

Article

Control structure comparison for three-product Petlyuk column[☆]Shengkun Jia¹, Xing Qian^{1,2,*}, Xigang Yuan^{1,*}, Sigurd Skogestad²¹ School of Chemical Engineering and Technology, Chemical Engineering Research Center, Collaborative Innovation Center of Chemical Science and Engineering (Tianjin), State Key Laboratory of Chemical Engineering, Tianjin University, Tianjin 300072, China² Department of Chemical Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, 7491, Norway

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ABSTRACT

The focus of this paper is to investigate different control structures (single-loop PI control) for a dividing wall (Petlyuk) column for separating ethanol, *n*-propanol and *n*-butanol. Four control structures are studied. All the results are simulations based on Aspen Plus. Control structure 1 (CS1) is stabilizing control structure with only temperature controllers. CS2, CS3 and CS4, containing also composition controllers, are introduced to reduce the steady state composition deviations. CS2 adds a distillate composition controller (CCDB) on top of CS1. CS3 is much more complicated with three temperature-composition cascade controllers and in addition a selector to the reboiler duty to control the maximum controller output of light impurity composition control in side stream and bottom impurity control in the prefractionator. CS4 adds another high selector to control the light impurity in the sidestream. Surprisingly, when considering the dynamic and even steady state performance of the proposed control structures, CS1 proves to be the best control structure to handle feed disturbances inserted into the three-product Petlyuk column.

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1. Introduction

Distillation is one of the most important and widely applied unit operations for separation in the chemical and petrochemical industries [1–9]. However, the energy efficiency of distillation operation can be improved. The Petlyuk column, usually implemented as a dividing wall column (DWC) to save also capital costs, provides a promising alternative for energy saving [10,11]. Compared with traditional distillation columns, 30% of energy saving can be expected from the DWC [12]. The configuration of a DWC is shown in Fig. 1, and it is thermodynamically equivalent to the Petlyuk configuration shown in Fig. 2. The DWC shown in Fig. 1 can be used for ternary distillation, and the components A, B, and C, which are arranged in the order of their volatilities, are recovered respectively in the top distillate *D*, the side withdraw *S*, and the bottom *B*. As shown in Fig. 2, the main feature of the Petlyuk

configuration, or DWC, is to have a prefractionator with a thermal coupling between the prefractionator and the main section by the inter-column streams D_p , L_p , V_p , and B_p . In terms of process control, the major difference between DWC and normal distillation column is that more freedoms are involved in the DWC due to the inclusion of the thermal coupling streams, which are reflected by the liquid and vapor splits as shown in Fig. 1. Such a complexity in control is also a main barrier for the industrial application of DWCs.

Because of the extra degrees of freedoms, more control loops are generally needed, and the difficulties in the control of DWC come mainly from the interactions among different control loops. Researches have been extensively reported in the literature on the controllability and operability of various distillation configurations, e.g. Petlyuk column [13–21], Kaibel column [22–25], reactive distillation (RD) [26–29], reactive dividing wall columns (RDWC) [30–32], extractive dividing wall columns (EDWC) [33–35], and azeotropic dividing wall columns (ADWC) [36,37]. The objective of this paper is to investigate multi-loop proportional–integral–differential (PID) control schemes of DWC for separating ethanol, *n*-propanol and *n*-butanol at atmospheric pressure.

In previous research, both temperature and composition controllers have been used. However, few studies have compared temperature control and temperature–composition control for three-product Petlyuk column. In the present paper, four typical control structures are proposed, and analyzed and compared by numerical simulation. The control structures include a pure temperature control structure (CS1), as well as control structures containing both the temperature and the composition controls (CS2, CS3, and CS4). CS2 adds a composition

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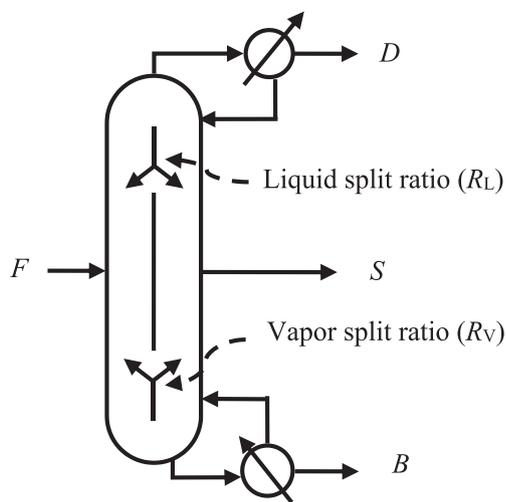


Fig. 1. The three-product dividing wall column (Petlyuk column).

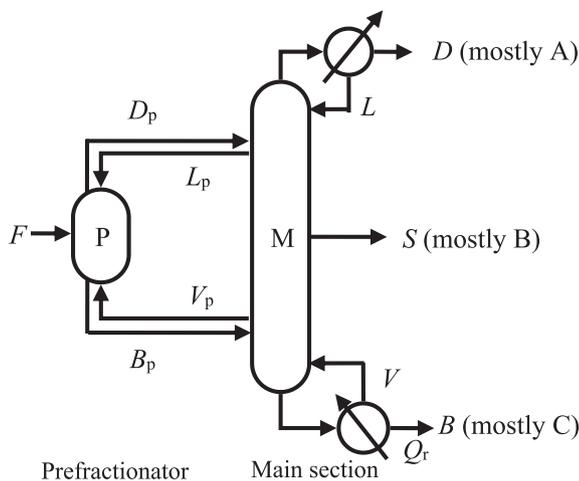


Fig. 2. Petlyuk configuration with prefractionator (P) and the main section (M) (thermodynamically equivalent to Fig. 1).

controller (CCDB) on top of CS1. CS3 adds two more temperature-composition cascade controllers and a high selector. CS4 adds another high selector. The performances of the control structures are tested in terms of the impurity composition time profiles with +20% step disturbances in either feed flow rate or feed compositions.

2. Design of Three Product Petlyuk Configuration

The atmospheric separation of ethanol (A), *n*-propanol (B) and *n*-butanol (C) is used for the investigation. The feed of $1 \text{ kmol} \cdot \text{h}^{-1}$ is equimolar saturated liquid. The relative volatilities for A, B and C are 4.46, 2.16 and 1, respectively, with respect to heavy component C. The three product purity specifications are all 99 mol%. Rigorous simulations are performed using Aspen Plus, and the nominal data of the Petlyuk column are shown in Table 1.

In Fig. 3, the V_{\min} diagram [4] shows the minimum vapor flows (with infinite number of stages) in various sections required for sharp separation of an equimolar A-B-C feed. 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. The V_{\min} diagram suggests that the BC-separation in the bottom of

Table 1
Nominal data for the DWC

Variables	Prefractionator	Main section
Total number of theoretical stages	15	53
Feed stages (from top)	8	20/35
Product stage (from top)	1/15	28
Operating pressure/MPa	0.1144	0.1013
Tray pressure drop/Pa	689	689
Top mole flow rate (D)/ $\text{kmol} \cdot \text{h}^{-1}$	0.577	0.335
Side product flow rate (S)/ $\text{kmol} \cdot \text{h}^{-1}$	–	0.330
Liquid split ratio (R_L) ^①	–	0.469
Vapor split ratio (R_V) ^①	–	0.601
Reflux flow rate (L)/ $\text{kmol} \cdot \text{h}^{-1}$	1.19	2.654
Condenser duty (Q_c)/kW	–	32.33
Reboiler duty (Q_r)/kW	–	30.86
Composition of A in distillate ^②	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

^① The vapor split ratio (R_V) is defined as the fraction of vapor that is sent to the prefractionator, i.e., $R_V = V_p/V$ (where V is the vapor flow below the vapor split and V_p is the vapor flow into the prefractionator). The liquid split ratio (R_L) is defined as the fraction of liquid that is sent to the prefractionator, i.e., $R_L = L_p/L$ (where L is the liquid flow above of the liquid split and L_p is the liquid reflux flow into the prefractionator).

^② Compositions are mole fractions.

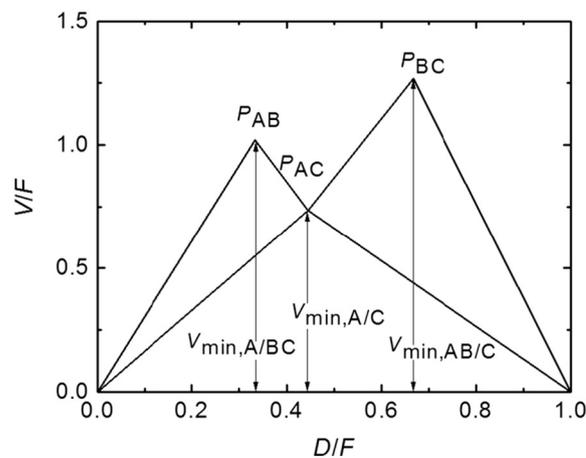


Fig. 3. V_{\min} diagram for sharp separation of equimolar A-B-C feed.

the main section is the more difficult separation compared with the AB-separation. The composition profiles of the prefractionator and the main section are shown in Fig. 4.

3. Control Structures

All the control behaviors are analyzed by dynamic simulations employing Aspen Plus Dynamics™. PI controllers are used in all loops, except P controllers for levels. We assume that the column pressure 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. With these three stabilizing control loops, there are five remaining degrees of freedom, which from a control point of view correspond to the following manipulated variables (u):

1. Reflux flow rate (L)
2. Reboiler duty (Q_r)
3. Liquid flow from the main section to the prefractionator (L_p)
4. Vapor flow from the main section to the prefractionator (V_p)
5. Side product flow rate (S)

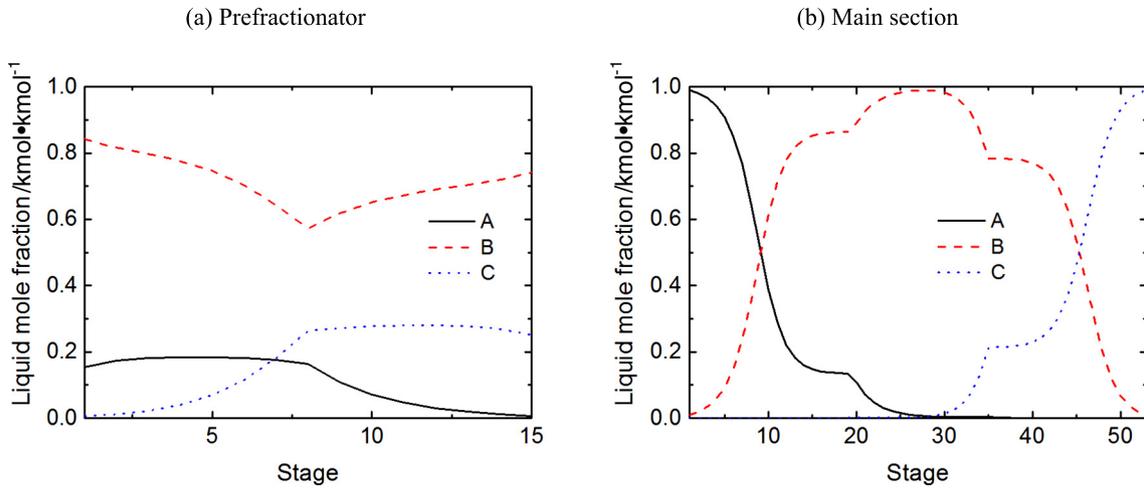


Fig. 4. Composition profiles of (a) prefractionator and (b) main section.

Note that the vapor split ratio ($(R_V = V_p/V)$) is assumed to be constant in this paper. According to the plantwide control procedure of Skogestad [38], the control system may be divided into a supervisory

layer, which controls the primary variables (CV_1), and a regulatory or stabilizing layer which controls drifting or sensitive variables (CV_2) that are easy to measure and control. In our case, the primary

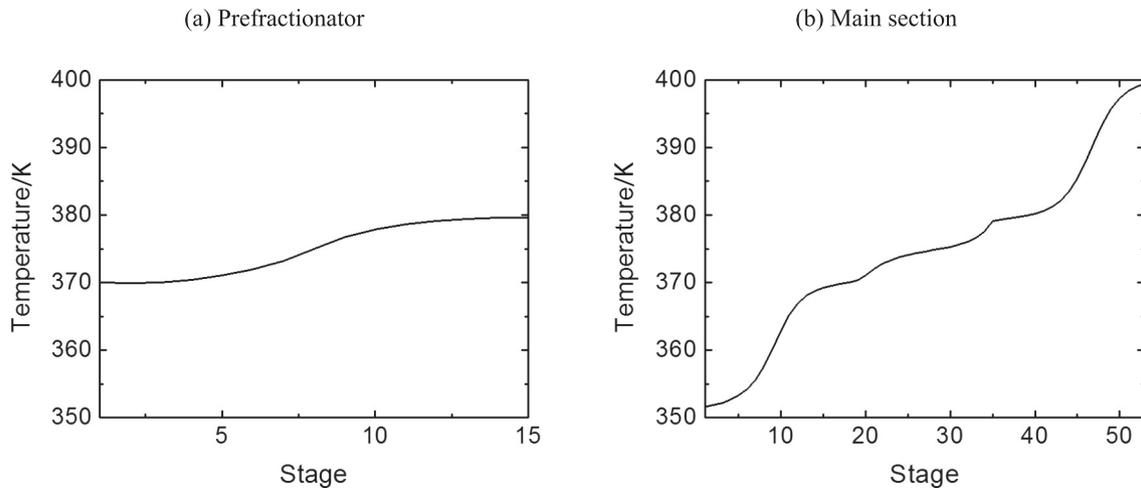


Fig. 5. Temperature profiles of (a) prefractionator and (b) main section.

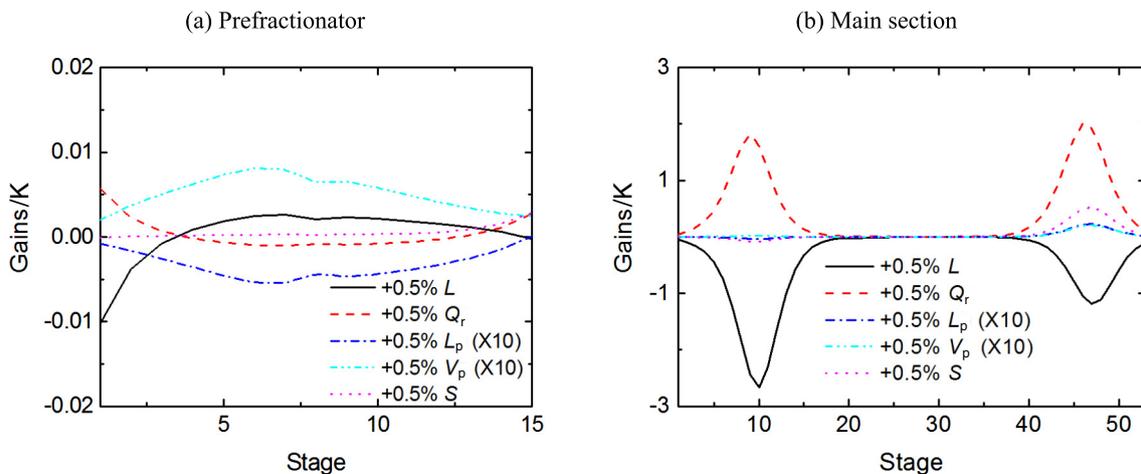


Fig. 6. Process sensitivity profiles (steady state gain, dT/du) for (a) prefractionator and (b) main section.

(economic) controlled variables (CV_1) are assumed to be the three product compositions. In addition, the two prefractionator “products” may be controlled in order to avoid breakthrough of C in the top (D_p) and breakthrough of A in the bottom (B_p). For distillation, the secondary controlled variables (CV_2) are usually temperatures.

The temperature profiles of the prefractionator and the main section are shown in Fig. 5. For stabilizing control, the first issue is to decide which temperatures to control. In general, we need one stabilizing temperature or composition loop for each split [39]. The prefractionator performs one split (A/C), and needs one stabilizing temperature controller. The main section performs two splits (A/B and B/C) and needs two stabilizing temperature controllers.

The temperatures used for stabilizing control should be sensitive to input changes [39]. In order to find the steady-state sensitivities (gains, dT/du) for the tray temperatures (T), small increases (+0.5%) have been made in each of the five independent variables (u). The changes were made one at a time with the other flows constant. The results are shown graphically in Fig. 6 for the prefractionator (left) and main section (right). The gains for L_p and V_p were relatively small and have been multiplied by a factor 10. In the prefractionator we need to close one stabilizing loop and the most sensitive tray of the prefractionator is the 6th tray ($T_{P,6}$, above the feed). In the main section we need to close two loops and from Fig. 6 we see that there are two clear peaks, corresponding to the 9th tray ($T_{M,9}$, above the liquid split) and the 47th tray ($T_{M,47}$, below the vapor split).

3.1. Control structure 1 (CS1)

Control structure 1 (CS1) is basically a stabilizing control system with only temperature controllers, see Fig. 7, where the pressure controller and the two level controllers are not shown. The selected controlled variables are the three sensitive temperatures observed in Fig. 6 ($T_{P,6}$, $T_{M,9}$, $T_{M,47}$). Note that we do not control any of the product compositions (CV_1) in control structure CS1.

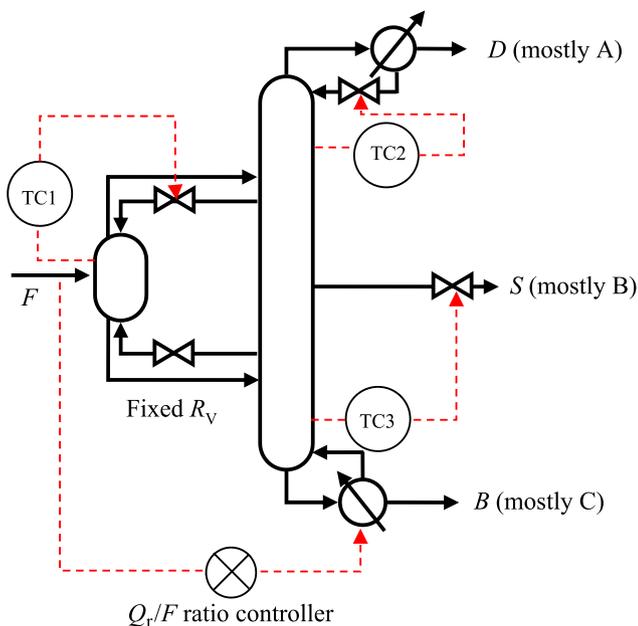


Fig. 7. Control structure CS1.

There are three temperatures to be controlled, so we only need to use three of the five manipulated inputs (u). As mentioned above, the vapor split ratio ($R_V = V_p/V$) is assumed to be constant, because it is fixed in the design of the DWC and cannot be used as a manipulated

Table 2
Controller tuning parameters of CS1

Control loop	Controlled variable	Manipulated variable	Controller gain	Controller integral time/min	τ_c /min
TC1	TP6	L_p	5.1	5.3	2
TC2	TM9	L	1.1	7.9	2
TC3	TM47	S	5.7	12.9	2

variable. The liquid coupling stream to the prefractionator (L_p) is therefore used to control the prefractionator temperature ($T_{P,6}$) because it has a relatively large gain and good dynamics (“pair close rule”). In the main section, one of the three manipulated inputs (L , S , Q_r) will not be used for stabilizing control, that is, it will be kept constant, at least on a short to intermediate time scale. The side stream flow rate (S) should not be kept constant, because otherwise it will not be possible to have pure products when there are disturbances in feed rate and feed composition. Essentially, all of component B should go in S , so we need to have $S \approx z_B F$ (where z_B is the mole fraction of B in the feed) where both

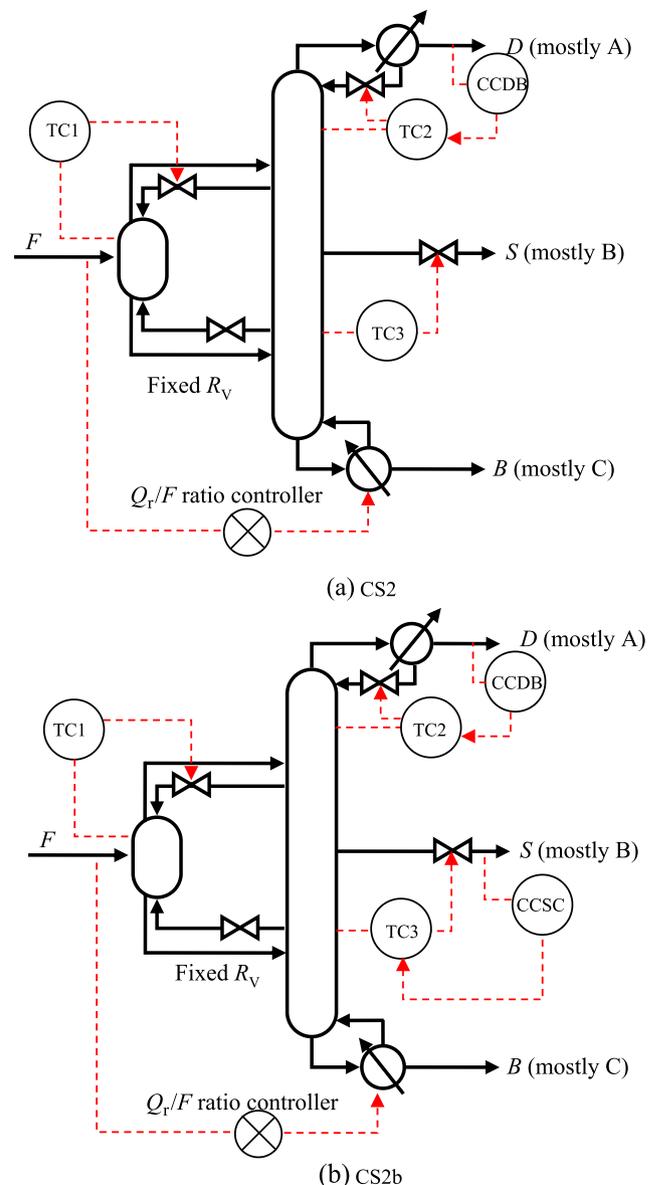


Fig. 8. Control structures 2 and 2b (CS2 and CS2b).

Table 3
Controller tuning parameters of CS2 and CS2b (on top of CS1 controllers)

Control loop	Controlled variable	Manipulated variable	Controller gain	Controller integral time/min	τ_c /min
CCDB	$x_{D,B}$	Set point of TC2	0.013	15.2	30
CCSC	$x_{S,C}$	Set point of TC3	0.047	2.19	50

z_B and F are unknown disturbances. Thus, S needs to vary and should be used for temperature control. From Fig. 6, we see that S mainly affects $T_{M,47}$, and this is also a good pairing dynamically according to the “pair close rule”. What remains now is $T_{M,9}$, which from Fig. 6 is effected somewhat more at steady state by the reflux (L) than by the boilup (Q_r). Furthermore, the “pair close rule” favors using reflux for controlling $T_{M,9}$.

In summary, the liquid flow to the prefractionator (L_p) is used to control the 6th tray temperature in the prefractionator (TC1), while the reflux flow rate (L) and the side product flow rate (S) are used to control the temperatures of the 9th tray (TC2) and the 47th tray (TC3) of the main section, respectively. The ratio of the reboiler duty to the feed flow rate (Q_r/F) is assumed constant in CS1, which can be realized using ratio control. The gains and integral times for the three temperature controllers are obtained based on SIMC tuning rules [38]. SIMC means “Simple control” or “Skogestad IMC”. The controller settings along with the selected tuning constants ($\tau_c = 2$ min in all loops) are shown in Table 2. The control structure performs very well as we see later.

3.2. Control structure 2 (CS2)

Control structures 2 and 2b (CS2 and CS2b), shown in Fig. 8, are introduced to reduce the steady state deviation of the product composition. In control structure CS2, the top composition loop is closed by manipulating the setpoint for $T_{M,9}$ for controller TC2. Actually, we tried to add more composition controllers (CCSC and CCBB), but this was not successful. In control structures 2b (CS2b), we attempt to reduce the steady state deviation of the side product composition by adding the controller CCSC which controls the mole fraction of heavy component (C) in the side stream. However, simulations show that

this was not successful. The system performs nicely when only one composition controller (CCDB) is used, see CS2. Controller tuning parameters are shown in Table 3.

3.3. Control structure 3 (CS3)

Control structure 3 (CS3) is shown in Fig. 9. In CS3, six composition controllers are added on top of CS1. The controlled variables of composition controllers CCP1, CCDB and CCSC are the impurity composition C in the top overhead vapor stream of the prefractionator, the impurity composition B in the distillate of the main section and the impurity composition C in the side stream of the main section. The manipulated variables of CCP1, CCDB and CCSC are set points of TC1, TC2 and TC3, respectively. The controlled variables of composition controllers CCP2, CCSA and CCBB are the impurity composition A in the bottom liquid stream of the prefractionator (B_pA), the light impurity composition A in the side product (SA) and the impurity composition B in the bottom stream (BB) of the main section, respectively. A high selector is used to choose the highest controller (CCP2, CCSA and CCBB) output value to manipulate the ratio of reboiler duty and feed flow rate (Q_r/F). The SIMC tuning rules was used and the controller tuning parameters of CS3 is shown in Table 4.

Table 4
Controller tuning parameters of CS3 (on top of CS1 controllers)

Control loop	Controlled variable	Setpoint	Manipulated variable	Controller gain	Controller integral time/min	τ_c /min
CCP1	$x_{Dp,C}$	0.0026	Set point of TC1	0.003	0.977	35
CCP2	$x_{Bp,A}$	0.0058	Q_r/F high selector	0.050	1.64	55
CCDB	$x_{D,B}$	0.01	Set point of TC2	0.007	2.48	30
CCSC	$x_{S,C}$	0.0042	Set point of TC3	0.030	4.19	10
CCSA	$x_{S,A}$	0.0058	Q_r/F high selector	0.042	3.19	50
CCBB	$x_{B,B}$	0.01	Q_r/F high selector	0.031	1.58	45

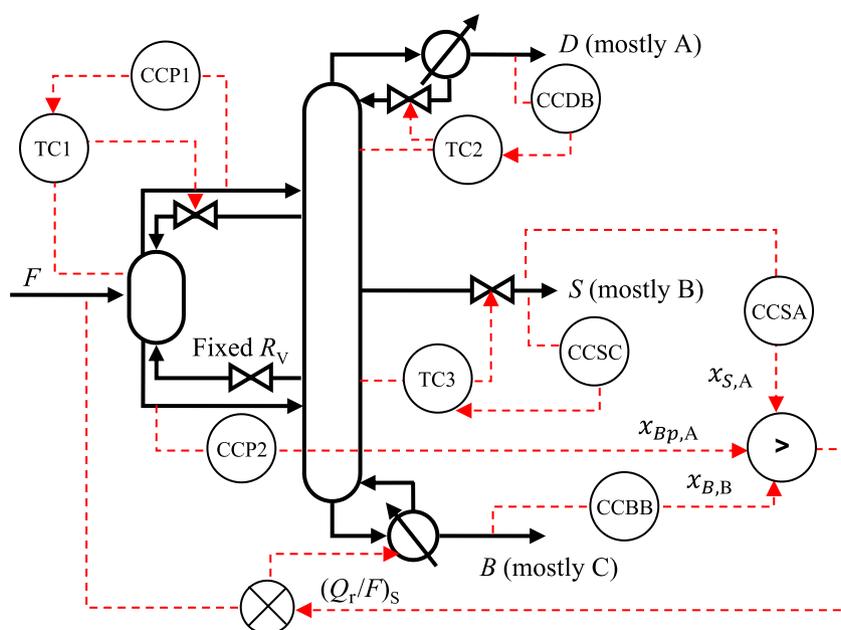


Fig. 9. Control structure 3 (CS3).

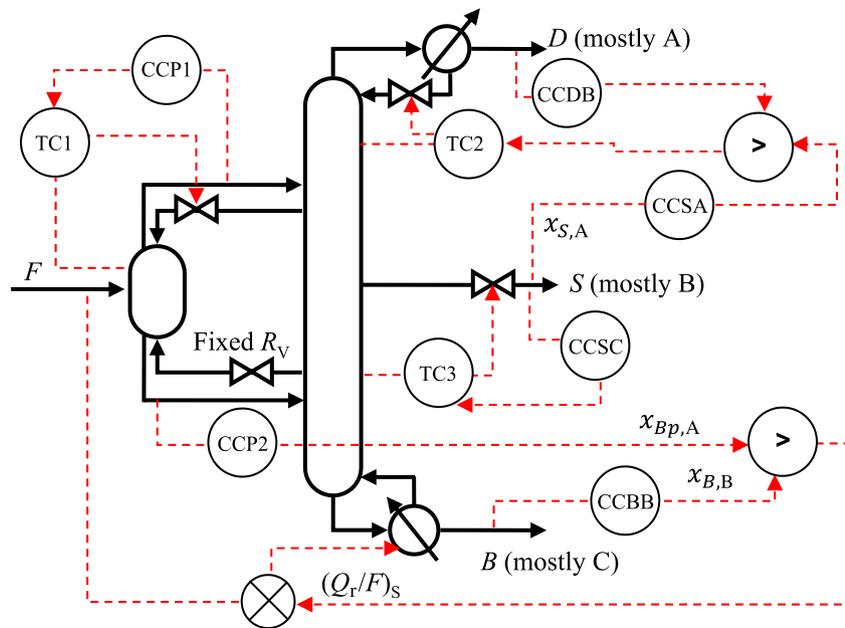


Fig. 10. Control structure 4 (CS4).

3.4. Control structure 4 (CS4)

Control structure 4 (CS4), as shown in Fig. 10, is an extension of CS3, where a high selector is used to select the higher value of outputs of controllers CCP2 and CCBB, while another high selector is added to select the higher value of outputs of controllers CCSA and CCDB. CS4 is introduced to reduce the interactions between different control loops in CS3.

The values for the gains and integral times for each control loops are obtained based on SIMC tuning rules [38]. Controller tuning parameters of CS4 are shown in Table 5.

Table 5
Controller tuning parameters of CS4 (on top of CS1 controllers)

Control loop	Controlled variable	Setpoint	Manipulated variable	Controller gain	Controller integral time/min	τ_c/min
CCP1	$x_{Dp,C}$	0.0026	Set point of TC1	0.003	0.977	35
CCP2	$x_{Bp,A}$	0.0058	Q_r/F high selector	0.050	1.64	55
CCDB	$x_{D,B}$	0.01	Set point of TC2 selector	0.007	2.48	30
CCSC	$x_{S,C}$	0.0042	Set point of TC3	0.030	4.19	10
CCSA	$x_{S,A}$	0.0058	Set point of TC2 selector	0.007	1.57	50
CCBB	$x_{B,B}$	0.01	Q_r/F high selector	0.031	1.64	45

4. Results and Discussion

The dynamic responses of the impurity compositions and the controlled temperatures for the proposed control structures to a +20% feed flow rate disturbance and +20% feed composition of A disturbance are shown in Figs. 11 and 12, respectively. A +20% feed composition increase of A is that A is increased from 0.333 to 0.4 while the other two (B and C) are both equal to 0.3. DA, SB, and BC mean 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, and SA mean B in distillate, C in side product, B in bottom product, and A in side product, respectively. Some composition control structures cannot have stable dynamic performances using the Aspen Plus Dynamics build-in Tyreus–Luyben method [40]. Therefore, SIMC tuning rules are used in this paper.

The dynamic responses of CS1 with only temperature controllers are very smooth. Although the impurity compositions have some steady state deviations, the deviations are small. In addition, the settling time is very short.

The dynamic responses with CS2 are smooth and very similar to CS1, and because of the added composition controller the impurity (component B) in the top product returns to its setpoint in this case. Also, all other impurity compositions are lower or at least the same as CS1.

The bottom composition shows some steady-state deviation with CS1 and CS2 for feed rate changes (e.g., see bottom right of Fig. 11), and the side stream composition shows deviations for feed composition changes (Fig. 12). CS3 has a selector where the maximum controller output value for the light impurity in the side product stream (SA), the impurity in the bottom product stream (BB) and the impurity in the bottom of the prefractionator (BpA) are controlled by manipulating the reboiler duty. However, an abnormal behavior of CCBB was observed during its tuning. When the reboiler duty increases, the impurity composition in the bottom product (BB) increases instead of decreasing as would be expected. These may be due to the strong interactions between the intermediate and bottom products. When the reboiler duty increases, the less volatile component in the side product stream (SC) increases. As the controller CCSC has been added, the side stream flow rate decreases. Because of mass balance, the bottom stream flow rate increases. The product in the bottom product stream (BC) decreases and the impurity in the bottom product stream (BB) increases. Thus, as a high selector is used in CS3, the bottom product (BB) is overpurified (Fig. 12).

In CS2b, in order to reduce the steady state deviation of the side product composition, controller CCSC is added to control the mole fraction of heavy component (C) in the side stream. However, simulations (Fig. 13) show that this was not successful as the bottom impurity increases beyond 2% when feed composition of A disturbance occurs.

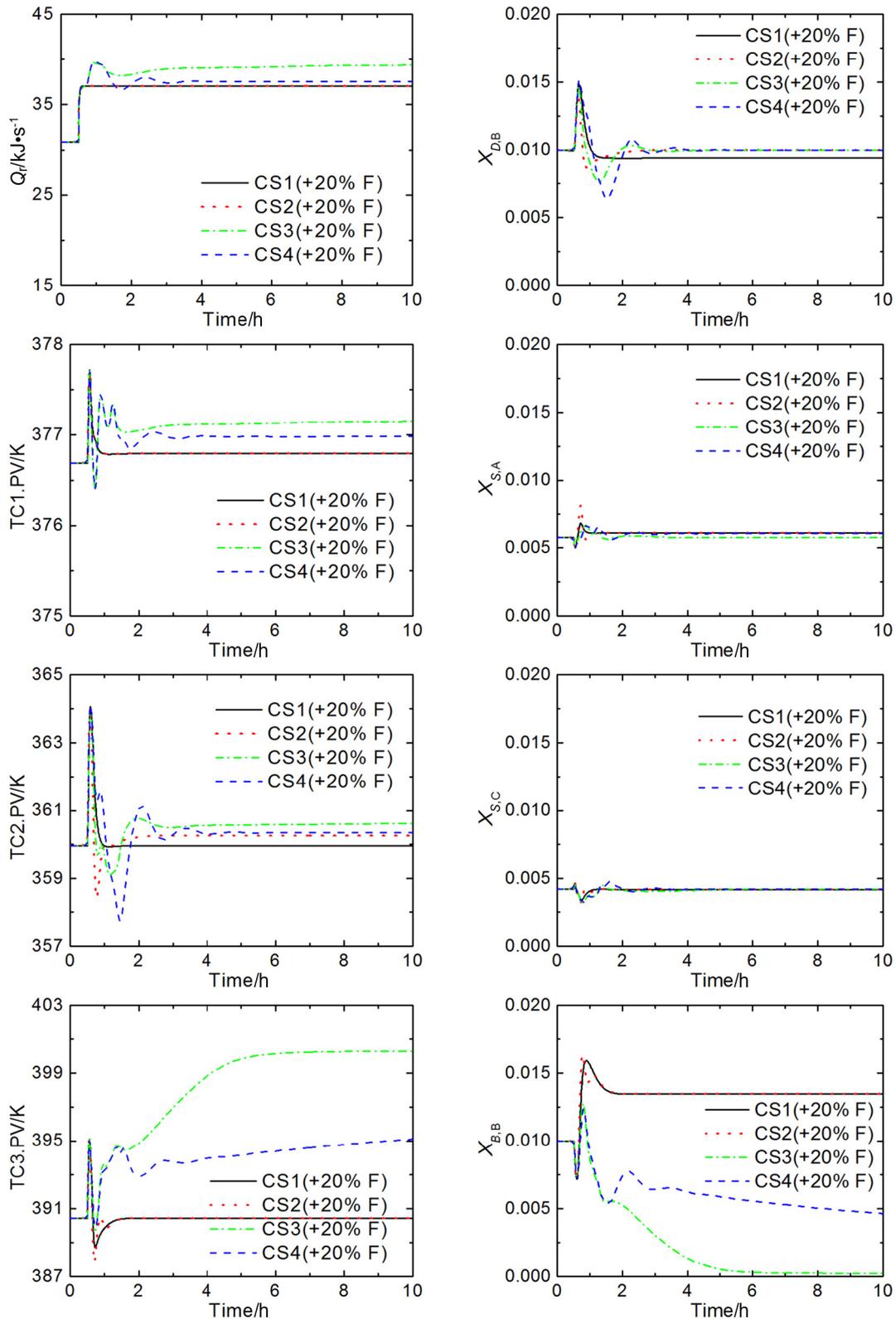


Fig. 11. Dynamic responses when +20% feed flow rate disturbance occur.

Thus control structure CS2b is not acceptable, as $T_{M,47}$ and $X_{B,B}$ drift away from their desired steady-state values. The reason is probably the strong interactions in the columns, which also result in the abnormal behavior of CCBB during its tuning in CS3.

In CS4, another high selector is added compared with CS3. Again, the bottom product (BB) is overpurified. The temperatures in dynamic

responses with CS4 are more stable than those with CS3. However, the energy consumption (Q_r) of CS4 is less than that of CS3.

The changes of the manipulated variable values for CS1 and CS2 are much smoother and with less oscillations than for CS3 and CS4. The dynamic changes in temperature are much faster than the variation of product composition because of the fast inner

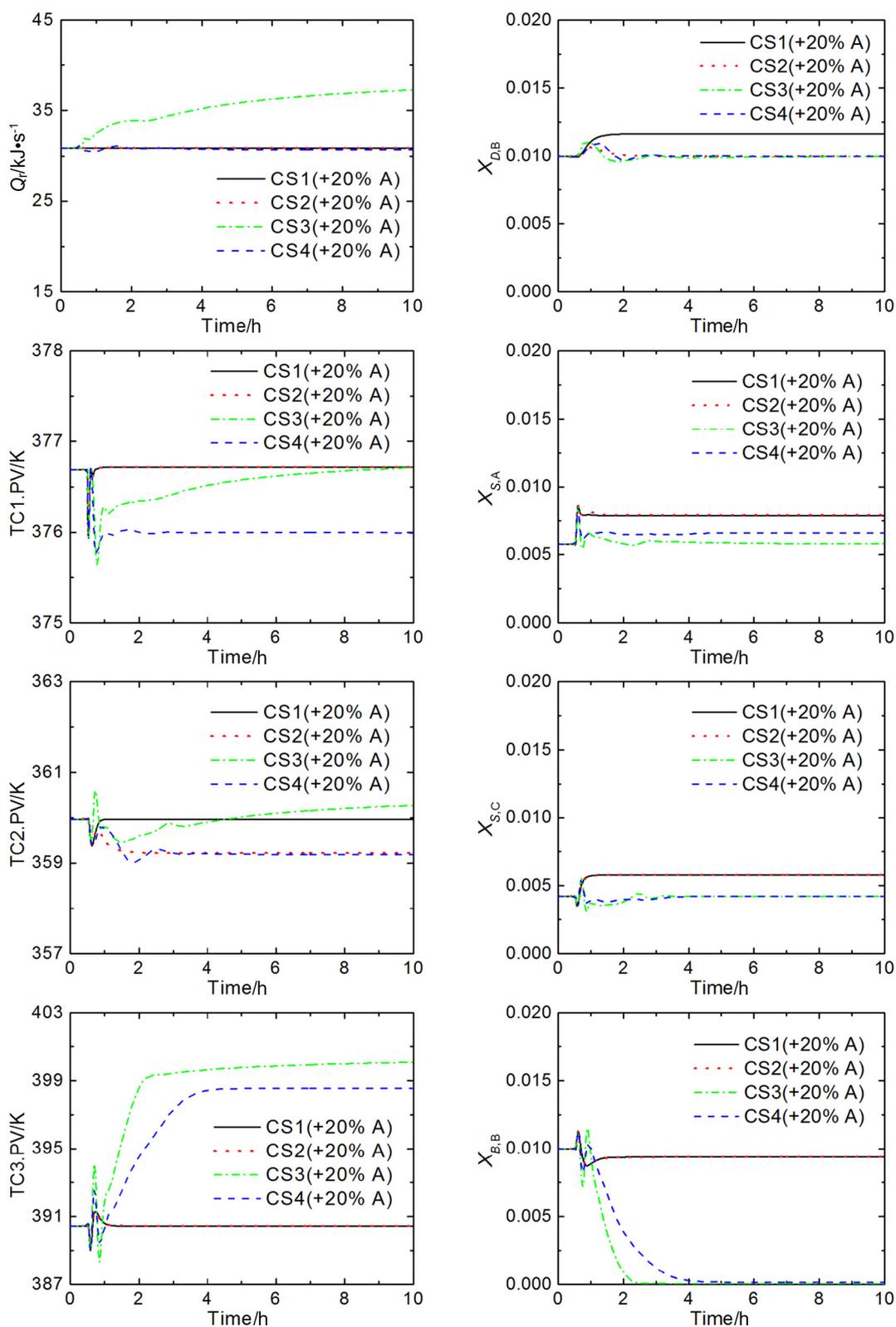


Fig. 12. Dynamic responses when +20% feed composition of A disturbance occur.

temperature loops. Therefore, temperature control is much faster than composition control. Overall, structures CS3 and CS4 have poor performance due to the large interactions. To deal with interactions one may consider using multivariable control (e.g. model predictive control, MPC).

For high-purity Petlyuk columns, integrated control and on-line optimization should be developed because it is difficult to achieve a good direct product quality control using traditional PID control or even multivariable predictive control due to some difficulties such as long response time [41].

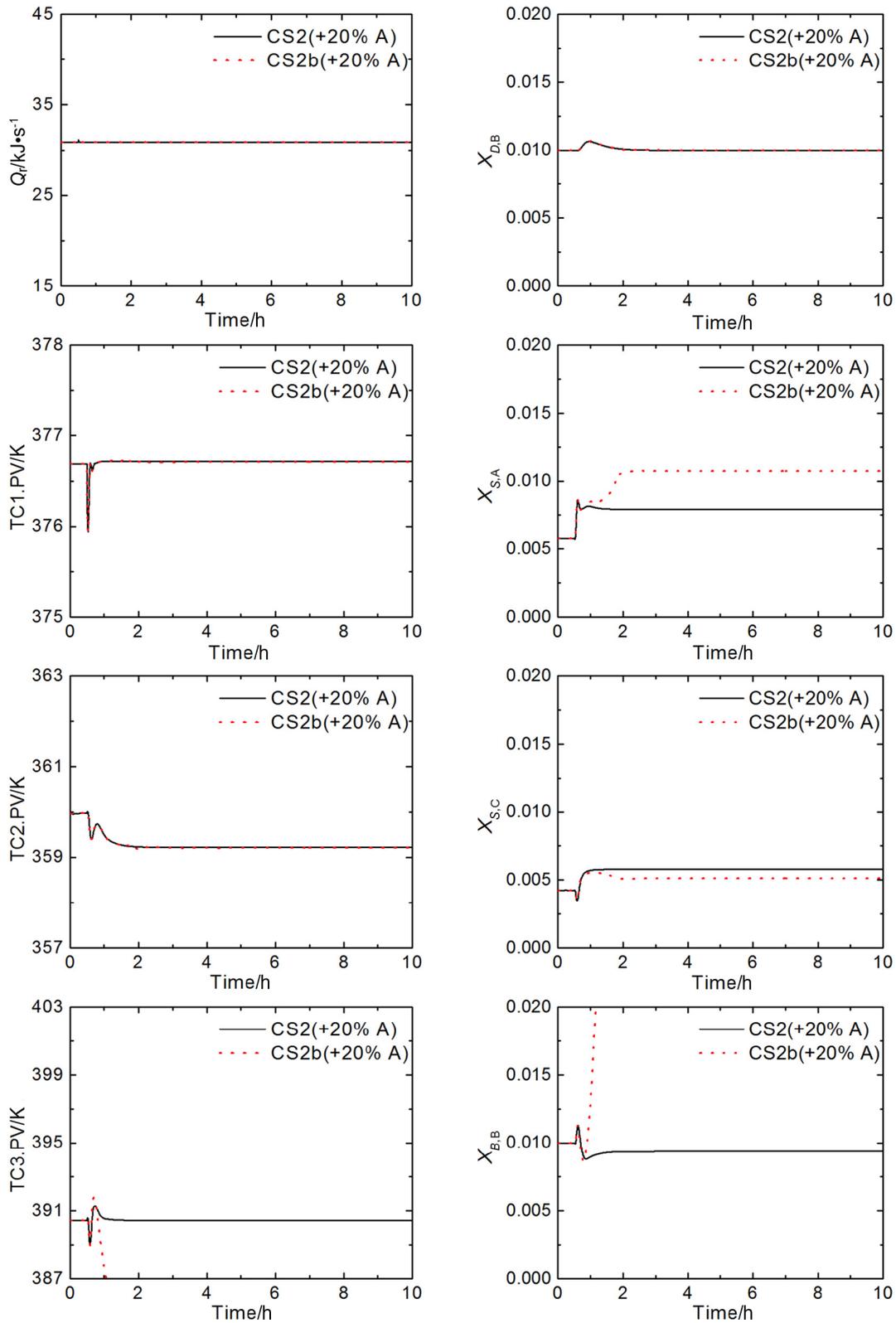


Fig. 13. CS2 vs CS2b: Dynamic responses when +20% feed composition of A disturbance occur.

5. Conclusions

Four control structures based on the PI control loops were simulated and compared. Control structure CS1 with three temperature control loops was shown to work well. Control structure CS2 with the addition of a distillate composition controller (CCDB) cascaded on top

of temperature control also works well. Control structure CS3 adds several composition loops and a selector to the reboiler duty and CS4 has an additional selector. Dynamic simulations for various disturbances showed that all control structures are able to maintain the desired steady states. Structures CS2, CS3 and CS4 all drive the impurity (B) in the top product to its setpoint, and the impurities in the side withdraw

product were also lower than or equal to those in CS1. However, CS3 and CS4 can give overpurified bottom product (BB), and the response time is longer than for CS1 and CS2. The results of the simulations show that even though the control structure with only temperature control (CS1) gives some steady-state deviations in the product compositions, the deviations is fairly small, and its dynamic performance is superior compared to CS3 and CS4. This suggests that temperature control should be basically used in the development of more advanced control structures for Petlyuk or DWC configurations.

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