Dynamic Simulation and Control of Vapor Recompression Column

Hojjat Dehghani, Mohammad Ali Fanaei*, Saeed Nadi
Department of Chem. Eng., Faculty of Eng., Ferdowsi University of Mashhad, I.R. Iran
fanaei@um.ac.ir

Abstract
Vapor recompression column is a type of energy integrated distillation columns that has a good potential for applying in industrial plants. In this paper the dynamic simulation and control of a vapor recompression column by using Aspen-Hysys 2009 was investigated. For this purpose a control structure with five control loops; two levels, one pressure and two compositions; was selected. The results of dynamic simulation showed that low interaction exists between the composition control loops and the selected control structure can work properly in case of changing in composition set-points and feed disturbances. In addition, the results showed that the energy saving by using this method would be about 75.8% in comparison with conventional column.

Keywords: Vapor Recompression Column, Control Structure, Dynamic Relative Gain Array

Introduction
Distillation is the oldest process that was used for separation in chemical plants. Although different purification methods like adsorption, membrane and etc. were improved in the last decades, but yet distillation is widely applied in the chemical industries because it is more economical in large scales.
Distillation columns have three important disadvantages that are consisting of:
1) The thermodynamic efficiency is usually low; for example, for a separation of close-boiling mixture it is about 10%.
2) High energy demand; about 40% of total energy consumed in japan refineries and chemical industries and also 6% of energy needed in United States is related to distillation columns and totally the portion of energy requirement for these units in the world is almost 3%.
3) Emissions of pollutant gases like CO_2.
To decrease these problems, different energy integration methods were considered in last decades. In 1937, Brugma introduced the thermally coupled distillation column and then corrected by Wright [1] and finally analyzed by Petlyuk [2] in 1965 for a ternary mixture. In 1976, Null [3] proposed heat-pump assisted distillation column or Vapor Recompression

* *To whom corresponding should be addressed.*

Column (VRC). In this configuration, top vapor stream of the column enters a compressor and its pressure and temperature increases, so this stream can be used as a heat source for the bottom stream of the column to supply the boil-up needed and also a portion of vapor stream would be condensed and then its pressure decreases to the column pressure. The remainder vapor may condensed by a trim condenser. Figure 1 shows the schematic of VRC configuration. Optimum conditions of a VRC based on a static model were investigated by Null and Quadri [3, 4]. Luyben et. al [5] modeled and controlled this system for the mixture of ethanol and water and compared it with the propane and propylene mixture. Jogwar et.al [6] did the similar work based on a multi-scale dynamic model. It is necessary to note that in most of previous studies some simplifying assumptions are used in static and dynamic modeling but in our work a complete detailed model is used for static and dynamic simulation.

The energy integrated distillation columns have disadvantages like more initial capital costs in comparison with conventional columns; but many researchers showed that the total annual cost of these methods is less than conventional columns. The biggest problems of these configurations are complex design and controllability of the process. In this paper, we simulated the VRC system for separating the mixture of water and methanol by Aspen-Hysys 2009 software in dynamic mode and compared its energy requirement with the conventional column. Also we selected a control structure for this configuration and finally the performances of the selected control structure were analyzed in case of changing in composition set-points and feed disturbances.

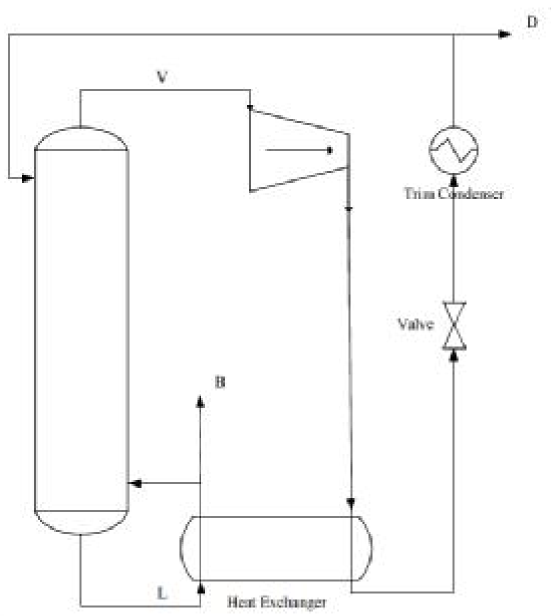

Figure 1. Schematic of VRC configuration

Simulation

Thermodynamic Model Validation

We can trust the simulation results when the thermodynamic model estimates the behavior of the mixture correctly. In our simulation we used NRTL equation for the mixture of methanol and water and compared T-XY diagram that is obtained with this equation and the experimental equilibrium data from Chemical Engineering Research Information Center in 2007, as you see in Figure 2. The binary coefficients of NRTL equation are presented in Table1.

Table 1 : Binary Coefficients of NRTL Equation

Components	Water	Methanol
Water	---	-48.673
Methanol	610.403	---

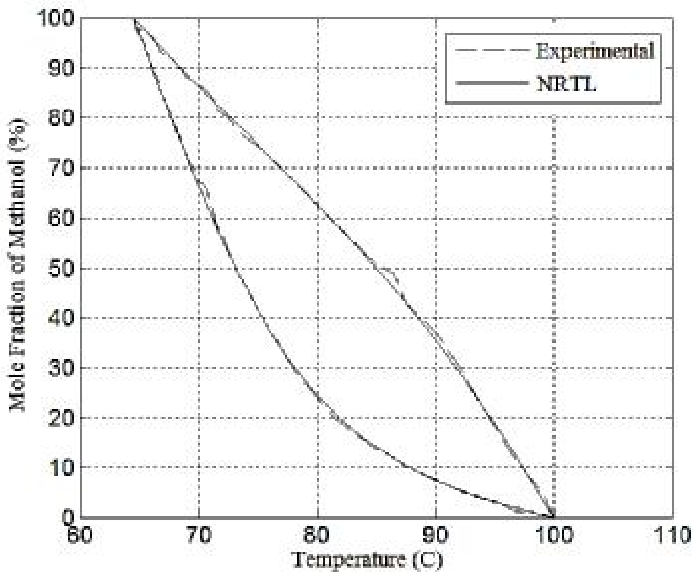

Figure 2. Equilibrium data for Methanol in the mixture of Methanol and Water

Simulation Details

Figure 3 shows the simulated flowsheet for the VRC configuration. The column and its feed specifications are summarized in Tables 2 and 3, respectively. The final desired compositions were 95.5% mole for the methanol as the distillate and 95% mole for the water as the bottom product. The compression ratio of the compressor was adjusted about 4.1 to ensure that the minimum temperature approach is close to 20 ^{o}C as a thumb rule for having nucleate boiling of the bottom liquid in the heat exchanger at steady state condition. The heat that should be exchanged between two streams is 3.234×10^{6} kj/hr to evaporate 81.21 kmole/hr of the bottom stream as the boil-up (boil-up ratio=1.417). The vapor that was condensed partially enters a throttling valve and its pressure reduces. In the trim condenser remainder vapor condenses, about 51.9 kmole/hr is refluxed to the column and 56.74 kmole/hr exits as the top product.

Table 2 : Column Specifications

Diameter (m)	2
Stages	12
Tray Spacing (m)	0.609
Feed Stage	6
Column Pressure (kpa)	103

Table 3 : Feed Specifications

Temperature (°C)		74.39
Composition (Mole Frac.)	Methanol	0.5
	Water	0.5
Flow (kmole/hr)		114

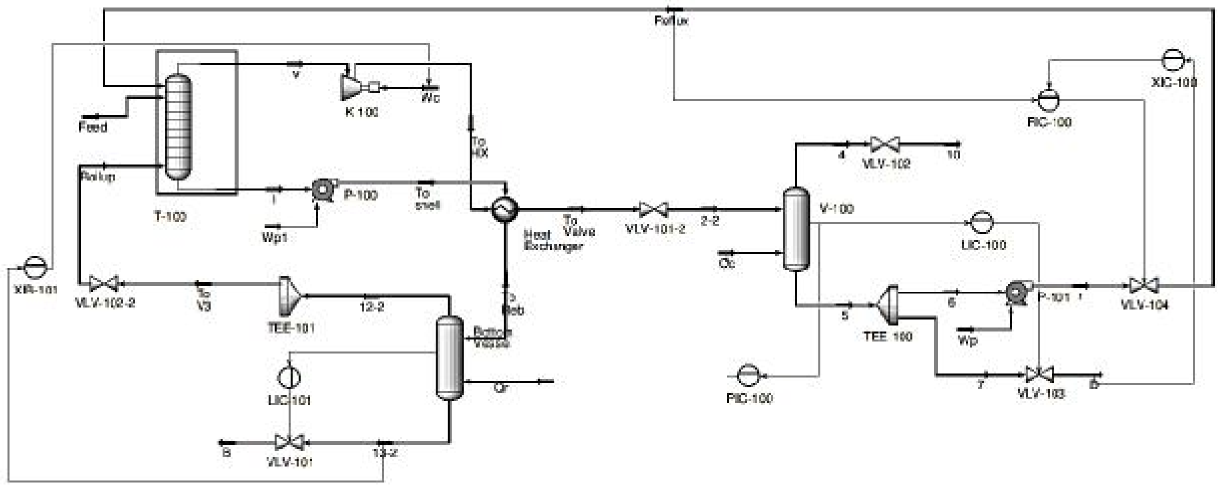

Figure 3. Simulated flowsheet of Vapor Recompression Column

Process Control Structure

The selected control structure has five main loops; one pressure controller (PIC-100), two level controllers (LIC-100 & LIC-101) and two composition controllers (XIC-100 & XIB-101). A cascade structure is used to control the composition of distillate, as shown in Figure 3 (XIC-100 is the master and FIC-100 is the slave controller). The Proportional-Integral (PI) mode is used for all controllers and the Relay feedback auto-tuner of Aspen-Hysys is used for the controller tuning. The controllers' specifications are shown in Table 4.

Table 4 : Controllers Specifications*

Controller	K	τ (min)	PV_{min}	PV_{max}
XIC-100	1.6	21.3	0.93	0.999
FIC-100	0.02	0.02	38	68 (kmole/hr)
XIB-101	0.7	11	0.85	0.999
PIC-100	0.0763	2.58	90	125 (kpa)
LIC-100	11.5	0.35	0	100 (%)
LIC-101	25	2	0	100 (%)

* Output signals change between 0 to 100%
PV=Process variable, K= Proportional gain, τ= Integral time constant

Results and Discussion

Energy Consumption

The main advantage of VRC is in the reduction of energy consumption and so operation costs. Table 5 shows the energy requirements for different units of conventional and vapor recompression columns. The total saved energy in VRC configuration was calculated by the following equation:

$$\text{Energy Saving}(\%) = \frac{(|Q_C|+Q_r) \text{ in Conventional column} - (|Q_C|+W_C) \text{ in VRC}}{(|Q_C|+Q_r) \text{ in Conventional column}} * 100 \quad (1)$$

Where Q_c, Q_r and W_c are condenser duty, reboiler duty and compressor power, respectively.

Table 5 : Comparison of energy consumption (kw)

Column	Q_c	Q_r	W_c	Energy Saving (%)
Conventional	-1062	905.4	---	---
Vapor Recompression	-324.9	0	150.3	75.8

Although the capital cost of VRC would be greater than conventional column but about 75.8% energy saving shows a large potential for reduction of total annual costs.

Performance of selected control structure

Interaction between the loops may cause poor controlling and deviations from set point or slow dynamic and in special cases instability problems. For a multi input-multi output (MIMO) system, Relative Gain Array (RGA) was proposed as a controllability measure by Bristol [7] in 1966. RGA gives a quantitative measure to determine the interaction effect and also shows the best pairings [8].

In VRC process, two compositions control loops have slow dynamics and may have interaction. In the first step of interaction analysis, a simple dynamic model of the process must be derived. For this purpose a step change (±3%) in reflux flow rate and compressor duty was applied and based on the recorded open loop responses (composition of top and bottom products) the following model was derived:

$$\begin{bmatrix} x_D \\ x_B \end{bmatrix} = \begin{bmatrix} \frac{0.19}{30.335S+1}e^{-3S} - \frac{0.03}{59.9S+1}e^{-85S} & \frac{-0.0246}{19.835S+1}e^{-3S} + \frac{0.0173}{73.35S+1}e^{-57.5S} \\ \frac{-0.424}{52.4S+1}e^{-3.2S} & \frac{0.19325}{45.75S+1}e^{-S} \end{bmatrix} \begin{bmatrix} R \\ W_c \end{bmatrix} \quad (3)$$

In steady state condition RGA matrix is calculated by:

$$\Lambda = G(0) \otimes (G^{-1}(0))^T \quad (4)$$

Where G(0) is the steady state process model and ⊗ means element by element multiplying.
Using the fitted transfer functions (Eq.3) and applying Eq.4 results:

$$\Lambda = \begin{bmatrix} 1.1112 & -0.1112 \\ -0.1112 & 1.1112 \end{bmatrix}$$

This matrix shows interaction is not too important and the pairings of $R - x_D$ and W_c - x_B are appropriate.

Another kind of RGA is dynamic mode (DRGA). The changes of RGA in different frequencies can be investigated by DRGA. In fact, steady state RGA is a special condition of DRGA. DRGA can be calculated by the following equation [8]:

$$DRGA_{ij}\{w\} = sign\left(l_{ij}\{0\}\right).\left|l_{ij}\{jw\}\right| \quad (5)$$

DRGA of VRC process in different frequencies was shown in Figure 4. This figure shows that the best paring is the same in all frequencies.

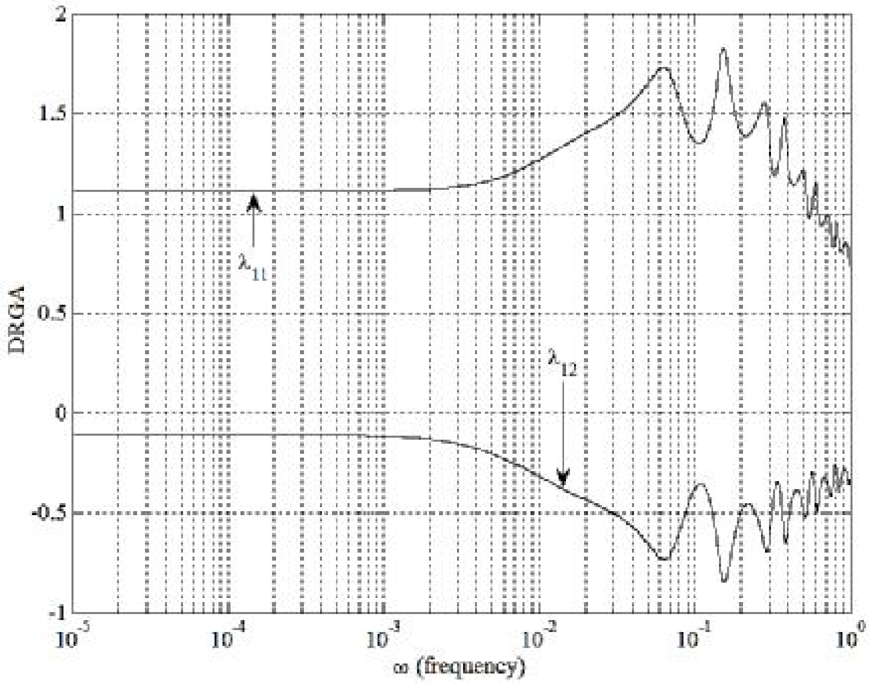

Figure 4. Dynamic Relative Gain Array of VRC process

To investigate the performances of controllers, two disturbances consisting of +5% changes of feed molar flow and changing the feed composition from 50% mole of methanol to 45% were introduced after 20 minutes. Figure 5a and Figure 5b show the responses of composition control loops when the feed flow rate and feed compositions was changed, respectively. In addition, a set-point change of 0.5% was applied in compositions of top and bottom products. The responses of two control loops are shown in Figure 6a and Figure 6b.

As can be seen from the results, both controllers have smooth responses and remove the error from process variables less than about 100 minutes.

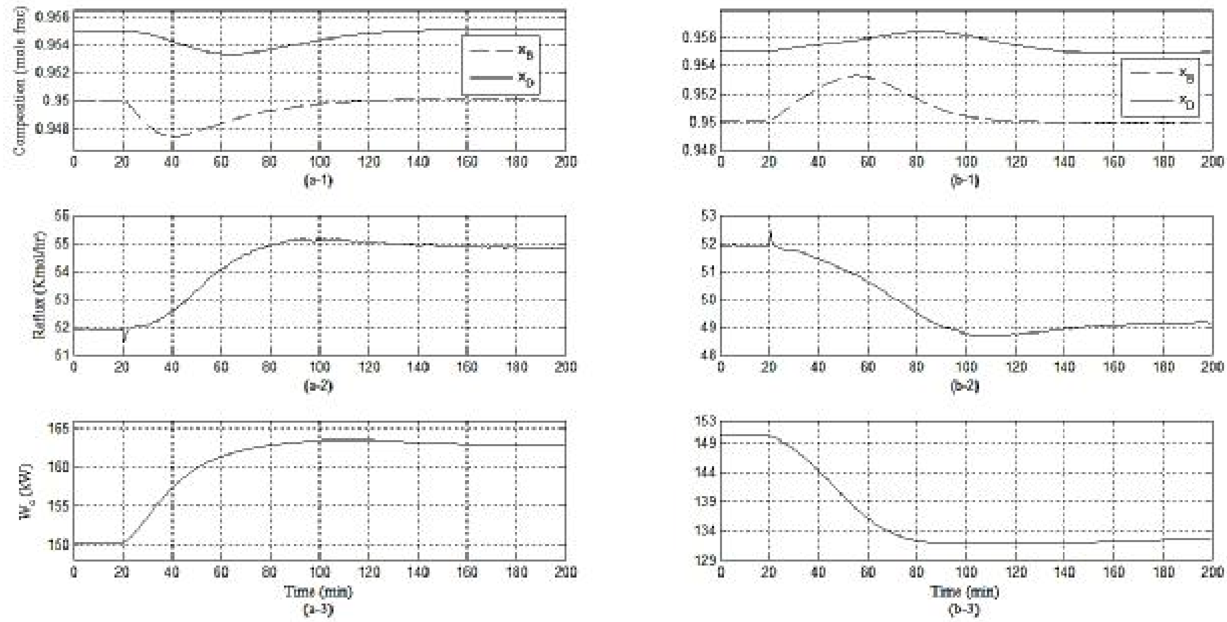

Figure5. (a-1): Responses of compositions for the feed molar flow disturbance; (a-2): Reflux flow changes; (a-3): Compressor duty changes; (b-1): Responses of compositions for the feed composition disturbance; (b-2): Reflux flow changes; (b-3): Compressor duty changes.

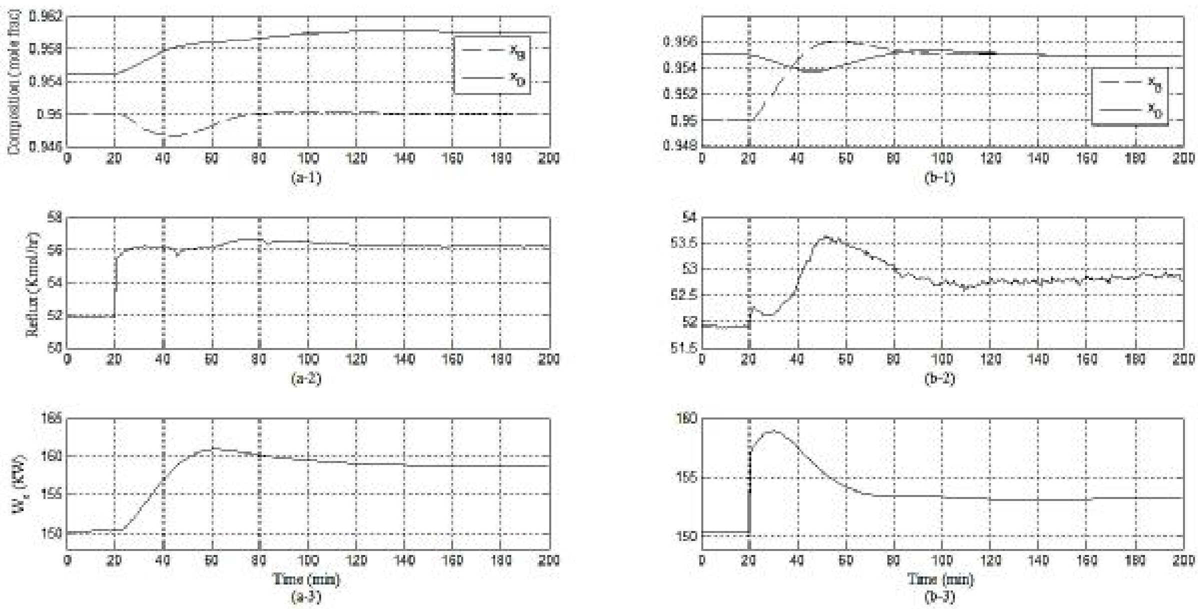

Figure 6. (a-1): Responses of compositions for changing the set point of XIC-100 controller; (a-2): Reflux flow changes; (a-3): Compressor duty changes; (b-1): Responses of compositions for changing the set point of XIB-100 controller; (b-2): Reflux flow changes; (b-3): Compressor duty changes.

The other important control loop is pressure, in Figure 7 the performance of this controller was shown for the changing of feed composition.

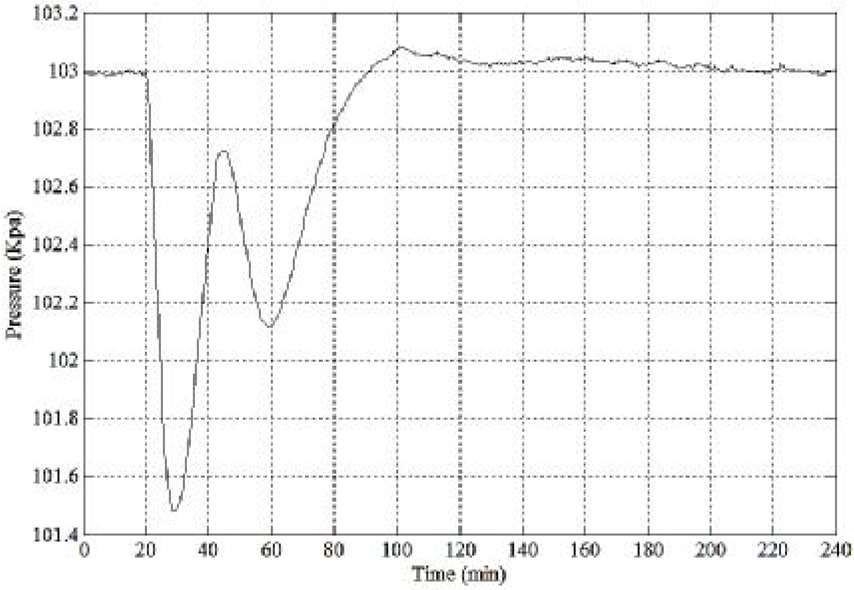

Figure 7. Response of pressure controller for the feed composition disturbance

Conclusions

In this study, dynamic simulation and control of vapor recompression column as one of the energy integrated distillation methods was considered for separating of water and methanol by using Aspen-Hysys 2009. Although energy consumption is reduced about 75.8% but controlling of the system needs more attention. For solving the control problem, a control structure that uses the compressor duty and reflux flow for controlling the bottom and top compositions respectively, was applied and DRGA shows that low interaction exists in this process. Also column pressure is controlled by condenser duty. The results show that the selected control structure has good performances against the disturbances and set-points changes.

References

[1] A.K. Jana, Heat integrated distillation operation, Applied Energy, 87 (2010) 1477-1494.

[2] F.B. Petlyuk, V.M. Platonoy, D.M. Slavinskii, Thermodynamically optimal method for separating multicomponent mixtures, Int. Chem. Eng., 5 (1965) 55-61.

[3] H.R. Null, Heat pumps in distillation, Chem. Eng. Prog., 73 (1976) 58-64.

[4] G.P. Quadri, Use of heat pump in p-p splitter, part1: process design part2: process optimization, Hydrocarbon Proc., 60 (1981) 119-126 & 147-151.

[5] C.A. Muhrer, M.A. Collura, W.L. Luyben, Control of vapor recompression distillation columns, Ind. Eng. Chem. Res., 29 (1990) 59-71.

[6] S.S. Jogwar, P. Daoutidis, Dynamics and control of vapor recompression distillation, J. Process Control, 19 (2009) 1737-1750.

[7] E.H. Bristol, On a new measure of interactions for multivariable process control, IEEE Trans. Auto. Control, AC-11 (1966) 133-134.

[8] W.D. Seider, J.D. Seader, D.R. Lewin, Product and process design principles, 2nd ed., Wiley, New York, 2004.