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Comparison of Controller and Interaction Analysis of Multi-Vessel Batch Distillation

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Abstract

Background/Objectives: This paper is focusing on choosing the best controller and interaction analysis on multi-vessel batch distillation (MVBD). **Methods/Statistical Analysis:** A mathematical model is developed first by adapting simple model assumption. Open loop and closed loop models are simulated using Matlab SIMULINK. Proportional (P) and Proportional Integral (PI) are implemented on the control system. The result of closed loop is then analyzed using Relative Gain Array (RGA) method to indicate the best control loop pairing. Set point changes analysis is done to ensure the stability of controller. **Findings:** Two level control with two manipulated variables (reflux flow and middle vessel flow) is chosen based on the RGA analysis. Level control with PI controller gives better performance for MVBD control system. Moreover, with the presence of two level controls, the system is also able to keep the vessel holdup constant and maintain the desired product purity at a time. **Application/Improvements:** The study of interaction analysis can be extended to other control strategies proposed for this system. Meanwhile, the performance of the controllers can be further improve by adapting different type of tuning methods.

Keywords: Multi-Vessel Batch Distillation, PI Controller, RGA Analysis

1. Introduction

Three mode controllers with proportional, integral, and derivative (PID) actions have become commercially available and gained widespread industrial acceptance for past few decades. These types of controllers are still widely used in process industries as no other controllers match the simplicity, clear functionality, ease of use, robustness and wide applicability[1].

Control system is very important in chemical industry in order to produce the product within specification, safety purpose and environmental aspects. In multi-vessel batch distillation, controller plays important roles to maintain the total reflux operation by keeping the vessel holdup constant along the time. Higher degree of separation can be achieved if the vessel holdup is kept constant at certain value during operation. Multi-vessel batch distillation is mainly used in specialty chemical, biochemical and pharmaceutical industries[2]. It is a combination of inverted and middle vessel batch distillation[3] and an energy-efficient batch separation unit compared to other batch distillation. Multi-vessel batch distillation is a MIMO system because it has multiple inputs and multiple outputs. Control of MIMO system is relatively complex. It is difficult to design a controller due to the fact that each manipulated variable has a tendency to affect each controlled variable. The RGA provides a quantitative approach to the analysis of the interactions between the controls and the output, and provides a technique for pairing manipulated and controlled variables to generate a control scheme[4]. In this paper, modelling and simulation, controller selection and interaction analysis of control loop are performed.

2. Modelling and Simulation of Multi-vessel Batch Distillation

A mathematical model of multi-vessel batch distillation is developed based on the first principle including mass and component balance. The model was developed based on the following assumptions: (1) Total condenser, (2) Constant vapour rate,(3) Molar vapour rate is always equal to the liquid rate, (4) Total reflux operation, (5) Each

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stages is in equilibrium[5]. Configuration of multi-vessel batch distillation as shown in Figure 1 consists of one condenser, one reboiler V_3, two column and two vessel V_1 and V_2 mounted along the column[1]. A three-component liquid mixture is charged to the reboiler and all vessels. Holdup in reboiler (B) and holdup in top vessel (H) and middle vessel (M) is specified in advanced[5]. Heat is input into the reboiler. The components vaporise according its boiling point. Vapour (y_1) coming out from the column is fully condensed into liquid. Light component (x_H) will be accumulated mainly in the top vessel, intermediate component (x_M) will be accumulated in middle vessel while the heavy component (x_B) are mainly in the reboiler. The products are collected after the system reaches steady state[2].

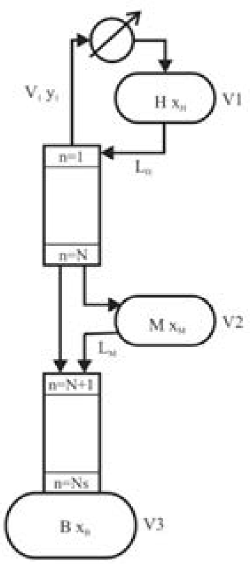


Figure 1. Multi-vessel Batch Distillation Column Configuration[2].

2.1 Control of Multi-vessel batch distillation

In order to achieve highest degree of separation, multi-vessel batch distillation needs to be operated under total reflux operation. To maintain total reflux operation, vessel holdup must be kept constant[6]. Level control is directly used to keep the vessel holdup constant as well as indirectly to maintain the product purity at desired level instead of composition control[7]. Composition control is not preferable due to high cost and very sensitive. Two-level control (Top vessel level and middle vessel level) with two manipulated variables (reflux flow and middle vessel flow) are selected based on degree of freedom calculation.

No advance process control is required. Conventional controller is sufficient enough to control the multi-vessel batch distillation system. P and PI controller are implemented to the system. Controller with lower settling time, no overshoot and acceptable rise time were selected.

2.2 Interaction Analysis (RGA)

A MIMO control scheme is important in systems with multiple dependencies and multiple interactions between different variables, as found in a batch distillation column, where a manipulated variable such as the reflux flow and vessels flow could directly or indirectly affect the vapour and liquid flow rate, the product composition, and the reboiler energy[4].

Thus, to design and implement a control scheme for a process understanding the dependence of different manipulated and controlled variables, MIMO control scheme could be extremely helpful. RGA is one of the method for designing and analysing a MIMO control scheme for a process in steady state. The RGA can be calculated based on following equation:

$$\text{? EMBED Equation.3 ???}_{11} = \frac{1}{1-\frac{K_{12}K_{21}}{K_{11}K_{22}}} \qquad (1)$$

$$\text{? EMBED Equation.3 ???} = \begin{bmatrix} \text{? EMBED Equation.3} \\ \text{? EMBED Equation.3} \end{bmatrix}$$

$$\begin{matrix} \text{???}_{11} & \text{? EMBED Equation.3 ???}_{12} \\ \text{???}_{21} & \text{? EMBED Equation.3 ???}_{22} \end{matrix} \qquad (2)$$

A matrix with each input variable in one column and each output variable in one row for the MIMO system is called array. This format allows a process engineer to match the input and output variables with the biggest effect on each other while also minimizing undesired side effects and easily compare the relative gains associated with each input output variable pair[4].

3. Results and Discussion

The simulation is done for closed loop model with P and PI controller. The response is shown in Figure 2-3.

Figure 2 shows the response of each vessel holdup with P controller. The response for both vessel shows stable response, no overshoot is present. Holdup in top vessel not achieved its set point (1 molar) about 2.5 percent. While holdup in middle not achieved its set point (4 molar) about 8 percent. The settling time is less than 4min for both response in top and middle vessel. Figure 3 shows the response of each vessel holdup with PI controller. For top vessel holdup, there is an overshoot present about 7 percent as shown in Figure 4 and the settling time of less than 5min is much higher compared to P controller. Meanwhile, for middle vessel, the overshoot presented is about 5 percent and the settling time is less than 8min.

The composition profile of component in each vessel is shown in Figure 5 (a)-(c).

Based on the figure, the product composition for each vessel reach steady state during 250min to 300min. The response of the product composition is stable and the desired product purity (0.95 mole fraction of ethanol) is successfully produced. The results shown ethanol is dominant in top vessel, 1-propanol is dominant in middle vessel and n-butanol is dominant in stillpot (reboiler).

Composition of final product is said to be indirectly related to level control in vessel holdup. If vessel holdup decreases the composition increases. Hence, in order to obtain desired product composition, the vessel holdup must be kept constant at specified value[6]. A study on the set point changes is also performed in this paper. The vessel holdup is changed to be half from previous value (0.65:2). The response of level holdup is shown in Figure 6-8.

The level profiles show that the system achieves its new set point with stable response for both P and PI controller. For PI controller, by referring to Figure 8 there is an overshoot occurred about 7.7 percent (top vessel) and 5 percent (middle vessel) and settling time about 8 minutes for both top and middle vessel. While for P controller, there is no overshoot occurred and settling time for both vessel is less than 4 minutes. However the set point for (0.65 molar) top vessel and (2 molar) middle vessel is not achievable with the offset about 7.7 percent and 2.5 percent for top and middle vessel respectively.

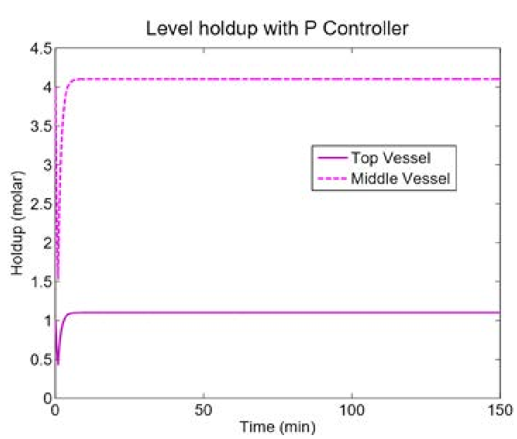


Figure 2. Level holdup with P controller (1:4).

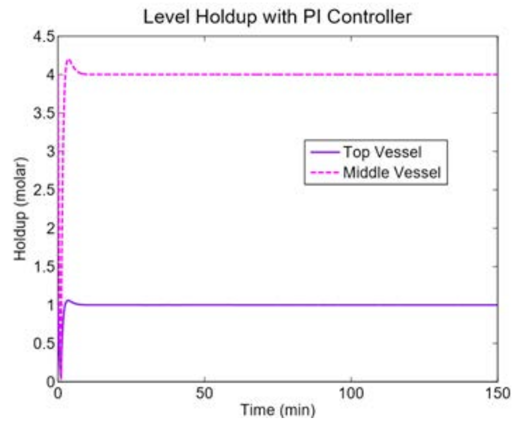


Figure 3. Level holdup with PI Controller (1:4).

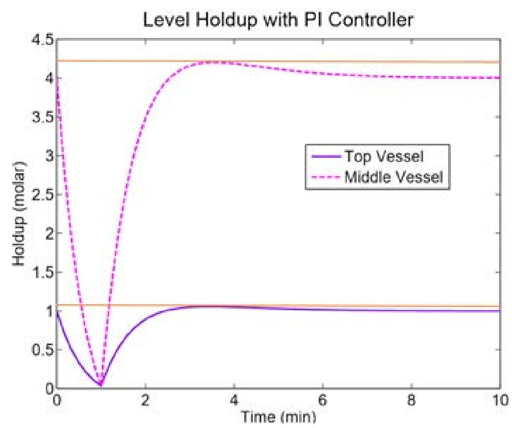
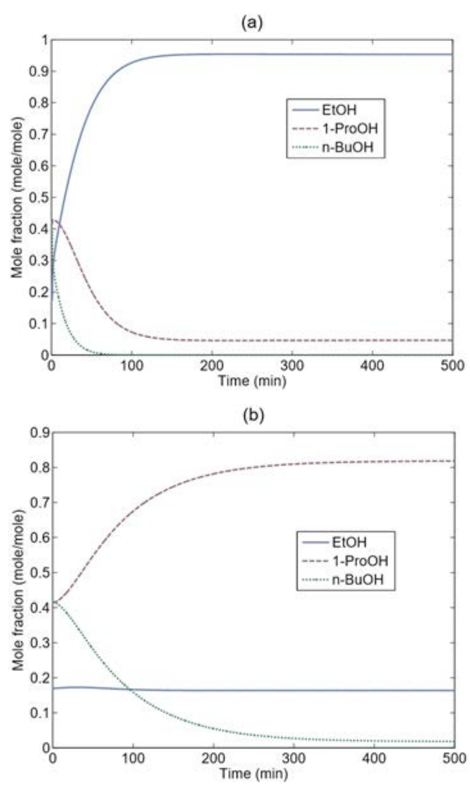


Figure 4. Overshoot of PI Controller.



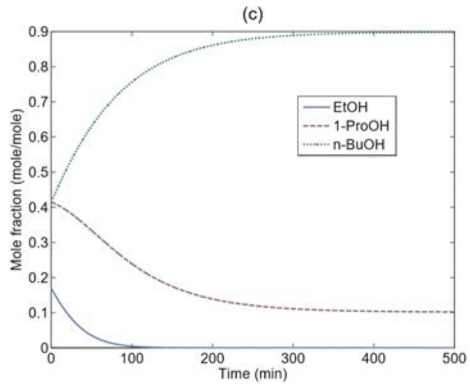


Figure 5. Composition Profile a)Top Vessel b)Middle Vessel c) Stillpot.

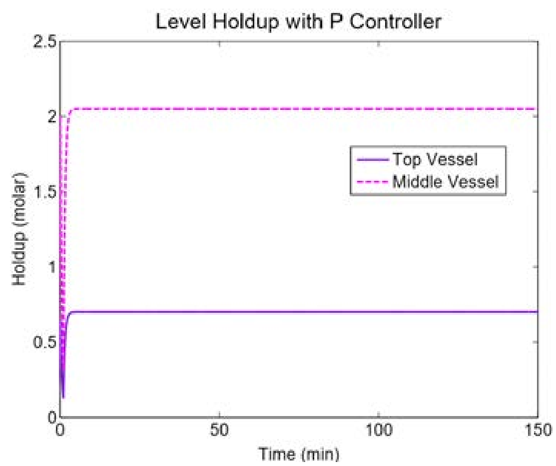


Figure 6. Level holdup with P Controller (0.65:2).

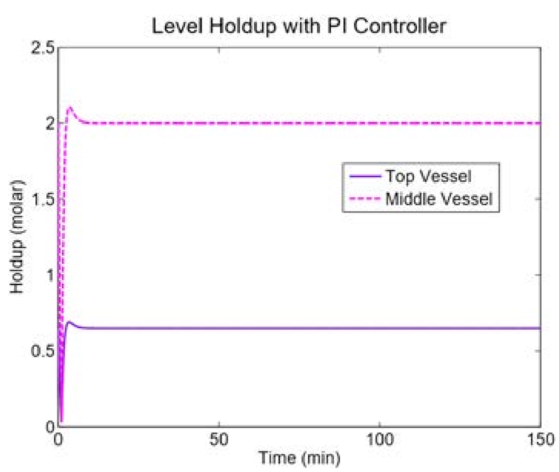


Figure 7. Level holdup with PI Controller (0.65:2).

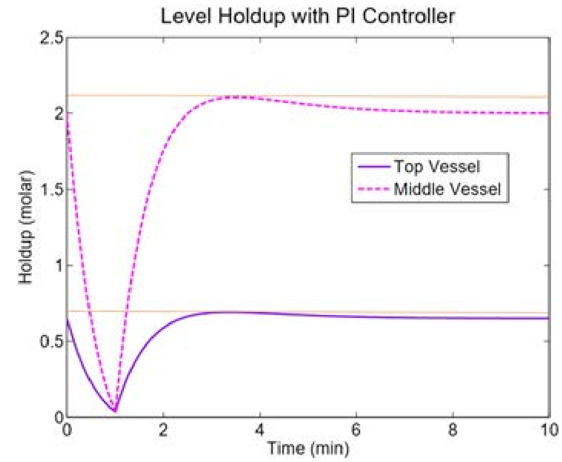


Figure 8. Overshoot of PI Controller.

3.1 RGA Analysis

The relative gain array can be evaluated from steady state gain matrix, thus the matrix below shows the result from calculation:

EMBED Equation.3 $= \begin{bmatrix} 2.95 & -1.95 \\ -1.95 & 2.95 \end{bmatrix}$ (3)

From the result of relative gain array best pairs of manipulated and controlled variables are found. Since only the pairing H_1-L_H and H_M-L_M have a positive relative gain value, thus reflux flow – level top vessel and middle vessel flow – level middle vessel is found to be best pairs.

4. Conclusion

In this paper, the study on type of controller is performed. Based on the result, level control with PI controller is preferable compared to level control with P controller because the system successfully achieved its set point with PI controller and gives better performance. The system is stable although the set point is changed. Product purity is depending on the vessel holdup. The lower the vessel holdup until certain value, the higher the product purity. Hence, it is important to keep the vessel holdup constant. According to composition response, level control with PI controller can guarantee to keep the vessel holdup constant. The interaction analysis between two level control loops is also performed. It is proven by RGA calculation that reflux flow is the best pair for level of top vessel and middle vessel flow is the best pair for level of middle vessel due the positive eigenvalue.

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