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# 內隔壁式蒸餾塔之動態與控制

# Dynamics and Control of Divided Wall Columns

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# 摘要

相較於傳統的蒸餾序列，內隔壁式蒸餾塔 (DWC) 是一種在分離多成分混合物時，可以節省更多的能量與設備成本的前瞻性設計。然而，內隔壁式蒸餾塔在設計上也較為困難，因為較傳統序列擁有更多的設計自由度。約莫五十年前，內隔壁式蒸餾塔的設計方法被提出討論，許多論文討論穩態設計問題，並提出啟發式和嚴謹的設計優化方法。但是，內隔壁式蒸餾塔的控制相對的得到較少的關注。此研究主要是針對內隔壁式蒸餾塔分離理想系統的可控性進行調查。對於不同類型的內隔壁式蒸餾塔、不同相對揮發度的分離指標、不同的進料條件，進行可控性的分析。並對於不同的控制策略，採用線性分析工具，相對增益陣列 (RGA) 和條件數 (CN) 進行分析。論文中為符合實際工廠使用的控制策略，利用進料擾動從動態上測試其排除干擾的能力。最後，從控制的角度提出一選擇何種類型內隔壁式蒸餾塔之指導方針。從控制的觀點發現，當進料含有較多輕成分時建議使用上隔板式蒸餾塔；當進料含有較多中間成分時建議使用下隔板式蒸餾塔；當進料含有較多重成分時建議使用上隔板式蒸餾塔。

關鍵字: 內隔壁式蒸餾，控制，相對增益陣列

# Abstract

The divided-wall column system is a promising energy saving alternative for separating multi-component mixtures compared with traditional distillation columns. However the design of DWCs is more difficult because there are more degrees of freedom. The control of the DWC have received much less attention. In this work, the controllability of a divided wall column for separating ideal system were investigated. The main objective of this work is to study the divided-wall column (DWC) controllability. A controllability analysis of the ideal system is done for the separation of different types of DWC, different ease separation index (ESI) and different feed condition. Different control structures are compared using linear analysis tools, relative gain array (RGA) and condition number (CN). Disturbances in feed fowrate and feed composition are used to demonstrate the effectiveness of the proposed control structure. Finally, a guideline for the selection of the divided-wall column is proposed. Based on control considerations for different feed conditions, it is found that: If there is more lightest component in the feed, DWCU is preferred. If there is more middle component in the feed, DWCL is preferred. If there is more heaviest component in the feed, DWCU is preferred.

Keywords: divided-wall column, control, relative gain array

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# 1 Introduction

## 1.1 Preface

Distillation is the most common method for separation in the chemical engineering industry. However distillation consumes a great deal of energy. Improving the structure of distillation columns for energy saving is an important issue.

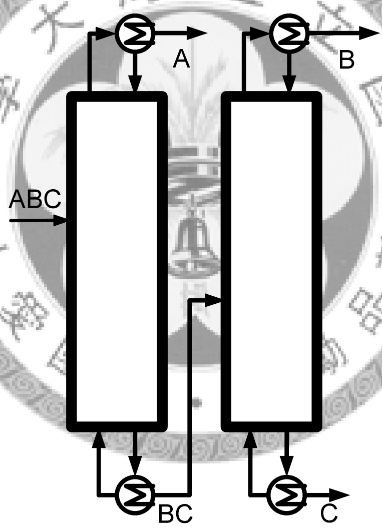


Fig. 1.1-1 Direct sequence (DS).

The remixing phenomenon is one reason for lower energy efficiency in traditional multi component distillation. Take the example of a three component separation where component A is the lightest component, B component is the intermediate component, and C component is the heaviest component. The traditional direct sequence (DS) is shown in Fig. 1.1-1.

The function of first column is to separate A and B. Product A goes out from the top of the column. The liquid mixture of B and C goes into the second column from the bottom of the first column. The separation between B and C takes place in the second column. By observing the composition profile (Fig. 1.1-2), it is found that the mole fraction of B is highest at an intermediate point where no B is removed. The concentration of B near the bottom is decreased due to the increasing concentration of component C. This phenomenon, which causes the decreasing of thermodynamic efficiency, is called the remixing phenomenon.

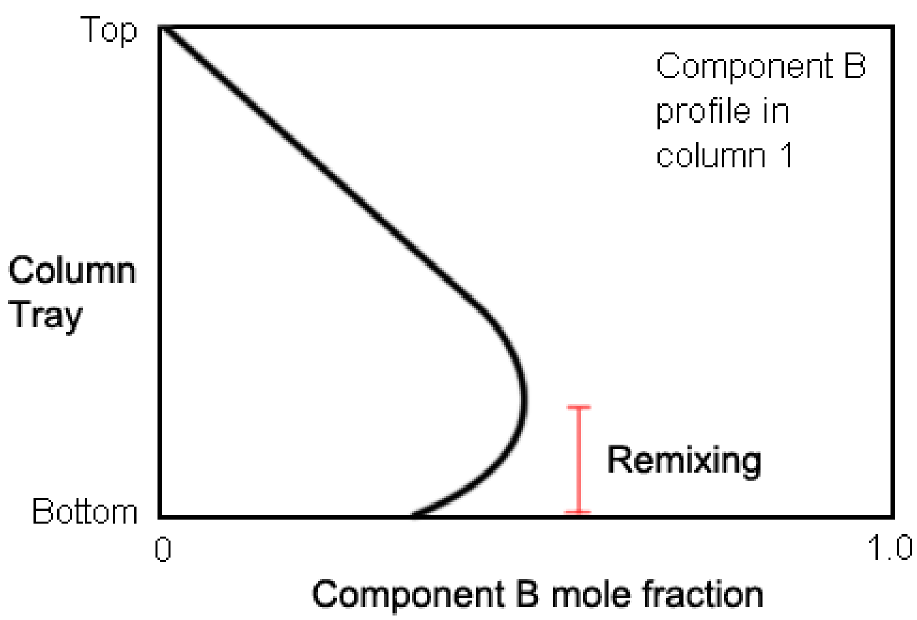


Fig. 1.1-2 B composition profile in the first column and remixing phenomenon.

In 1949, Wright and Elizabeth [1] proposed the divided wall column (DWC). It is a kind of heat integrated column. The remixing phenomenon can be reduced by using a DWC. This will also reduce energy consumption. Because the DWC is only one column, the capital cost is also usually reduced.

Compared to classic distillation design arrangements, DWC offers the following benefits :

- high purity for all three or more product streams reached in only one column
- high thermodynamic efficiency due to reduced remixing effects
- lower capital investment due to the integrated design
- lower energy requirements compared to conventional separation sequences
- small footprint due to the reduced number of equipment units
- reduced maintenance costs as compared to traditional distillation sequences.

Moreover, the list of advantages can be extended when DWC is further combined with reactive distillation leading to the more integrated concept of reactive DWC. Note however that the integration of two columns into one shell leads also to changes in the operating mode and the controllability of such an integrated system. Therefore, all these benefits are possible only under the condition that a good control strategy is available and able to attain the separation objectives.

## 1.2 Introduction for DWCs

All DWC columns have a wall in the column. According to the position of wall, DWCs can be classified into three types as discussed below.

### 1.2.1 DWCL

The first type of DWC is DWCL. The subscript means the wall is in the lower section of column. The DWCL requires two reboilers and one condenser. This construction is evolved from the indirect sequence (IS) (see Fig. 1.2-1).

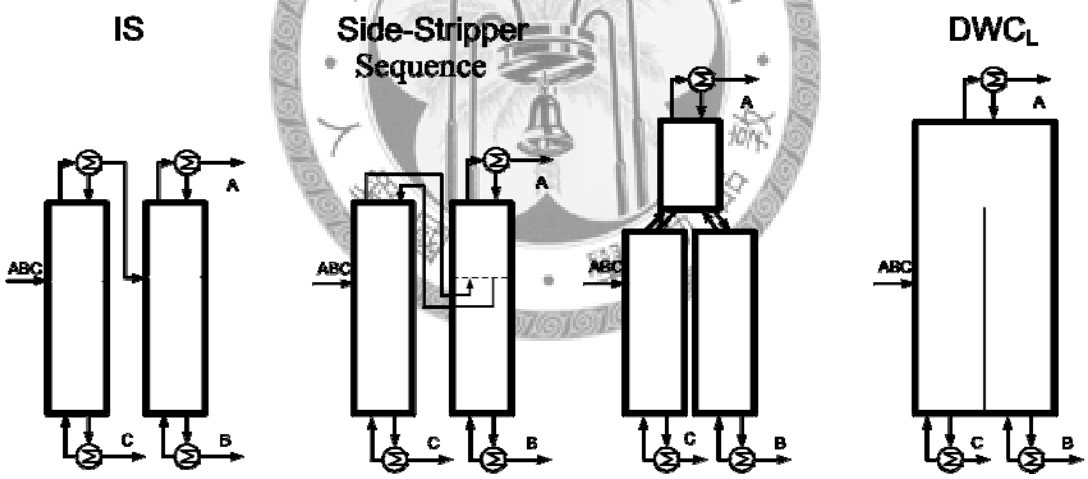


Fig. 1.2-1 The evolution of DWCL

The function of the first column is to separate B and C. Product C goes out from the bottom of the column. The liquid mixture of A and B goes into the second column from the top of the first column. The separation between A and B takes place in the second column.

If thermal coupling is used the condenser in the first column is removed. The reflux is split between the two columns at a certain tray, and the vapor is send to a certain tray in the second column. This structure is called the side striper sequence. The side striper sequence can be divided into three parts. The reflux from the upper section flows into the left section and right section. There is a reboiler in each left and right section. Vapor from left and right section meet at the upper section. A column with a wall in the lower section has the same effect as the side striper sequence, and DWCL is thermally equivalent to the side striper sequence.

### 1.2.2 DWCU

The second type of DWC is DWCU. The subscript means the wall is in the upper section of column. The DWCU has one reboiler and two condensers. This construction is evolved from direct sequence (DS) (see Fig. 1.2-2)

The function of first column is the separation between A and B. Product A goes out from the top of the column. The liquid mixture of B and C goes into the second column from the bottom of the first column. The separation between B and C takes place in the second column.

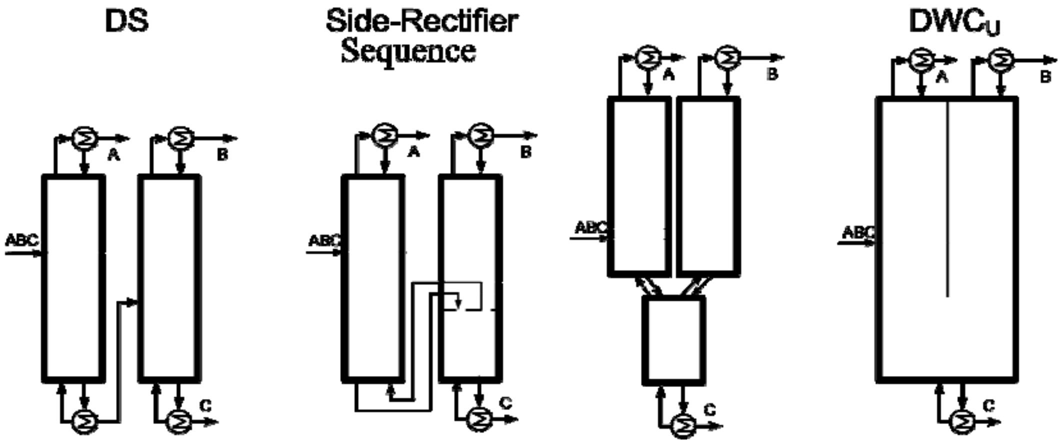


Fig. 1.2-2 The evolution of DWCU.

If we do the thermal coupling the reboiler in the first column is removed. The vapor is from a certain tray in the second column, and the reflux is sent to a certain tray in the second column. This structure is called the side rectifier sequence. The Side Rectifier sequence can be divided into three parts. The vapor from the lower section flows into the left section and right section. There is a condenser in each left and right section. Liquid reflux from the left and right section meet at the lower section. The column with wall in the upper section has the same effect with the side rectifier sequence. And DWCU is thermally equivalent to the side rectifier sequence.

### 1.2.3 DWCM

The third type of DWC is DWCM. The subscript means the wall is in the middle section of column. The DWCM needs only one reboiler and one condenser. This construction is evolved from prefractionator sequence (PF) (see Fig. 1.2-3).

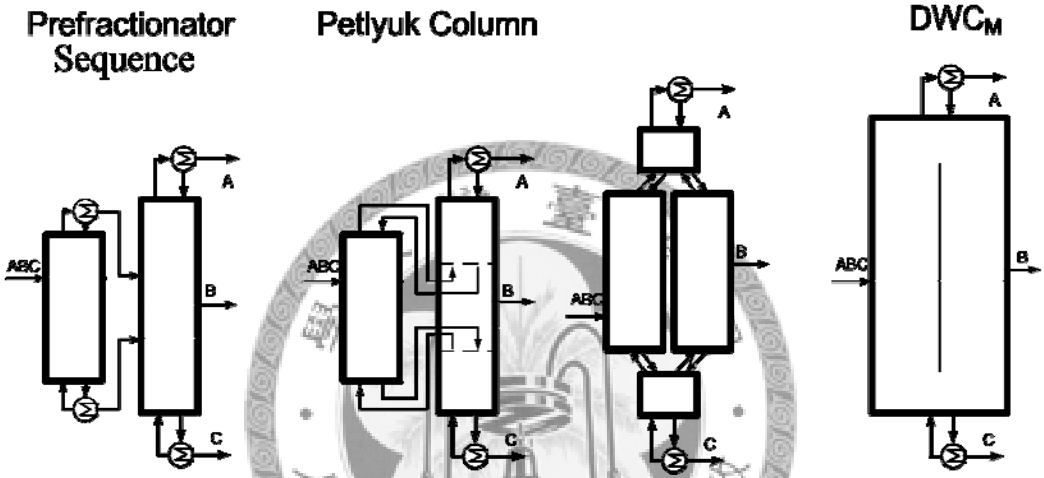


Fig. 1.2-3 The evolution of DWCM.

Compared with IS and DS, the difference for PF is the function of first column. The first column separates A and C. Most of species A goes into the second column near the top of the first column. Most of species C goes into the second column near the bottom of the second column. Part of the B goes into the second column near the top of first column and the other part goes into the second column near bottom of first column. The mixture of A and B from the first column will separate in the upper section of second column. The mixture of B and C from the first column will separate in the lower section of second column. Finally, A goes out from the top of second column, B goes out from the sidedraw and C goes out from the bottom of second column.

If we do the thermal coupling, the reboiler and condenser in the first column are removed. The vapor is from a certain tray in the second column. And the reflux is sent to a certain tray in the second column. The reflux is from a certain tray in the second column. And the vapor is sent to a certain tray in the second column. This structure is called Petlyuk Column. It is also called fully thermally coupled column.

A Petlyuk column can be divided into four parts. The vapor from the lower section flows into the left section and right section and meets at the upper section. Liquid reflux from the upper section flows into the left section and right section and meets at the lower section. The column with wall in the middle section has the same effect with Petlyuk column. And DWCM is thermally equivalent to Petlyuk column.

## 1.3 Literature survey

A literature study reveals that a variety of controllers are used for distillation columns. For the study of control of DWC systems, Wolff and Skogestad [2] proposed a control strategy for the ethanol/propanol/butanol system. They demonstrated that at some operating conditions the ‘holes’ phenomenon in the steady state feasibility space made the energy control structure infeasible. They used the M type of DWC systems. Abdul Mutalib et al. [3] proposed a control strategy for methanol/2-propanol/butanol system. Their performance is just for feed flow rate disturbance and they didn’t use the other manipulated variables to minimize energy consumption. In the same year they proposed a temperature control strategy for the same system [4]. Their simulation results showed that the control structure which controls two temperatures and fixes the side stream flow does not provide effective control. They used the M type of DWC systems.

Several authors studied the design phase of the dividing-wall column in order to improve the energy efficiency [5] [6]. The design stage of a DWC is very important as in this phase there are two DOF that can be used for optimization purposes. Halvorsen and Skogestad [7] discussed the steady-state behavior. They proposed two important objectives for the control policy. The first one is keeping the heaviest component from going out the top of the prefractionator. The second one is keeping the lightest component from going out the bottom of the prefractionator. The optimal solution surface of the minimal boilup is given as a function of the control variable liquid split and the design variable vapor split. They used response surfaces to describe the relationship between liquid split and energy consumption. They suggested that the control of temperature differentials is a good policy to infer composition. The system of DWC that they used was M type.

A more practical approach is suggested by Serra et al. [8]. A linearized model is used to design PI feedback controller. They proposed both PID control and DMC control strategies for three different systems. The authors used several linear analysis tools – Morari resiliency index (MRI), condition number (CN), relative gain array (RGA) to select variable pairings for three compositions control. They demonstrated that PID control gave better load disturbance than DMC control. In 2003 they concluded their previous work and gave two observations [9]. The first one is that DWC has better controllability for mixtures with ESI close to 1. The second one is that the DWC controllability at the optimal operating point is worse than the non-optimal one. The system of DWC that they used was M type.

A more advanced approach for DWC control is model predictive control (MPC) as discussed by Adrian et al. [10]. They proposed PID and MPC control strategies for butanol/petanol/hexanol system. In the PID control, the reboiler heat input was not used to control compositions, but it was in MPC control. The MPC controller outperforms a single PI loop. Three temperatures are controlled by the reflux ratios, the liquid split, and the sidedraw flow rate, respectively. The disturbance variable in this case was the feed flow rate. They used the M type of DWC systems.

Wang and Wong [11] proposed a control policy for the ethanol/1-propanol/ 1-butanol system. There were large product purity deviations for feed composition disturbances. The authors suggested using a temperature-composition cascade control structure to solve the problem. The performances in dynamic simulation were good. The system of DWC that they used was M type. Cho et al. [12] proposed a control strategy for the benzene/toluene/ p-xylene system. They proposed a profile position control scheme for the control of a DWC with vapor side draw. Relative gain array (RGA) and singular value decomposition (SVD) analysis were used to determine the optimal control configuration. Dynamic simulation showed that the profile position-product composition cascade control can keep the product purities at the desired values in the face of feed and internal disturbances. But they didn't use other manipulated variables to minimize energy consumption. The system of DWC that they used was M type. Ling and Luyben [13] proposed a control strategy for the benzene/toluene/o-xylene system. They concluded that the composition of the heavy component at the top of the prefractionator is an implicit and practical way to minimize energy consumption in the presence of feed disturbances. This specific composition was controlled by the liquid split variable. They also used the M type of DWC systems. Nowadays more and more research groups focus on the controllability of divided-wall column [14] [15].

Huang et al. [16] published a report on the development of DWC systems in industry. There are also many applications of DWC in industry that have been reported. In 1980 BASF built the first commercial DWC. Presently they have twenty-eight DWC columns in operation. BASF is in the minority of chemical companies which that have used DWC systems for over ten years. They focus on the application of DWC in petrochemical field.

## 1.4 Motivation

Although much of the literature focuses on the control of binary distillation columns, there are only a limited number of studies on the control of DWC. And from the literature survey we notice that most research focuses on DWCM. We don’t know that whether DWCL or DWCU is more controllable than DWCM or not.

In this work, we discuss the controllability for different type of divided-wall column and different ease separation index (ESI) and different feed composition. Finally the choice among the three configuration based on control aspect can be made.

## 1.5 Thesis organization

The thesis includes four chapters.

The first chapter is the introduction. Three types of DWCs and their evolutions are introduced. And we also introduce some benefits of DWCs. Then we survey the literature and expound the motivation for this work.

In the second chapter we discuss the steady-state analysis. We use shortcut method to get tray numbers of DWCs. And some linear tools – relative gain array and condition number are used for the steady-state analysis. Finally we show the results of RGA and CN.

In the third chapter we discuss the dynamic analysis. We use Aspen Plus simulator. Then we use IAE and ITAE to determine the better control structure. Finally we show the results of different cases.

The final chapter is the conclusion. The results and discussion of previous chapters are combined. Finally we make a conclusion for the thesis.

# 2 Steady-State Analysis

## 2.1 Thermodynamic properties

In this work, we consider an ideal system where the relative volatility is constant. We also assume constant molar flow. This means that $B_{vp}$ in the Antoine equation Eq. ( 2-1) is the same for all species. Finally we can get the ideal vapor-liquid equilibrium by combing Eq. ( 2-2) to Eq. ( 2-3). P is total pressure. $P^s$ means saturated vapor pressure. Table 2.1-1 shows the thermodynamic properties for system ESI>1. Table 2.1-2 shows the thermodynamic properties for system ESI=1. Table 2.1-3 shows the thermodynamic properties for system ESI<1. The definition of ESI is ESI= $(\alpha_A/\alpha_B)$ / $(\alpha_B/\alpha_C)$.

$$lnP_i^S = A_{VP,i} - \frac{B_{VP,i}}{T_j} \quad (2\text{-}1)$$

$$P = X_{j,A} P^S_{A(T_j)} + X_{j,B} P^S_{B(T_j)} + X_{j,C} P^S_{C(T_j)} \quad (2\text{-}2)$$

$$y_{j,i} = \frac{P^S_{j,i}}{P} X_{j,i} \quad (2\text{-}3)$$

Table 2.1-1 Thermodynamic parameters for ideal system ( ESI>1 )

| ESI > 1 | $\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 7.1 / 2.2 / 1 |
|---|---|
| $A_{vp1}$ (mm-Hg) | 15.200702 |
| $A_{vp2}$ (mm-Hg) | 14.028939 |
| $A_{vp3}$ (mm-Hg) | 13.240360 |
| $B_{vp}$ (K) | -2768.55 |
| Tb(A) (K) | 323.15 |
| Tb(B) (K) | 374.35 |
| Tb(C) (K) | 419.03 |

Table 2.1-2 Thermodynamic parameters for ideal system ( ESI=1 )

| ESI = 1 | $\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 4 / 2 / 1 |
|---|---|
| $A_{vp1}$ (mm-Hg) | 15.200702 |
| $A_{vp2}$ (mm-Hg) | 14.151030 |
| $A_{vp3}$ (mm-Hg) | 13.814470 |
| $B_{vp}$ (K) | -2768.55 |
| Tb(A) (K) | 323.15 |
| Tb(B) (K) | 368.27 |
| Tb(C) (K) | 385.53 |

Table 2.1-3 Thermodynamic parameters for ideal system ( ESI<1 )

| ESI < 1 | $\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 4 / 2.4 / 1 |
|---|---|
| $A_{vp1}$ (mm-Hg) | 15.200702 |
| $A_{vp2}$ (mm-Hg) | 14.689870 |
| $A_{vp3}$ (mm-Hg) | 13.814408 |
| $B_{vp}$ (K) | -2768.55 |
| Tb(A) (K) | 323.15 |
| Tb(B) (K) | 343.63 |
| Tb(C) (K) | 385.53 |

## 2.2 Shortcut method

In this work, we made the following assumptions

1. Constant relative volatility
2. Constant molar flow rate
3. Symmetric column

We consider that the relative volatility is independent of temperature and pressure. A symmetric column is a column with the same number of trays on both the left and right sides of the dividing wall. If the number of trays is different, the pressure drop may be different. This assumption is made for maintaining the same pressure on both sides of the wall.

There are a large number of degrees of freedom in DWC systems, so some simplifications are necessary. An ideal system will be used here for the whole work. We can get the tray number for each section by shortcut design.

Chu [17] built rational models for the three configurations, the net flow compositions can be obtained in an easy way. Underwood's method [18] will be applied to calculate minimum vapor flow for all three configurations.

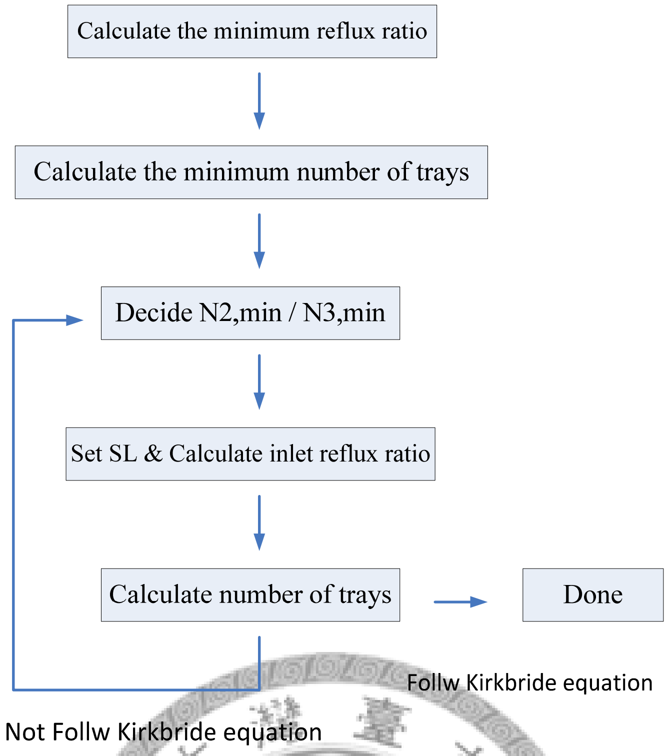


Fig. 2.2-1 Shortcut design procedure for DWCL

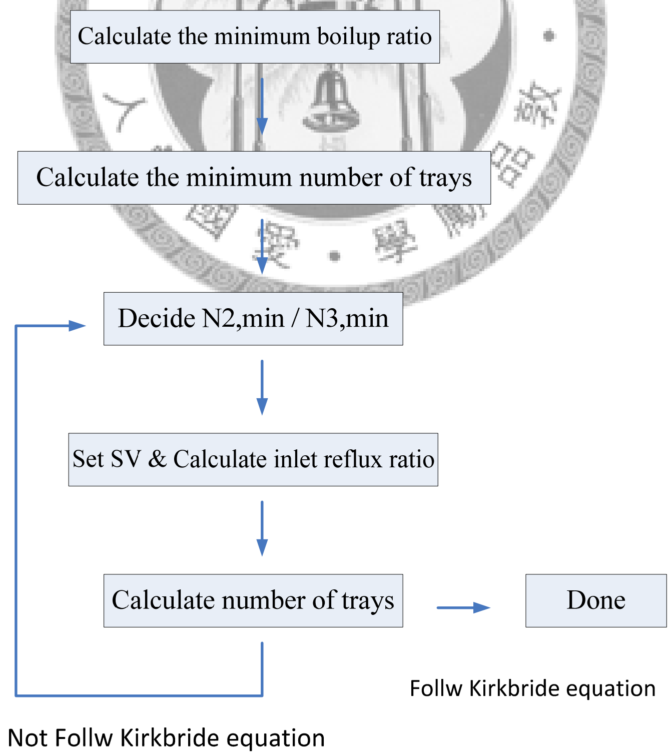


Fig. 2.2-2 Shortcut design procedure for DWCU

The ways to calculate minimum vapor flow for three DWCs are proposed by Halvorsen and Skogestad [19]. The minimum vapor flow is also used to calculate the minimum reflux ratio. After that, the development of the method is based on dividing the DWC into several parts and applying the methods of Fenske-Underwood-Gilliland [20] and the Kirkbride [21] equation. The detail for the shortcut design you can refer to Chu's thesis.

Fig. 2.2-1, Fig. 2.2-2 and Fig. 2.2-3 show the procedure of shortcut design for DWCs. The detail for the shortcut design you can refer to Chu's thesis.

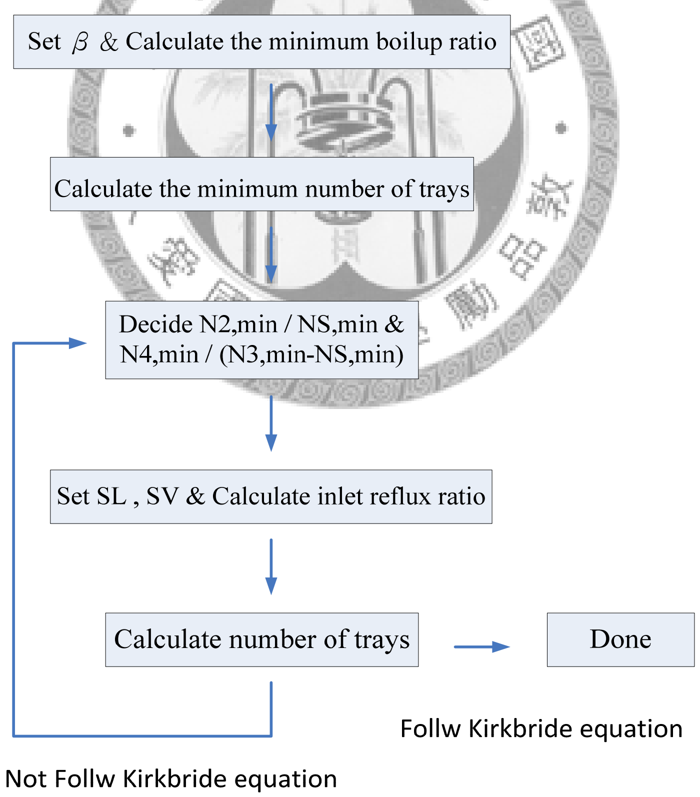


Fig. 2.2-3 Shortcut design procedure for DWCM.

The number of trays for DWCL are given in Table 2.2-1.

Table 2.2-1 Tray number of DWCL

| ESI>1 | | | | |
|---|---|---|---|---|
| Feed Composition | N1 | N2 | N3 | NF |
| 8,1,1 | 40 | 24 | 40 | 24 |
| 1,8,1 | 43 | 12 | 43 | 30 |
| 1,1,8 | 41 | 17 | 41 | 14 |
| 3,3,3 | 41 | 18 | 41 | 22 |
| ESI=1 | | | | |
| Feed Composition | N1 | N2 | N3 | NF |
| 8,1,1 | 44 | 38 | 44 | 27 |
| 1,8,1 | 47 | 18 | 47 | 33 |
| 1,1,8 | 51 | 29 | 51 | 17 |
| 3,3,3 | 48 | 28 | 48 | 26 |
| ESI<1 | | | | |
| Feed Composition | N1 | N2 | N3 | NF |
| 8,1,1 | 38 | 50 | 38 | 23 |
| 1,8,1 | 49 | 22 | 49 | 35 |
| 1,1,8 | 40 | 37 | 40 | 13 |
| 3,3,3 | 37 | 36 | 37 | 20 |

For example, the number of feed composition 8,1,1 in the table means the mole fraction of A component is 0.8 and the mole fraction of B and C component is 0.1.

N1 is the number of tray for column 1. N2 is the number of tray for column 2. N3 is the number of tray for column 3. NF is the feed location tray number. Fig. 2.2-4 Is the configuration of DWCL.

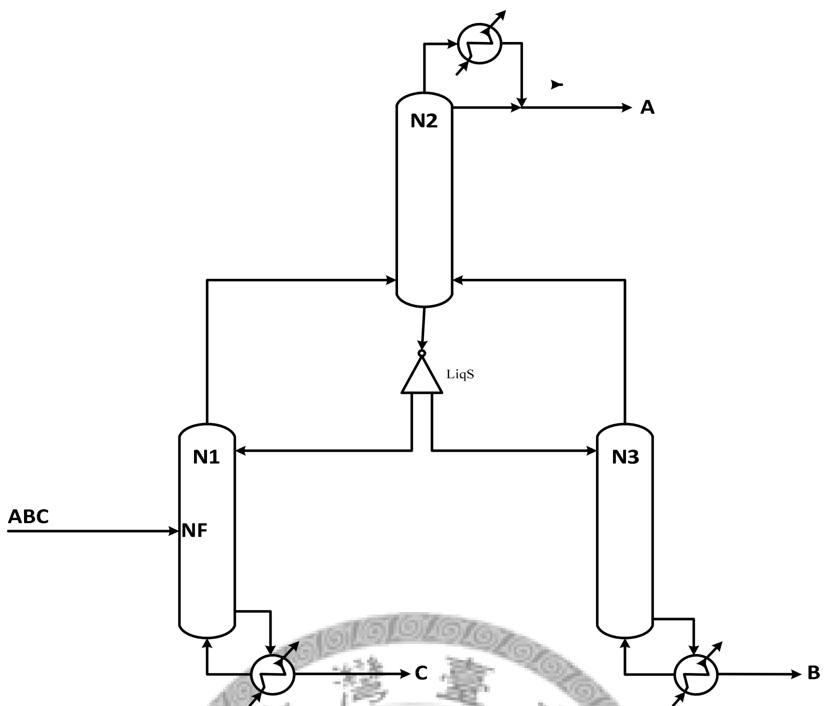


Fig. 2.2-4 The configuration of DWCL

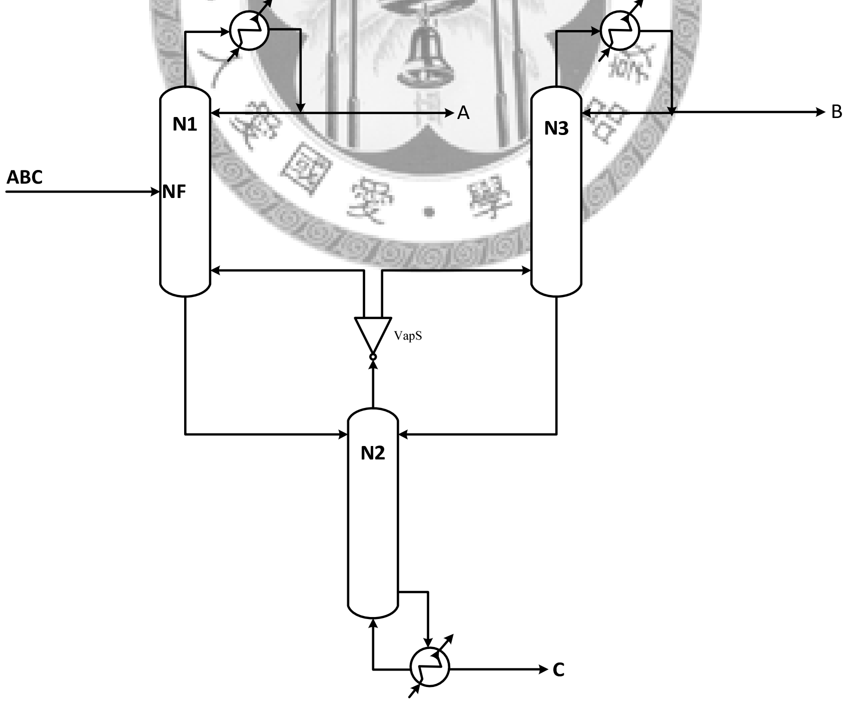


Fig. 2.2-5 The configuration of DWCU

The detailed tray number for DWCU are given in Table 2.2-2.

Table 2.2-2 Tray number of DWCU

| ESI>1 | | | | |
|---|---|---|---|---|
| Feed Composition | N1 | N2 | N3 | NF |
| 8,1,1 | 30 | 25 | 30 | 20 |
| 1,8,1 | 31 | 16 | 31 | 9 |
| 1,1,8 | 23 | 36 | 23 | 9 |
| 3,3,3 | 26 | 25 | 26 | 13 |
| ESI=1 | | | | |
| Feed Composition | N1 | N2 | N3 | NF |
| 8,1,1 | 51 | 29 | 51 | 34 |
| 1,8,1 | 43 | 18 | 43 | 13 |
| 1,1,8 | 44 | 41 | 44 | 17 |
| 3,3,3 | 45 | 28 | 45 | 21 |
| ESI<1 | | | | |
| Feed Composition | N1 | N2 | N3 | NF |
| 8,1,1 | 62 | 24 | 62 | 42 |
| 1,8,1 | 57 | 15 | 57 | 17 |
| 1,1,8 | 53 | 31 | 53 | 21 |
| 3,3,3 | 58 | 24 | 58 | 27 |

N1 is the number of tray for column 1. N2 is the number of tray for column 2. N3 is the number of tray for column 3. NF is the feed location tray number. Fig. 2.2-5 is the configuration of DWCU.

The detailed tray number for DWCM are given in Table 2.2-3.

Table 2.2-3 Tray number of DWCM

| ESI>1 | | | | | | |
|---|---|---|---|---|---|---|
| Feed Composition | N1 | N2 | N3 | N4 | NF | NS |
| 811 | 28 | 25 | 28 | 22 | 19 | 8 |
| 181 | 37 | 11 | 37 | 17 | 21 | 19 |
| 118 | 35 | 16 | 35 | 42 | 12 | 26 |
| 333 | 27 | 16 | 27 | 25 | 14 | 14 |
| ESI=1 | | | | | | |
| Feed Composition | N1 | N2 | N3 | N4 | NF | NS |
| 811 | 43 | 44 | 43 | 35 | 29 | 14 |
| 181 | 56 | 14 | 56 | 20 | 29 | 33 |
| 118 | 37 | 27 | 37 | 47 | 12 | 28 |
| 333 | 35 | 25 | 35 | 30 | 18 | 20 |
| ESI<1 | | | | | | |
| Feed Composition | N1 | N2 | N3 | N4 | NF | NS |
| 811 | 55 | 52 | 55 | 29 | 37 | 28 |
| 181 | 61 | 19 | 61 | 17 | 30 | 42 |
| 118 | 33 | 30 | 33 | 35 | 11 | 27 |
| 333 | 40 | 33 | 40 | 24 | 20 | 26 |

N1 is the number of tray for column 1. N2 is the number of tray for column 2. N3 is the number of tray for column 3. N4 is the number of tray for column 4. NF is the feed location tray number. NS is the sidedraw stream tray number. Fig. 2.2-6 is the configuration of DWCM.

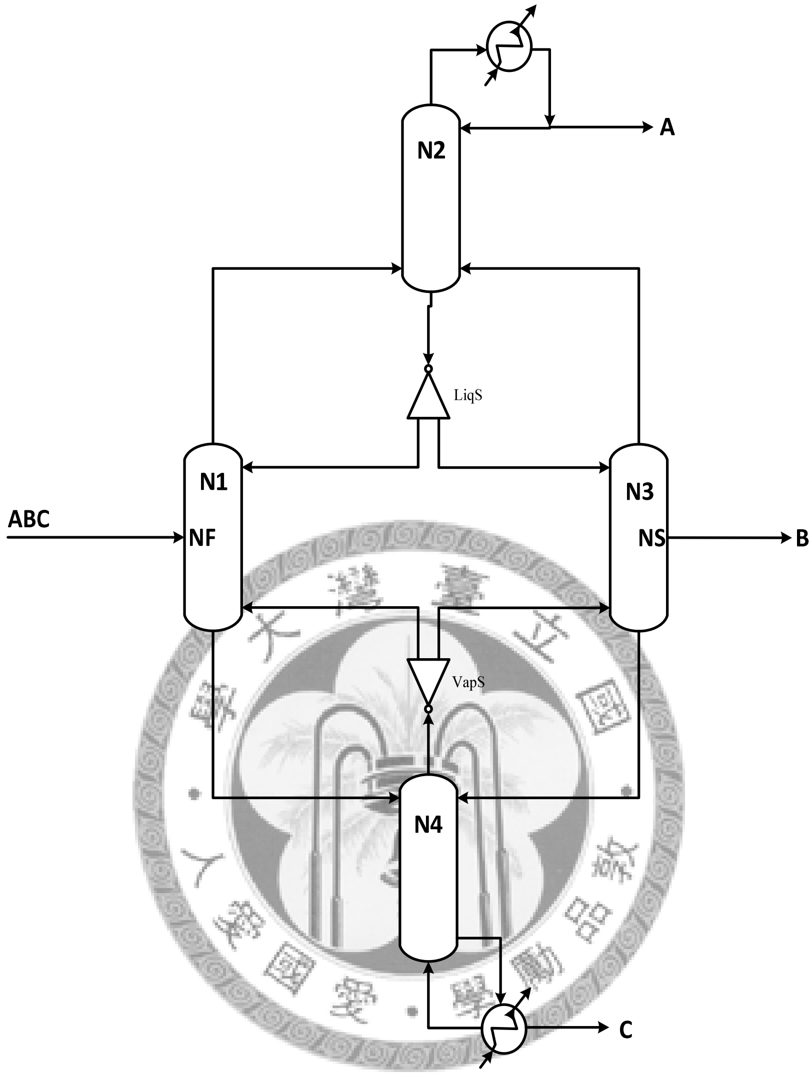


Fig. 2.2-6 The configuration of DWCM

## 2.3 Analysis method

### 2.3.1 Relative Gain Array

Bristol [22] developed a systematic approach for the analysis of multivariable process control problems. His approach requires only steady-state information (the process gain matrix *K*) and provides two important items of information :

1. A measure of process interactions.
2. A recommendation concerning the most effective pairing of controlled and manipulated variables.

Bristol's approach is based on the concept of a relative gain. Consider a process with n controlled variables and n manipulated variables. The relative gain $\lambda_{ij}$ between a controlled variable $y_i$ and a manipulated variable $u_j$ is defined to be the dimensionless ratio of two steady-state gain :

$$\lambda_{ij} \overset{\Delta}{=} \frac{(\partial y_i / \partial u_j)_u}{(\partial y_i / \partial u_j)_y} = \frac{\text{open} - \text{loop gain}}{\text{closed} - \text{loop gain}} \qquad (2\text{-}4)$$

for i = 1,2,…,$n$ and j = 1,2,…,$n$.

In the symbol $(\partial y_i / \partial u_j)_u$ denotes a partial derivative that is evaluated with all of the manipulated variables except $u_j$ held constant. Thus, this term is the open-loop gain (or steady-state gain) between $y_i$ and $u_j$, which corresponds to the gain matrix element $K_{ij}$. Similarly, $(\partial y_i / \partial u_j)_y$ is evaluated with all of the controlled variables except $y_i$ held constant. This situation could be achieved in practice by adjusting the other manipulated variables using controllers with integral action. Thus, $(\partial y_i / \partial u_j)_y$ can be interpreted as a closed-loop gain that indicates the effect of $u_j$ on $y_i$ when all of the other controlled variables ($y_i \neq y_j$) are held constant [23].

The RGA has several important properties for steady-state process models [24]:

1. It is normalized because the sum of the elements in each row of column is equal to one.
2. The relative gain are dimensionless and thus not affected by choice of units or scaling of variables.
3. The RGA is a measure of sensitivity to element uncertainty in the gain matrix $K$. The gain matrix can become singular if a single element $K_{ij}$ is changed to $K_{ij} = K_{ij}(1\text{-}1/\lambda_{ij})$. Thus a large RGA element indicates that small changes in $K_{ij}$ can markedly change the process control characteristics.

The RGA can be calculated from the expression

$$\Lambda = K \otimes H \tag{2-5}$$

Where $\otimes$ denotes the Schur product (element by element multiplication) :

$$\lambda_{ij} = K_{ij} H_{ij} \tag{2-6}$$

$$K_{ij} = \frac{\Delta y_i}{\Delta u_j} \tag{2-7}$$

$$H = (K^{-1})^T \tag{2-8}$$

$H_{ij}$ is an element of the transpose of the matrix inverse of $K$.

The RGA may be generalized to a non-square l × m matrix A by use of the pseudo inverse $A^+$. We have [25]

$$\Lambda(A) = A \otimes (A^+)^T \tag{2-9}$$

### 2.3.2 Condition Number

A measure of controllability is the condition number (CN). Assume that *K* is nonsingular. Then the condition number of *K* is a positive number defined as the ratio of the largest and smallest nonzero singular values :

$$CN = \frac{\sigma_{\max}}{\sigma_{\min}} \quad (2\text{-}9)$$

A small value of the condition number means that the system is well conditioned. The condition number also provides useful information about the sensitivity of the matrix properties to variations in the elements of the matrices. It is a typical index for the selection of the best set of manipulated variables [23].

## 2.4 Results

In section 2.4, we will show the results of relative gain array (RGA) and condition number (CN). These measures can indicate which control structure pairings are likely to work well.

These metrics are determined for three different type of divided-wall columns the L, U and M types. They are also calculated for different ease of separation index. First, the relative volatility for each component is $\alpha_A$ / $\alpha_B$ / $\alpha_C$ = 7.1 / 2.2 / 1. The separation of component A from component B is easier than the separation of component B from component C. The ease separation index is bigger than one. Second, the relative volatility for each component is $\alpha_A$ / $\alpha_B$ / $\alpha_C$ = 4 / 2 / 1. The difficulty of the separation of component A from component B is same as that of component B from component C. The ease separation index is equal to one. Third, the relative volatility for each component is $\alpha_A$ / $\alpha_B$ / $\alpha_C$ = 4 / 2.4 / 1. The separation of component B from component C is easier than the separation of component A from component B. The ease of separation index is smaller than one.

We can make step change (+/- 1%) by using Aspen Plus and we can get the open-loop gain. Then we substitute the open-loop gain into Eq. (2-4) and get matrix *K*. We can determine relative gain array by Eq. (2-5) and condition number.

### 2.4.1 DWCL

In this subsection we will discuss the L type of divided-wall column.

For the L type of divided-wall column, we have four manipulated variables, the reflux ratio (RR), two boilup ratios (BR1 and BR2) and split liquid (SL). So we will have four kind of control structures, RR-BR1-BR2, SL-BR1-BR2, RR-SL-BR2, RR-BR1-SL. The control structure RR-BR1-BR2 means that we control top A component by manipulating reflux ration, we control middle B component by manipulating boilup ratio one and we control bottom C component by manipulating boilup ratio two.

The following tables are the results of relative gain array and condition number for the L type:

We consider the case when ESI>1 ($\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 7.1 / 2.2 / 1).

If there is more lightest component in the feed: From Table 2.4-1, we can see that the RGA and CN show the control structure RR-BR1-BR2 is likely to work well.

Table 2.4-1 RGA and CN analysis for DWCL, ESI>1, F(8,1,1)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | BR1 | BR2 | | |
| XA | 1.0376 | 0.0053 | -0.0429 | | 1.0976 |
| XB | 0.0058 | 0.9902 | 0.0040 | | |
| XC | -0.0434 | 0.0045 | 1.0389 | | |
| | SL | BR1 | BR2 | | |
| XA | 0.8469 | -0.0198 | 0.1729 | | 1.5583 |
| XB | -0.0212 | 1.0210 | 0.0002 | | |
| XC | 0.1743 | -0.0012 | 0.8268 | | |
| | RR | SL | BR2 | | |
| XA | 0.8175 | 0.1797 | 0.0029 | | 1.9352 |
| XB | 0.1915 | 0.6821 | 0.1264 | | |
| XC | -0.0090 | 0.1383 | 0.8707 | | |
| | RR | BR1 | SL | | |
| XA | 0.8312 | 0.0003 | 0.1684 | | 1.5390 |
| XB | -0.0004 | 1.0229 | -0.0226 | | |
| XC | 0.1691 | -0.0233 | 0.8541 | | |
| | NRGA | | | | |
| | RR | BR1 | BR2 | SL | |
| XA | 0.9107 | 0.0023 | -0.0165 | 0.1036 | |
| XB | 0.0568 | 0.7180 | 0.0377 | 0.1875 | |
| XC | -0.0268 | 0.0023 | 0.9577 | 0.0667 | |

If there is more middle component in the feed: From Table 2.4-2, we can see that the RGA and CN show the control structure RR-BR1-BR2 and RR-SL-BR2 are both likely to work well.

Table 2.4-2 RGA and CN analysis for DWCL, ESI>1, F(1,8,1)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | BR1 | BR2 | | |
| XA | 1.0498 | -0.0477 | -0.0020 | | 1.1226 |
| XB | -0.0477 | 1.0803 | -0.0326 | | |
| XC | -0.0021 | -0.0325 | 1.0346 | | |
| | SL | BR1 | BR2 | | |
| XA | 1.3916 | -0.4177 | 0.0261 | | 1.9816 |
| XB | -0.4746 | 1.4702 | 0.0044 | | |
| XC | 0.0829 | -0.0525 | 0.9695 | | |
| | RR | SL | BR2 | | |
| XA | 1.1852 | -0.1796 | -0.0056 | | 1.4769 |
| XB | -0.1797 | 1.3147 | -0.1350 | | |
| XC | -0.0055 | -0.1352 | 1.1407 | | |
| | RR | BR1 | SL | | |
| XA | 0.9745 | -0.0743 | 0.0997 | | 1.8545 |
| XB | -0.0057 | 1.4239 | -0.4183 | | |
| XC | 0.0311 | -0.3497 | 1.3185 | | |
| | NRGA | | | | |
| | RR | BR1 | BR2 | SL | |
| XA | 1.1058 | -0.0280 | -0.0035 | -0.0743 | |
| XB | -0.1445 | 0.2880 | -0.1077 | 0.9642 | |
| XC | -0.0044 | -0.0101 | 1.1076 | -0.0931 | |

If there is more heaviest component in the feed: From Table 2.4-3, we can see that the RGA and CN show the control structure RR-BR1-BR2 and RR-SL-BR2 are both likely to work well.

Table 2.4-3 RGA and CN analysis for DWCL, ESI>1, F(1,1,8)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | BR1 | BR2 | | |
| XA | 1.2612 | 0.0238 | -0.2850 | | 1.9876 |
| XB | 0.1678 | 0.8956 | -0.0635 | | |
| XC | -0.4291 | 0.0805 | 1.3485 | | |
| | SL | BR1 | BR2 | | |
| XA | 1.4041 | -2.8544 | 2.4502 | | 27.8160 |
| XB | 0.0322 | 15.5269 | -14.5591 | | |
| XC | -0.4363 | -11.6725 | 13.1088 | | |
| | RR | SL | BR2 | | |
| XA | 1.2736 | 0.0280 | -0.3016 | | 1.9983 |
| XB | 0.1581 | 0.8998 | -0.0579 | | |
| XC | -0.4317 | 0.0722 | 1.3595 | | |
| | RR | BR1 | SL | | |
| XA | 1.0484 | -0.4817 | 0.4333 | | 19.2168 |
| XB | 0.0565 | 10.3006 | -9.3571 | | |
| XC | -0.1049 | -8.8189 | 9.9238 | | |
| | NRGA | | | | |
| | RR | BR1 | BR2 | SL | |
| XA | 1.2734 | 0.0005 | -0.3013 | 0.0275 | |
| XB | 0.1581 | -0.0009 | -0.0579 | 0.9007 | |
| XC | -0.4316 | 0.0039 | 1.3590 | 0.0687 | |

If there is equivalent component in the feed: From Table 2.4-4 we can see that the RGA and CN show the control structure RR-BR1-BR2 and RR-SL-BR2 are both likely to work well.

Table 2.4-4 RGA and CN analysis for DWCL, ESI>1, F(3,3,3)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | BR1 | BR2 | | |
| XA | 1.0081 | 0.0288 | -0.0369 | | 1.1400 |
| XB | 0.0383 | 0.9623 | -0.0006 | | |
| XC | -0.0465 | 0.0089 | 1.0376 | | |
| | SL | BR1 | BR2 | | |
| XA | 0.9890 | -0.2016 | 0.2126 | | 2.3810 |
| XB | -0.2683 | 1.2683 | -0.0001 | | |
| XC | 0.2793 | -0.0667 | 0.7874 | | |
| | RR | SL | BR2 | | |
| XA | 0.8821 | 0.1236 | -0.0057 | | 1.4152 |
| XB | 0.1589 | 0.8435 | -0.0024 | | |
| XC | -0.0410 | 0.0329 | 1.0081 | | |
| | RR | BR1 | SL | | |
| XA | 0.8589 | -0.0053 | 0.1464 | | 2.0382 |
| XB | -0.0052 | 1.3101 | -0.3049 | | |
| XC | 0.1463 | -0.3048 | 1.1585 | | |
| | NRGA | | | | |
| | RR | BR1 | BR2 | SL | |
| XA | 0.8650 | -0.0039 | -0.0015 | 0.1404 | |
| XB | 0.1262 | 0.2610 | -0.0019 | 0.6147 | |
| XC | -0.0376 | -0.0055 | 0.9900 | 0.0531 | |

Next we consider the case when ESI=1 ($\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 4 / 2 / 1).

If there is more lightest component in the feed: From Table 2.4-5, we can see that the RGA and CN show the control structure RR-BR1-BR2 is likely to work well.

Table 2.4-5 RGA and CN analysis for DWCL, ESI=1, F(8,1,1)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | BR1 | BR2 | | |
| XA | 1.0524 | 0.0047 | -0.0571 | | 1.1343 |
| XB | 0.0044 | 0.9836 | 0.0121 | | |
| XC | -0.0568 | 0.0117 | 1.0450 | | |
| | SL | BR1 | BR2 | | |
| XA | 0.7085 | -0.0313 | 0.3228 | | 2.8397 |
| XB | -0.0313 | 1.0329 | -0.0016 | | |
| XC | 0.3228 | -0.0016 | 0.6788 | | |
| | RR | SL | BR2 | | |
| XA | 0.9154 | 0.0923 | -0.0076 | | 2.6647 |
| XB | 0.0916 | 0.6243 | 0.2841 | | |
| XC | -0.0069 | 0.2834 | 0.7235 | | |
| | RR | BR1 | SL | | |
| XA | 0.8942 | -0.0007 | 0.1065 | | 1.3044 |
| XB | 0.0005 | 1.0271 | -0.0277 | | |
| XC | 0.1052 | -0.0264 | 0.9212 | | |
| | NRGA | | | | |
| | RR | BR1 | BR2 | SL | |
| XA | 0.9805 | 0.0022 | -0.0311 | 0.0484 | |
| XB | 0.0245 | 0.7570 | 0.0747 | 0.1438 | |
| XC | -0.0350 | 0.0066 | 0.9044 | 0.1239 | |

If there is more middle component in the feed: From Table 2.4-6, we can see that the RGA and CN show the control structure RR-BR1-BR2 is likely to work well.

Table 2.4-6 RGA and CN analysis for DWCL, ESI=1, F(1,8,1)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | BR1 | BR2 | | |
| XA | 1.0869 | -0.0842 | -0.0027 | | 1.2223 |
| XB | -0.0820 | 1.1469 | -0.0649 | | |
| XC | -0.0049 | -0.0627 | 1.0676 | | |
| | SL | BR1 | BR2 | | |
| XA | 1.4930 | -0.5151 | 0.0221 | | 2.2669 |
| XB | -0.6238 | 1.6104 | 0.0134 | | |
| XC | 0.1308 | -0.0952 | 0.9644 | | |
| | RR | SL | BR2 | | |
| XA | 1.2992 | -0.2916 | -0.0076 | | 1.8167 |
| XB | -0.2849 | 1.5434 | -0.2585 | | |
| XC | -0.0143 | -0.2518 | 1.2661 | | |
| | RR | BR1 | SL | | |
| XA | 0.9683 | -0.1312 | 0.1630 | | 2.0696 |
| XB | -0.0140 | 1.5309 | -0.5169 | | |
| XC | 0.0458 | -0.3997 | 1.3539 | | |
| | | NRGA | | | |
| | RR | BR1 | BR2 | SL | |
| XA | 1.0858 | -0.0846 | -0.0027 | 0.0016 | |
| XB | -0.1656 | 0.6745 | -0.1446 | 0.6358 | |
| XC | -0.0079 | -0.0424 | 1.1317 | -0.0813 | |

If there is more heaviest component in the feed: From Table 2.4-7, we can see that the RGA and CN show the control structure RR-BR1-BR2 and RR-SL-BR2 are both likely to work well.

Table 2.4-7 RGA and CN analysis for DWCL, ESI=1, F(1,1,8)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | BR1 | BR2 | | |
| XA | 1.0889 | 0.0286 | -0.1176 | | 1.8024 |
| XB | 0.2432 | 0.8625 | -0.1057 | | |
| XC | -0.3321 | 0.1089 | 1.2233 | | |
| | SL | BR1 | BR2 | | |
| XA | -0.1503 | 0.2431 | 0.9072 | | 3.0412 |
| XB | 1.8594 | -0.8641 | 0.0046 | | |
| XC | -0.7091 | 1.6209 | 0.0882 | | |
| | RR | SL | BR2 | | |
| XA | 1.2343 | 0.0201 | -0.2544 | | 1.7773 |
| XB | 0.1217 | 0.9289 | -0.0506 | | |
| XC | -0.3561 | 0.0511 | 1.3050 | | |
| | RR | BR1 | SL | | |
| XA | 0.9640 | 0.0533 | -0.0172 | | 2.6858 |
| XB | 0.0102 | -0.7916 | 1.7814 | | |
| XC | 0.0258 | 1.7384 | -0.7642 | | |
| | NRGA | | | | |
| | RR | BR1 | BR2 | SL | |
| XA | 1.2133 | 0.0041 | -0.2346 | 0.0172 | |
| XB | 0.1196 | -0.0152 | -0.0496 | 0.9453 | |
| XC | -0.3463 | 0.0443 | 1.2718 | 0.0303 | |

If there is equivalent component in the feed: From Table 2.4-8, we can see that the RGA and CN show the control structure RR-BR1-BR2 is likely to work well.

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Table 2.4-8 RGA and CN analysis for DWCL, ESI=1, F(3,3,3)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | BR1 | BR2 | | |
| XA | 1.0210 | 0.0292 | -0.0503 | | 1.1729 |
| XB | 0.0407 | 0.9581 | 0.0012 | | |
| XC | -0.0617 | 0.0127 | 1.0491 | | |
| | SL | BR1 | BR2 | | |
| XA | 0.7827 | -0.1829 | 0.4002 | | 5.9532 |
| XB | -0.2542 | 1.2546 | -0.0004 | | |
| XC | 0.4715 | -0.0717 | 0.6002 | | |
| | RR | SL | BR2 | | |
| XA | 0.8803 | 0.1079 | 0.0118 | | 1.4225 |
| XB | 0.1722 | 0.8213 | 0.0065 | | |
| XC | -0.0525 | 0.0708 | 0.9817 | | |
| | RR | BR1 | SL | | |
| XA | 0.9071 | 0.0056 | 0.0873 | | 1.5703 |
| XB | 0.0104 | 1.1790 | -0.1893 | | |
| XC | 0.0825 | -0.1845 | 1.1020 | | |
| | NRGA | | | | |
| | RR | BR1 | BR2 | SL | |
| XA | 0.8728 | -0.0016 | 0.0151 | 0.1136 | |
| XB | 0.0907 | 0.5940 | 0.0032 | 0.3122 | |
| XC | -0.0420 | -0.0143 | 0.9055 | 0.1508 | |

Next we consider the case when ESI<1 ($\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 4 / 2.4 / 1).

If there is more lightest component in the feed: From Table 2.4-9, we can see that the RGA and CN show the control structure RR-BR1-BR2 is likely to work well.

Table 2.4-9 RGA and CN analysis for DWCL, ESI<1, F(8,1,1)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | BR1 | BR2 | | |
| XA | 0.8384 | 0.2247 | -0.0631 | | 1.6706 |
| XB | 0.1515 | 0.7572 | 0.0913 | | |
| XC | 0.0101 | 0.0181 | 0.9718 | | |
| | SL | BR1 | BR2 | | |
| XA | -0.1152 | 1.3612 | -0.2460 | | 1.8784 |
| XB | 1.0746 | -0.3765 | 0.3019 | | |
| XC | 0.0407 | 0.0153 | 0.9441 | | |
| | RR | SL | BR2 | | |
| XA | 1.0042 | 0.0228 | -0.0270 | | 2.0227 |
| XB | 0.0503 | 0.7177 | 0.2320 | | |
| XC | -0.0545 | 0.2595 | 0.7950 | | |
| | RR | BR1 | SL | | |
| XA | 1.1278 | -0.1675 | 0.0398 | | 1.7007 |
| XB | 0.2172 | 1.2489 | -0.4661 | | |
| XC | -0.3449 | -0.0814 | 1.4263 | | |
| | NRGA | | | | |
| | RR | BR1 | BR2 | SL | |
| XA | 0.8465 | 0.2138 | -0.0614 | 0.0011 | |
| XB | 0.1159 | 0.4913 | 0.1407 | 0.2520 | |
| XC | -0.0133 | 0.0115 | 0.9077 | 0.0940 | |

If there is more middle component in the feed: From Table 2.4-10, we can see that the RGA and CN show the control structure RR-BR1-BR2 is likely to work well.

Table 2.4-10 RGA and CN analysis for DWCL, ESI<1, F(1,8,1)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | BR1 | BR2 | | |
| XA | 1.0333 | -0.0269 | -0.0065 | | 1.0634 |
| XB | -0.0317 | 1.0231 | 0.0085 | | |
| XC | -0.0017 | 0.0037 | 0.9979 | | |
| | SL | BR1 | BR2 | | |
| XA | 1.0420 | -0.1467 | 0.1047 | | 1.5748 |
| XB | -0.1652 | 1.1628 | 0.0024 | | |
| XC | 0.1233 | -0.0161 | 0.8929 | | |
| | RR | SL | BR2 | | |
| XA | 1.2649 | -0.2335 | -0.0314 | | 1.5476 |
| XB | -0.2636 | 1.2103 | 0.0532 | | |
| XC | -0.0014 | 0.0232 | 0.9782 | | |
| | RR | BR1 | SL | | |
| XA | 0.9731 | -0.0338 | 0.0608 | | 1.4718 |
| XB | 0.0127 | 1.2188 | -0.2316 | | |
| XC | 0.0142 | -0.1850 | 1.1708 | | |
| | NRGA | | | | |
| | RR | BR1 | BR2 | SL | |
| XA | 1.0330 | -0.0269 | -0.0064 | 0.0004 | |
| XB | -0.0542 | 0.9235 | 0.0129 | 0.1178 | |
| XC | 0.0002 | -0.0184 | 0.8811 | 0.1371 | |

If there is more heaviest component in the feed: From Table 2.4-11, we can see that the RGA and CN show the control structure RR-SL-BR2 is likely to work well.

Table 2.4-11 RGA and CN analysis for DWCL, ESI<1, F(1,1,8)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | BR1 | BR2 | | |
| XA | 1.0429 | 0.1122 | -0.1551 | | 2.3833 |
| XB | 0.3878 | 0.8471 | -0.2349 | | |
| XC | -0.4307 | 0.0407 | 1.3900 | | |
| | SL | BR1 | BR2 | | |
| XA | -0.3205 | -0.4930 | 1.8136 | | 4.8683 |
| XB | -2.0526 | 2.6818 | 0.3708 | | |
| XC | 3.3731 | -1.1888 | -1.1844 | | |
| | RR | SL | BR2 | | |
| XA | 0.8495 | -0.0594 | 0.2099 | | 2.0806 |
| XB | 0.5669 | 0.9477 | -0.5145 | | |
| XC | -0.4164 | 0.1117 | 1.3047 | | |
| | RR | BR1 | SL | | |
| XA | 0.9607 | 0.0645 | -0.0252 | | 2.6730 |
| XB | 0.2374 | 1.5586 | -0.7960 | | |
| XC | -0.1981 | -0.6231 | 1.8212 | | |
| | NRGA | | | | |
| | RR | BR1 | BR2 | SL | |
| XA | 0.8580 | 0.0049 | 0.1939 | -0.0568 | |
| XB | 0.4831 | 0.3963 | -0.3837 | 0.5044 | |
| XC | -0.3756 | -0.1165 | 1.0607 | 0.4315 | |

If there is equivalent component in the feed: From Table 2.4-12, we can see that the RGA and CN show the control structure RR-SL-BR2 is likely to work well.

Table 2.4-12 RGA and CN analysis for DWCL, ESI<1, F(3,3,3)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | BR1 | BR2 | | |
| XA | 0.5804 | 0.4177 | 0.0019 | | 7.5223 |
| XB | 0.4570 | 0.5680 | -0.0250 | | |
| XC | -0.0374 | 0.0143 | 1.0231 | | |
| | SL | BR1 | BR2 | | |
| XA | -0.0169 | 1.0056 | 0.0113 | | 1.1856 |
| XB | 1.0975 | -0.0763 | -0.0212 | | |
| XC | -0.0806 | 0.0707 | 1.0099 | | |
| | RR | SL | BR2 | | |
| XA | 0.9928 | 0.0120 | -0.0048 | | 1.1086 |
| XB | 0.0541 | 0.9676 | -0.0217 | | |
| XC | -0.0469 | 0.0204 | 1.0265 | | |
| | RR | BR1 | SL | | |
| XA | 0.6967 | 0.2999 | 0.0034 | | 29.5565 |
| XB | -2.5511 | -3.6726 | 7.2237 | | |
| XC | 2.8543 | 4.3728 | -6.2271 | | |
| | NRGA | | | | |
| | RR | BR1 | BR2 | SL | |
| XA | 0.7576 | 0.2382 | -0.0010 | 0.0052 | |
| XB | 0.1089 | 0.0772 | -0.0221 | 0.8360 | |
| XC | -0.0367 | 0.0153 | 1.0229 | -0.0015 | |

### 2.4.2 DWCU

In this subsection we will discuss the U type of divided-wall column.

For the U type of divided-wall column, we have four manipulated variables, two reflux ratios (RR1 and RR2), one boilup ratio (BR) and split vapor (SV). But in practical industrial, the split vapor is hard to control. So we get rid of the manipulated variable split vapor. We have only left one control structure RR1-RR2-BR to control the A component in top stream, the B component in middle stream and the C component in bottom stream, respectively. So it is unnecessary to compare the relative gain array and condition number here.

### 2.4.3 DWCM

In this subsection we will discuss the M type of divided-wall column.

For the M type of divided-wall column, we have five manipulated variables, the reflux ratios (RR), the sidedraw stream flowrate (S), the boilup ratio (BR), split liquid (SL) and split vapor (SV). But in practical industrial, the split vapor is hard to control. So we do not consider split vapor as a manipulated variable.

The following tables are the results of relative gain array and condition number for the M type:

We consider the case when ESI>1 ($\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 7.1 / 2.2 / 1).

If there is more lightest component in the feed: From Table 2.4-13, we can see that the RGA and CN show the control structure S-SL-BR is likely to work well.

Table 2.4-13 RGA and CN analysis for DWCM, ESI>1, F(8,1,1)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | S | BR | | |
| XA | 0.4911 | 0.6123 | -0.1034 | | 4.9421 |
| XB | 0.5918 | 0.3233 | 0.0848 | | |
| XC | -0.0829 | 0.0644 | 1.0186 | | |
| | SL | S | BR | | |
| XA | 0.3236 | 0.6599 | 0.0165 | | 2.6343 |
| XB | 0.6975 | 0.2736 | 0.0289 | | |
| XC | -0.0211 | 0.0665 | 0.9546 | | |
| | RR | SL | BR | | |
| XA | 6.8101 | -4.1641 | -1.6460 | | 10.0622 |
| XB | -3.2551 | 4.5338 | -0.2787 | | |
| XC | -2.5550 | 0.6303 | 2.9248 | | |
| | RR | S | SL | | |
| XA | 0.0676 | 0.6533 | 0.2791 | | 3.2731 |
| XB | -0.3056 | 0.2479 | 1.0577 | | |
| XC | 1.2380 | 0.0988 | -0.3368 | | |
| | NRGA | | | | |
| | RR | S | BR | SL | |
| XA | 0.0952 | 0.6263 | -0.0681 | 0.3467 | |
| XB | 0.2233 | 0.3074 | 0.0669 | 0.4024 | |
| XC | -0.0079 | 0.0652 | 0.9948 | -0.0521 | |

If there is more middle component in the feed: From Table 2.4-14 , we can see that the RGA and CN show the control structure RR-S-BR is likely to work well.

Table 2.4-14 RGA and CN analysis for DWCM, ESI>1, F(1,8,1)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | S | BR | | |
| XA | 0.8505 | 0.1360 | 0.0135 | | 1.6110 |
| XB | 0.1492 | 0.7496 | 0.1012 | | |
| XC | 0.0003 | 0.1144 | 0.8853 | | |
| | SL | S | BR | | |
| XA | -0.7346 | 0.6952 | 1.0394 | | 5.3665 |
| XB | 1.8749 | 0.1997 | -1.0745 | | |
| XC | -0.1403 | 0.1051 | 1.0352 | | |
| | RR | SL | BR | | |
| XA | 1.0574 | 0.1786 | -0.2360 | | 4.2795 |
| XB | -0.0542 | 2.5555 | -1.5013 | | |
| XC | -0.0032 | -1.7341 | 2.7373 | | |
| | RR | S | SL | | |
| XA | 0.8617 | 0.1286 | 0.0097 | | 1.8158 |
| XB | 0.1364 | 0.7023 | 0.1613 | | |
| XC | 0.0019 | 0.1691 | 0.8290 | | |
| | NRGA | | | | |
| | RR | S | BR | SL | |
| XA | 0.8499 | 0.1364 | 0.0142 | -0.0005 | |
| XB | 0.1490 | 0.7488 | 0.0993 | 0.0029 | |
| XC | 0.0003 | 0.1148 | 0.8781 | 0.0068 | |

If there is more heaviest component in the feed: From Table 2.4-15, we can see that the RGA and CN show the control structure BR-SL-S and RR-SL-S are both likely to work well.

Table 2.4-15 RGA and CN analysis for DWCM, ESI>1, F(1,1,8)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | S | BR | | |
| XA | 0.8748 | 0.1299 | -0.0047 | | 3.1518 |
| XB | 0.4198 | 0.0949 | 0.4853 | | |
| XC | -0.2946 | 0.7751 | 0.5194 | | |
| | SL | S | BR | | |
| XA | 0.0366 | 0.1213 | 0.8421 | | 1.5879 |
| XB | 0.8777 | 0.1230 | -0.0007 | | |
| XC | 0.0857 | 0.7557 | 0.1586 | | |
| | RR | SL | BR | | |
| XA | -12.2905 | 0.5510 | 12.7395 | | 25.3078 |
| XB | 1.8395 | -2.9683 | 2.1288 | | |
| XC | 11.4509 | 3.4173 | -13.8683 | | |
| | RR | S | SL | | |
| XA | 0.8699 | 0.1299 | 0.0002 | | 1.6114 |
| XB | 0.0006 | 0.1230 | 0.8764 | | |
| XC | 0.1295 | 0.7471 | 0.1234 | | |
| | | NRGA | | | |
| | RR | S | BR | SL | |
| XA | 0.5120 | 0.1247 | 0.3411 | 0.0223 | |
| XB | 0.0258 | 0.1215 | 0.0229 | 0.8299 | |
| XC | 0.0904 | 0.7520 | 0.0557 | 0.1019 | |

If there is equivalent component in the feed: From Table 2.4-16, we can see that the RGA and CN show the control structure S-RR-BR is likely to work well.

Table 2.4-16 RGA and CN analysis for DWCM, ESI>1, F(3,3,3)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | S | BR | | |
| XA | 0.3710 | 0.4851 | 0.1438 | | 3.9201 |
| XB | 0.7004 | 0.1784 | 0.1211 | | |
| XC | -0.0715 | 0.3364 | 0.7350 | | |
| | SL | S | BR | | |
| XA | 0.0204 | 0.5405 | 0.4391 | | 5.7614 |
| XB | 0.9255 | 0.1071 | -0.0326 | | |
| XC | 0.0541 | 0.3524 | 0.5935 | | |
| | RR | SL | BR | | |
| XA | 3.6243 | -0.1789 | -2.4454 | | 5.7433 |
| XB | -1.0512 | 2.3146 | -0.2634 | | |
| XC | -1.5731 | -1.1357 | 3.7088 | | |
| | RR | S | SL | | |
| XA | 0.5517 | 0.4582 | -0.0099 | | 9.3364 |
| XB | 0.1486 | 0.1222 | 0.7292 | | |
| XC | 0.2997 | 0.4196 | 0.2807 | | |
| | NRGA | | | | |
| | RR | S | BR | SL | |
| XA | 0.3217 | 0.4925 | 0.1831 | 0.0027 | |
| XB | 0.5077 | 0.1588 | 0.0788 | 0.2546 | |
| XC | -0.0272 | 0.3463 | 0.6474 | 0.0334 | |

Next we consider the case when ESI=1 ($\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 4 / 2 / 1).

If there is more lightest component in the feed: From Table 2.4-17, we can see that the RGA and CN show the control structure S-SL-BR and S-SL-RR are both likely to work well.

Table 2.4-17 RGA and CN analysis for DWCM, ESI=1, F(8,1,1)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | S | BR | | |
| XA | 0.5098 | 0.6770 | -0.1869 | | 8.6930 |
| XB | 0.3979 | 0.2631 | 0.3391 | | |
| XC | 0.0923 | 0.0599 | 0.8478 | | |
| | SL | S | BR | | |
| XA | 0.2714 | 0.7031 | 0.0255 | | 2.1816 |
| XB | 0.7227 | 0.2376 | 0.0396 | | |
| XC | 0.0059 | 0.0593 | 0.9348 | | |
| | RR | SL | BR | | |
| XA | 13.7625 | -7.0546 | -5.7079 | | 20.6965 |
| XB | -3.7160 | 7.4732 | -2.7571 | | |
| XC | -9.0464 | 0.5814 | 9.4650 | | |
| | RR | S | SL | | |
| XA | 0.0613 | 0.7000 | 0.2388 | | 2.0134 |
| XB | -0.0527 | 0.2342 | 0.8184 | | |
| XC | 0.9914 | 0.0658 | -0.0572 | | |
| | NRGA | | | | |
| | RR | S | BR | SL | |
| XA | 0.0363 | 0.7012 | 0.0104 | 0.2520 | |
| XB | -0.0044 | 0.2373 | 0.0364 | 0.7307 | |
| XC | 0.1216 | 0.0601 | 0.8201 | -0.0019 | |

If there is more middle component in the feed: From Table 2.4-18, we can see that the RGA and CN show the control structure RR-S-BR is likely to work well.

Table 2.4-18 RGA and CN analysis for DWCM, ESI=1, F(1,8,1)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | S | BR | | |
| XA | 0.9777 | 0.0983 | -0.0760 | | 1.3627 |
| XB | 0.0948 | 0.8893 | 0.0160 | | |
| XC | -0.0725 | 0.0125 | 1.0600 | | |
| | SL | S | BR | | |
| XA | 0.9520 | 0.3243 | -0.2763 | | 3.4628 |
| XB | 0.3097 | 0.6507 | 0.0396 | | |
| XC | -0.2617 | 0.0251 | 1.2366 | | |
| | RR | SL | BR | | |
| XA | 1.4028 | -0.4139 | 0.0111 | | 2.1509 |
| XB | -0.2584 | 1.1543 | 0.1041 | | |
| XC | -0.1444 | 0.2595 | 0.8848 | | |
| | RR | S | SL | | |
| XA | 1.3487 | 0.0125 | -0.3612 | | 1.9422 |
| XB | 0.1588 | 1.0506 | -0.2094 | | |
| XC | -0.5075 | -0.0631 | 1.5706 | | |
| | NRGA | | | | |
| | RR | S | BR | SL | |
| XA | 0.9637 | 0.1015 | -0.0788 | 0.0136 | |
| XB | 0.0934 | 0.8858 | 0.0163 | 0.0045 | |
| XC | -0.0716 | 0.0126 | 1.0621 | -0.0031 | |

If there is more heaviest component in the feed: From Table 2.4-19, we can see that the RGA and CN show the control structure RR-SL-S is likely to work well.

Table 2.4-19 RGA and CN analysis for DWCM, ESI=1, F(1,1,8)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | S | BR | | |
| XA | -2.8271 | 0.5055 | 3.3216 | | 10.6847 |
| XB | 3.8484 | -0.2547 | -2.5937 | | |
| XC | -0.0213 | 0.7491 | 0.2721 | | |
| | SL | S | BR | | |
| XA | -0.0020 | 0.1495 | 0.8526 | | 1.4269 |
| XB | 1.0019 | -0.0006 | -0.0012 | | |
| XC | 0.0002 | 0.8511 | 0.1487 | | |
| | RR | SL | BR | | |
| XA | 1.1868 | -0.0029 | -0.1839 | | 1.3637 |
| XB | -0.0093 | 1.0043 | 0.0050 | | |
| XC | -0.1775 | -0.0014 | 1.1789 | | |
| | RR | S | SL | | |
| XA | 0.9762 | 0.0265 | -0.0028 | | 1.0576 |
| XB | -0.0019 | -0.0005 | 1.0023 | | |
| XC | 0.0256 | 0.9740 | 0.0004 | | |
| | NRGA | | | | |
| | RR | S | BR | SL | |
| XA | 0.6467 | 0.0680 | 0.2878 | -0.0025 | |
| XB | -0.0033 | -0.0004 | 0.0010 | 1.0027 | |
| XC | -0.0434 | 0.6430 | 0.4006 | -0.0002 | |

If there is equivalent component in the feed: From Table 2.4-20, we can see that the RGA and CN show the control structure RR-SL-BR and S-SL-BR are both likely to work well.

Table 2.4-20 RGA and CN analysis for DWCM, ESI=1, F(3,3,3)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | S | BR | | |
| XA | 2.1061 | -0.1341 | -0.9719 | | 59.1920 |
| XB | -1.1054 | 0.6854 | 1.4201 | | |
| XC | -0.0006 | 0.4487 | 0.5519 | | |
| | SL | S | BR | | |
| XA | -0.0126 | 0.5864 | 0.4262 | | 7.8357 |
| XB | 1.0126 | -0.0356 | 0.0230 | | |
| XC | 0.0000 | 0.4492 | 0.5509 | | |
| | RR | SL | BR | | |
| XA | 1.7140 | -0.0023 | -0.7117 | | 2.5086 |
| XB | -0.0545 | 0.9627 | 0.0919 | | |
| XC | -0.6595 | 0.0397 | 1.6198 | | |
| | RR | S | SL | | |
| XA | 0.6420 | 0.3668 | -0.0087 | | 3.4076 |
| XB | 0.0182 | -0.0474 | 1.0292 | | |
| XC | 0.3398 | 0.6807 | -0.0205 | | |
| | NRGA | | | | |
| | RR | S | BR | SL | |
| XA | 0.3687 | 0.4602 | 0.1814 | -0.0104 | |
| XB | 0.0004 | -0.0359 | 0.0224 | 1.0130 | |
| XC | 0.0763 | 0.5011 | 0.4272 | -0.0046 | |

Next we consider the case when ESI=1 ($\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 4 / 2.4 / 1).

If there is more lightest component in the feed: From Table 2.4-21, we can see that the RGA and CN show the control structure S-SL-BR and S-SL-RR are both likely to work well.

Table 2.4-21 RGA and CN analysis for DWCM, ESI<1, F(8,1,1)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | S | BR | | |
| XA | 0.7541 | 0.5044 | -0.2585 | | 10.2864 |
| XB | 0.3618 | 0.4540 | 0.1842 | | |
| XC | -0.1159 | 0.0415 | 1.0744 | | |
| | SL | S | BR | | |
| XA | 0.3003 | 0.6396 | 0.0601 | | 2.8311 |
| XB | 0.6893 | 0.3159 | -0.0053 | | |
| XC | 0.0104 | 0.0445 | 0.9452 | | |
| | RR | SL | BR | | |
| XA | 3.5687 | -1.1208 | -1.4479 | | 4.9975 |
| XB | -0.8276 | 2.2662 | -0.4386 | | |
| XC | -1.7411 | -0.1454 | 2.8865 | | |
| | RR | S | SL | | |
| XA | 0.1423 | 0.6141 | 0.2436 | | 2.7886 |
| XB | 0.0101 | 0.3198 | 0.6702 | | |
| XC | 0.8477 | 0.0661 | 0.0862 | | |
| | NRGA | | | | |
| | RR | S | BR | SL | |
| XA | 0.1696 | 0.6092 | -0.0116 | 0.2327 | |
| XB | -0.0262 | 0.3059 | -0.0190 | 0.7392 | |
| XC | 0.1592 | 0.0485 | 0.7676 | 0.0246 | |

If there is more middle component in the feed: From Table 2.4-22, we can see that the RGA and CN show the control structure RR-S-BR is likely to work well.

Table 2.4-22 RGA and CN analysis for DWCM, ESI<1, F(1,8,1)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | S | BR | | |
| XA | 1.0099 | 0.0439 | -0.0538 | | 1.2232 |
| XB | 0.0305 | 0.9059 | 0.0636 | | |
| XC | -0.0404 | 0.0501 | 0.9903 | | |
| | SL | S | BR | | |
| XA | 7.8978 | -1.8711 | -5.0266 | | 11.6723 |
| XB | -3.7512 | 3.0213 | 1.7299 | | |
| XC | -3.1466 | -0.1501 | 4.2967 | | |
| | RR | SL | BR | | |
| XA | 0.9867 | 0.1812 | -0.1679 | | 2.5565 |
| XB | 0.0435 | 1.6065 | -0.6501 | | |
| XC | -0.0303 | -0.7877 | 1.8180 | | |
| | RR | S | SL | | |
| XA | 1.0208 | 0.0647 | -0.0855 | | 1.4709 |
| XB | 0.0316 | 0.8252 | 0.1431 | | |
| XC | -0.0525 | 0.1101 | 0.9424 | | |
| | | NRGA | | | |
| | RR | S | BR | SL | |
| XA | 1.0104 | 0.0448 | -0.0516 | -0.0035 | |
| XB | 0.0305 | 0.9023 | 0.0607 | 0.0064 | |
| XC | -0.0409 | 0.0528 | 0.9457 | 0.0424 | |

If there is more heaviest component in the feed: From Table 2.4-23, we can see that the RGA and CN show the control structure RR-SL-S is likely to work well.

Table 2.4-23 RGA and CN analysis for DWCM, ESI<1, F(1,1,8)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | S | BR | | |
| XA | -0.6428 | 0.2379 | 1.4048 | | 2.8543 |
| XB | 1.5927 | -0.0731 | -0.5197 | | |
| XC | 0.0501 | 0.8351 | 0.1148 | | |
| | SL | S | BR | | |
| XA | -0.0017 | 0.1919 | 0.8099 | | 1.6217 |
| XB | 1.0024 | -0.0021 | -0.0003 | | |
| XC | -0.0007 | 0.8102 | 0.1905 | | |
| | RR | SL | BR | | |
| XA | 2.6763 | -0.0089 | -1.6674 | | 4.3132 |
| XB | -0.0468 | 1.0319 | 0.0149 | | |
| XC | -1.6296 | -0.0229 | 2.6525 | | |
| | RR | S | SL | | |
| XA | 0.8749 | 0.1291 | -0.0041 | | 1.3461 |
| XB | -0.0010 | -0.0020 | 1.0030 | | |
| XC | 0.1261 | 0.8729 | 0.0010 | | |
| | NRGA | | | | |
| | RR | S | BR | SL | |
| XA | 0.6467 | 0.1455 | 0.2112 | -0.0035 | |
| XB | -0.0054 | -0.0018 | 0.0014 | 1.0058 | |
| XC | -0.1267 | 0.7472 | 0.3819 | -0.0024 | |

If there is equivalent component in the feed: From Table 2.4-24, we can see that the RGA and CN show the control structure RR-SL-BR is likely to work well.

Table 2.4-24 RGA and CN analysis for DWCM, ESI<1, F(3,3,3)

| | RGA | | | | CN |
|---|---|---|---|---|---|
| | RR | S | BR | | |
| XA | 0.7364 | 0.3333 | -0.0697 | | 20.6778 |
| XB | 0.2233 | 0.3047 | 0.4720 | | |
| XC | 0.0404 | 0.3619 | 0.5977 | | |
| | SL | S | BR | | |
| XA | 0.2874 | 0.4498 | 0.2628 | | 5.7013 |
| XB | 0.7191 | 0.1982 | 0.0828 | | |
| XC | -0.0064 | 0.3520 | 0.6545 | | |
| | RR | SL | BR | | |
| XA | 2.8434 | -0.8223 | -1.0211 | | 4.0138 |
| XB | -0.4153 | 2.0567 | -0.6414 | | |
| XC | -1.4281 | -0.2343 | 2.6624 | | |
| | RR | S | SL | | |
| XA | 0.5820 | 0.3577 | 0.0602 | | 9.2548 |
| XB | -0.0475 | 0.1755 | 0.8719 | | |
| XC | 0.4655 | 0.4667 | 0.0678 | | |
| | | NRGA | | | |
| | RR | S | BR | SL | |
| XA | 0.5776 | 0.3584 | 0.0020 | 0.0620 | |
| XB | 0.1318 | 0.2611 | 0.3125 | 0.2946 | |
| XC | 0.0896 | 0.3741 | 0.5285 | 0.0079 | |

## 2.5 Summary

From the results of RGA and CN of DWCL we can see that in most cases the control structures RR-BR1-BR2 and RR-SL-BR2 are preferred. (see Fig. 2.5-1, Fig. 2.5-2, Fig. 2.5-3)

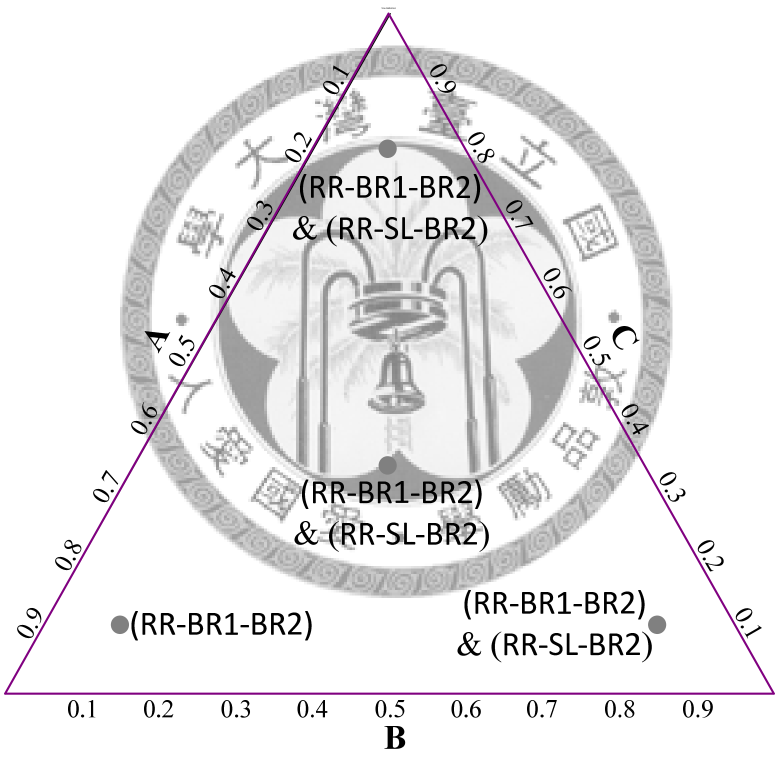


Fig. 2.5-1 Results of RGA and CN for DWCL of ESI>1

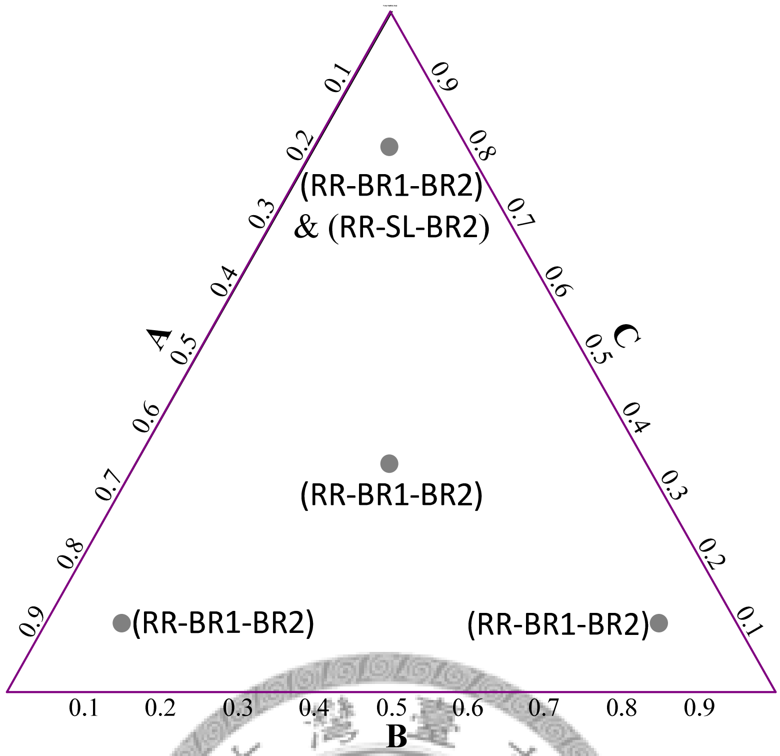


Fig. 2.5-2 Results of RGA and CN for DWCL of ESI=1

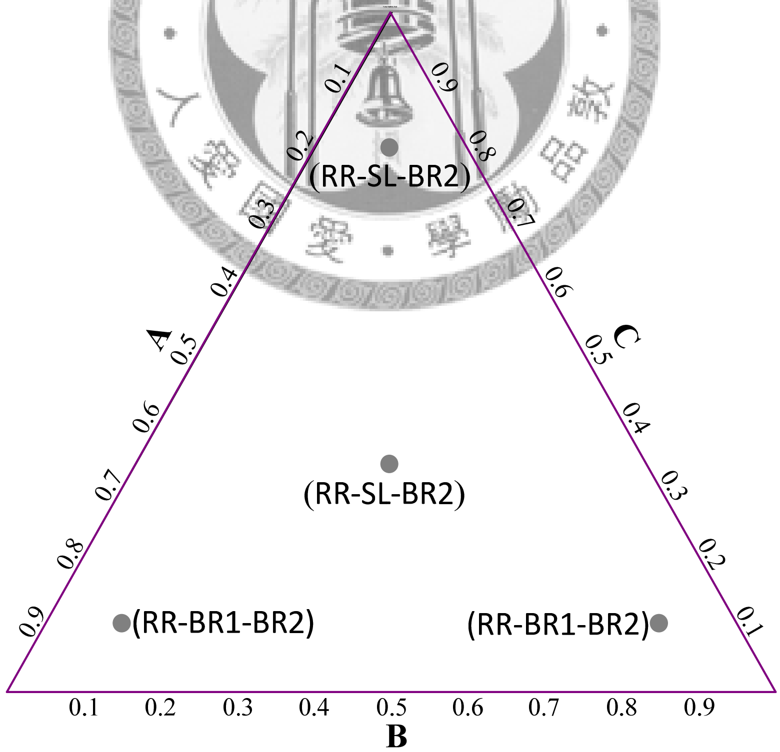


Fig. 2.5-3 Results of RGA and CN for DWCL of ESI<1

For DWCU, we have the only control structure RR1-RR2-BR.

From the results of RGA and CN of DWCM we can see that if there are more A component in the feed, it prefers the control structure S-SL-BR or S-SL-RR. If there are more B component in the feed, it prefers the control structure RR-S-BR. If there are more C component in the feed, it prefers the control structure RR-SL-S. (see Fig. 2.5-4, Fig. 2.5-5, Fig. 2.5-6)

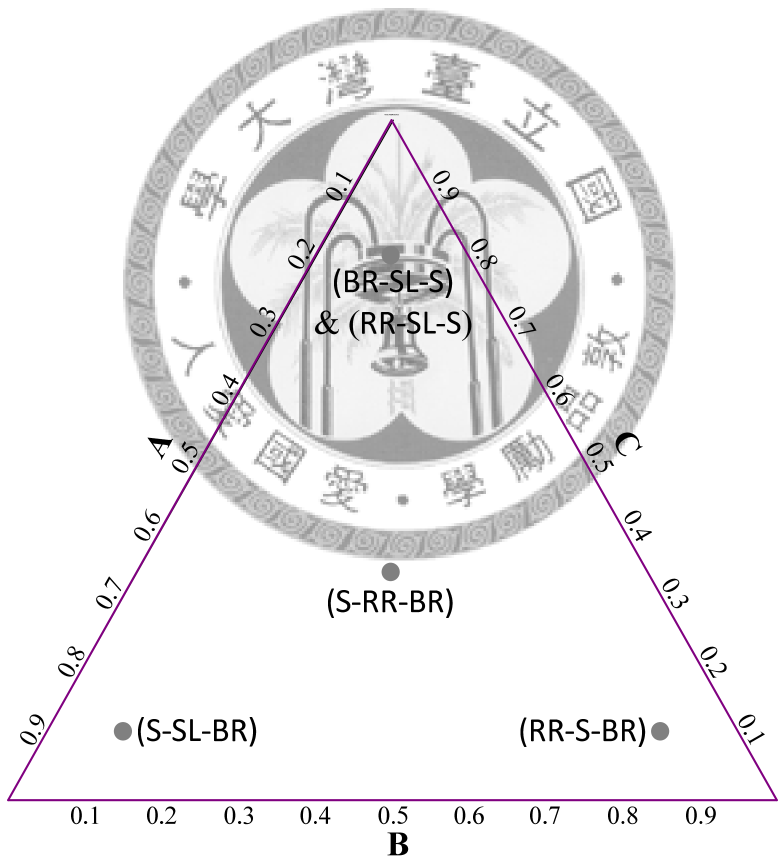


Fig. 2.5-4 Results of RGA and CN for DWCM of ESI>1

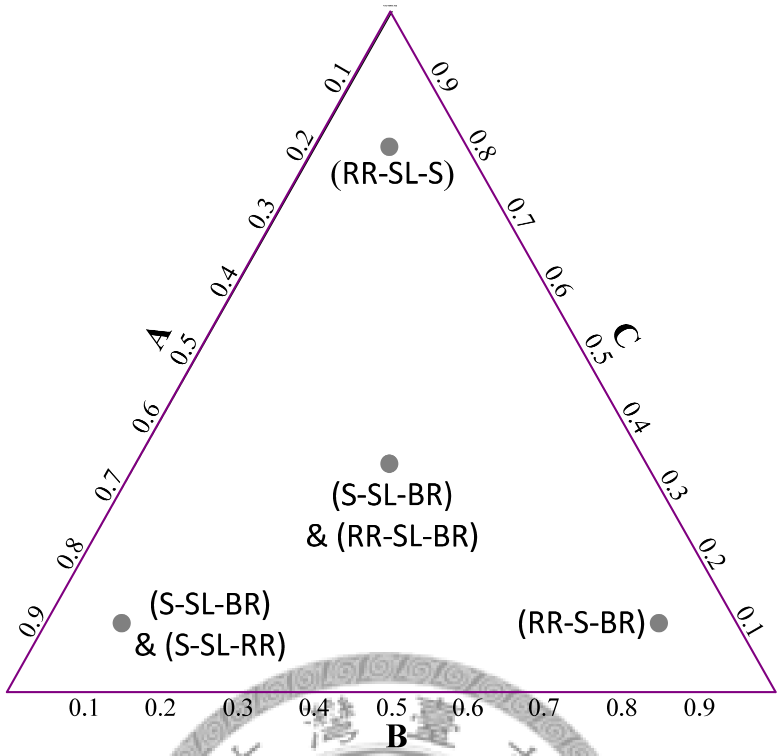


Fig. 2.5-5 Results of RGA and CN for DWCM of ESI=1

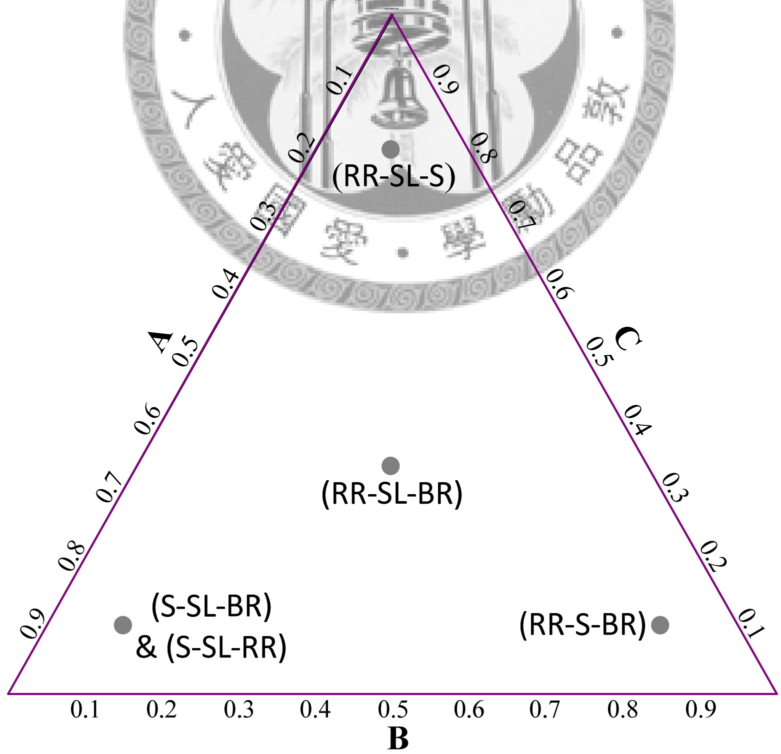


Fig. 2.5-6 Results of RGA and CN for DWCM of ESI<1

# 3 Dynamic Analysis

## 3.1 Dynamic simulation

With dynamic simulations, we can find the best process design methods and control strategies. In general, the factory does not have real steady-state which is the ideal situation to do the analysis. Feed or the environment, whether the interference of equipment are always affect the entire process. Then the transient behavior of such a procedure can be simulated by the dynamic simulation tools to be explored. Chemical processes are involved in the design and optimization of steady-state and dynamic behavior. Steady-state model can show the energy of the system and mass balance and evaluate different process. It means the steady-state simulation can reduce operating expenses and equipment costs for the maximum capacity and optimization procedure.

However, dynamic simulation can confirm that the process can work in a safe and simple way to operate and can produce products that meet the requirements of the factory. Steady-state analysis of the results are generally not known and the best control strategy. And the control loop dynamic considerations often affect the control effect is good or bad. Therefore it is best to use the dynamic simulation to test the control strategies for disturbance rejection ability. Then select the best control structure to implement the system.

In this chapter we will use the Aspen Dynamics to do the dynamic simulation to verify the suitability of different control structures and strategies.

## 3.2 Analysis method

### 3.2.1 Integral Error Criteria

Controller tuning relations have been developed that optimize the closed-loop response for a simple process model and a specified disturbance or set-point change. The optimum settings minimize an integral error criterion. Three popular integral error criteria are :

1. Integral of the absolute value of the error (IAE)
2. Integral of the squared error (ISE)
3. Integral of the time-weighted absolute error (ITAE)

The ISE criterion penalizes large errors, while the ITAE criterion penalizes errors that persist for long periods of time. In general, the ITAE is the preferred criterion because it usually results in the most conservative controller settings. By contrast, the ISE criterion provides the most aggressive settings, while the IAE criterion tends to produce controller settings that are between those for the ITAE and ISE criteria [23].

## 3.3 Results of feed flowrate disturbance

The following part show the dynamic responses of feed flowrate disturbance for different type of divided-wall column and different ease separation index (ESI) and different feed composition. By inspection of the diagrams, it's hard to tell which control structure is better. Therefore we will also compare the control structures by using IAE and ITAE.

### 3.3.1 DWCL

Fig. 3.3-1 shows the control structure RR-BR1-BR2. It means that A component in top stream was manipulated by reflux ratio (RR), B component in middle stream was manipulated by boilup ratio 1 (BR1) and C component in bottom stream was manipulated by boilup ratio 2 (BR2), respectively.

Fig. 3.3-2 shows the control structure SL-BR1-BR2. Fig. 3.3-3 shows the control structure RR-SL-BR2. Fig. 3.3-4 shows the control structure RR-BR1-SL.

In those control strategy, level control are using the P controller, the rest are using the PI controller. We will use the Relay-Feedback closed-loop testing and Tyreus-Luyben tuning method to arrive these PI controller parameters. The composition control was used. In the dynamic simulations in this work, disturbances of +/1 10% in the feed flowrate were used.

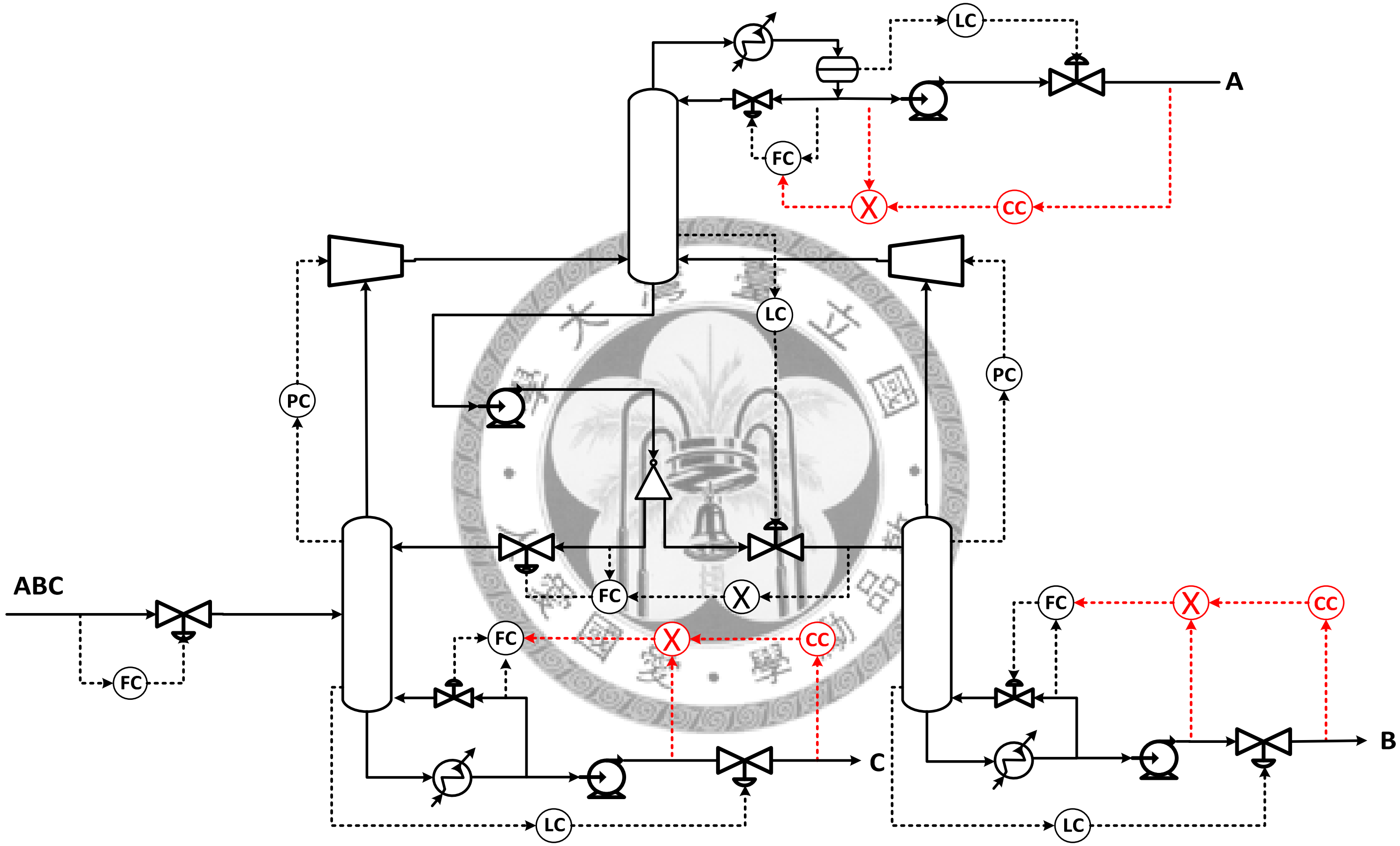


Fig. 3.3-1 Control Structure RR-BR1-BR2 for DWCL.

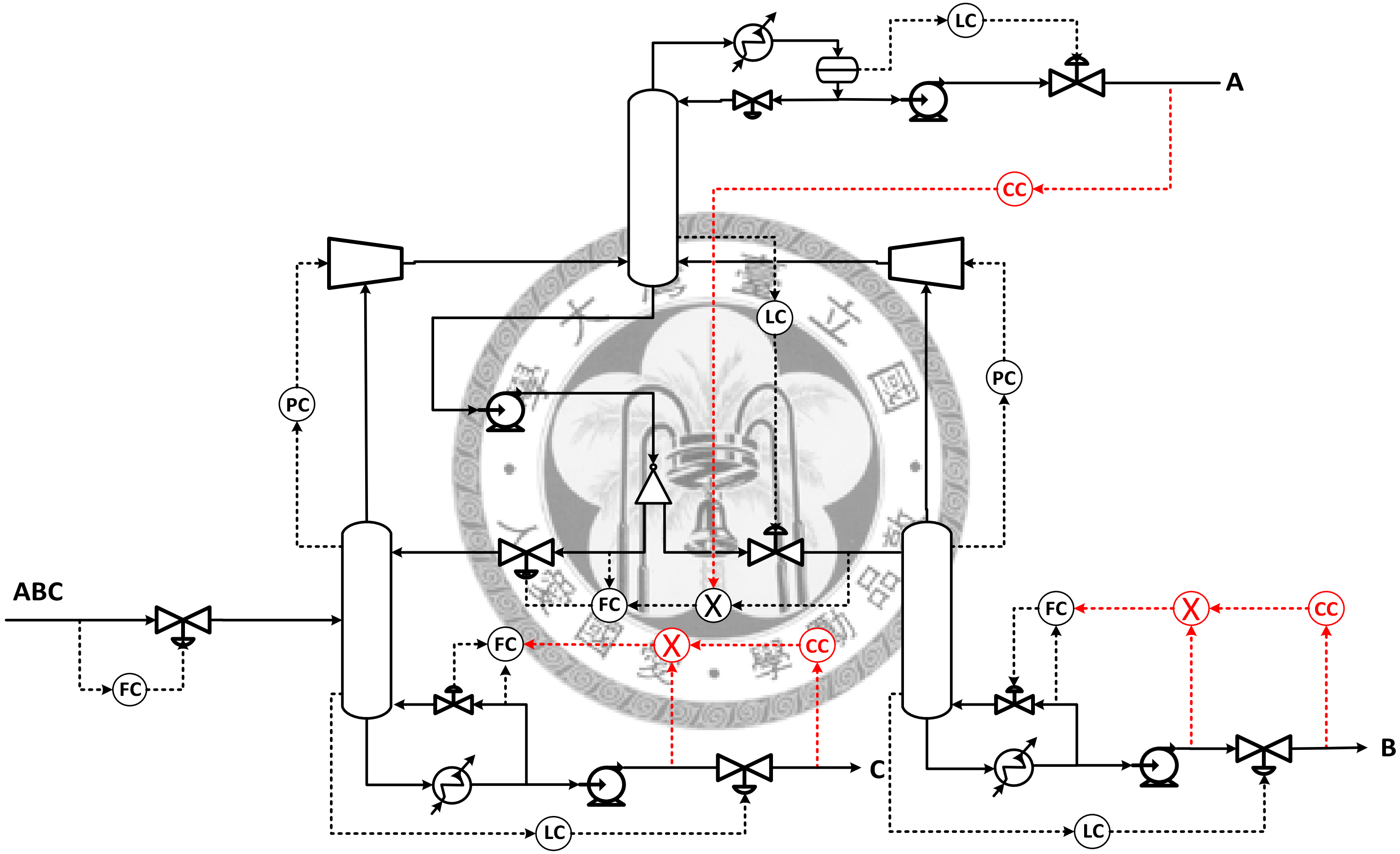


Fig. 3.3-2 Control Structure SL-BR1-BR2 for DWCL.

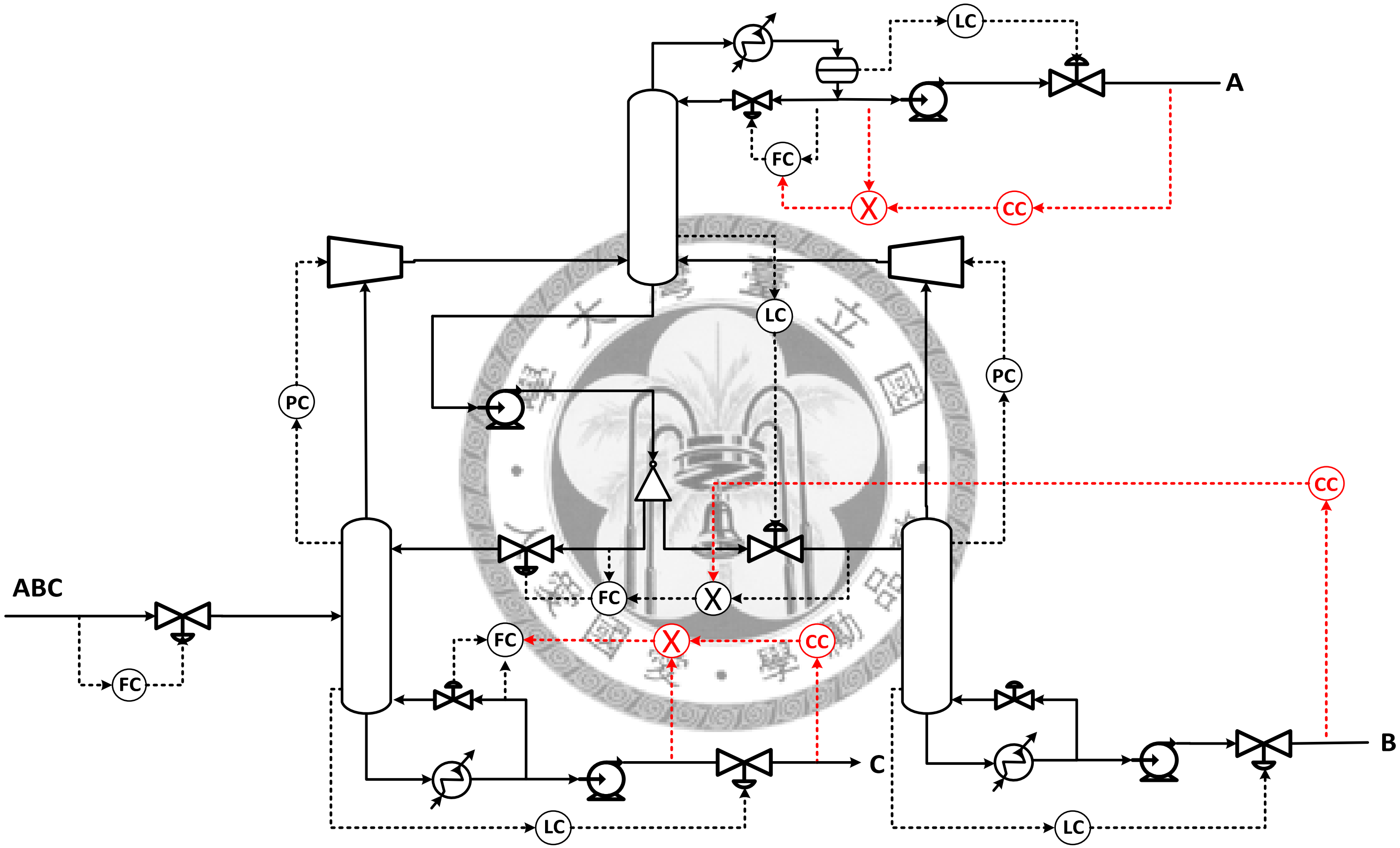


Fig. 3.3-3 Control Structure RR-SL-BR2 for DWCL.

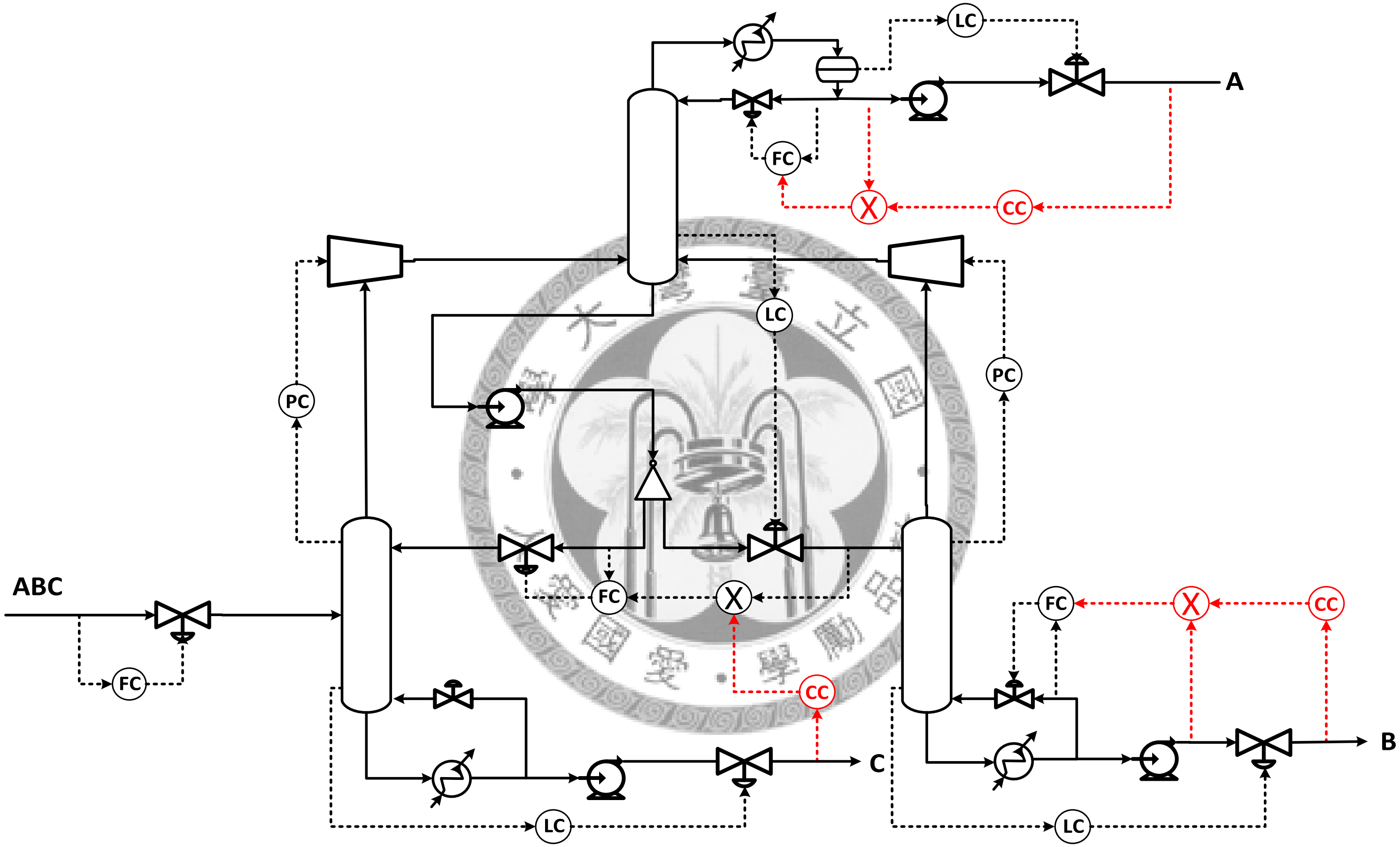


Fig. 3.3-4 Control Structure RR-BR1-SL for DWCL.

We consider the case when ESI>1 ($\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 7.1 / 2.2 / 1).

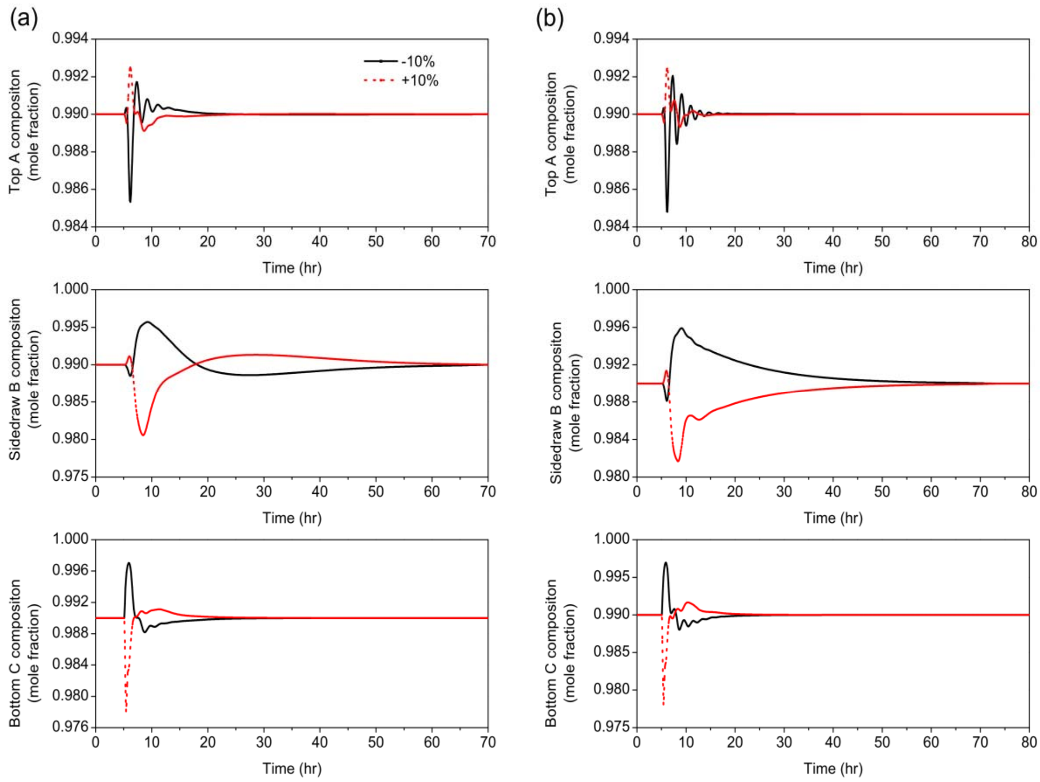


Fig. 3.3-5 Dynamic responses of DWCL, ESI>1, F(8,1,1) for +/-10% feed flowrate disturbances. (a) RR-BR1-BR2 (b) RR-SL-BR2

Table 3.3-1 IAE and ITAE value of DWCL, ESI>1, F(8,1,1) for different control structures

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-BR1-BR2 | 0.0316 | 0.5962 |
| RR-SL-BR2 | 0.1276 | 4.4745 |

Fig. 3.3-5 shows the dynamic responses of different control structures, when there are changes in feed flowrate. Table 3.3-1 shows that control structure RR-BR1-BR2 is better.

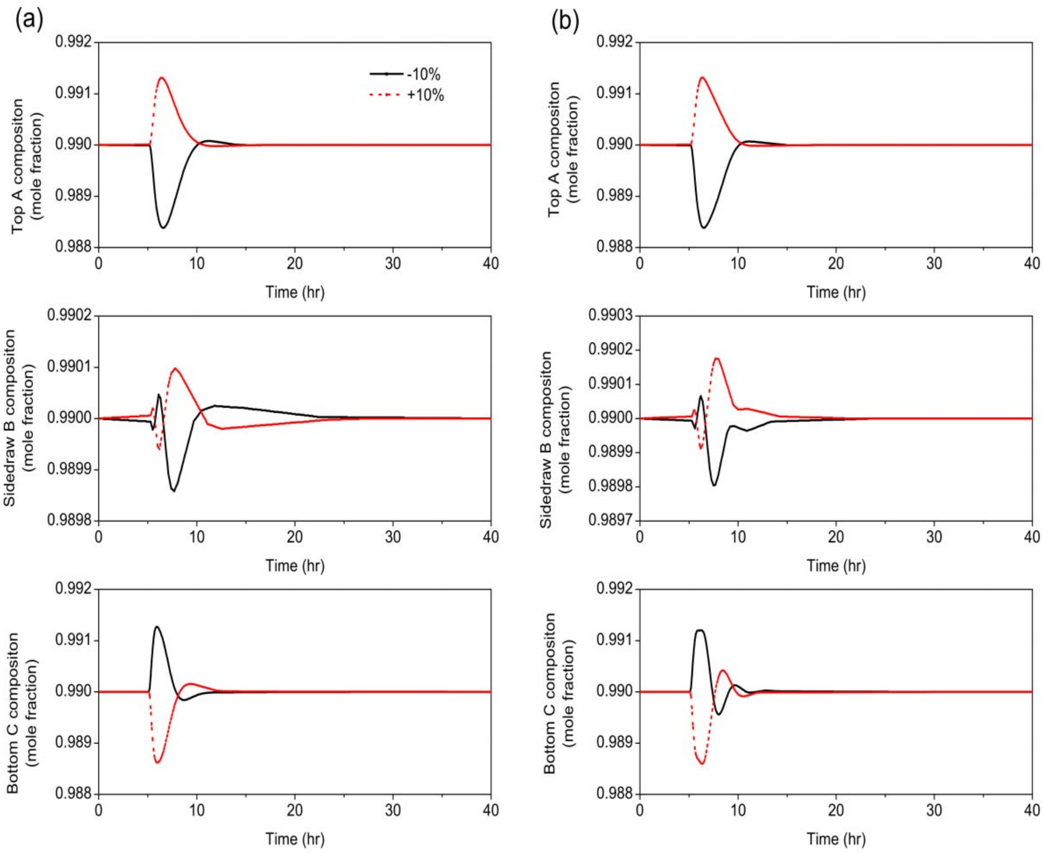


Fig. 3.3-6 Dynamic responses of DWCL, ESI>1, F(1,8,1) for +/-10% feed flowrate disturbances. (a) RR-BR1-BR2 (b) RR-SL-BR2

Table 3.3-2 IAE and ITAE value of DWCL, ESI>1, F(1,8,1) for different control structures

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-BR1-BR2 | 0.0023 | 0.0173 |
| RR-SL-BR2 | 0.0024 | 0.0181 |

Fig. 3.3-6 shows the dynamic responses of different control structures, when there are changes in feed flowrate. Table 3.3-2 shows that control structures RR-BR1-BR2 and RR-SL-BR2 are both good.

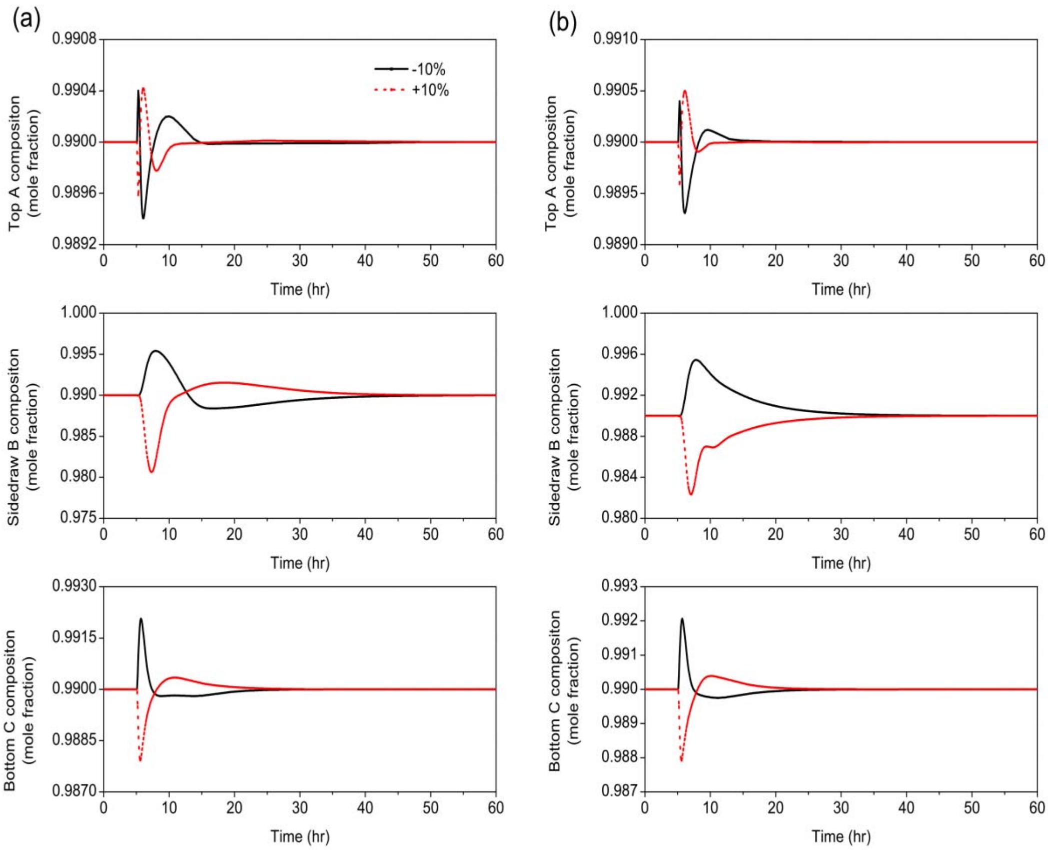


Fig. 3.3-7 Dynamic responses of DWCL, ESI>1, F(1,1,8) for +/-10% feed flowrate disturbances. (a) RR-BR1-BR2 (b) RR-SL-BR2

Table 3.3-3 IAE and ITAE value of DWCL, ESI>1, F(1,1,8) for different control structures

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-BR1-BR2 | 0.0182 | 0.2758 |
| RR-SL-BR2 | 0.0167 | 0.2087 |

Fig. 3.3-7 shows the dynamic responses of different control structures, when there are changes in feed flowrate. Table 3.3-3 shows that control structure RR-SL-BR2 is better.

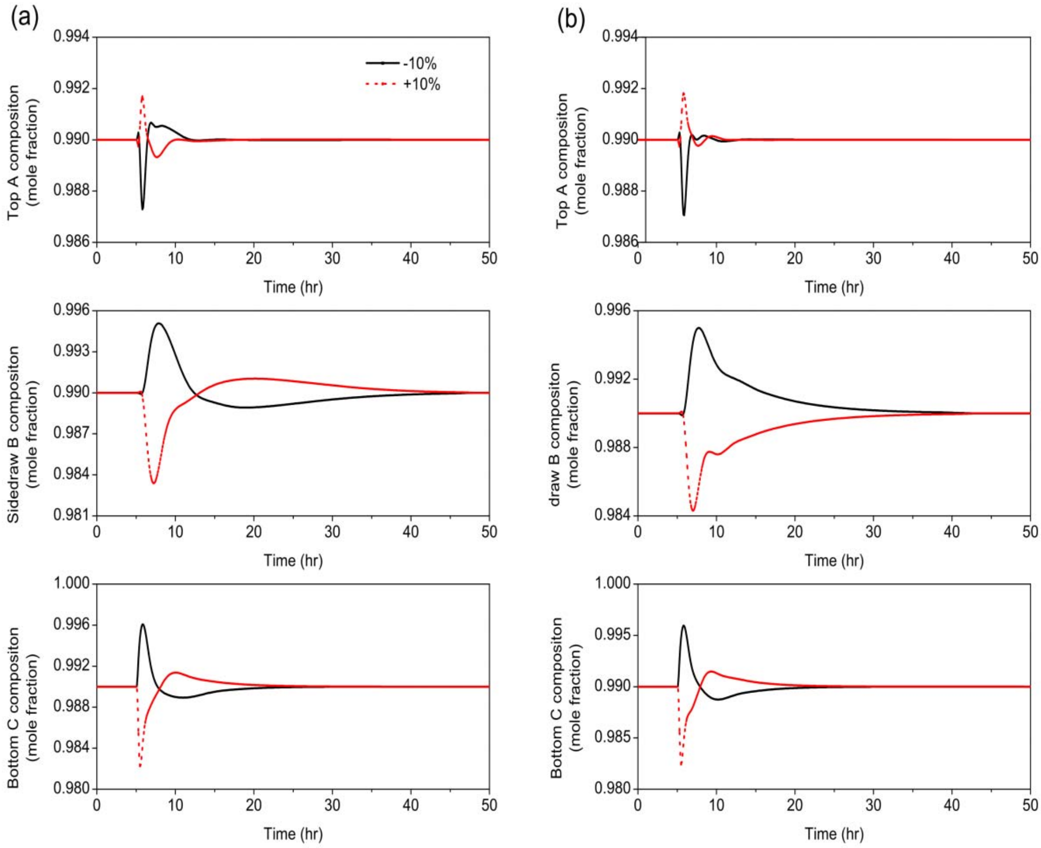


Fig. 3.3-8 Dynamic responses of DWCL, ESI>1, F(3,3,3) for +/-10% feed flowrate disturbances. (a) RR-BR1-BR2 (b) RR-SL-BR2

Table 3.3-4 IAE and ITAE value of DWCL, ESI>1, F(3,3,3) for different control structures

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-BR1-BR2 | 0.0182 | 0.2500 |
| RR-SL-BR2 | 0.0172 | 0.2016 |

Fig. 3.3-8 shows the dynamic responses of different control structures, when there are changes in feed flowrate. Table 3.3-4 shows that control structure RR-SL-BR2 is better.

Next we consider the case when ESI=1 ($\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 4 / 2 / 1).

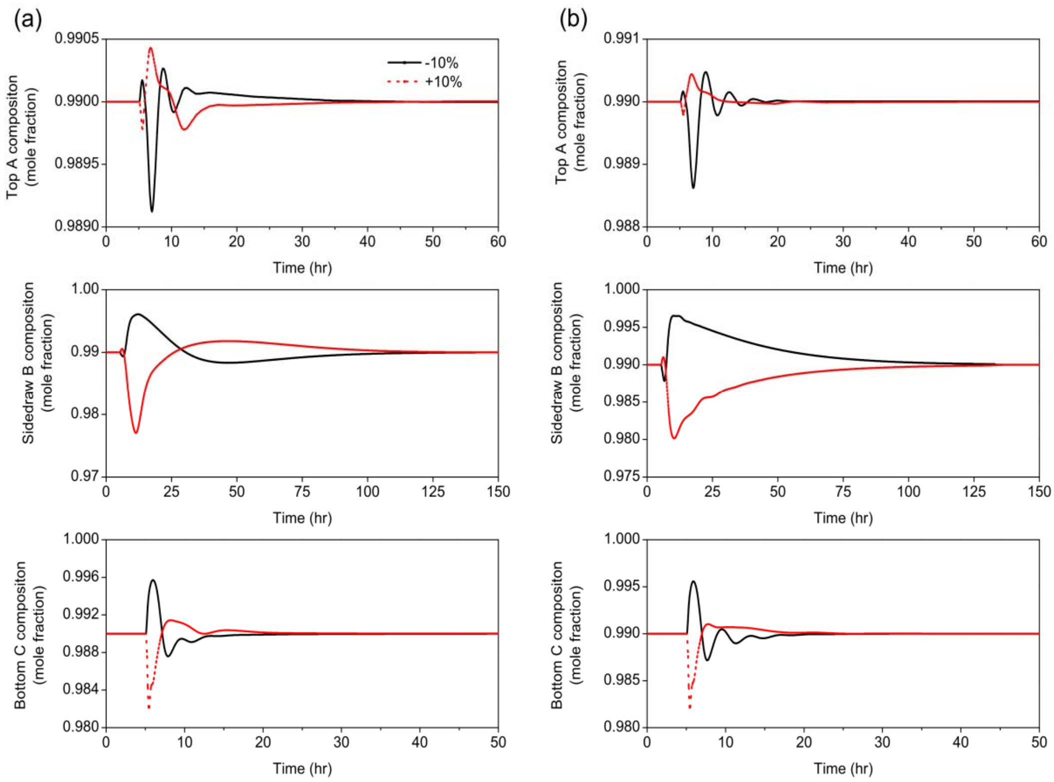


Fig. 3.3-9 Dynamic responses of DWCL, ESI=1, F(8,1,1) for +/-10% feed flowrate disturbances. (a) RR-BR1-BR2 (b) RR-SL-BR2

Table 3.3-5 IAE and ITAE value of DWCL, ESI=1, F(8,1,1) for different control structures

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-BR1-BR2 | 0.0619 | 2.0973 |
| RR-SL-BR2 | 0.0813 | 2.6297 |

Fig. 3.3-9 shows the dynamic responses of different control structures, when there are changes in feed flowrate. Table 3.3-5 shows that control structure RR-SL-BR2 is better.

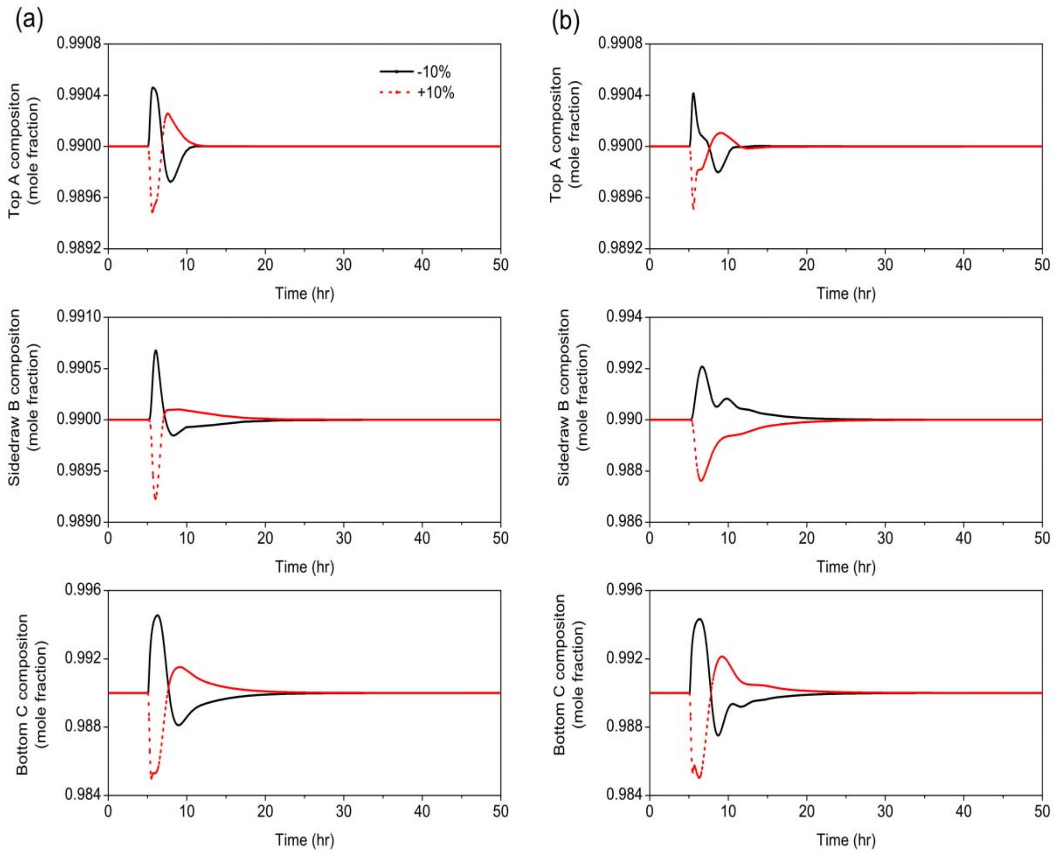


Fig. 3.3-10 Dynamic responses of DWCL, ESI=1, F(1,8,1) for +/-10% feed flowrate disturbances. (a) RR-BR1-BR2 (b) RR-SL-BR2

Table 3.3-6 IAE and ITAE value of DWCL, ESI=1, F(1,8,1) for different control structures

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-BR1-BR2 | 0.0062 | 0.0555 |
| RR-SL-BR2 | 0.0090 | 0.0847 |

Fig. 3.3-10 shows the dynamic responses of different control structures, when there are changes in feed flowrate. Table 3.3-6 shows that control structure RR-BR1-BR2 is better.

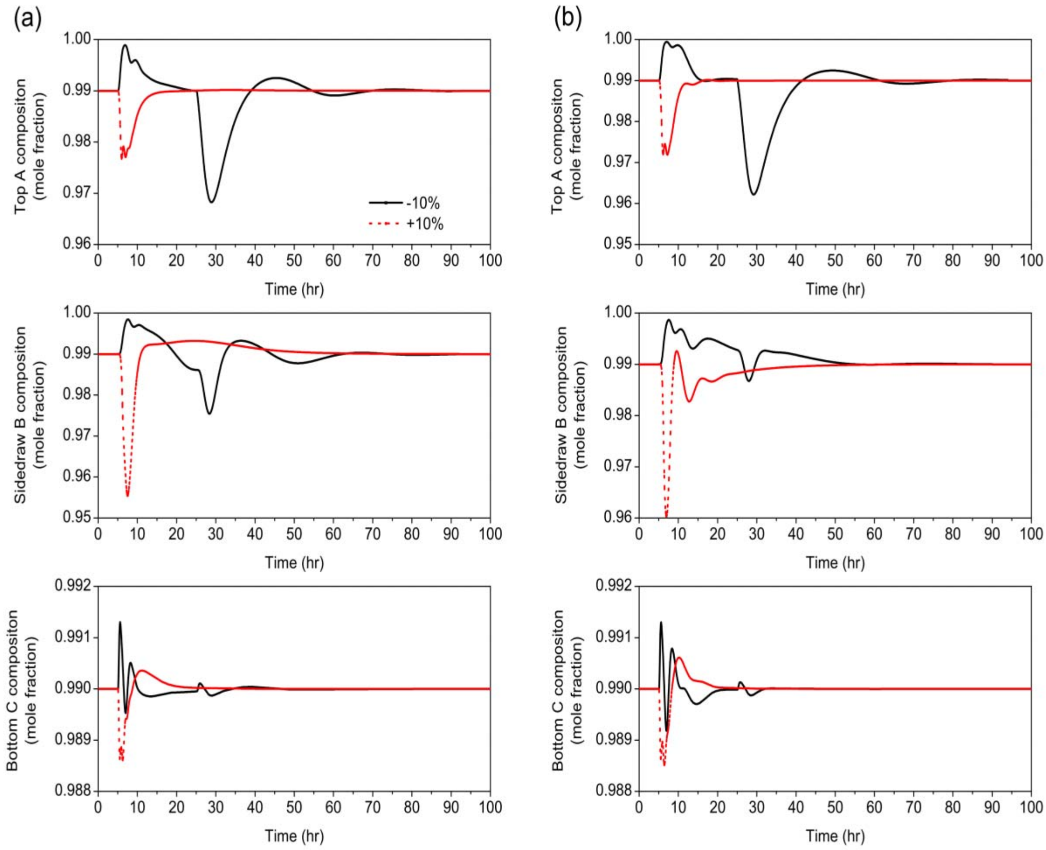


Fig. 3.3-11 Dynamic responses of DWCL, ESI=1, F(1,1,8) for +/-10% feed flowrate disturbances. (a) RR-BR1-BR2 (b) RR-SL-BR2

Table 3.3-7 IAE and ITAE value of DWCL, ESI=1, F(1,1,8) for different control structures

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-BR1-BR2 | 0.1123 | 2.6893 |
| RR-SL-BR2 | 0.1081 | 2.4944 |

Fig. 3.3-11 shows the dynamic responses of different control structures, when there are changes in feed flowrate. Table 3.3-7 shows that control structures RR-BR1-BR2 and RR-SL-BR2 are both good.

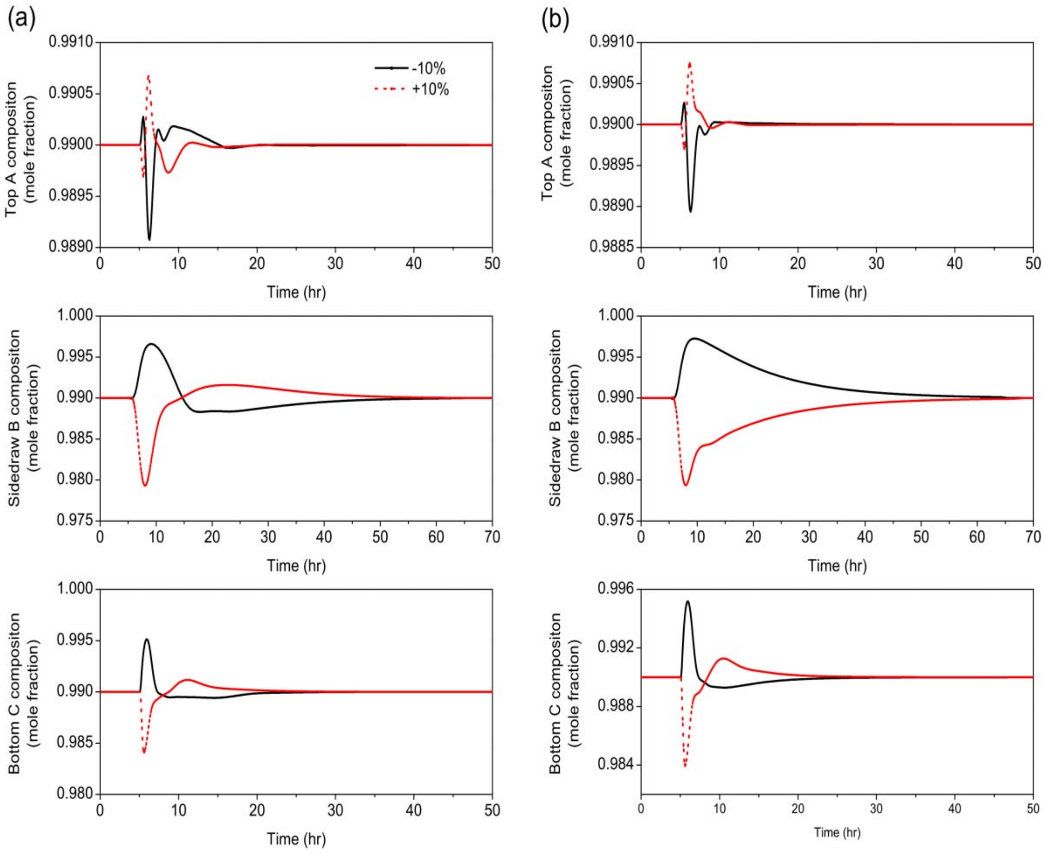


Fig. 3.3-12 Dynamic responses of DWCL, ESI=1, F(3,3,3) for +/-10% feed flowrate disturbances. (a) RR-BR1-BR2 (b) RR-SL-BR2

Table 3.3-8 IAE and ITAE value of DWCL, ESI=1, F(3,3,3) for different control structures

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-BR1-BR2 | 0.0275 | 0.4745 |
| RR-SL-BR2 | 0.0447 | 0.8162 |

Fig. 3.3-12 shows the dynamic responses of different control structures, when there are changes in feed flowrate. And Table 3.3-8 shows the control structure RR-BR1-BR2 is better.

Next we consider the case when ESI<1 ($\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 4 / 2.4 / 1).

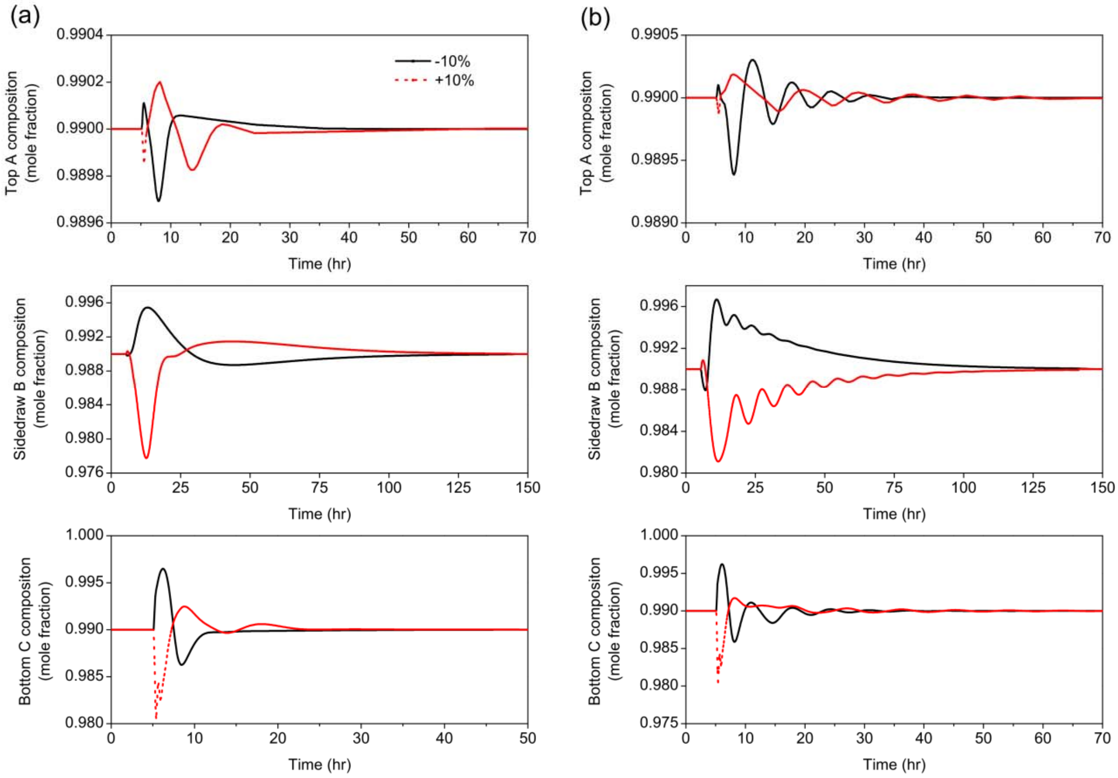


Fig. 3.3-13 Dynamic responses of DWCL, ESI<1, F(8,1,1) for +/-10% feed flowrate disturbances. (a) RR-BR1-BR2 (b) RR-SL-BR2

Table 3.3-9 IAE and ITAE value of DWCL, ESI<1, F(8,1,1) for different control structures

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-BR1-BR2 | 0.0540 | 1.7823 |
| RR-SL-BR2 | 0.0727 | 2.3709 |

Fig. 3.3-13 shows the dynamic responses of different control structures, when there are changes in feed flowrate. Table 3.3-9 shows that control structure RR-BR1-BR2 is better.

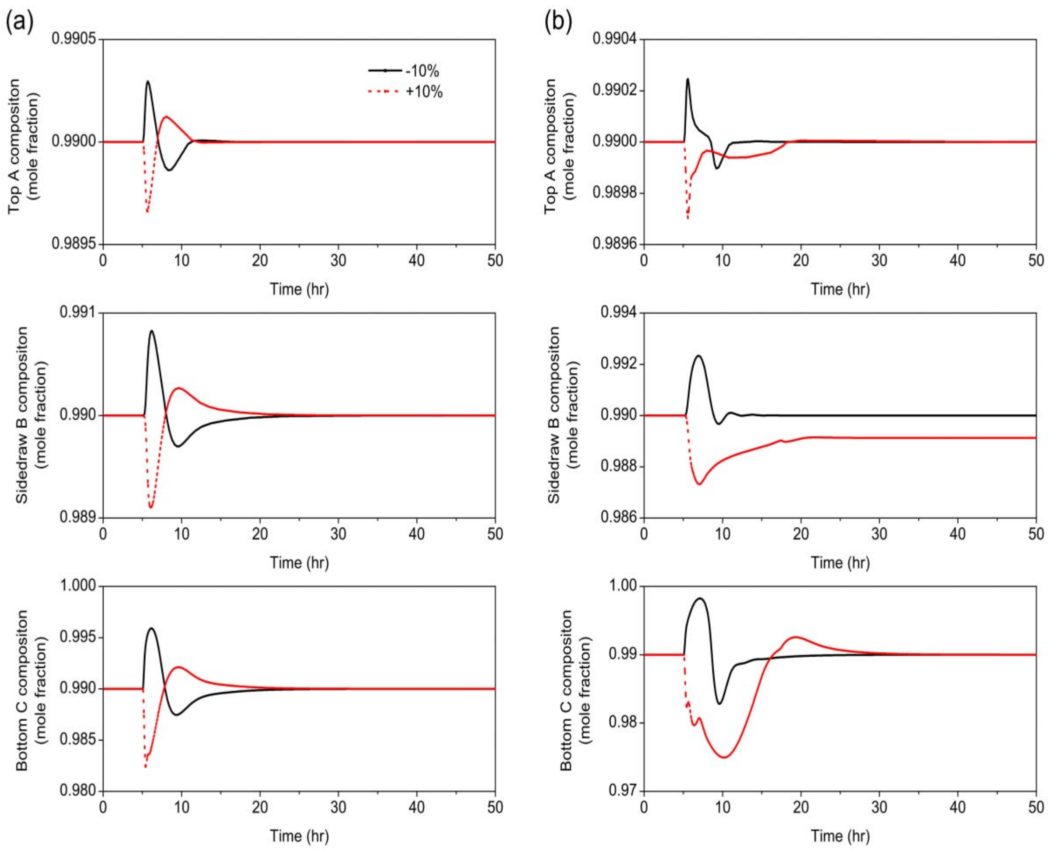


Fig. 3.3-14 Dynamic responses of DWCL, ESI<1, F(1,8,1) for +/-10% feed flowrate disturbances. (a) RR-BR1-BR2 (b) RR-SL-BR2

Table 3.3-10 IAE and ITAE value of DWCL, ESI<1, F(1,8,1) for different control structures

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-BR1-BR2 | 0.0084 | 0.0760 |
| RR-SL-BR2 | 0.0371 | 0.5106 |

Fig. 3.3-14 shows the dynamic responses of different control structures, when there are changes in feed flowrate. Table 3.3-10 shows that control structure RR-BR1-BR2 is better.

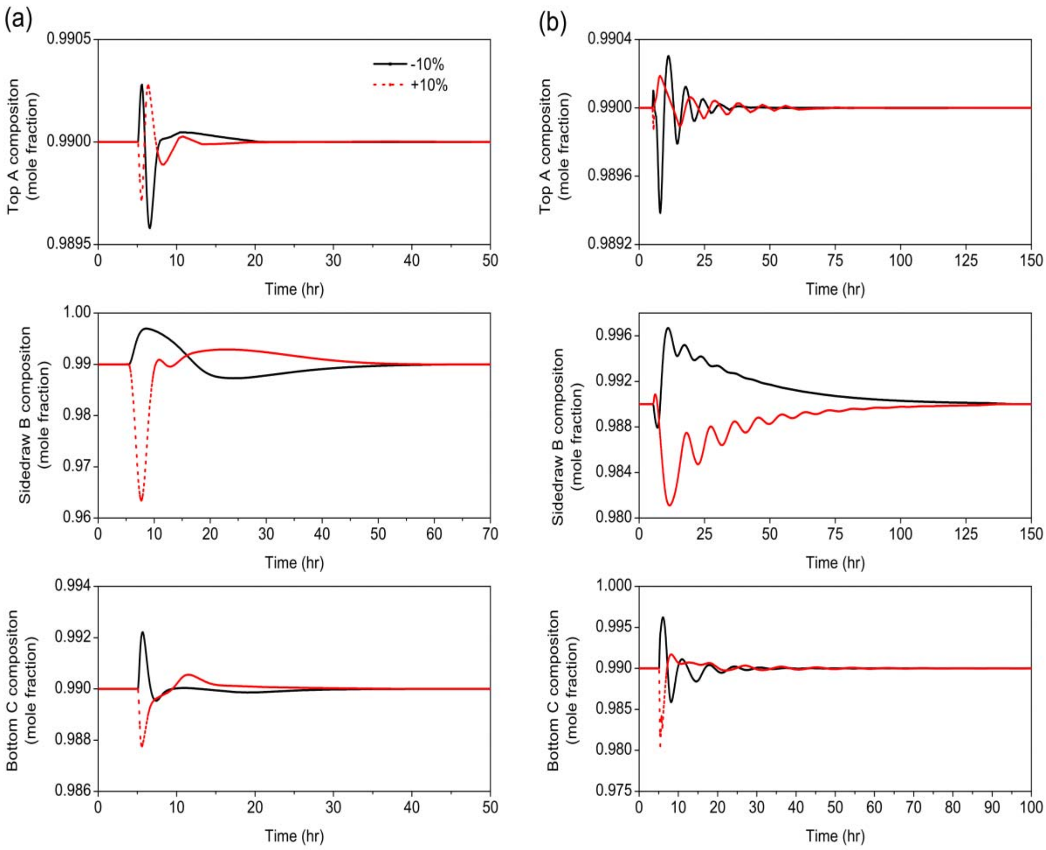


Fig. 3.3-15 Dynamic responses of DWCL, ESI<1, F(1,1,8) for +/-10% feed flowrate disturbances. (a) RR-BR1-BR2 (b) RR-SL-BR2

Table 3.3-11 IAE and ITAE value of DWCL, ESI<1, F(1,1,8) for different control structures

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-BR1-BR2 | 0.0396 | 0.7393 |
| RR-SL-BR2 | 0.0726 | 2.3481 |

Fig. 3.3-15 shows the dynamic responses of different control structures, when there are changes in feed flowrate. Table 3.3-11 shows that control structure RR-BR1-BR2 is better.

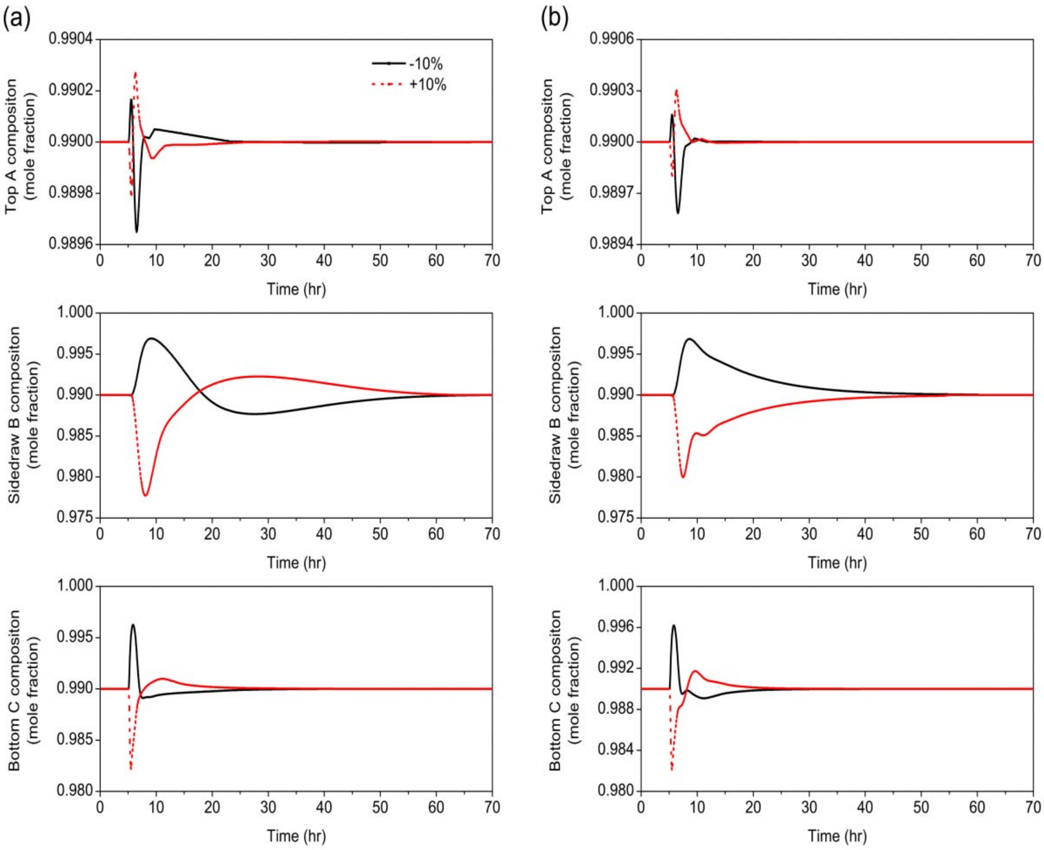


Fig. 3.3-16 Dynamic responses of DWCL, ESI<1, F(3,3,3) for +/-10% feed flowrate disturbances. (a) RR-BR1-BR2 (b) RR-SL-BR2

Table 3.3-12 IAE and ITAE value of DWCL, ESI<1, F(3,3,3) for different control structures

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-BR1-BR2 | 0.0403 | 0.8185 |
| RR-SL-BR2 | 0.0331 | 0.5145 |

Fig. 3.3-16 shows the dynamic responses of different control structures, when there are changes in feed flowrate. Table 3.3-12 shows that control structure RR-SL-BR2 is better.

### 3.3.2 DWCU

Fig. 3.3-17 shows the control structure RR1-RR2-BR. It means that the composition of component A component in top stream was manipulated by reflux ratio 1 (RR1), the composition of component B component in middle stream was manipulated by reflux ratio 2 (RR2) and the composition of component C component in bottom stream was manipulated by boilup ratio (BR), respectively.

In those control strategy, level control are using the P controller, the rest are using the PI controller. We will use the Relay-Feedback closed-loop testing and Tyreus-Luyben tuning method to arrive these PI controller parameters. The composition control was used. In the dynamic simulations in this work, disturbances of +/1 10% in the feed flowrate were used.

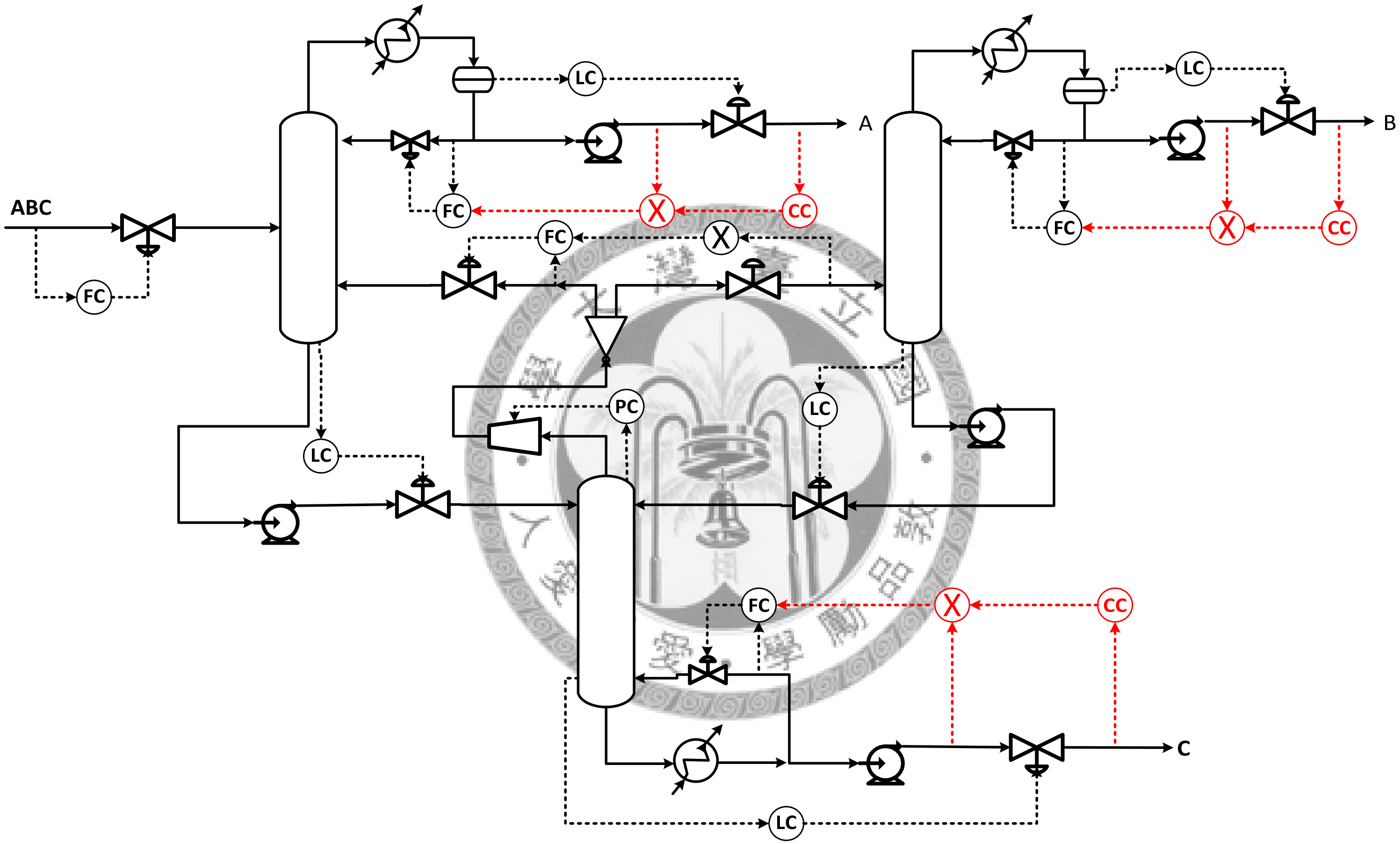


Fig. 3.3-17 Control Structure RR1-RR2-BR for DWCU.

We consider the case when ESI>1 ($\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 7.1 / 2.2 / 1).

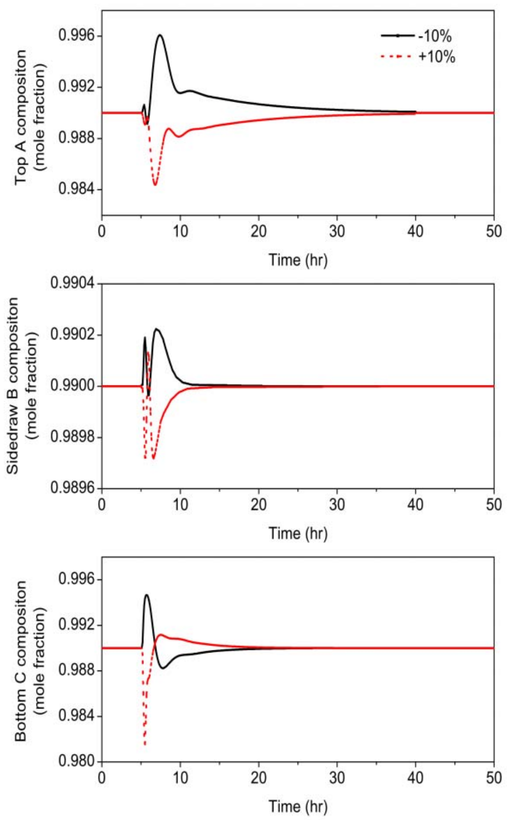


Fig. 3.3-18 Dynamic responses of DWCU, ESI>1, F(8,1,1) for +/-10% feed flowrate disturbances. RR1-RR2-BR

Table 3.3-13 IAE and ITAE value of DWCU, ESI>1, F(8,1,1)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR1-RR2-BR | 0.0138 | 0.1664 |

Fig. 3.3-18 shows the dynamic responses of control structure RR1-RR2-BR, when there are changes in feed flowrate.

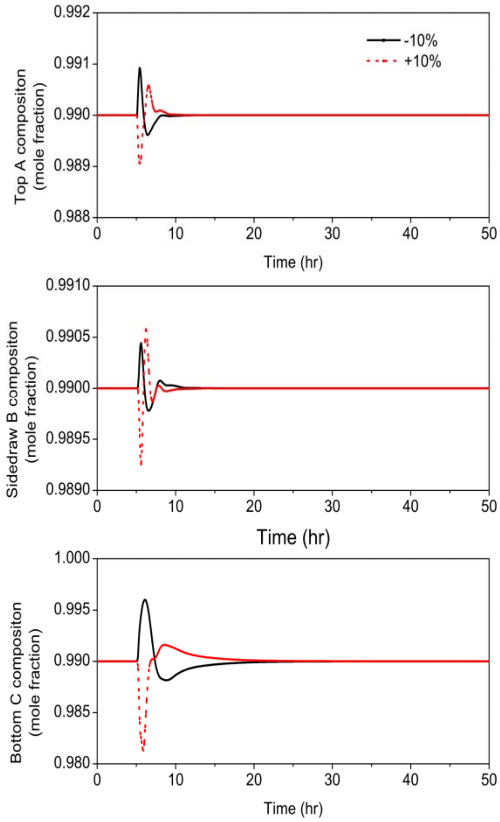


Fig. 3.3-19 Dynamic responses of DWCU, ESI>1, F(1,8,1) for +/-10% feed flowrate disturbances. RR1-RR2-BR

Table 3.3-14 IAE and ITAE value of DWCU, ESI>1, F(1,8,1)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR1-RR2-BR | 0.0060 | 0.0516 |

Fig. 3.3-19 shows the dynamic responses of control structure RR1-RR2-BR, when there are changes in feed flowrate.

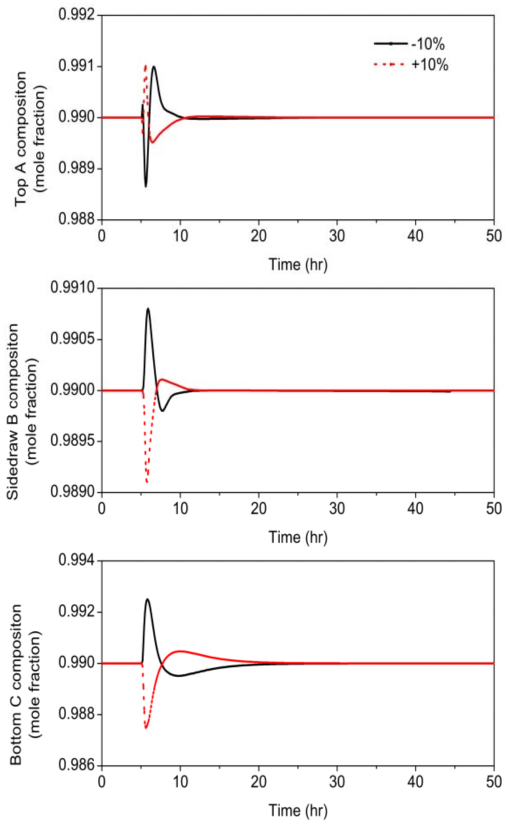


Fig. 3.3-20 Dynamic responses of DWCU, ESI>1, F(1,1,8) for +/-10% feed flowrate disturbances. RR1-RR2-BR

Table 3.3-15 IAE and ITAE value of DWCU, ESI>1, F(1,1,8)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR1-RR2-BR | 0.0031 | 0.0274 |

Fig. 3.3-20 shows the dynamic responses of control structure RR1-RR2-BR, when there are changes in feed flowrate.

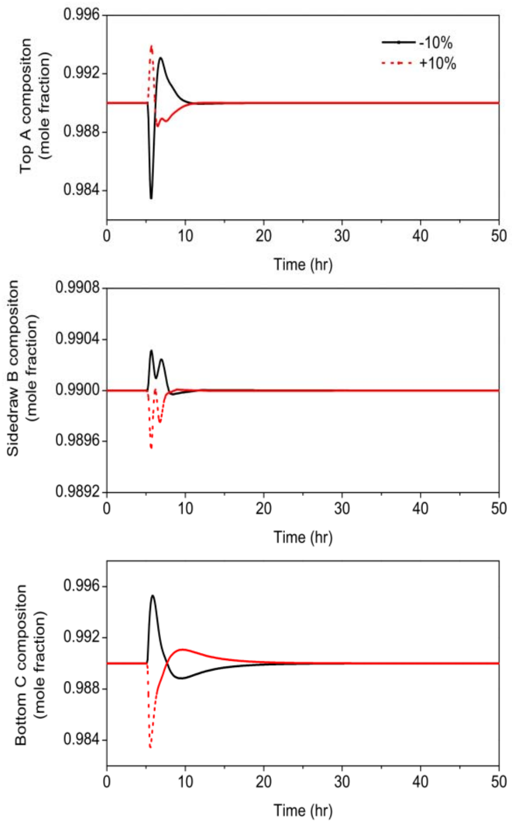


Fig. 3.3-21 Dynamic responses of DWCU, ESI>1, F(3,3,3) for +/-10% feed flowrate disturbances. RR1-RR2-BR

Table 3.3-16 IAE and ITAE value of DWCU, ESI>1, F(3,3,3)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR1-RR2-BR | 0.0070 | 0.0590 |

Fig. 3.3-21 shows the dynamic responses of control structure RR1-RR2-BR, when there are changes in feed flowrate.

Next we consider the case when ESI=1 ($\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 4 / 2 / 1).

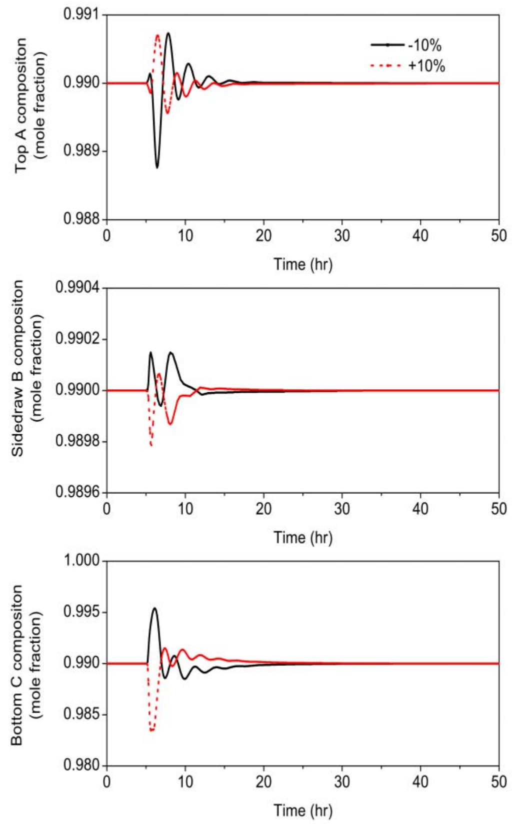


Fig. 3.3-22 Dynamic responses of DWCU, ESI=1, F(8,1,1) for +/-10% feed flowrate disturbances. RR1-RR2-BR

Table 3.3-17 IAE and ITAE value of DWCU, ESI=1, F(8,1,1)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR1-RR2-BR | 0.0055 | 0.0533 |

Fig. 3.3-22 shows the dynamic responses of control structure RR1-RR2-BR, when there are changes in feed flowrate.

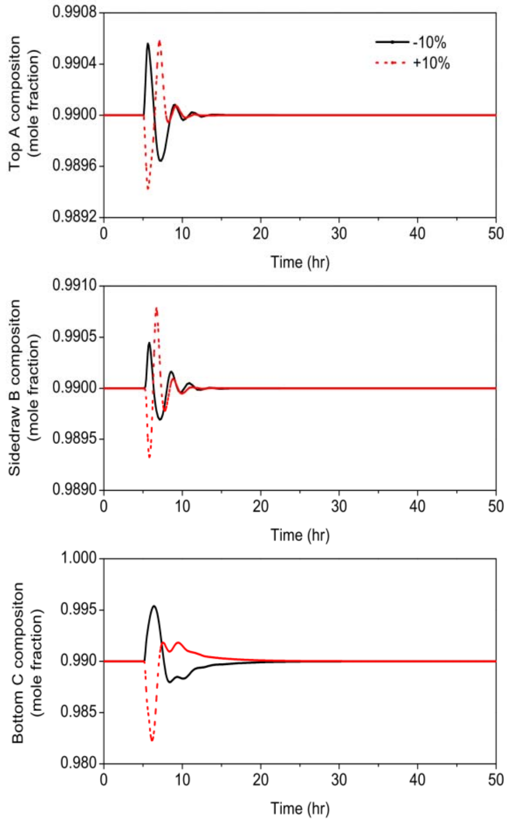


Fig. 3.3-23 Dynamic responses of DWCU, ESI=1, F(1,8,1) for +/-10% feed flowrate disturbances. RR1-RR2-BR

Table 3.3-18 IAE and ITAE value of DWCU, ESI=1, F(1,8,1)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR1-RR2-BR | 0.0065 | 0.0563 |

Fig. 3.3-23 shows the dynamic responses of control structure RR1-RR2-BR, when there are changes in feed flowrate.

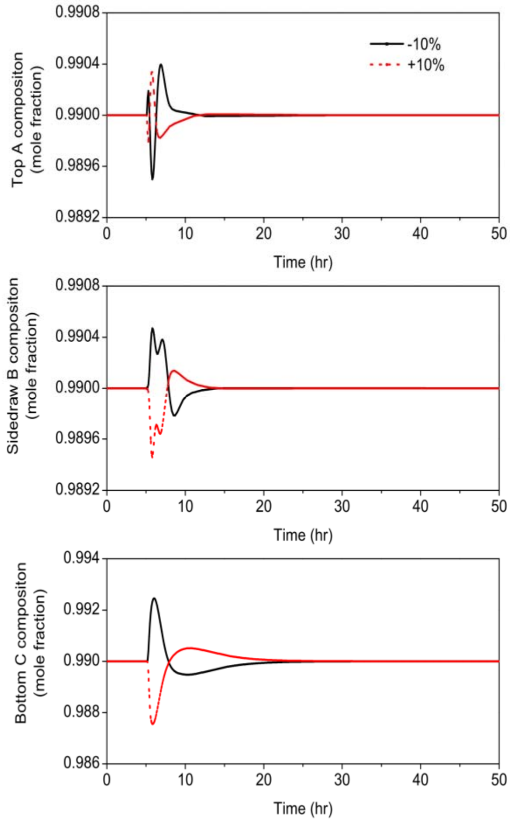


Fig. 3.3-24 Dynamic responses of DWCU, ESI=1, F(1,1,8) for +/-10% feed flowrate disturbances. RR1-RR2-BR

Table 3.3-19 IAE and ITAE value of DWCU, ESI=1, F(1,1,8)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR1-RR2-BR | 0.0031 | 0.0286 |

Fig. 3.3-24 shows the dynamic responses of control structure RR1-RR2-BR, when there are changes in feed flowrate.

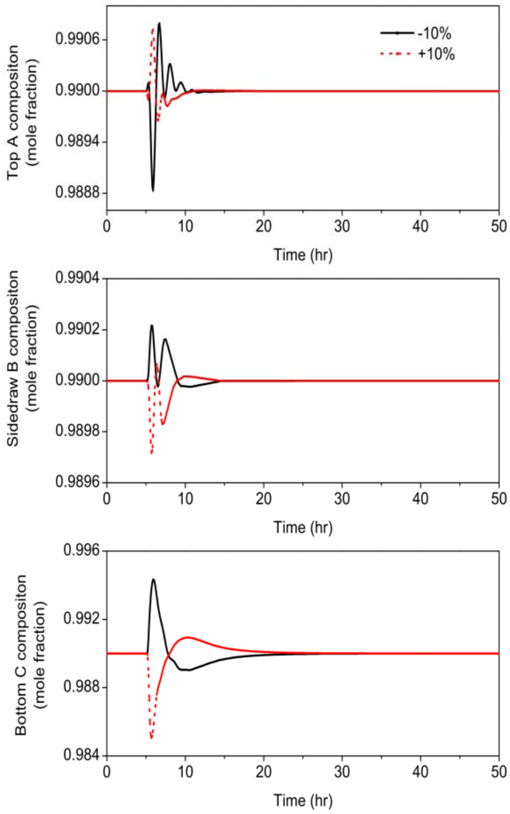


Fig. 3.3-25 Dynamic responses of DWCU, ESI=1, F(3,3,3) for +/-10% feed flowrate disturbances. RR1-RR2-BR

Table 3.3-20 IAE and ITAE value of DWCU, ESI=1, F(3,3,3)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR1-RR2-BR | 0.0044 | 0.0413 |

Fig. 3.3-25 shows the dynamic responses of control structure RR1-RR2-BR, when there are changes in feed flowrate.

Next we consider the case when ESI<1 ($\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 4 / 2.4 / 1).

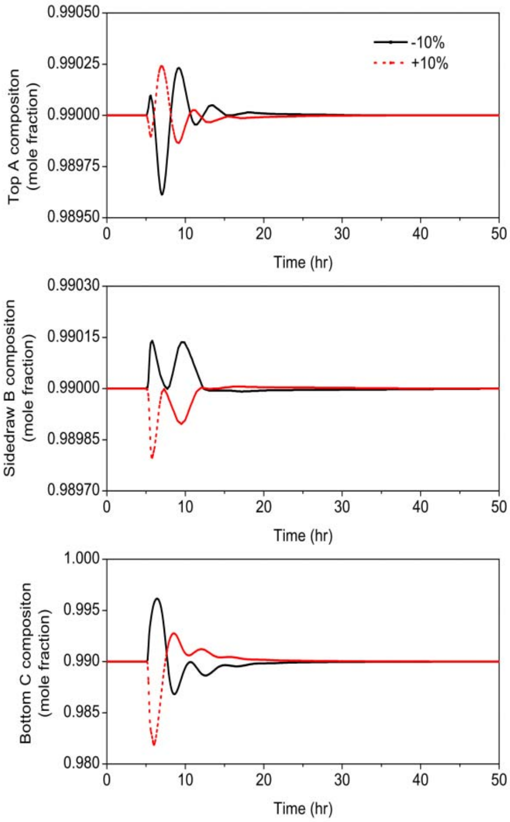


Fig. 3.3-26 Dynamic responses of DWCU, ESI<1, F(8,1,1) for +/-10% feed flowrate disturbances. RR1-RR2-BR

Table 3.3-21 IAE and ITAE value of DWCU, ESI<1, F(8,1,1)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR1-RR2-BR | 0.0078 | 0.0757 |

Fig. 3.3-26 shows the dynamic responses of control structure RR1-RR2-BR, when there are changes in feed flowrate.

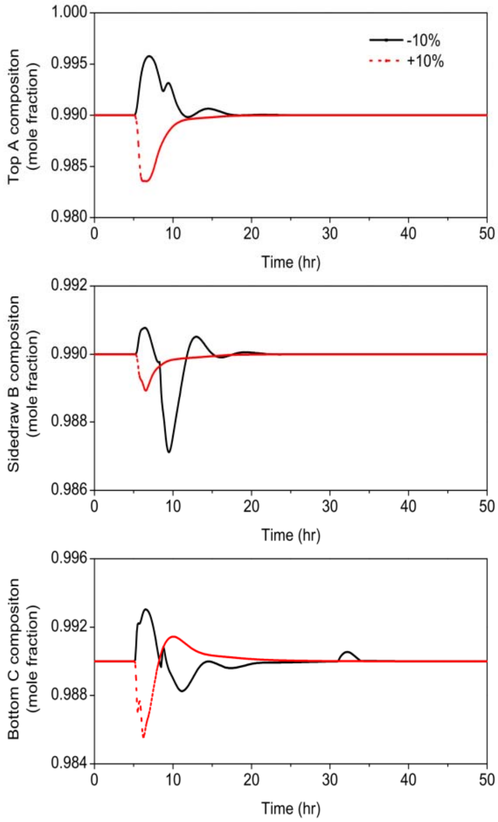


Fig. 3.3-27 Dynamic responses of DWCU, ESI<1, F(1,8,1) for +/-10% feed flowrate disturbances. RR1-RR2-BR

Table 3.3-22 IAE and ITAE value of DWCU, ESI<1, F(1,8,1)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR1-RR2-BR | 0.0140 | 0.1299 |

Fig. 3.3-27 shows the dynamic responses of control structure RR1-RR2-BR, when there are changes in feed flowrate.

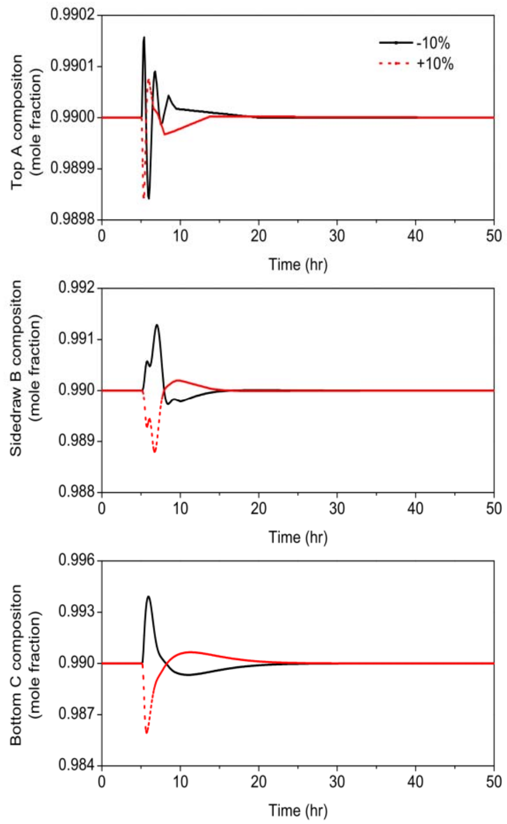


Fig. 3.3-28 Dynamic responses of DWCU, ESI<1, F(1,1,8) for +/-10% feed flowrate disturbances. RR1-RR2-BR

Table 3.3-23 IAE and ITAE value of DWCU, ESI<1, F(1,1,8)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR1-RR2-BR | 0.0043 | 0.0421 |

Fig. 3.3-28 shows the dynamic responses of control structure RR1-RR2-BR, when there are changes in feed flowrate.

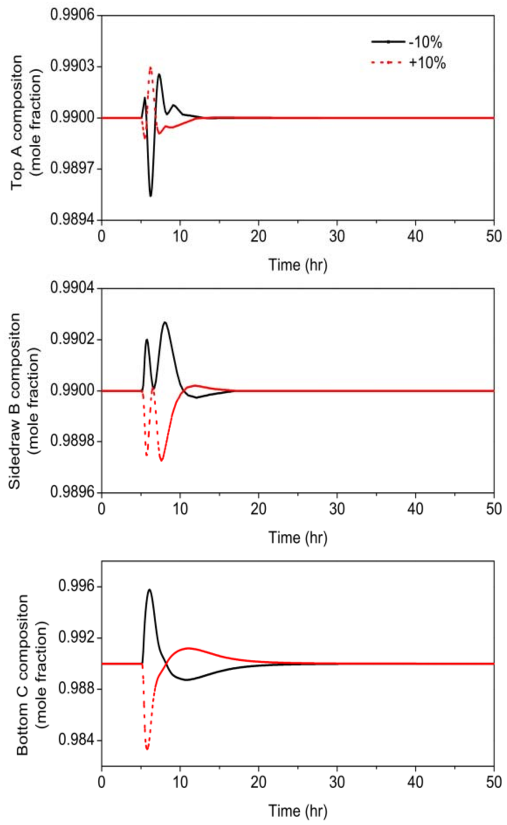


Fig. 3.3-29 Dynamic responses of DWCU, ESI<1, F(3,3,3) for +/-10% feed flowrate disturbances. RR1-RR2-BR

Table 3.3-24 IAE and ITAE value of DWCU, ESI<1, F(3,3,3)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR1-RR2-BR | 0.0061 | 0.0597 |

Fig. 3.3-29 shows the dynamic responses of control structure RR1-RR2-BR, when there are changes in feed flowrate.

### 3.3.3 DWCM

Fig. 3.3-31 shows the control structure RR-S-BR. The composition of component A in top stream was manipulated by reflux ratio (RR), the composition of component B component in middle stream was manipulated by sidedraw stream flowrate (S) and the composition of component C component in bottom stream was manipulated by boilup ratio (BR2), respectively.

Fig. 3.3-32 shows the control structure S-SL-BR. Fig. 3.3-33 shows the control structure BR-SL-S.Fig. 3.3-35 shows the control structure RR-S-SL. Fig. 3.3-36 shows the control structure RR-SL-S.

In those control strategy, level control are using the P controller, the rest are using the PI controller. We will use the Relay-Feedback closed-loop testing and Tyreus-Luyben tuning method to arrive these PI controller parameters. The composition control was used. In the dynamic simulations in this work, disturbances of +/1 10% in the feed flowrate were used.

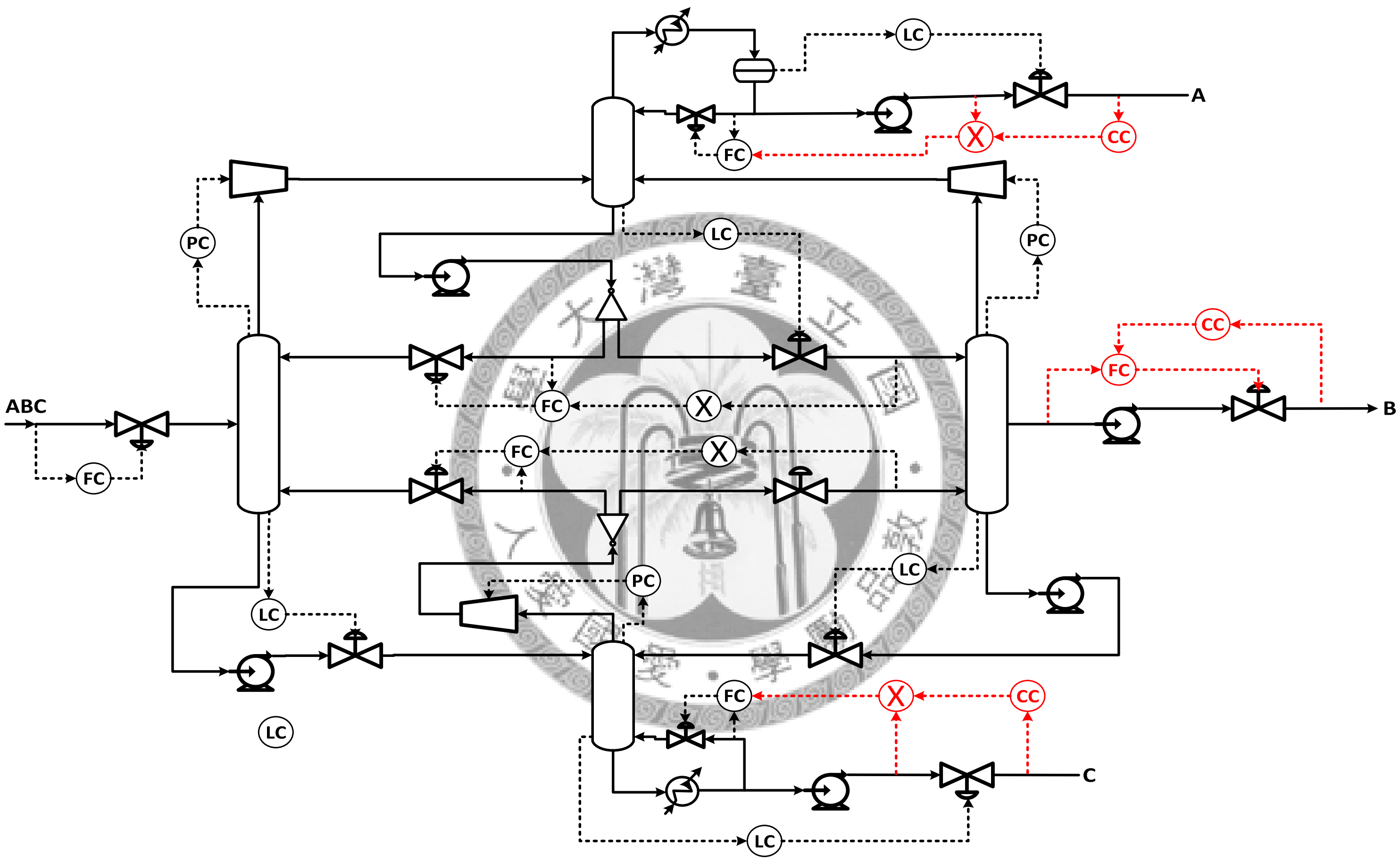


Fig. 3.3-30 Control Structure RR-S-BR for DWCM.

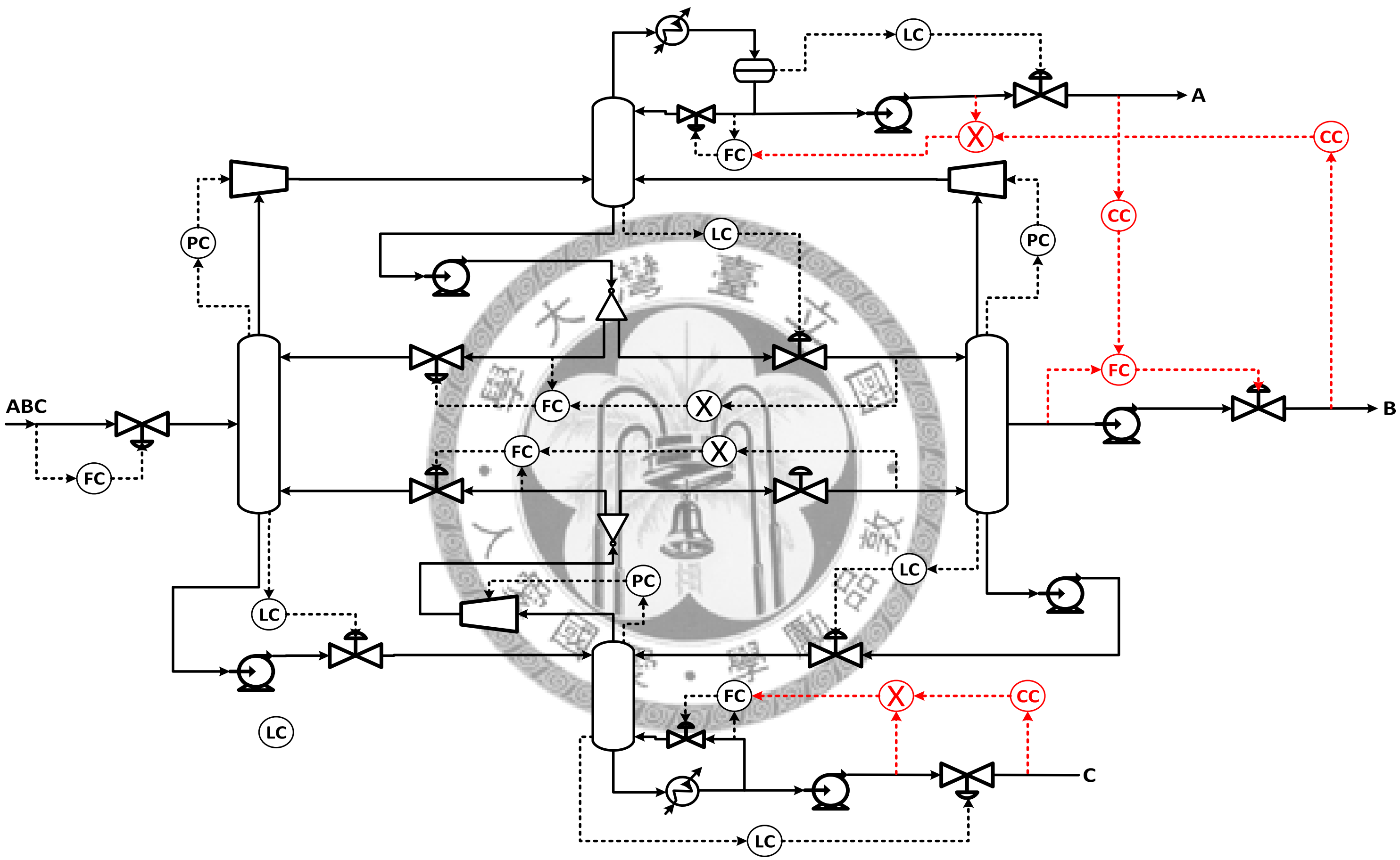


Fig. 3.3-31 Control Structure S-S-BR for DWCM.

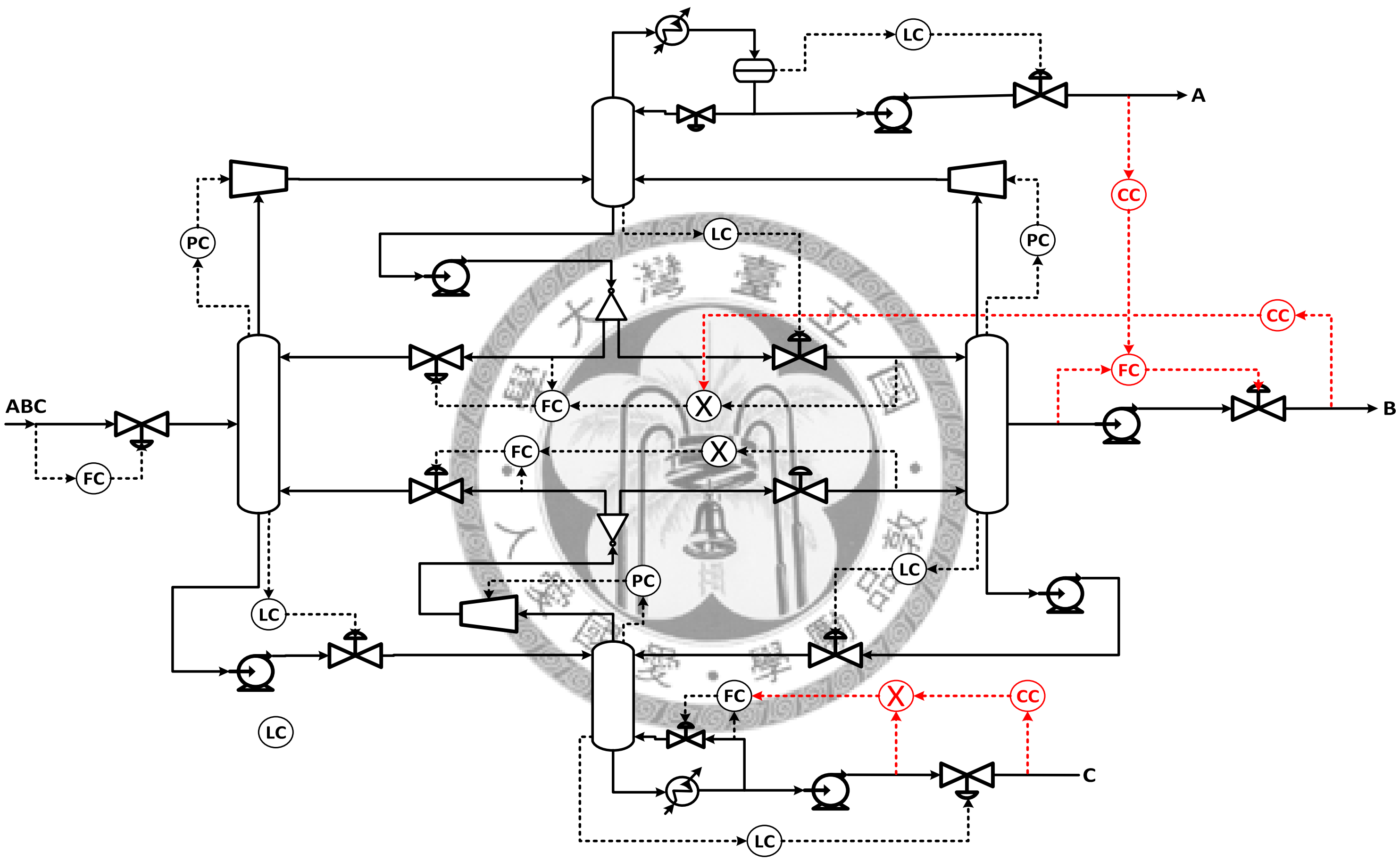


Fig. 3.3-32 Control Structure S-SL-BR for DWCM.

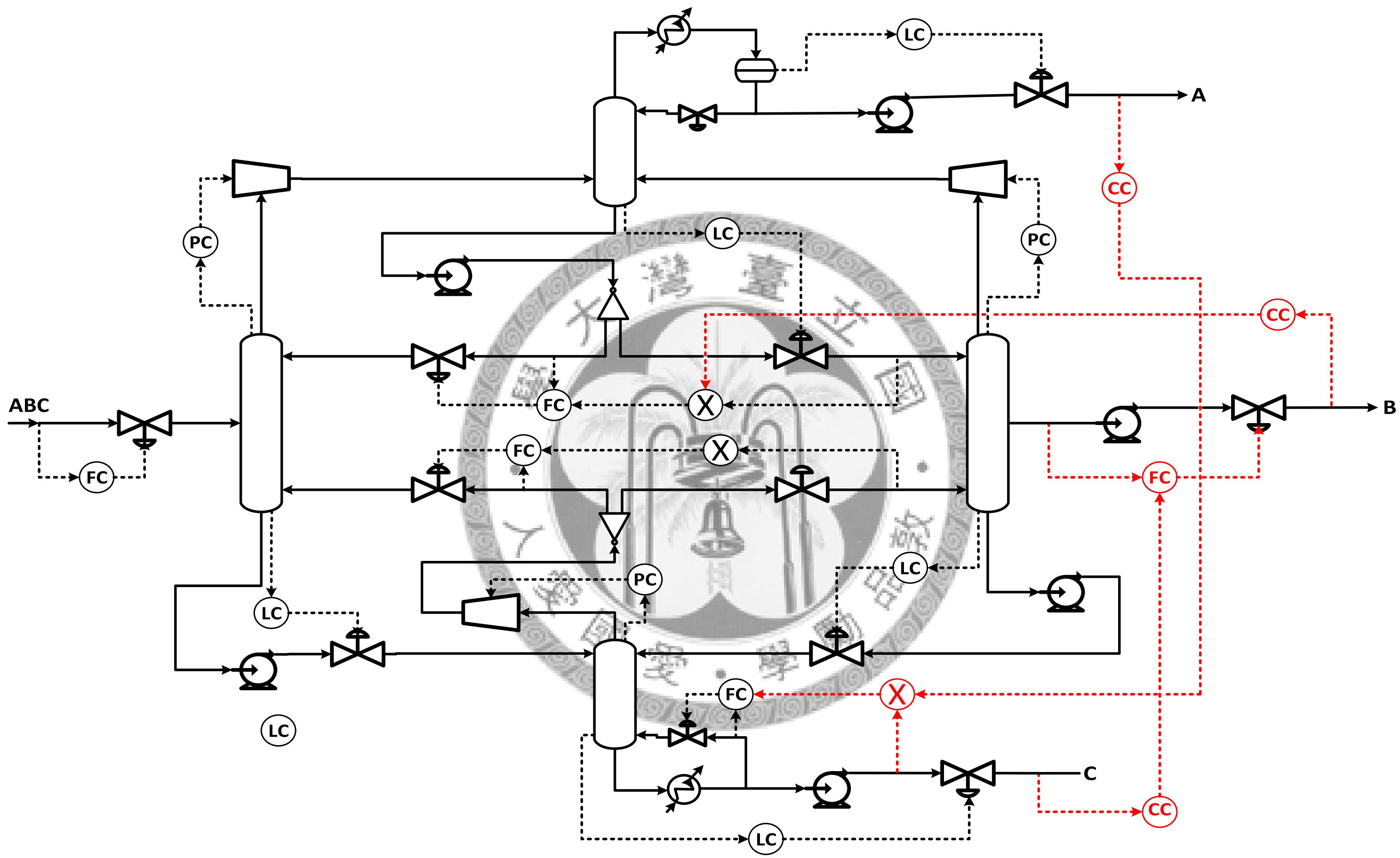


Fig. 3.3-33 Control Structure BR-SL-S for DWCM.

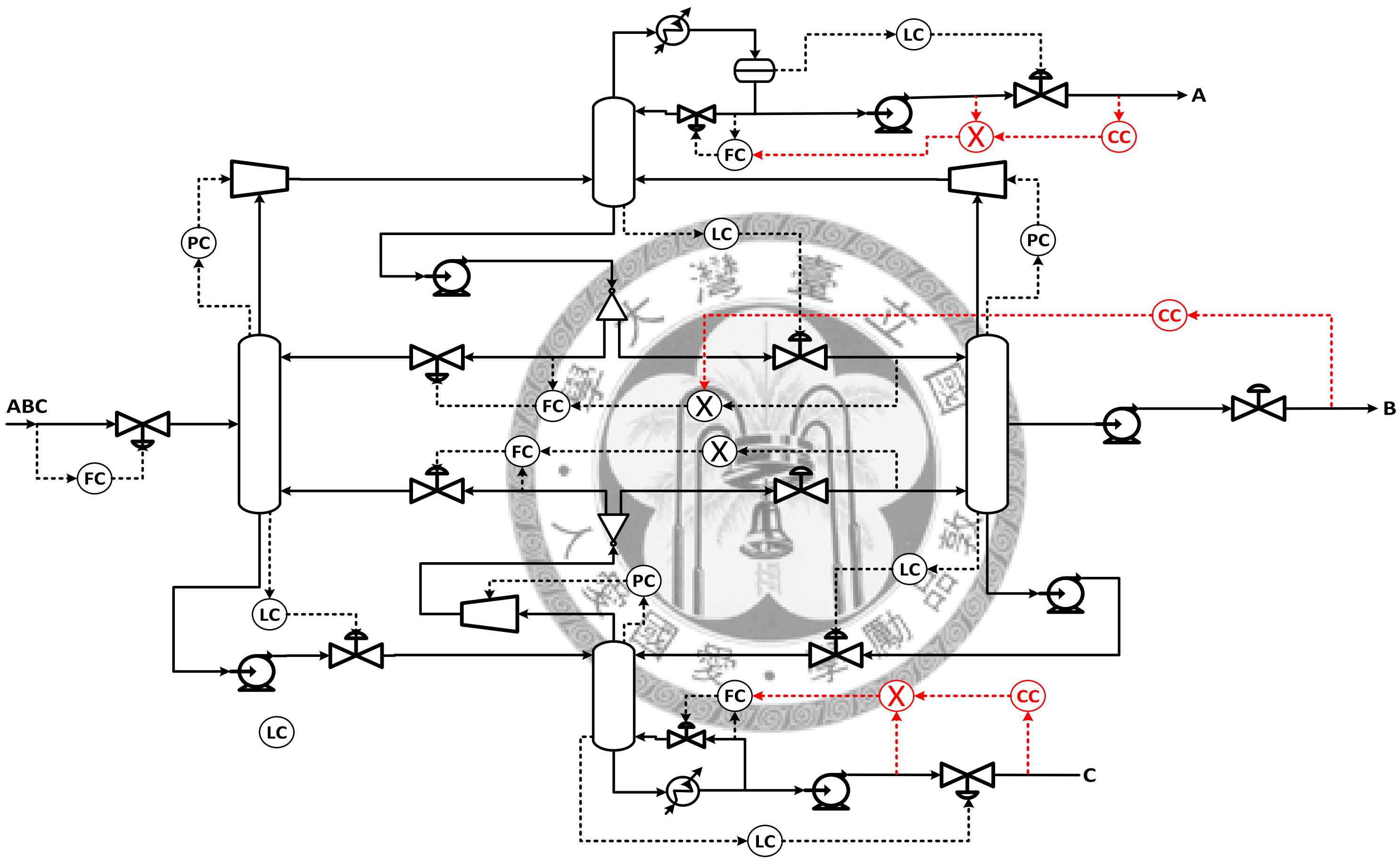


Fig. 3.3-34 Control Structure RR-SL-BR for DWCM.

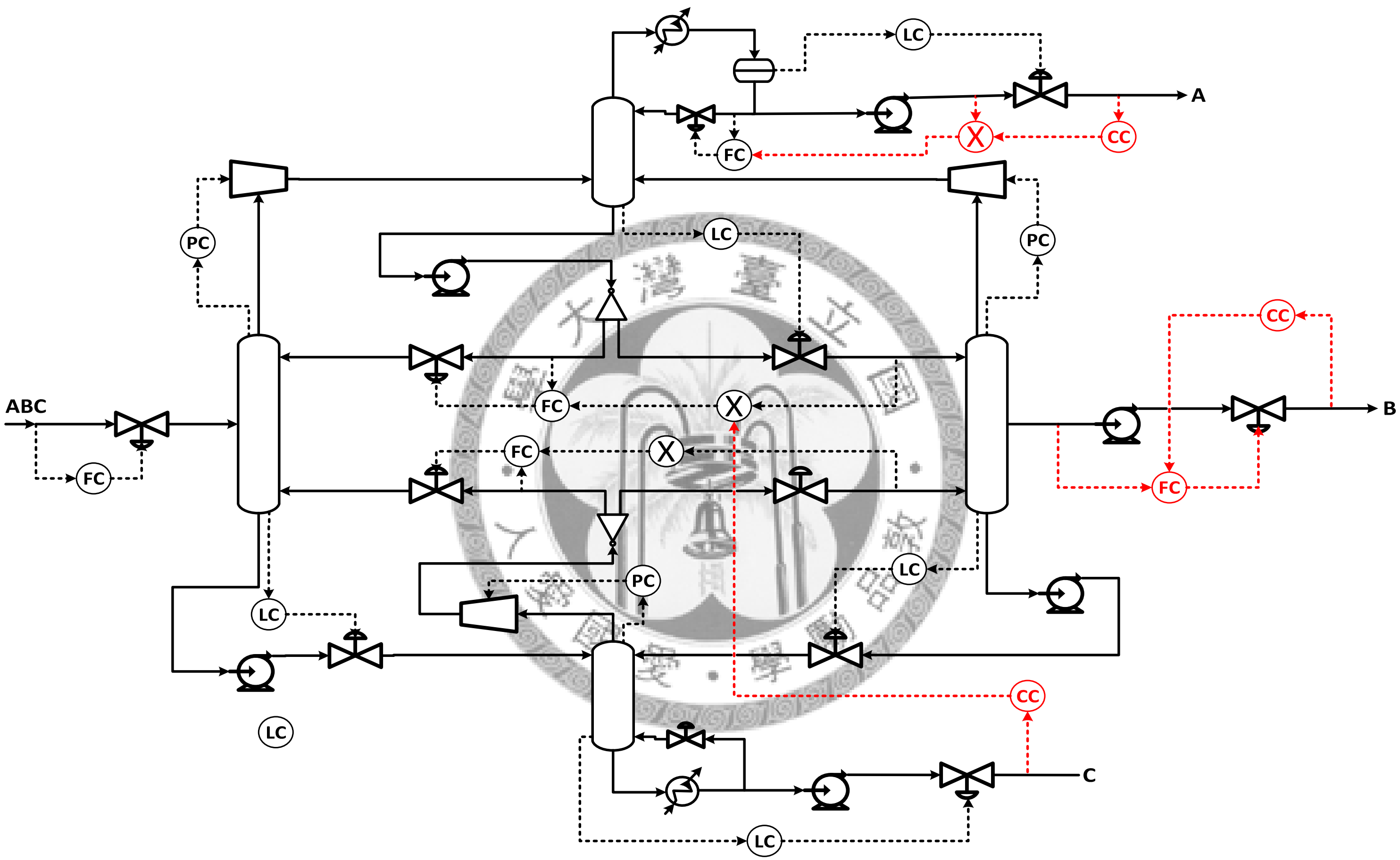


Fig. 3.3-35 Control Structure RR-S-SL for DWCM.

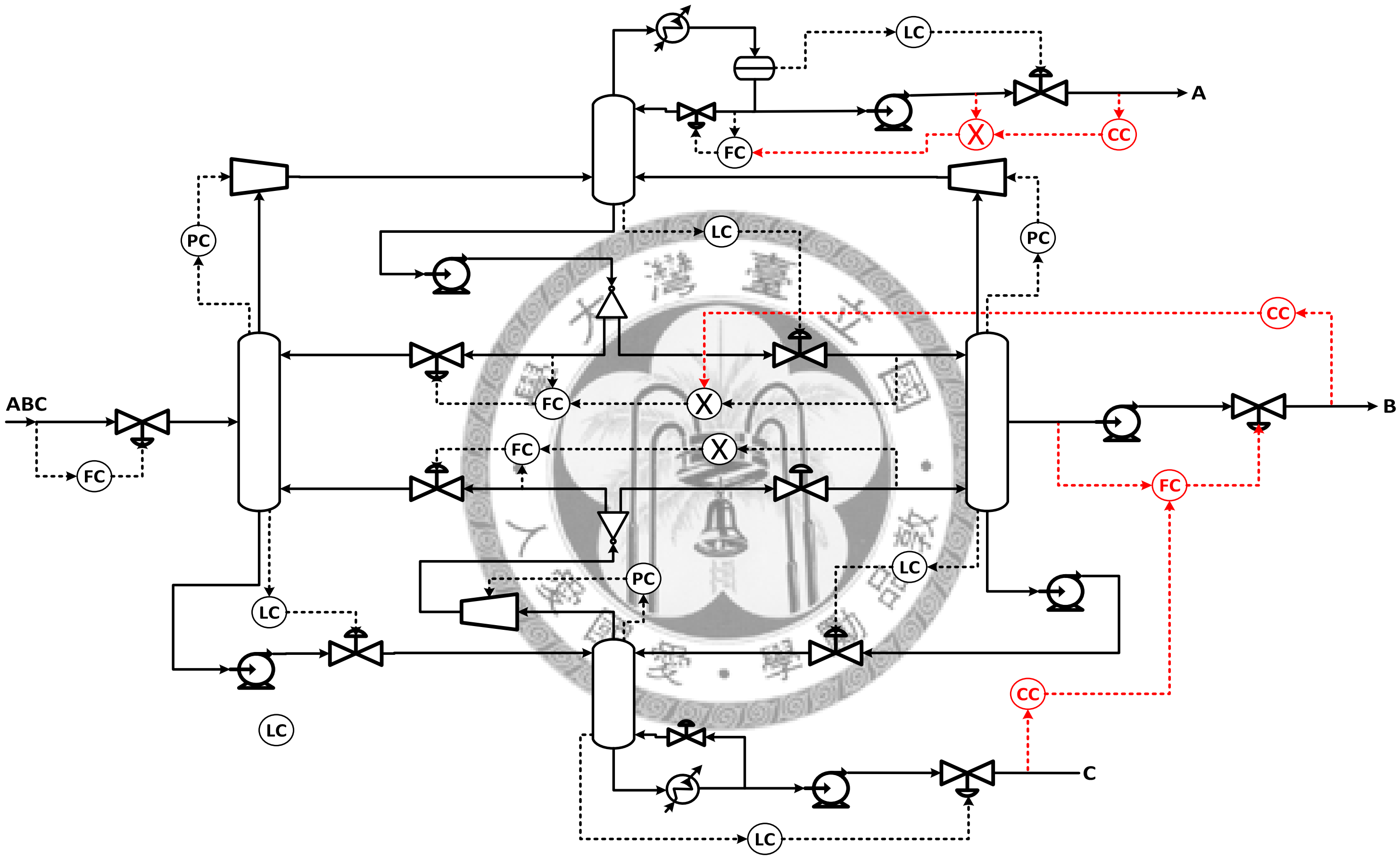


Fig. 3.3-36 Control Structure RR-SL-S for DWCM.

We consider the case when ESI>1 ($\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 7.1 / 2.2 / 1).

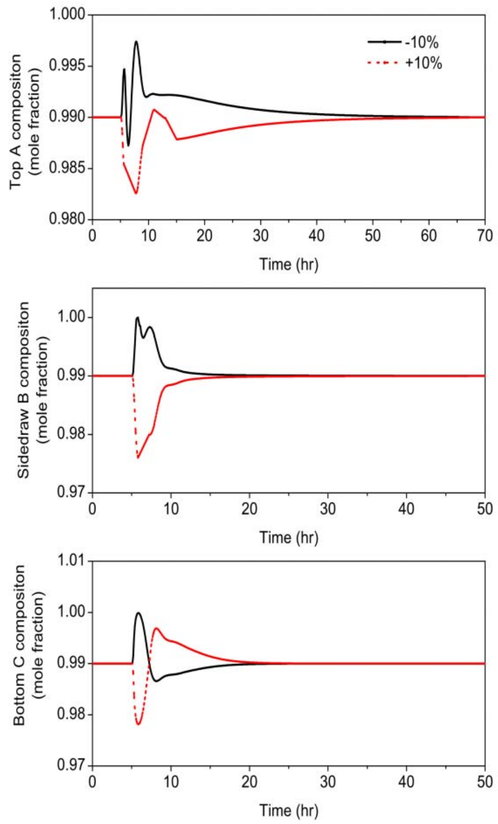


Fig. 3.3-37 Dynamic responses of DWCM, ESI>1, F(8,1,1) for +/-10% feed flowrate disturbances. S-SL-BR

Table 3.3-25 IAE and ITAE value of DWCM, ESI>1, F(8,1,1)

| Con Struc. | IAE | ITAE |
|---|---|---|
| S-SL-BR | 0.0441 | 0.5617 |

Fig. 3.3-37 shows the dynamic responses of control structure S-SL-BR, when there are changes in feed flowrate.

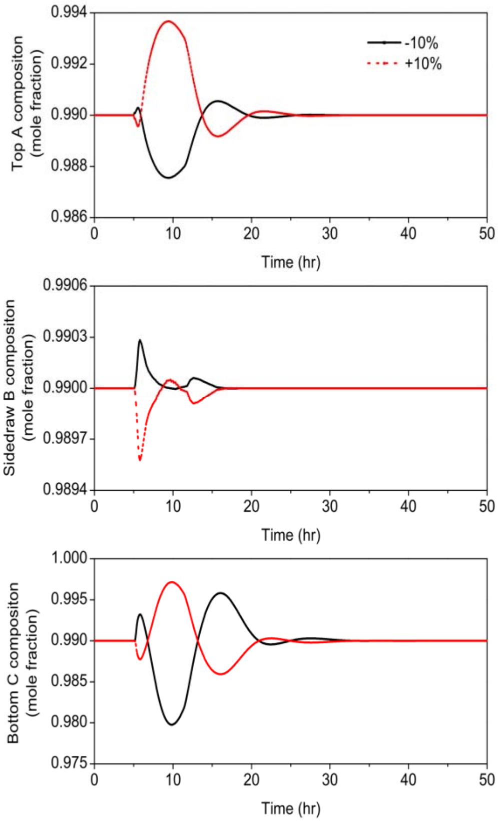


Fig. 3.3-38 Dynamic responses of DWCM, ESI>1, F(1,8,1) for +/-10% feed flowrate disturbances. RR-S-BR

Table 3.3-26 IAE and ITAE value of DWCM, ESI>1, F(1,8,1)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-S-BR | 0.0366 | 0.4441 |

Fig. 3.3-38 shows the dynamic responses of control structure RR-S-BR, when there are changes in feed flowrate.

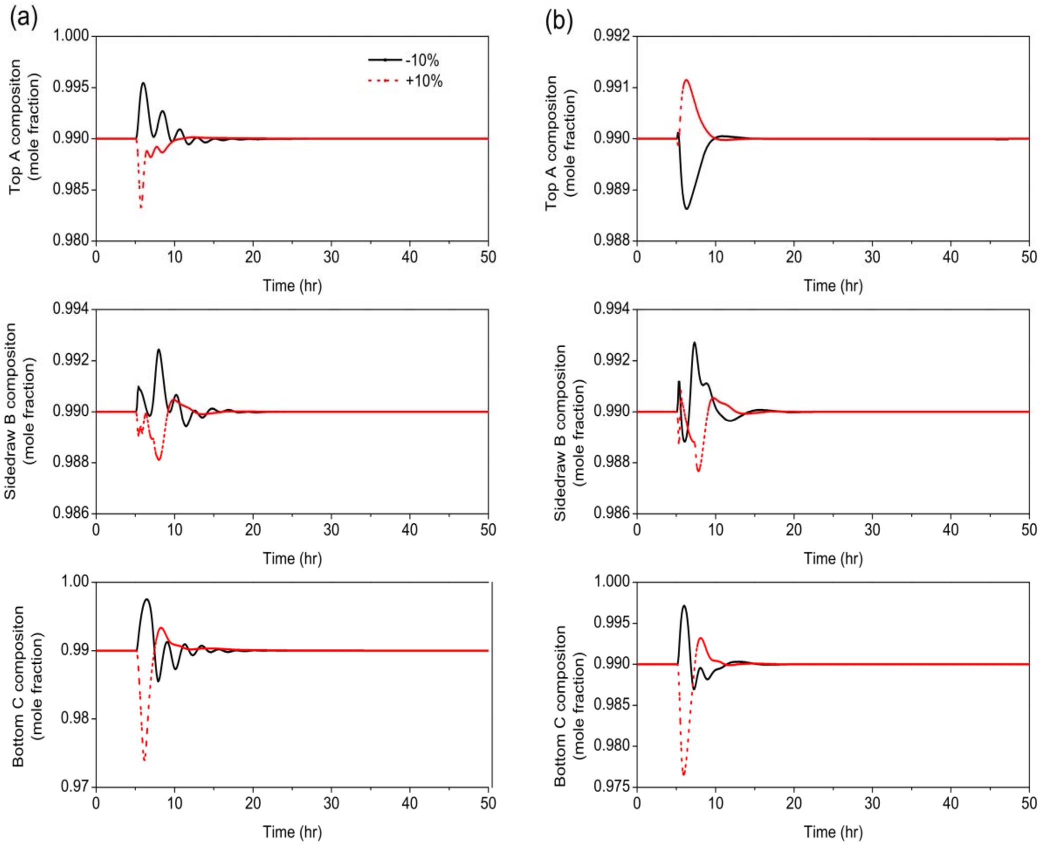


Fig. 3.3-39 Dynamic responses of DWCM, ESI>1, F(1,1,8) for +/-10% feed flowrate disturbances. (a) S-SL-BR (b) RR-SL-S

Table 3.3-27 IAE and ITAE value of DWCM, ESI>1, F(1,1,8)

| Con Struc. | IAE | ITAE |
|---|---|---|
| BR-SL-S | 0.0128 | 0.1016 |
| RR-SL-S | 0.0089 | 0.0663 |

Fig. 3.3-39 shows the dynamic responses of different control structures, when there are changes in feed flowrate. Table 3.3-27 shows that control structure RR-SL-S is better.

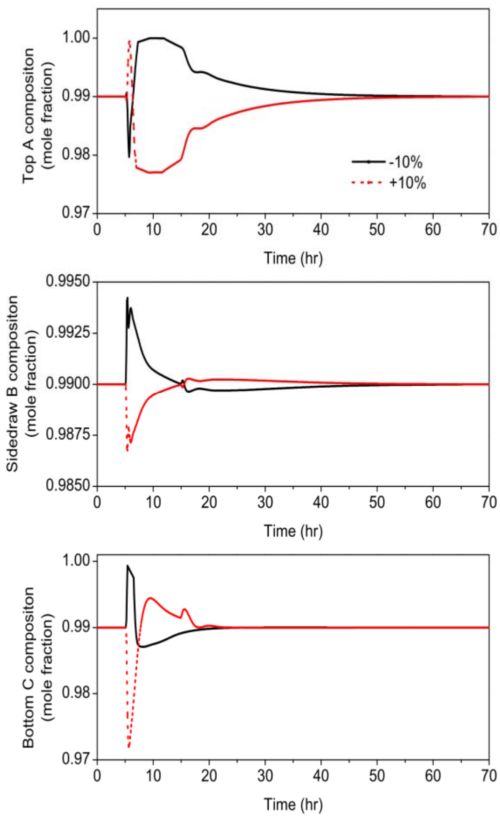


Fig. 3.3-40 Dynamic responses of DWCM, ESI>1, F(3,3,3) for +/-10% feed flowrate disturbances. S-RR-BR

Table 3.3-28 IAE and ITAE value of DWCM, ESI>1, F(3,3,3)

| Con Struc. | IAE | ITAE |
|---|---|---|
| S-RR-BR | 0.0740 | 1.0997 |

Fig. 3.3-40 shows the dynamic responses of different control structures, when there are changes in feed flowrate.

Next we consider the case when ESI=1 ($\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 4 / 2 / 1).

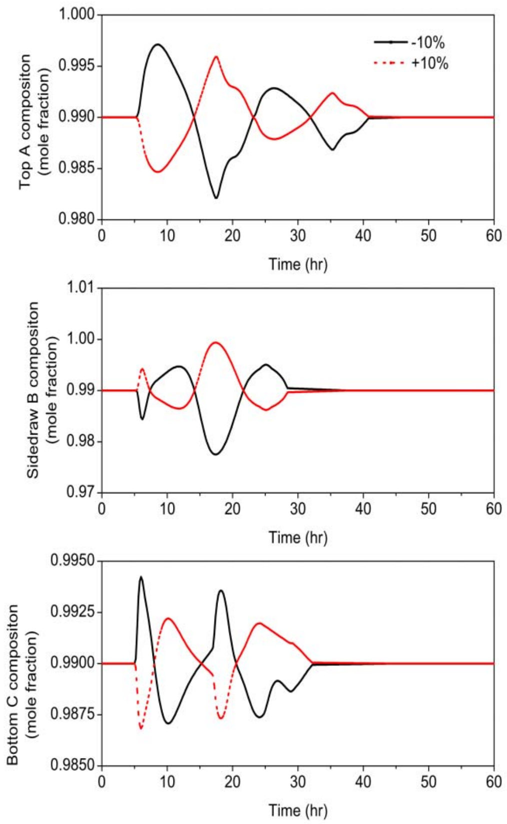


Fig. 3.3-41 Dynamic responses of DWCM, ESI=1, F(8,1,1) for +/-10% feed flowrate disturbances. S-SL-BR

Table 3.3-29 IAE and ITAE value of DWCM, ESI>1, F(8,1,1)

| Con Struc. | IAE | ITAE |
|---|---|---|
| S-SL-BR | 0.0753 | 1.3552 |

Fig. 3.3-41 shows the dynamic responses of control structure S-SL-BR, when there are changes in feed flowrate.

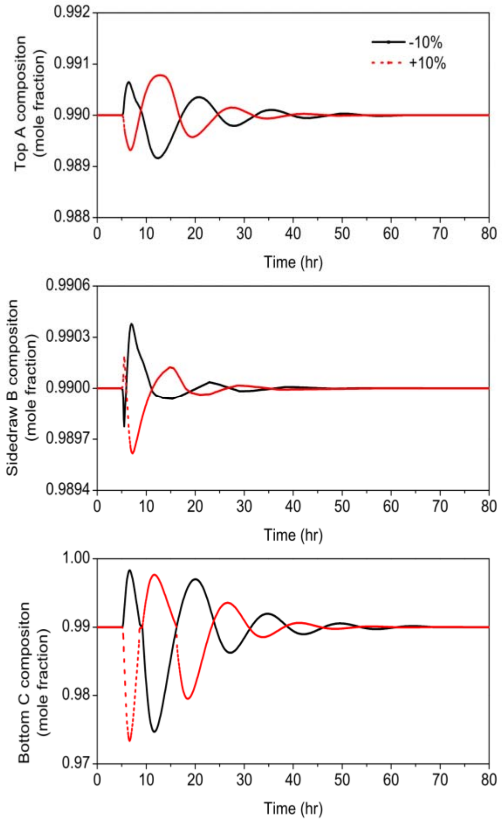


Fig. 3.3-42 Dynamic responses of DWCM, ESI=1, F(1,8,1) for +/-10% feed flowrate disturbances. RR-S-BR

Table 3.3-30 IAE and ITAE value of DWCM, ESI>1, F(1,8,1)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-S-BR | 0.0629 | 1.0528 |

Fig. 3.3-42 shows the dynamic responses of control structure RR-S-BR, when there are changes in feed flowrate.

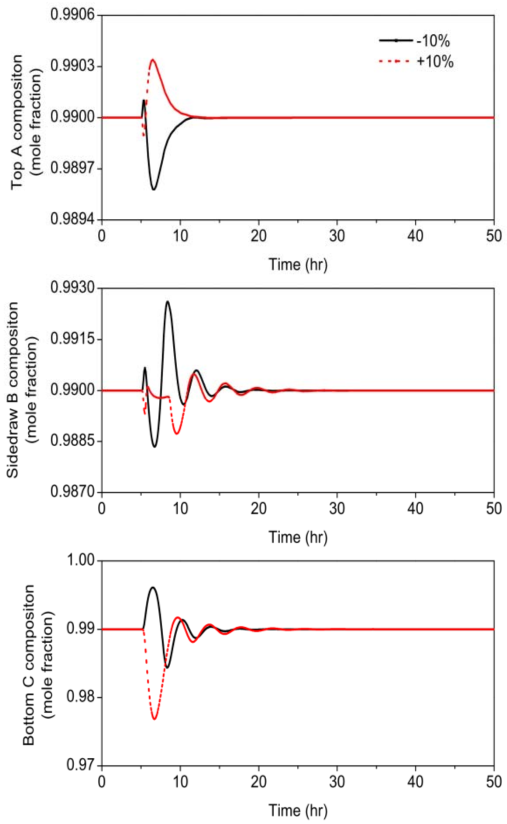


Fig. 3.3-43 Dynamic responses of DWCM, ESI=1, F(1,1,8) for +/-10% feed flowrate disturbances. RR-SL-S

Table 3.3-31 IAE and ITAE value of DWCM, ESI>1, F(1,1,8)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-SL-S | 0.0113 | 0.0960 |

Fig. 3.3-43 shows the dynamic responses of control structure RR-SL-S, when there are changes in feed flowrate.

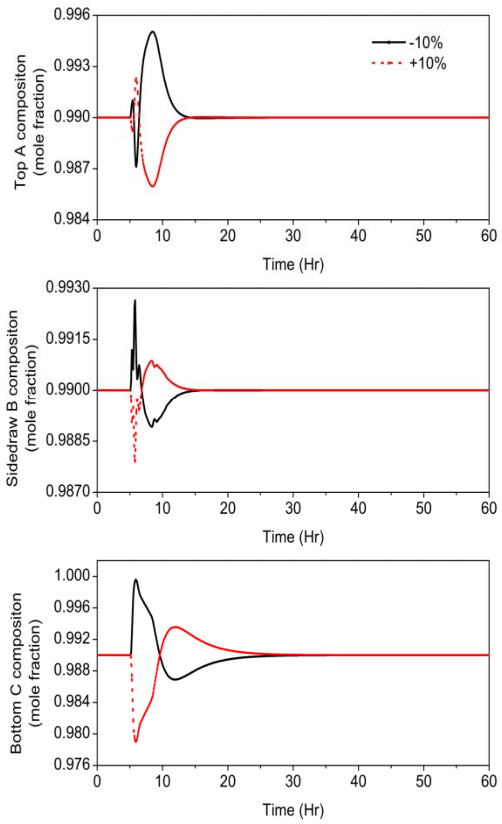


Fig. 3.3-44 Dynamic responses of DWCM, ESI=1, F(3,3,3) for +/-10% feed flowrate disturbances. S-SL-BR

Table 3.3-32 IAE and ITAE value of DWCM, ESI=1, F(3,3,3)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-SL-BR | 0.0236 | 0.2354 |

Fig. 3.3-44 shows the dynamic responses of different control structures, when there are changes in feed flowrate.

Next we consider the case when ESI<1 ($\alpha_A$ / $\alpha_B$ / $\alpha_C$ : 4 / 2.4 / 1).

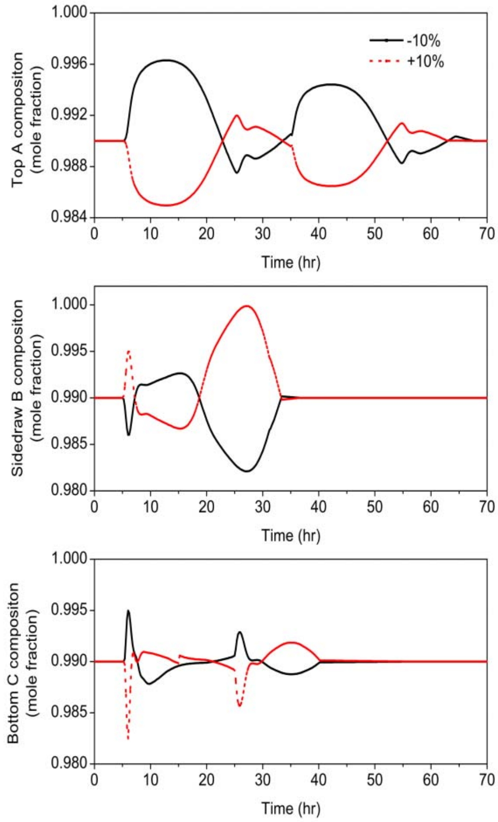


Fig. 3.3-45 Dynamic responses of DWCM, ESI<1, F(8,1,1) for +/-10% feed flowrate disturbances. S-SL-BR

Table 3.3-33 IAE and ITAE value of DWCM, ESI<1, F(8,1,1)

| Con Struc. | IAE | ITAE |
|---|---|---|
| S-SL-BR | 0.0956 | 2.3915 |

Fig. 3.3-45 shows the dynamic responses of control structure S-SL-BR, when there are changes in feed flowrate.

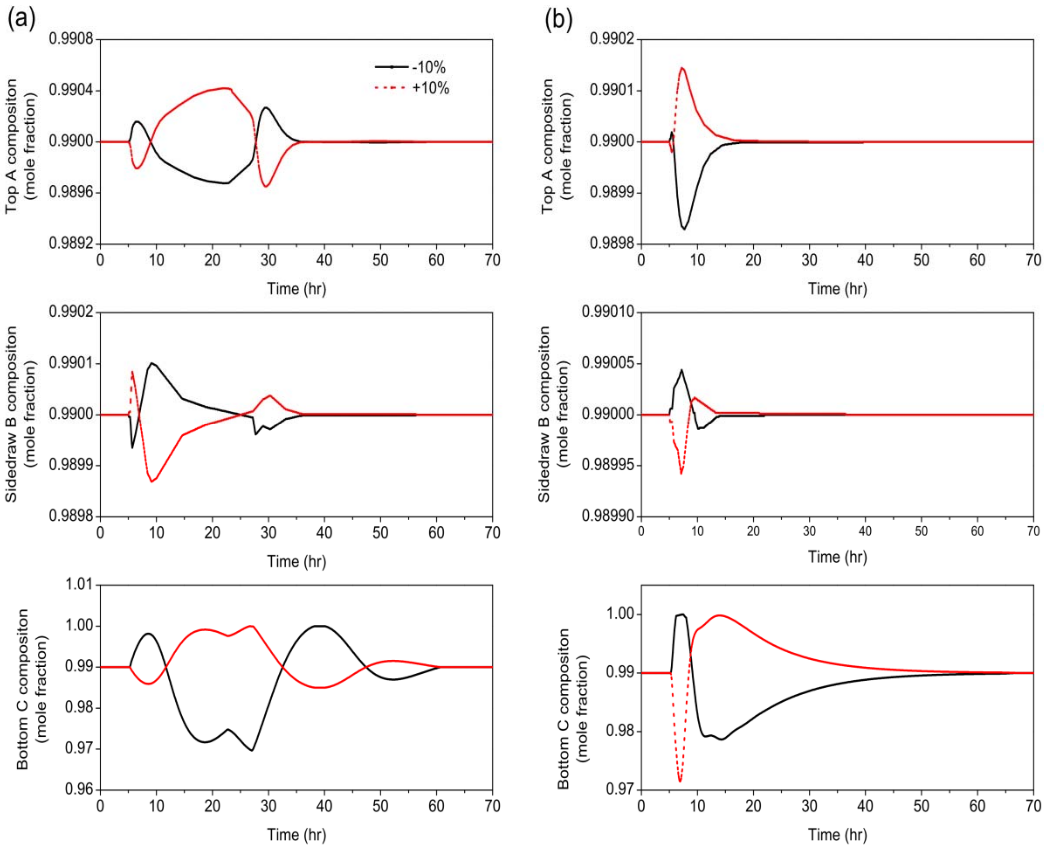


Fig. 3.3-46 Dynamic responses of DWCM, ESI<1, F(1,8,1) for +/-10% feed flowrate disturbances. (a) RR-S-BR (b) RR-S-SL

Table 3.3-34 IAE and ITAE value of DWCM, ESI<1, F(1,8,1)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-S-BR | 0.1134 | 2.9841 |
| RR-S-SL | 0.0688 | 1.2887 |

Fig. 3.3-46 shows the dynamic responses of different control structures, when there are changes in feed flowrate. Table 3.3-34 shows that control structure RR-S-SL is better.

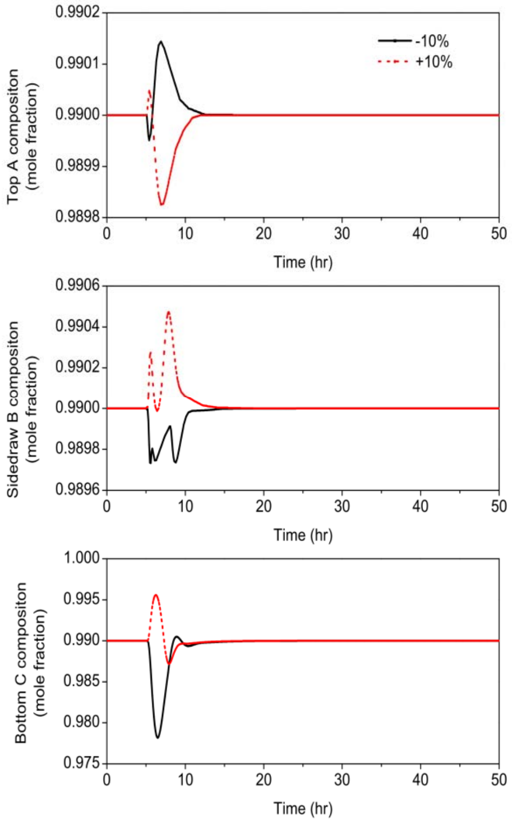


Fig. 3.3-47 Dynamic responses of DWCM, ESI<1, F(1,1,8) for +/-10% feed flowrate disturbances. RR-SL-S

Table 3.3-35 IAE and ITAE value of DWCM, ESI<1, F(1,1,8)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-SL-S | 0.0063 | 0.0463 |

Fig. 3.3-47 shows the dynamic responses of control structure RR-S-BR, when there are changes in feed flowrate.

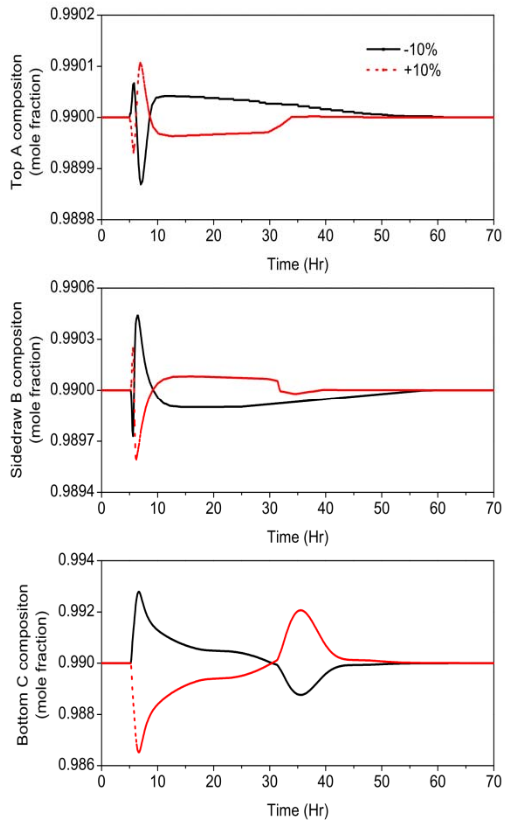


Fig. 3.3-48 Dynamic responses of DWCM, ESI<1, F(3,3,3) for +/-10% feed flowrate disturbances. S-SL-BR

Table 3.3-36 IAE and ITAE value of DWCM, ESI<1, F(3,3,3)

| Con Struc. | IAE | ITAE |
|---|---|---|
| RR-SL-BR | 0.0127 | 0.2682 |

Fig. 3.3-48 shows the dynamic responses of different control structures, when there are changes in feed flowrate.

## 3.4 Results of feed composition disturbance

The following part show the dynamic responses of feed composition disturbance for different type of divided-wall column. We only show the ease separation is equal to one and equimolar feed in this section.

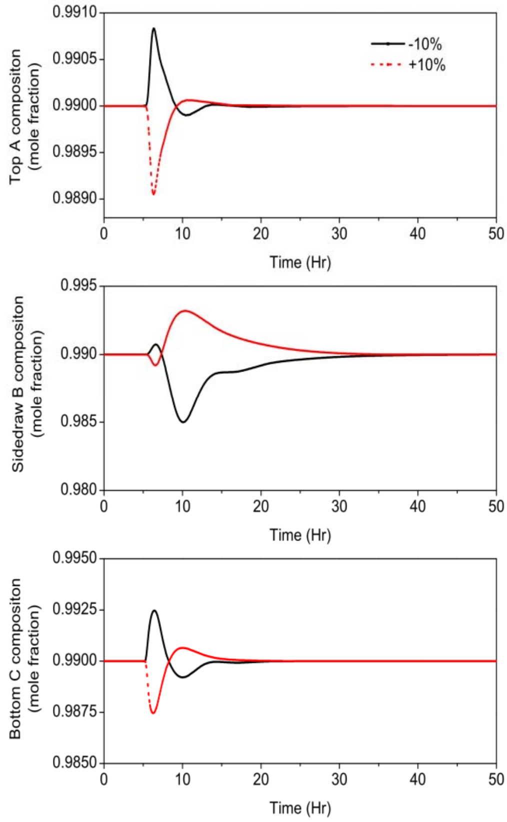


Fig. 3.4-1 Dynamic responses of DWCL, ESI=1, F(3,3,3) for +/-10% feed composition disturbances. RR-BR1-BR2

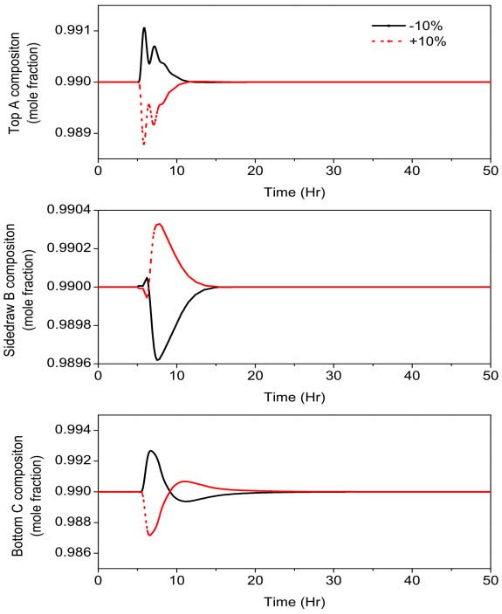


Fig. 3.4-2 Dynamic responses of DWCU, ESI=1, F(3,3,3) for +/-10% feed composition disturbances. RR1-RR2-BR

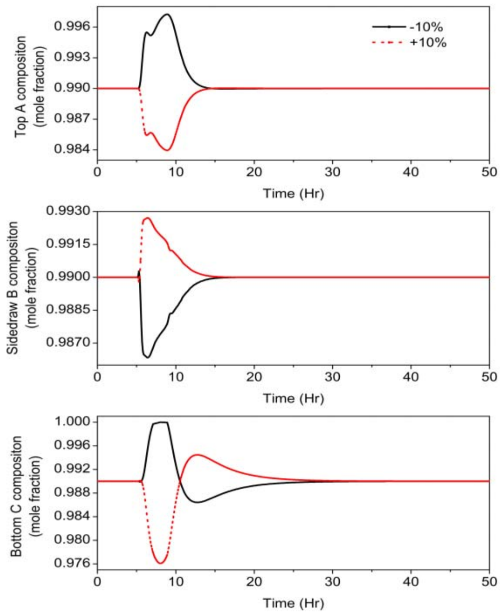


Fig. 3.4-3 Dynamic responses of DWCU, ESI=1, F(3,3,3) for +/-10% feed composition disturbances. RR-SL-BR

## 3.5 Summary

From the results of dynamic response of DWCL we can see that it almost prefers the control structures RR-BR1-BR2 and RR-SL-BR2 were the best. The dynamic analysis results are consist with the steady-state analysis results. (see Fig. 3.5-1, Fig. 3.5-2, Fig. 3.5-3)

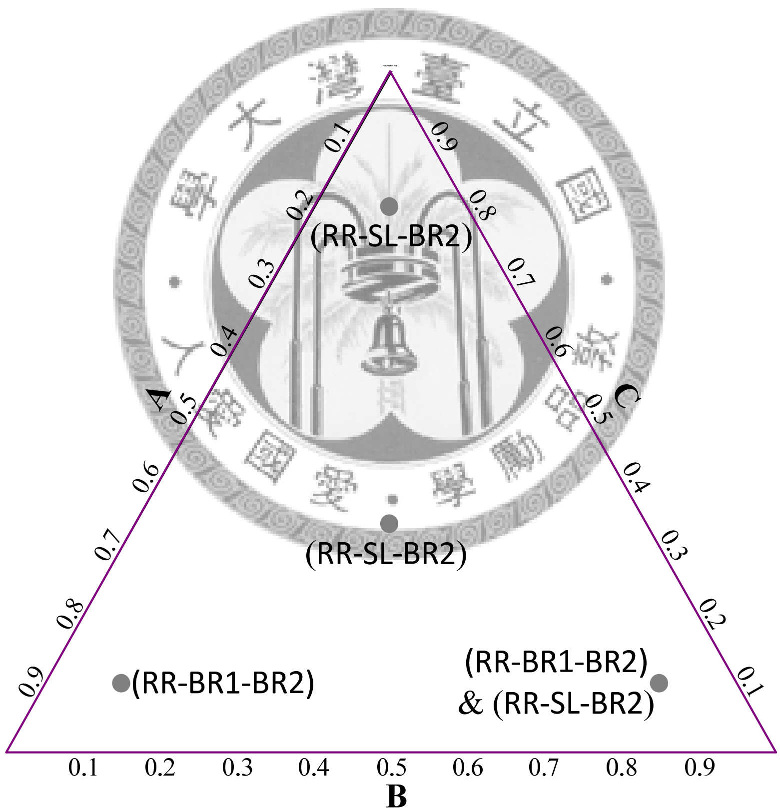


Fig. 3.5-1 Results of dynamic response for DWCL of ESI>1

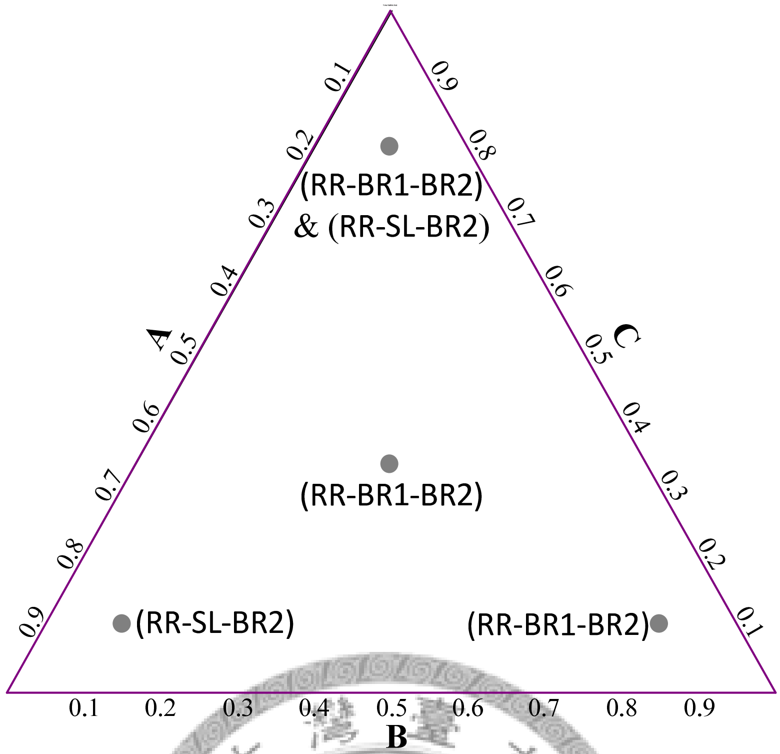


Fig. 3.5-2 Results of dynamic response for DWCL of ESI=1

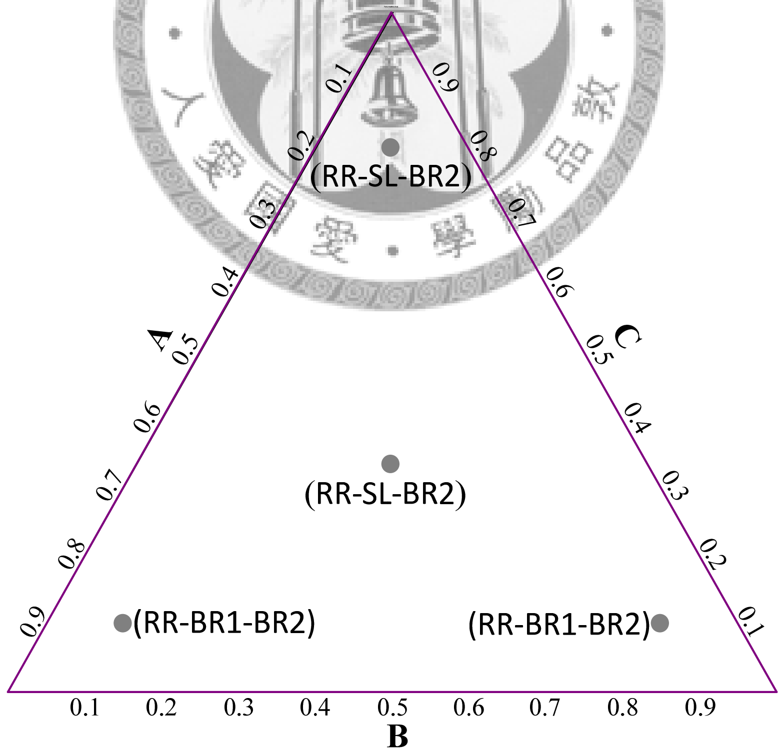


Fig. 3.5-3 Results of dynamic response for DWCL of ESI<1

For DWCU, we have the only control structure RR1-RR2-BR.

From the results of dynamic response of DWCM we can see that if there are more A component in the feed, it prefers the control structure S-SL-BR. If there are more B component in the feed, it prefers the control structure RR-S-BR for ESI>1 and ESI=1 and it prefers the control structure RR-S-SL for ESI<1. If there are more C component in the feed, it prefers the control structure RR-SL-S. The dynamic analysis results are consist with the steady-state analysis results. (see Fig. 3.5-4, Fig. 3.5-5, Fig. 3.5-6)

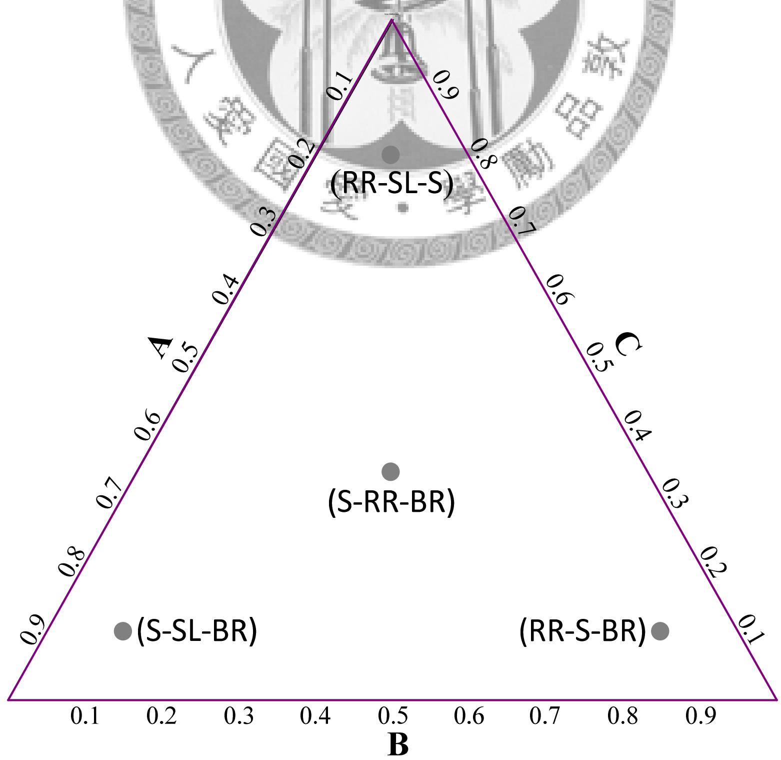


Fig. 3.5-4 Results of dynamic response for DWCM of ESI>1

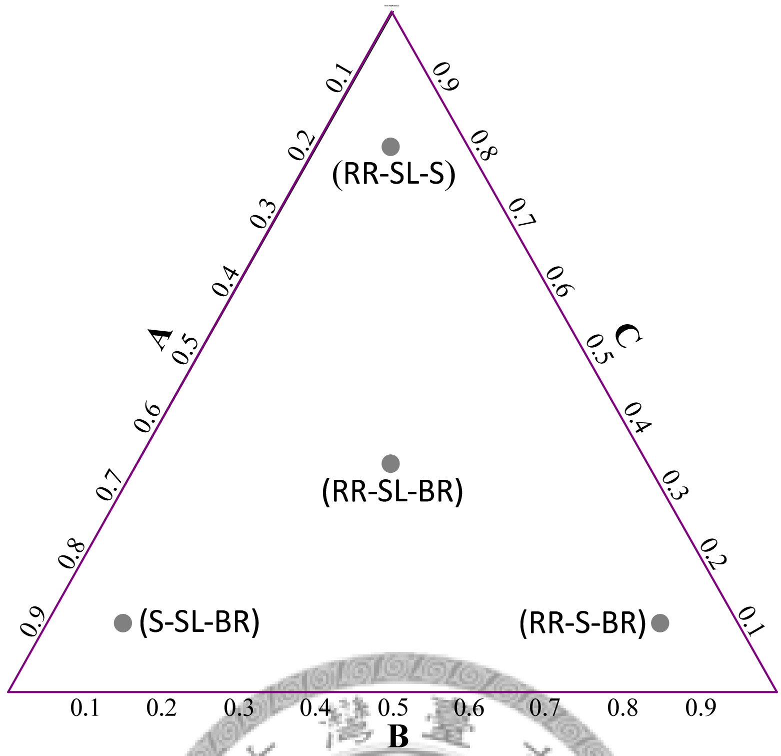


Fig. 3.5-5 Results of dynamic response for DWCM of ESI=1

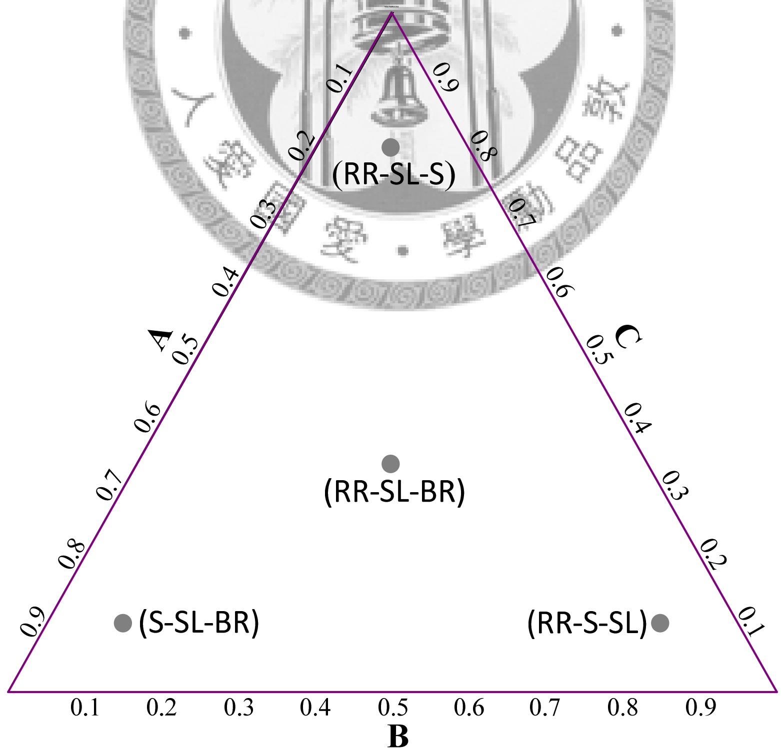


Fig. 3.5-6 Results of dynamic response for DWCM of ESI<1

# 4 Conclusion

From the results in the previous section, we know the best choice of DWC based on control aspect for different feed conditions. It is found that if there are more A component in the feed, we suggest you to use DWCU. If there is more B component in the feed, we suggest you to use DWCL. If there is more C component in the feed, we suggest you to use DWCU. This result is suitable for different ESI. Table 4-1 shows the priority of choices of different DWC type with different feed condition based on controllability.

Table 4-1 The priority of choice of DWC based on controllability.

| | Type of DWC |
|---|---|
| More A component | U > L > M |
| More B component | L > U > M |
| More C component | U > M > L |
| Equimolar feed | U > L&M |

Table 4-2 shows the priority of choices of different DWC type with different feed condition based on economic. This result is made by Kai-Ti Chu.

Table 4-2 The priority of choice of DWC based on economic

| | Type of DWC |
|---|---|
| **ESI > 1** | |
| More A component | U |
| More B component | M |
| More C component | L or U |
| **ESI = 1** | |
| More A component | M |
| More B component | M |
| More C component | L |
| **ESI < 1** | |
| More A component | L |
| More B component | M |
| More C component | L or M |

This work provides a guideline that can be used for the control of the divided-wall column..

Table 4-3 Results of the best control structure for DWCL

| ESI > 1 | | |
|---|---|---|
| Feed Composition | Control Structure | ITAE |
| 8,1,1 | RR-BR1-BR2 | 0.5962 |
| 1,8,1 | RR-BR1-BR2 | 0.0173 |
| 1,1,8 | RR-SL-BR2 | 0.2087 |
| 3,3,3 | RR-SL-BR2 | 0.2016 |
| ESI = 1 | | |
| 8,1,1 | RR-BR1-BR2 | 2.0973 |
| 1,8,1 | RR-BR1-BR2 | 0.0555 |
| 1,1,8 | RR-SL-BR2 | 2.4944 |
| 3,3,3 | RR-BR1-BR2 | 0.4745 |
| ESI < 1 | | |
| 8,1,1 | RR-BR1-BR2 | 1.7823 |
| 1,8,1 | RR-BR1-BR2 | 0.0760 |
| 1,1,8 | RR-BR1-BR2 | 0.7393 |
| 3,3,3 | RR-SL-BR2 | 0.5145 |

Table 4-4 Results of the best control structure for DWCU

| ESI > 1 | | |
|---|---|---|
| Feed Composition | Control Structure | ITAE |
| 8,1,1 | RR1-RR2-BR | 0.1664 |
| 1,8,1 | RR1-RR2-BR | 0.0516 |
| 1,1,8 | RR1-RR2-BR | 0.0274 |
| 3,3,3 | RR1-RR2-BR | 0.0590 |
| ESI = 1 | | |
| 8,1,1 | RR1-RR2-BR | 0.0533 |
| 1,8,1 | RR1-RR2-BR | 0.0563 |
| 1,1,8 | RR1-RR2-BR | 0.0286 |
| 3,3,3 | RR1-RR2-BR | 0.0413 |
| ESI < 1 | | |
| 8,1,1 | RR1-RR2-BR | 0.0757 |
| 1,8,1 | RR1-RR2-BR | 0.1299 |
| 1,1,8 | RR1-RR2-BR | 0.0421 |
| 3,3,3 | RR1-RR2-BR | 0.0597 |

Table 4-5 Results of the best control structure for DWCM

| ESI > 1 | | |
|---|---|---|
| Feed Composition | Control Structure | ITAE |
| 8,1,1 | S-SL-BR | 0.5617 |
| 1,8,1 | RR-S-BR | 0.4441 |
| 1,1,8 | RR-SL-S | 0.0663 |
| 3,3,3 | S-RR-BR | 1.0997 |
| ESI = 1 | | |
| 8,1,1 | S-SL-BR | 1.3552 |
| 1,8,1 | RR-S-BR | 1.0528 |
| 1,1,8 | RR-SL-S | 0.0960 |
| 3,3,3 | RR-SL-BR | 0.2354 |
| ESI < 1 | | |
| 8,1,1 | S-SL-BR | 2.3915 |
| 1,8,1 | RR-S-SL | 1.2887 |
| 1,1,8 | RR-SL-S | 0.0463 |
| 3,3,3 | RR-SL-BR | 0.2682 |

# Appendix A

Table A-1 Tuning parameter for inventory control

| Loop | Kc | τ | Control Action |
|---|---|---|---|
| Flow Control | 0.5 | 0.3 | Reverse |
| Level Control | 10 | 100000 | Direct |
| Pressure Control | 10 | 12 | Direct |

Table A-2 Tuning parameter for DWCL, ESI>1

| Feed | CV | MV | Kc | τ | Controller Action |
|---|---|---|---|---|---|
| (8,1,1) | XA | RR | 27.07 | 85.80 | Reverse |
| | XB | BR1 | 46.22 | 780.12 | Reverse |
| | XC | BR2 | 50.55 | 68.64 | Reverse |
| (1,8,1) | XA | RR | 29.27 | 62.04 | Reverse |
| | XB | BR1 | 580.40 | 77.88 | Reverse |
| | XC | BR2 | 62.41 | 66.00 | Reverse |
| (1,1,8) | XA | RR | 26.49 | 62.04 | Reverse |
| | XB | SL | 6.92 | 363.00 | Reverse |
| | XC | BR2 | 167.67 | 71.28 | Reverse |
| (3,3,3) | XA | RR | 22.12 | 84.48 | Reverse |
| | XB | SL | 8.60 | 337.92 | Reverse |
| | XC | BR2 | 64.25 | 79.20 | Reverse |

Table A-3 Tuning parameter for DWCL, ESI=1

| Feed | CV | MV | Kc | τ | Controller Action |
|---|---|---|---|---|---|
| (8,1,1) | XA | RR | 78.39 | 69.96 | Reverse |
| | XB | BR1 | 17.39 | 1306.80 | Reverse |
| | XC | BR2 | 62.08 | 72.60 | Reverse |
| (1,8,1) | XA | RR | 81.48 | 59.40 | Reverse |
| | XB | BR1 | 791.78 | 68.64 | Reverse |
| | XC | BR2 | 68.82 | 68.64 | Reverse |
| (1,1,8) | XA | RR | 3.21 | 142.56 | Reverse |
| | XB | SL | 5.13 | 583.44 | Reverse |
| | XC | BR2 | 188.98 | 77.88 | Reverse |
| (3,3,3) | XA | RR | 72.51 | 72.60 | Reverse |
| | XB | BR1 | 49.06 | 666.60 | Reverse |
| | XC | BR2 | 69.54 | 77.88 | Reverse |

Table A-4 Tuning parameter for DWCL, ESI<1

| Feed | CV | MV | Kc | τ | Controller Action |
|---|---|---|---|---|---|
| (8,1,1) | XA | RR | 120.88 | 64.68 | Reverse |
| | XB | BR1 | 24.22 | 1623.60 | Reverse |
| | XC | BR2 | 44.42 | 66.00 | Reverse |
| (1,8,1) | XA | RR | 159.20 | 54.12 | Reverse |
| | XB | BR1 | 378.52 | 62.04 | Reverse |
| | XC | BR2 | 45.62 | 63.36 | Reverse |
| (1,1,8) | XA | RR | 133.41 | 55.44 | Reverse |
| | XB | BR1 | 25.43 | 604.56 | Reverse |
| | XC | BR2 | 138.72 | 72.60 | Reverse |
| (3,3,3) | XA | RR | 148.09 | 58.08 | Reverse |
| | XB | SL | 6.35 | 415.80 | Reverse |
| | XC | BR2 | 53.51 | 73.92 | Reverse |

Table A-5 Tuning parameter for DWCU, ESI>1

| Feed | CV | MV | Kc | τ | Controller Action |
|---|---|---|---|---|---|
| (8,1,1) | XA | RR1 | 37.69 | 69.96 | Reverse |
| | XB | RR2 | 62.35 | 72.60 | Reverse |
| | XC | BR | 45.95 | 64.68 | Reverse |
| (1,8,1) | XA | RR1 | 26.41 | 60.72 | Reverse |
| | XB | RR2 | 114.85 | 64.68 | Reverse |
| | XC | BR | 50.93 | 58.08 | Reverse |
| (1,1,8) | XA | RR1 | 19.51 | 69.96 | Reverse |
| | XB | RR2 | 46.77 | 68.64 | Reverse |
| | XC | BR | 142.93 | 66.00 | Reverse |
| (3,3,3) | XA | RR1 | 9.90 | 113.52 | Reverse |
| | XB | RR2 | 50.83 | 79.20 | Reverse |
| | XC | BR | 65.77 | 68.64 | Reverse |

Table A-6 Tuning parameter for DWCU, ESI=1

| Feed | CV | MV | Kc | τ | Controller Action |
|---|---|---|---|---|---|
| (8,1,1) | XA | RR1 | 78.56 | 68.64 | Reverse |
| | XB | RR2 | 63.68 | 73.92 | Reverse |
| | XC | BR | 48.52 | 66.00 | Reverse |
| (1,8,1) | XA | RR1 | 67.55 | 56.76 | Reverse |
| | XB | RR2 | 164.65 | 72.60 | Reverse |
| | XC | BR | 53.28 | 60.72 | Reverse |
| (1,1,8) | XA | RR1 | 57.41 | 72.60 | Reverse |
| | XB | RR2 | 57.91 | 69.96 | Reverse |
| | XC | BR | 127.05 | 72.60 | Reverse |
| (3,3,3) | XA | RR1 | 73.69 | 71.28 | Reverse |
| | XB | RR2 | 61.11 | 79.20 | Reverse |
| | XC | BR | 67.96 | 67.32 | Reverse |

Table A-7 Tuning parameter for DWCU, ESI<1

| Feed | CV | MV | Kc | τ | Controller Action |
|---|---|---|---|---|---|
| (8,1,1) | XA | RR1 | 125.75 | 62.04 | Reverse |
| | XB | RR2 | 55.04 | 77.88 | Reverse |
| | XC | BR | 31.03 | 63.36 | Reverse |
| (1,8,1) | XA | RR1 | 8.39 | 106.92 | Reverse |
| | XB | RR2 | 55.28 | 88.44 | Reverse |
| | XC | BR | 49.35 | 60.72 | Reverse |
| (1,1,8) | XA | RR1 | 127.98 | 58.08 | Reverse |
| | XB | RR2 | 28.54 | 84.48 | Reverse |
| | XC | BR | 81.75 | 73.92 | Reverse |
| (3,3,3) | XA | RR1 | 121.74 | 60.72 | Reverse |
| | XB | RR2 | 39.21 | 85.80 | Reverse |
| | XC | BR | 41.65 | 66.00 | Reverse |

Table A-8 Tuning parameter for DWCM, ESI>1

| Feed | CV | MV | Kc | τ | Controller Action |
|---|---|---|---|---|---|
| (8,1,1) | XA | S | 11.18 | 381.48 | Reverse |
| | XB | SL | 15.38 | 43.56 | Direct |
| | XC | BR | 25.09 | 80.52 | Reverse |
| (1,8,1) | XA | RR | 21.55 | 52.80 | Reverse |
| | XB | S | 271.27 | 43.56 | Reverse |
| | XC | BR | 19.20 | 55.44 | Reverse |
| (1,1,8) | XA | RR | 34.26 | 55.44 | Reverse |
| | XB | SL | 11.25 | 38.28 | Reverse |
| | XC | S | 75.85 | 149.16 | Reverse |
| (3,3,3) | XA | S | 2.14 | 389.40 | Reverse |
| | XB | RR | 2.97 | 157.08 | Reverse |
| | XC | BR | 25.38 | 67.32 | Reverse |

Table A-9 Tuning parameter for DWCM, ESI=1

| Feed | CV | MV | Kc | τ | Controller Action |
|---|---|---|---|---|---|
| (8,1,1) | XA | S | 92.65 | 180.84 | Reverse |
| | XB | SL | 0.55 | 42.24 | Reverse |
| | XC | BR | 45.03 | 85.80 | Reverse |
| (1,8,1) | XA | RR | 51.36 | 59.40 | Reverse |
| | XB | S | 126.25 | 48.84 | Reverse |
| | XC | BR | 18.92 | 60.72 | Reverse |
| (1,1,8) | XA | RR | 75.73 | 67.32 | Reverse |
| | XB | SL | 13.10 | 55.44 | Reverse |
| | XC | S | 60.17 | 93.72 | Reverse |
| (3,3,3) | XA | RR | 10.72 | 62.04 | Reverse |
| | XB | SL | 4.19 | 56.76 | Reverse |
| | XC | BR | 19.97 | 67.32 | Reverse |

Table A-10 Tuning parameter for DWCM, ESI<1

| Feed | CV | MV | Kc | τ | Controller Action |
|---|---|---|---|---|---|
| (8,1,1) | XA | S | 207.80 | 203.28 | Reverse |
| | XB | SL | 0.67 | 44.88 | Reverse |
| | XC | BR | 37.42 | 71.28 | Reverse |
| (1,8,1) | XA | RR | 128.72 | 48.84 | Reverse |
| | XB | S | 1433.47 | 56.76 | Reverse |
| | XC | SL | 0.31 | 689.04 | Direct |
| (1,1,8) | XA | RR | 214.15 | 48.84 | Reverse |
| | XB | SL | 22.74 | 67.32 | Reverse |
| | XC | S | 119.92 | 182.16 | Reverse |
| (3,3,3) | XA | RR | 252.74 | 47.52 | Reverse |
| | XB | SL | 18.27 | 72.60 | Reverse |
| | XC | BR | 20.26 | 79.20 | Reverse |

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