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GABROVO

PID TEMPERATURE CONTROL OF A CHEMICAL PROCESS

Sara Stanišić, Sanja Antić*, Mihailo Knežević, Milentije Luković

University of Kragujevac, Faculty of Technical Sciences Čačak, Svetog Save 65, 32000
**Sanja Antić: sanja.antic@ftn.kg.ac.rs*

Abstract
Proportional-Integral-Derivative (PID) control remains one of the most widely adopted strategies in industrial automation due to its simplicity, robustness, and proven effectiveness across a broad spectrum of processes, including temperature, pressure, flow, and level control. This paper investigates the application of various PID tuning methods, including Ziegler-Nichols (ZN), Good Gain (GG), Internal Model Control (IMC), and Software-Based Tuning (SBT), in the context of a chemical process. The system aims to maintain the temperature at a specified reference value while ensuring stability, eliminating steady-state error, and optimizing the transient response. The performance of each tuning method is evaluated based on the quality of the transient response and the Integral of Time-weighted Absolute Error (ITAE) criterion. The system was implemented using both Simulink, within the MATLAB environment, and the LabVIEW software package.

Keywords: PID, Ziegler-Nichols, Good Gain, Internal Model Control, Software-Based Tuning, ITAE, temperature control, chemical process.

INTRODUCTION

Proportional-Integral-Derivative (PID) control is widely used in industrial automation due to its simplicity, robustness, and versatility in control processes like temperature, pressure, flow, and level. A well-tuned PID controller improves performance by reducing overshoot, enhancing stability, and minimizing steady-state error. Common tuning methods include Ziegler-Nichols (ZN), Cohen-Coon (CC), Good Gain (GG), Internal Model Control (IMC), Auto-Tuning (AT), Optimization-Based (OB), and Software-Based Tuning (SBT) [1-5].

The ZN method determines controller parameters using the ultimate gain and oscillation period, but it often results in high overshoot [1]. The CC method, based on step-response data, is suitable for first-order plus dead-time (FOPTD) systems, though it may perform poorly in systems with complex dynamics [2]. The GG method relies on iterative gain adjustments and is appreciated for its simplicity, albeit being time-consuming [3]. The IMC method represents a model-based analytical approach well-suited for advanced applications [3,4]. The AT technique, introduced by Åström and Hägglund, employs relay feedback to estimate tuning parameters and is widely implemented in distributed control systems (DCS) and programmable logic controllers (PLC) [5]. OB methods utilize optimization algorithms (e.g., Genetic Algorithm (GA), Particle Swarm Optimization (PSO)) to minimize performance indices such as IAE, ITAE, and ISE [6–9].

Software platforms such as MATLAB and LabVIEW provide graphical interfaces and built-in auto-tuning functionalities, making them valuable tools in both industrial and academic environments.

This paper presents a chemical process represented through a block diagram and

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offers a brief overview of selected PID tuning techniques, including Ziegler–Nichols (ZN), Good Gain (GG), Internal Model Control (IMC), and Software-Based Tuning (SBT). The obtained results are analyzed through temperature response plots generated in LabVIEW and MATLAB, with controller performance evaluated using transient response parameters and the ITAE criterion.

SYSTEM MODELLING

Control systems are widely used to regulate the temperature of chemical processes. An actuator and valve control the flow of a reactant, which affects vat temperature. This is measured and compared to a setpoint in a closed loop to maintain stable conditions.

Precise temperature control is essential as it affects reaction rate, selectivity, and safety, which are crucial in processes like synthesis, distillation, and fermentation.

Fig. 1 shows a closed-loop chemical system where temperature is continuously monitored and adjusted. Key components include a PID controller, actuator and valve, chemical process, and temperature sensor. The controller compares measured and reference temperatures, the sensor provides real-time data, and the actuator adjusts heat flow based on controller commands.

PID CONTROLLER DESIGN

Effective tuning of a PID controller is essential for achieving optimal performance in process control systems.

This section introduces three widely used approaches for determining PID parameters: the Ziegler-Nichols (ZN) method, the Good Gain (GG) method, the Internal Model Control (IMC) method, and Software-Based Tuning (SBT) method.

Ziegler-Nichols Method

In the ZN closed-loop method, the proportional gain (K_P) is increased until sustained oscillations occur. The corresponding gain is the ultimate gain (K_{Pu}), and the time between peaks is the ultimate period (T_{ku}).

Good Gain Method

This method uses a proportional gain (K_{Pou}) that produces a slight overshoot followed by a minimal undershoot, and T_{ou}, which represents the time interval between these two points.

Internal Model Control (IMC)

IMC tuning uses a model-based approach for robustness and simplicity, especially effective for systems with delay. For processes approximated by a second-order plus dead time (SOPDT) model:

$$G(s) = \frac{Ke^{-\tau s}}{(T_1 s+1)(T_2 s+1)}, \qquad (1)$$

the controller parameters can be derived analytically based on the model to achieve desired closed-loop performance.

The parameters recommended for these three PID tuning methods are given in Table 1, where λ represents the time constant of the IMC filter, which determines the balance between performance and robustness. A smaller λ results in a faster response but makes the system more sensitive to noise, resulting in decreased robustness. In contrast, a larger λ leads to a slower response but improves robustness.

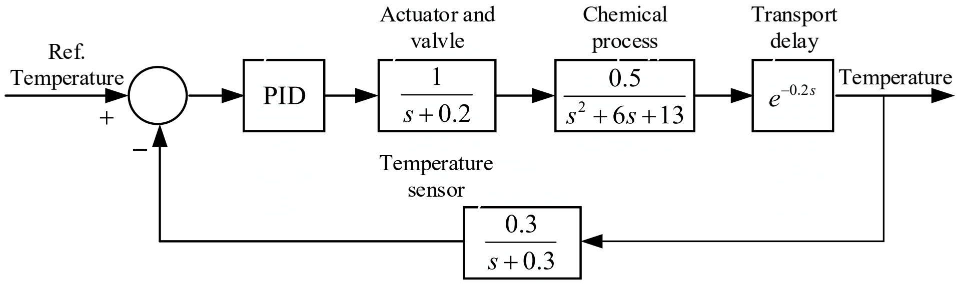

Fig. 1. *The closed loop chemical system.*

__Table 1__ Recommended parameters for tuning PID in a closed-loop system

Method	K_P	K_I	K_D
ZN	$0.6\ K_{Pu}$	$K_P\ 2/T_u$	$K_P\ 0.125T_u$
GG	K_{Pou}	$K_{Pou}/1.5T_{ou}$	$0.375K_{Pou}T_{ou}$
IMC	$\frac{T_1+T_2}{K(\lambda+\tau)}$	$\frac{K_P}{T_1+T_2}$	$K_P\frac{T_1T_2}{T_1+T_2}$

Software-Based Tuning (SBT)

SBT uses tools such as MATLAB and LabVIEW to automatically adjust PID parameters through built-in algorithms and real-time simulation.

RESULTS

When applying different methods of PID controller parameter synthesis, two software packages, LabVIEW and MATLAB, were used. LabVIEW offers an intuitive graphical interface ideal for real-time data acquisition and hardware integration, while MATLAB provides powerful tools for modeling, simulation, and analysis.

Fig. 2 shows the Front Panel of the implemented LabVIEW program, while Fig. 3 presents the Simulink model PID control of the chemical process with ITAE calculation.

Ziegler-Nichols method

Determination of K_{Pu} and T_u for ZN method implementation is given in Fig. 4.

Table 2 lists the PID controller parameters calculated from Table 1, based on K_{Pu}=70.5 and T_u=7.315.

In the remainder of the paper, Figs. 5, 8, 12, and 14 present the system's temperature responses obtained using LabVIEW, while Figs 6, 9, 13, and 15 show the corresponding MATLAB results.

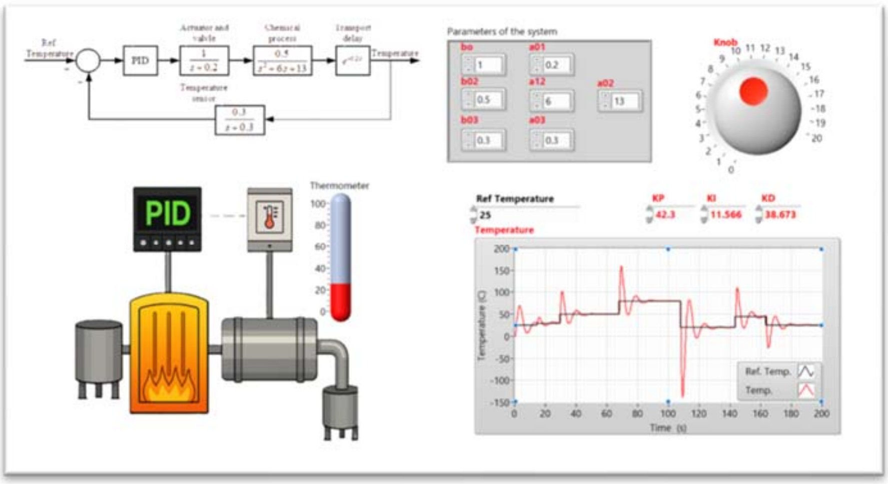

***Fig. 2.** The LabVIEW Front Panel developed for PID control of the chemical process.*

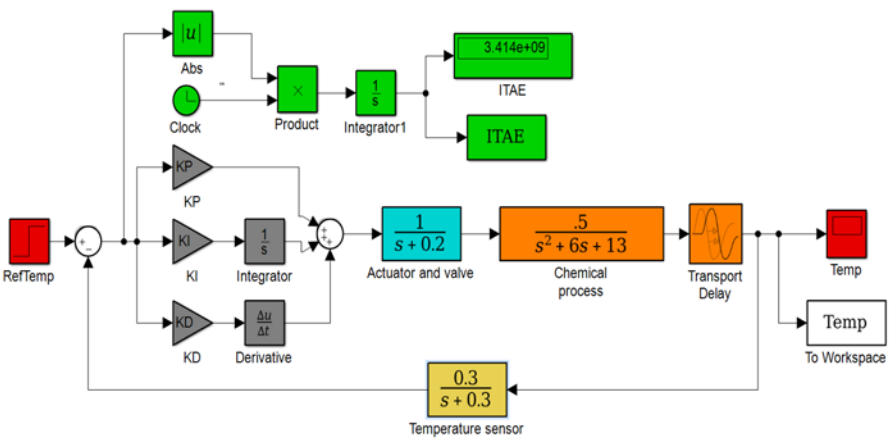

***Fig. 3.** The Simulink model of the PID control of the chemical process.*

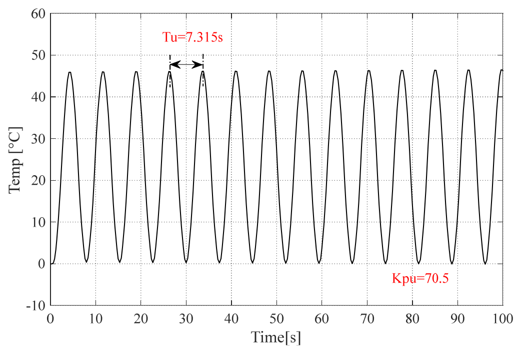

Fig. 4 *ZN method- determination of K_{Pu} and T_u.*

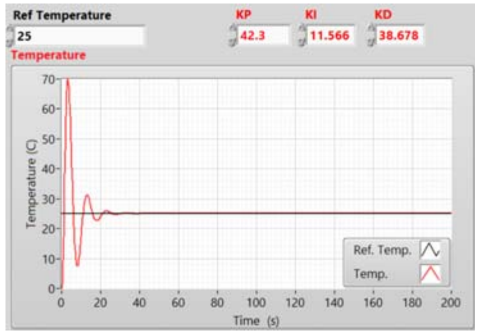

Fig. 5. *Temperature responses using the ZN PID controller in LabVIEW.*

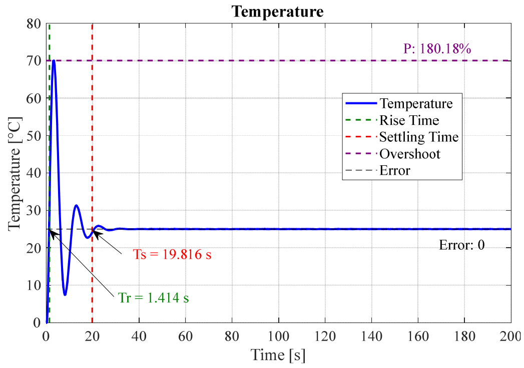

Fig. 6. *Temperature responses using the ZN PID controller in MATLAB.*

Good Gain method

Fig. 7 illustrates how the value of T_{ou} was determined for a proportional gain of K_{pou}=6.

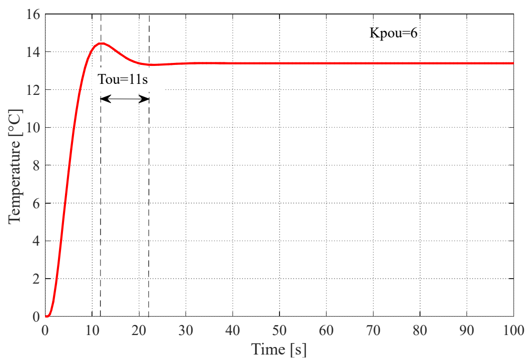

Fig. 7. *Determining the parameters for GG method.*

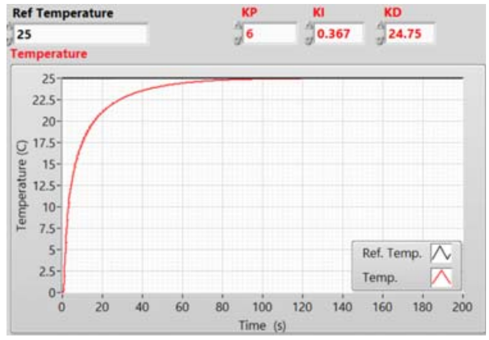

Fig. 8*. Temperature responses using the GG PID controller in LabVIEW.*

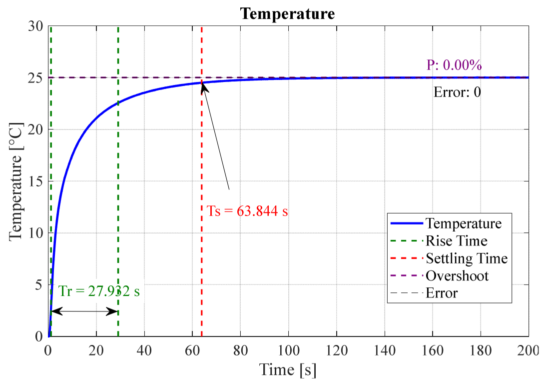

Fig. 9*. Temperature responses using the GG PID controller in MATLAB.*

Internal Model Control

By placing the transfer function of the temperature sensor in the direct branch, the open-loop transfer function of the system can be represented in the following form:

$$G(s) = \frac{0.15e^{-0.2s}}{(s+0.2)(s+0.3)(s^2+6s+13)}. \quad (2)$$

Applying the IMC method for PID tuning requires reducing the fourth-order system (2) to a second-order approximation. Since, the poles of the observed system are:

$$p_1 = -0.2,\ p_2 = -0.3,\ p_{3,4} = -3 \pm j2, \quad (3)$$

this approximation is made by neglecting the complex conjugate poles, as they are the farthest from the imaginary axis. Thus, the approximation of the model is obtained with:

$$G(s) = \frac{0.192e^{-0.2s}}{(5s+1)(3.333s+1)}.. \quad (4)$$

Fig. 10 illustrates the Simulink model of the system and its approximation, whereas Fig. 11 validates the introduced approximation. The responses of the chemical process and its second-order transfer function approximation almost completely overlap.

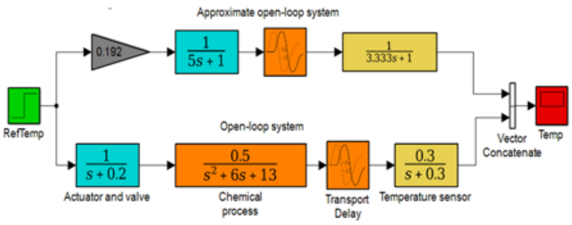

Fig. 10. *Simulink model comparing the open-loop chemical process and its approximation.*

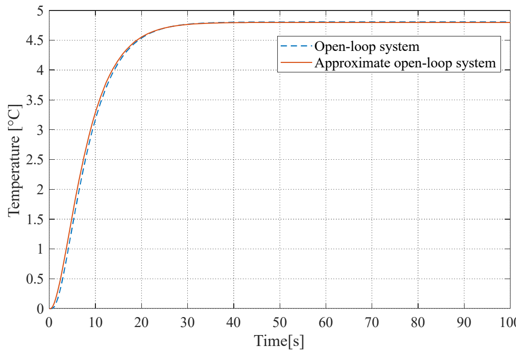

Fig. 11. *Comparison of the open loop systems responses.*

Based on (4), the parameters of SOPDT model (1) are:

$$K = 0.192,\ T_1 = 5,\ T_2 = 3.333,\ \tau = 0.2. \qquad (5)$$

Since τ is small, a good dynamic of the response in our case gave the selection:

$$\lambda = 40\tau\,. \qquad (6)$$

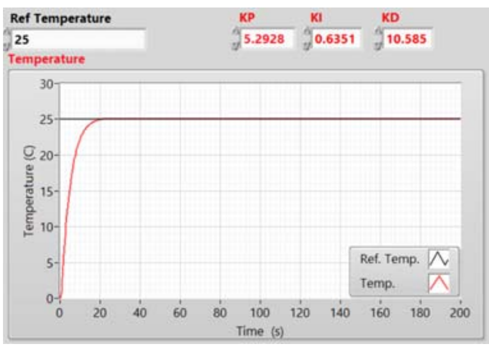

Fig. 12. *Temperature responses using the IMC PID controller in LabVIEW.*

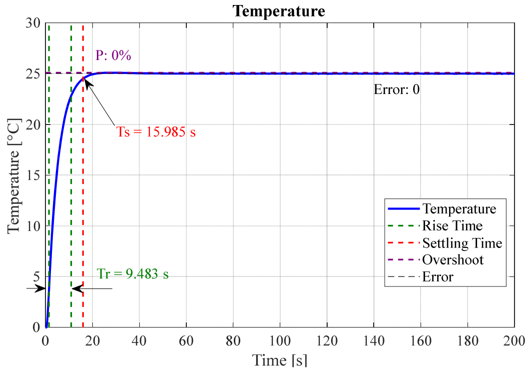

Fig. 13. *Temperature responses using the IMC PID controller in MATLAB.*

Software-Based Tuning (SBT)

Figures 14 and 15 present the temperature response results obtained using the SBT method implemented in LabVIEW and MATLAB, respectively.

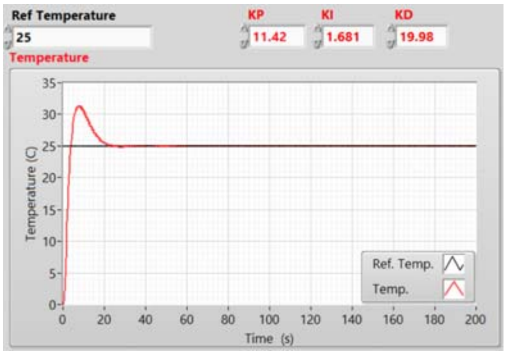

Fig. 14. *Temperature responses using the SBT PID controller in LabVIEW.*

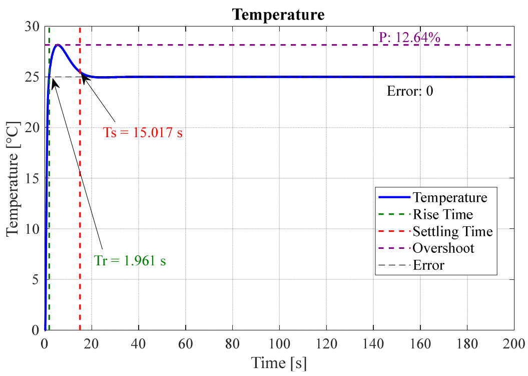

Fig. 15. *Temperature responses using the SBT PID controller in MATLAB.*

All outputs were generated using the calculated PID parameters listed in Table 2, based on the ZN, GG, CC, and SBT tuning methods.

Table 2 *Parameters of PID controller in a closed-loop system*

Method	K_P	K_I	K_D
ZN	42.3	11.566	38.678
GG	6	0.367	24.75
IMC	5.2928	0.6351	10.585
SBT	11.42	1.681	19.98

Table 3 provides a summary of the transient response parameters, including Rise time (T_r), Settling time (T_s), Overshoot (*PO*), Steady-state error (e(∞)), and ITAE, obtained for all four PID tuning methods.

Table 3 *Transient response parameters of the chemical process for various PID controller configurations*

	ZN	*GG*	*IMC*	*SBT*
T_r *[s]*	1.414	27.932	9.483	1.961
T_s *[s]*	19.816	63.844	15.985	15.017
PO[%]	180.18	0	0	12.64
e(∞)	0	0	0	0
ITAE	682.2	5921	1210	341.2

CONCLUSION

This paper examines temperature control in a typical chemical process and derives PID controller parameters using four distinct tuning methods: Ziegler-Nichols (ZN), Good Gain (GG), Internal Model Control (IMC), and Software-Based Tuning (SBT). System dynamics were simulated in both MATLAB and LabVIEW, with LabVIEW proving more effective for graphical signal tracing and MATLAB excelling in signal analysis. All obtained responses were stable with zero steady-state error. Among the methods, ZN yielded the fastest rise time, while IMC and SBT achieved the shortest settling times. Overshoot was eliminated using GG and IMC, and SBT produced the lowest ITAE value. Overall, IMC and SBT delivered the best transient performance, making them the preferred approaches for this application.

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