BINARY DISTILLATION COLUMN CONTROL TECHNIQUES

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Abstract. The purpose of this study is to propose the best control strategy for the binary distillation column. The control process is simulated on Matlab Simulink. Traditional controller settings including P, PI and PID are put to comparison. PI is found to result in a control superior to P and PID. The study finds that IMC tuning parameters relatively improves the PI controller response and robustness.
Key words: binary distillation column control, Matlab, P, PI and PID controllers

Annotatsiya. Ushbu tadqiqotning maqsadi ikkilik rektifikatsiya kalonnasi uchun eng yaxshi nazorat strategiyasini taklif qilishdir. Boshqarish jarayoni MATLAB Simulink-da simulyatsiya qilingan. An'anaviy kontroller sozlamalari, shu jumladan P, PI va PID taqqoslash uchun qo'yiladi. PI, P va PID dan ustun bo'lgan boshqaruvga olib keladi. Tadqiqot shuni ko'rsatadiki, IMC sozlash parametrlari PI tekshirgichining javobini va mustahkamligini nisbatan yaxshilaydi.
Kalit so'zlar: ikkilik rektifikatsiya kalonnasini boshqarish, Matlab, P, PI va PID regulyatorlari

Аннотация. Цель данного исследования - предложить наилучшую стратегию управления бинарной ректификационной колонной. Процесс управления моделируется в среде Matlab Simulink. Для сравнения используются традиционные настройки контроллера, включая P, PI и PID. Установлено, что PI обеспечивает более эффективное управление, чем P и PID. Исследование показало, что параметры настройки IMC относительно улучшают отклик и надежность PI-контроллера.
Ключевые слова: управление бинарной ректификационной колонной, Matlab, P, PI и PID-контроллеры

Introduction

An introductory will define and briefly explain the distillation process and control, and the topic control strategies. This study focuses on the performance of different control strategies named PID and MPC. An experiment based on binary distillation column will be simulated. The purpose of the control loop is to maintain the overhead and bottom product composition against disturbances. Step change in the required product purity will be introduced to investigate the control response. Control loop is designed and controllers are tuned to optimize performance. References for the design and tuning procedures for PID and MPC are explained. Matlab Simulink is utilized to simulate the process and test the controllers.

Materials and Methods

Among the technologies available for separation, distillation continues to the most commonly applied technology due to the simplicity and applicability of its principle of operation besides the high viability and low cost compared to other alternative separation process [1]. 95% of industrial separation systems implies distillation according to [2]. Distillation processes industrially take place in distillation columns where components of a mixture are separated based on the difference in volatilities. Distillation columns are said to be the least costly equipment for liquid separation as long as the ratio of volatilities of the feed composing components is at least 1.1 [3]. These columns can be classified according to the process operation, feed mixture nature, internal configuration as well as some other criteria.

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- Batch or continuous process,
- Binary or multi-component feed mixture,
- And tray or packed column.

The distillation column operates at a specific temperature and pressure and separates the two components of the mixture (Feed) such that the concentration of the light key is increased in the top product (Distillate) and decreased in the bottom product (Bottoms) whereas the opposite for the heavy key. A simple common example is a continuous binary distillation column separating a mixture of Methanol and Water. Methanol in this example is termed the "light key" because of its higher volatility as it boils at 64.7 °C compared to Water "heavy key" which boils at 100 °C in atmospheric pressure.

The following notations are commonly used, and will be used throughout this work, to describe the streams and compositions around a distillation column:

F: The molar flow rate of the feed stream;
D: The molar flow rate of the distillate (top product);
L: The molar flow rate of the reflux;
B: The molar flow rate of the bottoms (bottom product);
V: The molar flow rate of the boil-up;
Z_L: The mole fraction of the light key in the feed stream;
Z_H: The mole fraction of the heavy key in the feed stream;
Y_L: The mole fraction of the light key in the top vapor stream;
Y_H: The mole fraction of the heavy key in the top vapor stream;
X_L: The mole fraction of the light key in the bottom liquid stream;
X_H: The mole fraction of the heavy key in the bottom liquid stream.

A typical binary distillation column is illustrated in Figure 1.The column is utilized with a total condenser which liquefy the overhead vapor stream into a receiving drum. The condensed stream is then partially drawn as distillate (D) while part of the liquid is sent back to the distillation column as reflux (L) for control and purity enhancement purposes. Similarly, a reboiler vaporizes part of the liquid bottom steam to provide the boilup (V) flowing up through the distillation column and the rest of the liquid is drawn as bottoms product (B).

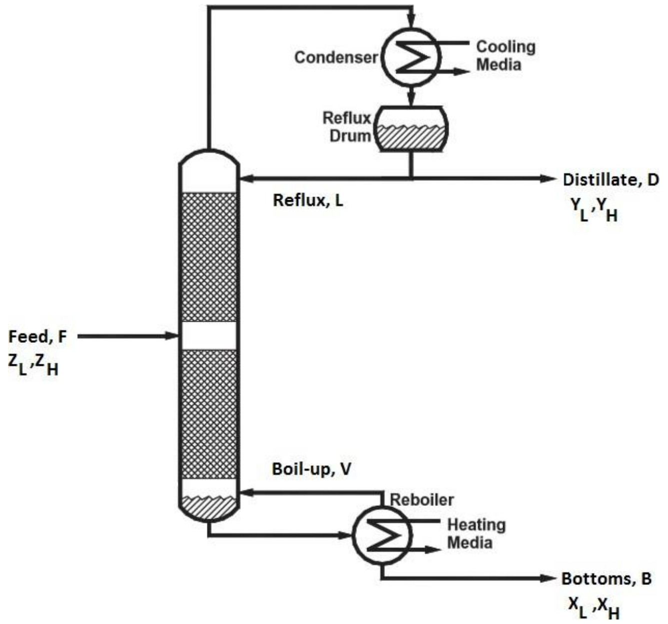

Fig.1. Basic Diagram of Distillation.

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A distillation process aims to produce products of an acceptable purity with regard to the plant requirement. Thus, control strategy must be well designed and tailored for any particular column. In contrast to the high viability of this technology, its control is quite a complex task mainly because of the inherent nonlinear behavior of distillation being a MIMO, multiple-input-multiple-output, process. Interaction between controlled variable which requires presence of decouplers especially in the case of dual composition control. Moreover, severity of disturbances adds up to the complexity of distillation columns control problems.

In practice, essential variables for the operation, such as pressure and level, are entertained prior to quality variables which are product compositions and flow rates [4]. Nevertheless, product quality carries high economic importance. In [5], it was suggested that for dual-composition control, one of the products shall be controlled by manipulating its respective energy term while the other product shall be controlled by its draw flow rate. In other words, either the distillate or the bottoms composition is controlled by manipulating the reflux or the boil up rate respectively. Whereas the other composition is controlled by manipulating its draw flow rate. Hence, the degree of interaction in the control problem shall be reduced.

Control configuration can be referred to as “configuration [L V]” indicating that reflux and boil up flows are the manipulated variable. Configuration [D V] or [L B] means that distillate and boil up or reflux and bottom product flow rates are the controlled variables.

Complexity of industrial processes and the demand of enhanced safety of operation and optimal quality of product have increased the significance of development in process control [6]. Various concepts define different control strategies that have been evolving since the past century. Process control strategies ca be categorized widely into conventional and advance process control.

A controller receives an input signal of measured variable from a sensor and calculate the error, which is the difference between a set point and measured controlled variable, and then correlates it to an output signal sent to the final-control element which adjust the manipulated variable. Different types of controllers utilize different mathematical correlation of input to output.

a) Conventional PID Controller

They are the most commonly used controllers in the industry with a dominance of 90%. These controllers correlate the error to the corrective action signals in a proportional, integral or/and derivative terms.

Proportional term:

$$p(t) = \bar{p} + K_c e^t \tag{1}$$

Integral term:

$$p(t) = \bar{p} + \frac{1}{\tau I} \int e^t \tag{2}$$

Derivative term:

$$p(t) = \bar{p} + \frac{1}{\tau D} \frac{d}{dt} e^t \tag{3}$$

Where:

$p(t)$: $controller\ output$, $\bar{p}$: $Bias\ (steady-state)\ value$, K_c : $gain$, $e(t)$: $Error\ signal$, τ_I : $Integral\ time-constant$, τ_D : $Differential\ time-constant$

In practice, proportional, integral and derivative control are combined together for optimal control actions. Integral is added to the proportional control in PI controller in order to eliminate the offset. However, the integral term introduces oscillatory behavior in the response and hence, derivative term is commonly introduced in the controller along with the proportional and integral to form PID.

b) Advanced Model-Predictive Control (MPC).

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Advanced process control (APC) came to emergence in the late 1970's to compete with conventional controller and overcome its weaknesses especially in nonlinear behavior process and when process variables are tightly coupled [7].
MPC is the most commonly used class of advanced process control in the industry [8]. It utilizes algorithms to predict the future behavior of a process based on a process model obtained from sufficient data coming from the real process that are usually identified at the commissioning stage [9]. It then solves the control problem optimally according to the predicted future response with a finite horizon at each sampling instant.
The process model developed by [10] was simulated on Simulink as appears in Figure 2. The process dynamic model is shown in Appendix I. Controllers were initially tuned utilizing Matlab's Auto Tuning. Table 1 shows the obtained parameters in order to compare which of P, PI and PID is a better option.

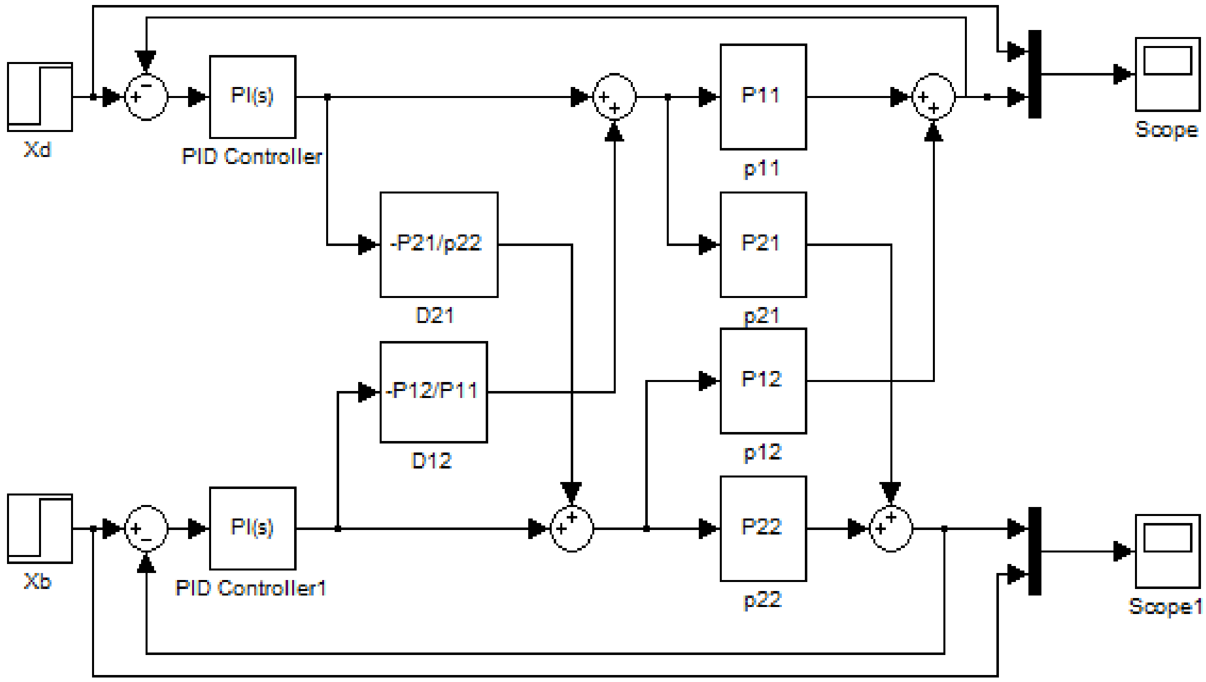

Fig.2. Simulink Block Diagram of the Distillation Process.

A step change in the overhead composition X_d from 0 to 10 was introduced to take place at time 10 seconds. Results are discussed in the next subsection.
After the best controller was identified, the controller was tuned using different methods available in the literature such as Ziegler Nichols, Cohen Coon, Internal Model Control (IMC), Integral of Time Absolute Error (ITAE) and Symmetric Optimum. Table 2 & Table 3 summarize the calculated tuned parameters.
Note that the calculated parameters are ought to resemble the Ideal form of a PI controller equation: $K = K_p(1 + \frac{1}{T_i s})$, while Simulink controller settings refers to an equivalent form

$$K = P + I\frac{1}{s}:$$

Table 1

Auto Tuned Parameters of the Overhead and Bottom Controller

Controller Parameter	**Overhead product controller**			**Bottom product controller**		
	P	**PI**	**PID**	**P**	**PI**	**PID**
Proportiona	0.49299	0.13928	0.4620595	-	-	-0.182426

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I	83	48		0.216033	0.095715	
Integral	-	0.0153928	0.043542	-	-0.01361	-0.006269
Derivative	-	-	0.2356692	-	-	-0.21862
Filter Coefficient	-	-	5.6844125	-	-	0.511546

Table 2

PI Controller parameters for Top Product Controller from Different Tuning Methods

Form of Equation	**Ideal**		**Matlab**	
Parameter / Method	**Ki**	**Ti**	**P**	**I**
Zieglar Nichols	1.029339	3.5	1.029339	0.294097
Cohen Coon	1.180729	2.959483	1.180729	0.398965
IMC	0.488647	16.7	0.488647	0.02926
ITAE	0.603526	16.37063	0.603526	0.036866
Symmetric Optimum	0.326172	32	0.326172	0.010193

Table 3

PI Controller parameters for Bottom Product Controller from Different Tuning Methods

Form of Equation	**Ideal**		**Matlab**	
Parameter / Method	**Ki**	**Ti**	**P**	**I**
Zieglar Nichols	-0.19409	7.5	-0.19409	-0.02588
Cohen Coon	-0.22698	6.977848	-0.22698	-0.03253
IMC	-0.13746	14.4	-0.13746	-0.00955
ITAE	-0.12709	14.46328	-0.12709	-0.00879
Symmetric Optimum	-0.09278	64	-0.09278	-0.00145

Results

As result of the step change in the top composition, the bottom composition was also altered. Hence, both controllers functioned to bring back the measurement to set points. The plots of responses by different controllers' settings were obtained as shown in Figure 3 & Figure 4. P Controller - the proportional only controller shows the response settling at 50 seconds but with an offset of -2.3. Moreover, Figure 4 indicates the behavior of the bottom product response. It was brought to the set point in 140 seconds with and overshoot of 0.22. PI Controller - the proportional-integral controller has a settling time of around 80 seconds with no overshoot for the overhead product composition. Likewise, the bottom product required 100 seconds to settle due to interaction between variable. It is notable that the bottom product response of the PI controller is the least vigorous. PID Controller - the proportional-integral-derivative controller response plot in Figure 3

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oscillates at a fast rise time and have a settling time of 70 seconds for the top product. Overshoot is almost negligible after 30 seconds. In the other hand, the bottom product response to the interaction is quite oscillatory with an overshoot of 0.2 and settling time slightly beyond 200 seconds.

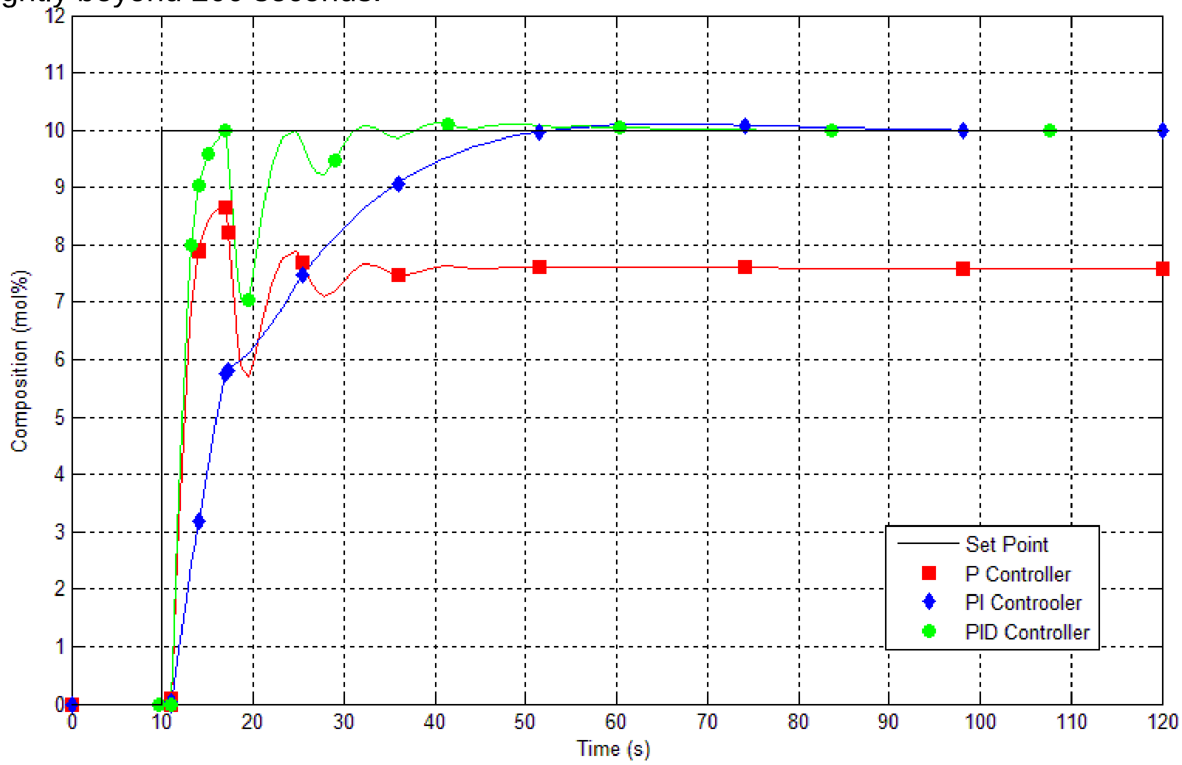

Fig.3. Response of the Top Product to a Step Change in its Controlled Variable by Different Controller Settings.

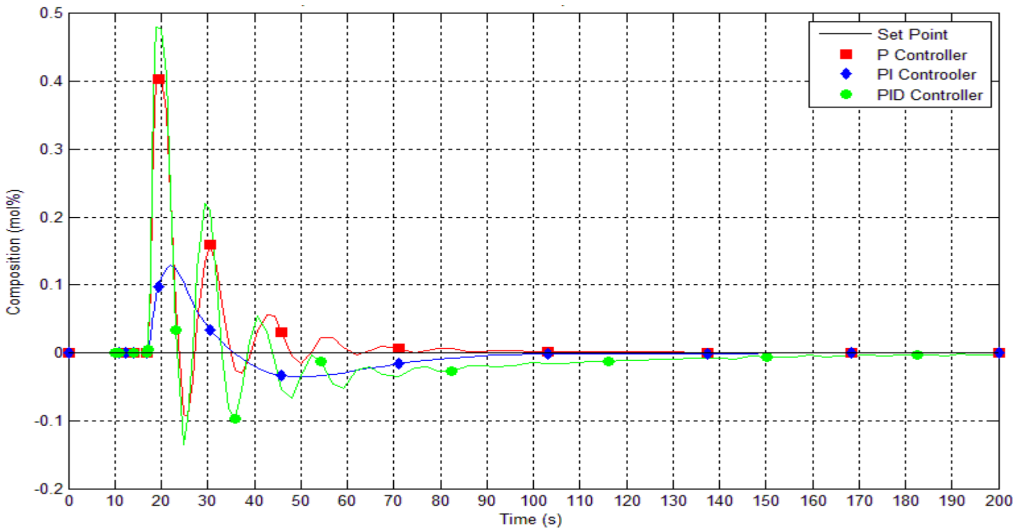

Fig.4. Response of the Bottom Product to a Change in its Disturbance Variable by Different Controller Settings.

Hence, based on the results obtained from the simulation which are summarized in Table 4, it is clear that the P controller is unable to maintain stability of control for this problem. In the other hand, in the case of the PI controller, the settling time was higher for the overhead product, 80 seconds compared to 50 seconds, but the main objective of the

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control was achieved and offset was completely eliminated. Likewise, the PID achieved the set point with even shorter settling time of 70 seconds. However, PI's response rise was steep while PID's was oscillatory.

The comparison is between PI and PID. Considering only the top product control where the step change was introduced, the analysis would favor PID over PI as it required less settling time. Nevertheless, considering the process as a whole, the PI managed to maintain the bottom product more efficiently than PID as latter went beyond 200 second for slow settling time in addition to the vigorous oscillation upon the moment of interaction. PI controller showed an overshoot five times less than that of the PID.

Table 4

Summary of Response Analysis for Controller's Setting Comparison

	Controller / Criteria	P	PI	PID
Top	**Settling time (s)**	50	80	70
	Offset	-2.3	0	0
	Overshoot	1	0	0
	Oscillation	Slight	None	Sligh
Bottom	**Settling time (s)**	140	100	200
	Offset	0	0	0.01
	Overshoot	0.4	0.47	0.2
	Oscillation	Moderate	Slight	Aggressive

Conclusion

The binary distillation column process model was simulated on Simulink. Traditional controllers, P, PI and PID, were set up and tuned using Matlab Auto Tuning Tool. Step change was introduced to the top product. Consequently, the inherent interaction affected stability of the bottom product as well. Response plots were obtained and different controllers were evaluated based on settling time, overshoot and stability of response.

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