PROCESS CONTROL IN MAJOR CHEMICAL ENGINEERING UNIT OPERATIONS: REACTORS, DISTILLATION COLUMNS, AND HEAT EXCHANGERS

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Abstract
Process control is fundamental to ensuring safety, efficiency, and product quality in chemical engineering operations. This paper reviews control strategies for three major unit operations reactors, distillation columns, and heat exchangers focusing on their unique dynamic challenges, from nonlinearity and thermal sensitivity in reactors to multivariable interactions in distillation and transport delays in heat exchange. Through a systematic literature review of authoritative journals and textbooks, the analysis highlights the continued dominance of Proportional-Integral-Derivative (PID) control in industrial practice due to its simplicity and reliability. However, advanced strategies such as Model Predictive Control (MPC) are increasingly essential for handling complex, constrained, and interactive processes. The paper also discusses realistic implementation challenges and emerging trends, including digitalization, data-driven modeling, and Industry 4.0 integration, which are shaping the future of intelligent and autonomous process control systems(Tseng et al., 2021).

Keywords: Process control; PID control; Reactors; Distillation columns; Heat exchangers; Model Predictive Control (MPC); Industrial automation; Review.

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1. Introduction

Process control is the engineering discipline that ensures chemical manufacturing plants operate within specified parameters of safety, efficiency, and product quality(Myerson et al., 2015). Its implementation is not merely a technical enhancement but a fundamental requirement for the economic viability and environmental sustainability of the industry. This is especially true for three ubiquitous and critical unit operations: chemical reactors, distillation columns, and heat exchangers. These units are where core value reaction, separation, and energy transfer occurs, and their stable operation is paramount. Therefore, this review paper aims to synthesize current knowledge and strategies for controlling these major unit operations, providing a focused resource for both practitioners and academics.

The importance of process control stems from its direct impact on critical industrial outcomes. First and foremost is safety. Exothermic chemical reactors, for instance, can experience thermal runaway if temperature control fails, leading to catastrophic pressure build-up and potential explosions. Similarly, loss of pressure or level control in distillation columns can cause hazardous flooding or drying conditions.

Second, control is crucial for economic efficiency. Distillation columns are notoriously energy-intensive, often consuming 40-60% of a plant's total energy(Kiss & Smith, 2020). Precise control strategies can optimize the trade-off between product purity and energy consumption in the reboiler and condenser, yielding significant cost savings. In reactors, tight control of temperature and reactant feed rates maximizes yield and minimizes by-product formation. Third, consistent product quality is impossible without robust control, as fluctuations in process variables directly translate into variations in product specifications.

However, achieving optimal control is challenging due to inherent real-world industrial problems. These include: (1) Process Instability caused by nonlinear dynamics (e.g., Arrhenius dependence of reaction rates on temperature) and significant time delays in heat exchangers and measurement systems; (2) Energy Waste from suboptimal operation of distillation columns and heat exchanger networks; and (3) Integrated Safety Risks where a control failure in one unit can cascade into a plant-wide upset. These challenges are compounded by limitations in real-time measurement of key variables like composition and the presence of unmeasured disturbances.

To address these points, the scope of this review is deliberately focused on the application of control strategies to reactors, distillation columns, and heat exchangers(Harmsen, 2007). The paper will first outline fundamental control concepts before critically reviewing strategies ranging from the ubiquitous Proportional-Integral-Derivative (PID) control to advanced multivariable techniques like Model Predictive Control (MPC). This theoretical discussion will be grounded in industrial applications and case studies, highlighting practical implementations and performance outcomes. Finally, the review will discuss prevailing challenges and future trends, including the role of digitalization and data-driven methods. By structuring the discussion around these three pivotal units, this paper provides a concise yet comprehensive overview of a central theme in chemical process engineering(Charpentier, 2002).

2. Fundamental Concepts of Process Control

Process control is the application of control principles to maintain key operating variables in chemical processes within desired limits(Edgar, n.d.-a). Variables such as temperature, pressure, flow rate, level, and composition must be regulated to ensure safe operation, stable performance, and consistent product quality. Because chemical processes are continuously affected by disturbances, effective process control is essential to maintain reliable plant operation.

A process control system consists of the process, measurement devices, a controller, and final control elements(Edgar, n.d.-b). Sensors provide real-time measurements of process variables, which are compared to target values or set points in the controller. When deviations occur, the controller generates corrective actions that are implemented through actuators such as control valves or heaters to bring the process back to its desired condition. In control systems, controlled variables represent the quantities to be maintained, while manipulated variables are adjusted to influence them. Disturbances are uncontrollable changes, such as variations in feed conditions or utility supply, that can disrupt process stability. The main objective of process control is to reduce the impact of these disturbances on the controlled variables.

Chemical processes exhibit dynamic behavior, meaning their responses occur over time and often involve delays and nonlinear characteristics. These features are especially prominent in reactors, distillation columns, and heat exchangers, making control design more challenging. To address these challenges, feedback control is widely used, as it continuously corrects deviations based on real-time measurements(Baillieul & Antsaklis, 2007). In systems with multiple interacting variables, changes in one input can affect several outputs simultaneously(Gevrey et al., 2006). Understanding these interactions is important for selecting suitable control strategies and achieving stable operation. These fundamental concepts form the basis for the control methods discussed in the following sections

3. Review of Control Strategies

3.1. Proportional Integral Derivative

In engineering practice, PID control is one of the most important control systems and consists of proportional, integral, and differential (derivative) actions (Preuveneers & Ilie-Zudor, 2017). PID control has become a major technology in industrial control due to its excellent stability, simple structure, ease of tuning, and reliable operation. Based on the figure 3.1, the PID control system mechanism begins when the set-point value is compared with the actual process value at the summing junction (Σ), resulting in an error signal. This error is simultaneously processed by three control actions, namely proportional, integral, and derivative(Willis, n.d.). The proportional action generates a control signal proportional to the instantaneous error, the integral action accumulates the error over time to eliminate steady-state error, and the derivative action responds to the rate of change of the error to anticipate rapid variations. The outputs of the proportional, integral, and derivative actions are then summed at the second summing junction to produce the control signal. This control signal is used to regulate the process so that the output approaches the set-point. The process output is subsequently fed back into the system, allowing continuous correction until a stable operating condition is achieved.

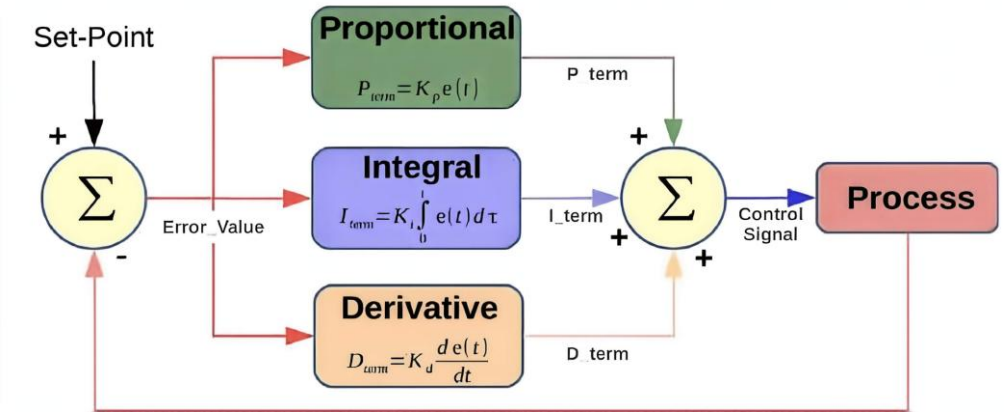


Figure 3.1 Systems with Proportional Integral Derivative Controller

The application of PID control is particularly beneficial when the designer does not fully understand the structure and parameters of the system under study, or when an accurate mathematical model is not available, making other control theories

difficult to apply(Fernandez-Cara & Zuazua, n.d.). Under such conditions, the structure and parameters of the controller are often determined based on experience and on-site tuning. Therefore, PID control techniques are highly suitable for systems that are not fully understood or when system parameters cannot be obtained accurately in a systematic manner. In practice, several variations of PID control are also widely used, with the most common classical forms being PI and PD control. A PID controller is a type of linear controller that generates a control signal based on the deviation between the set point and the actual output of the system. The PID control system is formed by a linear combination of the proportional, integral, and derivative components of the error signal. This controller is referred to as PID because it consists of these three main components. In the manufacturing industry, PID control plays a crucial role with its key applications in temperature, flow, pressure, speed, liquid level, quality, gas mixing, and mechanical positioning. By precisely adjusting production line speeds, maintaining constant temperature, pressure, and liquid levels, as well as achieving quality control, PID control contributes to improving production efficiency, product consistency, and system stability. In cases involving gas mixing and mechanical positioning control, PID control ensures accurate mixing ratios and precise positioning of mechanical equipment, further enhancing the competitiveness of the manufacturing industry and the reliability of production processes (Bhat, 2015).

3.2 Cascade Control

A typical configuration for cascade control is shown in figure (3.2), where an inner loop is originated from the introduction of an additional sensor in order to separate, as much as possible, the process fast and slow dynamics(Pérez et al., 2011). As a result, the control system configuration has an inner controller C2(s) with inner loop process G2(s) and outer loop controller C1(s) with outer loop process G1(s). Disturbance can entreat two possible distinct points: d1 and d2

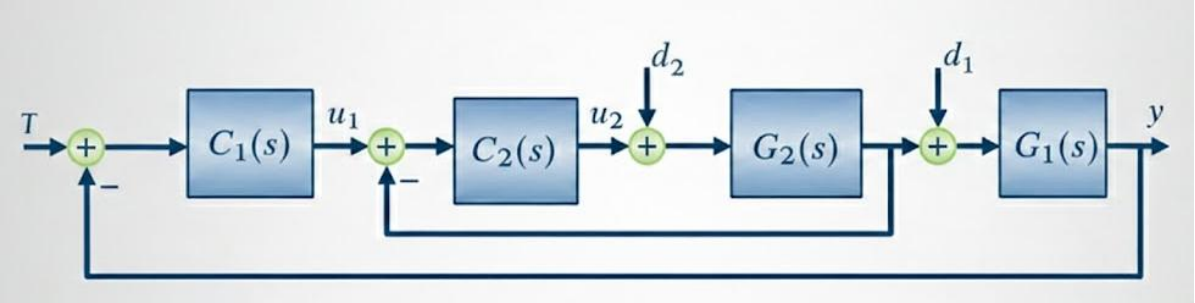


Figure 3.2 Systems Cascade Control

This configuration aims to compensate for disturbance d2 as quickly as possible before it affects the output of the outer loop. Therefore, the inner loop must exhibit faster dynamics to enable early disturbance compensation. Based on this requirement, the inner loop controller is designed as a regulatory controller that effectively rejects disturbance d2 while still maintaining the ability to track changes in the set point. When disturbance d1 occurs in the slow-dynamics part of the process, the outer loop controller responds by generating a varying set point for the inner loop(Sarkar, 2019).

In addition, the outer loop is responsible for compensating disturbances that are not detected by the inner loop as well as accommodating changes in the set-point input. Consequently, both the inner and outer loops particularly the inner loop are required to achieve good performance in both regulatory and servo modes.

3.3 Feed Forward Control

Feedforward control is a control strategy designed to anticipate the effects of disturbances on a process before they cause deviations in the controlled variable(Elliott & Sutton, 1996). Unlike feedback control, which reacts after an error has occurred, feedforward control operates by utilizing directly measurable disturbance information to perform corrective actions in advance. As illustrated in Figure 3.3, the feedforward control structure incorporates disturbance measurements directly into the control system, allowing corrective signals to be generated before the disturbance propagates through the process. In chemical engineering unit operations such as reactors, distillation columns, and heat exchangers, feedforward control is widely applied to handle disturbances arising from changes in feed conditions, flow rates, or inlet temperatures(Skogestad, n.d.). For example, in a heat exchanger, variations in inlet fluid temperature or flow rate can be promptly compensated through feedforward action, thereby maintaining the outlet temperature. Similarly, in distillation columns, disturbances due to fluctuations in feed composition can be anticipated before affecting product purity(Ammar Taqvi et al., 2019).

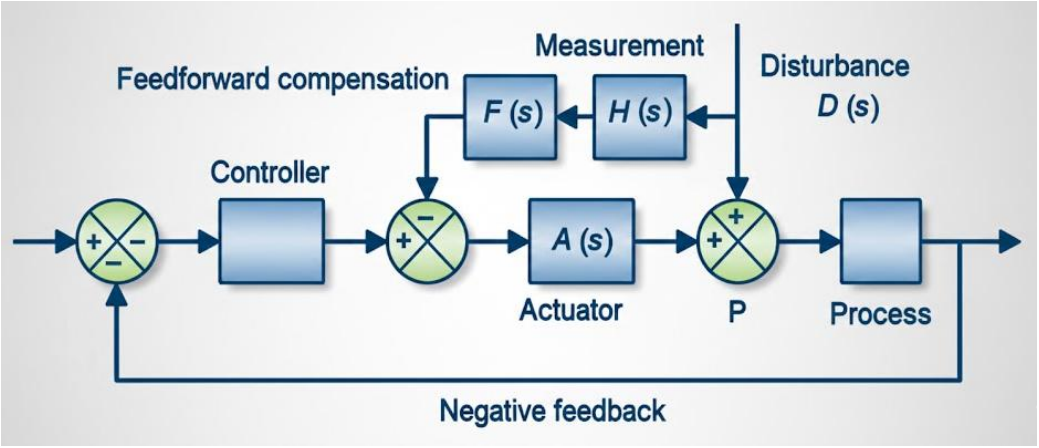


Figure 3.3 Systems Cascade Control

Feedforward control allows disturbances that can be measured to be compensated before they influence the controlled variable, leading to a quicker response and better process stability under changing operating conditions(Guzmán & Hägglund, 2024). However, its effectiveness depends on the accuracy of disturbance measurements and process models, and it cannot correct deviations once they have occurred; therefore, feedforward control is usually applied together with feedback control rather than used on its own.

3.4 Model Predictive Control

Model Predictive Control (MPC) is a class of advanced control methods that explicitly utilize a process model to predict the future behavior of a system(Schwenzer et al., 2021). Based on these predictions, MPC determines the optimal control action by solving an optimization problem that incorporates various operational constraints. As illustrated in Figure 3.4, the MPC framework consists of a prediction model, a cost function, and constraint handling, which together generate an optimal control sequence over a defined prediction horizon. MPC is one of the control strategies that directly accounts for system limitations, such as flow rate, temperature, pressure, and equipment capacity. MPC is also known as a receding horizon control method, in which only the first control action of the optimized sequence is implemented before the optimization is repeated at the next sampling instant (Y. Wang & Boyd, 2010). This concept implies that short-term predictive optimization can lead to optimal long-term performance, based on the assumption that prediction errors in the near future are relatively smaller than those associated with longer-term predictions. The integration of prediction and optimization is the key feature that distinguishes MPC from conventional control approaches, which generally rely on fixed control laws (Huang et al., 2023).

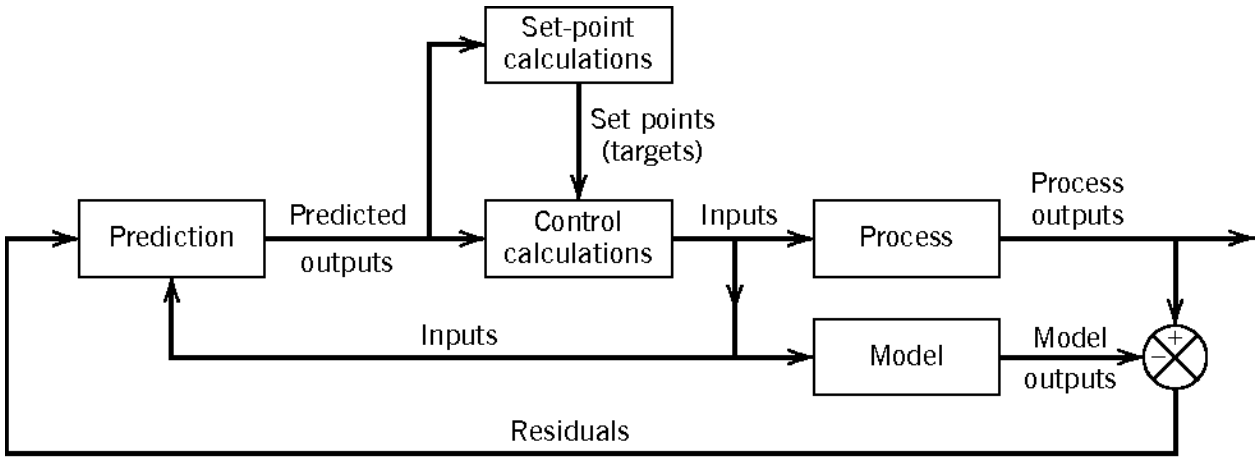


Figure 3.4 Model Predictive Control (Seborg et al., 2011)

The advantages of MPC include its ability to handle complex multivariable systems, consider interactions among process variables, and explicitly incorporate operational constraints, leading to more optimal and stable control performance. However, the disadvantages of MPC include the requirement for accurate process models, high computational complexity, and relatively higher implementation and maintenance costs compared to conventional controllers such as PID. (Veysi et al., n.d.)

4. Industrial Applications and Case Studies

4.1.1 Reactor Control

This case study examines the application of a Continuous Stirred Tank Reactor (CSTR) in continuous chemical industrial processes that require strict control of key operating variables(Vlahakis & Halikias, 2019). The CSTR is widely used in large-scale chemical production and is characterized by homogeneous liquid-phase reactions and dynamic operating conditions. In this context, the process variables analyzed include reactor temperature and pressure, as both play a crucial role in determining process stability, reaction conversion, and operational safety. Figure 4.1 illustrates the Piping and Instrumentation Diagram (P&ID) of a Continuous Stirred Tank Reactor (CSTR) equipped with temperature, pressure, and level control systems. Reactants A and B are fed into the reactor with controlled flow and pressure, while the reactor temperature is regulated using a reboiler to ensure stable operating conditions. The instrumentation shown is designed to maintain process stability and product quality during continuous operation. Figure 4.2 illustrates the block diagram of the CSTR control system, highlighting the interaction between the manipulated variables and the controlled variables used to regulate reactor temperature and pressure during operation. (Hasnain et al., 2024)

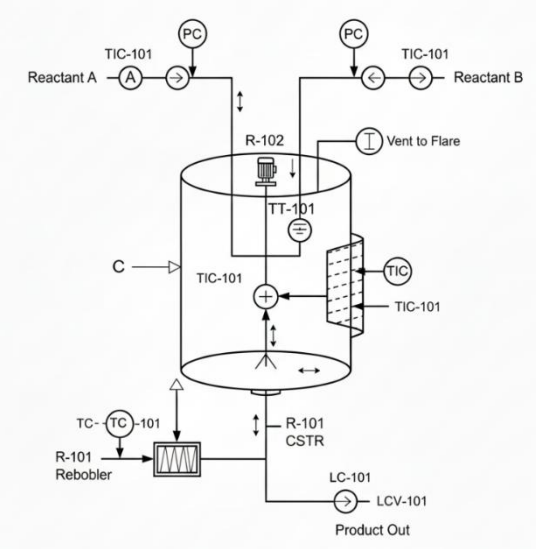


Figure 4.1 Reactor CSTR

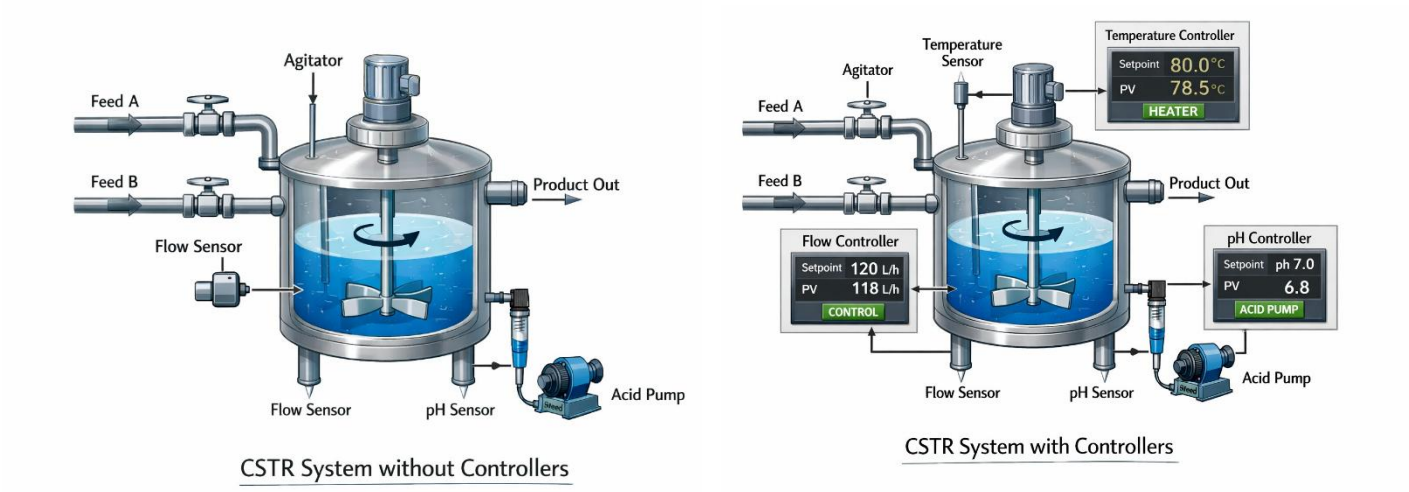


Figure 4.2 Continuous Stirred Tank Reactor (CSTR) and CSTR with Controller

In the reported case study, the CSTR is operated under specific conditions defined as the optimal process operating point. However, during operation, disturbances may occur, leading to deviations of temperature and pressure from their respective set points. Therefore, PID and PI-based control systems are implemented to restore the process variables to the desired operating conditions (Horbiichuk et al., 2025). Temperature control is achieved by regulating the flow rate of the heating medium supplied to the reactor, while pressure control is performed by adjusting the outlet valve to maintain the internal reactor pressure within safe limits.

The control system performance is evaluated by introducing controlled disturbances to the temperature and pressure set points and subsequently observing the reactor response. The performance indicators analyzed include the time required to reach steady-state conditions (response time), the magnitude of deviations from the set points, and the overall stability of the system during the transition to steady-state operation. To achieve optimal control performance, the controller parameters are tuned using experimental approaches and statistical optimization methods (Petrova & Dimitrov, 2025).

Based on the comparison presented in Table 4.1, which summarizes the operational and control performance reported in two different reactor-related journals, the results of the case study demonstrate that the implementation of an appropriate control system in a CSTR significantly enhances operational stability. The comparative analysis indicates that effective temperature control contributes to achieving high and consistent reaction conversion, as consistently observed in both referenced studies (H. Wang et al., 2025). Meanwhile, pressure control is shown to play a crucial role in maintaining reactor operational safety without exerting a significant impact on the quality of the produced output. Therefore, this case study confirms that the integration of CSTR operation with process control systems is an essential aspect of industrial reactor applications, particularly in ensuring safe, efficient, and sustainable operations (Alemede, 2025).

Table 4.1. Comparison of Temperature and Pressure Control Strategies for a CSTR Reactor

Comparison Aspect	PID Temperature Control	PI Pressure Control
Reactor Type	CSTR	CSTR
Control Objective	Maintain optimal reactor temperature	Maintain reactor pressure within safe limits
Controlled Variable (CV)	Reactor temperature	Reactor pressure
Manipulated Variable (MV)	Heating/Cooling medium flow rate	Outlet valve opening
Controller Type	PID	PI
Rationale for Selection	Fast response, reduced overshoot	Simple and stable structure
Process Characteristics	Nonlinear, highly temperature-sensitive	Dynamic but relatively stable
Disturbances	Feed temperature and flow rate changes	Feed flow rate and inlet pressure changes
Tuning Method	Experimental and optimization-based tuning	Response-based tuning
Performance Indicators	Response time, overshoot, stability	Settling time, pressure deviation
Main Results	Stable temperature and improved conversion	Safe and stable pressure control
Advantages	Flexible and responsive control	Easy implementation
Limitations	Sensitive to tuning parameters	Limited for large disturbances
Literature Source	Nasrul ZA et al.(Z.A et al., 2019)	Damanik et al.(Damanik et al., 2020)

4.1.2 Control of Distillation Columns

Distillation columns are widely applied unit operations in the chemical, petrochemical, and petroleum industries for separation and product purification processes(Kiss, 2014). Figure 4.3 illustrates the Piping and Instrumentation Diagram (P&ID) of a distillation column system equipped with a condenser, reflux accumulator,

and reboiler. The column (T-101) operates with temperature, flow, pressure, and level control loops to maintain stable separation performance. The overhead vapor is condensed in the condenser (E-101) and collected in the reflux accumulator (D-101), where part of the condensate is returned to the column as reflux, while the remaining stream is withdrawn as the overhead product. The bottom section is heated by the reboiler (R-101) using steam to generate vapor flow within the column, and the bottoms product is controlled through a level control valve. The instrumentation shown ensures effective control of temperature, flow rate, pressure, and liquid level throughout the distillation process. Based on numerous previous studies, the control of distillation columns remains a major challenge in industrial operations due to their multivariable (MIMO) nature, nonlinear behavior, the presence of significant dead time, and high sensitivity to disturbances and operating condition variations. These characteristics necessitate the implementation of appropriate control strategies to ensure process stability and consistent product quality

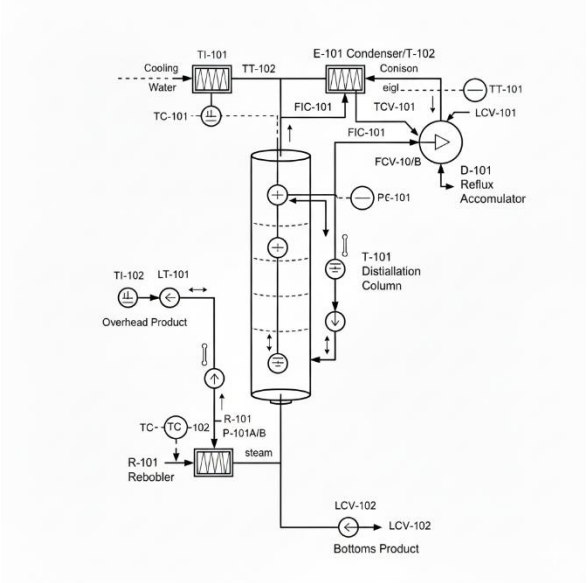


Figure 4.3 Distillation Column

Several previous studies have employed the Wood and Berry MIMO 2×2 distillation column model as a representation of industrial distillation column dynamics (Mittal et al., 2023). This model describes the interaction between two manipulated variables, namely the reflux flow rate and the reboiler steam flow rate, and two controlled output variables, which are the top product composition (XD) and the bottom product composition (XB). The MIMO 2×2 configuration is widely used because it effectively represents the interaction among process variables commonly encountered in industrial distillation columns and the associated difficulties in maintaining product composition at the desired set points. Figure 4.4 presents the block diagram of the MIMO 2×2 distillation column system, illustrating the interaction between the manipulated variables and the controlled outputs as well as the coupling effects that influence control performance (Kim et al., 2022).

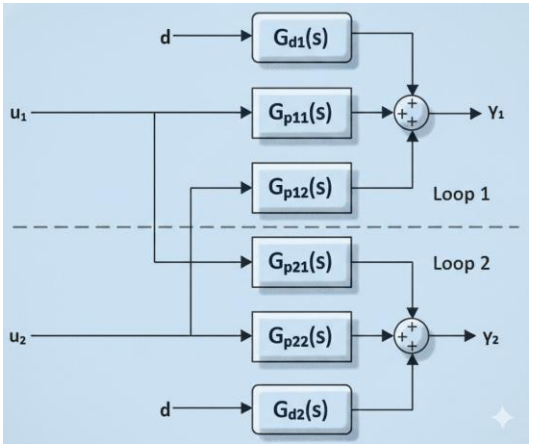


Figure 4.4 Block Diagram of MIMO 2×2 Interaction

In previous studies, variations in product composition set points as well as disturbances in the form of feed flow rate changes have been employed to evaluate the performance of control systems (Hussain et al., 2023). To address the issues of interaction among control loops and the presence of dead time, several control approaches have been applied, including Internal Model Control (IMC) and its developments such as IMC-PID and fuzzy gain scheduling IMC-PID as shown in Figure 4.3. The IMC approach is commonly combined with First Order Plus Dead Time (FOPDT) modeling and Relative Gain Array (RGA) analysis to minimize interactions among variables in MIMO systems (Divakar et al., 2024).

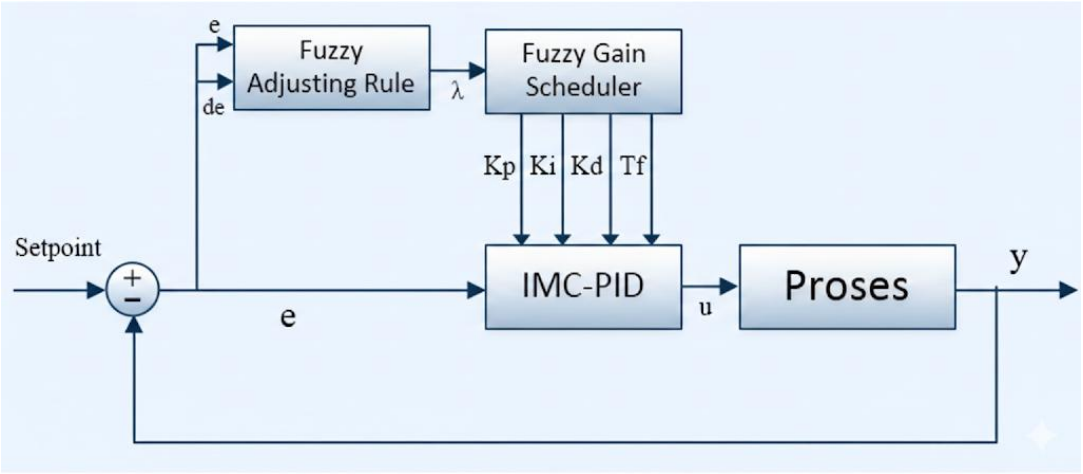


Figure 4.5 Fuzzy Gain Scheduling-Based IMC-PID Control System

Based on the comparison presented in Table 4.2, which highlights the key findings from two journals discussing distillation column control, the results of previous studies indicate that the implementation of IMC-based methods and their developments is capable of improving system response to set point changes, reducing overshoot, and decreasing the integral absolute error (IAE) values. The comparative evaluation shows consistent improvements in control performance across both studies, particularly in terms of dynamic response and stability (Sultana, 2023). These improvements contribute to enhanced operational stability, energy efficiency, and product quality, thereby indicating that IMC-based control methods are highly relevant for application in industrial distillation column control systems.

Table 4.2 Comparison of Control Strategies for Distillation Columns Based on PreviousStudies

Comparison Aspect	IMC-Based Control of a MIMO Distillation Column	Fuzzy Gain Scheduling IMC-PID Control for Industrial Distillation Columns
Object of Study	Binary distillation column represented by the Wood and Berry MIMO 2×2 model	Binary distillation column using the Wood and Berry MIMO 2×2 benchmark model
Control Objective	Maintaining top and bottom product composition at desired set points	Improving product composition control under disturbances and set point changes
Process Characteristics	Multivariable (MIMO), nonlinear system with significant dead time and loop interactions	MIMO system with strong variable interaction, dead time, and dynamic disturbances
Manipulated Variables	Reflux flow rate and reboiler steam flow rate	Reflux flow rate and reboiler heat input
Controlled Variables	Top product composition (XD) and bottom product composition (XB)	Distillate composition (XD) and bottoms composition (XB)
Control Strategy	Internal Model Control (IMC) and IMC-PID	Fuzzy Gain Scheduling IMC-PID
Process Model	First Order Plus Dead Time (FOPDT)	First Order Plus Dead Time (FOPDT)
Interaction Analysis	Relative Gain Array (RGA) analysis applied	RGA analysis combined with fuzzy-based gain adjustment
Disturbance Considered	Feed flow rate variation	Feed flow rate variation and set point changes
Performance Indicators	Overshoot, settling time, and Integral Absolute Error (IAE)	Overshoot reduction, faster settling time, and lower IAE
Key Findings	IMC-based control improves system stability and reduces interaction effects	Fuzzy gain scheduling enhances robustness and dynamic response compared to conventional IMC-PID
Literature Source	(Wara & Setiyono, n.d.)	(Pambudi & Setiyono, n.d.)

4.1.3 Heat Exchanger Control

This journal discusses a case study on the process control of a shell-and-tube heat exchanger applied in chemical process industries (Kumar & Yadav, n.d.). The heat exchanger operates as a critical thermal unit where maintaining a stable outlet temperature is essential for downstream process performance. In this system, the outlet temperature is defined as the controlled variable, while the flow rate of the heating medium is selected as the manipulated variable. Variations in inlet temperature, flow rate, and operating conditions act as process disturbances that may affect system stability (Yang et al., 2022).

The temperature control strategy applied in this case study is based on a feedback control system (X. Li & Yu, 2022). The schematic of the heat exchanger temperature control system is presented in Figure 4.6, which illustrates the relationship between the controlled variable, the manipulated variable, and the control elements employed. The outlet temperature of the heat exchanger is measured using a temperature sensor and compared with the specified set point (Herbinger & Groulx, 2022). The difference between the actual temperature and the set point is subsequently processed by a Proportional–Integral–Derivative (PID) controller to generate a control signal that regulates the opening of the control valve in the heating medium flow. This feedback mechanism enables the system to continuously correct temperature deviations caused by process disturbances during operation (Z. Li et al., 2023).

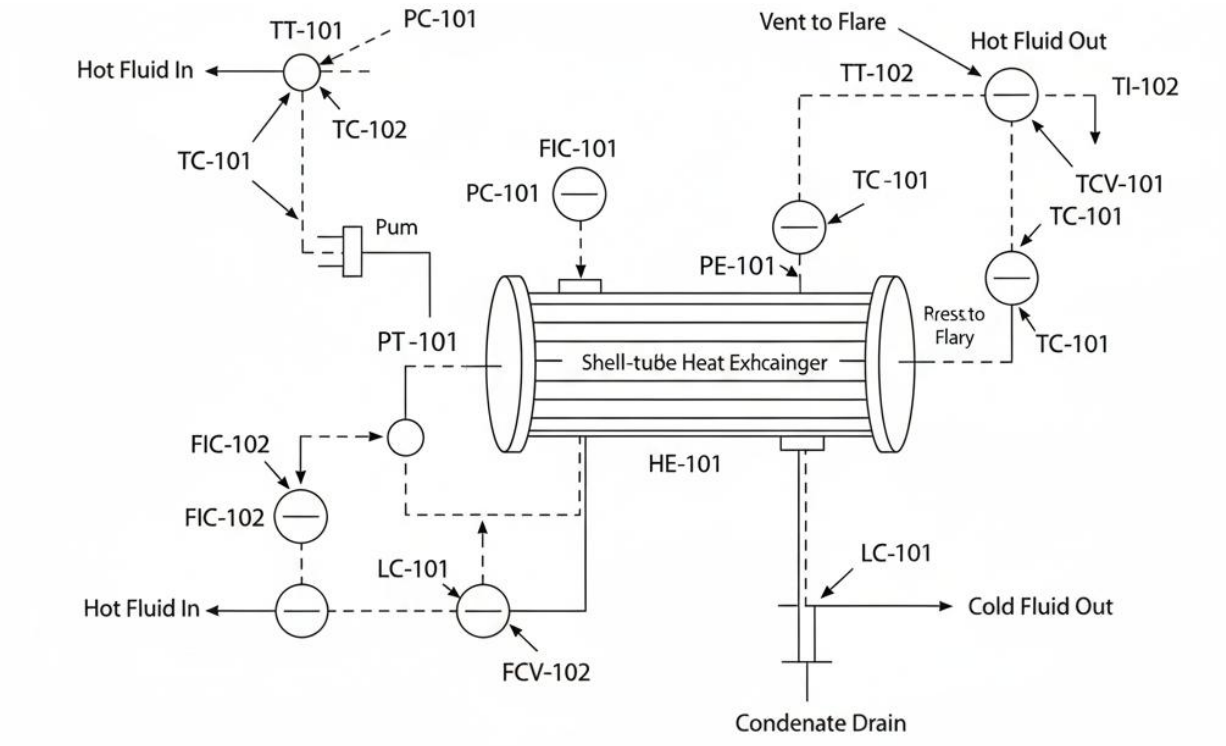


Figure 4.6 Feedback temperature control system of a shell-and-tube heat exchanger using a PID controller.

In addition to feedback control, the control structure is developed based on a dynamic process model of the heat exchanger (F. Zhang et al., 2024). The modeling procedure begins with a steady-state representation and is subsequently extended to a

dynamic model to capture the transient behavior of the system. Controller parameters are determined through a tuning process to achieve satisfactory closed-loop performance, including fast response time, minimal overshoot, and stable operation (Myerson et al., 2015).

The performance of the control system is evaluated by introducing step changes in the temperature set point and observing the closed-loop response (Liang & Zhao, 2023). Performance indicators such as rise time, settling time, steady-state error, and system stability are analyzed to assess controller effectiveness. The influence of control valve action on energy consumption is also considered as part of the control performance evaluation (X. Zhang et al., 2022).

Based on the comparison presented in Table 4.3, which summarizes the findings of two journals discussing heat exchanger control performance, the results indicate that the implementation of a properly tuned PID-based feedback controller significantly improves temperature regulation in the heat exchanger. The comparative analysis shows consistent agreement between the reported studies, where the control system effectively compensates for process disturbances and enhances operational stability (Tarek & Paran, 2024). Therefore, this case study demonstrates that feedback temperature control is a reliable and practical approach for heat exchanger operation in chemical process industries, contributing to improved efficiency, safety, and overall process reliability (Osintsev et al., 2023)

Table 4.3 Comparison of temperature control systems for heat exchangers

Comparison Aspect	PID Temperature Control	Advanced / Enhanced Control Strategy
Equipment Type	Shell-and-Tube Heat Exchanger	Shell-and-Tube Heat Exchanger
Control Objective	Maintain outlet temperature at the desired set point	Improve temperature stability and energy efficiency
Controlled Variable (CV)	Outlet temperature	Outlet temperature
Manipulated Variable (MV)	Heating or cooling medium flow rate	Heating/cooling medium flow rate
Controller Type	PID controller	PID with feedforward / enhanced control
Rationale for Controller Selection	Simple structure and ease of implementation	Better disturbance rejection and dynamic performance
Process Characteristics	Dynamic system with time delay	Dynamic system with disturbances and nonlinear behavior
Analyzed Disturbances	Inlet temperature and flow rate variations	Inlet temperature, flow rate, and load changes

Tuning Method	Conventional or experimental tuning	Optimized or adaptive tuning
Performance Indicators	Response time, overshoot, steady-state error	Reduced overshoot, faster settling time
Main Results	Stable temperature control under nominal conditions	Improved robustness and temperature stability
Advantages	Simple, reliable, and widely used	Higher control performance and efficiency
Limitations	Limited performance under large disturbances	Higher implementation complexity
Literature Source	(Maulinda et al., 2019)	(Santoso, n.d.)

5. Challenges and Future Trends

Despite the extensive use of reactors, distillation columns, and heat exchangers in chemical process industries, effective process control implementation remains challenging due to nonlinear behavior, process interactions, and sensitivity to disturbances. These characteristics require reliable control strategies to maintain operational stability, product quality, and process safety (Tewari, 2023).

In reactor systems, particularly CSTR, control challenges are mainly associated with temperature and pressure sensitivity, especially in exothermic reactions. Conventional PID controllers may exhibit limited performance under large disturbances and varying operating conditions, indicating the need for more robust and adaptive control approaches.

For distillation columns, the multivariable (MIMO) structure, strong loop interactions, and dead time significantly complicate control performance. Variations in feed conditions can lead to deviations in product composition, making simultaneous control of top and bottom products difficult. Advanced control strategies such as IMC, IMC-PID, and intelligent control methods have been developed to address these challenges, although practical implementation still faces model and tuning constraints (Divakar et al., 2024).

In heat exchangers, control challenges arise from external disturbances, time delays, and changes in heat transfer characteristics. Conventional feedback temperature control may be insufficient under dynamic conditions, particularly when energy efficiency is also a critical objective (Z. Li et al., 2023).

Future trends in process control are closely related to digitalization and Industry 4.0, including the adoption of advanced sensors, real-time data integration, and intelligent control techniques such as Model Predictive Control and data-driven approaches. These developments are expected to enhance control performance, energy efficiency, and operational sustainability in industrial process systems .

6. Conclusions

Based on the discussions and case studies presented, it can be concluded that process control plays a crucial role in maintaining operational stability, product quality, and safety in major chemical industry units, including reactors, distillation columns, and heat exchangers. The dynamic and nonlinear characteristics of these processes, along with the presence of disturbances and interactions among variables, highlight the importance of implementing appropriate and reliable control strategies in industrial operations.

The results of the study indicate that conventional control methods such as PID controllers are still widely applied due to their simplicity and ease of implementation. However, for systems with higher complexity, such as distillation columns, as well as for processes with high sensitivity, such as CSTR reactors and heat exchangers, conventional control approaches exhibit limitations in handling disturbances and variations in operating conditions. Therefore, the application of advanced control strategies, including Internal Model Control (IMC), IMC-PID, fuzzy-based control, and other intelligent control methods, is considered relevant to improve control performance.

Overall, the integration of process units with effective control systems contributes significantly to improved operational stability, energy efficiency, and process reliability. Furthermore, future developments in process control are expected to focus on the adoption of digitalization and Industry 4.0 concepts, such as real-time data integration, smart sensors, and model-based or data-driven control approaches, to support safe, efficient, and sustainable chemical industry operations.

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