**Control of Binary Distillation Column Using Fuzzy PI Controllers**

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**Abstract:** In this paper the automatic control of a binary distillation column is described. This control is done with fuzzy logic controllers. After a short explanation of the function and dynamic of a binary distillation column, its operating and control strategies are described. Then all the processes of the distillation column with its fuzzy controllers are simulated in MATLAB software as the results are shown at the end.

**Keywords:** Binary Distillation Column, Fuzzy Inference System, Simulation.

1. **Introduction**

Distillation columns are used in the chemical industry to separate liquid mixtures into their pure components or into several fractions of predefined composition. The two major types of classical distillation include continuous distillation and batch distillation. Continuous distillation, as the name says, continuously takes a feed and separates it into two or more products. Batch distillation takes one batch at a time for the feed and splits it into products by selectivity removing the more volatile fractions over time. Keeping a constant product quality in a distillation column is very important. A better control means a smaller variability of quality around the set point an operation closer to specifications and lower energy consumption. Traditional techniques to perform this task usually involve a model of the process, and such a model is not easy to obtain, since distillation columns are complex, highly nonlinear and multivariable processes. Usually operators’ knowledge plays an important role in complex industrial processes, and this knowledge may be integrated in the automatization system by means of fuzzy inference system (FISs). FISs allow obtaining control actions from input variables by using linguistically formulated rules; also, FISs don’t need an analytic model of the process, so their conception is greatly simplified. The experiments described in this paper have been developed and tested with the aid of a simulator written in MATLAB/Simulink, which is able to reproduce the dynamic behavior of the column.
2. The Distillation Column
Distillation column is probably the most popular and important process studied in the chemical engineering literature. Distillation is used in many chemical processes for separating feed streams and for the purification of final and intermediate product streams. Most columns handle multicomponent feeds, but many can be approximate by binary or pseudobinary mixtures. The objective is to split a liquid two component mixture into its fraction throughout stripping and rectifying processes. As it is shown in figure 1 the mixture is fed onto the feed tray $N_F$ with feed flow rate of $F$ (lb.mol/min) and composition of $z$ (refered to more volatile component). The more volatile component (water) leaves the top of the column while the less (methanol) leaves the bottom. The overhead vapor is totally condensed in a condenser and flows into the reflux drum with a composition $X_D$ and holdup liquid of $M_D$ (moles), and reflux is pumped back to the top tray of the column at a rate $R$, while overhead distillate product is removed at a rate $D$. At the base of column, a liquid product stream is removed at a rate $B$ with a composition $X_B$ and holdup of $M_B$ (moles). Vapor boil up is generated in a reboiler at a rate $V$. The column contains $N_T$ trays and the liquid holdup on each tray $n$ is $N_n$ with composition $X_n$, while the holdup of vapor is assumed to be negligible throughout the system.

3. Control Strategy
Consider the closed-loop response during the dynamic distillation of an ideal binary mixture in the column shown in figure 1, under two assumption of constant relative volatility ($\alpha$) at a value of 2.0 and constant molar vapor flow for a saturated liquid feed to tray $N_S$. Following the development by Luyben it is not necessary to include energy-balance equations for each tray or to treat temperature and pressure as variables [1]. Overhead vapor leaving top tray $N_T$ is totally condensed for negligible liquid holdup with condensate flowing to a reflux drum having constant and perfectly mixed molar liquid hold up $M_D$.

The reflux rate $L_{NT+1}$ is varied by a fuzzy proportional-integral (PI) feedback controller to control distillate composition for a set point of 0.98 for the mole fraction $X_D$ of the light component. Holdup of reflux in the line leading back to the top tray is neglected. Under dynamic conditions, $L_{NT+1}$ may not equal $X_D$.

At the bottom of the column, a liquid sump of constant and perfectly mixed molar liquid holdup $M_B$ is provided. A portion of liquid flowing from this sump passes to a thermosiphon reboiler, with the remainder taken as bottoms product at a molar flow rate $B$. Vapor boilup generated in the reboiler is varied by a fuzzy PI feedback controller to
control bottom’s composition with a set point of 0.02 for mole fraction $x_B$ of the light component. Liquid holdup in the reboiler and lines leading from the sump are assumed to be negligible. The composition of the boilup $y_B$ is assumed to be in equilibrium with $x_B$. The liquid holdup $M_n$ on each of the $N_T$ equilibrium trays is assumed to be perfectly mixed but will vary as liquid rates leaving the trays vary. Vapor holdup is assumed to be negligible everywhere. Tray molar rates $V$ vary with time but at any instant in time are everywhere equal. The dynamic material-balance and phase equilibrium equations corresponding to this description are as follow:

All trays, $n$:

$$ M_n \frac{dV_n}{dt} = F_n + L_{n+1} - L_n $$  \hspace{1cm} (1)

$$ \frac{d}{dt}(M_n x_n) = F_n x_n + L_{n+1} x_{n+1} + V_{n+1} x_{n+1} - V_n x_n $$ \hspace{1cm} (2)

$$ L_n = E_n + (M_n + \bar{M}_n)/\beta $$ \hspace{1cm} (3)

$$ y_n = \frac{1}{1 + (\alpha - 1)x_n} $$ \hspace{1cm} (4)

Where $F_n$ is nonzero only for tray $N_s$, $y$ and $x$ refer to the light component only such that the corresponding mole fractions for the heavy component are $(1 - y)$ and $(1 - x)$, $L_n$ and $\bar{M}_n$ are the initial steady-state values, and $\beta$ is a constant that depends on tray hydraulic.

For the condenser-reflux-drum combination:

$$ D = V - L_{N_T+1} $$ \hspace{1cm} (5)

$$ M_D \left( \frac{d x_D}{dt} \right) = \frac{V}{y_{N_T+1}} - V_{x_D} $$ \hspace{1cm} (6)

For the reboiler:

$$ B = L_1 - V $$ \hspace{1cm} (7)

$$ M_B \left( \frac{d x_B}{dt} \right) = L_1 x_1 - V y_B - B x_B $$ \hspace{1cm} (8)

$$ y_B = \frac{1}{1 + (\alpha - 1)x_B} $$ \hspace{1cm} (9)

4. Fuzzy PI controller

The structure of the fuzzy PI controller which has two inputs and one output is shown in figure 2. The inputs are the classical error ($e$) and the rate of the change of error ($e$ or $de$) that are defined in the equations 12,13 and the outputs of the controllers are the reflux and vapor boilup generated in the reboiler.

Triangular membership functions are used for both input and output variables that the input and output values are represented linguistically. (i.e., N=Negative, Z=Zero and P=Positive) as it is shown in figure 3.
Table 1: FAM Table for 2 inputs (e & de) and output (Reflux) that refers to $e_B$.

<table>
<thead>
<tr>
<th>de</th>
<th>N</th>
<th>Z</th>
<th>P</th>
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</thead>
<tbody>
<tr>
<td>N</td>
<td>N</td>
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<tr>
<td>P</td>
<td>Z</td>
<td>P</td>
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</tbody>
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Table 2: FAM Table for 2 inputs (e & de) and output (vapor boilup) that e refers to $e_D$.

<table>
<thead>
<tr>
<th>de</th>
<th>N</th>
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The input/output mapping of fuzzy controllers is also given in figure 4.

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Also we use the Mamdani inference system as inference engine and centroid method for defuzzification in the fuzzy controllers. The two PI controller equations are:

\[ V = \bar{v} - K_C \left( E_B + \frac{1}{1 + \tau} \int E_B \, dt \right) \]  
(10)

\[ L_{N_{\tau+1}} = \bar{L}_{N_{\tau+1}} + K_C \left( E_D + \frac{1}{1 + \tau} \int E_D \, dt \right) \]  
(11)

Where $\bar{v}$ and $\bar{L}_{N_{\tau+1}}$ are initial values, $K_C$ and $\tau$ respectively feedback controller gain and feedback reset time for integral action, $E$ is the error or deviation from the set point as given by:

\[ E_B = x_{B_{set}} - x_B \]  
(12)

\[ E_D = x_{D_{set}} - x_D \]  
(13)

Typical results for the initial steady-state conditions, fixed conditions, hydraulic parameters, and disturbance are listed in table 3.

Table 3: Initial and Fixed Conditions, Hydraulic Parameter and Disturbance

<table>
<thead>
<tr>
<th>Other Initial Conditions</th>
<th>Initial Liquid-Phase Composition</th>
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<tbody>
<tr>
<td></td>
<td>Tray</td>
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<tr>
<td>Trays: 100</td>
<td>Bottom</td>
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<tr>
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<td>1</td>
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<td>2</td>
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<td>11</td>
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<td></td>
<td>12</td>
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</tbody>
</table>

| Fixed Conditions | 13 | 0.61896 |
|                 | 14 | 0.68052 |
|                 | 15 | 0.74345 |
|                 | 16 | 0.80319 |
|                 | 17 | 0.85603 |

| Hydraulic Parameter | 18 | 0.89995 |
|                    | β=0.1 min | 19 | 0.93458 |
| Disturbance at $t^*$ | 20 | 0.96079 |

| Disturbance at $t^*$ | 0.55$\tau$ | Distillate | 0.98 |
5. Simulation
In this paper two case studies have been studied. In both simulations, it is used simulink toolbox of MATLAB software. In the first case the all processes of a binary distillation column (methanol/water) is simulated and in the second, according to the control strategy, the fuzzy PI controllers are designed and simulated. For simulation two external inputs are forced. First a step with the step time of 70s and final value of 10 is used as feed rate and also a step with step time of zero and final value of 0.05 is used as disturbance. Note that the initial values of feed rate and disturbance respectively are 100 and 0.5.

Figure 5: External Inputs: Top: Feed Rate, Bottom: Feed Composition (Disturbance)

Figure 6: Top: Top Composition ($E_D$), Bottom: Bottom Composition ($E_B$) (Number of epochs = 100)

Figure 7: Top: Top Composition ($E_D$), Bottom: Bottom Composition ($E_B$) (Number of epochs = 150)

Figure 8: Mole Fraction of the Trays 1 to 20 (Number of epochs = 100)

Figure 9: Mole Fraction of the Trays 1 to 20 (Number of epochs = 150)
6. Conclusion
We have presented the control system design of a binary distillation column under disturbance. Control of the top and bottom compositions of the column is a difficult task due to presence of the control loop interactions and nonlinearities. The structure allows taking into account dynamic variations of the process and adapting the controller parameters to this various conditions. Fuzzy controllers achieved a accurate performance in controlling the top and bottom compositions and also in controlling the feed rate, top and bottom rates. As it is shown in simulation results (figures 6 and 7) the defined errors are more close to zero and the system operates approximately around it's set points (0.02 and 0.98). Also according to the figures 8 and 9 we can see that the mole fraction on the trays 1 and 20 respectively close to 0.02 and 0.98 and for the other trays (2 to 19) the mole fraction varies from 0.02 to 0.98. Finally as it is shown in figures 10 and 11 the rates of the outputs (Bottom and Top products) is equal to the feed rate (input) as we expected.

7. Acknowledgment
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References:

Figure 12: A view of complete system

Figure 13: Binary Distillation Column
Figure 14: A sample of designed trays (trays 11-15)

Appendix

Nomenclature:

- $M_D$: Liquid Holdup in the Reflux Drum
- $M_B$: Liquid holdup in the Column Base
- $M_{n}$: Liquid Holdup on the $n^{th}$ Tray
- $x_n$: Liquid Composition on the $n^{th}$ Tray
- $y_n$: Vapor Composition on the $n^{th}$ Tray
- $L_n$: Internal Reflux Rate on the $n^{th}$ Tray
- $D$: Distillate Rate
- $B$: Bottom Rate
- $V$: Reboiler Rate
- $L$: Reflux Rate
- $F$: Feed Rate
- $F_F$: Feed Composition
- $X_D$: Top Composition
- $X_B$: Bottom Composition
- $I_{N_{T+1}}$: Initial Value of Reflux Rate
- $D$: Initial Value of Distillate Rate
- $B$: Initial Value of Bottom Rate
- $V$: Initial Value of Reboiler Rate
- $F$: Initial Value of Feed Rate
- $F_F$: Initial Value of Feed Composition
- $N_T$: Number of Trays
- $N_S$: Feed Tray (10^{th} Tray)
- $\alpha$: Relative Volatility
- $\beta$: Parameter of the Relationship between Liquid Holdup and Liquid Rate on each Tray.