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Comparison of stabilizing control structures for dividing wall columns

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Abstract: The focus of this paper is to investigate stabilizing control (single-loop PID control) of a dividing wall column (DWC) for separating ethanol, n-propanol and n-butanol at atmospheric pressure. Three control structures are studied: control structure with fixed split ratios (CS1), control structure with an active liquid split (CS2) and control structure with an active vapor split ratio (CS3). The dynamic performances of the three proposed control structures prove that the three control structures are able to handle feed disturbances inserted into DWC. The simple control structure with fixed split ratios (CS1) is more applicable in industry. Considering the vapor split ratio disturbance, CS2 and CS3 are better than CS1. If the feed composition of A rarely changes, CS3 is able to handle the other feed disturbances. This paper proves that the three-product DWC can be controlled with only three temperature controllers.

Keywords: Distillation columns, Automatic process control, Computer-aided control system design, Systems engineering, Process simulators, Numerical simulation

1. INTRODUCTION

Distillation is one of the most widely applied separation technologies in the chemical industries. However, conventional distillation is still a capital- and energy-intensive operation. Dividing wall column (DWC) provides a promising alternative for distillation process intensification. Dividing wall column (DWC) offers one of the most practical alternatives.(Dejanovic et al., 2010, Yildirim et al., 2011) The implementation of dividing wall column with a side product is shown in Fig. 1, and it is thermodynamically equivalent to the Petlyuk configuration which is shown in Fig. 2.

The difficulties in the control of DWC are due to its inner complex structure and interactions among different control loops. Skogestad et al. (Dwivedi et al., 2013) studied the composition control of three-product dividing wall column. Chien et al. (Wu et al., 2014) investigated the design and control of azeotropic dividing wall columns. Xu et al. (Xia et al., 2012) studied the different control structures for extractive dividing wall columns. The objective of this paper is to investigate multi-loop PID control schemes of DWC for separating ethanol, n-propanol and n-butanol at atmospheric pressure. No composition controllers are used since this is more practical in industrial applications. The performances of the control structures are tested in terms of the product composition time profiles with ±20% step disturbances in either feed flow rate or feed compositions.

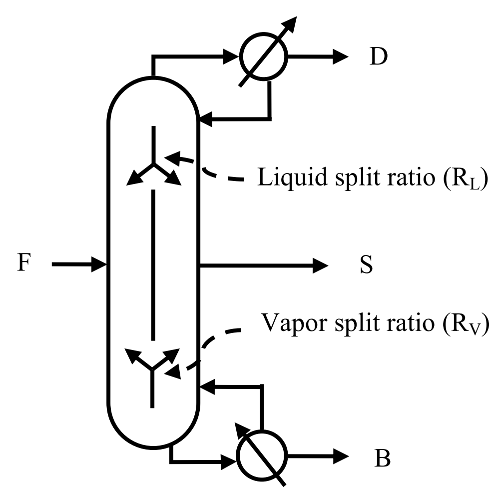

Fig. 1. Dividing wall column

Three control structures are proposed with or without use of liquid split ratio and vapour split ratio: control structure with fixed split ratios (CS1), control structure with an active liquid split (CS2) and control structure with an active vapor split ratio (CS3). In CS1, the liquid split ratio and the vapor split ratio are both fixed. In CS2, the liquid split ratio is used as a manipulated variable to control the sensitive tray temperature

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in the prefractionator while the vapor split ratio is fixed. In CS3, the vapor split ratio is used as a manipulated variable to control the sensitive tray temperature in the prefractionator while the liquid split ratio is fixed.

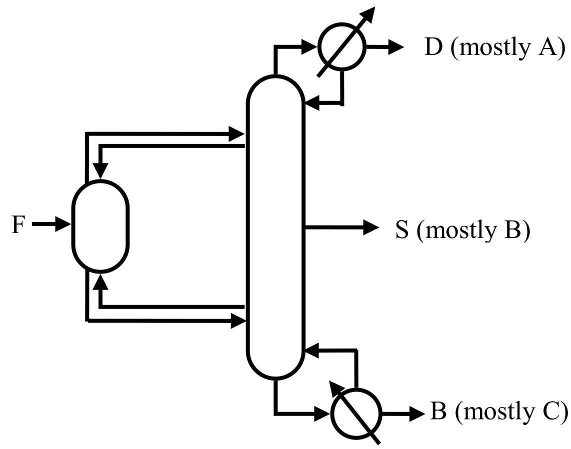


Fig. 2. Petlyuk configuration with prefractionator and the main column (Thermodynamically equivalent to Fig. 1)

2. STEADY-STATE DESIGN

The separation of ethanol, n-propanol and n-butanol is used as a case study of control structures of three-product DWC. The feed is equimolar saturated liquid and the feed flow rate is 1 kmol/h. The relative volatilities for ethanol (A), n-propanol (B) and n-butanol (C) are 4.46, 2.16 and 1, respectively.

Table 1 Nominal data for the DWC

Variables	Prefractionator	Main column
Stages	15	53
Feed stages (from top)	8	20/35
Side product stage	-	28
Reflux ratio	-	7.93
Distillate flow rate (kmol/h)	0.577	0.335
Side product flow rate (kmol/h)	-	0.330
Liquid split ratio (R_L)	-	0.469
Vapor split ratio (R_V)	-	0.601
Reboiler duty (kW)	-	30.86
Composition of A in distillate	0.259	0.99
Composition of B in side product	-	0.99
Composition of C in bottom product	0.255	0.99
Composition of B in distillate	0.739	0.01
Composition of B in bottom product	0.739	0.01
Composition of C in side product	-	0.004
Composition of A in side product	-	0.006

In Fig. 3, the Vmin diagram(Halvorsen and Skogestad, 2003) showing minimum vapor flows in various sections required for sharp separation of equimolar A-B-C feed is established. The y-axis shows the normalized minimum boilup (V/F) and the x-axis shows the net product withdrawal (D/F) in a conventional two-product column. The peak P_{AB} gives the minimum vapor flow (V/F) required for separating A and B. Similarly, point P_{AC} denotes the minimum vapor required to separate A and C. From the Vmin diagram we see that the BC-separation in the bottom of the main column is the most difficult compared with AB-separation and AC-separation.

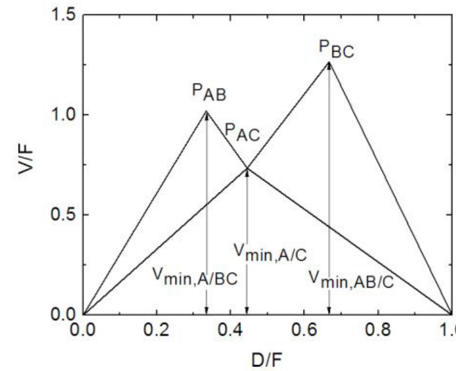
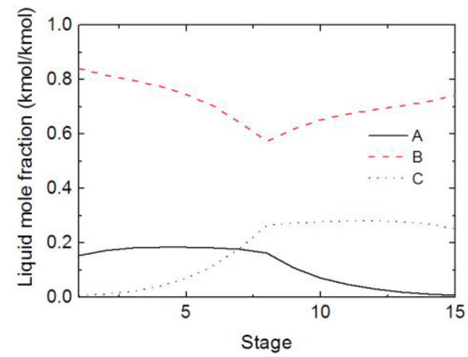
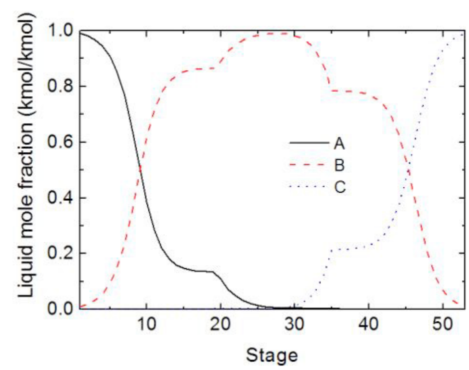


Fig. 3 Vmin diagram for sharp separation of equimolar A-B-C feed



(a) Prefractionator



(b) Main column

Fig. 4. Composition profile of the prefractionator and the main column

The rigorous simulation of the Petlyuk configuration is implemented employing Aspen Plus. The nominal data of the DWC are shown in Table 1. The composition profiles of the prefractionator and the main column are shown in Fig. 4. The product specifications are all set to 99%.

3. CONTROL STRUCTURES

To be more practical in industrial applications, no composition controllers are used. The sensitive trays are searched by increasing the reboiler duty by 0.1%. The most sensitive tray of the prefractionator is the 6^{th} tray, and the most sensitive trays of the main column are the 9th tray and the 47th tray. The liquid split ratio (LSR) in this paper is the fraction of the liquid from the main column going to the prefractionator. Similarly, the vapor split ratio (VSR) in this paper is the fraction of the vapor from the main column going to the prefractionator. All simulations are simulated with Aspen Plus Dynamics. The pressure of the main column is controlled by the condenser duty. The condenser level is controlled by the top distillate flow rate, and the sump level is controlled by the bottom product flow rate. The flow rate controllers, the pressure controllers and the level controllers are not illustrated in the figures.

3.1 Control structure with fixed split ratios (CS1)

The control structure with fixed split ratios (CS1) is shown in Fig. 5. In CS1, the liquid split ratio and vapor split ratio are fixed. The reflux flow rate and the side product flow rate are used to control the temperatures of the 9th tray and the 47th tray of the main column, respectively. Closed loop tuning is used and the Tyreus−Luyben methods are applied to achieve the gain and integral time constant. Controller tuning parameters of CS1 is shown in Table 2.

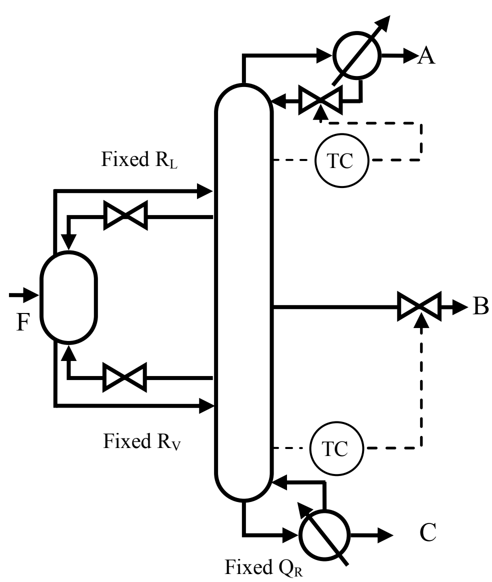


Fig. 5. Control structure with fixed split ratios (CS1)

Table 2 Controller tuning parameters of CS1

Control loop	Controlled variable	Manipulated variable	Controller gain	Controller integral time (min)
TC2	TM9	R	1.32	10.56
TC3	TM47	S	4.33	17.16

The dynamic responses of the three products when ±20% feed flow rate disturbances occur at 0.5h are shown in Fig. 6. DA, SB, BC means the light component A in distillate, the intermediate component B in side product and the heavy component C in bottom product, respectively. DB, SC, BB, SA means B in distillate, C in side product, B in bottom product, A in side product, respectively. The dynamic responses of the three products when ±20% feed composition of A, B and C disturbances occur at 0.5h are shown in Fig. 7. For example, +20% feed composition increase of A is that A is increased from 0.333 to 0.4, and the other two are both equal to 0.3.

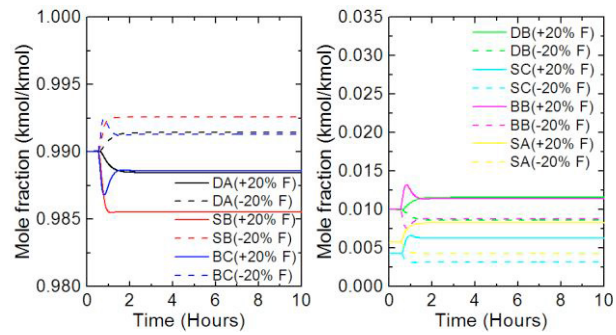
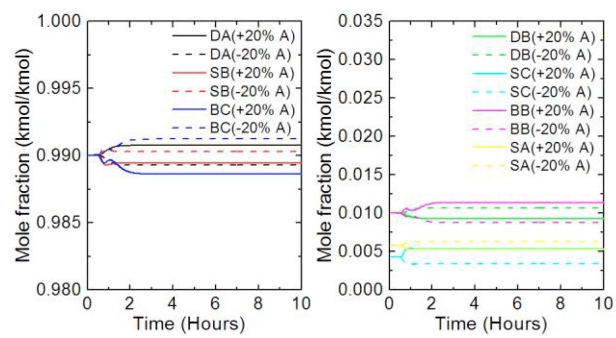
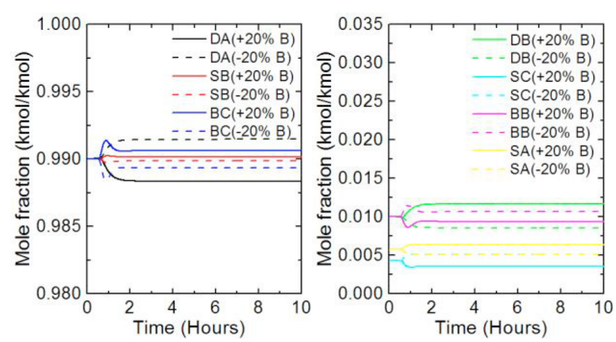


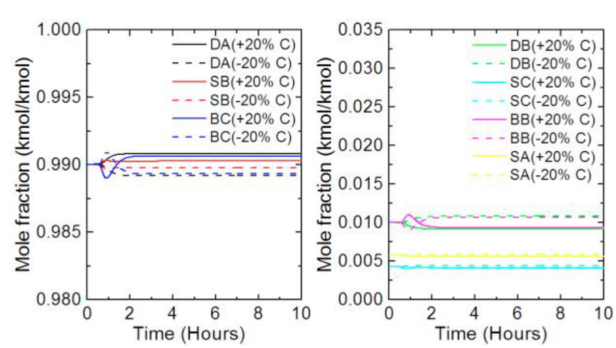
Fig. 6. CS1: Dynamic responses for the products when ±20% feed flow rate disturbances occur



(a) ±20% feed composition of A disturbances



(b) ±20% feed composition of B disturbances



(c) ±20% feed composition of C disturbances

Fig. 7. CS1: Dynamic responses for the products when ±20% feed composition disturbances occur

The dynamic responses of the three products when ±20% vapor split ratio disturbances occur at 0.5h are shown in Fig. 8. From Fig.6 and Fig.7, the deviations of the product purity are all less than 0.5%. The results show that temperature controllers are able to handle the feed disturbances added to DWC. However, the composition of B in side product exceeds the y-axis in Fig. 8, as the deviations of side products are relatively large when ±20% vapor split ratio disturbances occur. The composition of B in side product goes down to 95.4% when +20% vapor split ratio disturbances occur, while it goes down to 97.5% when -20% vapor split ratio disturbances occur. Vapor split ratio disturbances are expected in industry. For example, due to flow changes inside the colum. The dynamic responses of the three products when +10% or +20% feed vapor fraction disturbances occur at 0.5h are shown in Fig. 9. The deviations are relatively small.

Since most of the dynamic responses have the overshoot, the main effect of the disturbance may be collected by the steady-state change, as written in Table 5.

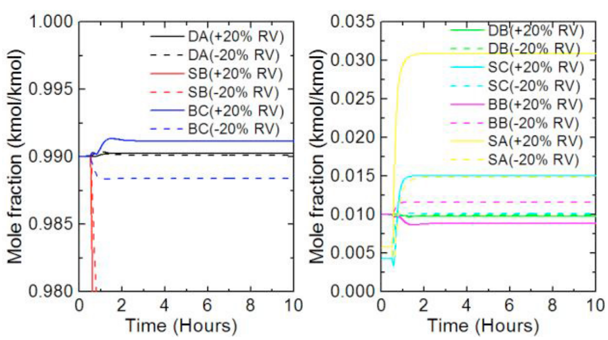


Fig. 8. CS1: Dynamic responses for the products when ±20% vapor split ratio disturbances occur

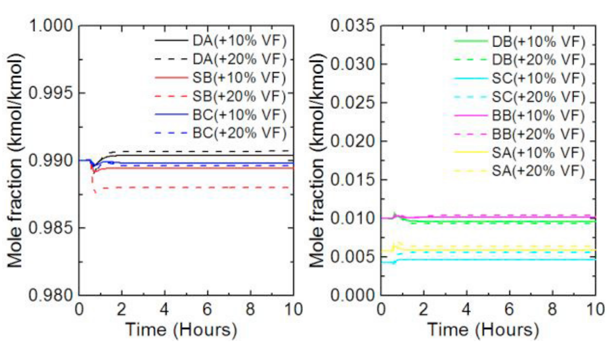


Fig. 9. CS1: Dynamic responses for the products when +10% or +20% feed vapor fraction disturbances occur

3.2 Control structure with an active liquid split (CS2)

The control structure with an active liquid split (CS2) is shown in Fig. 10. In CS2, the liquid flow to the prefractionator is used as the manipulated variable for temperature controller TC1. The controlled variable of TC1 is the 6th tray temperature in the prefractionator. Controller tuning parameters of CS2 is shown in Table 3.

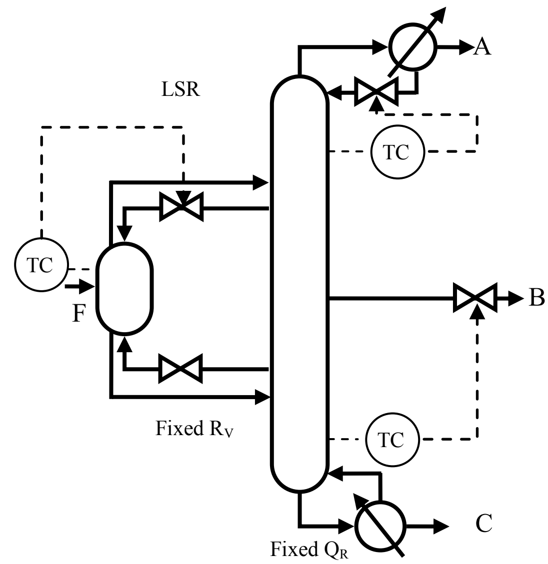


Fig. 10. Control structure with an active liquid split (CS2)

Table 3 Controller tuning parameters of CS2

Control loop	Controlled variable	Manipulated variable	Controller gain	Controller integral time (min)
TC1	TP6	LSR	4.29	13.2
TC2	TM9	R	1.12	11.88
TC3	TM47	S	6.30	11.88

The dynamic responses for the side product when ±20% feed flow rate and feed compostions disturbances occur using CS1, are slightly better than those using CS2. This is probably because it is not sharp split in the prefractionator, so tray temperature may not be able to reveal the compositions in the column very well. Dynamic responses for the products when +10% or +20% feed vapor fraction disturbances occur using CS2 are slightly better than those using CS1. This is probably due to the sensitive tray temperature of the prefractionator is controlled by the liquid split ratio, which will weaken the disturbances. Only the different dynamic responses are shown. The similar responses for other disturbances are not shown in this paper. The dynamic responses for the products when vapor split ratio disturbances occur at 0.5h are shown in Fig. 11. As expected, the control structure with an active liquid split (CS2) is better than the control structure with fixed split ratios (CS1) when ±20% vapor split ratio disturbances occur. This is because manipulating the liquid split ratio to maintain the sensitive tray temperature in the prefractionator able to lessen the disturbance of vapor split ratio. If the vapor split ratio is increased, too much heavy component C will be vaporized at the top of the prefractionator, and the liquid split ratio will be increased in CS2. Therefore, heavy component C at the top of the prefractionator is decreased, and the heavy impurity C in the side product is decreased.

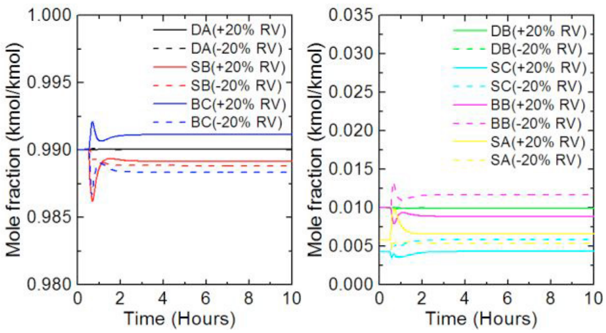


Fig.11. CS2: Dynamic responses for the products when ±20% vapor split ratio disturbances occur

3.3 *Control structure with an active vapor split ratio (CS3)*

The control structure with an active vapor split ratio (CS3) is shown in Fig. 12. In CS3, the vapour flow to the prefractionator is used as the manipulated variable for temperature controller TC1, while the liquid split ratio is fixed. The controlled variable of TC1 is the 9th tray temperature (sensitive tray below the feed stage) in the prefractionator. Controller tuning parameters of CS3 is shown in Table 4.

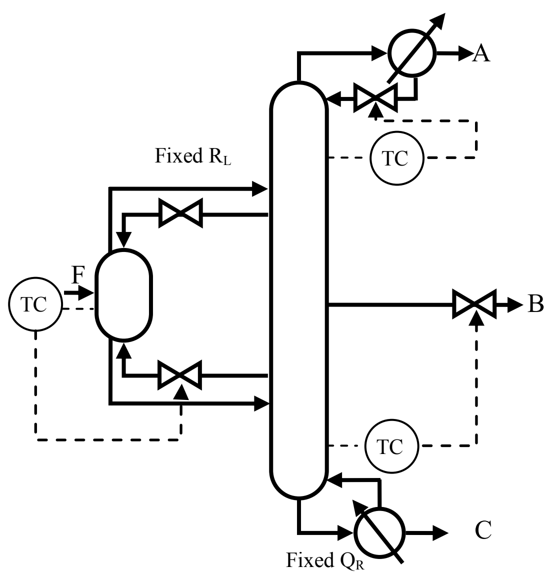


Fig.12. Control structure with an active vapor split ratio (CS3)

Table 4 Controller tuning parameters of CS3

Control loop	Controlled variable	Manipulated variable	Controller gain	Controller integral time (min)
TC1	TP9	VSR	3.69	10.56
TC2	TM9	R	0.97	11.88
TC3	TM47	S	4.61	15.84

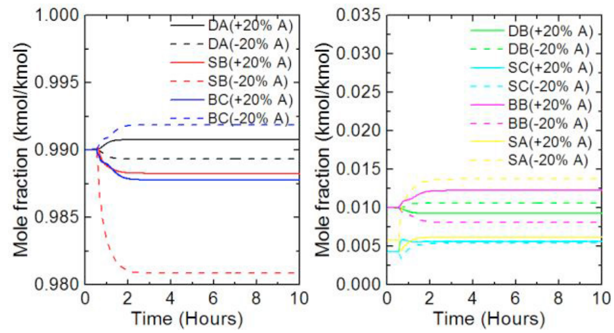


Fig. 13. CS3: Dynamic responses for the products when ±20% feed composition of A disturbances occur

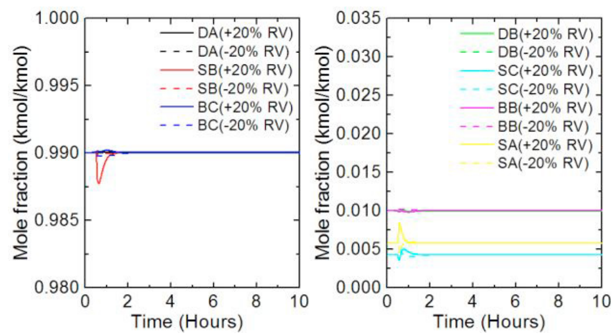


Fig. 14. CS3: Dynamic responses for the products when ±20% vapor split ratio disturbances occur

There is not too much difference of dynamic responses between CS2 and CS3. The most different dynamic responses are for ±20% feed composition of A disturbances as shown in Fig. 13. The light impurity A in side product stream is increased, so the purity of B in side product is decreased. This suggests that CS3 may not be able to handle the light component feed disturbances well. This may be because the reboiler duty is a constant in the proposed control structures. The dynamic responses of the three products when ±20% vapor split ratio disturbances occur at 0.5h are shown in Fig. 14. CS3 is insensible to vapor split ratio disturbances, as expected.

Table 5 shows the steady-state composition changes of the main components when feed disturbances or vapor split ratio disturbances occur.

Table 5 Steady-state composition changes of the main components ($⊿X_{DA}$, $⊿X_{SB}$, $⊿X_{BC}$)^T

Disturbance	CS1 (%)	CS2 (%)	CS3 (%)
	-0.15	-0.15	-0.15
+20%F	-0.45	-0.49	-0.46
	-0.14	-0.14	-0.12
	+0.14	+0.14	+0.14
-20%F	+0. 26	+0.34	+0.32
	+0.13	+0.13	+0.11
+20%A	+0.08	+0.07	+0.08

	-0.06	-0.06	-0.17
	-0.14	-0.14	-0.22
	-0.07	-0.07	-0.06
-20%A	+0.03	-0.25	-0.91
	+0.12	+0.12	+0.19
	-0.16	-0.16	-0.16
+20%B	+0.01	-0.37	-0.41
	+0.06	+0.06	+0.11
	+0.15	+0.15	+0.15
-20%B	-0.01	-0.29	-0.11
	-0.06	-0.06	-0.13
	+0.08	+0.08	+0.08
+20%C	+0.03	+0.03	-0.06
	+0.06	+0.07	+0.09
	-0.08	-0.08	-0.08
-20%C	-0.02	-0.05	+0.01
	-0.07	-0.07	-0.09
	+0.02	+0.01	0
+20%R_V	-3.58	-0.08	0
	+0.12	+0.11	0
	+0.01	+0.01	0
-20%R_V	-1.50	-0.12	0
	-0.16	-0.16	0
	+0.04	+0.04	+0.04
+10%VF	-0.06	+0.05	+0.05
	-0.02	-0.02	-0.06
	+0.07	+0.07	+0.07
+20%VF	-0.20	+0.06	+0.05
	-0.04	-0.04	-0.12

4. CONCLUSIONS

The dynamic performances of the three proposed control structures prove that the three control structures are able to handle feed disturbances inserted into DWC. When only two temperatures in the main column of DWC are controlled using the reflux flow rate and the side product flow rate to handle feed disturbances, the most robust is control structure with fixed split ratios (CS1). Considering the vapor split ratio disturbance, the control structure with an active liquid split (CS2) is better than CS1. CS2 adds a temperature controller TC1 to control the temperature in the prefractionator. However, the temperature and composition are not correlating well as it is not sharp split in the prefractionator. The performances of the control structure with an active vapor split ratio (CS3) are mostly not very different from those of CS2. The deviation of B in side product is relatively large when ±20% feed composition of A disturbances occur using CS3. This may be because the reboiler duty is a constant in the proposed control structures. This paper proves that the three-product DWC can be controlled with only three temperature controllers. This work demonstrates temperature controllers without composition controllers are able to handle disturbances inserted into DWC, which is an encouraging result for industrialization of DWC.

REFERENCES

Dejanovic, I., Matijasevic, L. and Olujic, Z. (2010). Dividing wall column-a breakthrough towards sustainable distilling, *Chemical Engineering and Processing* 49, 559-580.

Yildirim, O., Kiss, A. A. and Kenig, E. Y. (2011). Dividing wall columns in chemical process industry: A review on current activities, *Separation And Purification Technology* 80, 403-417.

Dwivedi, D., Halvorsen, I. J. and Skogestad, S. (2013). Control structure selection for three-product petlyuk (dividing-wall) column, *Chemical Engineering and Processing* 64, 57-67.

Wu, Y. C., Lee, H. Y., Huang, H. P. and Chien, I. L. (2014). Energy-saving dividing-wall column design and control for heterogeneous azeotropic distillation systems, *Industrial & Engineering Chemistry Research* 53, 1537-1552.

Xia, M., Yu, B. R., Wang, Q. Y., Jiao, H. P. and Xu, C. J. (2012). Design and control of extractive dividing-wall column for separating methylal-methanol mixture, *Industrial & Engineering Chemistry Research* 51, 16016-16033.

Halvorsen, I. J. and Skogestad, S. (2003). Minimum energy consumption in multicomponent distillation. 2. Three-product petlyuk arrangements, *Industrial & Engineering Chemistry Research* 42, 605-615.