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A REVIEW OF PID CONTROL DESIGN AND PERFORMANCE EVALUATION FOR DISTILLATION COLUMNS

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ABSTRACT

Distillation column operations represent one of the most common industrial processes, which face difficulties due to the dynamics of the system, process delay, nonlinearity, and multi-loop interconnection. Proportional–Integral–Derivative (PID) controllers are still relevant for regulation of process variables such as temperature, pressure, composition, level, and flow because of their simplicity and practicability. This review focuses on the dynamic characteristics of PID control applied to distillation columns and the fundamentals of PID control in terms of controlled and manipulated variables, objectives of control, and multi-loop interconnection. Important techniques of PID controller design include Ziegler–Nichols, Internal Model Control (IMC), Skogestad, relay/automatic, and interaction aware multiloop techniques. Performance of PID controllers is analyzed in terms of set point tracking, disturbance rejection, overshoot, settling time, IAE, ISE, ITAE, robustness, and control energy. Some of the main challenges related to nonlinearity of the process, process delay, process slowness, noise in measurements, actuator saturation, and operating point changes are highlighted. Overall, the review provides an integrated perspective on PID controller design, tuning, performance evaluation, current challenges, and future developments for efficient and stable distillation-column operation.

Keywords: PID Control; Distillation Columns; Controller Tuning; Process Control; Performance Evaluation; Robust Control.

1. INTRODUCTION

Distillation is a separation technique employed extensively across various industries such as chemicals, petrochemicals, pharmaceuticals, and food industries [1]. Distillation towers have complex dynamic characteristics because of the presence of process lags, nonlinear characteristics, high residence times, and interactions between various process variables. Consequently, proper control of distillation systems is important for ensuring process stability and safety.

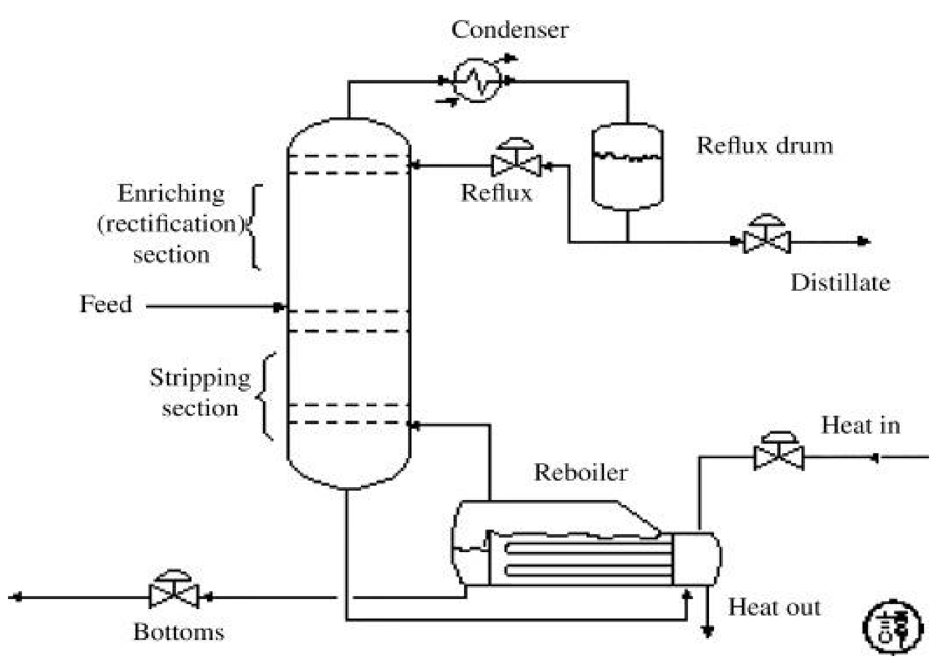

Figure 1: Distillation Columns [2]

The importance of the PID control strategy in industry is owing to its simplicity in design and implementation. PID control in distillation column applications typically includes the control of temperature, pressure, concentration, liquid level, and flows. Various issues like dead time, interrelated loops, measurement noise, actuator constraints, and varying process conditions can influence the performance of the PID controllers [3].

In order to overcome such issues and improve control performance, several PID controller tuning techniques have been proposed. These include Ziegler-Nichols, IMC, Skogestad, relay/auto-tuning, and interrelated techniques. This review article evaluates these control design and tuning techniques together with performance criteria like set-point following, disturbance rejection, overshoot, settling time, integral performance criteria, robustness, and control energy, among others [4].

1.1 Review Objectives

The main objectives of the present review are:

- To examine the dynamic characteristics and fundamentals of PID control in distillation columns.
- To review major PID tuning strategies and their applications in distillation-column control.
- To evaluate PID performance measures, key challenges, research gaps, and emerging control approaches.

2. REVIEW METHODOLOGY

This current study used the integrative literature review method to evaluate available literature on the design and analysis of performance of PID for distillation column control systems [5]. The literature was arranged based on the following themes; dynamics of distillation column, basics of PID, choice of variables, control objectives, multi-variable interactions, major tuning methods including Ziegler-Nichols, IMC, Skogestad, and automatic/relay tuning. Measures of performance included set point tracking, disturbance rejection, overshoot, settling time, IAE, ISE, ITAE, robustness, and control effort. The review also considered practical problems in the field as well as new methods of control including nonlinearity, dead time, loop interactions, constrained control, adaptive control, robust control, and data-based tuning. The available information was thematically analysed and synthesised to identify key practices, limitations, research gaps, and future perspectives in PID-based distillation-column control [6].

3. DISTILLATION COLUMN DYNAMICS AND PID CONTROL

Distillation columns are highly dynamic and interactive processes depending on mass balance, energy balance, vapor-liquid equilibrium, distillation operation, feed, condenser, and reboiler operations. The time lag, nonlinearity, time delay, and variable interactions present in distillation columns pose challenges to efficient control [7]. It becomes important to understand the dynamics of the distillation column, choice of variables, objective of control, and interaction between loops.

3.1 Dynamic Characteristics of Distillation Columns

Most distillation columns tend to be characterized by sluggish dynamics, delays, nonlinearity, and interaction between process variables. Fluctuations in the feed flow rate, change in reflux ratio, and reboiling duties have an impact on both distillate and bottom streams [8]. First-order-plus-dead-time models are some of the simplest models used in controller design.

3.2 PID Controller Fundamentals

The PID controller controls the process based on the deviation between the setpoint and measured values. The proportional term reacts instantly, while the integral term compensates for the steady state error, and the derivative term reacts to change in error [9]. It is essential that the parameters be tuned properly and with derivative filter and anti-windup actions.

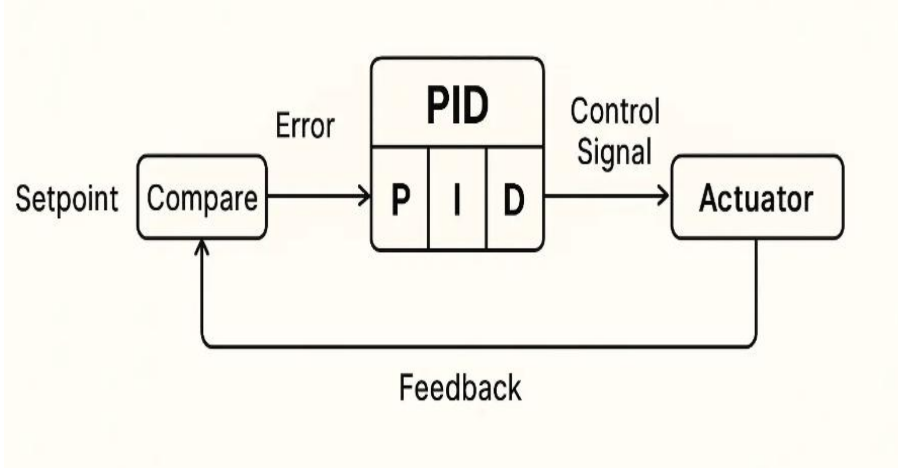

Figure 2: PID Control System [10]

3.3 Controlled and Manipulated Variables

Some of the common controlled variables are temperature, composition, pressure, level, and flow rate, whereas some of the manipulated variables are reflux rate, distillate flow rate, steam input to the reboiler, and heat duty. Proper association between variables is necessary to maintain stability and prevent loop interactions [11].

3.4 Control Objectives

The key aim of the PID control system is ensuring the stability of the column operation and quality of the output product. The controller needs to negate any disturbance caused due to variations in the feed properties, pressure, flow, and utilities without causing any overshoot or unnecessary efforts in control action. Thus, response speed, robustness, disturbance rejection, and actuator movement are important considerations.

3.5 Multivariable Interactions

Distillation columns have many interaction control loops where one MV can impact several CVs. In such a way, changing the reflux could impact overhead and bottoms composition. The RGA analysis can provide good variable pairing and also interaction management techniques such as decoupling, cascading, and feedforward can be utilized [12].

4. PID CONTROL DESIGN AND TUNING STRATEGIES

The process of designing and tuning the PID controller is crucial in order to get stable and satisfactory control of the distillation column [13]. Since the dynamics of distillation operations are relatively slow, the presence of dead time, nonlinearity, and inter-loop interaction, the choice of tuning procedure impacts the quality of setpoint regulation and disturbances rejection, as well as robustness and control action. Major approaches range from classical empirical methods to model-based and automatic tuning strategies [14].

4.1 Classical Ziegler–Nichols Tuning

The Ziegler–Nichols method is a classical technique for obtaining PID tuning constants based on the process response or ultimate gain characteristics [15]. Due to its simplicity, it is often applied for benchmarking purposes. However, in cases where a process has a large delay time or interaction, it may give aggressive responses or even oscillations.

4.2 IMC-Based PID Tuning

Internal Model Control (IMC)-based PID tuning uses a simplified process model to calculate PID constants and the response of the closed loop [16]. There is a tuning constant that allows adjusting the response time and robustness of the controller, which makes IMC appropriate for delayed processes with uncertain models.

4.3 Skogestad Tuning

Skogestad tuning uses simplified analytical relations and lower order process models to get a practical PI or PID tuning constants. It gives a compromise between the fast response and robustness of the closed loop.

4.4 Relay/Automatic Tuning

Automatic tuning based on relays detects process characteristics using excitation and reaction. This method eliminates manual adjustments and may be useful during commissioning and retuning. Still, the excitation should be limited by the safe operating area to prevent any unacceptable process variations [17].

4.5 Multiloop and Interaction-Aware Control

The distillation column consists of multiloops that are interconnected. The change of the reboiler or reflux ratio affects many controlled variables at the same time. The interaction-based approach takes into account the coupling between the variables and uses RGA analysis, decoupling, cascade, and feedforward approaches [18].

Table 1: Comparison of Major PID Control Design and Tuning Strategies for Distillation Columns [19]

Tuning strategy	Main principle	Major advantage	Major limitation	Suitability for distillation
Ziegler–Nichols	Empirical process or ultimate-response characteristics	Simple and easy to implement	May produce aggressive response and overshoot	Useful for initial tuning and benchmarking
IMC-based PID	Process model and desired closed-loop response	Provides a clear speed–robustness trade-off	Requires an adequate process model	Suitable for processes with delay and uncertainty
Skogestad tuning	Simplified analytical rules using reduced-order models	Practical and relatively simple	Model reduction may overlook complex dynamics	Useful for practical distillation-loop tuning
Relay/automatic tuning	Process excitation and response identification	Reduces manual tuning effort	Excitation must remain within safe operating limits	Useful for commissioning and retuning
Multiloop/interaction-aware control	Considers loop interaction and variable pairing	Addresses coupled column behaviour	More complex design and analysis	Important for strongly interacting distillation systems

As per the comparison made in Table 1, it can be seen that each of the above techniques has its own basis and requirement [20]. Classical methods are simple, model-based techniques give more control on the robustness factor, and automatic methods minimize the efforts in tuning. For columns with large interaction between variables, tuning should take into account the overall structure of the control loop.

5. PERFORMANCE EVALUATION OF PID-CONTROLLED DISTILLATION COLUMNS

Evaluation of performance plays a key role in assessing PID tuning both in normal and disturbed conditions. The following criteria have been applied in the evaluation of performance in distillation columns: set point tracking, disturbance rejection, transient behavior, accumulation of error, robustness and control effort [21].

- ***Set-Point Tracking***

Set point tracking reveals the ability of the controller to achieve and maintain the desired process variable. The criteria used for assessing sets point tracking include rise time, settling time, overshoot, and steady state error while ensuring minimal oscillations and control actions.

- ***Disturbance Rejection***

Disturbance rejection is related to the ability of the controller to minimize the effects of disturbance due to feed flow rate, feed composition, pressure, temperature, utility changes. Effective PID control will be able to bring the process variable to its desired level within an acceptable period [22].

- ***Overshoot and Settling Time***

Overshoot is defined as the maximum overshoot while settling time is the time taken for the response to stay within a certain range. They play a significant role in comparing transient behavior of various PID tuning algorithms.

- ***IAE, ISE and ITAE***

Integral error index measures the performance of control systems quantitatively. IAE measures the accumulation of absolute error while ISE and ITAE give more weight to larger error values and errors lasting for long periods respectively. They can be used for comparing various tuning techniques [23].

- ***Robustness and Control Effort***

Robustness is concerned with the ability of the controller to maintain acceptable performance levels under changes of the process or model parameter. Control effort is also crucial in this case as it helps in reducing valve movements which might increase process variability. Both factors should therefore be considered during evaluation.

Table 2: Summary of Selected Studies on PID and Advanced Control of Distillation Processes [25]

Reference	Focus of Study	Key Findings
Kramer & Morgado-Dias (2018) [26]	Applications of artificial neural networks in process control	Reviewed ANN-based process-control applications and highlighted their potential for handling complex and nonlinear process behaviour.
Mohammad et al. (2026) [27]	PID and Fuzzy-PID for steam-temperature control in a small distillation tank	Compared PID and Fuzzy-PID control approaches for steam-temperature regulation and evaluated their control performance.
Flores-Gómez et al. (2025) [28]	Fractional controllers for an extractive distillation column	Assessed fractional-order control performance and examined its applicability to improving control of an extractive distillation process.
Çağatay & Karacan (2022) [29]	Nonlinear GPC and discrete-time PID for reactive distillation	Experimentally compared nonlinear GPC and discrete-time PID for multivariable temperature control in biodiesel reactive distillation.
Piltan (2018) [30]	Multivariable filter-decoupling-based PID-like fuzzy control	Proposed an intelligent PID-like fuzzy control approach with filter-based decoupling for an uncertain distillation column.

Comparative Evaluation of Tuning Methods

Different tuning methods result in different levels of response, stability, rejection of disturbances, and energy used. To be able to compare the different approaches, the same process conditions, step change of set point, disturbance, and evaluation criteria should be considered for each approach.

6. CONCLUSION

This review concludes that PID control remains a practical and important approach for maintaining stable and efficient operation of distillation columns, particularly for controlling temperature, pressure, composition, level, and flow. The review demonstrates that successful PID control requires a clear understanding of the dynamic characteristics of distillation columns, appropriate selection of controlled and manipulated variables, consideration of multivariable interactions, and suitable controller tuning. Different tuning strategies, including Ziegler–Nichols, IMC-based, Skogestad, relay/automatic, and interaction-aware approaches, provide different means of achieving satisfactory control depending on process dynamics and operating requirements. The review further demonstrates that PID performance should be evaluated using multiple criteria, including set-point tracking, disturbance rejection, overshoot, settling time, IAE, ISE, ITAE, robustness, and control effort, rather than relying on a single performance measure. It also identifies nonlinear behaviour, dead time, slow dynamics, strong loop interactions, measurement noise, actuator constraints, and operating-point variations as important challenges that can limit conventional PID performance. It also identifies nonlinear behaviour, dead time, slow dynamics, strong loop interactions, measurement noise, actuator constraints, and operating-point variations as important challenges that can limit conventional PID performance.

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