BINARY DISTILLATION COLUMN CONTROL TECHNIQUES: A COMPARATIVE STUDY

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Abstract—The purpose of this study is to propose the optimum control strategy for the binary distillation column. Woods & Berry model is used to represent the distillation column process. 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. PI is then tuned using different tuning method including Ziegler Nichols, Cohen Coon, ITAE, IMC and Symmetric Optimum. The study finds that IMC tuning parameters relatively improves the PI controller response and robustness. It is suggested that IMC-tuned PI controller ultimately conclude a superior control technique for the binary distillation column.

Index Terms— Distillation, Control, Tuning, PID.

I. INTRODUCTION

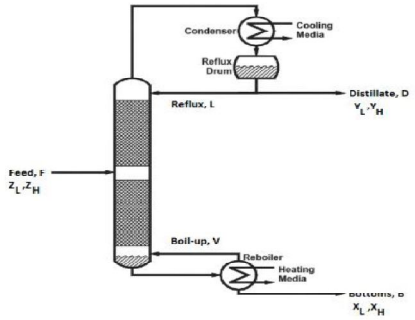


Fig. 1. Ideal Binary Distillation Column

Distillation is one of the most common processes with dominance of 95% of industrial separation processes due to its viability on wide range of application and relative low cost [1, 2].A distillation column has Multiple-Input-Multiple-Output and referred as MIMO process.A simple binary distillation column illustrated in**Error! Reference source not found.**. *D* and *B* denote for the distillate and bottoms compositions respectively which are the main controlled variable.

Complexity of industrial processes and the demand of enhanced safety of operation and optimal quality of product have increased the significance of development in control systems [3]. Control systems are divided into two classes; conventional controllers and advanced controllers.

A. Conventional PID Controllers

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

Proportional term: $p(t) = \bar{p} + K_c\, e(t)$

Integral term: $p(t) = \bar{p} + \frac{1}{\tau_I}\int e(t)$

Derivative term: $p(t) = \bar{p} + \frac{1}{\tau_D}\frac{d}{dt}e(t)$

Where:

$p(t) : controller\ output$

$\bar{p} : Bias\ (steady - state) value$

$K_c\ : gain$

$e(t)$: $Error\ signal$

$\tau_I : Integral\ time - constant$

$\tau_D : Derivative\ time - constant$

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 introduce oscillatory behavior in the response and hence, derivative term is commonly introduced in the controller along with the proportional and integral to form PID.

Different tuning method have evolved to optimize the controller performances. They mathematically correlate the controller's parameter;K_c, τ_I and τ_D, to the process parameters

B. Objectives

The objective of this work is to propose and suggest a superior control technique for the binary distillation column. Conventional PID controlapproaches will be optimized, analyzed and then compared. Performance indices for comparison include the overshoot, stability and speed of response (settling time).

The objective of the study is broken down into:

1. Determining the better traditional control setting; P, PI or PID.
2. Selecting the optimal tuning method.

C. Scope of Study

This study focuses on the performance of different control strategies named PID. 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 due to setpoint

changes. Step change in the required product purity will be introduced to investigate the control response.
Mathematical representation of the distillation column process is adapted from literature, Wood and Berry model, [4]. Control loop is designed and controllers are tuned to optimize performance. References for the design and tuning procedures for PID are explained in [5].
MATLAB Simulink® is utilized to simulate the process and test the controllers.

II. LITERATURE REVIEW

Performance of conventional feedback PID control strategies are doubtful in high purity distillation column. The main drawback is the late response of the corrective action especially that controlled variables (compositions) alters vigorously with the main disturbances (feed flow and composition) according to [6]. As a result, quality of product is affected and consequently, economical loss to plant is likely. It was also reported by [7,8] that the top and bottom product compositions tight interaction which make the process sensitive to small changes are a big concern in the industry.

III. METHODOLOGY

This study adopts the flow of methodology shown in Fig. 1to achieve objectives:

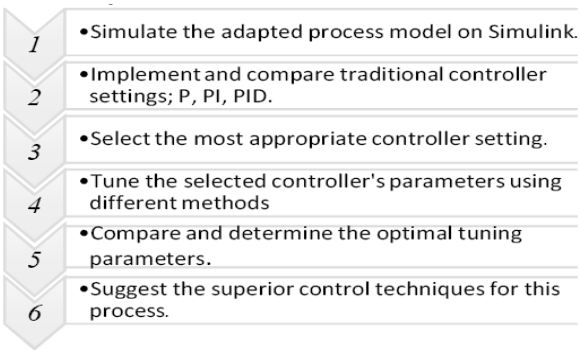


Fig. 1: The Methodology Flow

A. Process Model

The Woods & Berry binary distillation column process model adapted from [9] is given by the following equations:

$$\begin{bmatrix} X_D(s) \\ X_B(s) \end{bmatrix} = \begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{21}(s) & P_{22}(s) \end{bmatrix} \begin{bmatrix} R(s) \\ S(s) \end{bmatrix}$$

The decouplers are given by:

$$D_{12}(s)P_{11}(s) + P_{12}(s) = 0$$
$$D_{21}(s)P_{22}(s) + P_{21}(s) = 0$$

Where:

$$P_{11}(s) = \frac{12.8\,e^{-1s}}{16.7s+1} \quad P_{12}(s) = \frac{-18.9\,e^{-3s}}{21.0bs+1}$$
$$P_{21}(s) = \frac{6.6\,e^{-7s}}{10.9\,s+1} \quad P_{22}(s) = \frac{-19.4\,e^{-1s}}{14.4\,s+1}$$

B. Simulation Procedure& Calculations

The process was simulated on Simulink as inFig.
Controllers were initially tuned utilizing MATLAB Auto Tuning.Table 1 shows the obtained parameters.

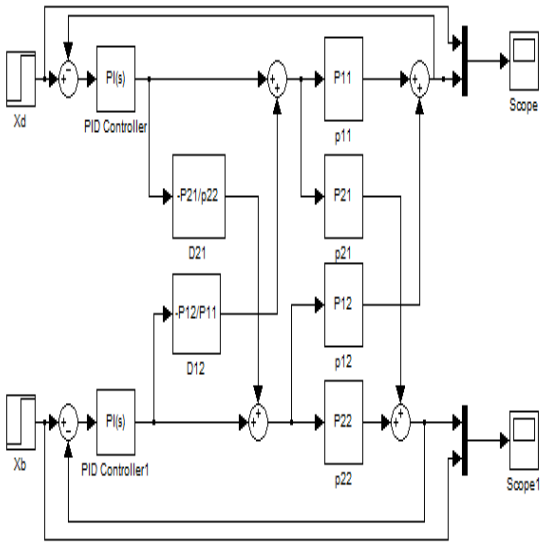


Fig. 3. Simulink Block Diagram of the Distillation Process

Table 1Auto Tuned Parameters of the Overhead and Bottom Controller

Controller / Parameter	Overhead product controller			Bottom product controller		
	P	PI	PID	P	PI	PID
Proportional	0.4929983	0.1392848	0.4620595	-0.216033	-0.095715	-0.182426
Integral	-	0.0153928	0.043542	-	-0.01361	-0.006269
Derivative	-	-	0.2356692	-	-	-0.21862
Filter Coefficient	-	-	5.6844125	-	-	0.511546

A step change in the overhead composition, *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 is 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.

Table 2PI Controller parameters for Top Product

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 3PI Controller parameters for Bottom Product

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

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

IV. RESULTS

A. Comparison of Conventional Controller Setting

It can be seen in Fig. and Fig. 2 that different controller settings produced different response behavior.

P CONTROLLER

The proportional only controller shows the response settling at 50 seconds but with an offset of -2.3. Moreover, Fig. 2indicates 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 Fig. 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.

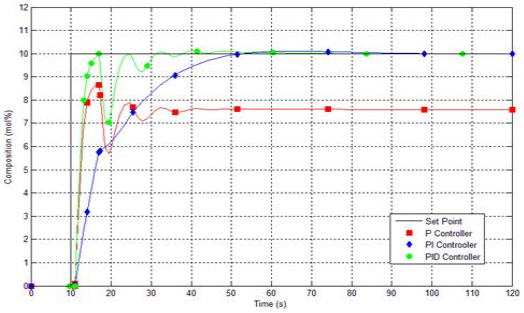


Fig. 4. Overhead Response for Different controller Settings

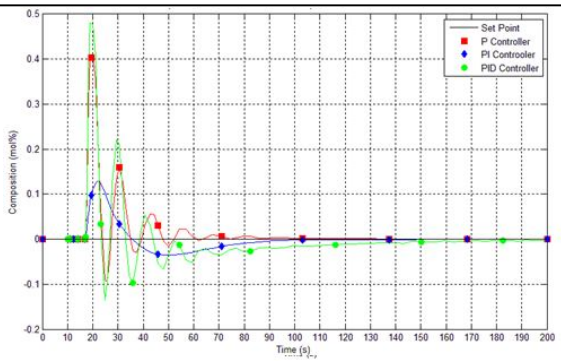


Fig. 2. Bottoms Response for Different controller Settings

B. Comparison of Tuning Methods

After specifying the better controller setting, it was then tuned using different methods. Results are plotted in Fig. 3&Fig. 4.

ZIEGLER NICHOLS

The Z-N tuning parameters worked well for controlling the top product composition with fastest settling time compared to the other four tuning methods. Overshoot was relatively high with 6.2 mol% change which resembles 62% of the step change introduced.

In the bottom product, the disturbance unsettled the composition for 49 seconds with an overshoot of 0.29. The analysis of Ziegler Nichols response had a sligh oscilation however it was only significant in the bottom product which had a notable overshoot compared to other methods.

COHEN COON

The C-C tuning parameters produce a similar response in handling the step change introduced to the controlled variable as it settled in 42 seconds and had an overshoot of 82% of the change introduced.

Response of the bottom to the coupled disturbance was the least satisfactory. It had the slowest respoinse time, 80 seconds, and largest overshoot, 0.41 mol% change. It also failed to compete the other tuning methods taking into acount the relatively moderate oscilatory response in the bottom product composition control.

INTEGRAL MODEL CONTROL

The IMC tuned parameters gave slightly slower response in manage the step change in the top product composition compared to the methods mentioned earlier. However, it was the steepiest and did not record any overshoot whivh gives it a plus point.

Moreover, the bottoms control showed to be superior to the other methods as it elimiated disturbance in 37 seconds with minimal overshoot of 0.03 and negligible oscillation.

ITAE

ITAE methodgave a reasonable response yet slower than Z-N, C-C and IMC. Overshoot is 30% and relatively moderate aggressiveness in the response.

Bottoms control is also satisfactory with competitive settling time of 41 and small overshoot of 0.05.

SYMMETRIC OPTIMUM

Last but not least, the SO method response analysis was the least stable in controlling the top product. It had an offset of -0.2 which is 2% of the step change. The response curve was the smoothest with no oscilation of overshoot at all. However, the settling time was the slowerst going slightly beyong 120 second.

For the bottom product disturbance control, SO had the best control with shortest time, 29 seconds and negligible oscillation and overshoot of 0.015.

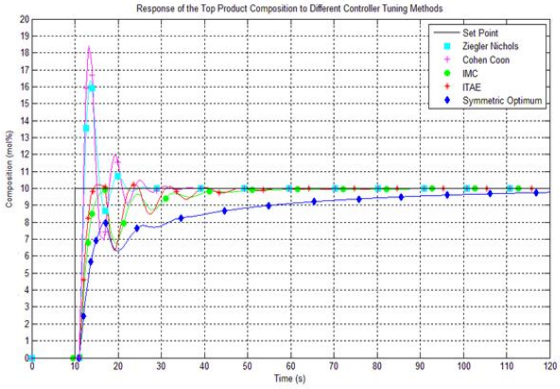


Fig. 3. Overhead Response for PI Controller with Different Tuning Parameter

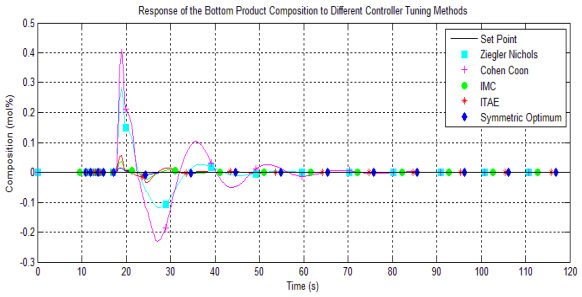


Fig. 4. Bottoms Response for PI Controller with Different Tuning *Parameter*

V. DISCUSSION

Based on the results obtained in part (A), which are summarized inTable 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 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.

As for part (B), the tuning methods comparison nominates IMC and ITAE for overall superiority to other methods with a slight preference to the IMC. The response data are summurized inTable 5.

Symmetric Optimum method gives a better result rejecting the indirect disturbance to bottoms composition 8 and 12 seconds faster than IMC and ITAE respectively but lacks that fast response in controlling the top. Ziegler-Nichols and Cohen Coon methods lacked stability with high overshoot in the top product composition when step change is introduced.

Table 4Summary 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

Table 5Summary of Response Analysis for Tuning Methods Comparison

	Controller / Criteria	ZN	CC	IMC	ITAE	SO
Top	Settling time (s)	40	42	49	64	120
	Offset	0	0	0	0	-0.2
	Overshoot	6.2	8.2	0	0.3	0
	Oscillation	Slight	Slight	Slight	Moderate	None
Bottom	Settling time (s)	49	80	37	41	29
	Offset	0	0	0	0	0
	Overshoot	0.29	0.41	0.03	0.05	0.015
	Oscillation	Slight	Moderate	Negligible	Slight	Negligible

CONCLUSION & RECOMMENDATION

The outcome of the response analysis favored PI slightly over P and PID. PI controller was then tuned using several tuning methods. IMC tuning parameters gave the best result compared to ITAE, Ziegler Nichol, Cohen Coon and Symmetric Optimum method.

As a result of this study, a PI controller tuned using IMC method is the best representative for the class of traditional controllers.To improve this study, it is recommended to test more tuning methods to select an ideal traditional controller. Moreover, the decouplers may also be worked out in a different technique for thorough comparison.

Lastly, MPC controller is a more advanced class of controllers that is claimed to be superior to traditional controller. It is suggested to be put in comparison against ideally tuned PI controller for the binary distillation column.

All in all, the study has achieved two objectives; the better conventional control setting which is found to be PI, and the better tuning method which is the IMC method. More thorough knowledge in the subject of advanced process control is required to compare the proposed PI controller to MPC.

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