Modelling and control of distillation column

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Abstract—Distillation column is one of the most important unit in a chemical plant. This paper provides a comprehensive study of mathematical model and control of binary distillation column. Wood-Berry distillation column model is considered in this paper which separates methanol from water. PID controller, decoupled PID controller and model predictive controller are used to control the distillation column.

Index Terms—Distillation column; Wood-Berry Model; PID controller; Model Predictive Controller

I. INTRODUCTION

Chemical process are multi variable and non-linear in nature. Due to relative uncertainties of the system, the chemical process are difficult to model as well as complex to control. Distillation is one of the most common unit operation used in most of the chemical and petroleum industries. Distillation is used to separate two or more components from a homogeneous fluid mixture. The quality and purity of distillation is of paramount importance, therefore proper control of the system is necessary.

A significant amount of literature is available on modeling and control of distillation column [1], [2]. This paper summarizes a few important literature. A tutorial perspective of dynamics and control of distillation column has been reported in [2]. Due to the nonlinear aspect of chemical process over a wide range of operating conditions, it is difficult to provide an accurate model of the system. The single linear time invariant (LTI) system is inadequate to describe the dynamics of the distillation column in both steady state as well as in transient state operation. In transient state when there is some major disturbances, the nonlinear characteristics of the process model becomes dominant. To counter this limitation of LTI model, linear parameter varying (LPV) model is used in process industries [2].

Researchers have tried to control distillation column using different conventional as well as intelligent control techniques. Terminal configuration control [2], model predictive control [3], [4], internal model control [2] and decentralized control [2] are some of the well known classical control algorithm used in distillation column.

Recently, intelligent control has been used in distillation column control which has generated a new research interest in this area. In intelligent control techniques, fractional PID and fractional order fuzzy PID controller has been used to control the distillation column in [2]. Control of distillation column using type-I and type-II fuzzy logic controller [2] and adaptive neuro-fuzzy (ANFIS) based controller [7] is reported in control literature. In [7], the researchers developed a self organizing fuzzy logic control (SOFLC) using general predictive control (GPC) on a Tagaki-Sugeno-Kang (TSK) model of controlled auto-regressive integrated moving average (CARIMA) structure. Neural network based control of distillation column is reported in [8].

This paper provides a comprehensive analysis of mathematical model and control of distillation column. Wood and Berry model of distillation column is considered which separates methanol from water. MIMO PID controller, decoupler based PID controller and model predictive controller are designed and performance of these controllers are evaluated using simulation platform.

The paper is organized as follows. Section II provides the basic working principle as well as mathematical modeling of distillation column. Section III provides the control strategy of the column and section IV provides results. Section V concludes the paper.

II. DISTILLATION COLUMN

A typical distillation column contains a vertical column where trays are used to enhance the component separations. A reboiler is used to provide heat for the necessary vaporization from the bottom of the column. Condenser is used to cool and condense the vapor from the top of the distillation column. Reflux drum is used to hold the condensed vapour so that liquid reflux can be recycled back from the top of the column. The distillation column contains one feed stream and two product streams. The feed contains a mole percent of the component called $x_F$. The product stream at the top has a composition referred as $x_D$. The product stream leaving the bottom contains a composition of $x_B$ of the light component. The schematic diagram of distillation column is illustrated in Fig. ??.

A. Mathematical Modelling

The mathematical model of the distillation column is provided below. Liquid holdup are assumed in every array of the distillation column. Francis-Weir formula is used for linearization and model the variable liquid hold up. It is represented as

$$ L_n = L_{n0} + \frac{M_n - M_{n0}}{\beta} \quad (1) $$

where

- $L_n$: Liquid hold-up at stage $n$
- $L_{n0}$: Initial liquid hold-up at stage $n$
- $M_n$: Mole flow rate at stage $n$
- $M_{n0}$: Initial mole flow rate at stage $n$
- $\beta$: Separation factor.
For reboiler the mathematical model is
\[
\frac{dM_B}{dt} = L_1 - V_B - B
\]
(12)
\[
\frac{dM_B X_B}{dt} = L_1 X_1 - V_B Y_B - B X_B
\]
(13)

\[\begin{align*}
\frac{dM}{dt} & = V_{NT} - (R + D_L + D_V) \\
\frac{dM_X}{dt} & = V_{NT} Y_{NT} - (R + D_L) X_D - D_V Y_D \\
\frac{dM_N}{dt} & = R + V_{NT} - Y_{NT} - V_{NT} \\
\frac{dM_F}{dt} & = L_{NF+1} - L_{NF} + V_{NF} - V_{NF} + F_L \\
\frac{dM_{NF}}{dt} & = L_{NF+1} X_{NF+1} - L_{NF} X_{NF} + V_{NF} - V_{NF} + F_L Z_L \\
\frac{dM_1}{dt} & = L_2 - L_1 + V_B - V_1 \\
\frac{dM_1 X_1}{dt} & = L_2 X_2 - L_1 X_1 + V_B Y_B - V_1 Y_1 \\
\end{align*}\]

B. Models of distillation column

Wood and Berry experimentally modelled a 9 inch diameter, 8-tray binary distillation column that separated methanol from water. The wood and berry model can be represented as

\[
\begin{bmatrix}
y_1 \\
y_2 \\
u_1 \\
u_2 \\
d
\end{bmatrix} = \begin{bmatrix}
12.8\times 10^{-6} & 16.7\times 10^{-6} & -18.6\times 10^{-6} & 21\times 10^{-6} & 14.9\times 10^{-6} & 3.8\times 10^{-6} & 1.2\times 10^{-6} \\
6.6\times 10^{-6} & 10.9\times 10^{-6} & -19.4\times 10^{-6} & 14.4\times 10^{-6} & 3.9\times 10^{-6} & 1.3\times 10^{-6} \\
\\
\end{bmatrix} \begin{bmatrix}
y_1 \\
y_2 \\
u_1 \\
u_2 \\
d
\end{bmatrix}
\]

(14)

Here \( y_1 \) is distillate methanol [mol\%], \( y_2 \) is water [mol\%], \( u_1 \) is reflux flow rate \([lb/\text{min}]\), \( u_2 \) is steam flow rate \([lb/\text{min}]\), \( d \) is unmeasured flow rate \([lb/\text{min}]\)

III. CONTROL STRATEGY

This section describes the control strategy for distillation column. The complete list of control variable and manipulated variable is shown in Fig. ?? The schematic diagram of complete control structure of distillation column is shown in Fig. ??.
controller based MIMO controller for distillation column is shown in Fig. ??.

Due to multiple variables, the control schemes needs decoupler. The block diagram of control scheme with decoupler is shown in Fig. ?? To check the interaction in a multi-loop control systems, decouplers are used. Static decouplers are used when fast controls are not required. They possess simple simple structure and their design does not require detailed description of the system. Relative Gain Array is a normalized form of the gain matrix that describes the impact of each control variable on the output, relative to each control variable impact on other variables. The decoupler can be found out using following equations

\[
T_{12} = \frac{G_{12}}{G_{11}}
\]

\[
T_{21} = \frac{G_{21}}{G_{22}}
\]

A. Model Predictive Control

In a MIMO control, the output vector can be represented as \( y = [y_1, y_2, \ldots, y_m]^T \) and input vector can be represented as \( u = [u_1, u_2, \ldots, u_r]^T \).

The MIMO model for the corrected prediction can be represented as

\[
\hat{Y}(k+1) = S \Delta U(k) + \hat{Y}^o(k+1) + \phi [y(k) - \hat{y}(k)]
\]

\[
\hat{Y}(k+1) = \begin{bmatrix}
\hat{y}(k+1) \\
\hat{y}(k+1) \\
\vdots \\
\hat{y}(k+P)
\end{bmatrix}
\]

\[
\hat{Y}^o(k+1) = \begin{bmatrix}
\hat{y}^o(k+1) \\
\hat{y}^o(k+1) \\
\vdots \\
\hat{y}^o(k+P)
\end{bmatrix}
\]

\[
\Delta U(k) = \begin{bmatrix}
\Delta u(k) \\
\Delta u(k+1) \\
\vdots \\
\Delta u(k+M-1)
\end{bmatrix}
\]

The dynamic matrix is defined as

\[
S = \begin{bmatrix}
S_1 & 0 & \ldots & 0 \\
S_2 & S_1 & 0 & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
S_{P-M} & S_{P-M-1} & \ldots & S_1 \\
S_1 & S_2 & \ldots & S_{P-M+1}
\end{bmatrix}
\]

IV. RESULTS

This section provides simulation results for the distillation column. Wood and Berry model is considered as the model for the distillation column. First of all simulation for open loop step response analysis and open loop transient analysis is carried out. The open loop step response of binary distillation column is shown in Fig. ??.

Open loop transient analysis is studied for the distillation column. Once the flow rate is varied, the response of output variable is studied in Fig. ?? and Fig. ?? respectively.
PID controller without decoupler is used to control the MIMO plant. Wood and Berry distillation column model is considered and PID controller is tuned using Zigler-Nichols tuning method. The controlled output of the system with PID controller is shown in Fig. ?? As it can be seen from the graph, the distillate and the bottom product are regulated using PID controller but there is significant overshoot in the control scheme.

Fig. 7. Open loop step response analysis

Fig. 8. Change in flow rate of distillation column

Fig. 9. Change in flow rate of distillation column

Fig. 10. Response of PID controller without decoupler

Fig. ?? presents the output response of model predictive controller in a distillation column. It can be shown in the graph that the model predictive control algorithm provides the best output response for a distillation column.

Fig. 11. Response of model predictive controller
V. CONCLUSION

This paper provides a detailed mathematical model of a distillation column and control part of the distillation column has been studied extensively. For simulation purpose, Wood-Berry distillation column model is considered. PID controller for MIMO plant is designed without decoupler and with decoupler unit. Model predictive controller is also studied and implemented for a distillation column. The performance of the control strategy is evaluated with the help of simulation analysis.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_n )</td>
<td>Internal liquid flow rate</td>
<td></td>
</tr>
<tr>
<td>( L_{n0} )</td>
<td>Reference value of internal flow rate</td>
<td></td>
</tr>
<tr>
<td>( M_{n0} )</td>
<td>Reference molar holdup for nth tray</td>
<td></td>
</tr>
<tr>
<td>( M_D )</td>
<td>lbmol</td>
<td>Liquid holdup in reflux drum</td>
</tr>
<tr>
<td>( R )</td>
<td>lbmol/h</td>
<td>Reflux flow rate</td>
</tr>
<tr>
<td>( D_L )</td>
<td>lbmol/h</td>
<td>Flow rate of liquid distillate</td>
</tr>
<tr>
<td>( D_V )</td>
<td>lbmol/h</td>
<td>Flow rate of vapour distillate</td>
</tr>
<tr>
<td>( X_D )</td>
<td>mol fraction</td>
<td>Composition of liquid distillate</td>
</tr>
<tr>
<td>( Y_D )</td>
<td>mol fraction</td>
<td>Composition of vapour distillate</td>
</tr>
</tbody>
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REFERENCES


