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Boundary PID Control for the Temperature of Chemical Pipeline Fluid

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ABSTRACT

In chemical production, the accuracy of pipeline fluid temperature control is very important for ensuring product quality, improving production efficiency and ensuring production safety. In this paper, the design and implementation of chemical pipeline fluid temperature control system based on boundary proportional-integral-derivative (PID) control algorithm are deeply discussed. Firstly, the principle of PID control algorithm and its advantages in the field of temperature control are expounded in detail. Secondly, according to the specific requirements of chemical pipeline fluid temperature control, the boundary PID control architecture is proposed and the key advantages are analyzed in detail. Finally, the effectiveness of the proposed control method is verified by simulation experiments. The results show that the system based on boundary PID control can respond quickly and achieve the goal of fluid temperature control, which provides reliable technical support for chemical production.

KEYWORDS

Boundary Control; PID Control; Chemical Pipeline; Fluid Temperature Control; System Design.

1. INTRODUCTION

In the process of chemical production, the temperature control of the fluid in the pipeline is a key link. Accurate temperature control can not only improve product quality, but also optimize production efficiency, reduce energy waste, and even in some cases, it is directly related to production safety.

For traditional control systems, including robot control [1], drone control [2], and control of circuit system [3], etc., are usually classified as lumped parameter systems. One of the main characteristics of this system is that its system dynamics are usually described by ordinary differential equations. However, due to the complex temperature evolution law of the fluid in the pipeline, the temperature distribution at different positions is different, which is essentially a distributed parameter control system. The state evolution of this system is usually described by partial differential equations and has infinite dimensional characteristics. For this distributed parameter system, there have been many researches on distributed control methods [4], [5]. However, although the distributed control method is effective, this control algorithm needs a large number of sensors and actuators, which has high control cost. For this reason, some scholars put forward the boundary control method, the core idea of which is to control the whole system state only by controlling the boundary position of the system [6]-[8]. However, the design of existing control methods depends on complex mathematical theory, which is not easy to be accepted by engineers. In addition, traditional temperature control methods are often difficult to meet the precise control requirements under complex working conditions, especially in the face of dynamic production environment, its response speed and stability are often insufficient.

As a classical control strategy, proportional-integral-derivative (PID) control algorithm is widely used in industrial control field because of its simple structure and strong adaptability [9]. Through the combination of proportional, integral and differential control methods, it can effectively cope with various complex control requirements. PID controller can adjust the control quantity in real time according to the deviation between the set value and the actual measured value, so as to realize the precise control of the controlled object. In the temperature control of chemical pipeline fluid, PID control algorithm can quickly respond to the temperature change, adjust the power of heating or cooling equipment in time, and ensure that the fluid temperature is always within the set range. However, the research of boundary PID control has not been considered.

The purpose of this paper is to discuss the realization method and performance of chemical pipeline fluid temperature control system based on PID control algorithm. By analyzing the principle of PID control algorithm, the key links of system design and the verification of simulation experiments in detail, an efficient and reliable solution is provided for temperature control in chemical production.

2. THE PRINCIPLE OF PID CONTROL ALGORITHM

PID control algorithm is a control algorithm that combines proportional, integral, and differential. Its basic principle is to operate according to the input deviation value and the functional relationship of proportion, integral and differential, and the operation result is used to control the output. By adjusting PID parameters (K_p、 K_i、 K_d), the dynamic and steady performance of the system can be optimized.

The mathematical model of PID control can be expressed as:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \tag{1}$$

where K_p is the proportional gain, K_i the integral gain, K_d the differential gain and $e(t)$ the difference between the given value and the measured value.

2.1. Proportional control

Proportional control is the most basic part of PID control, which reflects the deviation signal of control system in proportion. The proportional gain K_p determines the influence of deviation on the control quantity. Proportional control can quickly reduce the deviation, but it can’t completely eliminate the static error. When the deviation is large, proportional control can quickly adjust the control quantity and make the system quickly approach the set value. However, because the proportional control cannot completely eliminate the deviation, the system may still have some errors in the steady state.

2.2. Integral control

The main function of integral control is to eliminate static error and improve the control accuracy of the system. The integral gain K_i determines the influence of the accumulation of deviation in time on the control quantity. By integrating the deviation, integral control gradually accumulates the error, so as to continuously adjust the control quantity until the deviation is zero. Integral control can effectively eliminate the steady-state error, so that the system can maintain accurate control effect in long-term operation. However, integral control may also lead to the aggravation of system overshoot and even cause system oscillation.

2.3. Differential control

Differential control can predict the change rate of deviation, which is helpful to speed up the response speed of the system and restrain overshoot. Differential gain K_d determines the influence of deviation change rate on control quantity. Differential control can sense the variation trend of deviation in advance by differentiating the deviation, so as to adjust the control quantity in advance and make the system respond to the temperature change faster. Differential control can effectively suppress overshoot and improve the dynamic performance of the system. However, differential control is sensitive to noise, which may lead to fluctuation of control quantity.

3. DEMAND ANALYSIS OF FLUID TEMPERATURE CONTROL IN CHEMICAL PIPELINE

3.1. High precision requirements

Chemical production requires high temperature accuracy, and temperature fluctuation may affect product quality. In some fine chemical production processes, a slight change in temperature may lead to a significant decline in product quality. Therefore, the temperature control system needs to have high-precision control ability to ensure that the fluid temperature is always kept near the set value.

3.2. Quick response

In the process of chemical production, the temperature of pipeline fluid may be affected by many factors, such as environmental temperature change and fluid flow fluctuation. Therefore, the temperature control system needs to be able to quickly respond to temperature changes and adjust the control quantity in time to ensure the stable operation of the system.

3.3. Stability

The temperature control system should have good stability to avoid production accidents caused by temperature fluctuation. In chemical production, violent temperature fluctuation may lead to equipment damage, product quality degradation and even safety accidents. Therefore, the temperature control system needs to have robust stability and can maintain stable control effect under various working conditions.

4. CHEMICAL PIPELINE FLUID TEMPERATURE CONTROL PROBLEM

Different from lumped parameter systems, the fluid temperature control problem of chemical system belongs to the field of distributed parameter system control. The main feature of distributed parameter system is that its state is distributed. If it is represented by state space, it needs infinite system states. This means that not only infinite sensors are needed, but also infinite actuators are needed. Theoretically, this control mechanism is difficult to implement. That is, PID control mechanism cannot be directly used to realize distributed control of distributed parameter systems. However, many existing results introduce the idea of boundary control for distributed parameter systems, and feedback the control error of the system by collecting the data of the boundary points of the system to achieve the ideal control effect. However, for the boundary PID control problem, the existing literature still lacks the analysis/test results. This is the main motivation of boundary PID control proposed in this paper.

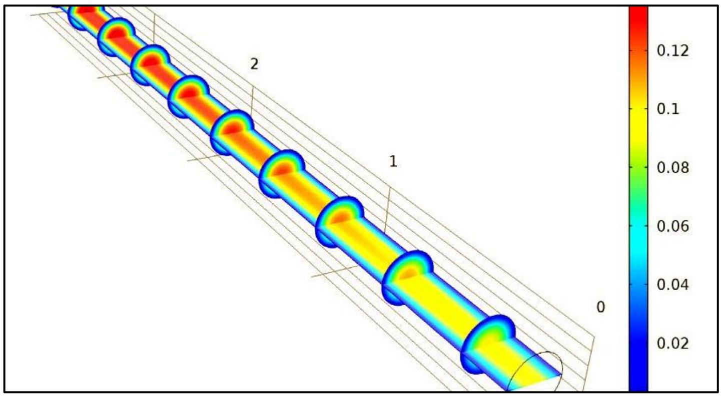

Fig. 1 Schematic diagram of temperature evolution of pipeline liquid

5. DESIGN OF TEMPERATURE CONTROL SYSTEM FOR CHEMICAL PIPELINE FLUID BASED ON PID

5.1. System modeling

The temperature evolution of the pipeline can be represented by the following partial differential equation:

$$\frac{\partial \mathrm{T}(x,t)}{\partial t} = \frac{\partial^2 \mathrm{T}(x,t)}{\partial x^2} + 60(1 - 0.1e^{-0.1x})\left(e^{\frac{-4}{1+\mathrm{T}(x,t)}} - e^{-4}\right) - 2\mathrm{T}(x,t) \tag{2}$$

$$\mathrm{T}(1,t) = 0,\ \left.\frac{\partial \mathrm{T}(x,t)}{\partial x}\right|_{x=l} = u(t) \tag{3}$$

where $\mathrm{T}(x,t)$ is the temperature variable, x the spatial position, t the time, l the pipe length, $u(t)$ the control input and generated by the PID controller.

5.2. Controller design

The temperature control system of chemical pipeline fluid based on PID is mainly composed of temperature sensor, controller and actuator. The temperature sensor collects the fluid temperature in real time, the controller performs PID operation according to the deviation between the set value and the actual value, and outputs a control signal, and the actuator adjusts the heating or cooling equipment according to the control signal, thus realizing temperature control. The system architecture is shown in Figure 2.

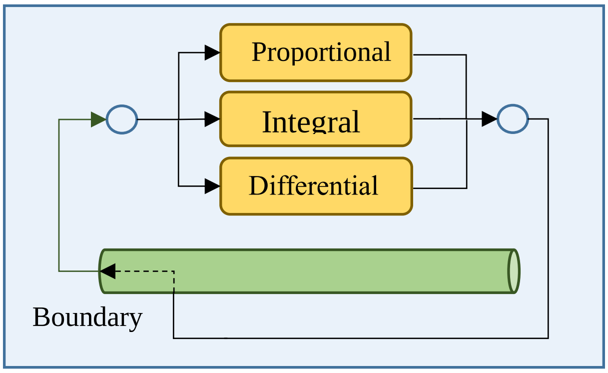

Fig. 2 Boundary PID control framework

Different from the traditional control system, because the distribution of pipeline temperature has infinite dimension characteristics, this paper uses PID control method to study the pipeline temperature control problem based on the framework of "boundary measurement and boundary control". The controller is designed as follows:

$$u(t) = K_p \mathrm{T}(l,t) + K_i \int \mathrm{T}(l,t)dt + K_d \frac{d\mathrm{T}(l,t)}{dt} \tag{4}$$

6. SIMULATION STUDY

Based on Matlab simulation platform, this paper verifies the effectiveness of the proposed boundary PID control algorithm by simulating partial differential equations (2) and (3). Select parameters $l = 1,\ K_p = 2,\ K_i = 0.1,\ K_d = 0.01$.

It should be noted that in order to fully simulate the state evolution of the system (2), it is necessary to discretize the system (2) by using the difference technique [10]. Accordingly, one can represent

$$\frac{\partial \mathrm{T}(x,t)}{\partial t} \approx \frac{\mathrm{T}(x,k) - \mathrm{T}(x,k-1)}{\Delta t} \tag{5}$$

$$\frac{\partial^2 \mathrm{T}(x,t)}{\partial x^2} \approx \frac{\frac{\mathrm{T}(x_+,t)-\mathrm{T}(x,t)}{\Delta x} - \frac{\mathrm{T}(x,t)-\mathrm{T}(x_-,t)}{\Delta x}}{\Delta x} = \frac{\mathrm{T}(x_+,t)+\mathrm{T}(x_-,t)-2\mathrm{T}(x,t)}{(\Delta x)^2} \tag{6}$$

where Δt is the time sampling step, x_+ the next spatial sampling position, x_- the last sampling position and Δx the spatial sampling step. In this article, select $\Delta t = 0.001\mathrm{s},\ \Delta x = 0.05\mathrm{m}$.

In addition, the initial condition is selected as follows

$$\mathrm{T}(x,0) = 1 + 0.3\cos(\pi x) \tag{7}$$

The simulation results are shown in Figure 3-6, in which Figure 3 and Figure 4 are the results of temperature evolution under open-loop control, and it can be found that the temperature distribution is in a divergent state. Figures 5 and 6 show the temperature evolution effect under closed-loop control, and it can be found that the temperature converges to the equilibrium point. The results show that the system can quickly respond to the temperature change and stably control the fluid temperature, which meets the high precision requirements of chemical production.

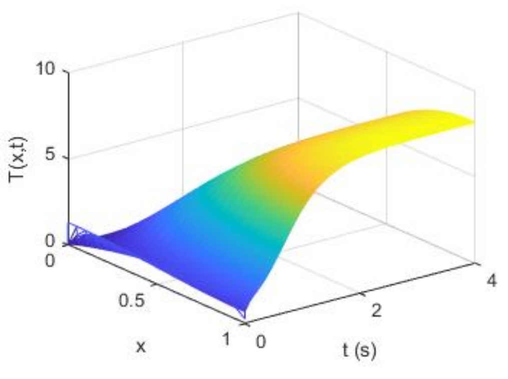

Fig. 3 Temperature evolution (open-loop)

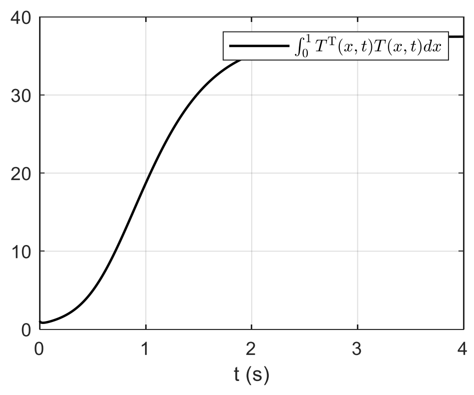

Fig. 4 Temperature norm (open-loop)

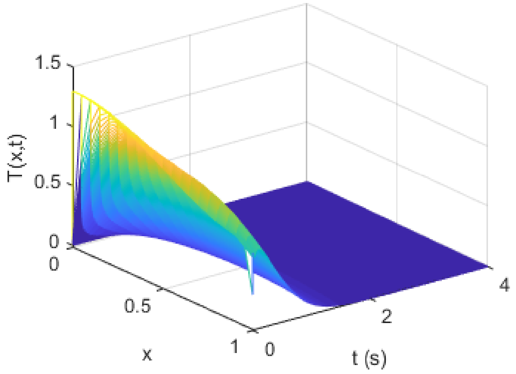

Fig. 5 Temperature evolution (closed-loop)

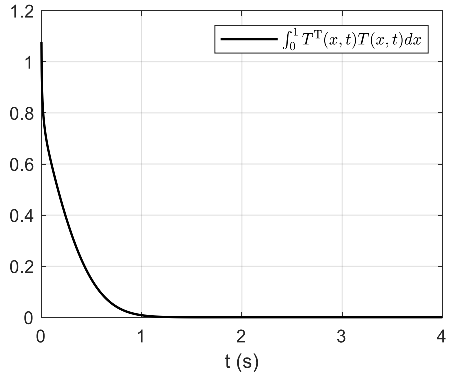

Fig. 6 Temperature norm (closed-loop)

In order to test the influence of parameters K_p, K_i, K_d, on system performance under different values, we define the following control indicator:

$$Error = \int_0^{t_f} \int_0^l |\mathrm{T}(x,t)| dxdt \tag{8}$$

where $t_f = 4$s. The simulation test results are given in Table 1.

From Table 1, it can be found that with the increase of K_p and K_i, the error of the system decreases, while with the increase of K_d, the system cumulative error increases.

Table 1 Control cumulative error under different parameter values

K_p	K_i	K_d	$Error$
2	0.1	0.01	0.2367
4	0.1	0.01	0.1278
6	0.1	0.01	0.1018
2	0.2	0.01	0.2334
2	0.3	0.01	0.2307
2	0.1	0.02	0.2380
2	0.1	0.03	0.2393

7. CONCLUSION

In chemical production, accurate control of pipeline fluid temperature plays a decisive role in ensuring product quality, improving production efficiency and ensuring operation safety. In this study, the analysis and design of fluid temperature control system for chemical pipeline based on boundary PID control algorithm are successfully designed and realized. By applying PID control algorithm, it gives full play to its advantages of fast response, good stability and strong robustness in the field of temperature control. The simulation results show that the proposed boundary control algorithm can effectively meet the actual needs of temperature control of chemical pipeline fluid, significantly improve the dynamic response speed and control accuracy of temperature, and realize the rapid and stable adjustment of temperature. The boundary control scheme based on PID provides reliable and efficient technical support for temperature control in chemical production process, and has important application value.

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