Control of three types of dividing-wall columns

Wei-Jyun Wang and Jeffrey D. Ward*

Department of Chemical Engineering National Taiwan University, Taipei, Taiwan

Abstract—Compared with conventional distillation columns, the dividing wall column is a promising design with high energy efficiency for separating multi-component mixtures. However, it is more difficult to design and control dividing wall columns because of their integrated designs. Complete study of control of the three types of the columns has never been discussed. Therefore, the main purpose of this work is to investigate the control of three types of dividing wall columns: columns with the dividing wall in the lower (DWCL) middle (DWCM) and upper (DWCU) portions of the column. The relative gain array (RGA) and condition number (CN) for these three column types are calculated for three different multicomponent systems. Based on these results, promising control structures are identified and tested in Aspen Dynamics. The results indicate that DWCU has the worst control performance of the three column types. DWCL outperforms DWCM in most cases, but the difference in controllability is not likely to justify the choice of a column configuration with higher costs.

I. INTRODUCTION

Distillation is the most widely used separation technology in the chemical industry. Although it has many advantages, the major drawback of distillation is its high energy demand. In general, distillation could occupy more than 50% of plant operating cost. [1] One of the major reasons that causes lower energy efficiency is the remixing phenomenon.

In 1949, a new design called "dividing wall column (DWC)" was proposed by Wright and Elizabeth [2]. There is a wall inside the column which divides the column into different sections. DWCs are heat-integrated design. By contrast, fewer columns, reboilers or condensers are required in DWCs than in traditional distillation sequences. Moreover, the remixing phenomenon can be further reduced in DWCs. Consequently, not only considerable energy consumption of about 30% [3] but also capital investment could be reduced.

In spite of these potential benefits, industrial implementation of dividing wall columns so far has been limited, in part because of concerns about operation and control. Accordingly, a number of researchers have investigated the operation and control of fully integrated dividing wall columns. [4-9] Skogestad and coworkers [10,11] investigated operation and control of dividing wall columns and discussed self-optimizing control structures that aimed to minimize energy consumption. Kim et al.[12] and Ling and Luyben[13] investigated temperature control of such columns. Serra et al.[14] and Kiss and coworkers[15] investigated advanced control methods for DWCM systems including model predictive control. Wang et al [16] investigated control of three types DWC with two ideal systems.

* J. W. Author is with the National Taiwan University , Taipei, Taiwan
1 Tel.: +886-2-2366-3037 Fax: +886-2-2369-1314 email: jeffward@ntu.edu.tw

Most researchers have focused on fully integrated dividing wall columns with the dividing wall in the middle of the column (DWCM), another alternative is to locate the dividing wall in the upper portion of the column (DWCU, analogous to a side-rectifier) so that it touches the top of the column and two condensers are employed or in the lower portion of the column (DWCL, analogous to a side-stripper) so that it touches the lower portion of the column and there are two reboilers. These other two configurations have received much less attention in the literature. Moreover, most of these studies investigate dividing wall columns only with nearly-ideal systems, such as BTX (Benzene, Toluene and Xylene). Also, controllability is one of important consideration in process design. Therefore, it is worthwhile to compare the controllability of these three types of dividing wall columns with highly non-ideal systems without azeotropes, which has never been done to our knowledge. That is the purpose of this work. In this work, we picked water, acetic anhydride and acetic acid (WAA) and acetic aldehyde, methanol and water (AMW) systems for studies.

II. DESIGN OF DIVIDING WALL COLUMNS

A. Studied Systems

In this work, two ternary systems were studied. The first one is water, acetic anhydride and acetic acid (WAA) with an feed composition (X_W,X_A,X_A)= (0.4,0.2,0.4). The second one is acetic aldehyde, methanol and water (AMW) with the same feed condition as WAA system.

The feed conditions are saturated liquid, a feed flow rate of 1 kmol/s and a feed pressure of 3 bar. Specifications for all three product purities are 99 mol%. The rigorous model in Aspen Plus is selected to calculate the hydraulic profiles in each module in all simulations. In this work, a design method proposed by Mao [17] was used to calculate the tray number in each section of the DWCs, liquid split ratio, vapor split ratio, reflux ratio and boil-up ratio for WAA and AMW systems.

B. Control Structure

B.1 Control Strategies

There are three important product quality variables that should be controlled in DWC systems which separate ternary mixtures. These are the purity of the three product streams: X_A, X_B and X_C In this study, multiple-point composition control is employed.

In a DWCL which is showed in Fig.1, there are four manipulated variables: reflux ratio (RR) in REC, boil-up ratio in SIDE_1(BR1), boil-up ratio in PRE (BR2) and liquid split ratio (SL). Therefore, there are four sets of three manipulated variables, (RR,BR1,BR2) , (SL,BR1,BR2), (RR,SL,BR2) and (RR,BR1,SL). We also consider the option suggested by several authors (references) of using the additional degree of freedom to control the composition of the heavy component at the top of the dividing wall (Xc')

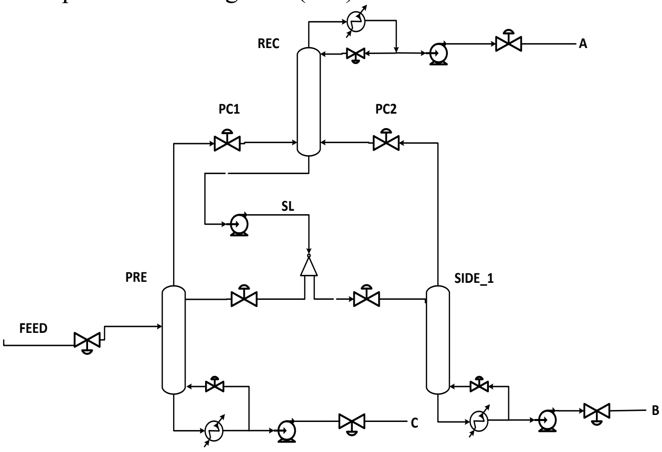

Fig 1. DWCL flowsheet.

There are only three manipulated variables in a DWCU which is showed in Fig.2, reflux ratio in PRE (RR1), reflux ratio in SIDE_1 (RR2) and boil-up ratio in STRI (BR). The vapor split ratio (SV) is determined by the location of the dividing wall and the pressure profile on both sides of the dividing wall and therefore it is not controllable. Thus, there is only one control structure for a DWCU column: (RR1-X_A) – (RR2-X_B) – (BR-X_C).

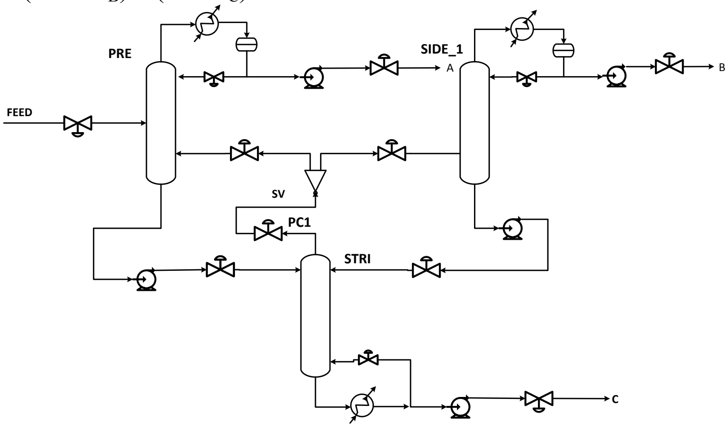

Fig 2. DWCU flowsheet

The Design of a DWCM column which is showed in Fig.3 is more complicated. There are four manipulated variables: reflux ratio (RR), liquid split ratio (SL), boil-up ratio (BR) and the flow rate of the side product liquid stream from SIDE (S). Therefore, there are four sets of three manipulated variables: (RR,S,BR), (SL,S,BR), (RR,SL,BR) and (RR,SL,BR). Similar to DWCL, for DWCM we also considered the possibility of controlling the composition of the heavy component at the top of the prefractionator using the additional degree of freedom.

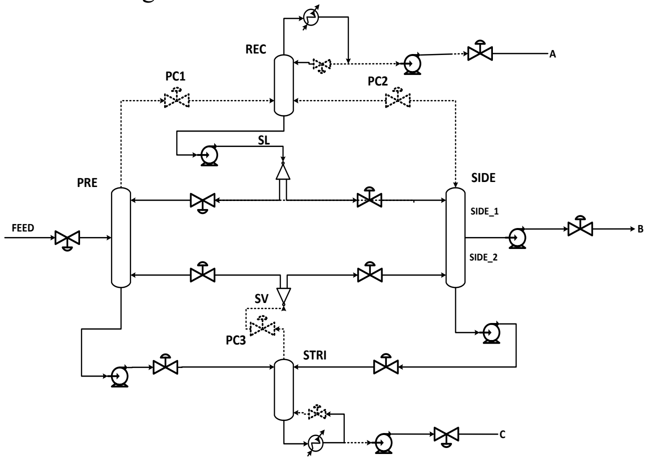

Fig 3. DWCM flowsheet

B.2 Relative gain array (RGA) and condition number (CN) analysis

Step changes (± 1%) were made in all manipulated variables in steady state simulations to determine steady state gain matrixes for all systems considered. Then, RGA and CN results were calculated to identify which control strategies are likely to work best.

- **WAA** ***with feed composition (*X_W*,*X_A*,*X_A*)= (0.4,0.2,0.4)*** **(Case 1) :** RGA and CN results are summarized in Table 1. Results suggest that for the DWCL, control structures (RR-X_A) – (SL-X_B) – (BR2-X_C) may work well. For the DWCM, control structures (RR-X_A) – (S-X_B) – (BR-X_C) – (SL-X_C'), or (S-X_A) – (RR-X_B) – (BR-X_C) – (SL-X_C') may work well.

- **AMW** ***with feed composition (*X_A*,*X_M*,*X_W*)= (0.4,0.2,0.4)*** **(Case 2) *:*** RGA and CN results are summarized in Table 2. Results suggest that for the DWCL, control structures (RR-X_A) – (BR1-X_B) – (BR2-X_C) – (SL-X_C') may work well. For the DWCM, control structures (RR-X_A) – (S-X_B) – (BR-X_C) – (SL-X_C'), or (S-X_A) – (RR-X_B) – (BR-X_C) – (SL-X_C') may work well.

Table 1. RGA and CN results of the WAA system

DWCL					DWCM				
RGA	RR	BR1	BR2	CN	RGA	RR	S	BR	CN
X_A	0.373	0.6367	-0.01		X_A	0.4753	0.6241	-0.0994	
X_B	0.6459	0.3589	-0.005	3.7105	X_B	0.5658	0.3853	0.0488	33.54
X_C	-0.0189	0.0045	1.0144		X_C	-0.0411	-0.0094	1.0505	
RGA	SL	BR1	BR2	CN	RGA	SL	S	BR	CN
X_A	0.0198	0.9998	-0.02		X_A	0.0227	0.6255	0.3519	
X_B	1.0284	0.0081	-0.037	1.0983	X_B	0.0908	0.3843	0.5249	5.11
X_C	-0.0483	-0.008	1.0562		X_C	0.8865	-0.0097	0.1232	
RGA	RR	SL	BR2	CN	RGA	RR	SL	BR	CN
X_A	1.027	-0.035	0.0078		X_A	216.994	-10.320	-205.67	
X_B	-0.015	1.0522	-0.038	1.0786	X_B	-214.87	34.577	181.3	411.7
X_C	-0.012	-0.017	1.0295		X_C	-1.1203	-23.257	25.377	
RGA	RR	BR1	SL	CN	RGA	RR	S	SL	CN
X_A	0.7349	0.2844	-0.02		X_A	0.3706	0.6244	0.005	
X_B	0.742	0.4111	-0.153	13.324	X_B	0.6239	0.3854	-0.0093	4.09
X_C	-0.477	0.3045	1.1724		X_C	0.0055	-0.0098	1.0043	

Table 2. RGA and CN results of the AMW system

DWCL					DWCM				
RGA	RR	BR1	BR2	CN	RGA	RR	S	BR	CN
X_A	1.0702	0.0212	-0.091		X_A	0.7045	0.4887	-0.1932	
X_B	0.0269	0.9665	0.0066	1.235	X_B	0.3759	0.0109	0.6133	2.158
X_C	-0.097	0.0124	1.0847		X_C	-0.0804	0.5005	0.5799	
RGA	SL	BR1	BR2	CN	RGA	SL	S	BR	CN
X_A	0.6775	-0.069	0.3919		X_A	0.0081	0.4853	0.5066	
X_B	-0.087	1.0889	-0.002	4.74	X_B	0.9898	0.0146	-0.0044	84.26
X_C	0.409	-0.0196	0.6105		X_C	0.0021	0.5001	0.4978	
RGA	RR	SL	BR2	CN	RGA	RR	SL	BR	CN
X_A	0.8198	0.1585	0.0217		X_A	-101.48	1.1751	101.309	
X_B	0.2397	0.6831	0.0772	1.943	X_B	1.4585	-2.851	2.3924	203.27
X_C	-0.0595	0.1584	0.9011		X_C	101.03	2.6758	-102.70	
RGA	RR	BR1	SL	CN	RGA	RR	S	SL	CN
X_A	0.8679	0.0041	0.1281		X_A	0.51	0.488	0.0022	
X_B	0.0071	1.0566	-0.064	1.433	X_B	0.003	0.015	0.9827	61.75
X_C	0.125	-0.061	0.9356		X_C	0.488	0.498	0.015	

I. DYNAMIC SIMULATION

Control structures were tested with disturbances that are summarized in Table 3. The Integral of the absolute value of the error (IAE) and integral of the time-weighted absolute value of the error (ITAE) were used as criteria to evaluate the performance of control structures. Additionally, the reboiler duty in the steady state designs of three types of DWCs were determined and used to evaluate the energy efficiency.

Table 3. Disturbance parameter

Feed Composition: $(X_A, X_B, X_C) = (0.4,0.2,0.4)$	Disturbance
Composition	($+6\%X_A$, $-6\%X_B$, $-3\%X_C$), ($-6\%X_A$, $+6\%X_B$, $+3\%X_C$)
Flow Rate	± 10%
Vapor Split	± 5%

Conventional PI controllers are employed in all control systems. Five minutes of dead time was incorporated into each composition control loop. Liquid level was controlled with a proportional-only controller with a gain of 10 and pressure was controlled using PI controllers with a gain of 20 and an integral time of 12 minutes.

Controllers were tuned by using sequential methods. Relay-feedback tests and Tyreus-Luyben tuning relations were used to calculate PI controller tuning parameters for each of composition controllers. For the controller which controls the composition of the heavy component at the top of the dividing wall was tuned by using open-loop tests and Zeigler-Nichols tuning relations. Sequential methods are stated below:

A. WAA with feed composition (X_W,X_A,X_A)= (0.4,0.2,0.4) (Case 1)

All control structures for the WAA system were tested with disturbances. The controllability of control structures for the DWCM was compared. Their dynamic responses are illustrated in Fig 4– Fig 5. As for the DWCM, the dynamic response of (S-X_A) – (RR-X_B) – (BR-X_C) – (SL-X_C') is much slower than (RR-X_A) – (S-X_B) – (BR-X_C) – (SL-X_C'). Thus, (RR-X_A) – (S-X_B) – (BR-X_C) – (SL-X_C') is more suitable for controlling the DWCM. The DWCL with (RR-X_A) – (BR1-X_B) – (SL-X_C), the DWCM with (RR-X_A) – (S-X_B) – (BR-X_C) – (SL-X_C') and the DWCU with (RR-X_A) – (BR1-X_B) – (BR2-X_C) – (SL-X_C') were further compared with the disturbances. The response of the DWCL is shown Fig 6. All IAE, ITAE and energy consumption results are summarized in Table 4.

The responses of the DWCU are shown in Fig 7. Unlike sluggish responses reported in [16], the DWCU has very good performance in this case. The control structure quickly adjusts all controlled variables back to their setpoints. The main reason is that the PRE (RR1-X_A) controller which is tuned by Tyreus-Luyben tuning relations in this case is more aggressive. Although an aggressive PRE (RR1-X_A) controller may improve controllability of the DWCU, feasibility of this kind of design may depend on scale of non-ideality of a system. (It is explained in the AMW system.) Fig 8 and Fig 9 are diagrams of relative volatility versus temperature. They demonstrate that non-ideality of the WAA system is not very large. Therefore, it is why the PRE (RR1-X_A) controller can be aggressive in this case.

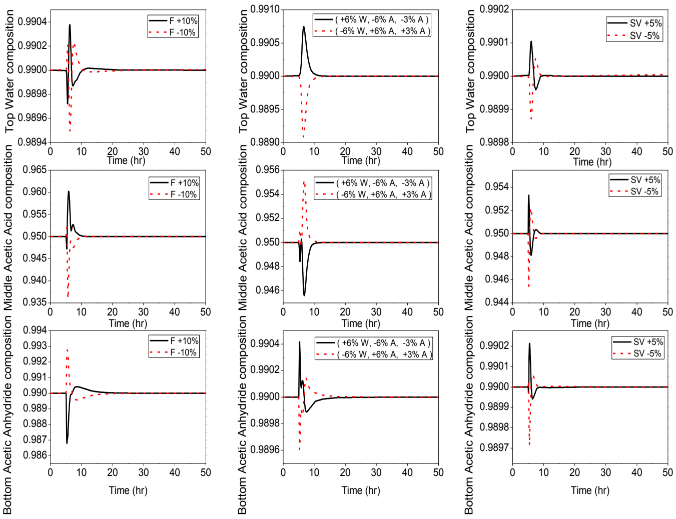

Figure 4. Dynamic responses of WAA DWCM (RR-X_A) – (S-X_B) – (BR-X_C) – (SL-X_C’)

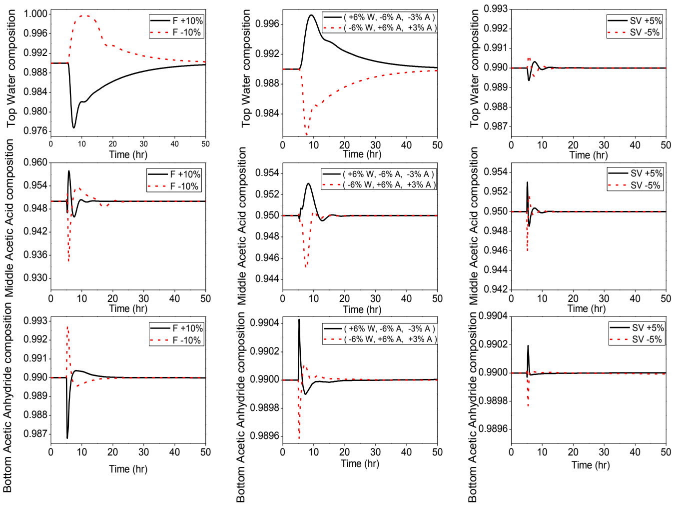

Figure 5. Dynamic responses of WAA DWCM (S-X_A) – (RR-X_B) – (BR-X_C) – (SL-X_C’)

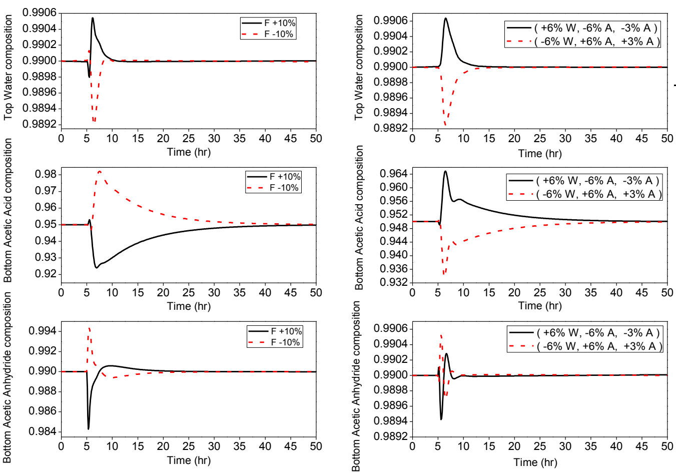

Figure 6. Dynamic responses of WAA DWCL (RR-X_A) – (SL-X_B) – (BR-X_C)

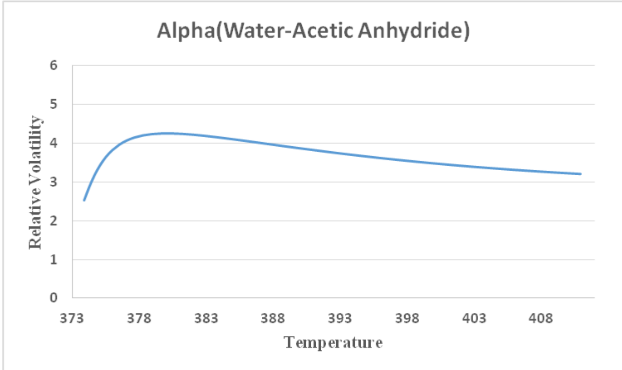

Figure 7. Relative volatility between water and acetic anhydride.

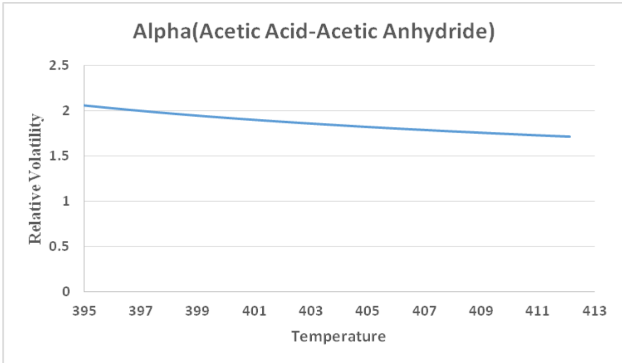

Figure 8. Relative volatility between acetic acid and acetic anhydride.

Table 4. IAE and ITAE value of WAA system (Case 1)

Large Disturbance	DWCL		DWCM		DWCU	
Control Structure	RR- X_A $BR1$-X_B $BR2$-X_C SL- X_C’		RR- X_A S-X_B BR-X_C SL- X_C’		$RR1$- X_A $RR2$-X_B BR-X_C	
	IAE	ITAE	IAE	ITAE	IAE	ITAE
Flow Rate	0.092916	1.33628	0.006186	0.046953	0.00263	0.02436
Composition	0.030537	0.421396	0.00328	0.025683	0.00147	0.01393
Vapor Split (SV)			0.001324	0.010828	0.00055	0.0055
Average* (Avg. without SV)	0.061726	0.878838	0.04733	0.036318	0.00205	0.01914
$Q_{Reboiler}$ (kW)	1903.7		1514.9		1728.7	

B. AMW with feed composition (X_A,X_M,X_W)= (0.4,0.2,0.4)

All control structures for the AMW system were tested with disturbances. All IAE, ITAE and energy consumption results are summarized in Table 5. The controllability of control structures for the DWCM were compared. Their dynamic responses are illustrated in Figure 9-10. As for the DWCM, the dynamic response of (S-X_A) – (RR-X_B) – (BR-X_C) – (SL-X_C’) is more sluggish than (RR-X_A) – (S-X_B) – (BR-X_C) – (SL-X_C’). Thus, (RR-X_A) – (S-X_B) – (BR-X_C) – (SL-X_C’) is more suitable for controlling the DWCM. The DWCL with (RR-X_A) – ($BR1$-X_B) – (SL-X_C) and the DWCU with (RR-X_A) – ($BR1$-X_B) – ($BR2$-X_C) – (SL-X_C’) were further tested with disturbances. The results are showed in Fig 11 and Fig 12. All IAE, ITAE and energy consumption results are summarized in Table 5.

In this case, the DWCU has the worst performance. Figure 11 shows the slow response of the DWCU with ($RR1$-X_A) - ($RR2$-X_B) - (BR-X_C) when it encounter disturbance (+6%X_A, -3%X_B, -3%X_C). The disturbance affects the system greatly. The mole fraction of acetic aldehyde immediately became 100%. Adding an aggressive PRE ($RR1$-X_A) controller is not feasible in this case, because of thermodynamic properties of the AMW system. Fig 12 and Fig 13 are diagrams of relative volatility versus temperature. Relative volatility between acetic aldehyde and water is much larger than relative volatility between water and acetic acid. Mole fraction of acetic aldehyde is sensitive to the reflux ratio. Therefore, this controller has to be conservative. Although the controller which controls reflux ratio of SIDE_1 ($RR2$-X_B) tried to raise the mole fraction, it was not effective until the ($RR1$-X_A) controller almost finished its adjustment and toluene stopped flowing out from the top of the prefractionater. After that, the ($RR2$-X_B) controller was finally able to return its controlled variable to the setpoint. That is the main reason why the DWCU has the slowest responses in this case.

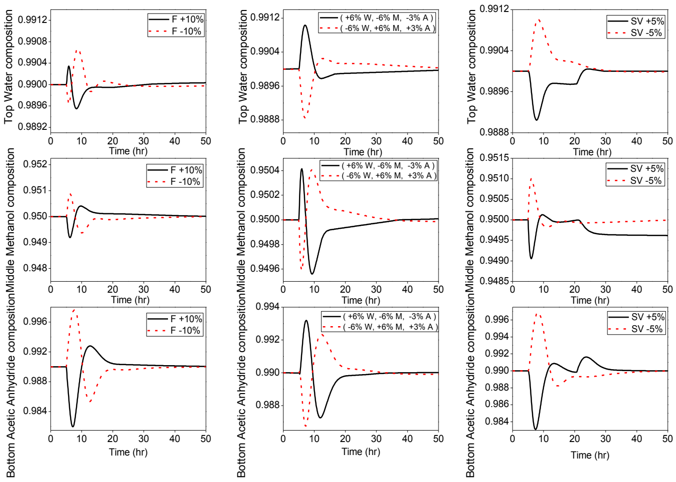

Figure 9. Dynamic responses of AMW DWCM (RR-X_A) – (S-X_B) – (BR-X_C) – (SL-X_C')

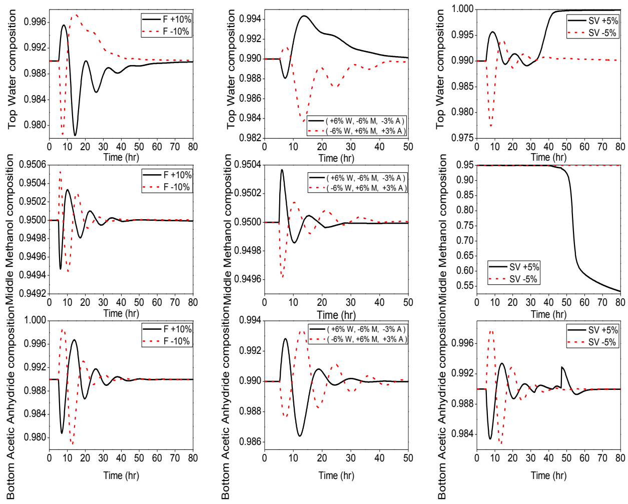

Figure 10. Dynamic responses of AMW DWCL (RR-X_A) – (S-X_B) – (BR-X_C) – (SL-X_C')

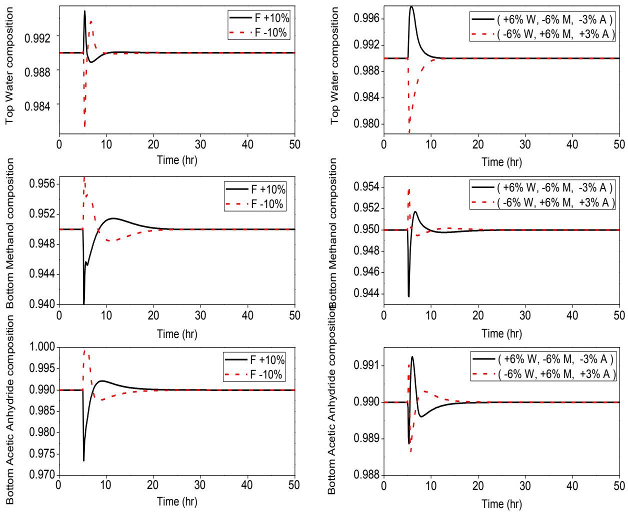

Figure 11. Dynamic responses of AMW DWCU ($RR1$-X_A)–($RR2$-X_B)–(BR-X_C)

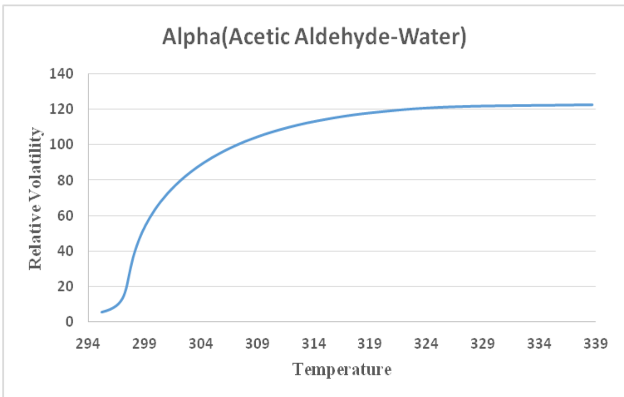

Figure 12. Relative volatility between acetic aldehyde and water.

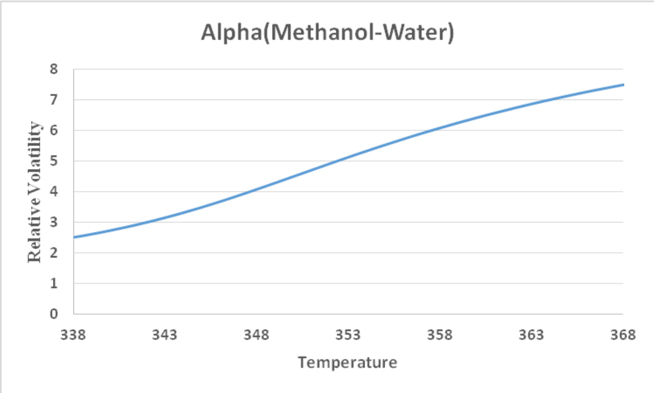

Figure 13. Relative volatility between methanol and water.

Table 5. IAE and ITAE value of AMW system (Case 2)

Large Disturbance	DWCL		DWCM		DWCU	
Control Structure	RR- X_A BR1-X_B BR2-X_C SL- X_C'		RR- X_A S-X_B BR-X_C SL- X_C'		RR1- X_A RR2-X_B BR-X_C	
	IAE	ITAE	IAE	ITAE	IAE	ITAE
Flow Rate	0.018019	0.161255	0.019076	0.245536	0.01306	0.11298
Composition	0.012623	0.061575	0.014849	0.158405	0.02427	0.40189
Vapor Split (SV)			0.01913	0.295858	0.01335	0.12644
Average* (Avg. without SV)	0.015321	0.111415	0.016962	0.201971	0.03404	0.25743
$Q_{Reboiler}$ (kW)	915.9		9459.3		877.4	

II. CONCLUSION

In this work, control strategies and dynamic behavior of three types of dividing wall columns with highly variable volatility were investigated. Initially, possible control structures for controlling DWCLs and DWCMs were determined by RGA and CN results. Then, dynamic simulations of all types of DWCs were carried out.

Unlike the DWCU with nearly constant volatility systems, the results suggest that controllability of the DWCU with highly non-ideal systems may depend on thermodynamic properties of these systems. Specific trend showing which type of DWC has better controllability or lower energy consumption. We will continue our investigation in the future.

APPENDIX

A = the lightest component
B = the middle component
C = the heaviest component
X_A = mole fraction of the light component in liquid
X_B = mole fraction of the middle component in liquid
X_C = mole fraction of the heavy component in liquid
Xc'= mole fraction of the heavy component at the top of the dividing wall
RR = reflux ratio
S = side liquid stream flowrate
BR = boiled up ratio
SL = liquid split ratio
SV = vapor split ratio
Q = reboiler duty

REFERENCES

[1] Anton A. Kiss, Costin Sorin Bildea, "A control perspective on process intensification in dividing-wall columns". Chemical Engineering and Processing, 2011, 50: p.281-292

[2] Wright, R.O. and N.J.Elizabeth, "Fractional apparatus". 1949. US Patent, 2,471,134

[3] Schultz, M. A.; Stewart, D. G.; Harris, J. M.; Rosenblum, S. P.; Shakur, M. S.; O'Brien, D. E., Reduce costs with dividing-wall columns. *Chem. Eng. Prog.* 2002, 98, (5), 64-71.

[4] Mutalib, M. I. A.; Smith, R. Operation and control of dividing wall distillation columns - Part 1: Degrees of freedom and dynamic simulation. *Chem. Eng. Res. Des.* 1998, *76*, 308.E. H. Miller, "A note on reflector arrays (Periodical style—Accepted for publication)," *IEEE Trans. Antennas Propagat.*, to be published.

[5] Serra, M.; Espuna, A.; Puigjaner, L. Control and optimization of the divided wall column. *Chem. Eng. Process.* 1999, *38*, 549.C. J. Kaufman, Rocky Mountain Research Lab., Boulder, CO, private communication, May 1995.

[6] Ling, H.; Luyben, W. L. New Control Structure for Divided-Wall Columns. *Ind. Eng. Chem. Res.* 2009, *48*, 6034.

[7] Ling, H.; Cai, Z.; Wu, H.; Wang, J.; Shen, B. X. Remixing Control for Divided-Wall Columns. *Ind. Eng. Chem. Res.* 2011, *50*, 12694.

[8] Wang, S. J.; Wong, D. S. H., Controllability and energy efficiency of a high-purity divided wall column. *Chem. Eng. Sci.* 2007, *62*, 1010

[9] Wang, Y. F.; Huang, K. J.; Luan, S. J.; Chen, W.; Wang, S. J.; Wong, D. S. H., Circumventing the Black-Hole Problem in Design and Control of Dividing-Wall Distillation Columns. *Ind. Eng. Chem. Res.* 2012, *51*, 14771.

[10] Wolff, E. A.; Skogestad, S. Operation of Integrated 3-Product (Petlyuk) Distillation-Columns. *Ind. Eng. Chem. Res.* 1995, *34*, 2094.

[11] Halvorsen, I. J.; Skogestad, S. Minimum energy consumption in multicomponent distillation. 2. Three-product Petlyuk arrangements. *Ind. Eng. Chem. Res.* 2003, *42*, 605.

[12] Kim, K.; Lee, M.; Park, S. Two-Point Temperature Control Structure Selection for Dividing-Wall Distillation Columns. *Ind. Eng. Chem. Res.* 2012, *51*, 15683

[13] Ling, H.; Luyben, W. L. Temperature Control of the BTX Divided-Wall Column. *Ind. Eng. Chem. Res.* 2010, *49*, 189.

[14] Serra, M.; Perrier, M.; Espuna, A.; Puigjaner, L. Analysis of different control possibilities for the divided wall column: feedback diagonal and dynamic matrix control. *Comput. Chem. Eng.* 2001, *25*, 859.

[15] van Diggelen, R. C.; Kiss, A. A.; Heemink, A. W. Comparison of Control Strategies for Dividing-Wall Columns. *Ind. Eng. Chem. Res.* 2010, *49*, 288.

[16] Wang,WJ, Jeffrey D. Ward. Control of three types of dividing wall columns. *Ind. Eng. Chem. Res.* 2013, *52*, 50.

[17] Teng-Yun Mao, "Steady state design of non-ideal divided wall columns systems". Department of Chemical Engineering College of Engineering National Taiwan University Master Thesis, 2012, 7