

An application of Smith predictor in PID controller for sucrose hydrolysis batch reactor model

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ABSTRACT

Temperature control in reaction systems, especially with exothermic reactions, is a challenging problem in the field of process control. For processes with significant time delay, the control systems encounter difficulties in maintaining stable operation. Numerous methods have been proposed to address the issues, among which O.J.M Smith suggested a method using a predictor combined with a PID (Proportional – Integral – Derivative) controller. Subsequent studies have been conducted and demonstrated the significant effectiveness of the Smith's method. In this study, we applied the Smith's method with a PID controller called PID-Smith controller. PID-Smith controller was employed to stabilize the temperature of a sucrose hydrolysis reactor and then compared its performance with that of a conventional PID controller. Experiments carried out with the PID parameters K_P , K_I and K_D being 80, 0.47 and 1600, respectively, showed that the PID-Smith controller significantly enhanced the control of system. The experiments were conducted with setpoints of 42°C, 46°C and 44°C, the PID-Smith controller outperforms the PID controller with shorter settling time, lower overshoot and taking substantially less time to stabilize the system. These result in a more stable process compared to the PID controller and show Smith's promise in enhancing the PID control systems.

Key words: Smith predictor, temperature control, batch reactor

INTRODUCTION

In reaction systems, reaction temperature is the most critical parameter having significant effects on product quality and system safety¹. Temperature is indeed a control parameter that exhibits thermal inertia and can introduce dead time in a system. In processes with large dead time, the effects of disturbances do not manifest immediately, but gradually appear. Furthermore, the effects of the controller also take time to be observed in the response of the control variables, and the control actions deal with the errors that have already occurred, rather than preventing them before they happen, making difficulties to achieve stable operation of the system². Therefore, PID controllers still face many challenges in dealing with large dead time. In 1957, O.J.M Smith proposed a method³, which was considered as the first and also the fundamental of Model Predictive Control (MPC) methods nowadays, for tuning the PID controller with a predictor to overcome the effects of dead time. The idea of the method is to use a model to predict the future output of the process based on past and present information of the process and control actions⁴. Smith's method has been studied in a number of thermal systems^{5,6} and reaction systems^{7,8}. The research⁷ applied the Smith predictor based parallel

cascade control strategy to enhance control of continuous bioreactor. The research⁸ applied Smith predictor with novel iterative learning control strategies, which are more complicated than PID control strategies, and showed the effectiveness of the method. But, the more complicated the strategies are, the more expensive of applying those in actual. Few research was conducted on the batch reactor system with a simple method to enhance the control of system. While simulations of the Smith predictor have been conducted in researchs, there's a need for more extensive experimentation to validate its real-world applications. In this research, in order to find a simple method with low cost, we applied Smith predictor in a PID controller. This method is much simpler and easy to develop, then compared the performance of this controller to the conventional PID controller in controlling reaction temperature. So that we could evaluate the performance of PID-Smith controller and also the drawback of this method.

MATERIALS AND METHODS

Sucrose hydrolysis reaction

Sucrose hydrolysis reaction is favored in the food and pharmaceutical industries because its products, a

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mixture of monosaccharides with an equal molar ratio of glucose and fructose, is known as inverted sugar. Inverted sugar is highly desirable due to its advantages as an instant source of energy, high osmotic pressure, and low crystallization tendency⁹. In addition, the sugar inversion reaction can take place under relatively mild temperature conditions¹⁰ making it easy to set up the reaction conditions for research. The sucrose hydrolysis reaction equation is represented as follows¹¹:



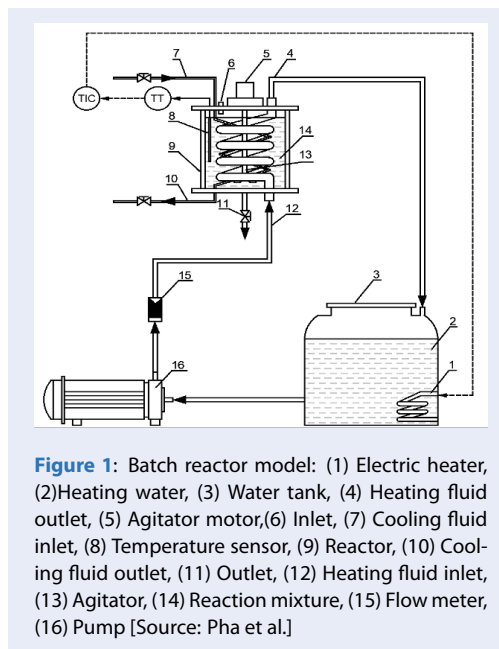
A wide variety of catalysts have been used in this reaction, including Tartaric Acid, Citric Acid, Lactic Acid, Acetic Acid, etc.¹². Among these, Citric Acid is a relatively non-toxic and readily available chemical, hence it will be used as the catalyst in the reaction.

The experiments were conducted with a batch reactor system in the Chemical Process Control Laboratory, Department of Chemical Engineering, Ho Chi Minh City University of Technology, Vietnam National University. The main equipment is a reactor (9) with an internal stirrer (13) and a coil heat exchanger. Heat is provided by a heating fluid from an electric heater (3) and pumped (16) into the heat exchanger. The reaction solution is fed into the reactor through the inlet (6) and after the reaction is completed, the products are discharged through the outlet (11). In the experiments, the cooling and heating streams had constant flow rates, and the controller adjusted the power into the electric heater to control the reaction temperature. The reaction temperature was measured by a 3-wire PT100 sensor. A Siemens S7 1212C DC/DC/DC PLC was used in the experiments for control and operation.

The experiments were conducted at three temperature levels: 42°C, 44°C, and 46°C. Previous studies have shown that the inverse sugar reaction with citric acid as a catalyst proceeds well under the established experimental conditions.

To demonstrate the effectiveness of the PID-Smith controller, the team conducted three experiments. All experiments were performed using a PID controller with the same parameters. Experiment 1 was conducted at a setpoint temperature of 42°C, experiment 2 at 46°C, and experiment 3 at various setpoint temperatures to evaluate the controller's response to changing input conditions.

The data in the study was collected directly from a PT100 temperature sensor and transmitted to a PLC, with the necessary data being output from the TIA Portal software.



For chemical reactions, temperature and reaction yield are not directly proportional; there is an optimal temperature range. When the reaction temperature is maintained within this optimal range, the reaction yield is highest. Moreover, temperature stability in reaction systems is closely related to the safe operation of the system. Therefore, stable temperature control is essential. Additionally, temperature sensors are widely employed devices renowned for their high accuracy, ensuring that the feedback temperature data is precise and reliable in comparison to other process variables. To streamline computational efforts, the feedback parameter is typically restricted to the requisite range and scale of the equipment. However, when stringent control precision is demanded, incorporating additional parameters beyond temperature emerges as a viable strategy.

Process identification

While Smith proposed the FOPDT (First-order-plus-dead time) model for process identification, in this research, a more complex model (SOPDT) was applied to describe the system's behavior compared to the simpler FOPDT model often used in temperature control. While FOPDT models are effective, SOPDT models can provide more accurate results, especially for forecasting. However, designing controllers for higher-order models is more challenging, so we need to carefully choose the right model complexity. We used a special tool in MATLAB called the Identification Toolbox to find the best mathematical equation

to describe our system. After testing different equations, we found that second-order model was the most appropriate model, correctly representing our system 98.15% of the time. This method was mentioned by Professor Lennart Ljung to estimate the orders of the model¹³.

$$Gp(s) = \frac{67.74}{(1 + 3746s)(1 + 34.146s)} e^{-46s}$$

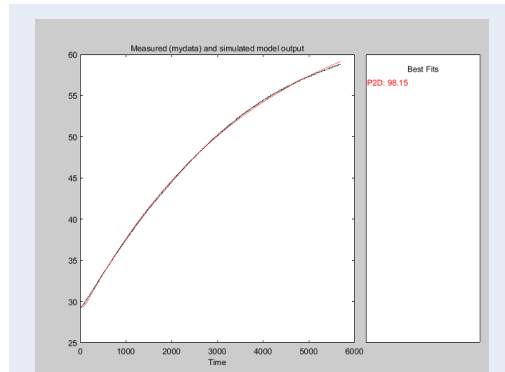


Figure 2: Model identification by MATLAB Identification Toolbox [Source: System Identification Toolbox, Release 2023a. Natick, MA, USA: The MathWorks Inc., 2023.]

With Siemens S7 1200 PLC requiring a discrete transfer function to work with, we need to approximate a continuous model to discrete model. There are numerous methods to do so, with the transformation from a continuous variable “s” into a discrete variable “z”, and they are given in Table 1.

Table 1: Approximation of variable “s”¹⁴

Method	Approximation
Forward rule	$s \rightarrow \frac{z-1}{T}$
Backward rule	$s \rightarrow \frac{z-1}{Tz}$
Trapezoid rule	$s \rightarrow \frac{2}{T} \frac{z-1}{z+1}$

The Trapezoid-rule is also known as the Tustin’s method, where in the approximation “T” is the sample time. In this research, the applied controller had the sample time of 1 second. Applying the Tustin’s method, we obtained the discrete transfer function as followed:

$$H(z) = \frac{0.01727z + 0.01727}{z - 0.9655} \frac{0.01085z + 0.01085}{z - 0.9997} z^{-46}$$

Controller design

The proportional-integral-derivative (PID) controller offers several advantages in temperature stabilization control. With the action of the integral term, the error will be eliminated. Furthermore, thermal processes often have thermal inertia, in such cases the derivative term can provide a more responsive control signal adjustment, thereby limiting the influence of thermal inertia and helping the system to stabilize faster. The following is a PID control block diagram for the above process:

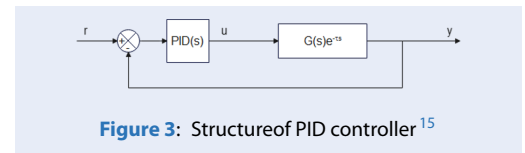


Figure 3: Structure of PID controller¹⁵

The controller parameters were found using the manual tuning method used in the experiment as follows: $K_P = 80$, $K_I = 0.47$, $K_D = 1600$

For processes with delay, O. J. M. Smith proposed a method using a predictor combined with a PID controller to achieve better control quality. This combination is called the PID-Smith controller. The proposed structure of the Smith predictor controller is as follows⁴:

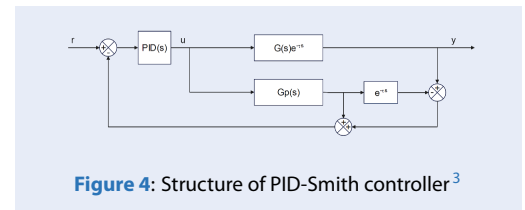


Figure 4: Structure of PID-Smith controller³

Where $G(s)e^{-\tau s}$ describes the actual process that occurs, $Gp(s)$ is the model of process dynamics, $e^{-\tau s}$ represents the process delay.

The idea behind this method is to use a process model that captures the inherent dynamics characteristics of the system $Gp(s)$ excluding the dead time of the process. Then we need to identify the delay time between the input and output $e^{-\tau s}$. In this case, the model acts as a predictor of the future of the process, and the calculated information from it becomes the input value for the controller, thereby minimizing the impact of delay on the process

The key point of this method is to accurately approximate the model of the process described by the function $Gp(s)$ and the value of the delay time $e^{-\tau s}$. If the model is exact to the process, the future information

predicted by the Smith predictor is the same as that of the process in the future. This method has been previously studied by simulating and it was shown that it can significantly improve the control quality¹⁶. In this research, we will use the transfer function $Gp(s)$ with delay time $e^{-\tau s}$ that was previously identified as the predictor for process. The parameters of the PID controller will be the same with $K_P = 80$, $K_I = 0.47$, $K_D = 1600$

Implementation on S7 1200 PLC

On Siemens S7 1200, PID controllers must be called in a cyclic interrupt with a known cycle time. These cyclic interrupt blocks halt the execution of the main PLC program in OB1 and execute their own code before restarting the main program at the exact point of interruption.

We use the “PID_Compact” technology object as the controller in S7 1200. This object continuously reads the measured process value (reaction temperature) and evaluates the error between it and the setpoint. The PID controller has two inputs: setpoint and reaction temperature. The PT100 sensor provides the signal with the reaction temperature information. The output of the “PID_Compact” is the control signal, which adjusts the actuator based on the error between the setpoint and the reaction temperature.

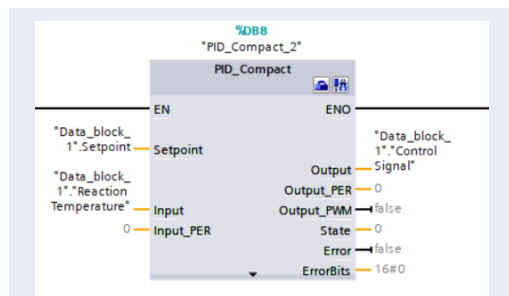


Figure 5: The “PID_Compact” function block [Source: TotallyIntegrated Automation (TIA) Portal, v16. Munich, Germany: Siemens AG, 2019.]

To apply the Smith predictor in to the S7 1200 PLC, we use the SCL programming language to create the Smith predictor function block. This block, based on a previously identified model, calculates the future value of the process from the input information. The function block has two inputs: the reaction temperature and the PID controller’s control signal. Its sole output is the predicted future value of the process.

In the PID-Smith controller, the predicted value from the Smith predictor becomes the new input to the

“PID_Compact”. This effectively replaces the actual measured value with the predicted value. The “PID_Compact” then calculates the control signal based on the error between the setpoint and the predicted future value. This approach aims to compensate for the inherent time delay in the process, allowing the controller to react proactively instead of reactively to process changes.

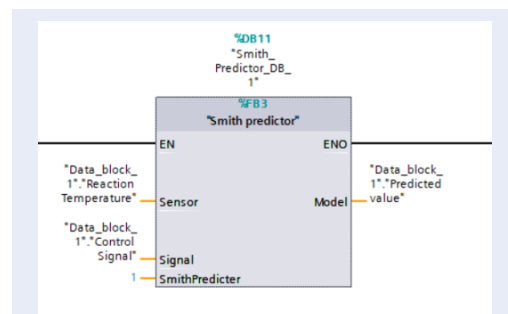


Figure 6: The Smith predictor function block [Source: Totally Integrated Automation (TIA) Portal, v16. Munich, Germany: Siemens AG, 2019.]

RESULTS AND DISCUSSION

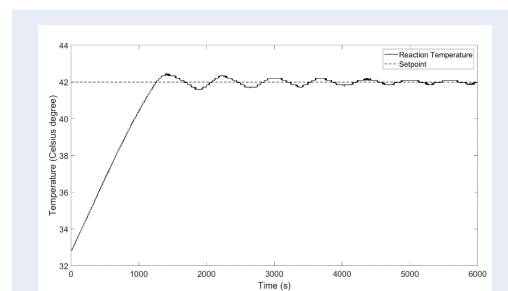


Figure 7: Reaction temperature control with PID controller, setpoint: 42°C [Source: Pha et al.]

The response time, settling time and overshoot of two controllers:

Table 2: Performance criteria of two controllers, setpoint: 42°C [Source: Pha et al.]

	Rise time (s)	Settling time (s)	Overshoot (%)
PID	1117	4426	1.10
PID-Smith	1110	2670	0.52

Figure 6 and Figure 7 shows the temperature response of the system when we applied PID and PID-Smith

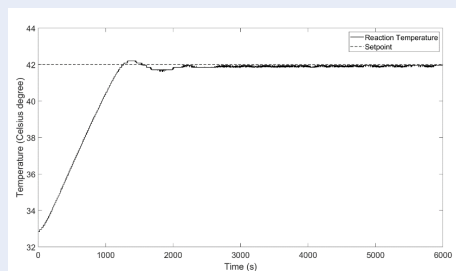


Figure 8: Reaction temperature control with PID-Smith controller, setpoint: 42°C [Source: Pha et al.]

controller with setpoint of reaction temperature of 42°C. Rise time, settling time and overshoot of two controllers in this experiment are shown in Table 2. The PID-Smith controller showed better performance than the PID controller. The PID-Smith controller could stabilize the process quicker than the PID controller, which led to shorter settling time. The PID-Smith controller also improved the overshoot of the process with lower overshoot than that of the PID controller.

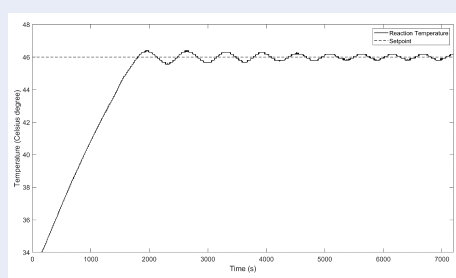


Figure 9: Reaction temperature control with PID controller, setpoint: 46°C [Source: Pha et al.]

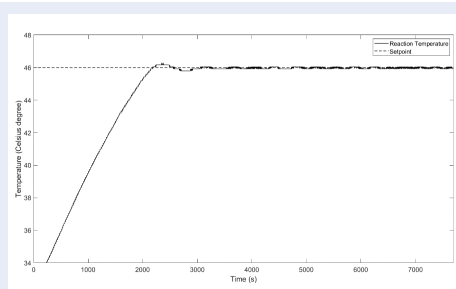


Figure 10: Reaction temperature control with PID-Smith controller, setpoint: 46°C [Source: Pha et al.]

Another experiment with both controllers was conducted with the setpoint of reaction temperature of 46°C. The response time, settling time, overshoot are:

Table 3: Performance criteria of two controllers, setpoint: 46°C [Source: Pha et al.]

	Rise time (s)	Settling time (s)	Overshoot (%)
PID	1074	4552	0.90
PID-Smith	1295	2377	0.62

Consistent with previous results, the PID-Smith controller once again demonstrated superior reaction temperature control compared to the conventional PID controller. This enhanced performance is directly attributable to its significantly shorter settling time, resulting in faster process stabilization. The Smith predictor introduced an inherent time delay into the control loop, resulting in the PID-Smith controller having a longer rise time than the PID controller. This delay stems from the predictor’s reliance on estimated values rather than real-time reaction temperature feedback. On the other hand, with the setpoint of 46°C, the PID controller gave significantly longer settling time than PID-Smith controller.

To further assess the performance of the two controllers under varying conditions, a multi-setpoint experiment was conducted. The results are presented in Figure 10 and Figure 11.

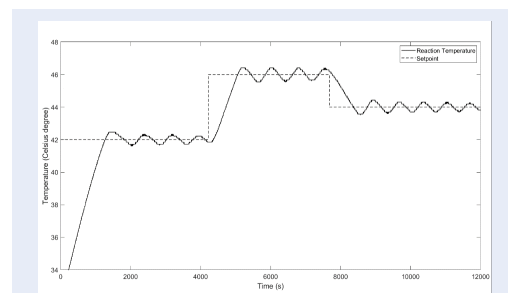


Figure 11: Reaction temperature control with PID controller, multi-setpoint [Source: Pha et al.]

This experiment demonstrated the clear superiority of the PID-Smith controller over the conventional PID controller. Upon setting the reaction temperature to 42°C, the PID-Smith controller exhibited a brief oscillatory period before rapidly achieving steady state. The conventional PID controller exhibited larger amplitude and more prolonged fluctuations in reaction temperature than the PID-Smith

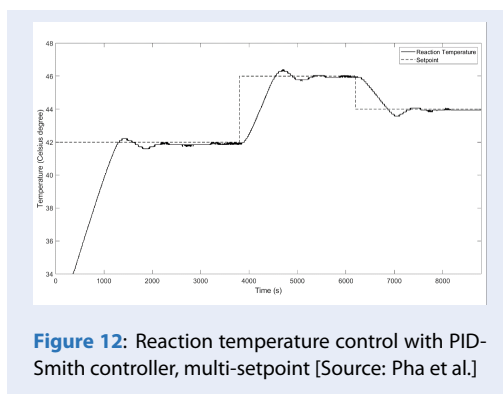


Figure 12: Reaction temperature control with PID-Smith controller, multi-setpoint [Source: Pha et al.]

controller. Until we changed the setpoint, the process still did not go into the steady state. With the setpoint of 46°C, we conducted longer time on the conventional PID controller to make the reaction temperature into the steady state but it failed to stabilize the reaction temperature. Instead, the temperature exhibited persistent oscillations around the setpoint, indicating the controller’s limitations. In contrast, the PID-Smith controller demonstrated exceptional control and stabilization of the reaction temperature, achieving steady state significantly faster than the conventional PID controller. Overshoots of the process were also lower when using the PID-Smith controller. The same things were shown when we change the setpoint to 44°C.

DISCUSSION

In this study, we observed the better performance of PID-Smith controller compared to the conventional PID controller. From Figure 6 and Figure 7, we can see that the fluctuation of temperature in the case using PID-Smith controller is lower than that of conventional PID controller. From the above figures, it can be seen that the PID-Smith controller outperforms the PID controller with significantly faster settling time, which is of great significance for quickly stabilizing the system state. In addition, the overshoot of the PID-Smith controller was also lower, which showed that this controller could limit the overshoot of the process, the highest temperature reached is 42.2°C, which is lower than 42.5°C when using the PID controller. A thing that we can conclude in this experiment is that the PID-Smith controller could settle the process faster than conventional PID controller with lower settling time and overshoot. Figure 8 and Figure 9 reveal the PID controller’s significantly degraded control quality at the higher setpoint. This is evidenced by a larger settling error (0.12 for this experiment and 0.07 for the experiment before) and more

pronounced fluctuations compared to its operation at 42°C. This is a common limitation of PID-based control systems which is their sensitivity to setpoint changes. This often necessitates retuning the PID parameters to maintain optimal performance across a wide operating range. Figure 10 and Figure 11 reconfirm a fundamental limitation of PID controllers: their difficulty in adapting to systems with highly dynamic conditions. But, The PID-Smith controller can solve this problem. This experiment underscores the significant value of the PID-Smith controller. Even with a setpoint change to 44°C, it demonstrated robust control and rapid process stabilization. This highlights its effectiveness in dynamic process environments where operating conditions may change. Numerous empirical studies have demonstrated the efficacy of PI controllers for temperature regulation. However, this research endeavors to develop a comprehensive PID-Smith control strategy incorporating proportional, integral, and derivative components, grounded in theoretical principles. While advanced control paradigms such as adaptive, fuzzy, or neural network controllers have gained prominence, their implementation often demands substantial investment and research due to their inherent complexity. Within the scope of this investigation, the objective is to enhance the control performance of a reaction system with a relatively simple method through the evolution of a basic PID controller, while maintaining a manageable design complexity. Besides, the PLC employed in this research is a digital controller with a sampling interval of 1 second. While the current study concentrated on developing and implementing a combined PID-Smith control strategy, the influence of varying sampling intervals on the digital PID controller’s performance was not comprehensively evaluated. This aspect presents a significant scientific inquiry and will be a focal point of future investigations. The scope of this study is about batch reactors with structures and properties similar to the system under investigation. Additionally, this method can be applied to certain types of helical coil heat exchangers with similar configurations. However, to extend this approach to other operating systems, such as continuous stirred-tank reactors (CSTRs), further research is required to identify process variables, suitable models, data collecting method and how to design controllers. A significant challenge arises in determining a suitable process model. The Smith predictor depends on a process model, our findings indicate that our model possesses sufficient accuracy. A poorly constructed model can indeed lead to degraded performance compared to a conventional PID controller. To determine

precise accuracy thresholds for optimal Smith predictor and also the applicable range of the method, further research is necessary.

The proposed method has the advantages of being simple and easy to develop. In industry, PID controllers are widely used. By utilizing the same model used to develop the initial PID controller, the Smith predictor is applied to enhance control performance. With minor adjustments and using existing resources, the control quality can be significantly improved from a simple PID controller. Within the scope of the current research, our team is unable to assess the actual economic benefits. Furthermore, based on the presented results, the control quality of the system will be significantly improved. Further quantitative data and empirical evidence are required to definitively assess the cost-effectiveness and practical feasibility of our proposed method. Future research will be dedicated to comprehensively investigating these aspects.

CONCLUSION

This research demonstrates the successful design and implementation of a simple, Smith predictor-based controller for a batch reactor system. The above experiments had demonstrated the effectiveness of the PID-Smith controller compared to the conventional PID controller, achieving reduced settling time and overshoot, which introduced significant improvement for reaction equipment systems. The primary advantage of the PID-Smith controller lies in its ability to achieve process setpoint stabilization significantly faster than a conventional PID controller. This enhances performance translates to smoother, more efficient operation, particularly in processes subject to varying operating conditions. Conversely, experiments have demonstrated a limitation of conventional PID controllers: they often exhibit suboptimal performance, longer settling time and instability, when confronted with setpoint changes. The Smith predictor provides a powerful technique for compensating time delays in control systems. Its effectiveness is particularly pronounced when an accurate process model is available. Additionally, the Smith predictor offers the advantage of straightforward implementation, requiring minimal cost and technical complexity.

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CONFLICT OF INTEREST

We declare that: in this paper, there is no conflict of interests.

AUTHORS' CONTRIBUTIONS

Bui Ngoc Pha: Conceptualization, Methodology, Funding acquisition, Supervision, Writing – original draft, Writing – review & editing. Tran Quoc Thanh, Trieu Thai Dang: Investigation, Data curation, Formal analysis, Visualization. All authors read and approved the final manuscript.

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Ứng dụng bộ dự báo Smith trong bộ điều khiển PID cho mô hình thiết bị phản ứng gián đoạn thủy phân đường sucrose

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TÓM TẮT

Kiểm soát nhiệt độ trong các hệ thống phản ứng, đặc biệt là với các phản ứng tỏa nhiệt, là một bài toán đầy thách thức trong lĩnh vực điều khiển quá trình. Đối với các hệ thống có thời gian trễ lớn, các hệ thống điều khiển thường gặp nhiều khó khăn trong việc duy trì trạng thái hoạt động ổn định. Nhiều phương pháp đã được đề xuất để giải quyết vấn đề này, trong đó O.J.M Smith đã giới thiệu một phương pháp sử dụng bộ dự báo kết hợp với bộ điều khiển PID (Tỉ lệ – Tích phân – Vi phân). Các nghiên cứu sau này đã được tiến hành và chứng minh hiệu quả rõ rệt của phương pháp Smith. Trong nghiên cứu này, chúng tôi đã áp dụng phương pháp Smith cùng với bộ điều khiển PID, được gọi là bộ điều khiển PID-Smith. Bộ điều khiển PID-Smith được sử dụng để ổn định nhiệt độ cho một thiết bị phản ứng thủy phân sucrose, sau đó hiệu suất của nó được so sánh với một bộ điều khiển PID truyền thống. Các thí nghiệm được thực hiện với các thông số PID K_P , K_I và K_D lần lượt là 80, 0.47 và 1600, cho thấy bộ điều khiển PID-Smith đã cải thiện đáng kể chất lượng điều khiển của hệ thống. Quá trình thực nghiệm được tiến hành với các giá trị đặt lần lượt là 42°C, 46°C và 44°C; kết quả cho thấy bộ điều khiển PID-Smith vượt trội hơn so với bộ điều khiển PID thông thường nhờ thời gian xác lập ngắn hơn, độ vọt lố thấp hơn và tốn ít thời gian hơn đáng kể để đưa hệ thống vào trạng thái ổn định. Những kết quả này mang lại một quá trình vận hành ổn định hơn so với bộ điều khiển PID đơn thuần, đồng thời cho thấy triển vọng của phương pháp Smith trong việc nâng cao hiệu năng của các hệ thống điều khiển PID.

Từ khoá: Bộ dự báo Smith, Điều khiển nhiệt độ, Thiết bị phản ứng gián đoạn

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