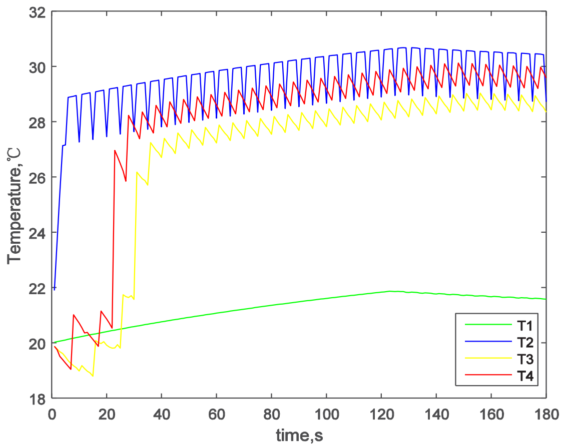

Fig. 9: step response of the system

In Fig.9, Sawteeth are caused due to the unequal of filling and switching time. There is an obvious delay from the heater outlet temperature to the dialyzer inlet temperature. The response of output temperature T_4 closes to the first order system curve.

3 Control Methods

The 3 parts above formed the main process of dialysis. Many delays occur in traversing the length of ducts and filling two balance chambers, so it is a delay system. And also because of the heater remotes from the dialyzer, it is a large inertia system. Fig.1 is the flow diagram of dialysis. Based on the characteristics of the system, we proposed 3 kinds of schemes.

3.1 Feedback With Predictive Method

This method is a most direct way to control. It does the whole feedback. The idea bases on feedback combined with predictive method, detecting the error of current original input T_1 and control target T_{4s} as a criterion, which can reflect future system performance and guiding current control input. This is a feedforward as predictive signal. Another part is also a feedback. We use the actual output value T_4 as a feedback. The PI controller (see Fig.9) can make use of current end output status as a compensation to future control output.

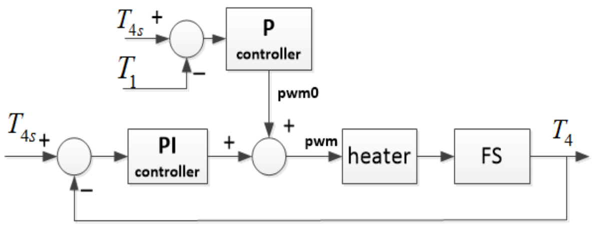

Fig. 10: Control block diagram of feedback with predictive method

Here are three kinds of control modes: P, PI, PID.

Feedforward:

$$T_{4s} - T_1 \xrightarrow{K} pwm0 \qquad (15)$$

Feedforward + feedback:

P: $pwm0 + (T_{4s} - T_4) \cdot k_1 \to pwm,$ (16)

PI: $pwm0 + (T_{4s} - T_4) \cdot k_1 + \sum(T_{4s} - T_4) \cdot k_2 \to pwm,$ (17)

PID: $pwm0 + (T_{4s} - T_4) \cdot k_1 + \sum(T_{4s} - T_4) \cdot k_2 + (\overline{T_4}(i) - \overline{T_4}(i-1)) \cdot k_3 \to pwm.$ (18)

Where k_1, k_2, k_3 are proportional gain, the integral term, and derivative term respectively.

3.2 Direct Feedback Method

This method was based on two feedback (see Fig.11). The error of T_4 and average $\overline{T_2}$ can be used to describe the section state between the end of heater and dialyzer inlet. This state can be transformed as feedback ΔT. $T_{4s} - \overline{T_2}$ can reflect the relationship of current heater's state and control target T_{4s}. Then we use this relationship and ΔT as another feedback to produce control amount pwm. This a direct feedback method.

$$T_{4s} - \overline{T_2} + \Delta T \xrightarrow{K} pwm, \qquad (19)$$

and

$$T_4 - \overline{T_2} \xrightarrow{K'} \Delta T\ , \qquad (20)$$

where $\overline{T_2}$ is the average value in a period of time, ΔT is a compensation term, calculated from the error of T_4 and $\overline{T_2}$, K', K is the proportion factor.

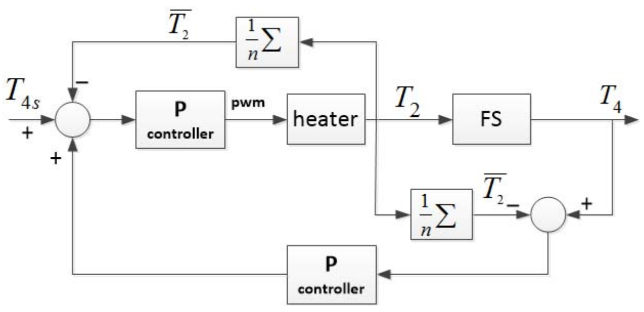

Fig. 11: Control block diagram of direct feedback method

3.3 Energy model Predictive control

This method is based on energy model (see Fig.12). Operating a period of time, we can get the actual effectiveness $\hat{\eta}$, which can reflect the relationship of the heater's power and end output T_4. In this way, we can consider that the $\hat{\eta}$ won't change suddenly, we just need to record the information $T_1(k)$ and $m(k)$, and regularly update the D in (22).

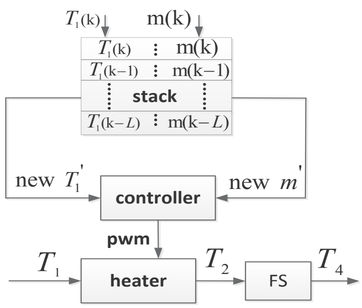

Fig.12: Control block diagram of method based on energy model

$$\eta \cdot P \cdot D = c \cdot m \cdot (T_4 - T_1), \tag{19}$$

where η is heat effectiveness, P is power of heater, D is duty cycle, c is specific heat capacity, m is flow mass in unit time. First we use the feedforward with predictive method to operate a period of time (10min), then calculate the average value

$$\overline{D} = \frac{D_1 \cdot t_f + D_2(t_w - t_f)}{t_w} \tag{20}$$

where t_f is the time of filling balance chamber, t_w is the time of switching balance chamber. Then calculate the average $\overline{T_1}$, $\overline{T_4}$ and $\bar{q}$,where $m = \frac{q}{60} * 10^{-3}$, q is flow rate, unit is ml/min, then calculate

$$\hat{\eta} = \frac{c \cdot \bar{q}(\overline{T_4} - \overline{T_1})}{P \cdot \overline{D}}, \tag{21}$$

Assume that $\hat{\eta}$ will not sudden change, we can get the next step control value

$$D = \frac{c \cdot m'(T_{4S} - T_1')}{\hat{\eta} \cdot P} = \frac{q' \cdot (T_{4S} - T_1')}{\bar{q} \cdot (\overline{T_4} - \overline{T_1})} \cdot \overline{D} = \frac{\overline{t_W} \cdot (T_{4S} - T_1')}{t_W' \cdot (\overline{T_4} - \overline{T_1})} \cdot \overline{D}, \tag{22}$$

where m', T' is the average value in a short time. In the follow control process, D will be updated in a short time (1 min).

4 Results

We linked the input and output with each model. For a balance chamber, its volume is 34 ml, filling time is 4.08 s, switching time is 5.1 s, initial temperature is 20 °C, the flow rate is constant 500ml/min, sampling interval 1 s. The controller was implemented in MATLAB-Simulink.

In all figures that follow, the temperatures T_1, T_2, T_3, T_4 are shown together for reader interpretation convenience. Sawteeth are caused due to the unequal of filling and switching time. T_{4S} is control target, we set 37.2℃, which is normal body temperature. The system block diagram of simulation is Fig.13.

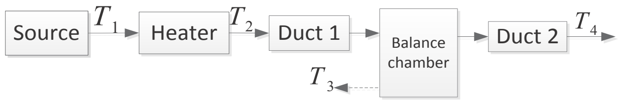

Fig.13: The system block diagram of simulation

There are many parameters tuning method [7]-[9]. For feedback with predictive method, adjusting the parameter K to make the T_4 response curve reach 37.2℃, then we use PI control to eliminate oscillation. Firstly we adjust the parameter k_1 to obviously eliminate oscillation, then adjust k_2 to eliminate static error. We got K is 4.8, k_1 is 2, k_2 is 0.2.

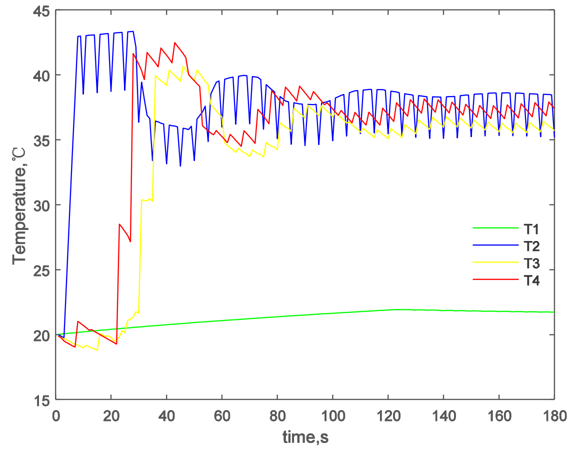

Fig. 14: Feedforward with predictive method

For T_2 feedback method, firstly we set $\Delta T = 0$, adjusting the parameter K to make the T_4 response curve's overshoot reach 37.2℃, Secondly operate a period of time. When the response curve enters steady station, adjusting K' to make the response curve reach 37.2℃. We got K is 7, K' is 0.5.

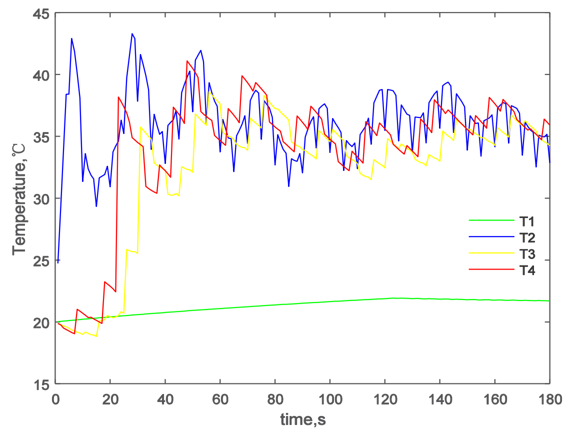

Fig. 15: Direct feedback method

For heater model predictive control, in this test, the flow rate is constant, operating feedback with predictive method, we got $\overline{D}$ is 70, $\overline{T_4}$ is 37.4, $\overline{T_1}$ is 22. In follow control, we update the D in every minute.

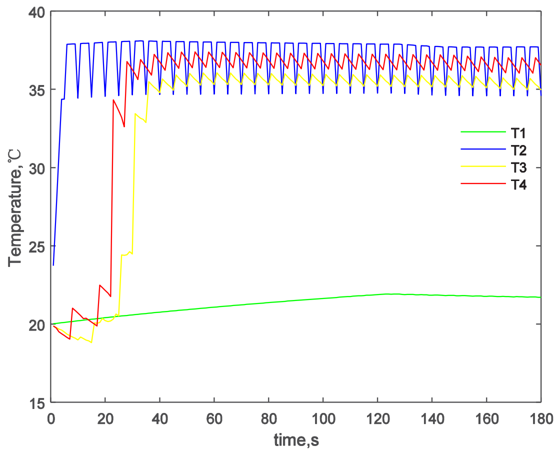

Fig. 16: Energy model predictive method

Table 1: Performance index

Method	Over (%)	Rise time (s)	Stable time (s)	Anti disturb
Feedback with predictive	14.2	27	96	normal
Direct feedback	10.2	22.3	173	normal
Energy model predictive	0.1	22.9	33	excellent

For feedback with predictive method, in the initial stage, the actual temperature T_4 as the reference of control can't reflect the actual control effect, so it will produce a considerable control bias. Therefore, the curve (see Fig.14) exists a big oscillation in the response stage. An advantage of this method is that the system has a relatively fast convergence rate. For direct feedback method (see Fig.15), curve is oscillatory convergence, and convergence time is too long. The reason is that in the response stage the T_2 changes a lot, even the average of T_2 can't reflect the state of whole liquid supply channel, the effect of the compensation term ΔT is poor. For energy model predictive method (see Fig.16), a useful feature of model-based predictive control contains characteristics of the system. Getting the effectiveness η, it can effectively avoid overshoot. Meanwhile, regularly updating the D can make it have a strong anti-interference ability. By comparing, we considered that the energy model predictive method is better.

5 Conclusion

Temperature as an important dialysis performance index is related to patient's user experience directly. Through a variety of methods for testing, model-based predictive control (MBPC) has achieved good results, having a meaningful guide for the actual work. Moreover, We modeled and analyzed the complex dialysis process, a lot of in-depth work can based on this deployment.

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