

Temperature Difference Control of a Four-Product Dividing-Wall Distillation Column

Xing Qian^a, Kejin Huang^{a,*}, Shengkun Jia^b, Haisheng Chen^a, Yang Yuan^a

^aCollege of Information Science and Technology, Beijing University of Chemical Technology, Beijing 100029, P. R. China

^bSchool 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 300350, P. R. China

huangkj@mail.buct.edu.cn

The four-product extended Petlyuk dividing-wall distillation column (FPEP-DWDC) can save about 50% energy as compared with the conventional direct and indirect sequences. However, the complex structure of FPEP-DWDC results in strong interactions among different control loops and highly nonlinear behaviors. For the control of the FPEP-DWDC, temperature control (TC) scheme cannot work to handle the disturbances inserted into the process and none of the proposed control schemes can avoid the employment of composition controller (which is not recommended in industrial processes) in the opening articles. The proposed TC scheme in the current work cannot handle the disturbances either. Therefore, a kind of temperature difference control (TDC) scheme for the FPEP-DWDC and simplified temperature difference control (STDC) are proposed. In the proposed TC, TDC, and STDC schemes for the FPEP-DWDC, only temperature controllers are needed for the product quality control. In order to be less complicated than the TC scheme in the opening literature, minimum allowable controllers are used in the proposed TC, TDC, and STDC schemes. One TC/TDC loop for each split is used to reduce interactions among different control loops. One TC/TDC loop is installed in the prefractionator to ensure the A/D sharp split and keep the impurity components leaving from the top and the bottom of the first divided wall. Two TC/TDC loops are arranged in the intermediate distillation column to guarantee the A/C sharp split and the B/D sharp split and keep the impurity components leaving from the top and the bottom of the second divided wall and the third divided wall. Three TC/TDC loops are settled in the main distillation column to ensure the A/B sharp split, the B/C sharp split and the C/D sharp split. An illustrative example of the FPEP-DWDC separating a mixture of methanol, ethanol, n-propanol and n-butanol are adopted to evaluate the effectiveness of the proposed TC, TDC, and STDC schemes while a wide range of feed disturbances are confronted. The outcomes show that the dynamic performances of the FPEP-DWDC are substantially enhanced in most cases by using the proposed TDC and STDC schemes, which is an encouraging result for the industrialization of the FPEP-DWDC.

1. Introduction

Dividing wall distillation column (DWDC), which has been successfully introduced into chemical industries, provides a promising trend for distillation process intensifications. DWDC is a single shell, direct material coupling distillation column which needs less energy, capital and space than a conventional distillation column. However, the complex structure of DWDC results in strong interactions among different control loops and highly nonlinear behavior. To deal with this problem, many researchers have investigated the controllability and operability of different three-product DWDC configurations. Mutalib and Smith (1998) studied degrees of freedom in the three-product Petlyuk DWDC. They reported that the three-product Petlyuk DWDC has two additional degrees of freedom (the liquid split and the vapor split) which can be used as manipulated variables compared with the conventional distillation column. However, the liquid split can be easily varied while the vapor split is impractical to be manipulated.

There are very few industrialized four-product DWDCs and relatively few studies have been done on the four-product DWDC configurations. Kaibel DWDC is the simplest four-product DWDC as it contains only one

vertical divided wall in the distillation column. Dwivedi et al. (2012) experimentally verified the vapor split as a manipulated variable for Kaibel DWDC for the first time. Qian et al. (2016) proposed different control schemes (including temperature control, composition control and composition/temperature cascade control) for Kaibel DWDC, and the results show that the dynamic performances of temperature control are very good.

The four-product extended Petlyuk dividing-wall distillation column (FPEP-DWDC), which contains three vertical divided walls in the distillation column as shown in Figure 1, is able to save about 50% energy as compared to the conventional direct and indirect sequences (Dejanovic et al., 2011). Due to the strong process intensification, the FPEP-DWDC has complicated dynamics which is worth to be studied. To deal with this problem, Dwivedi et al. (2013) proposed four kinds of control schemes for the FPEP-DWDC for separating a mixture containing methanol, ethanol, propanol and n-butanol. They developed pure temperature control scheme, pure composition control scheme, pure composition control scheme with a max-selector, and composition/temperature cascade control scheme with a max-selector. The first two control schemes cannot achieve the objective of disturbance rejection while the latter two control schemes can do this job because light impurity composition controls in the side streams were arranged in the latter two control schemes. However, composition controllers, which are not recommended in the real industrial processes because of their unreliability, high cost, and long dead time, were needed in the control schemes proposed by Dwivedi et al. (2013). Therefore, it is worth to develop a novel control scheme containing only temperature controllers for the FPEP-DWDC.

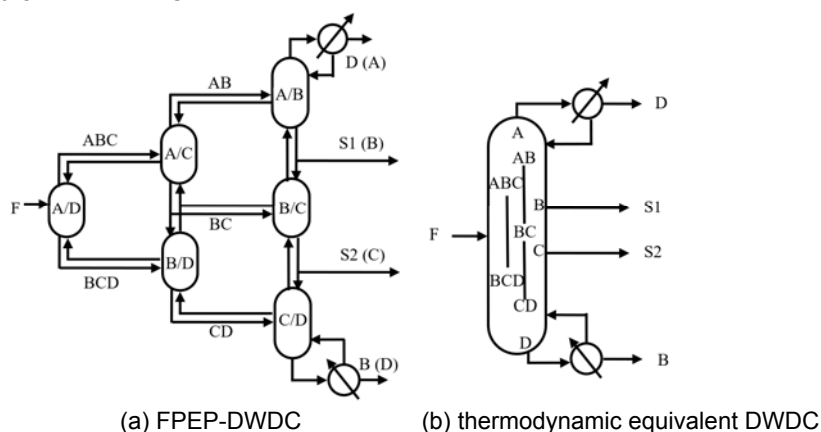


Figure 1: FPEP-DWDC and its thermodynamic equivalent DWDC

In the current work, three control schemes are proposed including temperature control (TC), temperature difference control (TDC), and simplified temperature difference control (STDC) schemes. However, the sensitive temperature cannot indicate the corresponding compositions appropriately, which results in the failure of TC. Temperature difference is able to indicate the variance of compositions. Therefore, all TC loops are replaced by TDC loops in the TDC scheme. In order to be less complicated, the STDC scheme is proposed. In the STDC scheme, TDC loops are used in the prefractionator and the intermediate distillation column (IDC) while TC loops are used in the main distillation column (MDC). Because there are all sharp splits between adjacent components and nearly no other components exist in each part of the MDC as shown in Figure 1, the sensitive temperatures are able to indicate the corresponding compositions appropriately. The dynamic performances are evaluated for a wide range of feed disturbances (the dynamic performances for feed composition disturbances will be shown in the extended paper). The results are further discussed and conclusions are drawn in the last section.

2. Process description

The FPEP-DWDC and its thermodynamic equivalent DWDC configurations studied in this work are sketched in Figure 1. The FPEP-DWDC is established for separating a mixture containing methanol (A), ethanol (B), n-propanol (C), and n-butanol (D). The feed is equimolar saturated liquid. The feed flow rate is 1 kmol/h. The relative volatilities are 7.1, 4.43, 2.15, and 1, respectively. The steady state design of FPEP-DWDC was performed with Aspen Plus while the dynamic analyses were conducted with Aspen Plus Dynamics. The property method is NRTL. The specifications for the four products are set as 99 mole %. The steady-state design of FPEP-DWDC and its temperature profiles are shown in Figure 2.

There are three sections in the FPEP-DWDC. The prefractionator performs a sharp A/D split, while B and C are distributing components. The upper part of the IDC performs a sharp A/C split, and B is the distributing

component. The lower part of the IDC performs a sharp B/D split, and C is the distributing component. The upper part of the MDC performs a sharp A/B split. The middle part of the MDC performs a sharp B/C split. The lower part of the MDC performs a sharp C/D split. In general, one stabilizing temperature or composition loop is needed for each split (Skogestad, 2007). Since temperature sensor is much faster and less expensive than composition analyzer, temperature control is generally more preferred than composition control in the chemical industry. In the current work, TC, TDC, and STDC are studied in order to promote the industrialization of FPEP-DWDC.

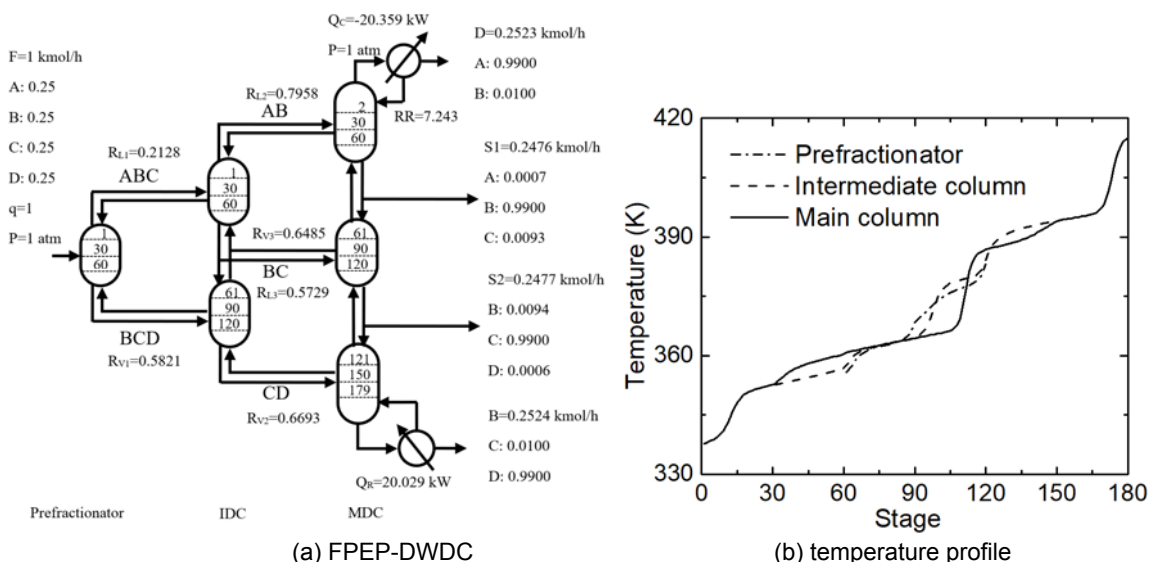


Figure 2: FPEP-DWDC and its steady-state behavior

3. Control schemes

Proportional-integral (PI) controllers are used in the current work, except proportional (P) controllers for levels. The pressure control (PC) and level control (LC) are not illustrated in the figures of the control schemes. The pressure of the FPEP-DWDC is controlled with the condenser heat duty (Q_C). The sump level is controlled by the bottom product flow rate B. The level of the reflux drum is controlled by the reflux flow rate R (since the reflux ratio $RR = 7.243 > 3.0$). Q_R/F ratio controller is introduced into the control scheme to be more adaptable when feed flow rate disturbances occur. With pressure and level control loops closed, there are ten remaining degrees of freedom, which correspond to the following manipulated variables (u): 1. Reboiler heat duty (Q_R), 2. Distillate product flow rate (D), 3. First side product flow rate (S1), 4. Second side product flow rate (S2), 5. Liquid reflux stream from the IDC to the prefractionator (L1), 6. Vapor boilup stream from the IDC to the prefractionator (V1), 7. Liquid reflux stream from the MDC to the IDC (L2), 8. Vapor boilup stream from the MDC to the IDC (V2), 9. Liquid side stream from the IDC to the MDC (L3), 10. Vapor side stream from the MDC to the IDC (V3). In the current work, the three thermally coupled vapor streams are not used as manipulated variables (i.e. the three vapor splits R_V are fixed) in order to be more applicable for the industrialization of FPEP-DWDC. Therefore, seven degrees of freedom can be used as manipulated variables. Although simple, TC scheme is relatively not good when feed flow rate disturbances inserted into the FPEP-DWDC. Therefore, TDC scheme and STDC scheme are proposed for the FPEP-DWDC. Both of the two control schemes have improved dynamic performances as compared with the TC scheme. Besides, STDC scheme utilizes fewer temperature sensors than the TDC scheme. The proposed TDC scheme and STDC scheme are much less complicated than the available composition/temperature cascade control schemes for the FPEP-DWDC (Dwivedi et al., 2013). Differential temperature control has been used for many years in traditional multi-component distillation column. Therefore, TDC scheme and STDC scheme proposed for the FPEP-DWDC are probably able to use in chemical industry. In the current work, one TC/TDC loop for each split is used. The prefractionator needs one TC/TDC loop because it performs a sharp A/D split. The IDC needs two TC/TDC loops because the upper part of the IDC performs a sharp A/C split and the lower part of the IDC performs a sharp B/D split. The MDC needs three TC/TDC loops because the upper part of the MDC performs a sharp A/B split, the middle part of the MDC performs a sharp B/C split and the lower part of the MDC performs a sharp C/D split. There are six sharp splits in the FPEP-DWDC. Therefore, at least six

TC/TDC loops should be used for control of FPEP-DWDC. In the TC scheme, six TC loops are employed to ensure the six sharp splits.

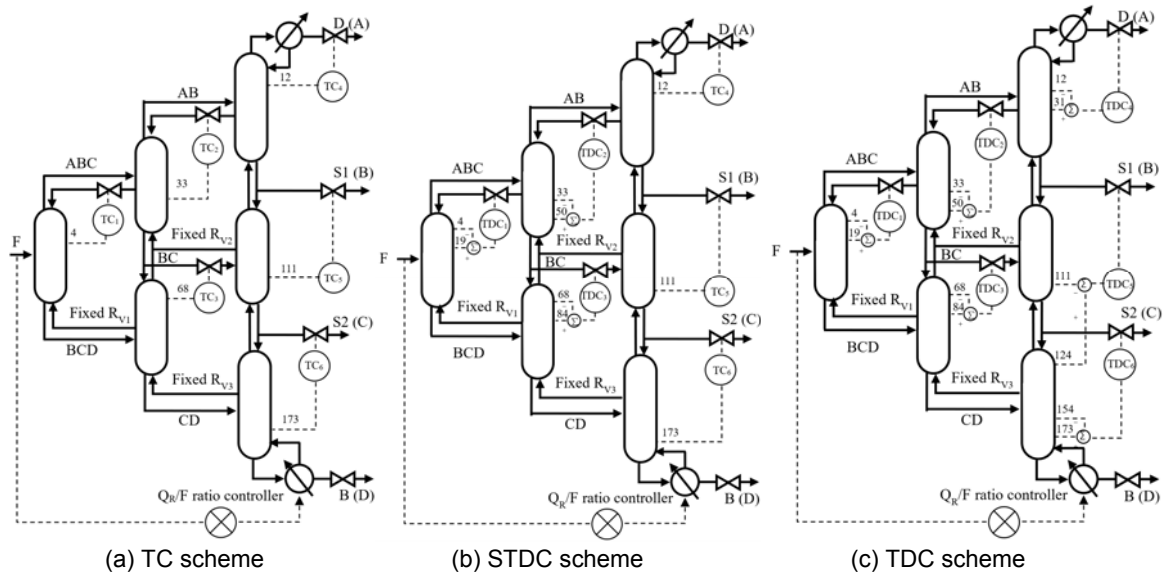


Figure 3: TC, STDC, and TDC schemes for the FPEP-DWDC

It is important to decide which sensitive stages should be controlled. Sensitivity analysis (SA) is used for selecting sensitive temperatures. Singular value decomposition (SVD) is used for selecting reference temperatures. The detailed principles for determination of sensitive and reference stages in terms of SA and SVD techniques can be found in the opening literature (Ling and Luyben, 2010). The proposed TC, STDC, and TDC scheme for the FPEP-DWDC in the current work are shown in Figure 3. The Tyreus-Luyben tuning method embedded in Aspen Plus Dynamics was employed to tune the six controllers (the dead time in each loop is set to be 1 min). First of all, the D loop in the top of the MDC is tuned as it affects all the other process variables. Secondly, with the D loop on automatic, the S1 loop is tuned. Thirdly, with the D and S1 loops on automatic, the S2 loop is tuned. Then, with the D, S1, and S2 loops on automatic, the L2 loop in the top of the IDC is tuned. Then, with the D, S1, S2, and L2 loops on automatic, the L3 loop is tuned. Finally, with the D, S1, S2, L2, and L3 loops on automatic, the L1 loop in the top of the prefractionator is tuned. Controller parameters for TC, STDC, and TDC are shown in Table 1.

Table 1: Controller parameters of the TC, STDC, and TDC schemes

Control scheme	Control loop	KC	Tl (min)
TC	L1	8.26	17.16
	L2	5.43	15.84
	L3	3.94	14.52
	D	10.26	43.56
	S1	2.24	30.36
	S2	3.98	21.12
STDC	L1	0.697	14.52
	L2	0.365	14.52
	L3	0.228	15.84
	D	12.82	44.88
	S1	2.25	30.36
	S2	3.62	21.12
TDC	L1	0.697	14.52
	L2	0.365	14.52
	L3	0.228	15.84
	D	0.933	38.28
	S1	0.779	23.76
	S2	0.816	18.48

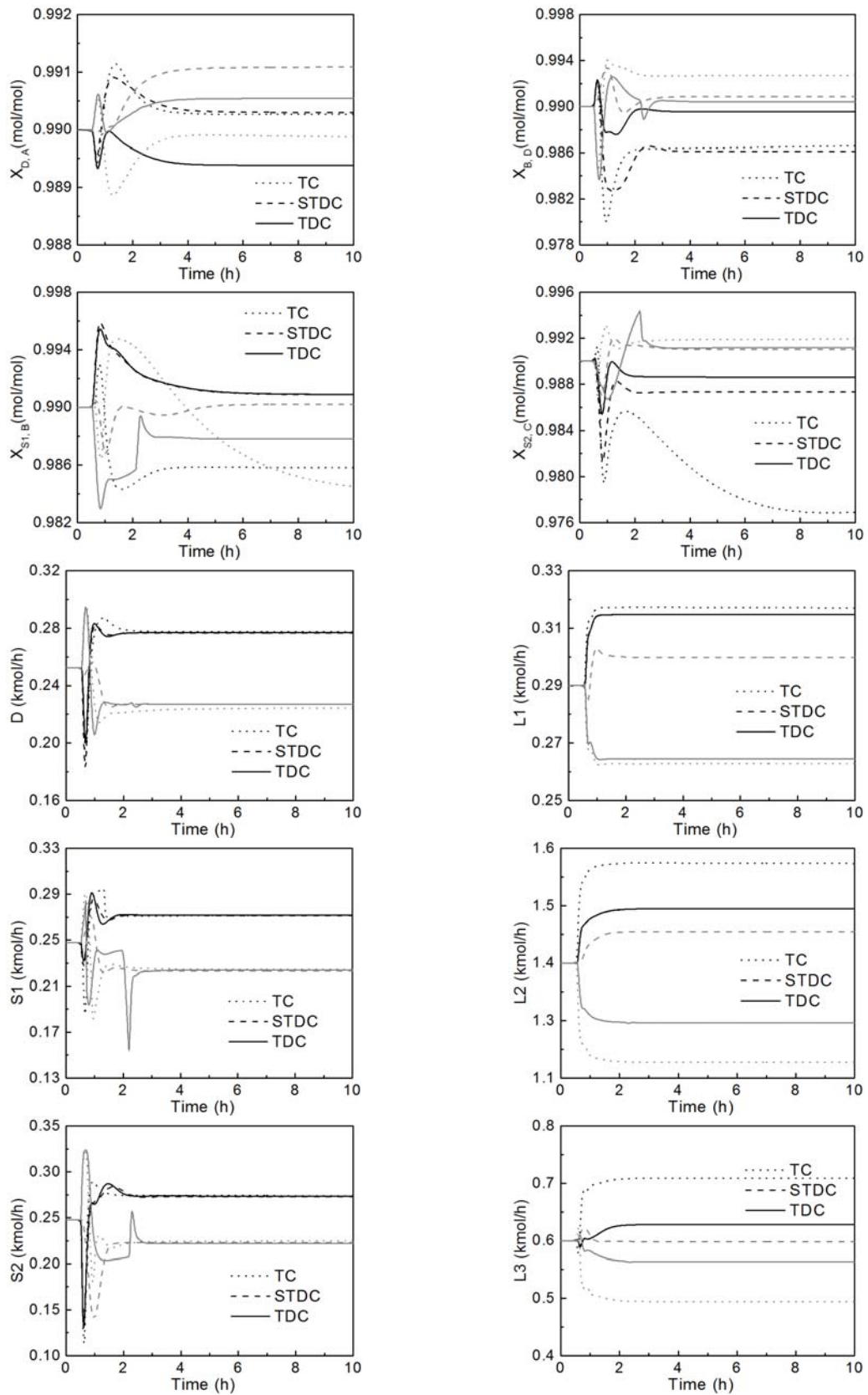


Figure 4: Comparison between the TC, STDC, and TDC schemes in face of a $\pm 10\%$ step change in feed flow rate

4. Results and discussions

The dynamic performances are satisfying using the proposed STDC and TDC schemes. Comparison between the TC, STDC, and TDC schemes in face of a $\pm 10\%$ step change in feed flow rate is shown in Figure 4. The TC scheme is shown in dot curves while the TDC and STDC schemes are shown in solid and dash curves, respectively. The solid TDC curves in some figures overlap the dash STDC curves because the manipulated variables are the same in the prefractionator and the intermediate distillation column. The dynamic performances using TC scheme are relatively not good. The second side product composition decreases to 97.7% using TC scheme when +10% step change in feed flow rate disturbance occurs. The first side product composition settles down in about 10 hours using TC scheme when -10% step change in feed flow rate disturbance occurs. The failure of the TC scheme is due to the complicated dynamic behaviors of the FPEP-DWDC, i.e., the inherent strong interaction and the high degree of process nonlinearity. Compared with the TC scheme, the steady-state deviations and the peak deviations are suppressed substantially employing the STDC and TDC schemes.

5. Conclusions

With three pairs of thermally coupled liquid streams and vapor streams, the FPEP-DWDC shows inherent strong interactions and highly nonlinear behaviors. The complicated dynamic behaviors of the FPEP-DWDC preclude the TC scheme to achieve tight product quality control. However, the dynamic performances of the FPEP-DWDC are substantially enhanced in most cases by using the proposed STDC and TDC schemes. TC scheme works surprisingly well for the four-product Kaibel DWDC (Qian et al., 2016) because it is practically sharp split between adjacent components in each column section (B/C sharp split in the prefractionator and A/B, B/C and C/D sharp split in the MDC). In the FPEP-DWDC, it is not sharp split between adjacent components in the prefractionator and the IDC. In other words, multiple components (distributing components and key components) coexist in the prefractionator and the IDC. Therefore, the sensitive temperature cannot indicate the corresponding compositions appropriately. These reasons result in the failure of TC scheme of the FPEP-DWDC. Temperature difference is able to indicate the variance of compositions, so STDC and TDC schemes show better performances than TC scheme. Compared with the TC scheme proposed by Dwivedi et al. (2013), four TC/TDC loop corresponding to three vapor splits and one reboiler heat duty are reduced, as one TC/TDC loop is used for each split. These not only decrease installation cost and maintenance cost, but also reduce excessive interactions among different control loops. There are no feasible control schemes without composition controllers to control the FPEP-DWDC in the opening literature. The proposed STDC and TDC schemes are the feasible control schemes of the FPEP-DWDC with pure temperature controllers for the first time. This is an encouraging result for the industrialization of the FPEP-DWDC.

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